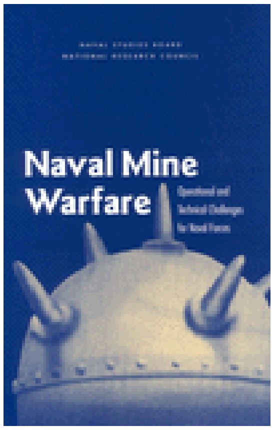

The Carbon Dioxide Dilemma: Promising Technologies and Policies

National Academy of Engineering, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

The Carbon Dioxide Dilemma

Promising Technologies and Policies

PROCEEDINGS OF A SYMPOSIUM

April 23–24, 2002

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Preface

The energy future of the United States could take a number of directions, depending on international politics, technology development, the health of the economy, and life-style changes. Added to this mix are growing concerns about climate change, specifically the role in global warming of anthropogenic carbon dioxide produced from millions of sources around the globe. Today, everyone is familiar with the chart showing the dramatic rise in levels of atmospheric carbon dioxide since the advent of the Industrial Revolution in the late 1700s, especially since 1900. Given the possible role of carbon dioxide in global warming, future controls on carbon emissions are inevitable.

One way to reduce atmospheric levels of carbon dioxide is through sequestration or the safe disposal of large quantities of carbon dioxide in locations where it will not reenter the atmosphere. A group of specialists met at the National Academy of Sciences Building, under the auspices of the National Academy of Engineering and the Board on Energy and Environmental Systems of the National Research Council, on April 23 and 24, 2002, to discuss ways of achieving this. The purpose of the meeting was not to find a consensus for dealing with the myriad issues associated with carbon dioxide sequestration, but to present a range of options for consideration by the scientific and engineering communities. The options discussed included ocean disposal, terrestrial disposal in geologic reservoirs, moving toward a noncarbon-based economy, and several biomass-based approaches. Market-based approaches coupled with carbon trading were also considered. However, no single policy emerged as a clear winner, and studies of the cost, effectiveness, and social impacts of all these options are ongoing.

Approaches to carbon dioxide sequestration vary widely and involve a wide range of disciplines. The presentations reflected this diversity and represented a broad spectrum of views regarding the severity of the problem and how we should deal with it.

Brad Allenby of AT&T opened the meeting with a broad, theoretical overview of the problem. Robert Socolow of Princeton University then described the situation as a century-scale problem. Socolow believes we will make several false starts toward a solution before we get it right, well after conventional carbon-based fuels have run out. The most basic approach currently under discussion is sequestration in geologic formations. Franklin Orr of Stanford University presented an introduction to this approach. The history of the use of carbon dioxide for enhanced gas and oil recovery was discussed by Gardiner Hill of BP Group. Sally Benson of the Lawrence Berkeley National Laboratory then discussed the research and safety aspects using these techniques.

The direct capture of carbon dioxide at energy-production facilities promises high levels of efficiency, especially when power plants are located near injection wells. This approach was discussed by Dale Simbeck of SFA Pacific, a consulting company, who has been studying this issue for many years from the point of view of the economics and associated carbon taxes for new energy technologies. David Hawkins of the National Resources Defense Council then made the case for the deployment of low-carbon technologies based on specific carbon-emission goals set far in the future.

The next group of presentations addressed the option of ocean disposal. Peter Brewer of the Monterey Bay Aquarium Research Institute described experiments with direct injection of carbon into the oceans. These experiments pointed to interesting possibilities for safe disposal. As a follow up, Ken Caldeira of Lawrence Livermore National Laboratory focused on ocean fertilization, which involves adding iron to the ocean to stimulate photosynthetic activity, thus increasing the fixation of carbon dioxide.

In a shift to terrestrial-based solutions, Gary Jacobs of Oak Ridge National Laboratory gave an overview of using terrestrial ecosystems to reduce carbon dioxide emissions to enhance photosynthesis. This was followed by a presentation by John Kadyszewski of Winrock International on ways of measuring and monitoring terrestrial-carbon dynamics. Lowell Wood of Lawrence Livermore National Laboratory then moved the discussion into space, suggesting that it might be necessary to place scattering material into space to reflect incoming radiation. This approach, although somewhat radical, might be the last step in a series of steps to address the problem.

In a complete change of direction, James Lake of the Idaho National Engineering and Environmental Laboratory turned the discussion to nuclear energy systems that have zero carbon emissions and coproduce hydrogen through electrolysis. Howard Herzog of Massachusetts Institute of Technology then enumerated the top 10 points everyone should understand about sequestration. A final talk was provided by Mike Walsh of Environmental Financial Products LLC, who discussed the feasibility and recent performance of long-term carbon-trading schemes.

This collection of transcribed, informal talks is intended to be an introduction to the major approaches to carbon sequestration. The positions of the speakers do not represent current government policy or a consensus of best approaches. They do reflect fairly recent thinking on the subject. Much more research will be necessary, of course, before the government and its partners in the private sector can begin to chart a course of action. All of the participants agreed that the concentration of carbon dioxide in the atmosphere will continue to increase for some years to come and that humankind will have to find ways of dealing with the impacts. The scope, scale, and severity of these impacts are relatively unknown, however, and it may be several decades before the atmospheric concentration of carbon dioxide reaches a steady state, which will be significantly higher than it is today.

Wm. A. Wulf
President
National Academy of Engineering

Staff:
Jack Fritz, Senior Program Officer
Brendan Dooher, Fellow
Carol R. Arenberg, Managing Editor
Rebecca Weiss, Senior Project Assistant

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Introduction

Global Climate Change and the Anthropogenic Earth

BRADEN R. ALLENBY
AT&T

> So long as we do not, through thinking, experience what is, we can never belong to what will be. . . . The flight into tradition, out of a combination of humility and presumption, can bring about nothing in itself other than self-deception and blindness in relation to the historical moment.
>
> -Martin Heidegger

At this point in the evolution of our species, we appear to be deeply afflicted with a failure of perception precisely as Heidegger described it, and the lack of vision that results makes us increasingly dysfunctional and even dangerous. The most evident example of this failure of thinking and vision is our profound reluctance to understand precisely what we have done to our Earth (Allenby, 2002). I recently had a fascinating conversation with a planetary geochemist who was explaining what we would have to do to terraform Mars. It sounded futuristic and exotic, and somewhat speculative, until I realized that, in fact, terraforming on a planetary scale is exactly what we have done to our own planet. Terraforming planet Earth has not been the work of the twentieth century but of many centuries; and it is a project that has now come to fruition (Derr, 1996; Grubler, 1998; McNeill, 2000). Try this thought experiment. Think of an alien surveying this sector of space and suddenly coming upon our planet. It would see landscapes of invasive species, urbanism and agriculture, the chemical composition of the atmosphere and surface waters, and the dynamics of the grand cycles of carbon, nitrogen, sulfur and phosphorous all affected by, in many cases determined by, human activity. Biological structures at all scales, from the genetic to the regional, would similarly reflect the choices, impacts, and activities of humans. It would be difficult for an alien to avoid concluding that Earth is a planet designed to support a single species—ours. This is a monoculture, a profoundly human planet, the anthropogenic Earth.

But we do not admit this, even to ourselves. I think there are at least two reasons for this. First, if we admit that we have “designed” Earth for our own purposes, we must also admit that we have some moral responsibility for what we have done—and that is really frightening. Second, many of us, for reasons that can be traced back in history, have learned to regard "Nature" as sacred (Abrams, 1971; Allenby, 2002). Thus, if we accept that we have terraformed the Earth, we will feel as if we have blasphemed—disturbing a powerful feeling, largely on an unconscious level. These very intense feelings may indeed, in Heidegger's formulation, lead us to "flee into tradition" to try to avoid "experiencing what is" and encourage us not to realize what we have actually accomplished. But the time is coming when denial will no longer be acceptable. For we do have a responsibility, and we must exercise it rationally and morally.

To be sure, the world is not simply a human artifact. Not everything on Earth is a human creation or intentionally designed as we now think of that activity. The Arctic and the rain forests are not human artifacts, but their dynamics are influenced by humans in ways that we are just beginning to appreciate. Even in the Amazon, for example, evidence increasingly demonstrates that humans long ago constructed large earthen structures. Even more impressively, up to 10 percent of the soil area in the Amazon rain forest—an area the size of France—is covered by a rich, dark loam known as *terra preta do Indio* (Indian dark earth), the intentionally created product of generations of indigenous humans (Mann, 2002).

Earth is thus "engineered" in the same sense that a city or the Internet is engineered. "Though human made, the Internet is not centrally designed. . . . the Internet is closer to an ecosystem than to a Swiss watch" (Barabasi, 2002). Earth is a highly complex, self-organizing, interactive system with components, from agricultural systems to genetic structures, that are increasingly anthropogenic. Given the scale of human technological and economic systems and human demographic patterns, this trend will intensify in the future unless there is a catastrophic collapse of the species.

Approaching the current global climate-change negotiating process, which I will call the Kyoto process for short, with this perspective, it is apparent that the real question is not simply how to withdraw the human presence from the globe, by presuming, for example, to reduce all carbon emissions to preindustrial levels. That approach is indeed a "flight into . . . self-deception and blindness," for human population levels and economic dynamics make such a path highly unlikely, absent massive systems collapse. The real question is slightly different and far more challenging. If the effect of our activities has been to create the anthropogenic Earth, including, of course, elements of the carbon cycle that, through atmospheric dynamics, can have effects on the climate system, don't we have to take real moral responsibility for that? If so, we must begin not by fantasizing a utopia we wish to perceive, but by struggling to shape the path of very complex and coupled systems—which means that we must assume responsibility for choosing a path. That is a very different proposition.

The Kyoto process is a wonderful learning process, in part because of its flaws. Begin with a simple observation that the global climate-change negotiating process, like virtually all international negotiations, is being conducted entirely by nation states. Indeed, under international law, nation states are the only entities that have sovereign power. This governance structure is, however, both increasingly obsolete and increasingly dysfunctional. It may have made sense in 1648 when it was institutionalized by the Treaties of Westphalia that ended the Thirty Years' War, but nation states are clearly no longer the only relevant actors in international governance systems. Their authority, while still significant (especially in determining local cultural and institutional structures), is being increasingly eroded by the growth of large transnational firms and nongovernmental organizations (NGOs) (Cooper, 1996; Mathews, 1997), global patterns of technological evolution and management (Grubler, 1998), the evolution of transnational standards of human rights, often enforced by pressure from NGOs rather than governments (Sassen, 1996), and the growth of communities and groups across information networks, which are not limited to geographic boundaries (Castells, 2000; Barabasi, 2002). Thus, the very governance structure that underlies the Kyoto process is obsolete. It is like trying to design a modern jet airliner while limiting oneself to using the tools and methods available to sixteenth-century shipwrights.

Another very interesting aspect of the Kyoto process—something it has in common with other global negotiations, as well as technological developments now going forward—is that the process takes systems that were previously relatively separate from human systems and embeds them deeply into human systems. This "commoditization" process means that the natural dynamics of these "natural" systems are augmented with the dynamics that characterize human systems (such as economies), particularly contingency and reflexivity. Thus, we can interpret the Kyoto process in a Marxist way as the "commoditization" of the carbon cycle. When companies buy chunks of the rain forest in Costa Rica so they can emit carbon dioxide from a generating plant, that is commoditization—a previously "natural" system has become monetized and can now be bought and sold like any other commodity.

In fact, this is not a new phenomenon. A major feature of the anthropogenic Earth, however, is the commoditization of vast swathes of natural cycles, beginning with agriculture, and now accelerating into genetic engineering, carbon cycle management, and the like. Humans inherently change natural systems by importing into them the dynamics of human systems; indeed, this is a principle effect of cultural and technological evolution.

In *The Communist Manifesto* (1872), Marx said something else relevant to our discussion. He said that continued expansion of the market structure is inherent in the nature of capitalism. In his view, that was a major reason for colonialism and imperialism, but we can just as easily apply it to the relationship between humans and their environment. As humans and our technologies, societies, and economies have matured, we have also increasingly dominated the environment (Marx, 1872):

> In place of old wants, satisfied by the productions of the country, we find new wants, requiring for their satisfaction the products of distant lands and climes. In place of the old local and national self-sufficiency, we have intercourse in every direction, universal interdependence.

The combination of commoditization and the globalization of commerce is extremely powerful. Both have significantly changed the fundamental structures of "natural" systems as they increasingly become coupled to human systems, such as the economy. Absent economic or social collapse, this process does not appear to be reversible

From a postmodernist perspective, the Kyoto process raises more subtle issues. For example, many of the ideas or cultural constructs that participants bring to the debate are stable in the short term but very unstable in the long term simply because they are cultural constructs, and cultures change, relentlessly and powerfully, over time (Hacking, 1999). For instance, when the New World was first settled, people took it for granted that they should go out and turn forests and jungles into Gardens of Eden. This was reflected in the way they regarded the concept of "wilderness," which was considered evil, satanic, ungodly, and full of demons. Contrast that with the way we now think of wilderness—as sacred space. In just 200 years, the concept of wilderness has changed completely. The same is true of many concepts underlying environmental discourse (Allenby, 2002). It used to be, for example, that "natural" was considered the opposite of "supernatural." Now, partly as a result of environmental discourse, "natural" is considered the opposite of "human." Whatever is built or made by humans is considered unnatural—despite, of course, the obviously oxymoronic structure of this mental model. Humans are so far incapable of creating anything that cannot be explained by physical, chemical, or biological principles and laws.

However, the rates of change of cultural constructs are irrelevant for most environmental projects. Cleaning up a hazardous waste site, for example, or implementing regulations regarding clean air and water does not take long enough for cultural constructs to change during the process. But if we are talking about establishing future evolutionary paths for the carbon cycle, the nitrogen cycle, or the climate cycle, we can predict with certainty that all of our current cultural concepts will change during the relevant time period. We don't know how they will change—but we know that they *will* change and that, thanks to an increasingly information-intensive economy, they will most probably change faster than they have in the past. Thus it is highly likely that the cultural constructs we implicitly treat as fixed for purposes of the climate change negotiations are, in fact, variable and that by treating them as if they were fixed, we may be unintentionally mischaracterizing both the problem and its complexity. Rather than implicitly assuming that in the future preference structure will reflect ours (e.g., by restricting economic growth now in a speculative effort to reduce global climate change forcing), perhaps we should try to develop policies and regulatory structures that can evolve as cultural constructs and preferences change. But that would require understanding our preferences as contingent, not absolute, and that is unlikely, especially in such an ideologically charged environment.

Another interesting aspect of the Kyoto process is cultural homogeneity. Environmental discourse, almost by definition, leads to homogeneity. Has any of us heard anyone at Kyoto express opposition to the concept of sustainable development? Of course not, because only people who believe in sustainable development have been included—more accurately, have chosen to participate—in the process. That means the Kyoto discussions do not take into account many other voices.

If we were dealing with a bounded environmental problem, such as the kind of technology to use for a treatment of end-of-pipe effluents, limiting the discussion to an environmentalist discourse in this way would be entirely appropriate because that's where the expertise is, and the decision is not likely to have broad economic or cultural impacts. But if we are discussing how to reconfigure the potential pathways for human economic development for the next 300 years or the energy technologies that will be available for development in Asia, Latin America, or Africa, which is what the Kyoto process implicitly involves, we need a very different kind of discussion. Environmental issues that have enormous cultural and economic implications require a discussion that goes beyond environmentalist discourse and a much more transparent process.

Thus, for example, even though developing countries are sensitive to the potential impacts of climate change on them, when the subject of establishing quotas for renewable energy technologies came up at the Johannesburg World Conference on Sustainable Development, they were virtually unanimous in their opposition. They are also sensitive to the possibility of implicit cultural imperialism in the climate change negotiation process. A dialogue that purports to affect the potential evolutionary pathways of much of humanity, and, for that matter, much of the biosphere, requires a transparent process that is open not just to the powerful but also to the powerless (Habermas, 1975). There are no existing institutions that can provide such a broad forum, but the principle is apparent.

Even linguistic patterns can make a difference. A few years ago, I watched a televised debate sponsored by Resources for the Future about climate change between an environmentalist and a representative of the American petroleum industry. I found the debate rather unsatisfying, but only later did I understand why—there was a complete disconnect between the language used and the underlying, very different realities each side represented. Knowing that the appropriate language for an environmental discussion was scientific and technical, the participants expressed their arguments accordingly. Therefore, there was no indication in the dialogue that, in fact, the essence of the discussion was religious not scientific. The participants spoke as if their positions had been rationally derived from the data, but they were clearly based on different foundational beliefs about what the world was, is, and should be. Therefore, nothing scientific or factual that was said by either could affect the other's position. This is a common phenomenon in the environmental arena.

The problem of linguistic dissemblance occurs when ideologies, or even theologies, are driven underground. In the Kyoto process, for example, the discussion is really about how society, culture, and, indeed, the world that increasingly reflects our activities should evolve over the next 300 to 400 years. Self-evidently, that is a very profound challenge in a multicultural world. But it would be far more productive to accept that challenge and address the real issues than to keep up the pretense that these ideological differences are not important. The Kyoto process is, perhaps, the first unrecognized, but explicit, attempt to develop policies intended to design the world of the future, and it cannot succeed, even if a policy is ratified, unless we accept the reality and the attendant moral responsibility for what we create.

Moreover, there is a perception, especially among some groups in the United States, that the global climate-change negotiations are as much about social engineering as anything else. These critics cite as proof European insistence that the United States should not be allowed to use purchased carbon credits or other mechanisms to meet its treaty requirements in full but be required to reduce substantially its own emissions. Obviously, the carbon cycle does not "care" where emissions reductions, if that is the chosen measure, occur.

The impression, reinforced in statements by European negotiators and environmentalists, is that the real issue is that the pattern of consumption, especially in the United States, is inappropriate, or even evil, and, since it cannot be controlled directly, it must be changed indirectly. The Kyoto process then becomes a means for doing so. Obviously, this is a complex issue. Environmentalists, for example, would argue that developing countries are more likely at some point to participate in the process if developed countries have also had to make sacrifices. But the perception of unfairness complicates the negotiating process, and the failure to address it will not dispel it.

The Kyoto process, and the Montreal Protocol process before it that eliminated emissions of chlorofluorocarbons that were decreasing ozone concentrations in the stratosphere, have been wonderful learning experiences. But we must be sensitive to the differences between the two. The Montreal Protocol has indeed been effective, but, in retrospect, it is apparent that it was a manageable extension of traditional environmental policy. The Kyoto process is about something much more fundamental. The current approach to global climate change carries within it not just policies, but also a vision, a teleology of the world that is, in important ways, both unexpressed and exclusionary (Allenby, 2002). Perhaps for this reason, the role of technology has been relatively ignored throughout the negotiating process and, when it has come up, has been quickly marginalized.

In fact, there are many possible technologies that might reduce carbon loading in the atmosphere, but many of the most important ones are out of favor. For example, nuclear energy has been excluded by general agreement, and geoengineering (e.g., aluminum balloons in the stratosphere to reduce incoming energy to the atmosphere) has been shunted aside, regarded as the dream of a few eccentrics (Keith, 2000). Biotechnology to improve agricultural efficiency and biological carbon sequestration are clearly not acceptable to many participants in the Kyoto process, and to many environmentalists generally. The rejection of these and other technologies tends to reinforce the impression that the Kyoto process is an exercise in social engineering by Europe targeted at the United States. Regardless of the truth, this impression is obviously conducive to conflict and deadlock (as indeed has happened).

Unfortunately, we cannot afford the luxury of not acting. The issue of global climate change cannot be solved by freezing everything where it is. The shifts in climate patterns and the complex cultural, economic, and technological evolution of a world of six billion people will not stop while we try to figure out how to manage the world we have created or pretend that burying our heads in the sand is an effective and moral response (as, indeed, Heidegger warns). Thus, workshops like this one that focus on existing and potential technological options and pathways have great value.

What happens if Kyoto fails? What happens if we try the social engineering route and it fails? Proponents of the Kyoto process have created the sense that, if it fails, we have collectively somehow failed as well, that all forward progress has been stalled. Making the Kyoto process the only game in town is a very high-risk tactic, and it seems to have misfired. The pressure generated by such a position may help it to succeed, but if it does not, we may have dangerously limited our options.

There are some grounds for hope, however. The Kyoto process may or may not continue without the participation of the United States, but complex systems —and the integrated human/climate system is arguably complex beyond our current understanding—do evolve, and they do so in ways that are difficult to predict. Moreover, once the ideological blinders have been removed, a number of potential mitigating technologies—from active carbon sequestration at fossil fuel plants to carbon sequestration through ocean fertilization with iron to industrial-scale scrubbing of the ambient atmosphere to geoengineering options—can be explored. Not all of these technologies are well understood, and even a cursory glance at some of them raises significant concerns, but there are technological options. And technologies are also evolving.

A useful process that would contribute significantly to the rational, ethical management of the future would be to categorize technological possibilities and determine, as objectively as we can, their risks and benefits and the optimal scale for each. We could then develop a portfolio of options for future negotiations. Technology, especially in emotionally and ideologically charged environmental debates, almost never provides complete answers. But an array of technological options enables choice and thus increases the chances that we will be able to balance the disparate values, ethics, and design objectives and constraints implicit in the climate change discourse. Technology may help us respond to the world we are creating in responsible, ethical, and rational ways.

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The Century-Scale Problem of Carbon Management

ROBERT H. SOCOLOW
Princeton University

There are six important things to remember about the greenhouse problem and carbon management.

1. The greenhouse problem is a century-scale problem.

The greenhouse problem is not a decade-scale problem or a millennium-scale problem. It cannot be solved in the short term, but it does not require an extremely long view either. This observation is based on a simple quantitative estimate of when the greenhouse problem will become dangerous. It won't be next year—but when? If we assume the greenhouse problem will become serious when the carbon dioxide (CO_2) concentration in the atmosphere reaches twice the preindustrial concentration, it will happen sometime in the second half of this century, if current trends continue. Is doubling the right place to locate the yellow flashing light warning us that we are entering the danger zone? Some have proposed a lower figure. The 1992 U.N. Framework Convention on Climate Change gives no guidance on how to decide when human interference in the climate system becomes dangerous.

It is hardly surprising that, faced with a century-scale problem, the tendency is to postpone taking action. Moreover, if we wait, the argument goes, we will no doubt be smarter about the science, the risks, and the technologies.

Can we justify acting now? One argument for acting now is that it would leave us room to maneuver. We are currently unsure of future damage from higher levels of CO_2 in the atmosphere. At a later time, when we know more, we may decide that today's estimates of damage are underestimates and that tougher concentration objectives are warranted. Acting now will make adjusting to such knowledge less painful. Another argument for acting now is that we are ready now. In many cases, all we have to do is combine already commercialized technologies in new ways.

2. From a one-century perspective, the characteristics of fossil fuel production look complex and unfamiliar.

Today, two of the most debated issues are the geopolitics of oil and competition between coal and natural gas. But by midcentury, conventional oil and natural gas are not likely to be as prominent as energy sources. Coal will still be very much in evidence, but unconventional fuels, like tar sands and shales and methane clathrates, may also be major sources of energy.

We must understand the importance of coal. Relative to oil and gas, coal is abundant, and it has a low feedstock cost. China and India, as well as the United States, are certain to be using a great deal of coal far into the future. But coal has a terrible legacy—danger to workers, acid runoff, subsidence, air laden with particulates, acid rain. A great deal of interest is being focused on "clean coal," which usually means coal burned with greatly reduced emissions. But to earn the attribution "clean," coal must meet other criteria as well.

Coal comes out of the ground contaminated with elements other than carbon, hydrogen, and oxygen . Many of these contaminants require management. Work is now being done to capture the carbon in coal as CO_2. Might we be able to co-capture and co-store ("co-sequester") some of these nasty contaminants along with the CO_2? Today, in Alberta, Canada, and elsewhere, CO_2 and hydrogen sulfide are routinely removed together from natural gas and co-stored below ground. Could that practice be extended and generalized? A complete answer will require working out the effect of impurities on the components of power plants (which could be redesigned), on pipelines to disposal sites, and on storage reservoirs.

3. Hydrogen is intimately connected with carbon management.

About half of the fossil carbon we use today is distributed to small users (e.g., vehicle engines, furnaces in buildings, etc.) before being burned. It is unlikely that we could collect CO_2 out of the tailpipes of cars and out of the chimneys of home furnaces the way we collect aluminum cans. Once these fuels are dispersed, the cost of carbon retrieval is probably prohibitive. Electricity is a carbon-free form of energy, but an all-electric economy is unlikely. Fuels are likely to continue to be preferred for many applications. The most likely carbon-free system will involve the distribution of both electricity and hydrogen, which would be used either in fuel cells or in combustion devices.

Hydrogen can be produced in many ways. One way is from natural gas or coal, with co-product electricity and with a stream of concentrated CO_2 ready for transport and storage. Hydrogen produced from either natural gas or coal, with CO_2 captured and stored, may be cheaper than hydrogen produced from renewable or nuclear energy. If hydrogen is produced from coal, probably the first step will be oxygen-blown gasification.

If we were to begin right now to implement a hydrogen-plus-electricity economy, one benefit would be that we would confront, rather than vaguely worry about, hydrogen safety. Today, hydrogen is handled only in specific industries by trained workers, with, I believe, a low accident rate. But could the general public be given a hydrogen system that is safe and, in some sense, idiot proof?

4. Early action on the permitting of CO_2 storage sites will reveal many difficult, largely unresolved issues.

What level of storage integrity should be required in the permitting of a CO_2 storage site? Clearly, no catastrophic releases that present substantial risks to human health can be tolerated. But should we be relaxed about the loss of 1 percent of the stored CO_2 each year through slow leaks? What about the loss of 1 percent a year from 10 percent of the sites? Probably, the level of leakage allowed during the first few decades of storage can be higher than in later decades, not only because we will learn as we go and make improvements, but also because the total quantities stored will increase over time.

Other questions arise. Should we strive to develop a storage system that future generations can undo? What techniques are available for monitoring a storage site and responding constructively to evidence that the behavior of stored materials is deviating from what we expected? How will we keep the overall costs of storage from escalating to the point where the prognosis for the whole strategy becomes bleak, as has happened with nuclear power.

There are two obvious precedents for storage of CO_2 in the United States, and both of them are poor. These precedents are the underground injection of hazardous waste and the storage of nuclear waste. The underground injection of hazardous wastes is governed by a permitting process regulated by the Environmental Protection Agency. As best I can tell, the process involves absurdly detailed modeling intended to prove that nothing serious will happen below ground after injection, followed by little, if any, postinjection monitoring and verification of what is actually happening below ground. The program to store nuclear waste began with great hubris; the public was promised leak-proof, very long-term storage. But under close scrutiny, these promises could not be met. If the nuclear community had admitted from the start that containment in waste repositories might occasionally lead to small leaks, long-term nuclear waste disposal facilities might already be operating.

The public will understand that carbon storage has imperfections. Only some, not all, of the carbon brought out of the ground will be captured. And some additional carbon will be brought out of the ground to provide the energy necessary to capture and store carbon.

5. Carbon management is not a winner-take-all strategy.

We have a whole portfolio of options for achieving major changes in the global energy system. And we will need many of them. Two options, at opposite ends of the spectrum in readiness for deployment, are: (1) improved energy efficiency; and (2) the direct capture of CO_2 from air.

Those of us who have worked on improving energy efficiency have been frustrated that many good ideas have not been implemented. We still build buildings as if energy were practically free. Most of the relevant institutional issues were identified back in the 1970s but have still not been addressed.

David Keith and Klaus Lackner are investigating ways to pull CO_2 directly out of the atmosphere and concentrate it (e.g., using the reactions $CaO + CO_2 \rightarrow CaCO_3$ and $CaCO_3 \rightarrow CaO + CO_2$). Could machines, located wherever we wish, remove CO_2 from the atmosphere as fast as we put it in, or maybe even faster?

6. Carbon management confronts us with ethical issues.

Carbon management is intended to avoid dangerous interference with the climate system. “Dangerous” to whom? To what? Carbon management is, simultaneously, environmental technology and survival technology. As environmental technology, it is directed toward minimizing the impact of human activity on the biosphere. As survival technology, it is directed toward maximizing human welfare. The two objectives are not necessarily at odds, but they are distinct.

Engineering is the profession most closely associated with maximizing traditional measures of human welfare. Earth systems engineering is a name often given to attempts to take charge of the Earth and organize its processes for human benefit. “Stabilization,” our newly articulated goal for future CO_2 concentration in the atmosphere, is a word borrowed from engineering, specifically from control theory.

Trying to take charge of the planet via Earth systems engineering is rather like trying to take charge of our own bodies via genetic engineering. We need rules for both activities. One difference is that we can choose not to modify the human genome, but we are already changing the planet week by week.

Sequestration in Geologic Formations

Sequestration via Injection of Carbon Dioxide into the Deep Earth

FRANKLIN M. ORR, JR.
Stanford University

We have a number of alternatives for dealing with large quantities of carbon dioxide (CO_2) in ways that do not put it into the atmosphere. We know, for example, that oil and gas reservoirs store carbon on geologic time scales—millions of years. If we start with the premise that geologic formations can store carbon on this scale, then we can conclude, I think, that the possibility exists of putting large quantities of carbon back into such formations and leaving it there for long periods of time.

The question is whether we can take advantage of this possibility. We do have some technologies already in place that are capable of injecting CO_2 into geologic formations. The engineering issues associated with oil and gas recovery and sequestration are closely linked, and a considerable body of engineering expertise already exists. I will discuss three alternatives for injection sequestration: (1) oil and gas reservoirs; (2) coal beds; and (3) deep saline aquifers.

We already have the technology to inject CO_2 into oil and gas reservoirs. We also have technology available for recovering methane in coal beds, and we know how to inject CO_2 into deep aquifers that contain salt water. If we can resolve safety issues and accurately predict the long-term fate of the injected CO_2, it may be possible to store large quantities of CO_2 in geologic formations.

But, as we approach the entire problem of atmospheric CO_2, we are not likely to find a single solution. Moreover, the volume of atmospheric CO_2 is enormous—gigatons per year. In other words, to make a difference, we must be able to store, say, a billion tons of CO_2 per year. That would require us to store something in the neighborhood of 25 million barrels of CO_2 per day under typical reservoir conditions. We now move about 75 million barrels of liquid petroleum around the planet every day, as well as large amounts of natural gas. So we already move large quantities of fluids, but the volume of CO_2 would be very large. We are going to need many options, the ones already mentioned and many we have not yet thought of. We must plan to develop a portfolio of responses.

An obvious possibility that goes with storing CO_2 in geologic formations is to inject the CO_2 to recover oil and gas. CO_2 is already being injected into oil- and gas-bearing formations to displace the oil and gas from porous rocks into wells where it can be recovered. That is a very different concept from inject-and-forget storage. With recovery, we actively displace oil from one spot to another, and there is field evidence that this can be done with reasonable efficiency.

In the mid-1990s in the United States, there were 66 projects involving injection of high-pressure CO_2 to recover oil. Most of the injected CO_2 is recovered from underground formations in the Four Corners area and transported by pipeline to west Texas, where it is injected to recover oil in the carbonate oil fields north of Midland. The amount of CO_2 injected is a small fraction of the total amount of CO_2 emitted in the United States, however, about 0.50 percent of current U.S. fossil-fuel emissions. In addition, these projects do not sequester atmospheric CO_2 because they use natural CO_2 tapped from underground. However, one project in Canada uses CO_2 recovered from a coal-gasification plant to recover oil in a nearby field. It is also true that options for recovering natural gas have not been as well explored as options for recovering oil.

If CO_2 were abundantly available, it would be much more widely used for oil recovery because it is a very efficient agent for recovering oil. The primary limit on CO_2 injection for oil recovery is the availability of CO_2. If sufficient volumes of injection gas were available, it could be used in a very wide range of reservoir situations. The reason it is not used this way now is entirely a consequence of availability.

The effectiveness of CO_2 as an oil-recovery agent is attributable to the phase equilibrium of CO_2 with oil. CO_2 dissolves in oil, and components in the oil transfer into the CO_2-rich phase. The resulting mixtures can then displace oil efficiently in the zones swept by the injected CO_2. The efficiency of the displacement process is often limited, however, by reservoir heterogeneity—that is, the natural variability of the rocks. CO_2 has low viscosity and finds easy flow paths through the reservoir rocks. In a displacement from an injection well to a production well, the injected gas flows preferentially through high-permeability flow paths. One of the limits in this setting is the fraction of the reservoir's volume that can be swept without recycling major amounts of CO_2.

Gravity segregation of the injected CO_2 can also be important. If there is reasonable vertical permeability, the injected CO_2 can flow upward to create a thin tongue of low viscosity under shales or other barriers to vertical flow. Once these zones of fast flow have connected the injection well to the production well, surrounding zones of less rapid flow are invaded more slowly. Considerable effort has been expended to reduce the amount of CO_2 required to recover oil. If the objective were to store the maximum amount of CO_2, the design constraints would be different.

Unfortunately, oil and gas fields are not necessarily located near the places where CO_2 is produced. Thus, another factor that becomes significant in sequestration is transportation costs, which could make this method of storing CO_2 inefficient in some parts of the world. It can be a good solution for places where appropriate geological formations are not far from the CO_2-generating sources.

A key factor will be accurate prediction of displacement performance. If monitoring and permitting are important issues, then predicting where the fluids will go in the subsurface and determining where they have gone will be issues for consideration. We will have to learn how to monitor storage projects at reasonable cost.

The second possible area for geologic CO_2 sequestration is in coal beds. About 5 percent of the natural gas produced in the United States is methane that comes from coal beds. The fact that methane is found in coal is well established and has been a problem for coal miners. Most methane is adsorbed on the surfaces of coal particles. CO_2 also adsorbs on coal particles, and it does so more strongly than methane. Suppose we injected CO_2 and the CO_2 then adsorbed on the coal surface, displacing some of the methane. We could then use the fracture network of the coal to transport the methane to wells where it could be taken to the surface. This adsorption behavior has been studied for some time now. Coal surfaces could adsorb about twice as much CO_2 as methane.

Thus, coal beds might be used as chromatographs. Here is how that would work. Starting with a coal-bed concentration high in methane, we could inject a mixture of CO_2 and nitrogen, producing a separation so that the nitrogen is forced out first. The CO_2 would then be trapped, while the methane was recovered. To pursue this technique, we will have to have better ways of predicting flow behavior—sorting out the adsorption details, studying what happens to fracture permeability as the CO_2 adsorbs, and determining the state of stress in the reservoirs. We will also need broader brush techniques so we can select appropriate coal seams. In addition, we will have to look more carefully at the long-term fate of adsorbed CO_2.

Methane is adsorbed on coal surfaces for geologic periods of time, so it is possible that similar long-term storage of CO_2 is possible. Coal-bed dewatering and water disposal issues will also be important, and we should not discount them. To move other fluids, we will have to displace water and dispose of it properly. The effect of these procedures on aquifers will also have to be taken into account.

One test of this method is under way in the Four Corners area using CO_2 from the same pipelines that carry natural CO_2 to west Texas. In the test, CO_2 has been injected for a considerable time with minimal breakthrough, but serious problems with water and water handling have been encountered. There is a lot more to be learned in this area.

The third possible method of CO_2 sequestration is injection in aquifers. For the sequestration of large amounts of CO_2, we require large volumes of porous rocks, typically sandstones and carbonates. Many are not oil and gas reservoirs but contain salt water, and these porous formations could be used to sequester CO_2. The big difference between an oil and gas reservoir and an aquifer is that, in an oil and gas reservoir, we know there is a seal—a geologic formation with some combination of impermeable rocks that traps the oil or gas. With an aquifer, that is not necessarily the case. Moreover, not much money has been spent to delineate aquifers in the same detail that oil and gas reservoirs have been delineated. The immediate problems in aquifer formations are the significant uncertainties in the geometry, extent, and flow properties (permeability distribution.) Similar uncertainties pertain to characterizating oil and gas reservoirs, but much more information is available.

One aquifer injection project is under way in Norway where a high tax on carbon makes it cheaper for companies operating there to reinject CO_2 than to emit it into the atmosphere. This test involves the injection of about a million tons per year of CO_2 into an aquifer.

CO_2 injection into aquifers, of course, creates interesting geochemical problems. CO_2 displaces water relatively inefficiently. It also dissolves in both brine and fresh water making an acid capable of dissolving carbonate rocks. There are also other potentially problematic mineral interactions, some of them long-term problems.

The injection technology required is essentially the same as the technology for injecting CO_2 into oil reservoirs. For aquifers, however, permitting and monitoring are certain to be larger issues than they are for oil and gas reservoirs. In addition, we have not yet sorted out the long-term geochemical questions.

Let's turn now to verification and monitoring. It is easy to figure out how much CO_2 we put into the ground. The oil industry does this all the time using injection metering. But monitoring where the CO_2 goes next is a different story. In settings where there is some production, where fluid is removed from the reservoir, we can immediately find out where the CO_2 has gone by looking at the composition of the fluids produced. But in large-scale aquifer storage, immediate tracking is less likely to be available. The cost of monitoring will very likely limit aquifer storage to experimental situations.

Monitoring could be based on seismic information, both time-lapse and cross-well data. It may also be possible to obtain information passively by listening with down-hole sensors. Now that sensors are becoming cheaper, it is possible to equip a set of wells with sensors and listen to them all the time for changes in an aquifer or reservoir. It is also possible that other electrical methods or synthetic-radar aperture methods could be used.

CO_2 poses unique safety questions. Although it is not flammable, it is an asphyxiant, and it is relatively dense. If it leaks at the surface and there is little wind, it pools, creating a dangerous area that could suffocate people who inadvertently venture into it. This is not a theoretical problem. Just such an accident occurred in west Texas in the mid-1970s, when a leak occurred in a surface facility during the night. The leaking gas also contained hydrogen sulfide—a lethal mixture. Four people were killed when they drove into the area and were rapidly overcome. We must address these safety issues very carefully.

We already deal with related issues in large-scale engineering systems. For example, we transport natural gas around the country in large pipelines that present fire and explosion hazards that do not exist for CO_2. The greatest risk is probably in well-bore failures. When we inject CO_2, we want it to go all the way to the formation and not depart en route. It will take some effort to understand how to achieve that. But these kinds of problems are addressed all the time in industry, and I think they can be dealt with in this instance.

A more serious problem may be long-term subsurface reservoir leakage. Information about the integrity of the geologic seal will be vital. We know that changes in geologic stress can damage the seal above an oil reservoir over the lifetime of the reservoir. In aquifer settings, there are more uncertainties than in oil reservoir settings.

The basic technologies for injecting CO_2 already exist. For CO_2 sequestration to be practical, however, we will have to put forth significant effort. We must also expect that many approaches will be part of the solution. There will be no silver bullet.

Using Carbon Dioxide to Recover Natural Gas and Oil

GARDINER HILL
British Petroleum Group

Being more of a businessman than an academic, I want to start by talking about the challenge of cost. If you look at carbon dioxide (CO_2) capture and storage projects, you see that 75 percent of the cost of a new project is in the capture technology, and 25 percent is in the storage technology. Overall, the cost of capture and storage today are very high. Capture and storage are already used in the food processing industry, so we know it can work on that scale, but cost will remain a big issue. We are looking to find a cost-effective, verifiable, viable way to store at least a million tons of CO_2 in reservoirs.

The next challenge we face is health and safety, which we believe must always remain at the top of the agenda. People are right to have safety concerns about the use of CO_2. We have to ensure that when we use CO_2, when we capture it and store it in geologic formations, we do it safely.

The third challenge we face is environmental. In trying to solve the current environmental problem, we don't want to create a new environmental problem with the solution we think is appropriate today. We must be mindful of how the world may change in the future.

Another challenge is assurance. If we are putting CO_2 into a reservoir, we must be able to ensure that it will stay there for as long as we want it to stay there. That is especially important if money is changing hands in connection with treatment or offsets. People want to be sure that their investments are long term and sensible.

We believe technology is the key to solving the problem, but as other speakers have pointed out, there is no silver bullet. We need a portfolio of options for the most efficient solutions to distinctly different problems. Some technologies will have to be retrofitted, some will have to be new, some can be used to inject CO_2 into oil and gas reservoirs, and some storage may take place in aquifers.

Two other major challenges are scale and time frame. When is action necessary? Many people believe that it is urgent that we act now. But what actions should people or companies take today? What about future uncertainty, given all the uncertainties about the future? What policies might future governments introduce? What incentives or tax situations might be available in ten years? How do we know the actions we take today will be appropriate in the future?

There is a real bias, a strong preference today, for taking preventive action. A number of companies, governments, and academics want to use the time available to us to identify solutions. To that end, a large number of companies are working together, sharing resources and experiences to reduce the risks and costs of finding a solution to the climate problem.

Public/private partnerships, like the CO_2 Capture Project, will be very important to the solution, and they represent a great opportunity. These partnerships and cofunding agreements give industry the confidence to move forward. The CO_2 Capture Project is taking a distinctive integrated approach to the use of CO_2 to recover natural gas and oil and, hence, to stretch our natural reserves. The project is exploring the possibilities in the context of real applications—specific fields and operations where we would like to capture and store CO_2.

We know that large-scale storage technologies are not available today. The showstopper to using storage technology could well be the problem of subsurface monitoring. If we don't handle that correctly, we may not get permission to use capture and storage technology as an option for mitigating against atmospheric CO_2 concentrations.

Why are we focusing on capture and storage technology? First of all, capture and storage technology clearly provides an opportunity to add value to the use of CO_2. It enables us to reduce CO_2 emissions both by attacking a large-scale source of CO_2 emissions and by using geological formations as storage. Many energy companies already have large sources of CO_2 and sinks. The synergy between sinks and sources could be an advantage in tackling this complex problem.

The CO_2 Capture Project has two very simple objectives. First, we want to reduce the costs of CO_2 storage through technology development. We hope to achieve a 50-percent reduction in cost for retrofits and a 75-percent reduction in new-build applications. Second, we want to demonstrate to external stakeholders that CO_2 storage is safe, measurable, and verifiable. We plan to initiate at least one large-scale application that will be in operation by 2010. For this specific project, however, we will have a proof-of-technology concept by the end of 2003.

Nine companies are involved in the project—BP, Chevron, Texaco, ENI, Norsk, EnCana, Shell, Statoil, and Suncor. It is split into three distinct regions: (1) the United States, which is the largest; (2) Norway; (3) and the rest of Europe. Each region participates in a cofunding arrangement, and the companies share technologies, experience, and learning to avoid duplication and to promote the development of the technology. The participants put up about 54 percent of the overall funding ($25 million). The U.S. Department of Energy is putting up 21 percent of the total. The European Union and Norway are putting in 12 and 30 percent respectively.

The program is nearing the halfway point. It began in early 2000 with a review and evaluation phase to define the state of the art at that time and to identify the most favorable areas for technology development. Next came an analysis phase to identify the technologies with the greatest chance of meeting program objectives. The program is now in the contract and procurement stage fostering broad technology development. This phase should last until the end of 2003, when a proof-of-concept of the technology will be demonstrated.

We are investigating three types of capture technology. The first is pulse combustion decarbonization to capture CO_2 from flue gas. This technology is already in use in the food processing industry, which uses an amine absorption process to scrub CO_2 from flue gas and compress it to make it available for geologic storage. The second method is called precombustion decarbonization, which takes fossil fuel, reforms it to make hydrogen and CO_2, compressing and storing the CO_2 and using the hydrogen to generate power and heat. The third method is called oxyfuels. This method uses fossil fuel in the presence of oxygen to generate water, steam, CO_2, power, and heat. Oxyfuels is the least developed and the least understood of the three, but it is important because it captures and separates CO_2 from fossil fuels.

On the storage side, we are looking at the classical geological options—storage in oil and gas recovery infrastructure, storage in depleted oil and gas reservoirs, and storage in coal beds. Gas and coal-bed methane are much less mature options than oil reservoirs but may have considerable potential.

The large-scale use of CO_2 to stretch our natural resources began in Texas in 1972. Today there are more than 70 CO_2-based projects worldwide, many of them in the United States. In 2001, about 30 million tons of CO_2 were injected, producing 180,000 additional barrels of domestic oil a day—a significant achievement. However, only about 7 million tons of that CO_2 was man-made; most of it was natural CO_2.

Oil and gas reservoirs have a potentially huge capacity to store CO_2. A conservative estimate is that 40 to 50 billion tons of CO_2 could be stored in oil reservoirs. We are not aware of any CO_2 being used to enhance gas recovery, but a number of companies have begun looking into the potential of using CO_2 in this way. Under some conditions, using CO_2 for gas recovery could be valuable. The CO_2 storage capacity in gas reservoirs could be significant—estimates suggest it could be almost double the capacity of oil reservoirs, perhaps as much as 80 to 100 billion tons of CO_2.

Coal-bed storage could be very useful as well. There are at least two coal-bed methane projects in the continental United States. Coal beds could have a huge storage capacity, conservatively estimated between 50 and 200 billion tons.

The mechanism for coal-bed storage is actually very interesting because CO_2 attaches itself to the surface of the coal and displaces the methane, thus enhancing methane production.

Finally, CO_2 might have other uses. Maintenance of reservoir pressure is the most important use. CO_2 could be used extensively in oil and gas reservoirs, as well as to offset subsidence. CO_2 may also have other industrial uses, such as in the production of carbonate steels.

The CO_2 Capture Project is addressing many important questions. What formations are suitable for CO_2 traps, and what are their most important properties? How will faults and cap rocks respond, both in geochemical and geotechnical ways, to large quantities of CO_2? How would the competence of the cap rock change? How is that change related to reservoir pressure that may vary over long periods of time? How will defaults change over time when they are subject to large concentrations of CO_2? What will the chemical reactions and products of rock water and CO_2 interactions be? If precipitation reduces the ability of the reservoir to store CO_2, what would the impact be on storage efficiency? Would it reduce the actual capacity and volume available and plug up reservoirs and wells?

Furthermore, can we inject CO_2 over the long term? Will injection be permanent? How do we define permanent? If injection is not permanent, what leakage rates are acceptable? How might CO_2 actually be stored, monitored, and verified? What is the best method of monitoring and verifying costs? The method we typically use today is very expensive and is implemented in a time frame of 50 to 100 years, which could translate into huge long-term costs.

In terms of costs, what are the economic drivers? How long will it be necessary to take those into account? When we develop oil and gas reservoirs, we typically think in terms of 20- and 30-year periods. Now we may be talking about periods of hundreds, perhaps thousands, of years.

In the end, we are looking for geological storage sites and technologies that will be acceptable to the public and to regulatory agencies and that will pose the fewest safety and environmental risks. The CO_2 Capture Project has identified a number of gaps in the work that has already been undertaken. The first gap is in cost, which remains very high. Monitoring phases could potentially become very expensive, and individual surveys can run into the millions of dollars. Many surveys over hundreds of years using current methods would add prohibitive costs.

Another topic we identified as very important is risk assessment. This means putting mitigation strategies in place to deal with risks and taking steps to reduce them. Consider the risk of leakage. First, the most likely leakage will occur not at the surface but within the formation, so we will need mitigation strategies to reduce that risk. Leakage into formations might lead to the contamination of drinking water, which could cause serious health problems, especially if contaminated water leaches through certain minerals or metal lines. Mitigation measures would be necessary to reduce that risk to as low as practically possible.

Long-term monitoring standards are another problem. We are using current tools and practices, but for monitoring to be cost effective and sustainable over a long period of time, we will need new tools and new procedures. And verification will be essential. We must be able to demonstrate that CO_2 is going where we say it is going and staying where we said it would stay. If money is changing hands to provide storage, and if carbon credits are offset, the money people must know they are making robust investments. We are not paying for CO_2 to leak back into the atmosphere.

The CO_2 Capture Project has adopted a whole-risk assessment approach, using safety assessment methodologies and establishing risk assessment frameworks important for public perceptions and public involvement. Monitoring is a major component of risk assessment, and we have monitors in place to tell us the effects of injection properties on reservoirs and cap rocks. We are also looking into novel geophysical techniques to monitor the movement of CO_2, such as long-term sealing of wells, which are the most likely sources of leaks. Natural reservoirs have been storing hydrocarbons for geological time frames. When we punch wells into them, we break the integrity of the seal, hence the leakage potential from wells. Integrated simulation is another important tool. Through simulation and modeling of basins, we hope to learn how CO_2 might migrate. We can also do verification by using natural CO_2 analogs and investigating fracture mechanisms to evaluate seal integrity.

Let me summarize what we have done so far. We have completed the review and evaluation phase. In the analysis phase, we reviewed more than 100 technologies and identified 30 key technologies we believe have the potential to meet the program and project objectives. Cofunding is in place, and we have already issued 100 contracts for work on capture and storage technologies. We have participated in some outreach, and we are creating more outreach programs. We are working with academics and nongovernmental organizations to improve public perceptions of this technology, particularly for CO_2 storage and CO_2 injection into oil and gas reservoirs. We want an open dialogue to gather information to incorporate into our programs. All of the participating companies have endorsed the research and development (R&D) plan, and we have established the project as an integrated international corporation agreement.

What next? As we move through the R&D phase, we will narrow down the number of technologies we are working on, focusing on the ones with the most promise of meeting our objectives. In addition, we are always looking for novel ideas. We will continue to have a constructive dialogue with external stakeholders and work hard to understand the cost levers to meet project objectives. Our goal is to develop technology that gives us options at a cost industry can afford. We are working on economic models to help us achieve that.

In 2003, we'll be planning how we will demonstrate the technology and determine if it will be appropriate at scale. Our objective is then to make that technology available and put it into general use throughout the industry. Finally, we will continue to share information on our web page at *CO2captureproject.org*.

Geologic Sequestration of Carbon Dioxide

SALLY BENSON
Lawrence Berkeley National Laboratory

Today I will give you a few examples of the research going on to support the development of geologic sequestration of carbon dioxide (CO_2). But first, let's review our needs. First, we must have a better understanding of technologies for so-called value-added CO_2 sequestration—that is, enhanced oil and gas recovery. These technologies could greatly lower the cost of sequestration. A second very important area is the development of reliable, low-cost monitoring technology, not only to monitor where CO_2 is going, but also to monitor interactions between CO_2 and host materials. Third, we need performance assessment models, basically simulation technologies to help us predict and optimize the important factors in sequestration. Simulation technologies must include: where the CO_2 is going; how it interacts with rocks; what geomechanical stresses it places on the system; and whether it interacts with microorganisms. We will need robust simulation tools to enable us to do all of this. Fourth, we will need methods of assessing storage capacity. The storage capacity in oil and gas reservoirs is significant, and the capacity in brine formations is huge. A great deal more work must be done before we can place some bounds on these capacity assessments. Finally, we will need criteria for selecting sites.

The U.S. Department of Energy began its research and development programs in geologic sequestration three or four years ago. As the discussion broadened to include more interaction with industry, environmental organizations, nongovernmental organizations, and other stakeholders, some very pressing issues have emerged. The first of these is that we will need robust performance requirements to enable us to decide whether a site is suitable or not for CO_2 storage. We will have to decide what the critical issues are and how to go about permitting a facility on a solid scientific foundation. Finally, a very important area is risk assessment and mitigation technologies. How do we assess risks in a predictable and repeatable way that the public, regulatory agencies, and project operators will all understand and agree with?

CURRENT RESEARCH

Value-Added Sequestration

The first major area of active research is technologies for value-added sequestration. Enhanced oil recovery is a mature technology, as others have pointed out. In fact, enhanced coal-bed methane production, although a much less developed technology, is also receiving a lot of attention in the industry. Nevertheless, even mature technologies will require more research to assess the best way to use CO_2 sequestration.

The idea behind CO_2 sequestration for enhanced gas recovery (CSEGR) is to take CO_2 separated from a power plant, compress it, and reinject it into a natural-gas reservoir to enhance natural-gas production. This technology is not in use today. In fact, when it was first suggested, the conventional wisdom was that it would not work. Many believed that when the CO_2 was put into a gas reservoir, it would mix with the natural gas very quickly. But a number of studies have shown otherwise, so we decided to study it more, in hopes of squeezing out the last bits of natural gas from a depleted reservoir. Natural gas reservoirs are also very attractive targets for CO_2 sequestration because they offer known containment and proven isolation for gas in the subsurface geologic environment.

What kind of research is being done on gas recovery? First, research is focused on molecular diffusion between the CO_2 injected into the reservoir and the natural gas still present to determine how quickly this takes place. Analytical systems have been developed for studying this question. For example, Figure 1 shows that in a 100-meter-thick reservoir, it would take more than 800 years for the CO_2 to mix completely with the methane. This suggests that the engineering process of CSEGR will take place in a much faster time frame. The results of these analyses suggest that natural recovery is worth pursuing.

The next question is whether we can show that the injection of CO_2 into a reservoir will provide pressure support quickly enough to enhance production. Simulations have shown that pressure support would indeed be fast enough (Plate 1). In fact, it moved quickly enough that natural gas recovery could be increased; at the same time, the plume of CO_2 would take about 20 years to move across the reservoir. Moreover, for the first 10 years, methane production could be increased with almost no contamination or dilution by CO_2. Thus, total natural-gas recovery from this reservoir could potentially be increased by as much as 30 percent. This was the second critical step in evaluating the feasibility of CSEGR.

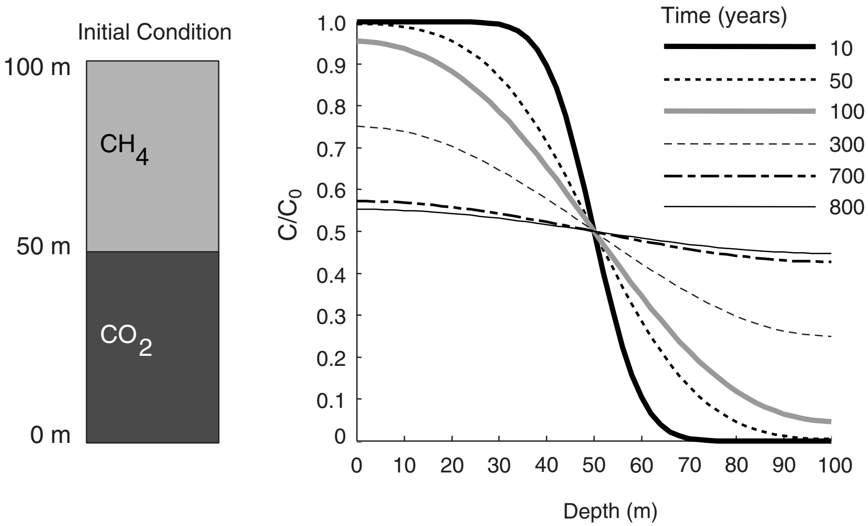


FIGURE 1 Conceptual model and results calculated from a new analytical solution for diffusion of gases with different densities. Source: adapted from Patzek et al., 2003.

Early simulations were highly conceptualized and idealized in many ways. In the next phase, simulations showed what would happen in a real reservoir engineering-type well pattern, the so-called five-spot pattern—the typical way we inject CO_2 into a reservoir from which we also want to produce natural gas (Plate 2). When we injected CO_2 into the lower right-hand side of this system and produced methane out of the top, we found that the CO_2 did not move quickly from the injection well to the producing well. Because CO_2 is so much denser than the resident methane, it basically formed a pancake and swept upward through the reservoir. This attribute would be very favorable for CSEGR. This is just one example of the kind of innovative work that may help us develop more options for value-added sequestration.

Monitoring Technology

A second focus of research is low-cost, reliable monitoring technology. In Figure 2, monitoring is simulated in the context of the security of geologic storage. When we inject CO_2 into a completely closed hydrostratographic trap, we expect the CO_2 to be retained in the structure. In that case, the security of storage is very high. The job of monitoring is to show that the CO_2 indeed stays in the trap.

Some systems we call open traps. If CO_2 is injected into these systems, over very long periods the CO_2 may be free to migrate and interact with the rocks. In

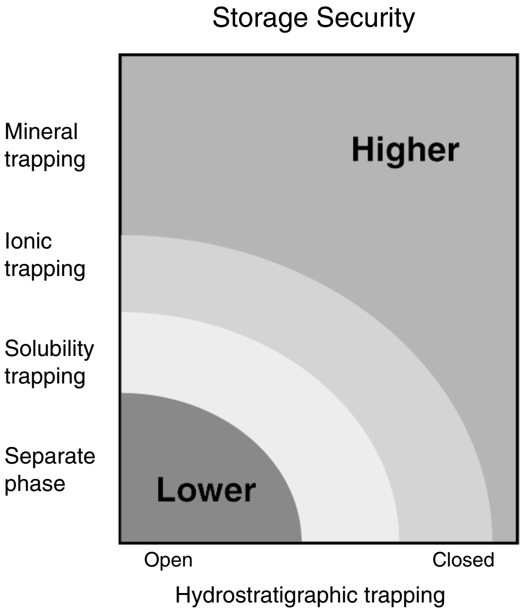


FIGURE 2 Conceptual description showing that the security of CO_2 storage depends on physical and geochemical trapping.

open-trap systems, the security of storage will depend heavily on the extent of geochemical interactions between CO_2 and the host materials. For instance, some CO_2 could dissolve into water or oil. In addition, adsorption may occur, for example, onto coal. Finally, there might be mineral trapping, in which case stable mineral phases might be created that would remain underground. We would like to put together a suite of monitoring technologies that can tell us not only about the physical trapping of CO_2, which we already understand quite well, but also about the geochemical trapping of CO_2.

A pilot project has been conducted along these lines in the Lost Hills Oil Field in California by Chevron and Texaco. In this enhanced oil recovery project, the participants agreed to provide a suite of monitoring wells to determine where the CO_2 was going. The goal was to develop complementary monitoring technologies. We decided to look at cross-well seismic imaging, which provides very high-resolution images between the injection and producing wells. We also tried electromagnetic methods, which complement seismic technologies by transmitting information about the saturation of water in the pore bases, a very important piece of information. We also looked at other monitoring technologies, such as high-resolution, single-well seismic monitoring, and we added a suite of tracers so we could begin looking at issues of solubility and mineral trapping (Figure 3).

By the time this project was completed, it had become very challenging,

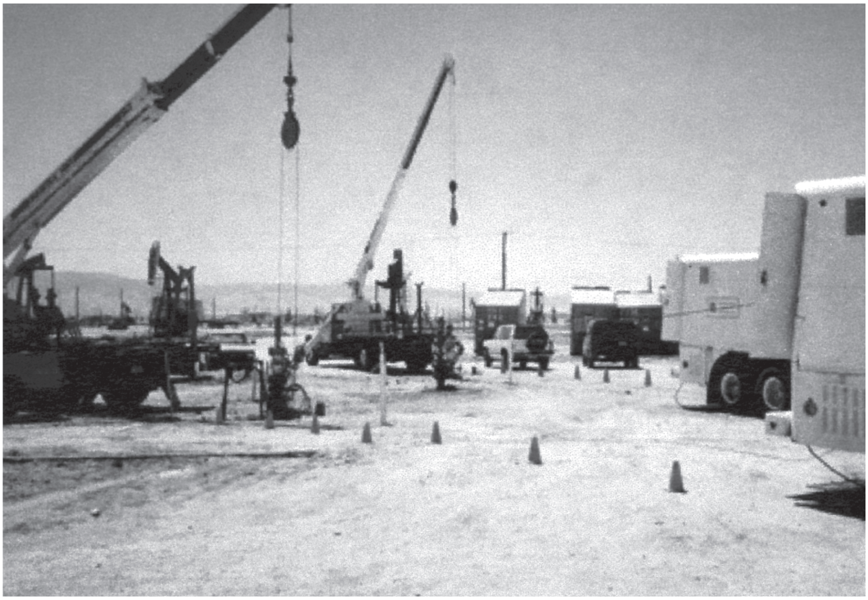


FIGURE 3 Photograph of the monitoring setup for cross-well seismic tomography at the Lost Hills CO_2 injection pilot project.

particularly in light of what we were trying to accomplish. We wanted to measure the saturation of CO_2 into the pore spaces. I have come to believe that this is going to be very complicated in mature oil and gas reservoirs, because an oil and gas reservoir has multiple fluid phases present—oil, gas, and water. The presence of multiple fluid phases, particularly the presence of free gas, makes it extremely difficult to track CO_2. We are working on methodology for combining multiple geophysical techniques, such as high-resolution electromagnetic and seismic imaging technologies to tell us something about the saturation of CO_2 in the formation (Plate 3).

Performance Assessment

We now turn to performance assessment models. How do we predict what will happen when we put CO_2 underground? This, I think, is best considered in the context of the security of CO_2 storage. We would like to know about where CO_2 will migrate, about solubility trapping, and about mineral trapping and absorption in mineral phases.

One of the very practical problems we face is how much CO_2 we can store underground and how we can use simulation models to provide information about it. If we inject CO_2 into a reservoir, we expect that, because of the low viscosity of CO_2, it will only partially sweep out the pore spaces. In fact, the average saturation of CO_2 in a water-filled system may be 30 to 50 percent. We are starting to understand some of the fundamental processes and features we think will be important to determining the most effective use of underground storage capacity.

It is also important that CO_2 is significantly less dense than the brines that will receive injections. CO_2 densities at reservoir depths typically range from 600 to 800 kg/m^3. Brine densities will be on the order of 1,000 kg/m^3. The density difference leads to strong buoyancy forces that drive the CO_2 plume upward to the base of the cap rock. To understand these forces, we need tools to model them.

Because of the natural heterogeneity of all geologic systems, we will need simulation models to predict the influence of this more complex sort of plumbing. We can start with models first developed by the oil and gas industry, then by the environmental cleanup industry, which have been available for decades. We can then modify and enhance these models to simulate geologic sequestration of CO_2. We start with a subsurface grid, divide the subsurface into a number of pixels or boxes, and assign physical properties to them. We can then simulate what happens in these systems when we inject CO_2. The available simulators cover the full spectrum of physical processes, chemical processes, and geomechanical processes. Although they are not perfect, we are developing the capability to study these issues, particularly for short-term processes. We will also have to understand much longer term processes, particularly the chemical processes that are likely to lead to mineral trapping over very long periods of time.

Figure 4 shows how multiphase flow, buoyancy forces, and reservoir influence storage capacity heterogeneity. In Plate 4, the subsurface is assumed to be uniform, with no buoyancy forces. Over a 20-year period, the volume we are studying is swept out by CO_2. Plate 5 shows a uniform, three-dimensional model in which gravity plays a role. The CO_2 plume forms an upward cone as the result of buoyancy forces. This is likely to be a very important effect that could have a serious impact on our ability to use the full thickness of the brine formations available for sequestration.

In Plate 6, a heterogeneous system with buoyancy, intricate subsurface plumbing has a huge impact on where the CO_2 goes. It appears that heterogeneity may help us use the subsurface volume more effectively. This goes against the assumption of most reservoir engineers that heterogeneity is not helpful. In this case, subsurface heterogeneity may actually act like a set of baffles to increase the contact area between the injected CO_2 and the rocks and other aspects of the structure, thus helping to counteract the influence of gravity. The influence of gravity can have a severe impact on available storage volume, sometimes even halving it. Evidently, heterogeneities can help mitigate the effects of gravity.

We can also compare the total capacity of the subsurface system as a function of time for these three cases (Figure 5). In a homogeneous reservoir with no

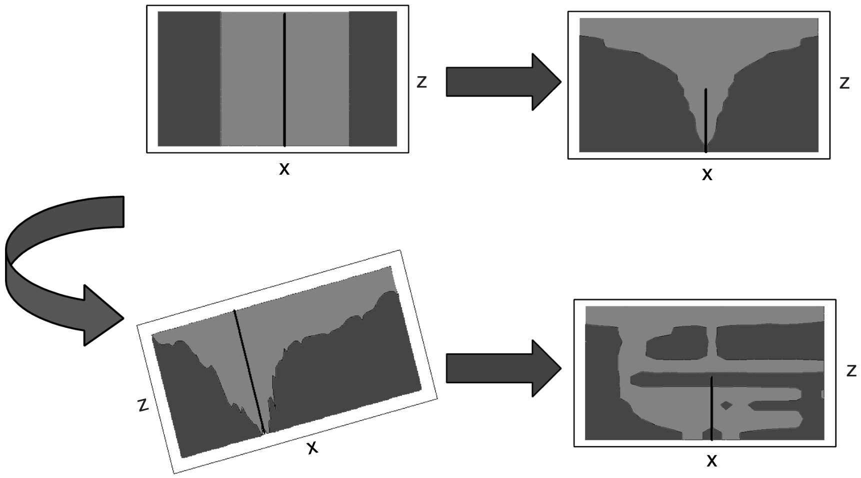


FIGURE 4 Schematic drawing showing how multiphase flow, buoyancy, and reservoir heterogeneity influence storage capacity of a geologic formation. Source: adapted from Doughty et al., 2001.

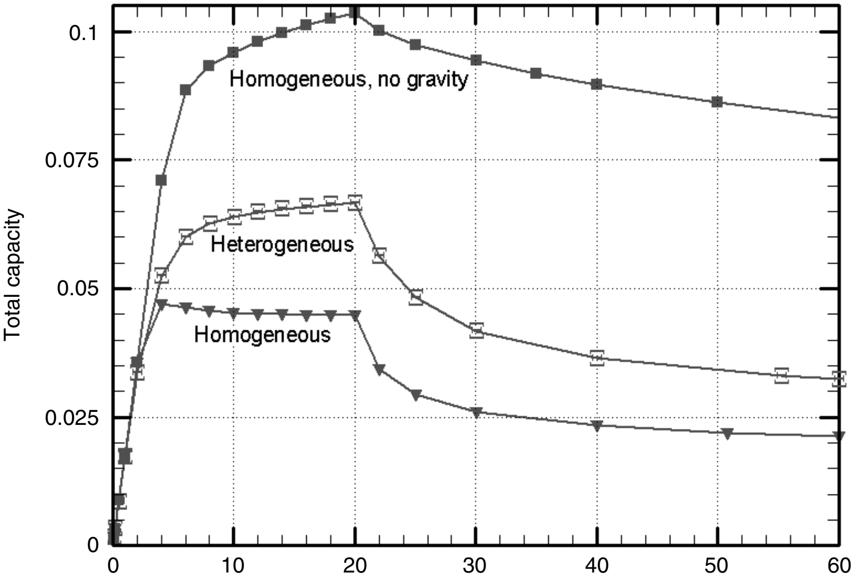
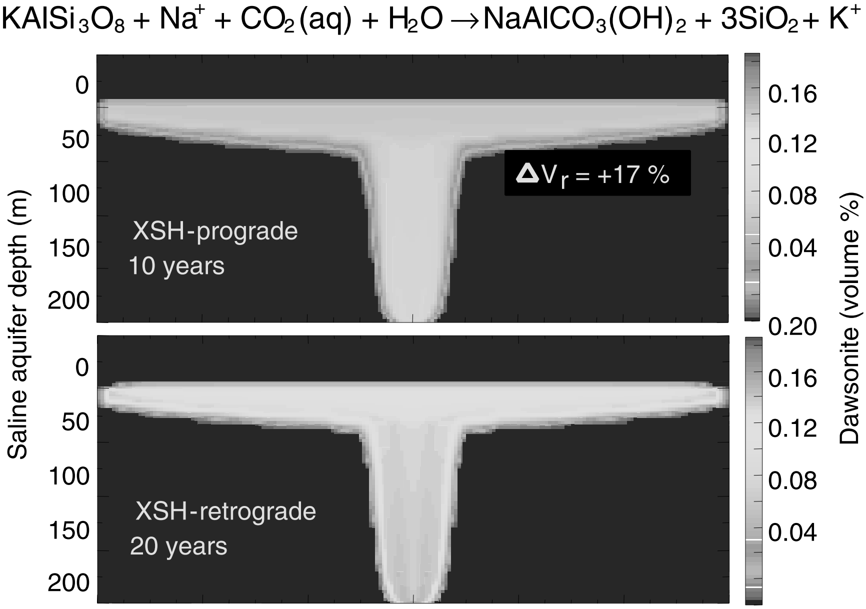


FIGURE 5 Comparison between the sequestration capacities of the three simulations shown in Plates 4–6.



$KAlSi_3O_8 + Na^+ + CO_2(aq) + H_2O \rightarrow NaAlCO_3(OH)_2 + 3SiO_2 + K^+$

FIGURE 6 Reactive geochemical transport simulation showing the precipitation of dawsonite within the CO_2 plume. Source: adapted from Johnson et al., 2001.

buoyancy forces, nearly 10 percent of the volume could be available; buoyancy cuts the capacity nearly in half. The heterogeneous case is midway between the homogeneous reservoirs, with and without gravity. This confirms that heterogeneities do, in fact, make it possible to store more CO_2 in the reservoir. After 20 years, when we stop injecting, the CO_2 concentrations actually start to decrease. Thus, after CO_2 injections stop, factors such as buoyancy forces continue to move CO_2 out of the system and upwards, until it either finds a stable trap or returns to the surface.

Further simulations are being developed for geochemical reactions. Scientists at Lawrence Livermore National Laboratory have found that a small degree of dawsonite cementation may occur in the pore spaces, not enough to plug things up, but plugging—trapping CO_2 as a mineral—is one more aspect of secure storage (Figure 6). Another interesting simulation shows that carbonate precipitation is unlikely to occur within the plume but will occur in rinds at the edges of the plume (Figure 7).

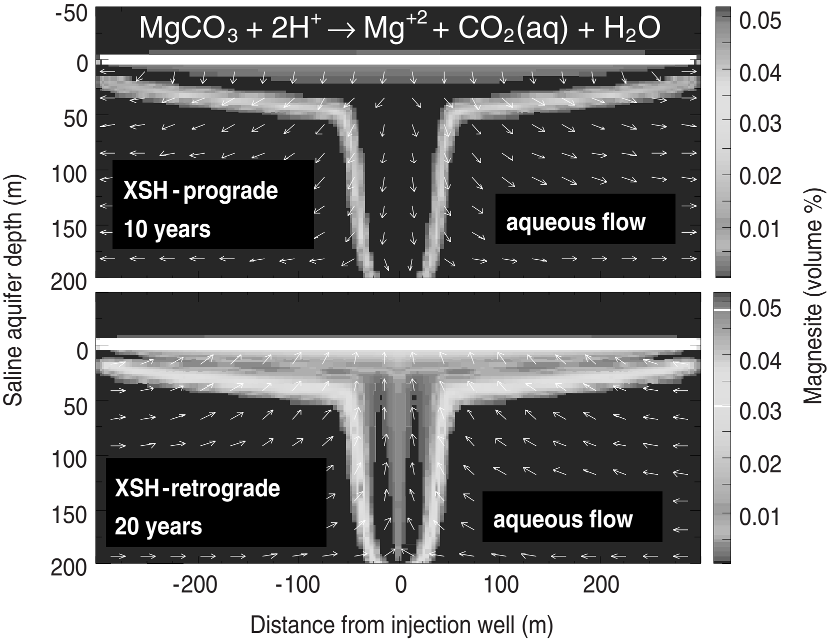


FIGURE 7 Reactive geochemical transport simulation showing precipitation of calcium carbonate at the edge of the CO_2 plume. Source: adapted from Johnson et al., 2001.

Capacity Assessment

The Texas Bureau of Economic Geology has done some interesting work based on an examination of 21 formations and 19 basins in the United States. The study concluded that most of these have viable targets for sequestration. The targets are permeable formations with sufficiently thick reservoirs and thick low-permeability cap rocks. Detailed studies are being done of the Frio formation in Texas, a structure that underlies the Houston area and covers the entire Gulf Coast. The formation has high-permeability sand and very thick cap rock.

We are now beginning a pilot study in the Frio formation. Texas, which is the largest emitter of CO_2 in the United States, has a significant interest in this study. The plan is to conduct a pilot injection experiment, injecting about 7,000 tons of CO_2 into the formation. The Frio formation offers a very large sequestration target at an ideal depth of about 1.5 kilometers below the surface; the sand thickness varies from 100 to 500 meters; the porosity is about 30 percent. The project will include site characterization, modeling, CO_2 injection, monitoring, and data evaluation. We must do these field experiments to make progress.

Performance Requirements

Much more progress has been made in the technology arena than in establishing performance requirements. Not enough work has been done on performance and engineering specifications for geologic storage. How long do we want CO_2 to remain underground? What will the requirements be for releases from active and abandoned wells? Will we allow releases from reservoirs? Will we allow surface leakage? What, if any, will be acceptable human and ecological impacts? What about impacts to groundwater? What about induced seismicity? Will it be permissible for a CO_2 plume to migrate to an adjacent property, or will that be banned? All of these issues will have huge impacts on the way geologic sequestration actually moves forward.

Another very important question is whether we will use performance-based requirements or a practice-based permitting scheme. One example of performance-based requirements is in the nuclear waste storage industry, which has very basic requirements for storing nuclear waste that limits the permissible radiation dosage the public might receive. To assess the safety of a nuclear waste storage site, engineers work backwards from these requirements through an elaborate set of models that tell them how to design the waste canister and other aspects of the site. In contrast, a practice-based permitting scheme is used in the design of injection wells for the deep injection of hazardous waste. If you conform to the requirements in the way you complete the injection well, you can have a permit. Which style of permitting is more appropriate for CO_2 sequestration? This question must be addressed before large-scale sequestration can proceed.

Previous speakers have mentioned risk assessment. Models are now being developed to show migration of CO_2 from the storage formation up to the surface. Coupled with atmospheric models, they will help us assess acceptable rates of surface leakage that will not cause unsafe build up CO_2.

A large community of researchers is interested in the problems of simulation, and an international effort is under way to bring together teams from all over the world to improve simulation capabilities, as well as to establish some benchmark problems that can be used to demonstrate to the public and the regulatory community that these models are reliable and robust.

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Sequestration in the Oceans

Direct Injection of Carbon Dioxide into the Oceans

PETER G. BREWER
Monterey Bay Aquarium Research Institute

It is now almost 40 years since we made our first measurements of carbon dioxide (CO_2) in seawater, and the science has changed enormously during that time. Last week, I was at sea carrying out a small-scale carbon sequestration experiment. For about the last five years, my laboratory group and our colleagues have been carrying out deep ocean experiments; they are difficult, but fun, and they raise all kinds of important questions. I want to talk with you about some of our results.

Instead of dwelling on policy issues, I will focus on the numbers, on the technology, and on the present level of scientific understanding. A 1998 cover story in *Environmental Science and Technology*, a journal of the American Chemical Society, raised the question of whether we should actively dispose of CO_2 in the oceans (Hanisch, 1998). That really begs the question, because we already do. Our current, de facto policy for disposing of carbon dioxide, both in the United States and internationally, is to dispose of it first in the atmosphere. We recognize that the atmosphere then moves across the surface of a large-scale saline "aquifer" containing dissolved carbonate minerals, and we neutralize the CO_2 by a reaction with carbonate ion dissolved in seawater, thus converting it to sodium bicarbonate. This aquifer covers 70 percent of the Earth's surface, and the reaction with the alkalinity of surface ocean waters is the primary modifier of the increase of CO_2 in the atmosphere. Ocean circulation then transports these CO_2-modified surface waters to water mass conversion regions and subduction zones. By these convective and sinking processes, the fossil-fuel signal is mixed into the abyssal flows. The mean circulation time of oceanic deep waters is about 550 years, and every year about 30 percent of atmospheric fossil fuel CO_2

emissions are taken up by the ocean. In the very long run, about 85 percent of all CO_2 emissions will reside there (IPCC, 1990).

We now have more than a hundred years of experience with this "technology," and the numbers are very large. The volume of the oceanic "aquifer" is about 10^{21} liters. A very large fraction of the emissions from the early part of the twentieth century are now in deep waters, well along on the exchange path between the upper ocean and the deep ocean; the oceanic fossil-fuel signal has reached a depth of >1,000 meters. The front is moving down at about 1 meter a month (Wallace, 2001). Thus the distinction between ocean "uptake" and ocean "disposal" has become increasingly blurred. Ocean CO_2 uptake (in effect surface ocean disposal) is now about 20 to 25 million tons of CO_2 per day, of which the U.S. contribution is about 6 million tons of CO_2 per day.

Like it or not, that is our de facto carbon dioxide policy, and it has been for decades. Every U.S. citizen emits the equivalent of about 120 pounds of CO_2 a day, and about a third of that goes rather quickly into the ocean. One significant problem is that we are "disposing" of this CO_2 in the surface waters of the ocean where most of the marine life lives and where reef-building corals are. We have already lowered surface ocean pH by about 0.1 pH units, and, if the Intergovernmental Panel on Climate Control "Business as Usual" scenario is followed, by the end of this century, we will have lowered carbonate ion concentrations in surface ocean waters by >50 percent (Brewer, 1997). This will significantly affect the calcification process in coral reefs. Moreover, during the atmospheric residence time of the released CO_2, it creates the well known global warming signal. The combined effects of heat and lower pH are causing serious concerns for coral reef systems (Table 1).

DIRECT OCEAN SEQUESTRATION

Cesare Marchetti (1977) made the first suggestion of direct carbon sequestration in the ocean about 25 years ago. Since then, there have been numerous conferences to study the problem and discuss theoretical analyses. However, only about five or six years ago a number of us decided to initiate small-scale field experiments. We realized that all we had to go on was, in effect, sketches and cartoons of the process—not because contributors to the field were bad or ignorant, but because nobody had any actual experience (e.g., Figure 1). Journal articles were illustrated with sketches and cartoons, leading to all kinds of confusion. The sketch that appears in the 1998 *Environmental Science and Technology* article shows blocks of dry ice being dropped into the surface ocean—a forbiddingly expensive idea.

Another sketch shows the ocean floor with some kind of reactor and a pile of hydrates. These sketches offer intuitive, but possibly confusing, images of how ocean carbon sequestration might work. It was clearly time to carry out real

TABLE 1 The Evolving Chemistry of Surface Seawater under “Business as Usual”

Time/years	pCO_2 (μatm)	Total CO_2 (μmol kg^{-1})	pH	HCO_3^- (μmol kg^{-1})	CO_3^{2-} (μmol kg^{-1})	H_2CO_3 (μmol kg^{-1})
1800	280	2,017	8.191	1,789	217	10.5
1996	360	2,067	8.101	1,869	184	13.5
2020	440	2,105	8.028	1,928	161	16.5
2040	510	2,131	7.972	1,968	144	19.1
2060	600	2,158	7.911	2,008	128	22.5
2080	700	2,182	7.851	2,043	113	26.2
2100	850	2,212	7.775	2,083	97	31.8

Under IPCC “Business as Usual,” the pH of surface seawater drops by 0.4 pH units by 2100. CO_3^- in surface water drops by 55 percent from preindustrial values. It will be hard to meet even these goals. Fossil fuel CO_2 is now a major ion of seawater. Source: IPPC, 1990.

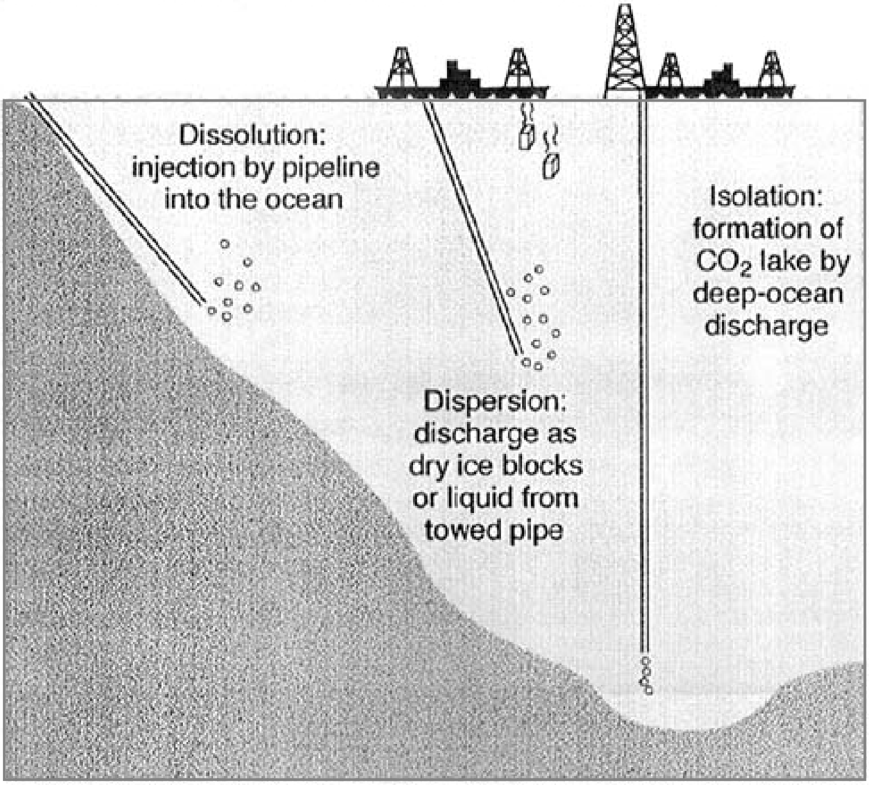

FIGURE 1 Options for direct ocean disposal of CO_2. Disposal scenarios that are the focus of current research include droplet plume and dense plume dissolution, dry ice and towed pipe dispersion, and isolation as a dense lake of CO_2 on the sea floor. Towed pipe and droplet plume scenarios may offer the best approach in the near future. Source: Hanish, 1998.

experiments, and we were fortunate to have access to modern, remotely operated vehicles (ROVs) to attempt this.

The 1998 President's Council of Advisors on Science and Technology Energy R&D Panel recommended storing CO_2 as a clathrate hydrate on the seafloor. At high pressure and low temperature, CO_2 will react with water to form an ice-like solid ($CO_2.6H_2O$), which is denser than seawater. This would aid enormously in sinking CO_2 to the ocean floor and, it was presumed, greatly extend its time there.

CO_2 can indeed form a hydrate, and we now have extensive experience of working with this property (Brewer et al., 1999). The nucleation and growth rates can be capricious, but liquid CO_2 undergoes a transformation to the solid hydrate form on the seafloor at a depth of 3,600 meters (Brewer et al., 2002).

The first question we addressed was the release of CO_2 from a pipeline into the mid-depth ocean (e.g., between 400 and 1,500 meters). This scheme formed the basis of a very fine modeling effort carried out by the Bergen group in Norway (Alendal and Drange, 2001; Drange et al., 2001). The hypothesis was that, when CO_2 was released in liquid form it would quickly break up into small droplets. Because at these depths liquid CO_2 is less dense than seawater, the droplets would float upward and dissolve rather quickly. The Norwegian study showed that, if the location and depth of release were carefully selected, the water masses labeled with this excess dissolved CO_2 would be advected to the North Atlantic deep-water formation regions and transported into the abyssal flows. This would ensure sequestration for >250 years before reventilation of the water masses in the Antarctic circumpolar flows.

First Experiments

Critics of this approach—and I was a bit skeptical earlier—suggested that the dissolution might not be quite that easy. For our study, we took an ROV fitted with a high-definition TV camera and attempted direct imaging of the release, rise, and dissolution sequence. In effect, we had a 7,000-pound vehicle on an almost one-kilometer-long pendulum, subject to continuous, and variable, ocean forces.

We requested that the pilots fly to the release point, release a small quantity of liquid CO_2, and follow this during upward transit over hundreds of meters, while the ROV takes images of the droplets with a precision of a tenth of a millimeter. This was excruciatingly difficult—painstaking, classical, hard work. Every release required about an hour of intense concentration, as well as hand-eye coordination. But we actually pulled it off, and we were able to track the changing size of droplets in a classical manner (Brewer et al., 2002).

We were able to show that the modeling done by the Norwegian group, and also laboratory pressure vessel studies in Japan (Aya et al., 1997), are probably correct. CO_2 released in the ocean at a depth of about 800 meters (4.4°C) will dissolve at a rate of about 3 $\mu mol/cm^2/sec$. This means that for droplets initially about 1 cm in diameter, about 90 percent of the dissolution occurs within 30 minutes and within 200 meters of the release point. That is very close to the modeling result from the Bergen group.

When CO_2 is injected into the ocean at a relatively shallow depth, both observations and modeling studies show there is a good chance that some of it could return to the atmosphere. Flow in the ocean is primarily along isopycnal (constant density) surfaces, and a key diagnostic tool is where a particular density layer is ventilated, or exposed, to the atmosphere. The North Pacific Ocean has the densest seawater exposed at northern latitudes. Waters deeper and denser are exposed to the atmosphere thousands of miles away, and several hundred years later, in the Antarctic region. Over much of the North Pacific, this isopycnal surface lies at a depth of about 600 meters. Thus, our simple field experiment illustrating dissolution of a plume in the 800- to 600-meter depth zone probably represents the shallowest depth at which effective ocean CO_2 sequestration should be considered.

The Fate of CO_2 Hydrates

On the basis of these results, we next asked how important the hydrate skin was in controlling the outcome of the experiment. If we had done the experiment in the warmer deep waters of the Mediterranean, would the results have been different? When we store hydrates on the seafloor, should they be in a stable form? Or would they dissolve? Clearly the deep ocean thermodynamic conditions of temperature and pressure favor hydrate formation, but it is also essential that chemical saturation occur. Deep ocean waters are approximately 500-fold undersaturated with respect to dissolved CO_2.

We thus decided to do an experiment to measure directly the oceanic dissolution rates of CO_2 hydrates themselves—testing the idea of hydrate storage on the ocean floor (Rehder et al., in press). Working with colleagues from the U.S. Geological Survey (USGS) and Lawrence Livermore National Laboratory, we fabricated both CO_2 and methane hydrates in the USGS laboratory. These specimens were squeezed at high pressure at Lawrence Livermore National Laboratory into dense solid units about the size of 35-millimeter film cassettes, placed in a specially designed pressure vessel under about 15.5 MPa methane pressure, and packed in ice.

This unit was then driven down to our base in Moss Landing, California, and taken out to sea. The specimens were transported by the ROV Ventana to the ocean floor at 1,028 meters (3.6°C) along with a time-lapse camera to record the results. By exceptionally dexterous robotic manipulation, the pressure vessel was opened, and the hydrates were exposed on the seafloor and positioned so that good images could be recorded.

Within a few hours, it was clear that both the methane and the carbon dioxide hydrates were dissolving. After appropriate corrections, we found that the effective release rate of CO_2 to ocean waters was very similar to the release rate of the liquid droplets mentioned above. The shrinkage rate of the solid diameter was 9×10^{-2} μm/sec. We were able to observe an apparent correlation between dissolution rate and current velocity.

The data were of remarkable quality. The methane hydrate also dissolved, but at a rate about 10.5 times slower. This experiment taught us something valuable about the lifetime of hydrates of all kinds in the ocean and provides a basis for making powerful, simple predictions based on saturated-boundary theory. The ratio of both the solubility and the observed hydrate dissolution rates of CO_2 to methane is about 10.5:1. Simply stated, the control on dissolution rate (and the limiting factor of hydrate lifetimes in the ocean) is the existence of a thin, saturated, molecular-boundary layer controlled by diffusion. Higher velocities in the bulk fluid reduce the thickness of this layer and accelerate dissolution.

Making and Testing Predictions

If we were to go down to a depth of 3,000 meters, we predicted that we would get a reduction in dissolution rate by about a factor of 2, based on the changing solubility (or ease of formation) of the hydrate. We also did that experiment, devising techniques for transporting CO_2 to below 2,750 meters, to a depth where the fluid is gravitationally stable. Using one of our newer vehicles, we flew a small amount of CO_2 to a depth of 3,600 meters. We punched a small hole in the seafloor so the CO_2 wouldn't roll away and then inserted a pH electrode directly into the mass of liquid. This neither broke the liquid surface, as in pricking a balloon, nor caused simple elastic stretching of the surface. Rather, as the liquid surface deformed microscopic cracks occurred, which were quickly annealed with hydrate, as both water and CO_2 flowed into the cracks and combined to renew the skin with remarkable effectiveness.

Having thus made a water pocket inside the blob of CO_2, we then locked the electrode in place and waited for half an hour. Slowly, the CO_2 dissolved into the water; the dissolution rate is given by the observed drop in pH. The result was almost precisely a factor of 2 slower than it was at 1,000 meters—as predicted by thermodynamic-equilibrium and saturated boundary-layer theory. We are now beginning to understand this process quite well at the molecular scale. Our Japanese colleagues conducted a similar experiment earlier in the laboratory and described the hydrate-film rebuilding process (Aya et al., 1997).

Thus, in several classic experiments over the course of the last few years, we've determined that CO_2 in all forms does dissolve at significantly high rates in the ocean. It reacts quickly with water to form carbonic acid and then with carbonate ion to add to the pool of dissolved bicarbonate in ocean waters. The tracer plume that would result from disposal would be detectable by techniques common to recovering the fossil-fuel signal from oceanic observations.

Biological Impacts

Some obvious questions arise at once. What is the cost? And what are the environmental impacts? We are now beginning to address these questions directly. A colleague of mine, his postdoctoral students, and I are carrying out experiments with CO_2-biological interactions right now. We emplace about 20 liters of liquid CO_2 in a small corral on the seafloor at 3,600 meters. The corral holds about the same amount of CO_2 as an individual U.S. citizen puts into the ocean every day via the atmosphere-ocean gas-exchange process. We then set up a number of experimental enclosures containing a variety of marine animals captured locally at varying distances from the small CO_2 source (Barry et al., in press).

We measure the pH from a set of recording instruments, and we examine the physiological responses of the marine animals to the lower-pH plume that is formed. Because the velocity signal is dominated by the tidal ellipse, the plume passes over any one site or specimen about twice a day.

The work is going very well, but it raises all kinds of interesting issues and technical difficulties. Occasionally, a small amount of CO_2 may wash over as a result of ROV thrust—one of the problems of using ROVs near a liquid—or as a result of hydrate formation, thus creating large volume changes. It is very common for deep-sea fish to observe our work closely. They are curious, and they come close up to our experiments, apparently unperturbed, for long periods of time. In a one-month study, we simply used a time-lapse camera to record the fate of a 20-liter corral of CO_2 on the seafloor. Although various animals moved closeby, there was no recorded interaction or perturbation in their behavior. The pool of CO_2 simply slowly dissolved, with no detectable biological response.

SUMMARY

These small-scale, very careful experiments are revealing the rate of CO_2 dissolution in the ocean, its physicochemical properties, and its environmental impact. They suggest many possibilities for safe and effective oceanic disposal of CO_2. We hope we will be able to make some objective evaluations about the feasibility and ethics of this option.

Many aspects of this problem have yet to be investigated. As every participant has said during these meetings, a large part of the cost of sequestration is in the initial capture of CO_2. A number of people have suggested that one solution to minimize costs is simply to take the CO_2-nitrogen mixture resulting from combustion and inject it into the ocean without chemical separation (Saito et al., 2000). At a depth of about 300 meters, the ratio of CO_2 solubility to nitrogen solubility changes significantly, with strongly preferential dissolution of CO_2. Thus, a bubble stream would quickly evolve into a pure nitrogen gas phase and a dense CO_2 rich aqueous phase, which could be piped to great depth. We plan to conduct experiments on this process.

Many other issues have been raised, such as the enormous amount of fluids involved, suggesting a very large-scale engineering enterprise. Ken Caldeira and Greg Rau (2000) have examined the use of crushed limestone to provide a carbonate buffer for the CO_2-rich fluids, thereby permitting disposal at much shallower ocean depths. Over the next few years, we plan to conduct small-scale experiments to move this science ahead and provide objective data about these extraordinary problems.

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The Effectiveness and Unintended Consequences of Ocean Fertilization[1]

KEN CALDEIRA
Lawrence Livermore National Laboratory

Numerical simulation can shed some fresh light on the idea of ocean fertilization. An analysis of the IS92A Intergovernmental Panel on Climate Change (IPCC) scenario shows that to stabilize climate at 2°C of warming, if climate sensitivity is at the low end of the accepted range, approximately 75 percent of all power production would have to come from sources free of carbon emissions by the end of this century. If climate sensitivity is at the high end of the accepted range, nearly all of our energy would have to come from carbon-emission-free sources. We can perform much the same sort of calculation for a range of climate sensitivities and a range of acceptable levels of warming. For stabilization at 2°C with a midrange climate sensitivity, we would have to add approximately one gigawatt of carbon-free primary power per day somewhere in the world.

The magnitude of this problem is enormous, and there is no magic bullet to solve it. As other speakers have suggested, we have to work on reducing energy demand, on sequestration, and on developing nonfossil sources of energy.

Speakers today have already discussed geologic storage of carbon dioxide (CO_2), ocean storage by direct injection, and land biosphere storage, although this is likely to be limited by land availability. Others have proposed geochemical techniques, such as accelerating silicate or carbonate weathering.

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One problem with putting CO_2 into the ocean is that nobody thinks this will be good for the ocean. We may decide to do it, however, if it turns out that the adverse environmental consequences of putting it somewhere else are worse. Ocean carbon sequestration would only make sense if it diminishes the overall adverse consequences of releasing CO_2 into the environment.

We are already putting two gigatons of carbon into the ocean each year. That works out to about five kilograms per day per U.S. citizen. At present, we are also putting carbon into the atmosphere, which may create significant climate change. But eventually, the ocean will absorb about 80 percent of the carbon released to the atmosphere. The idea of ocean sequestration is to put the CO_2 into the ocean deliberately, thus avoiding most of the global warming. The argument is that this could have some adverse impacts on the marine environment, but at least we would avoid most of the climate change.

Recognizing that we are already sequestering carbon in the ocean unintentionally is very important, and determining the biological effects of CO_2 on organisms in the ocean is one of the most important goals of current research. It is essential that we know the effects of increased oceanic concentrations of CO_2, even if we decide to put it into the atmosphere.

Several ocean fertilization options have been proposed (e.g., adding chemicals, such as nitrate and phosphates to the oceans). My work is focused on simulations of iron-based ocean fertilization.

The basic idea of iron-based ocean fertilization (see Figure 1) is to add iron to the upper ocean to stimulate biological activity and increase photosynthetic activity, and thus generate more organic carbon—removing it from the surface. Some of the organic carbon then sinks into the deep ocean. The goal of fertilization is to remove carbon from the surface ocean, fix the CO_2 as organic carbon, and then sink it into the deep ocean mostly by gravitational sinking of the total particles. Because CO_2 would come from the surface ocean, the pressure of CO_2 in the surface ocean box would be decreased, which would lead to a compensating flux of CO_2 from the atmosphere into the ocean and draw more CO_2 out of the atmosphere.

If this were the end of the cycle, we would have permanent sequestration, and everything would be fine. However, when the organic carbon gets into the deep ocean, it is oxidized back to CO_2, which can get mixed back up to the surface ocean and then can escape back into the atmosphere. The time scale of the exchange between the upper ocean and the deep ocean is on the order of several centuries. The upper mixed layer equilibrates with the atmosphere roughly on a time scale of a year or so. Thus, ocean fertilization provides only temporary storage.

A number of simulations have been done using general circulation models and schematic ocean models. These simulations suggest that, after fertilizing the southern ocean for a century, it would be possible to store carbon in a range of 100 gigatons to 250 gigatons. I worked on a highly idealized simulation of

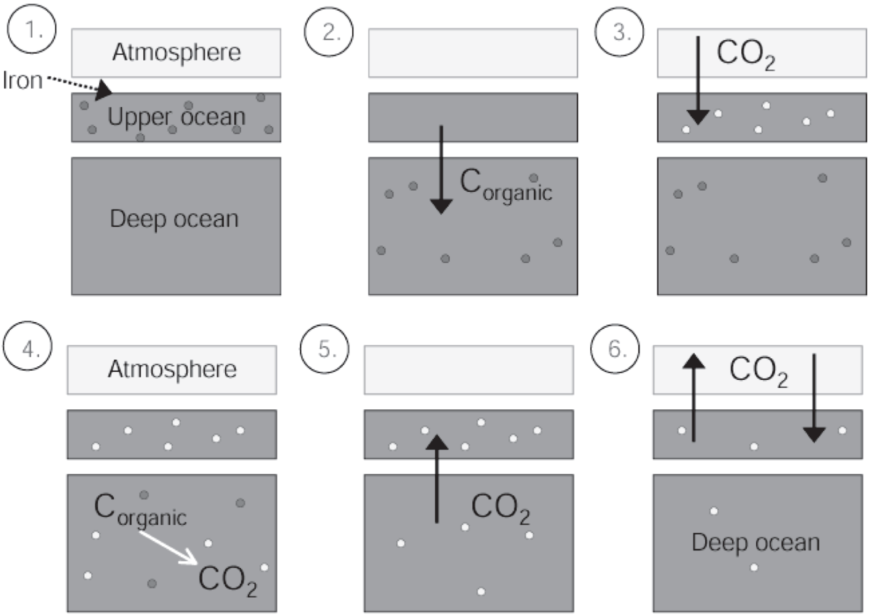

FIGURE 1 Schematic representation of the concept of ocean fertilization. (1) Adding nutrients to the surface ocean can stimulate marine production of organic carbon. (2) Some of the organic carbon sinks to the ocean interior. (3) CO_2 enters the surface ocean from the atmosphere to replace some of the carbon removed from the surface ocean. (4) In the ocean interior, the organic carbon is oxidized to CO_2. (5) This CO_2 is eventually mixed up to the surface ocean. (6) Once in the surface ocean, the CO_2 equilibrates with the atmosphere.

fertilization (the Los Alamos Parallel Ocean Program [POP] models) that began with the premise that we could add enough micronutrients to the ocean south of 30 degrees to completely deplete surface macronutrients, such as phosphate. One early discovery with this simulation was that, after only three years, CO_2 would already begin to leak back into the atmosphere. If we compared three years, 30 years, and 300 years, we found that previously sequestered carbon was leaking back out over much of the rest of the ocean, and by 300 years, there was significant leakage in the tropics. There are two reasons for leakage: (1) carbon placed in the deep ocean eventually mixes back up to the surface; and (2) along with the organic carbon, we sent nutrients down into the deep ocean, thus increasing the deep-ocean nutrient content at the expense of the surface ocean. Biological productivity in other parts of the ocean then began to diminish.

In the POP simulation, approximately 375 additional gigatons of carbon are stored in the ocean over a period of 400 years (see Figure 2). On this time scale,

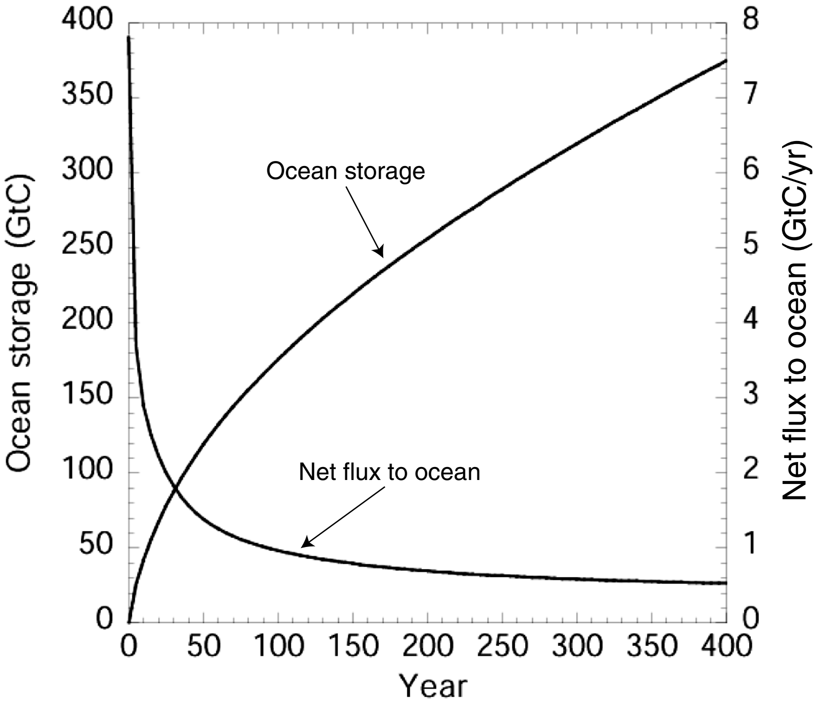

FIGURE 2 Amount of additional carbon stored in the ocean and amount of additional storage per year (net flux to the ocean) as computed at Lawrence Livermore National Laboratory for idealized iron fertilization south of 30 degrees using the POP ocean model.

the storage is on the order of about one gigaton per year. The net flux starts out close to eight gigatons. At about 100 years, net additional storage (new storage minus leakage) is about one gigaton per year. At 400 years, net additional storage is about half a gigaton per year.

My sense is that these are upper bound numbers because in the real world we would probably not fertilize the entire ocean south of 30 degrees, and the areas that were fertilized would probably not perform up to maximum possibilities. It is important to understand that ocean fertilization, insofar as it works and is environmentally and politically acceptable, might become part of a portfolio of responses. In itself, it won't solve the problem.

As we continue fertilizing, we move phosphate and nitrates away from the upper ocean. Thus, the effectiveness of iron fertilization diminishes over time as the surface ocean runs out of macronutrients. In addition, the ratio of added carbon to the added exports from the surface ocean to the deep ocean decreases with time because previously stored carbon leaks back into the atmosphere.

What is the residence time of carbon in the ocean? The ocean transports tracers along surfaces of constant density, controlled largely by temperature. Denser surfaces outcrop at the colder poles. Some surfaces in the deep ocean are not well ventilated, so even though more organic carbon is being transported, more carbon is retained in those areas. In other parts of the ocean, CO_2 slips back into the atmosphere much more quickly.

To determine how ocean carbon sequestration would change allowable emissions, we can calculate the net benefits as functions of a discount rate and assume a price trajectory. With a zero discount rate, there is no time preference, and there is no point in ocean fertilization because future value would not be discounted. We should look at the discount rate minus the emission cost because, if we have a 3-percent discount rate but the cost of carbon emissions rises at the rate of 3 percent, once again we would gain nothing. Taking the range of discount rates that are typically used in business, we would have to sequester initially three gigatons of carbon, say at 0.33, in order to get one gigaton of carbon's worth of sequestration value. In other words, we use roughly a factor of three to account for the fact that this is not a permanent sequestration.

In one simulation, organic carbon that sank into the deep ocean oxidized, thus consuming ambient dissolved oxygen in the water column. After 300 years, regions formed in the model ocean that had severe oxygen depletion, suggesting potential harm to oxygen-breathing organisms.

Green Sea Ventures estimates that the cost of iron fertilization would be $7 to $7.50 per ton. But because it would be a temporary sequestration, we must also consider that it might be necessary to multiply the cost by approximately a factor of three to get the net present value. Macronutrient strategies would be considerably more expensive. Some have also suggested that ships could dribble along some iron to compensate for the flux of CO_2 admitted by ships.

Models are helpful for clarifying conceptual situations, but a model is only as good as the basic knowledge that goes into it, and most models include many unknowns. We don't know to what extent adding nutrients to the surface ocean would stimulate marine production of organic carbon or how that would vary from environment to environment. Although we're making progress, we are still not sure what fraction will sink to the deep ocean when organic carbon production is increased. Of the organic carbon that sinks to the deep ocean, some carbon can mix up from below, and some CO_2 can come from the top. A deficit in the surface ocean may also remain. It is not clear how much a flux of CO_2 from the atmosphere would compensate for this sinking flux or how deep the CO_2 would sink in different environments before it is oxidized. Once it is oxidized, we don't know how long it would stay down before it cycles back up to the surface. There is also some disagreement, although I think I know the answer, for how we should account for the sort of out-gas seen in de-gasing situations.

If all of the CO_2 we sequester eventually leaks back into the atmosphere, then all we are really doing is time-shifting emissions. We're putting CO_2 in today. and it's leaking out 100 years or 200 years from now. How can we put a value on the time-shifting of an emission? This is not simply a question of economics. One advantage might be that it would give us time to invent new, carbon-emission-free energy technologies. It might be worth reducing emissions in the short term in anticipation of new energy technologies coming online in the long term.

Sequestration in Terrestrial Ecosystems

Using Terrestrial Ecosystems for Carbon Sequestration

GARY K. JACOBS
Oak Ridge National Laboratory

Using the world's terrestrial ecosystems to sequester carbon is a familiar idea. I'm going to take a slightly different tack to this question and share some thoughts on research and technology that might help us harness the power of our terrestrial ecosystems. I want to thank and hold harmless many of my colleagues from the U.S. Department of Energy (DOE) Research Consortium for Enhancing Carbon Sequestration in Terrestrial Ecosystems (CSiTE). Some of the results I will present are preliminary and subject to change. I am grateful to my colleagues for allowing me to share their information, any errors are mine and not theirs. I also wish to thank the DOE Office of Science for their support of this research.

What do we really mean when we talk about sequestration in our terrestrial ecosystems? Many interrelated processes go on in these systems. Fundamentally, the first thing we can do in terrestrial ecosystems is to protect, recover, and manage existing resources; that has a certain benefit numerically. Next, there may be opportunities to intervene and enhance existing resources. We are trying to solve a global problem, but some of our options will involve manipulations or interventions that actually make changes at the molecular level—for instance, to protect soil organic carbon. There are three basic intervention strategies: (1) increasing the productivity of ecosystems, thereby creating more biomass and more inputs to the soil-carbon pool; (2) partitioning carbon to the long-lived components of ecosystems (e.g., converting from grassy to woody systems); and (3) altering the longevity of existing pools (e.g., protecting soil by changing agricultural practices). There may also be ways to adjust soil-microbial communities to promote certain behaviors that protect soil organic carbon.

But let's be honest. Terrestrial ecosystems alone will not be able to balance fossil-fuel emissions. The potential contribution from terrestrial ecosystems is not as minuscule as some have implied, but neither is it *the* answer. Terrestrial ecosystems can buy some time for our global community, and using ecosystems to sequester carbon would have some other benefits (e.g., erosion protection, improved soil productivity, increased biodiversity, and retention of soil moisture).

The challenge is to shift both the rate of carbon accumulation and the capacity to store it. Right now, we do not even know for certain what the capacity is. And even if we can shift these rates, we don't know the potential consequences. They could be very positive (e.g., improving soil productivity, reducing erosion, retaining moisture more thoroughly) or less positive (e.g., changing biodiversity, shifting valuable lands from one crop to another). We must consider all the implications.

Right now, the terrestrial biosphere acts as a biological scrubber that removes roughly two gigatons of carbon per year (GtC/y) from the atmosphere. Of course, one must also recognize that global change could alter their current behavior, and ecosystems could become net emitters of carbon. Nevertheless, there are several options for increasing the current sequestration rate. Through reforestation, afforestation, restoration of degraded lands, improved agricultural practices, and the use of biomass feedstocks, the global *potential* might be as high as 5 GtC/y. These rates could be sustained for perhaps 10 to 50 years, resulting in a total sequestration potential of 50 to 250 GtC—a significant help to meeting the global challenge.

But we are concerned not only about the impact of carbon dioxide (CO_2) but also about the total integrated impact of any intervention on the Earth's climate system. That is the real issue we have to evaluate with any option. For example, growing more forest will have an impact on the reflectivity of the Earth's surface and the water cycle. If we do too good a job of restoring degraded lands, might we change the amount of wind-blown desert particles that fertilize the ocean? We have to remember that none of these systems can be viewed independently. We can change land area or the below-ground carbon or the above-ground carbon, but we have to keep in mind the dynamics of whole ecosystems and evaluate how we might affect the global system.

Scientific efforts in various disciplines could potentially contribute to important solutions. The first of these is the selection and engineering of species. Consider a tree, and hypothesize that there are genetic controls on the allocation of below-ground and above-ground carbon (i.e., roots versus shoots). Furthermore, there may be genes that are important in the partitioning of the carbon within lignin, hemicellulose, and cellulose, both above and below ground. Stan Wullschleger and Jerry Tuskan of Oak Ridge National Laboratory and their colleagues are trying to discover the genes that might allow us to take advantage of this allocation behavior. Their preliminary results are encouraging.

The DOE Office of Science has just initiated some exciting research with the Joint Genome Institute in this area. The first tree to be sequenced, *Populus*, is a species with many potential uses in the energy area. Current domesticated varieties are leafy, thin, and competitive with one another. Once the genome sequence is completed, we could begin to address important issues, such as reducing competition within a plantation, optimizing the wood chemistry for either fuel or products, increasing resistance to pests, increasing the yield, enhancing storage of soil organic matter in the below-ground system, and expanding the range of effective plantations to other climate regimes. In 25 years, could we double the yield? Could we reduce the price of harvesting and processing? Could we sequester carbon at the same time? The possibilities are intriguing.

The DOE Office of Science Genomes-to-Life Program offers many other possibilities. As we develop a better understanding of complex soil-microbial communities, we may be able to enhance certain functions that will yield soil-organic materials that are more resistant to further degradation. In addition, Julie Jastrow of Argonne National Laboratory is working on new methods of fractionating various types of organic matter that may yield clues to how we can protect soil-organic matter from microbial degradation.

Research is also being done on promoting behaviors in soils that encourage the formation of humic material that is more resistant to degradation. Jim Amonette of Pacific Northwest National Laboratory is studying relationships among organic monomers, enzymes, and manganese oxides that may promote humification reactions. The challenge is to optimize cycling between oxidizing and reducing conditions while increasing concentrations of monomers and stabilizing the enzymes. It is feasible that we might learn to do this via a combination of crop rotations and new amendments applied during fertilization.

In 1975, DOE's FermiLab began restoring a tall-grass prairie. Julie Jastrow and others are following the changes in the soil carbon over a significant amount of time in this chronosequence. The good news is that carbon can accumulate and that this accumulation is occurring without fertilization. Sampling of the soil indicates a pretty substantial increase in soil carbon, and preliminary evidence suggests that its mean residence time could be 127 years.

Changes in land-management practices also offer opportunities for substantial accrual of organic carbon. It will be critical to do a full accounting of greenhouse gases for every new method, from conventional to no-till practices. As management strategies change, there will necessarily be consequences, good and bad. It is essential that we develop tools to carry out truly comprehensive evaluations.

We must evaluate all impacts and costs for all sequestration options. We are already doing that systematically for terrestrial ecosystems. Tris West and Gregg Marland of Oak Ridge National Laboratory are developing methods of performing a full accounting of greenhouse gases from shifts in agricultural or forest management practices. Gregg Marland is also developing relationships so we can compare the values of storing carbon for different lengths of time. It is important to be able to represent the time-value of carbon in products. Cesar Izaurralde and colleagues at Pacific Northwest National Laboratory and several universities are improving models for evaluating the environmental aspects of sequestration options. The factors being addressed include soil carbon, erosion, nutrient availability, runoff, and non-CO_2 greenhouse gases. Finally, there is the matter of economics. Bruce McCarl of Texas A&M University is addressing the issue of what is possible within economic constraints. He has shown that the value of carbon will have a large impact on the potential for ecosystem management that contributes to a global solution.

How much difference can innovative research make in realizing a significant role for terrestrial ecosystems? First of all, we already manage a large portion of our Earth's terrestrial resources. There are estimates that we already "use" 10 to 55 percent of terrestrial production. Agricultural productivity has increased dramatically in the last 50 years, and some studies project that similar increases will continue for the next 50 years.

Earlier, I said that future carbon sequestration rates could be, say, 2 to 5 GtC/y for several decades. Roger Dahlman of the DOE Office of Science has estimates (based on results of the Ameriflux Program) of perhaps 3 gigatons being sequestered globally in forests. Thus, my stretch goal of 5 gigatons may not be unreasonable. I believe that science and technology will enable us to extend what we are already doing for a longer time, increase rates of sequestration, and eventually lead to higher capacities for carbon storage.

What we need most right now is the ability to do things on a practical scale to discover what works and what doesn't. Implementing these practices over a large land area will, of course, pose some engineering challenges, but only large-scale tests and demonstrations will determine what motivates behavior and what the impediments (technical, social, and economic) are and how they can be overcome. Our challenge is to deploy some near-term options to buy some time and do some learning.

The bottom line is that we know a lot right now. Through innovative research, terrestrial ecosystems could substantially help solve the problem, buy us some time, and provide meaningful ancillary benefits to human and ecological systems. But they are not the sole answer. Fully integrated evaluations will be critical to informed decisions, and we urgently need large-scale test systems operating in parallel with excellent fundamental science.

Monitoring Carbon Adsorption in the Terrestrial Ecosphere

JOHN KADYSZEWSKI
Winrock International

Terrestrial ecosystems may offer near-term, cost-effective ways of storing carbon. We are trying to bring good science to the monitoring and verification of carbon storage—to determine if carbon is actually being stored, if so, in what quantities, and if the storage is cost effective. Today I want to talk about monitoring systems and the practical field testing and application of monitoring systems, discuss some examples of large-scale measurements, and put forth future monitoring options we think may change the way business is done.

On a global basis, there is a net emission of carbon from terrestrial ecosystems. Loss of forest cover and changes in land use in recent decades have already put a significant amount of carbon into the atmosphere, and we are trying to monitor what is there now. There is a widespread belief that sequestration is a near-term option, and a number of sequestration projects are ready to go forward.

When creating a monitoring system, the first point to consider is design objectives. What are the criteria? We designed a monitoring system for accuracy and precision at predictable levels. Integrity of results was very important. The methods I will discuss here have been peer reviewed and are available free on our website (*www.winrock.org*). We will be publishing a revised set of methods, in partnership with the Center for International Forestry Research in Bogor, Indonesia. We do regular updates, so we encourage everybody to make suggestions or recommendations.

A monitoring plan has certain essential parts. First, we stratify projects to minimize the costs of measurement; we use the statistical sampling approach. We are trying to reduce the variability within each stratum so we can get high levels of accuracy and precision with fewer sampling plots. We sample the variability of the particular class of carbon that is being stored. When we put together standard operating procedures for doing the measurements, we find that setting projects in a long time scale introduces an element of uncertainty.

When setting up a monitoring system, it is essential that the instructions be very specific, because the system may be in place for 50 years and may be run by different people and different management systems. The instructions must address the most minute aspects of the system, for instance, whether to put the tape under the vine or over the vine and how to deal with a forked tree. We put in recommended frequencies for monitoring, quality assurance, quality control plans, and soil blanks in the soil samples to check the calibration of the equipment.

Then the data must be archived. Over the 10 years of this project, the software has been changed half a dozen times. Try to envision deciding on a form to keep your data in so it can be referenced 50 years in the future. That is not a trivial decision.

To stratify sample sites, we try to pool available data. In the United States, it is easy to find digital elevation models and topographic maps, aerial photography, and satellite imagery. When we put in preliminary plots, we can determine the variability within those strata and estimate the number of plots.

There is a trade-off between cost and precision. The more precise you want your numbers to be, the more plots you have to put in. But the more plots, the more the expense; it is always important to keep an eye on costs. Fixed and variable costs are different. Fundamental design cost is unavoidable, no matter how big the project is. But the costs of methodology details can be found in the Intergovernmental Panel on Climate Change year 2000 special report, *Land Use, Land-Use Change and Forestry*. The lead author on the chapter about project monitoring is one of my coauthors, Sandra Brown (2000).

These techniques do not require cutting-edge science. Monitoring methods are based on the principles of forest inventory, soil sampling, and ecological surveys and have been in place for decades. By talking to scientists involved in those areas, you can arrive at consensus about acceptable methods. There may be some debate, more in the soil community than in the forestry community (e.g., whether a geomorphologist's approach is more useful than a microbiologist's approach in soil analysis), but there is general consensus about methods that have been used with confidence over long periods of time by a variety of institutions.

For non-carbon dioxide (CO_2) flux gases, however, methods are not as well established. When we talk about the complete package—especially, when we look at methane and nitrous oxide—monitoring methods are not clearly established in the literature, especially for comprehensive accounting that requires manipulating inputs in large land systems. Pilot projects would provide a good opportunity for trying out methods.

We always put in permanent plots. We use mean grass-type diameter for trees, and we use regression equations to convert mean grass-type diameters into biomass content. When looking at understory litter, we use clip plots with standard rings to dry the samples for carbon analysis.

Dead wood is an important element in most forestry systems; it can be up to 20 percent of the total carbon in the pool. The flux changes a good deal depending on the climate conditions. For a standing biomass, one can use regression equations for dead wood on the ground. We use a line-intersect method and sampling for density to estimate the carbon.

We currently dig soil pits (currently 30 centimeters deep) into a permanent plot. If we go to 50 centimeters, we blend the 30-centimeter and 50-centimeter samples together. We put the samples through a 2-millimeter sieve, air dry them, and then do a carbon analysis. We also take a bulk density from a vertical wall in one of the pits. This process is labor intensive and somewhat expensive. We have been following some interesting work on laser-induced breakdown spectroscopy that we think will reduce the costs of soil sampling. But, for now, we are using the traditional approach.

We decide which pools will be measured based on a number of criteria. Not all of the pools have to be measured, but every pool expected to be negative must be measured. Beyond those, we decide which pools to measure based on the cost of measurement, the expected value of the carbon, the amount of carbon we expect to find in the pool, how fast and in what direction we expect the change to be, and how accurate we want to be.

When measuring changes in soil carbon over time, we are trying to detect much smaller changes against a larger background than when we measure trees. Therefore, we need larger sample plots, so the costs are higher for, perhaps, a smaller amount of carbon. Those factors can influence your decisions depending on the project design.

Measuring below-ground biomass is a complicated exercise and quite expensive. We are now measuring more than a million hectares on a global scale. In those projects, our cost estimates are based on regressions. Three categories of measurements were agreed on in the Kyoto negotiations: additionality, baselines, and permanent leakage.

Most regulatory systems and trading systems have guidelines that govern what must be measured. Besides the physical properties and presence of carbon, other concerns may be taken into account, such as the three major classes of error: sampling error, measurement error, and regression error. By far the largest errors are sampling errors, which reflect flaws in the preliminary design and the stratification and estimated variability. Measurement errors are mostly transposed numbers on forms, which are very difficult to eliminate. Regression errors, surprisingly, do not seem to make much difference in measuring carbon in classes of trees. Standard regression equations from 34 different species of eastern hardwoods east of the Mississippi in the United States reveals a 0.99 curve fit. Many people predicted that measurements for tropical forests would be very different, but a regression for 224 species of tropical hardwoods in a mixed tropical forest was 0.97. Predicting root structure based on these factors for below-ground biomass, we end up with a regression correlation of only 0.83.

As a nonprofit institution interested in environmental sustainability, we emphasize another aspect of measurement—the co-benefits. In this respect, there are clear differences among different types of carbon-storage projects, which may have biodiversity benefits or habitat benefits or watershed-restoration or wetland benefits. We try to measure those types of benefits in the same transparent ways. The same also holds true for socioeconomic benefits, such as changes in income, availability of jobs, and sustainable production systems.

For example, the Noel Kempf project, designed by the Nature Conservancy, is probably the largest carbon project implemented to date. It is a $10-million program that covers about 1.5 million acres (640,000 hectares) in Bolivia. The Nature Conservancy project bought together all of the logging concessions harvesting trees from the forest to maintain the area as a park; the Conservancy also tried to reduce the influx of slash-and-burn farmers on the park perimeters. We broke up the 1.5 million acres into half a dozen different strata and put in 625 permanent sample plots in the park. This is probably the first large-scale carbon assessment of a mixed natural tropical forest. Our conclusion was that the park was sequestering 225 tons of carbon per hectare. Across the site, we surmised that inundated soils would have a lot more carbon in them, and we were very interested in providing data to support that guess. This was also an issue in a number of other projects.

The Nature Conservancy ran another project in Brazil's Parana state, in the Atlantic forest. The project sponsors bought up buffalo ranches and reforested them to defragment a natural Atlantic forest. Land holdings were added to restore the integrity of the block of forest. When we went in to monitor the carbon content in different areas, we had to give different expected carbon values to different parts of the land holdings. We are studying average carbon density, as well as minimums and maximums. The diverse results we are getting give us a sense of the accuracy and precision that can be achieved across the statistical sampling regime.

In the future, we hope to bring down the cost of measurement. The cost for the work I just described on the Atlantic forest project has been less than 25 cents per ton of carbon. We actually could have achieved 20 to 22 cents for that measurement. To bring down costs in other ways, we are looking into remote-sensing techniques and working on combining those with existing ground-based measurements. The goal is to bring costs into the 10- to 15-cent range.

We have also been working to develop new technological approaches to monitoring. We considered using satellites, but found that, at this point, they are more expensive and unreliable than sending people in on the ground. We tried some aerial techniques but found we had a hard time differentiating crown dimensions. We have now developed a camera system for aerial monitoring that uses digital cameras and digital video cameras, logged with a global positioning system (GPS) system hooked to a satellite, an internal onboard navigational system to correct for pitch and yaw, and a laser range finder that shoots 2,000 pulses a second so we can get canopy height and ground height in overflights. We are also using dual cameras to get a stereo image that enables us to differentiate crown heights.

This is how the system works. When flying over a site, the cameras take two positions equidistant from a point in the frame; we then put together an epipolar model that allows us to come up with a three-dimensional terrain map of a complex forest. Between the height of the trees and the crown diameters, we can come up with good estimates of biomass. This gives us a fairly high degree of confidence and certainty that the trees we are measuring are there. Over a period of time, we can go back and look at a specific tree (all trees are given georeference points). The data are all there. At any point, we can zoom in on a particular tree and flip it into a three-dimensional model, doing a real-time measurement on the crown and the crown height. With this technique, circling the crowns and taking their heights, we can do a sampling routine based on flying over a strip and identifying trees and crown diameters, rather than having to send in a ground crew.

Currently, we are working on automating the process of drawing crown diameters, which, in two dimensions, had been very difficult. In three dimensions, however, it appears to be feasible.

Early results of fly-overs with a large number of samples and higher levels of precision have been surprisingly good. When we tried to do aerial photography, the R-squared were about 0.6. But with three-dimensional terrain modeling, we have been getting R-squared higher than 0.9 on a regular basis. So far, we have only tried it in about a dozen places, so we are not sure what the limitations are. In one example, the ground plots gave us 89 tons of carbon per hectare with a 95-percent competence interval, whereas our aerial measurements gave us 87.7 tons of carbon per hectare with a 95-percent competence interval. We think we will be able to reduce error with new regression equations that go directly from crown diameters to biomass instead of going through existing algorithms.

The aerial monitoring equipment, which was designed to be inexpensive, can be flown on any small aircraft; we put it into a suitcase and take it on the Cessna with us. Weather constraints have not been a problem for collecting data and imagery, which was one of the problems we had with satellite data.

Aerial monitoring with this camera system can also be used for other kinds of projects, such as soil projects. For example, we could monitor compliance of a group of farmers who had agreed to use no-till management. With this kind of imagery at low altitude, with the benefits of a three-dimensional model, we can see the furrows in a field to determine if farmers had been plowing. If there are minimum setback requirements, we could measure, say, the distance between a field and a river. We could look at the impact of water and flooding regimes because we would have a georeferenced digital elevation model for the area. We could also determine access points—how to get into a particular site to do measurements.

Most of all, over time, this kind of information gives people a high level of confidence that, in fact, what you say is there, is there. Whether in the United States or in a remote place in Bolivia, pictures are sometimes more convincing than statistical reports full of tables of data. We are excited that this aerial monitoring system cannot only take measurements but can also increase the confidence in near-term markets because of their potential to buy time in the short term while other technologies are being developed.

Thanks to developments on the Internet in the last two years, this information may also be layered into a data-rich field. It is now possible to add all kinds of data layers. We can put down a topographic map, overlay the hydrology on top of it, put in the road system, gas pipelines, transmission lines, put down landsat photos. When you go to a particular project site and lay in that image, the new data you collect can be layered onto all of the existing data from the Internet. This means this tool can be used for a much broader range of environmental assessments and change detection.

At any point in a flight, you can look down at a specific location, ask what is going on, and take a measurement. By moving my cursor over a tree, for instance, I can tell how tall the tree is. If I want to know the distance between a road and a particular point, I can do the same kinds of measurements in real time off a dataset, knowing all of the other details that are embedded in this image for tracking purposes. For forest certification stewardship, just in terms of harvesting, we can tell how many trees were taken out in a selective harvest; we can also measure the size of those trees and how many board-feet of timber was probably in those trees. This method of data collection could be used not just for single points but also for large areas.

Let me close by saying that we are very concerned about the integrity of measurement systems. We need transparent standards based on good science. We believe new imaging tools will reduce overall monitoring costs and enable us to measure a broader range of environmental attributes for projects and, at the same time, make the projects more credible. All in all, we think that it will be possible to make accurate measurements for forestry projects anywhere in the world at low cost.

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Advanced Research and Development and Engineering Processes

The Forms and Costs of Carbon Sequestration and Capture from Energy Systems

DALE SIMBECK
SFA Pacific

SFA Pacific is a consulting firm that provides second opinions to people high on the learning curve before they make investments. We have no vested interest in promoting anything. Most of our work is in the private sector, and a lot of it is done outside the United States. In fact, about two-thirds of our work related to carbon dioxide is done abroad. We have been working on carbon dioxide for about 15 years, in the last two or three years mostly for private industry. When private industry asks people like us to get involved you know they take the issue very seriously.

Power generation is going through some enormous changes, 20 years of difficulty driven by newly deregulated utilities entering the competitive free market. The big ugly "C" word that all regulated utilities fear the most is competition. People who still work in power generation probably have ulcers and high blood pressure.

The sector of power generation operating in the greatest uncertainty today is not transmission or distribution, but power generation itself. The uncertainties for power generation are tremendous, especially when it comes to environmental law, which is constantly changing and is very prohibitive to new power plants. Incredibly, we have created a situation in which utilities are actually driven by economics to extend the lines of old, "big dirty," inefficient power plants because environmental laws grandfather them in. Fifty percent of the power in this country is generated by coal-fired power plants with a mean age of 25 to 30 years. These aging plants produce about half of the total kilowatt hours generated in this country. In the last 15 years, essentially no new coal plants have been built for two reasons—environmental laws and cheap natural gas.

One of the key things that has come out of Kyoto is that the Kyoto agreement basically will not work. Nevertheless, companies are trying to make it work. Shell and British Petroleum, for example, are five years ahead of governments on effective, transparent, internal trading of carbon emissions. These private industries are actually ahead of their schedules in terms of reductions.

There are only four basic options for reducing carbon dioxide (CO_2) emissions: (1) reducing world population; (2) reducing the standard of living in industrialized countries; (3) reducing energy intensity; or (4) reducing carbon intensity. For meaningful worldwide reductions in CO_2, there are really only two places to look—energy intensity and carbon intensity in the world's two 800-pound gorillas, the United States and China. The United States accounts for 25 percent of the world's greenhouse gas emissions. But that is because we also create more than 25 percent of the world gross domestic product. We produce a high level of CO_2 emissions because we are the economic engine that drives the entire world. China will probably surpass us in the next 20 years because that country's industry is mostly coal based, and its energy systems are very, very inefficient.

Keep in mind that power generation is where the growth is. Power generation grows at the same rate as gross domestic product, whereas other end-use energies grow at about half that rate.

The United States has an incredible overall energy balance. Power generation accounts for 35 or 36 percent of the whole; transportation fuels account for about 26 percent. Those two add up to about 62 percent of the total energy consumed in this country. But an enormous amount of energy is wasted in our power generation, which is only 33 percent efficient. This is an embarrassing situation. Moreover, our transportation is only 20 percent efficient.

What is even worse, the efficiency numbers are not going up. In fact, they are going down. Power plants are becoming more inefficient because our pollution laws encourage old power plants to add scrubbers that extend their lifetimes, making them even less efficient. Transportation efficiency numbers keep going down because of the American love affair with sport utility vehicles (SUVs). Last year for the first time more SUVs were sold than cars. The efficiency numbers for fleet sales of cars last year declined to 20 miles per gallon, the lowest point since 1980. We are going in the wrong direction.

Three sectors are to blame for carbon emissions in the United States: the industrial sector, the transportation sector, and the power-generation sector. Which of these will have to be responsible for the major share of CO_2 reduction? If a carbon tax is put in place, the U.S. industrial sector will move to China. The transportation sector won't ever be expected to comply with a carbon tax, because SUVs are our sacred cows, and no one can gore a sacred cow and be reelected to Congress. (By the way, don't blame Detroit for SUVs. Blame yourselves, because automakers produce what you want.) So which sector is left? Power plants.

The power-generation sector operates aging, inefficient, coal-burning plants with efficiencies of less than 35 percent, that produce 35 percent of the emissions in the United States and 9 percent of the emissions around the world. Power plants are vulnerable because they cannot move to China. Therefore, we should rethink power plants because there are a lot of ways to improve them, both by improving efficiencies and by using lower carbon fuels. But ultimately, we will probably need carbon capture, and, to do that, we will need large point sources, such as existing, coal-fired power plants.

The win-win situation for reducing carbon emissions in power generation is increasing energy intensity. There are two ideologically opposed approaches to higher efficiency. The regulated utilities want to build new ultra-supercritical coal plants. The industrial sector wants cogeneration. In my opinion, the utilities should focus on their old plants. Under current laws, if they try to improve their old coal plants, they are punished. We have to change the laws to encourage utilities to make their old plants more efficient. For new capacity, however, we should look to cogeneration. The key factor in cogeneration is that it works effectively, not with steam cycles but with gas turbines, because cogeneration is heat-host limited, a very simple issue that most people don't appreciate. For a given heat host, you need technologies that give the highest power per unit of cogenerated heat. That is why you use gas turbines, which are already commercially proven. If we ever develop intercooled gas turbines, we will actually double the efficiency numbers.

Cogeneration is critical to increasing energy intensity. Without going into depth, I would point out that cogeneration could be brought into play in the two critical places—North America and China. Cogeneration will not become important in the United States until the old coal-burning power plants are no longer life extended. The marginal load dispatch of old plants is so low that you can't compete with them. In China, the enormous potential for cogeneration is being stymied because it is not in the best interests of China's regulated utilities to buy high-efficiency cogeneration from others. They make their money on guaranteed return on investment because 50 percent of China's coal use is in very small boilers with very low efficiency and very high pollution.

Later in these sessions, you will hear talks about biosinks, which are good for mankind but questionable for net carbon reduction. First of all, they are not really sinks; they are carbon offsets. In addition, there are long-term issues that must be addressed in terms of permanence, verification, transparency, and especially fairness. The problem is that carbon offsets would allow Americans to take unfair advantage of poorer nations.

The important thing is to reduce the carbon content of fuels. We could use natural gas if it were cheap. But one thing you can be sure of is that in a carbon-constrained world natural gas will not be cheap.

Another win-win situation will be to life-extend existing nuclear plants. We cannot build new nuclear plants until we go through the ugly side—the shutting down and decommissioning of parts of the existing fleets. We must also resolve the waste issue before we can build new nuclear plants.

When it is cost effective and when we can deliver it at a sound price, we want to co-fire biomass in existing boiler systems. Generally speaking, nuclear energy, renewable energy sources, and reforestation biomass are great ideas, but they have very limited possibilities, and we must appreciate these limits. Some popular ideas will never be very useful. When we think of biomass, we should concentrate on waste biomass, because afforestation doesn't mean much for an existing coal plant; the economics of growing biomass for power are terrible. Wind turbines are great, but we have to be honest about what they can and can't do. Cycling-load wind turbines can't replace a base-load coal plant because they cycle low, and they need backup. Those are very real problems. Compare the 30-percent annual load factor produced by wind turbines with the 85-percent load factor produced by coal plants.

The new approach to reducing carbon intensity is CO_2 capture and storage. This concept has changed the debate in the last five years because capture and storage cost less than the most politically correct approach—wind turbines. The best approaches to capture and storage appear to be through enhanced oil reservoirs and coal-bed methane production. Those are the places to start. Sequestering CO_2 will increase cost by an order of magnitude. There are many pure CO_2 vents out there right now.

The next thing to look at is gasification, repowering existing coal plants and ultimately building new plants with cogeneration or polygeneration systems. Most power-plant engineers will tell you that gasification is not commercially viable. They say it is very risky, and it doesn't work, but that is not correct. A large demonstration in gasification is going on right now. Because expertise in chemical processes is necessary to make gasification work effectively, it is being used primarily in refineries. There are 65 commercial gasification plants right now, mostly in China, most of them producing ammonia. They also make pure hydrogen with gasification, and they do it every day. Hydrogen is becoming increasingly important for producing carbon-free energy. In fact, after conducting a series of tests, General Electric now guarantees performance for burning hydrogen-rich gas in its turbines. In other words, the technology for gasification is all commercially available today. The issue is cost.

One commercial power plant in the United States now makes pure hydrogen and pure CO_2 by gasification from coke, which is basically coal without the volatile fraction. Farmers in the Midwest own the oil refinery that makes the coke they feed to the gasification plant. What the U.S. coal-based utilities say can't be done, farmers in this country are doing commercially right now, with no subsidies.

Polygeneration is a unique approach. Commercial polygeneration plants are in production right now, with high availability and no spare gas fires. These plants are very cost effective, and several are operating commercially in major oil refineries without subsidies. All of these new plants represent the future of gasifcation. No central power plant will be able to compete against them.

Now let's turn to the cost of power generation with CO_2 control. First, we have to define a baseline—a natural-gas combined-cycle power plant. Next, we must determine which energy source will be most cost competitive. Then, we must look at the costs of recovering CO_2. The cost of capturing CO_2 includes 50 percent to get the pure stream, about 25 percent to compress it, and 25 percent to dispose of it down a well. That is very important because, if the transfer price of the CO_2 goes from this operating cost to the byproduct credit, it reduces the overall cost by about 50 percent.

If we compare a new coal plant and a new natural-gas combined-cycle plant, both built without CO_2 capture, the incremental cost for a gasification plant to add CO_2 capture is much less than for the natural-gas plant. A new coal plant will probably not be built until the price of natural gas climbs to about $4.50. If a carbon tax comes into play, the cost of new plants will continue to go up. Under those constraints, we would use natural gas until the carbon tax became very high. But that assumes a constant price for natural gas. In a carbon-constrained world, the price of natural gas would go way up.

A more exciting idea is retrofitting existing coal plants. Retrofitting has many possibilities. The most important thing I have to say today is that repowering old coal plants with gasification would increase their capacity and efficiency and, at the same time, reduce all emissions to zero. Retrofitting is the only large-scale way to use CO_2 and is, perhaps, the most important issue in CO_2 capture and storage.

Old coal plants are a major problem. No carbon stick is big enough to beat old coal plants to death. A carbon tax would have to reach $200 to $300 per ton to make it cheap enough for coal plants to change. We have considered allowing caps and trades with old coal plants. Many people in the power-generation sector would prefer to pay the carbon tax, which, in a net-sum game, would supply funds to those who want to reduce CO_2.

In sum, Kyoto has big problems, but the key thing is that international industries are leading the way. Besides the Carbon Capture Project, another very ambitious project, called the Canadian Clean Power Coalition, plans to have a 300-megawatt, retrofitted, coal-fired power plant with CO_2 capture in service five years from now. This project will probably lead the way for the future of coal plants.

Utilities will be forced to comply with most of the CO_2 reductions, primarily because they can't move to China. We won't be seeing new central power plants. The sensible choices for efficient new capacity will be polygeneration and co-generation with gas turbines. The utilities will have to be a lot more objective about where they are going in the future, but they have a lot of options. The key thing for the long term is CO_2 capture.

To sum it up, there are two important issues that have to be addressed, the two 800-pound gorillas, the United States and China. China is putting in inefficient systems under a regulated environment. The cogeneration and gasification expertise already used in Chinese ammonia plants is twice as efficient. The United States also has to change many things, starting with addressing the issue of old, inefficient coal plants.

Public Policy on Carbon Emissions from Fossil Fuels

DAVID G. HAWKINS
National Resources Defense Council

As Dale Simbeck pointed out, we need to end coal-plant life extensions. But these extensions haven't been caused by the Clean Air Act; they have been caused by violations of the Clean Air Act. Actions to enforce the Clean Air Act are now before U.S. courts, and the operators of existing plants, not surprisingly, are investing lots of money in lobbyists to fight these enforcement actions. Today I want to stress the importance of moving ahead with the deployment of low-carbon technologies, including technologies like coal gasification, that are compatible with geologic carbon sequestration. We need to take this step to avoid a technology lock-in caused by additional commitments to high-carbon energy systems.

The fundamental aspects of the science of climate change are already settled. We know that carbon dioxide (CO_2) emissions lead to increases in atmospheric concentrations, which lead to increases in temperature. Although we cannot forecast precise temperature increases as a result of any particular concentration level, the link between emissions and concentrations is clear. A given emissions path will produce a given concentration. To avoid going above a target concentration, we need a carbon budget. To stabilize carbon concentrations, as called for in the 1992 Climate Convention, only a fixed amount of carbon can be put into the atmosphere. We have to start thinking of this as a budgeting problem.

The difficulty is that we haven't decided what the concentration target should be. In other words, instead of a classic budgeting problem, we have an options-preservation problem. What must we do to make sure we can achieve lower targets? Clearly, once we decide on the target level, we must put ourselves on a path that keeps our options open to achieve a "safe" concentration level. This means we have to begin now, first to slow down increases in emissions to below the business-as-usual forecast and then to turn global emissions downward.

In the last few hundred years, since human beings started systematically transferring fossil carbon into the biosphere, we have emitted about 300 gigatons into the atmosphere. A possibly "safe" cumulative emissions budget for this century is 600 gigatons. The bad news is that the midrange reference forecasts for carbon emissions in the next hundred years are 1,500 gigatons—way above a safe budget. Midrange reference forecasts indicate that in the next quarter century we will put another 300 gigatons into the atmosphere—half the prudent budget for the next century.

Let's say we want to preserve our option to stabilize CO_2 concentrations at 450 parts per million volume (ppmv), a figure established in a study by the Intergovernmental Panel on Climate Change that summarizes five categories of environmental and health threats: (1) the risks to unique and threatened ecosystems; (2) risks posed by extreme climate events, such as more frequent storms, more intense storms, and droughts; (3) widespread negative impacts; (4) total negative impacts; (5) the risk from large-scale discontinuities. The last category relates to abrupt climate change, the surprise scenario, which by definition has a high degree of uncertainty. The chart shows the temperature increase that will put humanity into the red, or danger, zone for each risk category (Figure 1).

With the 450-ppmv scenario, a change of just 2°C, which is the midpoint for the 450 scenario, would plunge us into the red zone for the first category. The midpoint estimate for the 550-ppmv scenario is 3°C, which would place us in the red danger zone for the first two categories. At the upper limit of the uncertainty range for the temperature response to the 550 concentration, we would enter the red zone for three or four of the five categories.

We now face this dilemma: the longer we stay on a 550 ppmv or higher scenario, the more difficult it will be to get off of it. The long lifetime of CO_2 in the atmosphere means that we are committing not only ourselves but also future generations to unknown consequences. For this reason alone, we should preserve the option of stabilizing CO_2 at lower concentrations.

How are we doing? The newest forecasts from the Energy Information Administration (EIA) of total greenhouse gas emissions (expressed as carbon equivalence and gigatons of carbon) for the next 20 years (Figure 2) show that the United States is going to go from a little less than 1.5 gigatons of annual carbon emissions in 1990 to more than 2 gigatons in 2020. We also see big jumps in emissions in China and India. The total for the globe according to this forecast will go from about 6 gigatons in 2002 to 10 gigatons in 2020—not a good picture.

But I want to focus on something even more significant. Emissions are a function of energy investment, and energy investments are not annual phenomena. A much longer term commitment, the remainder of the century, is embedded in them. Once you make investments, you are committed to them for the life

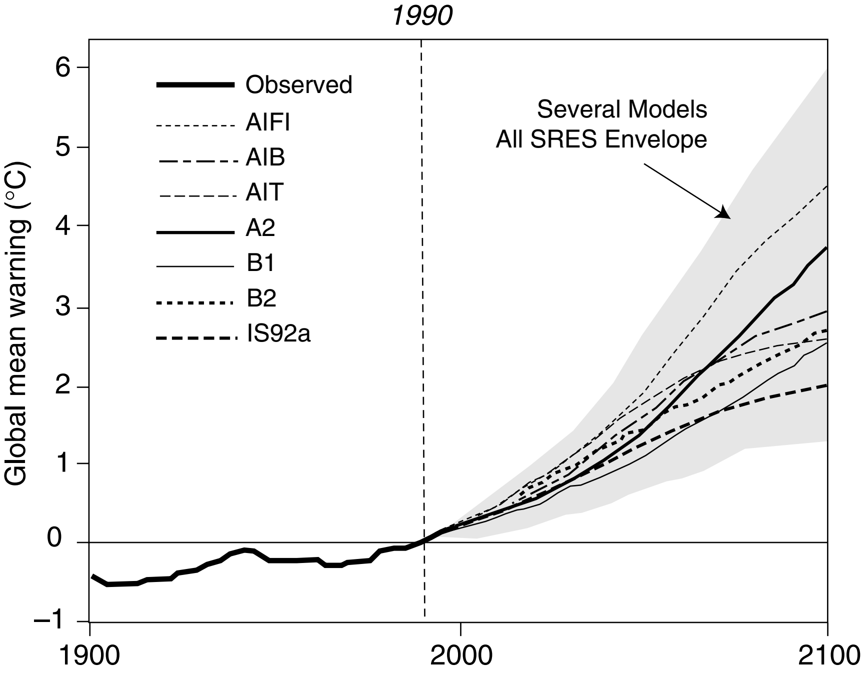

FIGURE 1 Charts showing the relationship between higher emissions and higher risks. Source: IPCC, 2001.

of a facility, absent a breakthrough in technology that makes it very cheap to change something after the fact.

I want to focus on new conventional coal plants, which have the potential to consume a significant amount of the twenty-first-century carbon budget. The EIA forecasts nearly 200 gigawatts of new coal capacity in just three countries: 100 in China, 65 in India, and 31 in the United States. Unless we change our policies, almost all of that will be from conventional coal plants rather than from gasification plants. The implications of this are significant. Every decade that we delay establishing a policy of investing in low-carbon energy systems means additional long-term commitments to high-carbon systems. Ironically, current U.S. policy puts us at a serious disadvantage. The longer we stand by while rapidly growing countries invest in technologies that have a high-carbon commitment, the less of the carbon budget will be available for the rest of the century.

Does that mean that we should wave a stick at these countries, and say don't do it? No, that isn't going to work. A better approach would be to recognize that it is in our strategic interest to develop both *technologies* that will avoid high-carbon emission commitment and *diplomacy* that will convince rapidly growing

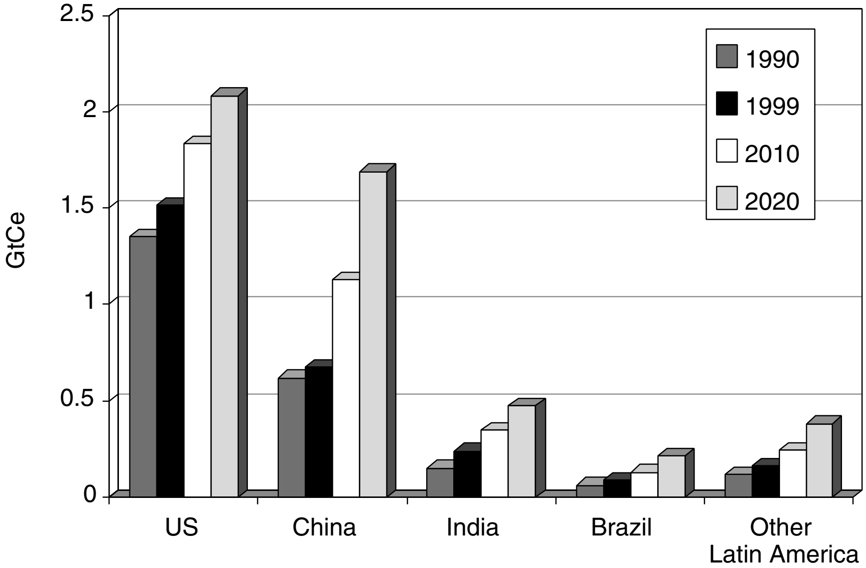

FIGURE 2 Projections of international emissions. Source: EIA, 2002.

economies that it is in their interest to deploy these technologies. But that won't happen unless we also deploy them at home.

Let's examine the portfolio options. Whatever the state of our economic growth and population growth, the portfolio will include increased efficiency. We will be better off if we use our resources more efficiently, and there are many untapped opportunities to help us achieve that. Wind power, solar power, and other renewable energy sources won't solve the entire problem—certainly not in the next several decades—but they will be important components of a comprehensive response. Carbon capture and geologic sequestration is another important strategy. To stabilize concentrations at lower levels, we will have to pursue all of these approaches very aggressively.

What should our emphasis be? Should we focus on buying down the costs or on new gasification plants or on retrofitting existing plants? Currently, there is a very high energy penalty associated with an existing combustion unit for separation techniques, such as amines. There is also an economic penalty. So when we build a new power plant, we must assess how long it can operate without limiting its carbon emissions. To be comfortable with new commitments to conventional coal plants, we would have to assume we will find a magic bullet to bring down costs for those plants so that their carbon can be captured. If this does not happen, we will face an unpleasant choice. Either we will have to incur large retrofitting or premature retirement costs, or we will have to accept continuing high emissions. In my view, a wiser approach would be to minimize the construction of new conventional coal plants.

To do this we will have to deploy gasification technologies in the field to persuade skeptics in the industry and in the investment community who would apply a significant financial penalty to such projects. We have to demonstrate that gasification technologies can make electricity in the United States, and this will require more than the few subsidized gasification plants producing electricity today. Gasifiers are already making fertilizer in China and chemicals in Tennessee.

Here are the challenges we face. Compared to the existing baseload plants, the capital costs of integrated-gasification combined-cycle (IGCC) are high compared to alternatives. Current gas prices are too low to stimulate investment in IGCC; it is cheaper to build natural gas plants. Because of the policy confusion about climate change, nobody knows if there will be a payoff in the near term, or even in the midterm, for investing in a technology that facilitates future sequestration of carbon. Accordingly, gasification technology is hardly being considered for new projects.

A final challenge is the schizophrenic federal policy of subsidies and incentives. For instance, the House Energy Bill and the pending Senate Energy Bill both include a mix of incentives for coal-fired power generation. They include some research and development (R&D) programs, focused largely on gasification and sequestration—thanks to some quiet advocacy by the environmental community rather than to efforts by the coal industry or the electric generating industry. However, the money for R&D is offset by much more lavishly funded policies, federal tax production incentives amounting to a billion dollars or more over the next 10 years to patch up existing, old, conventional coal plants, the very plants that should be replaced. In other words, with these energy bills, Congress is making our energy policy go to war with itself. There are dollars to move IGCC forward, but there are also dollars on the table to push it back by keeping existing conventional capacity running longer. This is not a recipe for rapid progress, but it is a recipe for spending a lot of money, a lot of your money. Clearly, there is a major disconnect in our energy policy.

The results are predictable. The EIA Energy Outlook forecasts a need for large additional capacity in the next 20 years. But the predictions about what kind of capacity will be built don't include more widespread coal-gasification technology; and there is very little increase in renewables or improvements in efficiency to meet this need. The new coal in the forecast is assumed to be all conventional. Natural gas dominates the picture with nearly 300 gigawatts of new capacity. The picture is clear. Instead of finding ways to proliferate coal-gasification technology, the plan ignores it. Under current policy, investors will minimize capital costs by building natural gas plants, assuming that gas prices will not increase before they get their money out. The necessary steps

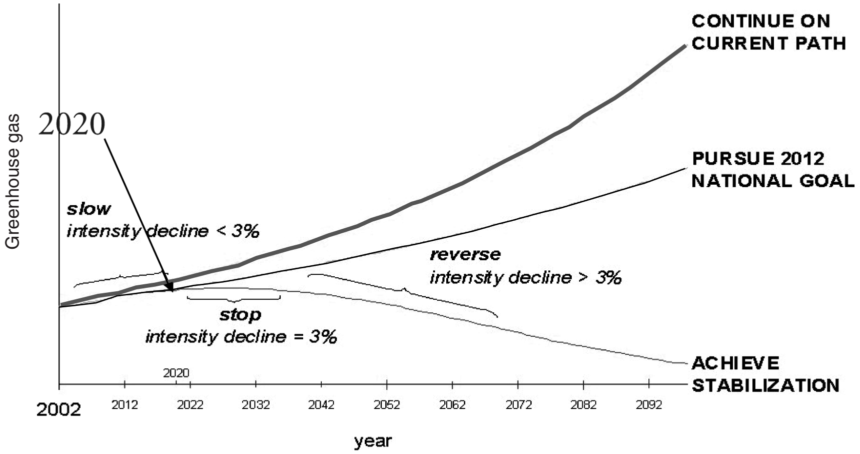

FIGURE 3 Graph showing the government's "path to long-term stabilization." Dates have been estimated and added by the National Resources Defense Council. Source: adapted from EPA, 2002.

to demonstrate ways of capturing and storing carbon from advanced coal technologies are not in the picture.

On February 14, 2002, President George W. Bush said the government's policy toward greenhouse emissions would be to "slow and stop" them. The day before, his advisors had him add the phrase "and, as the science justifies, reverse global warming emissions." The question is by when? The White House released graphics about greenhouse gas emissions, but they don't include dates for emissions increases to end. Our calculations of the implied dates, based on available information, shows that the United States must basically get to zero growth in greenhouse gas emissions by 2020 (Figure 3).

If the White House really believes that a prudent course of action would be for us to get to a zero growth rate in greenhouse gas emissions in the United States by 2020, wouldn't it help to announce that now? Delaying the announcement only eats into our lead time. We urgently need a signal from the president indicating the path ahead. So far, the administration is withholding the signal the private sector needs to make more climate-friendly investments in new capacity. Let us hope we can get beyond this impasse because we have no time to waste. If we allow climate change to progress at its current rate, we will incur lasting damages that we cannot undo.

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Active Climate Stabilization

Practical Physics-Based Approaches to Preventing Climate Change[1]

RODERICK A. HYDE
Lawrence Livermore National Laboratory

EDWARD TELLER
Stanford University and Lawrence Livermore National Laboratory

LOWELL L. WOOD
Stanford University and Lawrence Livermore National Laboratory

It is not generally realized that Earth's seasonally averaged climate is colder now than it has been 99 percent of the time since life on Earth got seriously under way with the Cambrian Explosion 545 million years ago. Nor is it widely appreciated that atmospheric concentrations of carbon dioxide (CO_2) are only very loosely correlated with average climatic conditions over this extended interval of geologic time. In fact, it has been much colder with substantially higher air concentrations of CO_2 and also much warmer with substantially lower atmospheric levels of CO_2 than at present. Indeed, the CO_2 level in the air in the geologic record is one of the weaker determinants of globally and seasonally averaged temperature. If one nevertheless wishes to maintain global climate at its current temperature level—or at the somewhat higher level that characterized the Holocene Optimum several thousand years ago or at the lower value of the Little Ice Age of three centuries ago or at any other reasonable level—then the purposeful modification of the basic radiative properties of Earth (i.e., active management of the radiative forcing of the temperature profiles of Earth's atmosphere and oceans by the Sun) is an obvious gambit. Indeed, active management is likely to be the most practical approach overall.

This paper is concerned with the best way to effect—to actively manage—the desired changes in radiative forcing of Earth's fluid envelopes. "Best" will be

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determined in terms of practicality; the economic efficiency mandated by the U.N. Framework Convention; minimal interference with human activities; aesthetic considerations; collateral effects; and so on. We make no pretense that there is an absolute or objective way to determine practicality. Our examples are merely illustrative of what might be accomplished in the very near term, how much it might cost, and what some of the more obvious externalities might be. Detailed supporting information can be found in our earlier paper (Teller et al., 1997).

RADIATIVE BUDGET CONTROL

We note at the outset that basic concepts for purposeful modification of Earth's radiative properties did not originate with us; they were proposed at least as long ago as 1979 by Dyson and Marland in the context of CO_2-driven global warming and, perhaps most prominently, by the National Research Council (NRC) global change study group in 1992, which noted what appeared to them to be the surprising practicality of active intervention. A subsequent study in 1995 by the Intergovernmental Panel on Climate Change produced similar findings. Our studies are set in the context of the U.N. Framework Convention, Article 3, which states in part that "policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost." We have merely mass-optimized and cost-optimized previous schemes and offered a few new ones, with a little attention given to how near-term studies of optimized schemes for ensuring climatic stability might commence.

The comparatively rudimentary atmospheric and oceanic circulation models currently used to predict climate variability with time predict increases in mean planetary temperature of between ~1.5 and ~5 K, for doubling of atmospheric CO_2 concentrations from the current level of ~350 ppm to ~700 ppm (and associated changes in the mean concentrations of atmospheric water vapor, other greenhouse gases, such as CH_4 and N_2O, aerosols of various compositions and sizes, Earth-surface and atmosphere reflectivity, and radiative transport changes, etc.). Temperature changes of this magnitude would also be induced by a change in either solar heating or terrestrial radiative cooling of about 2 W/m^2, which is of the order of 1 percent. Thus, if sunlight is to be preferentially scattered back into space or if Earth is to be induced to thermally radiate more net power, the characteristic surface area involved in changing net solar input by a space-and-time average of 2 W/m^2 is $\sim 10^{-2} A_{proj} \sim 1.3 \times 10^{16}\ cm^2 \sim 1.3 \times 10^{12}\ m^2 \sim 1.3 \times 10^{6}\ km^2$, where A_{proj} is the area the solid Earth projects onto the plane perpendicular to the Earth-Sun axis. To impose a change uniformly over the entire Earth, it must be four times this size (i.e., the ratio of Earth's surface area to the surface area of its disc).

Radiative budget control on the scales of present interest thus centers on generating and maintaining coverage of this 1- to 2-percent fraction of Earth's surface—or its Sun-presented disc—with one or another of the materials that substantially modify the transport of either incoming sunlight (i.e., insolation) or outgoing thermal radiation emitted at or near Earth's surface over this area. If sunlight is blocked but terrestrial thermal radiation of ~20× greater wavelength is allowed to pass out into space, then Earth will cool by the desired amount in the space-and-time average. Conversely, if sunlight is allowed to pass through to Earth's surface but terrestrial thermal radiation is blocked from escaping into space, then Earth will warm by the same amount—again in the space-and-time average.

Govindasamy and Caldeira (2000) and Govindasamy et al. (in press) have shown that fractional removal of insolation uniformly over the entire surface of Earth not only results in temperature changes of the predicted amounts in the space-and-time average, but *also* preserves the present climate in its seasonal and geographic detail, at least down through the mesoscales in space and time that are treated more or less aptly by present-day global circulation models. The most notable modeling results (Plate 7)—contrary to previous pessimistic hypotheses, which were unsupported by modeling—have been confirmed by subsequent work and indicate that terrestrial climate may be stabilized by adding or subtracting insolation along the lines that we propose, not only "in the large," but *also* in the considerable spatial and temporal detail of interest to the man on the street who experiences the highest frequency components of climate as the daily weather in his microclimate. Govindasamy and collaborators also have offered a plausible mechanistic explanation for why these remarkable results might have been expected.

WAYS AND MEANS OF ACTIVE MANAGEMENT OF RADIATIVE FORCE

"Covering" a million square kilometers of Earth's area with something that substantially affects the sunlight falling on it—or Earth's thermal re-radiation—might appear to be a rather ambitious task. However, because matter may be made to interact quite strongly with radiation, if its composition and geometry are properly chosen, the principal challenge is *not* the preparation or handling of the quantities of materials involved, but rather ensuring that they will stay in place for usefully long intervals. (The average thickness of scattering material over this $\sim10^6$ km^2 is at most 10^{-4} cm, so that the total volume is about 10^{12} cm^3 [the volume of a cube 100 meters on an edge]; the associated mass is only about 1 million tonnes.) As a specific example and looking ahead to one of our results, the present concern about global warming centers on the input of about 7 *billion* tonnes of carbon into the atmosphere each year and several times this level several decades hence. The annual deployment of barely 0.01 percent of this mass of sulfur (roughly one ten-thousandth as much sulfur as carbon) in appropriate form and location can be made to offset entirely the "greenhouse effect" of the 35,000-fold greater mass of added CO_2.

We examined such considerations in some detail, combined with the summary of earlier results, and came up with the following conclusions. From a basic physics viewpoint, materials vary greatly in their ability to interact with, and thus to manipulate, optical-spectrum radiation. Resonant scatterers have the greatest mass efficiency by far; good metals have about 10,000 times less specific radiative-interaction efficiency than resonant scatterers; and dielectrics have about 1 percent the specific radiative-interaction power of the best metals. *Each* of these classes of materials offers distinct, independent, eminently practical ways and means of accomplishing the technical management of radiative forcing.

Positioning scatterers of incoming solar radiation in Earth's upper atmosphere—specifically in the middle to upper stratosphere—is a venerable approach that appears to provide the most practical deployment for two reasons: (1) operational lifetimes of engineered scatterers can be as long as five years; and (2) required replacement rates are correspondingly modest. Thus, the stratosphere is where we would deploy all of the insolation-modulation scattering systems we propose for near-term study.

Insolation-reducing means that have been demonstrated twice in the past two decades (by the eruptions of El Chichon and Mount Pinatubo, two large tropical volcanoes) and that were noted in the NRC study illustrate the simplest kind of radiative forcing management—Rayleigh scattering by aerosols of dielectric materials—although in a grossly nonoptimized way. Each volcanic event injected sufficient sulfate aerosol into the stratosphere to *decrease* ground-level temperatures in various regions of the Northern Hemisphere for 1 to 3 years by 10 to 30 percent of the amount that CO_2 is variously predicted to *increase* these temperatures by 2100. Optimized formation and emplacement of sulfate aerosol is the most mass-costly—although one of the more dollar-economical—means of scattering back out into space the sunlight fraction necessary to offset the predicted effects of atmospheric CO_2 concentration in 2100. Interestingly, Rayleigh scattering of sunlight performed by stratospherically deployed aerosols, with quite small diameters compared to the wavelength of light itself, will selectively scatter back into space the largely deleterious ultraviolet (UV) component of sunlight while only imperceptibly diminishing the light we see and the light plants use for photosynthesis.

From the human perspective, if a stratospheric Rayleigh scattering system were deployed, skies would be bluer, twilights would be more visually spectacular, plants would be less stressed by UV photodamage and thus would be more productive, and children playing outdoors would be much less susceptible to sunburn (and thus to skin dysplasias and dermal cancers as adults).

We estimate the dollar outlay for active management of radiative forcing on the 2100 scale to be about $1 billion per year. No one to our knowledge has taken issue with this estimate since we offered it five years ago. Indeed, the NRC study implicitly acknowledged the practicality of this kind of approach, although it considered only thoroughly nonoptimized dielectric aerosol scattering.

Incidentally, the costs appear to be an order of magnitude lower than the savings in health care from avoidance of UV skin damage in the United States alone, and far smaller than the gains from increased agricultural productivity as a result of the avoidance of crop photodamage in the United States alone.[2] Thus, the cost to the U.S. taxpayer of implementing this system of benefit to all humanity would appear to be negative, because the economic benefits in just the U.S. would greatly outweigh the costs.

Metals are greatly superior to dielectrics in the specific efficiency with which they scatter radiation, and the several particular means we considered for using metals in the management of radiative forcing reflect a 10-fold to 100-fold mass savings over dielectric aerosols. The geometries of metallic scatterers center on metal dipoles and metallic screens, with dimensions selected to be comparable to the reduced wavelengths of the portion of the solar spectrum we wish to scatter. The physics of metallic scatterers (which also include small, thin, metallic-walled superpressure balloons) suggest that they could most effectively scatter back into space the UV portions of solar insolation, just as dielectric scatterers do. These more highly engineered scatterers would cost significantly more to replace in the stratosphere than would dielectric aerosols, but because they have far lower

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[2] There are approximately 6,000 cases of fatal melanoma in the United States each year, almost all of them attributed to solar UV-B and UV-C exposure, along with approximately 1,000,000 cases of UV-B/-C-induced erythema (sunburn) severe enough to require professional medical treatment; a *per capita* cost of a melanoma fatality (medical care + economic loss of life) of $500,000, plus a *per capita* (medical care + time loss) cost per case of $300 for severe sunburn, represents a loss to the U.S. economy of $3.3 billion per year. Costs in the rest of the First World are probably at least as high. Thus the worldwide annual cost from photodamage to human skin is at least $7 billion per year. U.S. crops currently have a market value of slightly less than $100 billion per year, and direct and indirect photodamage (due to UV-B and UV-C and ozone, respectively) may be very conservatively estimated to be several percent (corresponding to a mean ground-level ozone concentration of 50 to 70 ppb), for a United States-only cost of several times $1 billion per year. Worldwide costs are likely to be at least 12 times higher, or several times $12 billion per year, as the United States accounts for less than 8 percent of global production of primary crops. Skin and crop photodamage thus likely amounts to a substantial multiple of $20 billion annually, most of which could be avoided by scattering back into space from the stratosphere the majority of the incoming solar UV-B and UV-C irradiation, as well as the “hard” or blue “tail” of the UV-A spectrum.

Recent work with the IBIS terrestrial biosphere model in conjunction with the CCM3 Community Climate Model (Govindasamy et al., in press) has provided estimates of plant productivity changes associated with decreasing of insolation to just offset a doubled atmospheric concentration of CO_2. These results indicate that plant productivity would be substantially increased, essentially everywhere, mostly because of the fertilizing effects of doubled CO_2, but also associated with less heat-related water stress on plants. The corresponding large gain in agricultural productivity—almost double, globally—has a market value of roughly $1 trillion per year. More importantly, this gain in plant productivity would provide a badly needed margin of twenty-first century food production in the Third World. These huge additional benefits from active climate stabilization are not included in the estimate of net economic impact of active climate stabilization in the text above.

masses, the estimated annual costs to address the reference year 2100 problem might be as much as five times lower than approaches of comparable efficacy based on dielectrics, that is, about $0.2 billion per year (Teller et al., 1997). Because highly engineered scatterers would also diminish the intensity of a portion of the solar spectrum that is damaging to both plants and animals, their beneficial side effects would be comparable to those of dielectric aerosol Rayleigh scatterers. Again, the net economic cost of deployment would be negative.

Resonant scatterers of sunlight offer huge gains in mass efficiency—although much of this gain seems likely to be lost in "packaging" these materials so that they would be both harmless and unharmed in the photoreactive stratosphere. Overall, these novel materials appear to offer mass budgets a few-fold lower than the most interesting metallic scatterers but have operating costs comparable to dielectrics. This novel type of climate stabilization probably would be used to attenuate the near-UV solar spectrum, and thus the net economic costs would again be negative.

Most of these atmospherically deployed scatterers would remain "locked" into the air-mass parcels into which they were initially deployed and thus eventually would descend from the stratosphere, mostly as a result of vertical transport in the polar vortices at high latitudes. Once out of the stratosphere, they would "rain out" along with other tropospheric particulate material. The quantities deposited would be tiny compared to natural particulate depositions (e.g., wind-lofted dust and volcanic aerosols). The radiative forcing "magic" results from the midstratospheric deployment of these optimally formed scatterers. Virtually no natural particulate—except for a small fraction of particulates from explosive volcanic eruptions—ever ascends that high. Thus no other particulates are atmosphere-resident for as long, or "work" as hard. Tropospheric particulates usually rain out in a few days to a few weeks. Even volcanic aerosol particulates are far too large to be mass optimal, besides which they are loaded with chemical impurities that unfavorably impact stratospheric ozone levels. In fact, they are of interest in the present discussion only as an undoubted proof-of-concept of the several types of engineered-scatterer systems we propose.

Finally, deployment of one or more metallic scattering screens, so diaphanous as to be literally invisible to the human eye, just inside the interior Lagrange point of the Earth-Sun system and on the Earth-Sun axis, represents the absolute optimum of all means known to us for ensuring long-term climate stability. Barely 3,000 tonnes of optimally implemented metallic screen would suffice to stabilize climate against worst-case greenhouse warming through preferential scattering of near-infrared solar radiation so that it would just barely miss Earth. The same size screen in a slightly off-axis position could be used to prevent future Ice Ages by scattering "near-miss" solar radiation back onto Earth. It isn't clear exactly how the deployment of such a long-term capital asset of the human race would be deployed, so no cost estimates can be made.

CONCLUSIONS

If you are inclined to subscribe to the U.N. Framework directive that mitigation of anthropogenic global warming should be effected with the "lowest possible cost"—*whether or not* you believe that Earth is indeed warming significantly above and beyond natural rates and *whether or not* you believe that human activities are largely responsible for such warming and *whether or not* you believe that problems likely to have significant impacts only a century hence should be addressed with current technological ways and means rather than deferred for obviating with more advanced means—then you will necessarily prefer active technical management of radiation forcing to administrative management of greenhouse gas inputs to Earth's atmosphere. Indeed, if credit is properly taken for improved agricultural productivity resulting from increased CO_2 and decreased solar UV fluxes—and human dermatological health benefits are properly accounted for—we expect that the net economic cost of radiative forcing management would be negative, perhaps amounting to several hundred billions of dollars each year, worldwide (Plate 8). The spectacular sunrises and sunsets and bluer skies would be noneconomic benefits.

Active technical management of radiative forcing would entail expenditures of no more than $1 billion per year, commencing about a half-century hence, even in worst-case scenarios.[3] Thus we might just put a sinking fund of $1.7 billion into the bank for use in generating $1 billion per year forever, commencing a half-century hence, and proceed with business as usual. All of Earth's plants would be much better fed with CO_2 and much less exposed to solar UV radiation, kids could play in the sun without fear, and we would continue to enjoy today's climate, bluer skies, and more beautiful sunsets until the next Ice Age commences. There is no obvious economic counterargument to this approach. Human-impacts counterarguments are even less obvious. Based on preliminary examinations to date, the externalities of active technical management, including environmental costs, seem likely to be small.

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[3] Assuming a time-averaged discount rate of 5 percent, the present value of an eternal cash stream of $1 billion per year commencing a half-century hence is about $1.74 billion. This amount put into the bank today at 5-percent interest would grow to $20 billion by 2050; the principal amount, in turn, would throw off the requisite $1 billion per year of radiative forcing management expenses until the end of time. The $1.74 billion of present-day "expense" for the "privilege" of continuing to enrich the atmosphere with CO_2 is equivalent to the amount of federal gasoline tax collected every month or so. If one wishes to be very conservative and assume that the true, inflation-corrected, long-term discount rate is only 3 percent and that full-scale mitigation of greenhouse gas inputs might have to be commenced as soon as a third-century hence, then one would need to deposit $12.4 billion in present dollars to fund the operation of the most expensive active radiative forcing management systems at $1 billion per year (in 2002 dollars) for the rest of eternity, starting in 2035. This eternal endowment for perpetual care of the atmosphere is about one year's receipts of federal gasoline taxes.

We therefore conclude that technical management of radiative forcing of Earth's fluid envelopes, not administrative management of gaseous inputs to the atmosphere, is the path *mandated* by the pertinent provisions of the U.N. Framework Convention on Climate Change. Moreover, this appears to be true by a very large economic margin, almost $1 trillion dollars per year worldwide, because crops could be fertilized by greater concentrations of atmospheric CO_2 without climatic regrets. One of the most pressing problems facing the human race in the twenty-first century—how to nourish a population that increases by 60 percent—thereby begins to look distinctly manageable. The areas of greatest gain in land-plant productivity would largely coincide with the areas of the planet where the largest gains in human population are projected (Plate 8). With active management of the radiative forcing of the atmosphere and oceans, humankind would be able to air-fertilize its way around the basic food-production challenge of the twenty-first century.

We have put forward four independent sets of technical options for implementing active management of radiative forcing, three of which could commence operation as soon as desired. All three have been peer-reviewed in international conferences and *ad hoc* specialist workshops for the past five years. We therefore suggest that the U.S. government would be well advised to launch an intensive program immediately to address all of the salient issues in active technical management of radiative forcing, including well-designed subscale experiments in the atmosphere. All of these experiments would terminate naturally back onto the present climatic posture on known, relatively short time scales. Because of the obvious global impacts of *any* management scheme, broad international participation in this program should be invited.

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Nuclear Energy

Large-Scale, Zero-Emissions Technology

JAMES A. LAKE
Idaho National Engineering and Environmental Laboratory

It is widely recognized that abundant, affordable energy supplies are critical to a healthy world economy and an improved standard of living for future generations. World energy demand is growing at about 2.7 percent per year, driven primarily by underdeveloped countries. Because world supplies of fossil fuels are reaching their predictable limits, this growth is driving up prices; in addition concerns are growing about the global effects of increasing air pollution on human health and rising greenhouse-gas emissions on climate. Developed nations like the United States have a moral obligation to take the lead in the deployment of advanced, clean-energy technologies, including nuclear power, to ensure that remaining supplies of affordable fossil fuels will be available in the future.

CURRENT STATE OF NUCLEAR POWER

Four hundred thirty-nine nuclear power plants in 31 nations currently generate 16 percent of world electricity demand (6 percent of total world energy demand). Compared with coal-combustion plants, nuclear power plants annually avoid the worldwide emissions of more than 610 million tons (Mt) of carbon (2,200 Mt of carbon dioxide). Nuclear power, with a carbon-emissions intensity (measured in kilograms of carbon per kilowatt hour of electricity) only 1/50 of coal and 1/25 of the best liquefied natural-gas combined-cycle electricity-generating technology, has prevented emissions in the United States alone of more than 90 Mt of sodium dioxide (SO_2) and 40 Mt of nitrogen oxides (NO_x), in addition to 2.5 billion tons of carbon, in the last 25 years.

Nuclear power in the world is influenced (positively and negatively) by national politics. It is highly valued for its positive energy-security attributes and low operating costs, but it is burdened with high capital costs that inhibit growth, especially in a deregulated energy market. Public support for nuclear power is positive overall (but fragile), hinging on perceptions of safety and physical protection. Finally, nuclear power faces an uncertain social and political future because of questions about waste disposal and concerns about the proliferation of growing inventories of spent nuclear fuel. In 2002, the U.S. government took positive steps to open a national geological waste repository at Yucca Mountain.

In spite of an uncertain future, the economic and safety performance of the world nuclear fleet continues to improve, and interest is being expressed in many nations, including the United States, in expanding the use of nuclear energy for economic, energy security, and environmental reasons (Lake, 2002; Lake et al., 2002). The U.S. National Energy Policy calls for "the expansion of nuclear energy in the United States as a major component of our national energy policy" (NEPDG, 2001).

CHALLENGES TO THE GROWTH OF NUCLEAR ENERGY

To fulfill its potential of providing affordable, abundant, clean energy, nuclear energy must overcome challenges associated with sustainability; economics; safety and reliability; proliferation; and physical security.

Sustainability

Sustainability is defined as the ability to meet the needs of the present generation while improving the ability of future generations to meet its needs. The 1987 World Commission on Environment and Development described sustainable development in terms of three dimensions: economic, environmental, and social.

Future sustainable nuclear energy systems must have the following characteristics:

- They must have a substantial, positive impact on the quality of the environment, primarily through the displacement of polluting electricity and transportation energy sources by clean, nuclear-generated electricity and nuclear-produced hydrogen transportation fuels.
- They must enable geological waste repositories to accept nuclear wastes from substantially more megawatt hours of nuclear plant operations by producing less waste and reducing the decay heat of waste from the open (so-called once-through) fuel cycle.
- They must simplify the scientific basis for safe, long-term repository performance and licensing by greatly reducing the lifetime and toxicity of residual radioactive waste material committed for long-term geological disposal.

- They must extend future nuclear fuel supplies to centuries and eliminate uncertainties associated with known, affordable uranium reserves by recycling used nuclear fuel to recover its residual energy.

Economics

The economic performance of nuclear power is country or region specific. The cost of nuclear electricity generation in many countries (including the United States) is the same as or lower than the cost of producing electricity from the burning of coal and substantially lower than the cost of producing electricity from oil or natural gas. In some countries (including the United States), the high capital cost and financial risk of constructing new nuclear power plants is a significant deterrent, especially in deregulated energy markets. To be competitive in the future, nuclear energy must meet several criteria:

- overall competitive life-cycle and energy-production costs through innovative advances in plant and fuel cycle efficiency, design simplification, and perhaps, plant sizes matched to market conditions
- reduced economic risk through a reduction in regulatory uncertainty and the development of innovative fabrication and construction techniques
- production of other products, such as hydrogen, fresh water, and other process heat applications, to open up new economic markets for nuclear energy

Safety and Reliability

Safety is the key to worldwide public acceptance of nuclear energy. The safety performance of nuclear energy has improved substantially since the Three Mile Island II and Chernobyl accidents, and current safety performance indicators, tracked by the World Association of Nuclear Operators, are excellent. Public support for continued nuclear power operations is also strongly influenced by confidence in the regulatory process. Continuous improvement in nuclear power technology and operations is essential to the growth of nuclear power.

Future nuclear energy systems must have the following goals:

- disciplined, safe, and reliable nuclear operations and deliberate, transparent regulation of nuclear operations worldwide
- improved accident management and minimization of accident consequences to the public to reduce or eliminate the need for off-site emergency response
- protection of the financial investment in the plant
- increased use of so-called inherent or passive safety features and

transparency in the safety performance capabilities of nuclear power that can be more easily understood and evaluated by the public

Nonproliferation and Physical Security

Fissile materials in civilian nuclear power programs are very well protected by effective international safeguards overseen by the International Atomic Energy Agency. Furthermore, the very robust designs and security systems of current nuclear power plants effectively protect them against acts of terrorism. Nevertheless, future nuclear reactors and fuel-cycle systems, and future nuclear materials safeguards regimes, should be designed with even higher levels of resistance to the diversion of nuclear materials and the undeclared production of nuclear materials for nonpeaceful purposes. Finally, future nuclear energy systems must provide better physical protection against real or perceived threats of terrorism.

Future proliferation-resistant nuclear energy systems must have the following characteristics:

- more intrinsic barriers and extrinsic safeguards against diversion or the production of nuclear materials for nonpeaceful purposes
- better physical protection against terrorism

U.S. GOVERNMENT PROGRAMS

The U.S. Department of Energy (DOE) has three programs to address challenges to the continued use and growth of nuclear power: the Nuclear Power 2010 Program; the Generation IV Advanced Reactor Program; and the Advanced Fuel Cycle Program.

Nuclear Power 2010 Program

In February 2002, Secretary of Energy Spencer Abraham unveiled the Nuclear Power 2010 initiative in response to recommendations of the DOE Nuclear Energy Research Advisory Committee (DOE, 2002). The goal of the program is to establish a public-private partnership to build new nuclear power plants in the United States before the end of the decade. The initiative will accomplish three things: (1) explore federal and private sites that could host new nuclear power plants in the future; (2) demonstrate the efficiency and timeliness of the new 10 CFR52 Nuclear Regulatory Commission licensing process, which is designed to make licensing of new plants more efficient, more effective, and more predictable; and (3) conduct research to make the safest and most efficient nuclear plant technologies available to the U.S. marketplace.

Gas-cooled, high-temperature reactors, such as the gas-turbine modular helium reactor (GT-MHR) and the pebble bed modular reactor (PBMR), are examples of advanced technologies that could be deployable sometime after 2010. Engineering teams in South Africa, Russia, France, Japan, and the United States are pursuing gas-cooled reactor system designs and technologies, and the South African utility, ESKOM, plans to build a prototype PBMR plant before the end of this decade.

The PBMR design is based on a fuel element called a "pebble," a billiard-ball-sized graphite sphere containing 15,000 uranium oxide particles about the size of poppy seeds. The fuel particles are coated with layers of high-strength graphite and silicon carbide to retain the products of the fission process during reactor operations or accidental high-temperature excursions. About 333,000 of these pebbles are placed in a large vessel surrounded by a graphite shield to form the reactor core. Inert-helium coolant is circulated through the bed of pebbles to remove heat to the power generation system. High-temperature refractory materials throughout the core enable the PBMR to operate with a helium-coolant outlet temperature of 850°C, substantially higher than conventional nuclear power plants. With the heat fed directly to a gas-turbine electrical generator, the high-temperature PBMR can produce electricity with thermal efficiencies that exceed 40 percent.

PBMR technology will have several attractive features. First, with its high-temperature refractory core materials, the large thermal capacity of the graphite in the system, and inert-helium coolant, the PBMR can survive a complete loss-of-helium-coolant accident without the fuel melting or the loss of core integrity that could release the contained fission products. This passive safety capability could greatly increase public acceptance of nuclear power. Second, because of the comparatively small size of the PBMR, it can be produced by factory fabrication. Third, because it requires substantially fewer plant operating and safety systems (about a dozen compared with more than 200 in a water-cooled reactor plant) and because its power output is only 120 to 140 megawatts (compared to 1,000 to 1,400 megawatts for large, water-cooled reactors), PBMR could significantly reduce the plant capital cost and may be better suited to meeting increased power demands in deregulated markets. Finally, the helium temperature of 850ºC enables the thermochemical or thermoelectrical production of hydrogen from water, which could expand the market for nuclear energy to include transportation fuels.

Generation IV Advanced Reactor Program

The Generation IV International Forum (GIF) was founded in 2000 for the purpose of facilitating international cooperation in the design, development, and deployment of next-generation advanced nuclear energy and fuel-cycle systems. Its purpose was to identify across the board features that could be licensed, constructed, and operated in world markets in a way that would provide competitively priced, reliable, secure energy products. At the same time, GIF wanted to identify opportunities to improve reactor safety and waste management, ease concerns about proliferation, and improve physical protection. The 10 member countries of GIF (Argentina, Brazil, Canada, France, Japan, the Republic of Korea, South Africa, Switzerland, the United Kingdom, and the United States) produced a comprehensive Generation IV technology road map to accomplish this goal. The road map describes the requirements for constructing one or more demonstrated Generation IV advanced reactor systems for deployment in the world market by 2030. The road map was completed in 2002 and published at *www.inel.gov*. Currently, a broad spectrum of advanced-reactor concepts are being considered. These concepts include high-temperature, gas-cooled reactors; liquid-metal cooled reactors using liquid sodium or lead alloy; and water-cooled reactors that use supercritical water. Special consideration is being given to fast-neutron-spectrum systems and a closed fuel cycle that would enable the effective management and "burn up" of plutonium and other long-lived materials. In addition, the goal is to produce systems that provide efficient conversion of fertile uranium to fissile fuel, thus providing a sustainable fuel cycle for the future.

Advanced Fuel Cycle Program

One of the most important issues facing nuclear energy is the disposal of nuclear wastes and spent nuclear fuel. Since the late 1970s, the policy of the United States has been to dispose of these materials geologically and not to process or recycle the remaining fuel constituents in spent nuclear fuel. Whereas this policy is technically feasible, and the U.S. government is making progress in the development and licensing of a geological repository at Yucca Mountain, Nevada, this approach has turned out to be both scientifically difficult and enormously expensive. In addition, the social and political acceptability of direct geological disposal is problematic.

Several countries, notably France, the United Kingdom, and soon Japan, have taken a different approach that involves the treatment, recycling, and transmutation of spent fuel to reduce the quantity, toxicity, and lifetime of wastes that require geological disposal and to improve energy security by extracting substantially more of the energy content of spent fuel materials. The advantages of this approach are: (1) it can reduce the cost and improve the safety of the geological repository; and (2) it can reduce inventories of plutonium in spent fuel.

The U.S. National Energy Policy directs that "in the context of developing advanced nuclear fuel cycles and next generation technologies for nuclear energy, the United States should reexamine its policies to allow for research, development and deployment of fuel conditioning methods (such as pyroprocessing) that reduce waste streams and enhance proliferation resistance" (NEPDG, 2001). The research program would have the following goals:

- to reduce the volume of high-level nuclear waste, principally through the extraction of uranium, which constitutes 96 percent of spent fuel
- to reduce the cost of geological disposal of waste residues, principally by the optimum use of the repository to store smaller volumes of separated, shorter lived wastes and by eliminating the need for a second repository
- to reduce the national security risks associated with growing inventories of civilian plutonium by recycling this material and burning it in advanced reactors
- to reduce the toxicity and lifetime of high-level nuclear waste by removing long-lived, highly toxic plutonium and other actinides from the waste streams and burning or transmuting this material in advanced reactors so that the residual fission-product waste materials in the repository will decay to the level of natural uranium in less than 1,000 years

The Advanced Fuel Cycle Program, which will be initiated in 2003, will develop and demonstrate proliferation-resistant, spent-fuel treatment and transmutation technologies to enable the government to make an informed decision about future fuel-cycle policy and deployment alternatives in five to six years.

NEW MISSIONS FOR NUCLEAR ENERGY

Nuclear energy currently supplies 16 percent of worldwide electrical generating capacity. This amount could increase considerably, especially because electricity demand is growing faster than total energy. However, electricity represents only about one-third of total energy demand. Transportation fuel, which accounts for another third, is dominated by oil, a substantial fraction of which is imported from politically unstable parts of the world. Furthermore, oil is a rapidly depleting resource and, consequently, represents our most immediate energy security challenge.

In January 2002, Energy Secretary Spencer Abraham announced a new public-private partnership called FreedomCAR to develop and deploy hydrogen as a primary fuel for fuel-cell-powered cars and trucks as part of the U.S. effort to reduce its dependence on foreign oil. Currently, hydrogen is produced from the steam reforming of natural gas with incumbent emissions of greenhouse gas. Although this process produces fewer emissions than the direct combustion of oil, it substitutes one depleting fossil fuel for another and, at best, is an interim solution to what is expected to be an enormous market for hydrogen in the future. Therefore, a truly large-scale, zero-emissions, hydrogen-production technology is critical to meeting the goal of a zero-emissions transportation fuel that meets our energy security needs. The preferred source of hydrogen fuel is water.

High-temperature nuclear energy, such as energy from a gas-cooled reactor, represents a unique, high-efficiency, zero-emissions capability for manufacturing hydrogen from water. Although it is possible to produce hydrogen by standard electrolysis using nuclear-generated electricity, the low efficiency of the process (perhaps 25 percent overall) is less likely to be economical, except for distributed, point-of-use hydrogen generation. Current research is focused on two primary high-efficiency alternatives: high-temperature steam electrolysis and thermochemical cycles.

High-temperature steam electrolysis uses a combination of heat from a high-temperature reactor to produce steam at 700 to 800°C and electricity from the same reactor to electrolyze the water in a high-temperature solid-oxide fuel cell at 50 to 55 percent net efficiency. With this system, the operating utility could also sell electricity during peak price periods and produce hydrogen during lower price periods, either for direct sale or for storage for the subsequent generation of electricity from fuel cells during peak demand.

Several *thermochemical cycles* (and some hybrid thermochemical/thermoelectrical cycles) for splitting water are under development. A leading thermochemical candidate is the iodine-sulfur process, which uses high-quality heat from a high-temperature reactor at 800 to 1,000°C to drive an iodine-catalyzed dissociation of sulfuric acid. This reaction can produce hydrogen at efficiencies exceeding 60 percent, but the use of highly caustic and corrosive chemicals at high temperature and pressure will require materials research and may present some difficult safety issues. The capacity of a relatively small-scale hydrogen-production facility using a 600 MW_{th} gas-cooled reactor and thermochemical water splitting is about 7,500 kg/hour (sufficient to power 175,000 hydrogen-fueled vehicles).

CONCLUSION

The economic performance, operating performance, and safety performance of nuclear power today are excellent. Nuclear power can respond to the challenges associated with rising world energy demand, diminishing fossil energy resources, and growing concerns about environmental quality and emissions of greenhouse gases. The current U.S. nuclear energy production of 100 GW_e results in the avoidance of 640 Mt of carbon emissions per year (175 Mt of CO_2 per year) compared with the combustion of coal.

With ongoing license extensions, the current fleet of 103 U.S. nuclear power plants will continue to contribute at this level of performance until about 2030; the level will decrease as older plants are retired. The U.S. nuclear industry road map, *Vision 2020*, contemplates the construction of 50 new 1,000-MW_e plants by 2020 and an overall increase of 10 percent in output from existing plants to achieve 160 GW_e of U.S. electrical generation in 2020 (this will be necessary just to keep the overall share of nuclear-plus-hydroelectric emissions-free capacity near 30 percent of projected U.S. electricity demand in 2020) (NEI, 2002). If this can be accomplished, the contribution to greenhouse-gas emissions reduction by U.S. nuclear power will increase to more than 1 billion tons of CO_2 per year.

Generation IV nuclear energy systems will come into the marketplace between 2020 and 2030, leading to substantially faster growth in nuclear capacity. With a goal of 50 percent of projected U.S. electrical generating capacity, plus nuclear-generated hydrogen displacing 25 percent of oil for transportation fuel by 2050, the required nuclear capacity could be as high as 700 GW_e. At this rate, nuclear energy could account for the avoidance of more than 4.5 billion tons of CO_2 per year, compared with energy from coal.

Whether this growth in nuclear energy can be achieved with Generation IV technology in a world with substantially higher energy demand and depleted fossil-fuel resources is a matter for debate. However, as the preceding examples illustrate, nuclear energy, as a major source of electrical energy and a growing source of hydrogen transportation fuel, can have a significant impact on future greenhouse-gas emissions.

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Economic Issues

Can Emissions Trading of Carbon Dioxide Bootstrap the Transition?

MICHAEL J. WALSH
Environmental Financial Products LLC

If I could question a roundtable of social scientists, physical scientists, and technologists, the first thing I would ask them would be what we have allowed ourselves to get into on this planet. We are facing major environmental problems that are going to take real collaboration among all of these groups, demanding new technologies, and scientific breakthroughs to solve.

Emissions trading can not only "bootstrap" the transition but can also accelerate it, making it more acceptable to the public and to the political organizations we all work with. Trading in markets is really the only logical mechanism for efficiently orchestrating all of the available mitigation options. Economic efficiency is not just a luxury or a background concern; it is of major importance. As we start this transition, the public will demand that we do it intelligently—that we not waste resources and that we use the resources we have wisely.

Many decades from now, trading will continue to be the management mechanism we use to slow down our depletion of the planet's carrying capacity for climate change. Why? First, I believe the pricing mechanism will ensure that we never run out of fossil fuels. Second, it will be more than a hundred years before we reach the point when the net value of fossil fuels is negative. Even though we are beginning to realize that the net value of fossil fuels is substantially lower than we thought it was because of negative externalities, I assume that fossil fuels will continue to be used and, at the same time, that the optimal level of greenhouse-gas emissions is not zero. Earth has a finite absorptive capacity, a finite carrying capacity. Nevertheless, a hundred years from now, we will still have to restrain and manage the release of greenhouse gases, and markets are a logical and proven mechanism for doing so.

In this paper, I explain what emissions trading is, why it is desirable, what our experience has been with it, and the steps we are initiating to build institutions to support emissions trading for greenhouse gases.

It usually takes about 30 years for a problem to be identified, for capital to be dedicated to the problem, and for markets to be initiated and reformed until they are mature and in a liquid state. With greenhouse gases, we are about 10 years into that process. Ten years from now, we may have reasonably functional markets. Twenty years from now, emissions trading will be routine. And that's what we want it to become, a routine part of business—not particularly costly and not difficult to maintain.

This conviction is based on my philosophy and my educational background. I was trained as an economist, and I spent some time in the academic world and some in the U.S. Treasury Department. I then joined the Chicago Board of Trade, which, in the early 1990s, was exploring opportunities for new markets and initiated a partnership with the Environmental Protection Agency (EPA) to help administer the auction mechanism as part of the sulfur dioxide (SO_2) trading program. The colleagues I have worked with since 1995 have been active for several decades in designing, building, and trading in new markets. We have experience in the agricultural, financial, energy, and now emissions markets. In fact, we have done several greenhouse-gas trades, and nearly all of them have been exports from the United States to other countries. This may turn upside down the idea that the United States is the high-cost producer of mitigation services.

Social scientists and economists tend to have a unique point of view on environmental issues. To economists, a stable climate, or protecting against climate change, can be considered a public good, and public goods have several common characteristics. First, they are "nonrival," that is, one person's enjoyment of a stable climate does not take away from another's. Second, a public good is nonexcludable. One person can't prevent another from having access to a stable climate or from protection against climate change. These fundamental characteristics are very different from the characteristics of private goods, when one person's consumption takes away from another's and people can be excluded. With public goods, the economy often yields what is termed a "market failure," that is, the market fails to provide the right amount of a good or service, in this case, a stable climate.

A market failure that damages local commons or global commons is often considered a rationale for a coordinated response, which is often thought to be most effective when taken by a government. But many of the organizations we work with that pursue common actions are associations of like-minded individuals or like-minded entities rather than governmental entities. In a way, they reflect the club theory of activity. People decide they will govern themselves, their own group, and they form their own municipality, such as their own tennis club or their own local orchestra. Like-minded individuals come together for a broader good.

The larger problem when dealing with a public good, particularly management of Earth's climate, is that until now, we have not put a price on its use. We have implicitly said that people could use as many resources as they like and release as much greenhouse gas as they see fit. Because no one was paying a price to consume the resource, no concerns were raised. Naturally, when the price for a resource is zero, the resource will be overused. We've mispriced our resources, so we have overused them. As a result, the concentrations of greenhouse gases in the atmosphere have escalated to the point that they now threaten the stability of the planet.

Overuse is common for many aspects of climate and resources. A very tragic example is the world's fisheries, a global common resource. With some very important exceptions where trading instruments have been used effectively to manage the resource, we have not sufficiently restricted access to fishing stocks. Other examples of overuse are easy to find—in our air and water resources and our land-use resources. The local, regional, and global commons have been grossly damaged by our failure to put a proper price on them and to build restraint into the system.

Early in the last century, a well known economist, Arthur Pigou, said the problem was that the price was too low and that we should put a tax on polluting activity—either on the manufacturer or on the product so that there would be less pollution. This does not mean we have to drive every harmful activity to zero. That may be necessary sometimes—with lead pollution, for example—but usually simple restraint is enough. The general rule is: the price is too low and we have to restrain the activity, so let's put a tax on it.

The tricky part is that taxes raise all sorts of fiscal and revenue questions. On an administrative basis, it's very difficult to determine the level of tax that would get us back to the desired level of activity. Using taxes to restrain and reduce pollution has proved to be a bit too tricky. In fact, taxes have not been pursued as aggressively as they might have been. But, eventually, pollution taxes will probably become part of the mix of tools we will have to use.

In the 1960s, Ronald Coase at the University of Chicago, who was awarded a Nobel prize, argued that common resources should have property rights—ownership shares or some sort of private ownership. In the case of pollution, for instance, the parties closest to the problem—the recipients of the pollution and those who cause it—could effectively negotiate an efficient, effective solution to the problem. This could happen, provided that there are rights in clearly divided shares to the property and that the transaction costs are not too high. The idea is that, if somebody owns the resource, better care will be taken of the resource than if it is owned by everyone but taken care of by no one.

Based on Coase's idea, we could approach our environmental problems on a property-like basis. In the 1970s, an attempt was made to institute a tradable-permits regime in big U.S. cities and industrial areas. The early trials of this ad hoc trading mechanism were quite clumsy, the instruments were poorly defined, and the transaction costs were very high. Gradually, we evolved a more commodity-like market, with clear ownership, clear definitions, and low transaction costs. We are now working in the American Midwest to build the institutions to make emissions-trading markets for greenhouse gases a reality.

The economic rationale for emissions trading is that it provides flexibility so emissions can be cut at lower cost. Cost effectiveness is important because, if we spend more than is necessary to address a problem, we take away resources from other pressing issues. The idea is to use our scarce resources wisely. The philosophical rationale is that emissions trading works with businesses. It makes cutting pollution less of a problem and more a part of ordinary management routine.

On the macrolevel, an emissions-trading program should provide price signals so that low-cost mitigation options are pursued first, and those who face higher costs can contract with others to meet some of their commitments. Markets produce price signals that indicate the real costs of achieving an objective. In Washington, D.C., this aspect of emissions trading is especially important. Instead of lobbyists arguing endlessly over the cost of achieving an environmental objective, the market can give us a much clearer answer. Over time, emissions trading will lead to innovations that will lead to dynamic efficiency. Those who create mitigation options and techniques will be rewarded as environmental protectors. That is the right way to shift the balance.

How does emissions trading work? First, we determine how much of a particular pollutant an ecosystem can tolerate, and we set an overall target. By defining the target, we turn the resource into a limited property. Second, we divvy up the shares, establishing ownership rights to the property, called an “emission allowance.” Third, we require that the emission sources be monitored according to standards and that the emission levels be reported on an ongoing basis. Then we allow emission allowances to be transferred among those who find it advantageous to do so. Finally, we have an annual “true-up.” At the end of the year, participants must surrender to the market administrator enough certificates (emission allowances) to cover the emissions they have released during the year.

The overall idea is that those who can cut pollution at the lowest cost will do more of it. Those who face a higher cost to cut pollution will outsource, that is, somebody else will make the reductions on their behalf. This way we will find a smarter, more efficient way to use mitigation resources.

Emissions trading is appropriate when emissions come from many sources—SO_2 and many other pollutants and greenhouse gases. The common problem in the current situation is the increasing concentration of greenhouse gases and the risks of climate change.

We can define and monitor the reduction objectives. We know what the levels should be in the long term, and various global conventions have agreed on an intermediate goal of stabilization at a rather high level of greenhouse-gas concentrations (e.g., doubling of the preindustrial levels). To get the market going, we must define near-term objectives.

The economic advantages of emissions trading arise when there are differences in mitigation costs among emission sources and mitigation projects. In other words, some sources face high costs to cut emissions, and others face low costs to cut or mitigate emissions. Under these conditions, trading between these two entities can offer opportunities for gains. The question is whether we can enforce limits on greenhouse gases while maintaining other environmental protections. The emission of greenhouse gases is not an isolated problem. Indeed, in the acid rain program, there was great concern that trading of emission allowances would cause local pollution hot spots. To prevent them, we continue to apply the national ambient air quality standards for local air quality. Whether we do that well enough is an open question. Emission-allowance trading can only work within certain limits; we cannot allow violations of ambient air quality standards.

Finally, for emissions trading to work, there must be a reasonably functional legal and business environment; capable institutions must be in place. Many countries simply do not have these institutions, so it will be necessary for them to evolve further before they can support emissions trading.

The United States first made a rather clumsy attempt to initiate emission trading in the 1970s, with some perverse results. In the 1990 Clean Air Act, the first Bush administration signed into law a program calling for a 50-percent cut in SO_2 emissions. SO_2 and nitrogen oxides (NO_x), pollutants associated with acid rain, harm forests, streams, and lakes, as well as human health and infrastructure. The 50-percent cut, which was to be phased in over time, was implemented through an emissions-trading program. The success of the program makes it a benchmark and a reference point for many other emissions-trading proposals. The main goal was to cut SO_2 emissions from power plants from 18 million to 9 million tons per year. When we divided the shares to create the emission allowances, some were allocated based on political considerations and some were allocated neutrally. Political considerations did not adversely affect the environmental outcome. The law stipulated how the power companies must monitor and report emissions. Then industry was allowed latitude in the methods, locations, and timing for cutting emissions.

I have stacks of records documenting the naysayers. In 1992, when I was on the Chicago Board of Trade staff and we struck a partnership with EPA to run the annual auction, we spent a lot of time educating industry and regulators about the program. The media skewered the idea, and the trade publications said it was wrong and that it simply could not work.

But the program is a complete success, with 100-percent compliance. There has not been a single material violation of the program, trading has been active, and the economic outcomes have been efficient. But first and foremost this is an environmental program, and we have made major progress. In the very early years, the U.S. Geological Survey found immediate reductions in the acidity of precipitation in the most severely affected part of the country. Progress has continued as the level of allowed emissions continues to come down. New York State had rather high sulfur deposition rates before the program began but substantially lower rates after implementation. The Appeals Court there has now thrown out an effort to restrict the sale of emissions allowances from New York to so-called upwind states. Depending on weather conditions, upwind could have been defined as Florida or Maine. In reality, the flow tends to be west to east. Nevertheless, the Appeals Court ruled that restricting the sale of emissions allowances would constitute interference with interstate commerce.

The naysayers said the huge pollution sources in the Ohio River Valley region would just buy allowances from other places and continue to pollute. And some of that has occurred. But there simply are not enough allowances in other states to allow the Ohio River plants to avoid making reductions, and they have made major cuts. In fact, the program is working quite well.

From an economic point of view, the market outcome has been fascinating. The consensus prediction in the early 1990s was that the cost of cutting SO_2 would be in the range of $350 to $1,000 per ton. Fearing that the price might climb too high, Congress established a set-aside pool of allowances for independent power projects at $1,500 a ton. Some people believe that this might be the eventual market price. In the 10 years of auctions at the Chicago Board of Trade, the price has averaged $135 a ton. This means that the annual costs of cutting sulfur emissions by half from power plants is in the range of $1.2 billion a year, less than 1 percent of production costs for electricity in this country. In other words, with a 1-percent cost increase, we have cut acid rain by 50 percent. In the context of estimated benefits ranging from $10 billion to $30 billion a year, that's a mere blip on the screen. But in terms of market trading, it's a 10:1 to 30:1 leveraged trade. That's a good trade, the kind of trade we should be trying to make whenever possible.

Some people find the idea of trading in pollution confusing. But some of the best trades in this market were made by a group of 12-year-old middle-school children from Glens Falls, New York. They pooled their funds to come up with $3,000 to buy up emission allowances at auction. The next year, several middle schools in the area formed a syndicate and pooled $21,000 of their own money, earned from bake sales, rock concerts, auctions, and similar activities. They bought a whole bunch of allowances at $66 apiece. On average, they have doubled their money, and their success has given us the best ammunition in the world. If someone on Capitol Hill suggests that the program isn't logical or isn't working, we can bring some of these children before Congress to defend their property rights. This exciting, successful program is our model, a proven example, a proven technology, a market technology.

The economist Joseph Schumpeter described three phases of the inventive process. First, there is the invention. One might say the early emissions-trading trials were the invention of that concept. The second stage is the standardizing and commodifying of the innovation. For emissions trading, this occurred when trading was made easy, lowering transaction costs. We are now in the third phase, the imitation and replication stage. Now we want to take this technology, this market tool for managing pollution, and replicate it and extend it to other pollutants.

I've been working on greenhouse-gas trading full time for about 7 years, and I've spent 12 years working with emissions trading generally. Regrettably, progress has been limited and very slow. It seems that government structures, particularly multilateral structures, have a very difficult time building new market institutions. To address this problem, we asked the Joyce Foundation of Chicago to study the feasibility of starting a greenhouse-gas reduction market on our own. The study indicated that this could work; we would have to have self-regulation, which is possible. This may not be the ultimate answer, but it would certainly be a step in the right direction.

We then asked private-sector companies if they needed such a market. The idea was that, if there were half a dozen entities—a few power companies, an oil company, some farmers and foresters and landfill gas collectors—we could create a small test market, a *voluntary pilot program*. We invited about 60 or 70 potential participants, and many said they would be interested. Based on their interest, we formed the Chicago Climate Exchange (CCX), a voluntary, pilot, greenhouse-gas trading program for emissions sources and offset projects in North America. We also want to experiment with an international mechanism by having offset projects in Brazil.

Our first objective is proof of concept; we want to prove that a greenhouse gas cap-and-trade mechanism, like the SO_2 program, can work and can be supplemented with individual projects, such as sequestration and other small mitigation projects. Our second objective is to develop market infrastructure and skills. We expect it will take several decades to get it right. Third, we want to use the price information as a basis for future programs. We want to know what it costs to mitigate greenhouse gases. The CCX will provide real market information from actual mitigation activities. We want to provide a modest, but predictable, greenhouse-gas reduction schedule and start the process.

We want to start small because we believe we can't start too big. The United Nations (U.N.) cannot tell us how to set up a market. The U.N. may be a beautiful mechanism for getting agreement, but the people who know how to set up markets are in the private financial and industrial sectors. They are the ones who should take the lead.

Currently, there is an inchoate market in greenhouse gases. Our company has been involved in half a dozen international trades, but the instruments and the commodity are not well defined, and transactions costs are very high. There are more lawyers involved than financiers, and that's a bad sign. We want to standardize trading in greenhouse-gas reductions, to make them routine and easy, and to liquefy the market so the capital market can work. Once resources can flow freely and actively, we will have the financial leverage to solve the problem.

The steps that we propose for standardizing and routinizing and liquefying the market largely mimic the steps that have been taken in other commodity markets. We are also proposing reduction schedules, starting with a 1998–2001 baseline because we have emissions data for those years. We agreed that the reductions will start at 1 percent below baseline in 2003 and will fall 1 percent per year thereafter. CCX will be a four-year pilot program and is designed to bring in new emissions sources. We think we have some reasonable and balanced ways to do so.

We were looking for half a dozen entities to lead the way in establishing a greenhouse-gas market; we have found them, and many more, which is an indicator of the demand for action on this front. There were 14 founding members of the CCX—and it continues to grow—representing 250 million tons of carbon dioxide (CO_2) emissions, equal to half the emissions in all of Canada. The founding members include diverse energy, manufacturing, and service sector entities, several with global reach. The initiative has already spread beyond industrial sectors to other major sources of emissions, including a municipal government (the city of Chicago).

Many local, small initiatives have also been undertaken in the agricultural, forestry, and conservation stewardship sectors, which not only absorb carbon, but will also have huge side benefits. We are all very excited about this. Trees and grasses and properly managed soils can not only absorb carbon, but they can also improve water quality, provide habitat protection, and reduce energy consumption. Groups like Ducks Unlimited, which owns a great deal of land, are involved, as well as farm groups that will act as aggregators for individual farmers. Some financial and inspection groups are also participating. If the carbon side can help finance some of the benefits of good stewardship of land, we'll all be better off at the end of the day.

Why would a big industrial concern subject itself to paying to mitigate emissions of greenhouse gases? Why would a company write a check to somebody else to mitigate greenhouse gases? Some companies cannot quickly shift their coal-based power plants to gas or other lower polluting technologies. These companies come to the table first because they want some of the first-mover advantages. They recognize that regulation is coming, and they want not only to enjoy the potential commercial benefits, but also to help design the protocols for future programs based on their experience (rather than on lobbyists' notions and arguments). Second, they want to be able to manage greenhouse gases and trade skillfully while maintaining their ongoing businesses. Third, many of them are big coal burners, and they intend to continue operating their facilities. They recognize that they will be required to mitigate some of the greenhouse emissions from those facilities, and they want a low-cost mechanism for doing that. In this way, they would be able to continue to burn coal provided they can offset their emissions. So they are looking for a structure that can help them through the transition—and transition is the key word here—to cleaner technologies and energy systems.

Finally, there is a growing recognition that sustainable companies, those that are cleaner and more attentive to environmental concerns than their peers, ultimately seem to yield higher returns than their not-as-sustainable compatriots. This does not mean that an environmentally sound company will automatically have higher profits. However, it appears that sustainable companies are also smarter companies. They do many things better than other companies, which shows in their financial performance. That is important because share prices are hugely important to CEOs and boards, which are always looking at the financial bottom line. If a company is going to become an environmental leader, it will be because it improves its financial bottom line.

In discussing this issue, I use the word stakeholder rather than stockholder because every day corporations are coming to recognize that their greatest asset is their human capital. Young people often want to work for companies they like and respect, and a company's ability to attract talent is being driven, at least in part, by its environmental signature. Moreover, companies that are better environmental citizens have better relations with customers, suppliers, and governments. It has taken several decades for this ethic to enter the marketplace, but companies now recognize that environmental leadership is in their best interest. This is why some companies are prepared to make some outlays now to get ahead of the curve and be on the right side of the issue. They recognize that there really is a wrong side and a right side of this issue.

Undoubtedly, 10 to 20 years from now we will look back and realize that some of the things we did were flat-out wrong—the market design was wrong, the quantification was wrong, the global warming potential conversion value was wrong. But the only way to find that out is to go through the process. We've debated this issue for more than 10 years now, but there has been virtually no hard action on the ground. It's time we get started. With greenhouse-gas trading, we can make a start—we are crawling children—but if we want to be able to sprint and leap the high hurdles in 20 or 30 years, we have to crawl first. We know there are massive uncertainties, but if we can start to test techniques for bringing individual landowners in with very simple structures, perhaps naively simple structures, at least we will make progress. At the same time, researchers funded by universities and taxpayers and private budgets must continue to work on the scientific fundamentals.

Let me review. Economic institutions offer attractive and feasible ways to manage the transition to a less-carbon-emitting economy. In addition, economic mechanisms will still be necessary a hundred years from now because fossil fuels will continue to be consumed. Markets, which are a proven tool, seem to be the only logical way to orchestrate efficiently all of the mitigation options (e.g., agriculture, forestry, industry, energy, and transportation). We can change, and it won't take rocket science, but it will take a lot of leg work, and it can be done.

It takes about 30 years from the time a problem is identified until a market is mature. We are nearly half-way along that curve. At the CCX we have made a start in a small and simple way with an association of like-minded entities. We are optimistic that this problem can be solved intelligently and efficiently using a capital-markets approach.

The Top Ten Things You Should Know about Carbon Sequestration

HOWARD HERZOG
Massachusetts Institute of Technology

We started our research program at MIT in 1989, when there were only a handful of active research groups. Over the past 13 years, I have seen tremendous growth and accomplishments in the field.

On the agenda, my talk was subtitled "What is the Right Economic and Social Mix?" Although I will address related issues, I am not going to attempt to answer that question because I don't feel we are at a point where we can determine the right mix. The right mix will ultimately be shaped by the marketplace and the political environment. Rather than answering this question, I will tell you the top 10 things I think you should know about carbon sequestration.

10. Fossil fuels are here to stay.

Let me qualify that I don't mean forever, but fossil fuels will be our dominant energy source for at least the next 50 years, if not the next 100 years. We have invested trillions of dollars in infrastructure, and even in Washington, D.C., that is a big number. Fossil fuels have more than 85 percent of the market share, and that market share is rising. I just don't see any scenario in which fossil fuels will drop below 50 percent of the market share in the next 50 years.

This is not to say that we should consider carbon sequestration as a way to perpetuate the use of fossil fuels. It does say that fossil fuels are a reality and that we need technologies to deal with that reality. These technologies will make fossil fuels more expensive, which in turn will help nonfossil-fuel technologies penetrate the market. Sequestration can not only help reduce carbon emissions from fossil fuels, but can also help other technologies enter the marketplace sooner.

9. Sequestration technologies exist today.

Capture plants exist today. Pipeline networks exist today. Injection of carbon dioxide (CO_2) underground exists today. Norway has the Sleipner Project and a new North Sea project called Snovit, which will be very similar to Sleipner. Norway is considering gas-fired power plants with CO_2 capture. In Norway, power plants are a big, politically charged issue. A couple of years ago, this issue caused the fall of a government; that government is now back in power and trying to resurrect the power plants in a somewhat different way.

The infrastructure issue may seem overwhelming, but just compare our world to a hundred years ago when the Wright brothers hadn't yet flown their first plane. After this session, I will go to the reception, but I will still be in my bed in Boston by 11 o'clock tonight. The infrastructure of airline travel would seem incredible to people from a hundred years ago. So would the interstate highway system. In a hundred years, infrastructure can change enormously. If we think of changing it in one day, it can be overwhelming; but if we think of changing it over a long period of time, it is not.

8. Sequestration is nondiscriminatory; it likes both electrons and protons.

One way sequestration works is through energy carriers (electrons and protons). Electricity is the energy carrier today, and its use is increasing. A potential new energy carrier is hydrogen, and we may or may not develop a hydrogen economy. Either way, it does not really matter for sequestration. Carbon can be sequestered from electric power plants and from hydrogen production plants. Sequestration is a viable alternative for many different futures. The basic technology for sequestration is a robust solution for a wide range of future scenarios.

7. Fantasizing about winning the lottery is fun, but don't bet the farm on it.

We have heard about many technologies today. Some we may call evolutionary; others are revolutionary. Some things we talked about today are very risky. They may have big payoffs, but they may also have high risks. You can't put all of your money in that basket. You have to spread your research effort around. Some of the more mundane technologies, the evolutionary technologies, are like your rent money, and its not wise to gamble with your rent money.

6. Sequestration costs less than you may think.

The point I want to make is that wind has been called a viable energy source because of a 1.7 cent/kWh production tax credit. If you give fossil-fuel plants a 1.7 cent/kWh production tax credit for sequestration, you will see quite a bit of sequestration at those plants. About a year ago, I heard a talk by someone at the

Nuclear Energy Institute, who said building a new nuclear plant would cost 6 to 7 cents/kWh for electricity. That is in the same ballpark as the cost of sequestration.

One hundred dollars per ton of carbon is equivalent to a 25-cent tax on gasoline. I don't know about the gas prices in your neighborhood, but the gas prices in my neighborhood in the last two months have gone up more than 25 cents. We are not talking about a $100/ton of carbon tax being put on today, but maybe over a period of several years. The economy definitely can absorb carbon prices at that level.

5. What the heck is "dollars per ton avoided"?

Lately, I have come to the conclusion that "dollars per ton avoided" is the most misused term in the carbon-mitigation world. It does have its place, and the best place for it is in project pricing. I also want to say a *mea culpa* because I am as guilty as anybody else of misusing this term. The reason the term is misued is because you not only have to analyze new technologies, you also have to compare them to a base case. But what is the base case for a new integrated-gasification combined-cycle plant with sequestration? Is it an integrated-gasification combined-cycle plant without sequestration? Is it a pulverized-coal plant? Is it a natural-gas plant? The numbers change dramatically, by more than a factor of two, depending on which base case you use. Dollars per ton avoided is correctly used only for a given project. Look at Option A and Option B, and compare those options to find the dollars per ton avoided. If the market sets a price for carbon that is higher than my project cost, then the project should go ahead. If the project cost is more than the market price, I should just buy permits or pay the tax. Using dollars per ton avoided to compare projects or technologies that have different conditions is really misusing the term.

A better analysis can be done using integrated assessment models that include all of these technologies and then ask at what marketplace price of carbon these technologies will advance. But even that has problems. Here is an example. One of my students is working with our economists to represent carbon sequestration into a general equilibrium model. The base numbers he is using were developed by another of my students. I am also working with David Keith of Carnegie Mellon University, using the exact same numbers and putting them into their dispatch model. The models are a little different. The general equilibrium model takes into account a lot of feedback from the general economy and is highly aggregated, but it doesn't look at dispatch. It is much too aggregated for that. David's model looks at dispatch, but doesn't have a lot of the feedback we have. When David runs his model with basically the same cost numbers, he gets a number on the order of $100 per ton of carbon. When we run our model, we get a number of about $200 per ton of carbon.

What is going on here? Who is right and who is wrong? They are both right, and they are both wrong. Why are they both right? Given the assumptions of the models, I believe the calculations in both cases are right. But the models use different assumptions, which can make a fairly big difference in the price. Every time you hear numbers like this, you have to question them. You have to ask that they be put in context so you can understand what they mean.

Number 4. Every silver lining has a touch of gray.

We should look into four major kinds of reservoirs for carbon sequestration. Three are geologic reservoirs—coal beds, aquifers, and oil and gas reservoirs; the fourth is the ocean. All four have advantages and potential, but they also all have significant problems that will have to be overcome. In other words, they have a touch of gray.

In terms of sequestration, the reservoir is a critical path item. And I don't think it is a case of either/or. The more kinds of reservoirs available, the better off we will be. If you live in Chicago, you are not interested in ocean reservoirs. If you live in Tokyo, you don't have geologic reservoirs, so you are very much interested in ocean reservoirs. Local circumstances are very important for sequestration. The more reservoir options that are available, the wider spread and the more economical use we can get from them.

Number 3. Legislation cannot remove the ocean from the carbon cycle.

More than 80 percent of the CO_2 emissions emitted today will end up in the ocean in the next thousand years. Today, about 30 percent of the emissions in any one year are in the ocean—2 gigatons of carbon per year out of a little more than 6 gigatons end up in the ocean. In an experiment in Hawaii, we had trouble in the permitting process, and we met with some local opposition. A coalition to stop CO_2 dumping was formed. Members had "Stop CO_2 Dumping" bumper stickers on their cars, right above the tailpipe, where the CO_2 was coming out. Of course, eventually 80 percent of this CO_2 ends up in the ocean. Nature simply will not let us put the oceans off limits. Unless we are incredibly lucky, we are either overusing or underusing the ocean. Which is it? I don't know, but I think it is very important that we find out.

The worst case would be to find out 20 or 30 years from now that climate change is really serious and that we have got to do something quick. Unless we work today to gain a scientific understanding, we will be under enormous pressure and may make some really dumb decisions.

Number 2. Can't we all just get along?

We must keep as many options open as possible. When it comes to implementation, we may wind up with only a few options, but local variables will be important. Certain areas are amenable to solar energy, others to wind, others may need sequestration. Some countries may be more amenable to nuclear power. Different areas will require different solutions.

I think all options should be kept open; all of them have pluses and minuses. Today, people are justifying the one they are working on, saying Technology A is better than Technology B; as long as it is not Technology B, it is good.

The *Groundwater Journal* recently ran a piece called "Can Hydrology Save the World?" that included these two sentences: "Deep ocean injection faces strong resistance from environmental groups and is unlikely to emerge as an important option for CO_2 storage. Deep geologic injection is emerging as the most promising option for CO_2 disposal." It should come as no surprise that this writer is working on geologic injection. I don't necessarily disagree with his statements, but they are based purely on bias and not on a hard analysis. I would rather see a statement that geologic diposal is emerging as a promising option because of A, B, and C, than a statement that geologic disposal is worthwhile because it is not ocean disposal.

Sooner or later, we may decide we can't keep so many balls in the air. When we finally do adopt a carbon policy, the marketplace should decide. Besides being economically viable, the different approaches will have to win public acceptance through some sort of permitting process.

I think research today should be focused on determining the effectiveness and impacts of sequestration. When there is market incentive to reduce carbon emissions, there will be a great incentive to reduce costs, and I believe that they will be reduced. But the environmental and safety issues are noncommercial, and understanding them will be to everybody's benefit. Therefore, this is an appropriate subject for government-sponsored research.

Number 1. You can visit me at *sequestration.mit.edu.*

Appendix

Biographies

Braden R. Allenby is the environment, health, and safety vice president for AT&T and an adjunct professor at Columbia University. He graduated *cum laude* from Yale University in 1972, received his J.D. from the University of Virginia Law School in 1978, his M.A. in economics from the University of Virginia in 1979, his M.A. in environmental sciences from Rutgers University in 1989, and his Ph.D. in environmental sciences from Rutgers in 1992. Dr. Allenby is coauthor or author of several engineering textbooks, including *Industrial Ecology* (Prentice-Hall, 1995), *Industrial Ecology and the Automobile* (Prentice-Hall, 1997), and *Industrial Ecology*: *Policy Framework and Implementation* (Prentice-Hall, 1999).

Sally Benson is deputy director for operations at Lawrence Berkeley National Laboratory. For the past four years, she has been working on carbon sequestration, particularly sequestration in deep geologic formations. A groundwater hydrologist and reservoir engineer, Dr. Benson has conducted research on a range of issues related to energy and the environment, including environmental remediation, gas storage, and geothermal energy production. Dr. Benson earned a B.A. in geology from Barnard College at Columbia University and an M.S. and Ph.D. in materials science and mineral engineering from University of California, Berkeley.

Peter G. Brewer is an ocean chemist and senior scientist at the Monterey Bay Aquarium Research Institute (MBARI). Prior to joining MBARI in 1991, he spent 24 years as a researcher at the Woods Hole Oceanographic Institution, where he rose to the rank of senior scientist. He has taken part in more than 30 deep-sea cruises and has served as chief scientist on major expeditions worldwide. A fellow of the American Geophysical Union and the American Association for the Advancement of Science, he was also a member of Vice President Gore's Environmental Task Force. Mr. Brewer's research interests include the ocean geochemistry of the greenhouse gases and techniques for measuring and extracting the oceanic signatures of global change. His current interests include the geochemistry of gas hydrates, the evolution of the oceanic fossil fuel CO_2 signal, and strategies for the sequestration of fossil-fuel CO_2 in the deep ocean. He is author or coauthor of about 100 scientific papers and the editor of several books.

Ken Caldeira works in the Climate and Carbon Cycle Modeling Group at Lawrence Livermore National Laboratory. He has also been scientific codirector of the U.S. Department of Energy Center for Research on Ocean Carbon Sequestration. Dr. Caldeira is a member of the UNESCO International Oceanography Commission CO_2 Panel of Experts and the Scientific Steering Group for the U.S. Global Carbon Cycle Science Research Plan. He received his B.A. from Rutgers University and his M.S. and Ph.D. in atmospheric sciences from New York University. Dr. Caldeira has performed and published numerical calculations relating to global change, including ocean carbon sequestration by means of fertilization, direct injection of CO_2, and carbonate dissolution; economics of storing carbon in a leaky reservoir; the carbon-emissions-free power requirements by the end of this century; the role of the southern ocean in absorbing anthropogenic CO_2 released to the atmosphere; the combined impact of growing forests on the climate and the carbon cycle; and natural CO_2 degassing from the Earth.

David G. Hawkins has worked in public-interest law since his graduation from Columbia University Law School in 1970. He joined the National Resources Defense Council (NRDC) in 1971. With another attorney, Dick Ayres, he began the NRDC Clean Air Project, which helped the federal government design the Clean Air Act and provides a voice for the public in decisions by the Environmental Protection Administration and state agencies involved with improving air quality. Since 1990, Mr. Hawkins has directed NRDC's Air and Energy Program, and in 2001 he became director of the NRDC Climate Center, which focuses on advancing policies and programs to reduce pollution that contributes to global warming and harmful climate change.

Howard Herzog is on the staff of the Massachusetts Institute of Technology (MIT) Laboratory for Energy and the Environment. He received his undergraduate and graduate education in chemical engineering at MIT and has industrial experience with Eastman Kodak, Stone & Webster, Spectra Physics, and Aspen

Technology. Since 1989, he has led research at the MIT Laboratory for Energy and the Environment on technologies to capture, use, and sequester CO_2 from large stationary sources. Dr. Herzog is also the program manager for the Carbon Sequestration Initiative, an industrial consortium that began in July 2000.

Gardiner Hill, head of environmental technology for British Petroleum Group (BP), is responsible for developing strategies and new technologies to support BP's commitments on environmental performance. In addition, Mr. Hill is chairman of the board of the CO_2 Capture Project, an international cooperative activity. Mr. Hill has almost 20 years of technical and managerial experience directly relevant to technology, business, and project management. He earned his M.S. and B.S. in petroleum and civil engineering from Heriot-Watt University in Scotland.

Roderick A. Hyde earned his B.A. in 1972, his M.A. in 1973, and his Ph.D. in 1976 (in aeronautics and astronautics), all from Massachusetts Institute of Technology. His Ph.D. thesis was focused on the design and behavior of ribless solar reflectors. His work has been published in *Energy in Physics*, *Applied Optics*, and several other industry journals. Dr. Hyde has been with Lawrence Livermore National Laboratory since 1972.

Gary K. Jacobs is co-coordinator of the U.S. Department of Energy Consortium for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems and program development director of the Oak Ridge National Laboratory Environmental Sciences Division. His research interests and experience include problem solving, research, and management in the earth sciences. His scientific interests include: aqueous geochemistry; fate and transport processes; carbon sequestration; kinetics and thermodynamics of rock-water interactions; gas hydrates; geochemical modeling; biogeochemical dynamics in microbial systems; high-temperature petrology; and environmental restoration technologies with an emphasis on in situ methods. He earned a B.A. in geology from the University of Vermont and a Ph.D. in geochemistry from Pennsylvania State University.

John Kadyszewski has worked on energy and resource management issues for 25 years and has research and development and project implementation experience in the United States and more than 20 countries in Africa, Latin America, Asia, and Europe. He is currently coordinator for the Ecosystem Services Group of Winrock International, where he has led the development and field testing of peer-reviewed methods and procedures for measuring carbon storage in forestry and agroforestry projects. His recent work has been focused on the development of advanced monitoring tools that combine aerial digital imagery with spatial information systems to improve measurement and analysis of land-management practices and associated environmental impacts. From 1993 to 1999, he was director of Winrock's Renewable Energy and Environment Program. He helped found the International Cane Energy Network in 1994 to stimulate collaborative research and development on technical issues associated with the production and sale of energy by the sugar industry and was a cofounder of the Environmental Enterprises Assistance Fund established in 1991 to address the shortage of investment capital in the developing world for environmentally beneficial businesses. Mr. Kadyszewski earned an engineering degree from Princeton University.

James A. Lake is associate laboratory director for nuclear and energy systems at Idaho National Engineering and Environmental Laboratory (INEEL) where he is responsible for basic research and development on nuclear energy, nuclear safety and risk management, nuclear science and nuclear technology, energy efficiency and renewable energy, fossil energy, and industrial, transportation, and building energy management programs. The author of more than 30 publications on reactor physics, nuclear engineering, and reactor design, Dr. Lake is an elected fellow and 2000–2001 president of the American Nuclear Society. He is a graduate and Distinguished Engineering Alumnus of the Georgia Institute of Technology, where he earned an M.S. and Ph.D. in nuclear engineering.

Franklin M. Orr, Jr., is the Keleen and Carlton Beal Professor of Petroleum Engineering and director of the Global Climate and Energy Project at Stanford University. He served as dean of the School of Earth Sciences at Stanford from 1994 to 2002 and was head of the miscible flooding section of the New Mexico Petroleum Recovery Research Center, New Mexico Institute of Mining and Technology, from 1978 to 1985. From 1976 to 1978, he was a research engineer at the Shell Development Company, Bellaire Research Center. Dr. Orr's research interests include: multiphase flow in porous media; interactions of high-pressure-phase equilibria of multicomponent mixtures with multiphase flow; enhanced oil recovery by gas injection processes; contaminant transport in aquifers; energy systems with low greenhouse emissions; and geologic sequestration of CO_2. He has a Ph.D. from the University of Minnesota and a B.S. from Stanford University, both in chemical engineering.

Dale Simbeck is vice president of technology and a founding partner at SFA Pacific, Inc., a consulting company. He has been involved with the technical and economic assessment, process design, start-up, and operation of commercial energy technologies since the late 1960s. He has also evaluated numerous energy technologies that are under development. Mr. Simbeck's background includes hands-on experience with commercial plant start-ups and operation, conceptual process design, and technical, economic, and market assessments. He heads SFA Pacific's extensive work in assessments of the costs and options for greenhouse gas mitigation. Mr. Simbeck is the author or coauthor of more than 50 professional papers. He received his B.S. in chemical engineering from Pennsylvania State University and is a registered professional engineer in California.

Robert H. Socolow is professor of mechanical and aerospace engineering and a member of the Center for Energy and Environmental Studies at Princeton University. He teaches in the School of Engineering and Applied Science and in the Woodrow Wilson School of Public and International Affairs. Dr. Socolow's current research focuses on global carbon management, the hydrogen economy, and fossil-carbon sequestration. He is the coprincipal investigator (with ecologist, Stephen Pacala) of Princeton University's new Carbon Mitigation Initiative, a $20-million, 10-year project, supported by BP and Ford. He is the editor of *Annual Review of Energy and the Environment* (Annual Reviews, Inc.) and a founder of the research approach known as industrial ecology. Dr. Socolow earned a B.A. in l959 and a Ph.D. in l964 from Harvard University in theoretical high-energy physics. He is a fellow of the American Physical Society and the American Association for the Advancement of Science. From 1992 to 1998, he was a member of the National Research (NRC) Council Committee on the Human Dimensions of Global Change. Currently he is a panel member on the NRC Committee on Alternatives and Strategies for Future Hydrogen Production and Use.

Edward Teller is best known for his work on the development of nuclear explosives and for his advocacy of a strong defense for America. He is also a noted physicist and the author of more than 100 technical publications, several books, some patents, and numerous articles in the popular media. Born in Budapest in 1908, Dr. Teller received his Ph.D. in physics under Werner Heisenberg in 1930; he continued to work under Heisenberg for another year. In 1931–1932, he worked at the University of Göttingen, in association with James Franck and Arnold T. Euken. When the Nazis rose to power, he left Germany and spent a year (1933–1934) in Copenhagen at the Niels Bohr Institute on a Rockefeller Fellowship. In 1939 when the discovery of fission was announced, Dr. Teller was a theoretical physicist, working in the fields of quantum physics, molecular physics, and nuclear physics. After a short sojourn in London, he was appointed professor of physics at the George Washington University in Washington, D.C., where he continued to work until 1941.

In 1941, Dr. Teller's interest turned to the use of nuclear energy, both fission and fusion, and he began work on the Manhattan Project at Columbia University and the University of Chicago with Enrico Fermi and Leo Szilard. In 1943, he continued his work on both fission explosions and early plans for thermonuclear bombs at Los Alamos National Laboratory. In 1946, he returned to the University of Chicago for two years as professor, again as a close associate of Enrico Fermi and Maria Mayer. He spent 1949 and 1950 in Los Alamos, where his work was concentrated on the hydrogen bomb; he contributed to the decision to make thermonuclear reactions a major part of the program. In 1952, at the time of the first test of the hydrogen bomb, Dr. Teller joined the University of California at Berkeley and began working at the newly founded Lawrence Livermore

Laboratory. In 1953, he was named professor of physics at the university, as well as associate director and then director (1958–1960) of Lawrence Livermore.

In 1960, Dr. Teller became University Professor of Physics at the University of California, while retaining the position of associate director at Livermore. Since he retired from these positions in 1975, he has been Director Emeritus at Livermore and Senior Research Fellow at the Hoover Institution at Stanford University.

Michael J. Walsh is senior vice president of Environmental Financial Products L.L.C., which specializes in providing customized risk management and trading services and developing new financial, commodity, and environmental markets. Dr. Walsh previously was senior economist with the Chicago Board of Trade, where he directed the development of exchange-based environmental markets. He has written extensively on the economics of energy efficiency and the implementation of efficiency programs and has published numerous articles, led seminars on emissions trading for industry and government officials from several eastern European countries, has been a speaker at United Nations climate conferences at Geneva, Kyoto, Buenos Aires, Bonn, and The Hague, and has been a keynote speaker at industry conferences and educational workshops around the world. Dr. Walsh has been a member of the faculties of the University of Notre Dame and the Stuart School of Business at the Illinois Institute of Technology and has lectured at Princeton, Northwestern, Colorado, Illinois and Johns Hopkins (Bologna) universities. He has a B.S. in economics and political science from Illinois State University, an M.S. and Ph.D. in Economics from Michigan State University, and has attended the University of Chicago Graduate School of Business.

Lowell L. Wood is a senior staff scientist at Lawrence Livermore National Laboratory and a member of the Director's Technical Staff. He received a B.S. in chemistry and mathematics in 1962 and a Ph.D. in astrophysics in 1965 from the University of California at Los Angeles (UCLA). From 1965 to 1972, he was a consultant at the University of California Lawrence Livermore Laboratory and an assistant research geophysicist at UCLA. In addition, he was an assistant professor at the University of California Davis/Livermore Department of Applied Sciences. His scientific work during this period (in collaboration with John Nuckolls) culminated in technical proposals leading to the establishment of the National Inertial Confinement Fusion Program. From 1972 to 1975, Dr. Wood served as the associate head of the Physics Department at Lawrence Livermore National Laboratory, where he founded the Special Studies Group in 1972 and the related Special Studies Program in 1975.

Dr. Wood is the author or coauthor of several hundred papers, briefing documents, and government-classified papers and the owner or co-owner of approximately 25 patents. In 1981, he received the E.O. Lawrence Award from the U.S. Department of Energy for "outstanding contributions to national security in the area of directed energy, inertial confinement fusion, underwater communication, nuclear design concepts and computer technology." In 1991, he received the ADPA Abrahamson Award for work that has "led directly to the revitalization of a strategic defense systems programs and made all elements more robust and cost-effective."

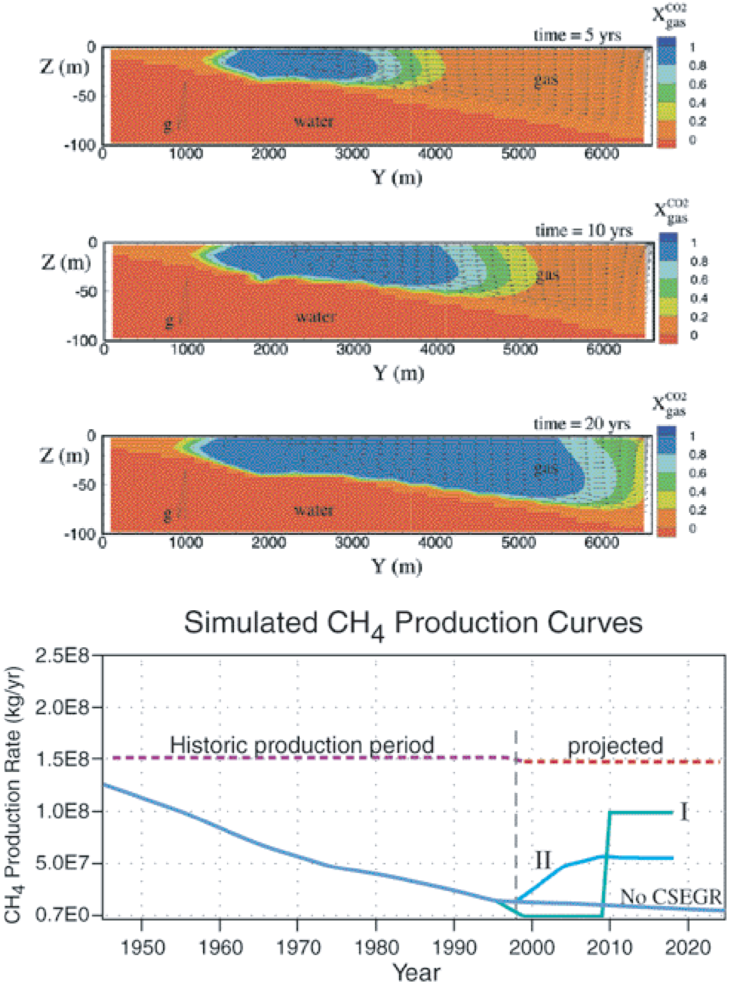

PLATE 1 Results from numerical simulations of carbon sequestration enhanced natural gas recovery (CSEGR) showing that pressure diffusion is more rapid than molecular diffusion and that up to 30 percent more natural gas could be produced from the Rio Vista Gas Field in California with CSEGR. Source: adapted from Oldenburg et al., 2001.

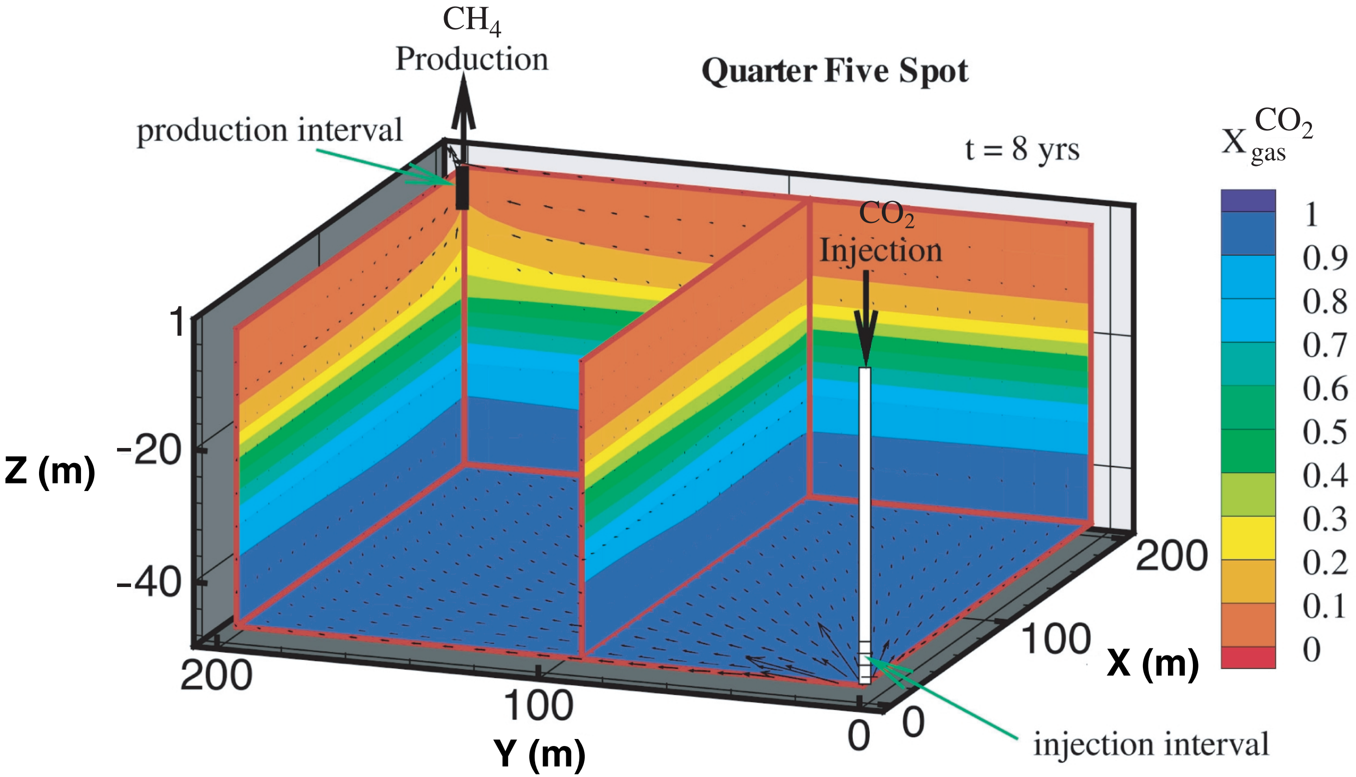

PLATE 2 Simulation showing the concentration of CO_2 in a 5-spot injection pattern, which shows that the CO_2 sweeps upward from the bottom of the reservoir. Source: adapted from Oldenburg et al., 2002.

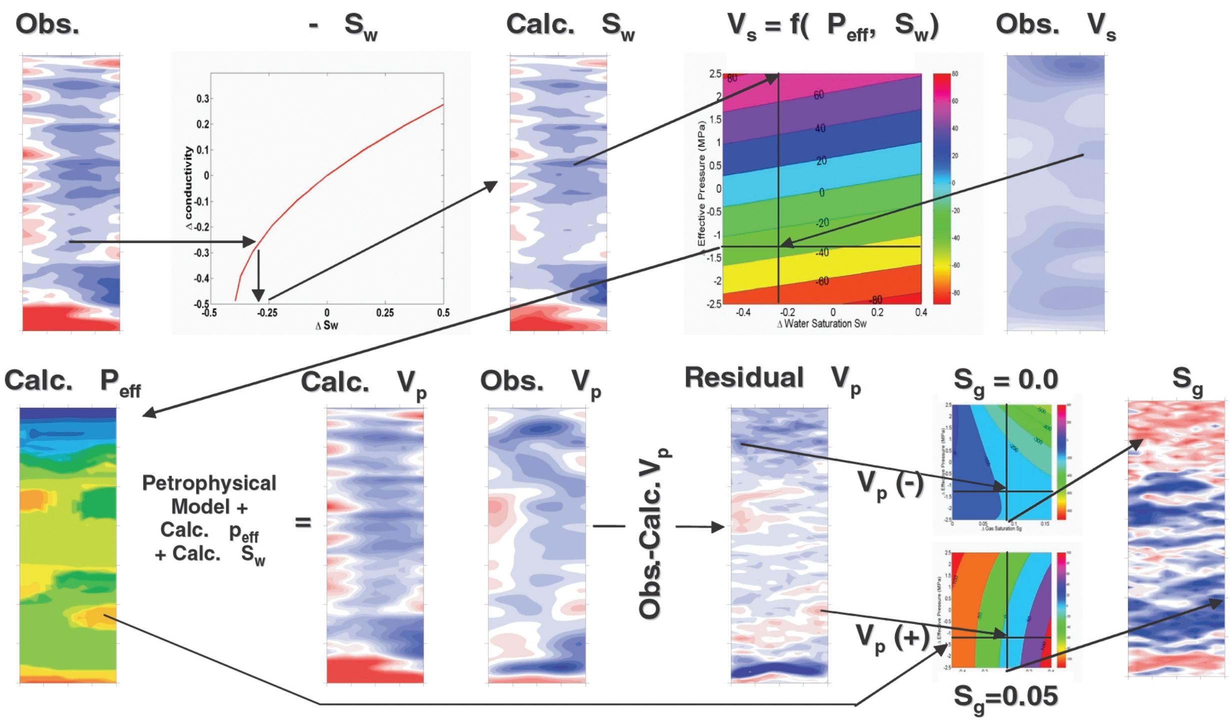

PLATE 3 Schematic drawing showing how the combination of electromagnetic and seismic imaging can be used to detect CO_2 saturation in a reservoir. Source: Hovesten et al., in press.

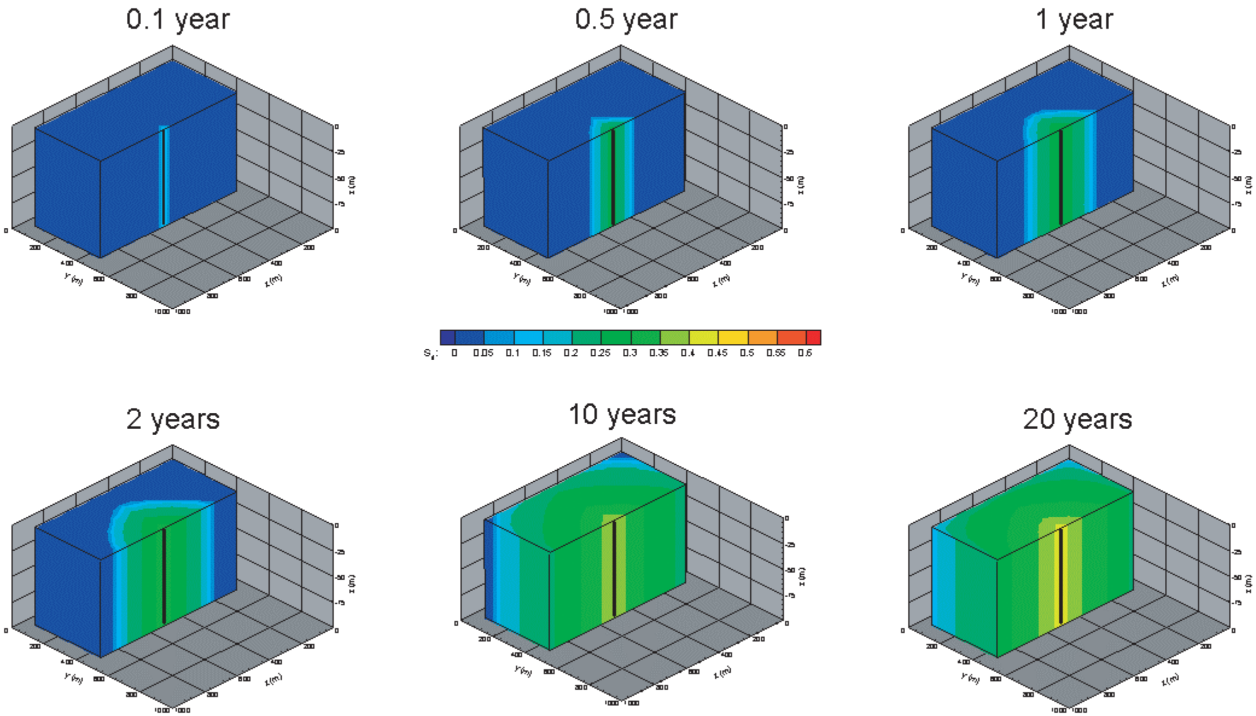

PLATE 4 Simulation of CO_2 migration in a homogeneous reservoir where buoyancy forces are neglected. Source: adapted from Doughty et al., in press.

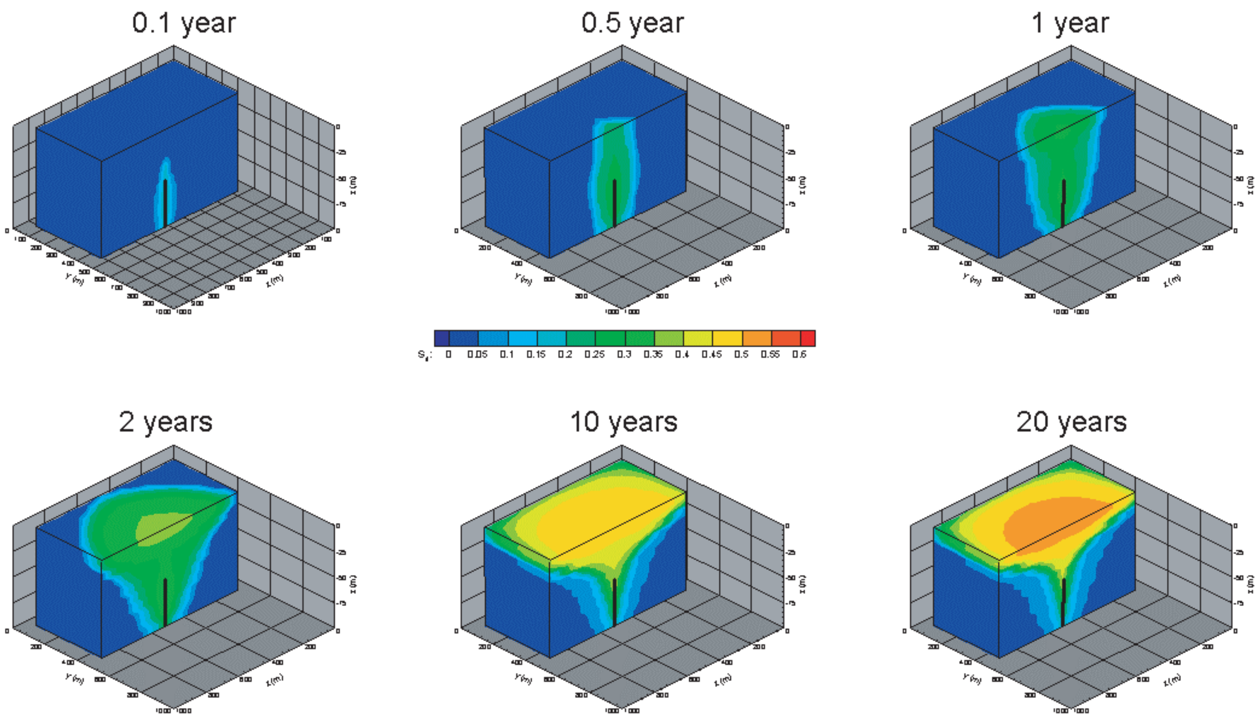

PLATE 5 Simulation of CO_2 migration in a homogeneous reservoir. Source: adapted from Doughty et al., in press.

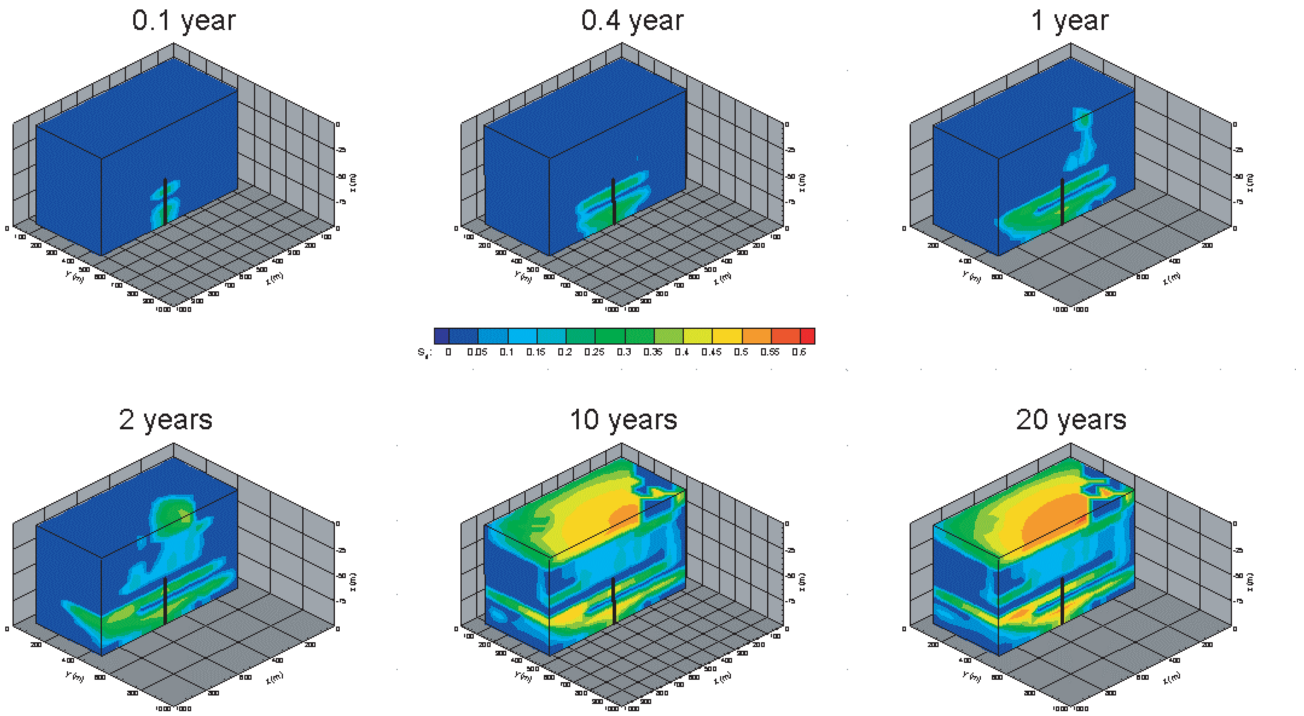

PLATE 6 Simulation of CO_2 migration in a homogeneous reservoir where buoyancy forces are neglected. Source: adapted from Doughty et al., in press.

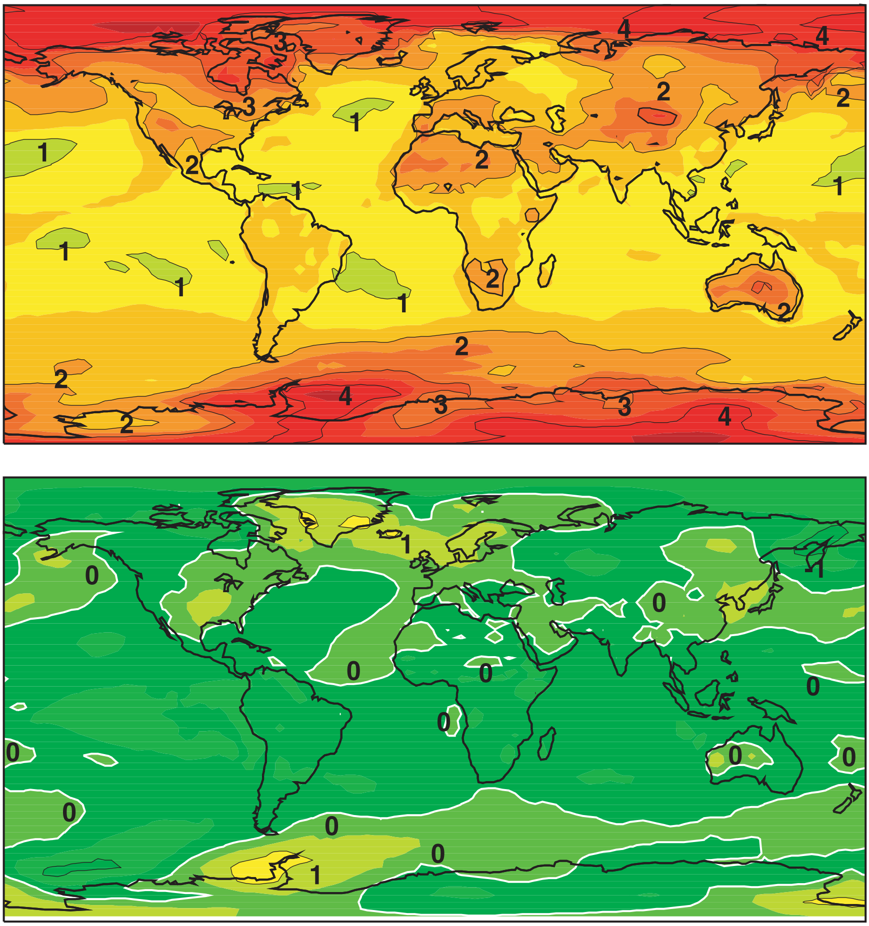

PLATE 7 The upper panel depicts the space-averaged and time-averaged temperature change (°C) with a doubling of atmospheric CO_2 concentration from the preindustrial baseline. The lower panel shows the same result, again for a doubling of CO_2 concentration, accompanied by a 1.8-percent reduction in insolation. No significant temperature changes are seen. Sources: Govindasamy and Caldeira, 2000.

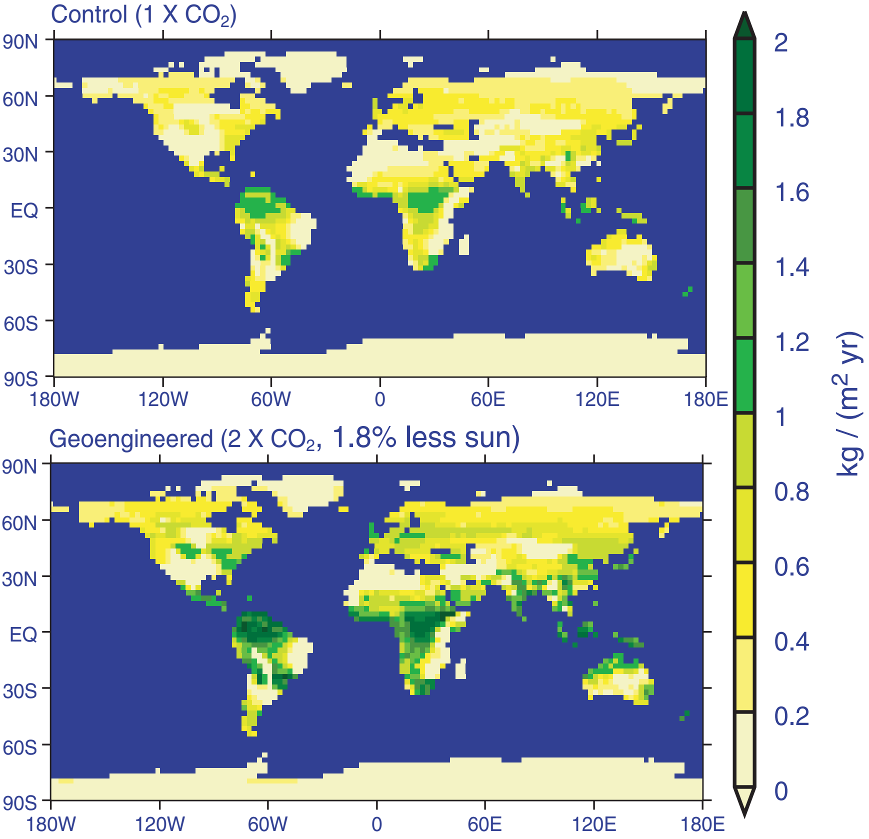

PLATE 8 Net primary (plant) productivity of terrestrial land masses, as modeled by IBIS code with slab ocean used in conjunction with the Community Climate Model (CCM3). The upper panel shows Earth with a preindustrial atmospheric CO_2 concentration and with 1.8 percent less insolation. The globally aggregated land-plant productivity in the lower panel is nearly twice that of the upper panel, which implies an agricultural crop value difference of about $1 trillion per year in the enriched CO_2 case. Source: Govindasamy et al., 2000.