Good-bye to a Greenhouse Gas

Dumping carbon dioxide underground or in the oceans could slow global warming

By RICHARD MONASTERSKY

Last year off the coast of central California, a robotic submarine pumped a thin stream of liquid carbon dioxide onto the seafloor, more than 3.6 kilometers below the ocean surface. Instead of mixing with the water, the fluid formed marble-sized balls that bounced on the silty bottom and jiggled like clear Jell-O in slow motion. A grenadier fish, sleek and curious, idled by and considered the blobs rolling downhill toward the Pacific's abyssal depths.

"The fish just looked. It seemed like it was trying to decide whether to eat the experiment," says ocean chemist Peter G. Brewer, who led the project from a ship overhead.

Oyvind Hagen, Statoil

A platform in the North Sea injects liquid carbon dioxide into rocks far below the ocean floor.

In the next few years, residents of the deep ocean will have ample opportunity to consider this strange, new addition to their environment. Researchers from the United States, Japan, Norway, and Canada are planning to inject 50 to 100 tons of liquid carbon dioxide into the ocean off the coast of Kona, Hawaii, in 2001. Their aim is to study the possibility of dumping this greenhouse gas into the dark reaches of the sea—a tactic designed to slow the atmospheric buildup of carbon dioxide and thereby reduce the threat of climate change.

The Hawaiian experiment will deep-six just a pittance of the 27 billion tons of carbon dioxide (containing 7.4 billion tons of carbon) that human activities emit into the atmosphere each year. Yet the ocean test rides a new wave of thinking about the most notorious greenhouse gas. As countries scramble to find ways of reducing their heat-trapping pollution, scientists are combing the planet to locate suitable disposal sites for carbon dioxide. The storage options include brine-filled aquifers, deep coal seams, depleted oil formations, and the ocean bottom.

In late April, Sen. Frank Murkowski (R-Alaska) and nine cosponsors introduced a bill that would establish a long-term research program to develop this strategy, called carbon sequestration. Earlier the same month, the Department of Energy issued a 223-page report on the state of the science underlying carbon sequestration.

As a goal, DOE proposes that nations develop the potential to dispose of up to 3.7 billion tons of carbon dioxide annually by the year 2025 and 15 billion tons by 2050—targets that would set the world on course to stabilize atmospheric concentrations of this gas. Toward that objective, the department dramatically increased its funding for sequestration research from $1.6 million last year to $13 million in fiscal year 1999, with $29 million proposed for FY 2000.

At the same time, energy officials are campaigning to boost interest in this approach. In a speech last month before representatives of the coal industry, Energy Secretary Bill Richardson called carbon sequestration "one of the best options for reducing the buildup of greenhouse gases, not only in this country but in China, India, and elsewhere. It is the only climate-change option that won't require a wholesale changeover in our energy infrastructure."

Yet some scientists and environmentalists view this approach as fundamentally misguided—akin to hiding a lumpy problem by shoving it under a rug. Critics charge that pumping carbon dioxide into the oceans or geologic formations could harm poorly understood ecosystems and threaten human safety, both now and for generations to come.

The concept behind this contentious approach surfaced in 1977 in the imagination of Italian energy specialist E. Marchetti. He proposed a two-step process for getting rid of carbon dioxide. First, separate that gas from the rest of the pollution belching out of power plants. Then, pump the carbon dioxide into the ocean off the coast of Gibraltar, where dense Mediterranean waters spill into the Atlantic. The sinking current of salty Mediterranean water would sweep the carbon dioxide into the deep sea and keep it out of the atmosphere.

In 1984, Meyer Steinberg of Brookhaven National Laboratory in Upton, N.Y., and his colleagues assessed the economics of Marchetti's approach. "What we found was that it would double the cost of power," says Steinberg.

Given that dire forecast, the sequestration concept captured little attention. Researchers instead focused on other ways to reduce carbon dioxide pollution, such as increasing energy efficiency and developing alternative power sources that emit little or no greenhouse gases.

In recent years, some energy experts have grown convinced that these more prosaic approaches will not, on their own, enable nations to reach the emissions limits they agreed to in Kyoto, Japan, in 1997. "There's really no short-term or mid-term good alternative to fossil fuels, at least on the scale that would be needed to cut back fossil fuels. And if you believe that, then [sequestration] is the only other real alternative to address climate change," says Howard J. Herzog of the Massachusetts Institute of Technology (MIT), who has studied carbon disposal since the early 1990s.

Today, the term sequestration encompasses a broad variety of options, all of which store carbon dioxide somewhere

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other than the atmosphere. In its recent report, DOE even considered techniques such as planting trees and fertilizing the oceans, approaches that cause plants and bacteria to absorb greater-than-normal amounts of carbon dioxide (SN: 9/30/95, p. 220).

For the energy industry, however, the long-term focus remains on finding ways to continue using an inherently cheap and dirty source of fuel without adding pollution to the air. Few companies today are willing to take on the extra expense of separating and sequestering carbon dioxide, but researchers are working on techniques to boost the efficiency of the process and lessen its cost (see sidebar).

On an artificial island in the middle of the North Sea, engineers with Norway's state-owned oil company, Statoil, form the vanguard in the field of sequestration.

Since 1996, Statoil and its partners have been pumping natural gas out of a geologic formation called the Sleipner field. The deposit, although prodigious, has a crucial flaw. Natural gas from the Sleipner West field contains 9 percent carbon dioxide, almost four times the amount allowed by exportation rules.

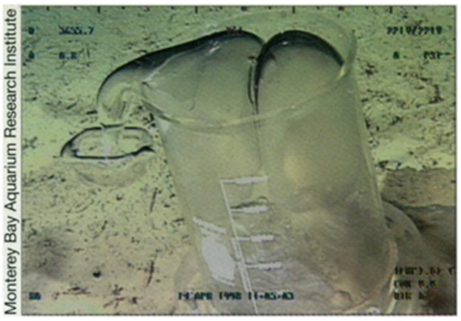
Normally, production companies would separate the carbon dioxide and then vent it into the air. Statoil, however, pumps the carbon dioxide down into an aquifer 1,000 meters below the seafloor. The company disposes of 1 million tons of the gas each year this way. That amount would boost Norway's carbon dioxide emissions by 3 percent if released into the air.

Statoil undertook this costly operation to avoid paying a tax on carbon dioxide emissions, says Olav Kaarstad of Statoil's research center in Trondheim. The facility for separating and injecting carbon dioxide cost $80 million to install, but the carbon tax would amount to $50 million a year.

For years, many petroleum companies have been injecting carbon dioxide into oil formations to boost output. This technique differs from the Sleipner project, however, because the carbon dioxide leaks back out with the oil, rather than remaining locked underground.

"Sleipner is the only operation of its kind in the world. It is the only place where [sequestration] is done because of climate-change concerns," says Kaarstad.

This month, Statoil and a consortium of other companies begin probing the aquifer with seismic waves to track how quickly the carbon dioxide is moving in the formation. Statoil plans to carry on with its carbon dioxide disposal for the next 2 decades, eventually putting some 20 million tons of the gas into the aquifer.



Monterey Bay Aquarium Research Institute

In the first deep-sea experiment of its kind, researchers pumped liquid carbon dioxide into a beaker 3.6 kilometers below the ocean surface. The carbon dioxide expanded and spilled out. A thin layer of icelike hydrate forms a coating around the carbon dioxide.

Across the Atlantic in the Canadian province of Alberta, engineers are conducting an experiment to see whether they can get rid of carbon dioxide at a profit. The Alberta Research Council is injecting carbon dioxide into a coal deposit 1,300 meters underground, too deep to make mining worthwhile. Despite its depth, the deposit has economic potential because it also contains significant quantities of trapped natural gas, which companies can remove through a well.

Pumping carbon dioxide down into a coal bed causes it to release the pent-up natural gas, says William D. Gunter of the Alberta Research Council in Edmonton. Last year, Gunter and his colleagues injected a stream of nearly pure carbon dioxide into a coal bed with positive results. This year, they plan to use a much more dilute stream of carbon dioxide, closer in composition to the mix of gases that comes out of smokestacks.

"The basic target is to see how pure the carbon dioxide has to be," says Gunter. If the process will work with a relatively dilute stream, then companies may be able to increase natural gas recovery by pumping in the exhaust gases from a power plant, with little extra expense. The injected carbon dioxide seeps into the coal and should remain imprisoned there, says Gunter.

In the United States, coal deposits of this sort have the potential to store 37 billion tons of carbon dioxide, six times the nation's total annual emissions. A much greater capacity may exist in deep briny aquifers, which could hold nearly 500 billion tons, according to the most optimistic assessment quoted in the recent DOE report.

The International Energy Agency estimates that aquifers worldwide could perhaps accommodate more than 20 times the U.S. figure, enough to store 350 years' worth of global emissions at present rates.

The oceans have an even greater ability to sequester carbon dioxide—vast enough, in theory, to outlast all the coal, oil, and natural gas available on the planet. Scientists have proposed that liquid carbon dioxide, when injected into the deep sea, would settle as lakes in depressions on the seafloor.

The results of the experiment off the coast of California last year suggest that a thin layer of icelike hydrate would develop on top of lakes if they were situated below depths of 4,500 meters, the investigators

The quest to clean up fossil fuels

Carbon dioxide is the uninvited guest that shows up whenever coal, oil, or natural gas burn. To keep this interloper out of the environment, engineers are exploring strategies to lock up the carbon before it can do any harm.

In the past, sequestration strategies have focused on pulling carbon dioxide out of the stream of gases made by burning fossil fuels. In one standard technique, the exhaust bubbles up through an amine solvent, which absorbs the carbon dioxide and lets other gases escape.

A newer concept would strip the carbon out of the fossil fuel before combustion, leaving behind an enriched hydrocarbon that could be further transformed into hydrogen. Power plants would burn the hydrogen, like they do natural gas, or hydrogen could provide electrical energy through highly efficient fuel cells.

The advantage of this approach is that it would permit countries to continue using fossil fuels—even coal, the dirtiest and most abundant one. "This is a coal strategy as well as an oil and gas one. We think coal is the long-term fuel for the second half of the 21st century," says Robert H. Socolow of Princeton University.

The possibility of divorcing fossil fuels from their pollution may help make emissions limitations more palatable for the energy industry, the harshest critic of international efforts to curb carbon dioxide pollution, concluded Harvard's E.A. Parson and D.W. Keith in the Nov. 6, 1998 SCIENCE.

At present, separating carbon from fossil fuels or combustion gases is the most expensive part of any sequestration strategy. Even at its most efficient, the separation process adds roughly 50 percent to the cost of producing electric power, says Meyer Steinberg of Brookhaven National Laboratory in Upton, N.Y.

Using zeolite crystals, membranes, and other substances, researchers are now trying to develop more efficient methods of pulling carbon out of fossil fuels. Eventually, industries might be able to find some use for this extracted material, perhaps as solid carbon to use in the walls of 21st-century houses. *—R.M.*

report in the May 7 SCIENCE. This skin would slow down the rate at which carbon dioxide dissolves into the seawater.

"The ocean looks like it could take that material quite well, if you know what you're doing," says Brewer of the Monterey Bay Aquarium Research Institute in Moss Landing, Calif.

Although the oceans have almost unlimited capacity to absorb carbon dioxide, it remains unclear how marine life will react to such an intrusion. "At present, we do not have enough information to estimate how much carbon can be sequestered without perturbing marine ecosystem structure and function," says the DOE report.

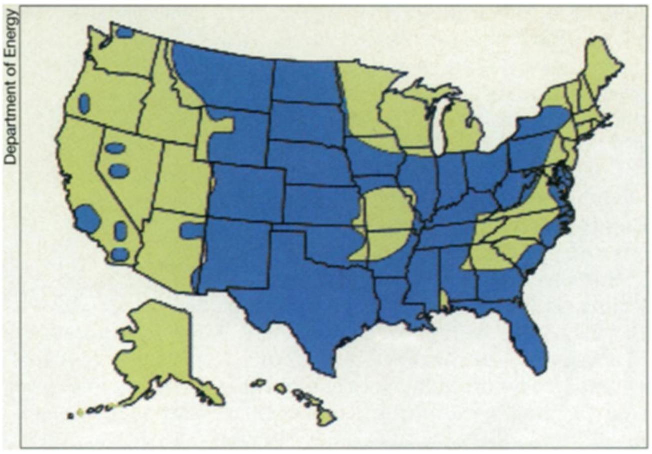
The deep-water experiment off Hawaii marks the first step in gathering that data, says project manager Stephen M. Masutani of the University of Hawaii at Manoa in Honolulu. Researchers will measure how the carbon dioxide spreads from the end of the pipe and how quickly it dissolves into the water.

"The predictions indicate that if you put the carbon dioxide deep enough in the ocean, 1,000 m or greater, the carbon dioxide will stay there for centuries," says Masutani. Water from that depth does not readily mix with the surface layers, he says.

Critics of the ocean-disposal idea argue, however, that the added carbon dioxide will acidify the deep ocean and could harm the complex web of animals and microbes there.

"We really don't have any idea what it would do to those ecosystems," says oceanographer Sallie W. Chisholm of MIT, adding that no ecological studies are planned as yet. "It would take years of study and tons of money to even begin to understand what the influence might be," notes Chisholm, who contributed to the DOE report.

Environmental concerns have caused some sequestration advocates, such as Steinberg, to give up on the idea of ocean storage in favor of pumping carbon dioxide into geologic formations. Yet even these sites have their potential hazards, says Wim C. Turkenburg of Utrecht University in the Netherlands, a country currently considering whether to go forward with a project to pump carbon dioxide into an aquifer.


Department of Energy

The United States has numerous deep saline aquifers (blue areas), which may make suitable places to store carbon dioxide. Other potential sites include oil, gas, and coal deposits. One crucial question is whether carbon dioxide will stay locked up in these deposits for many centuries.

"If it is stored in an aquifer," asks Turkenburg, "will it be there decades from now? If there is a crack, if there is an earthquake, what might happen? Carbon dioxide is a heavy gas, so if it comes up from the underground, then you will have a layer of carbon dioxide close to the ground. That is, of course, not so good if you want to have oxygen for breathing."

A volcanic lake in Cameroon provided a natural illustration of this scenario in 1986, when a bubble of carbon dioxide escaped from the water and killed 1,700 people.

Supporters of carbon sequestration counter that they are only beginning to study the various options. "We need to do more research to assure ourselves we are not doing something that will substitute one problem for another," says Herzog. "Secondly, we want to make sure it's effective, that the carbon dioxide will stay there and have the benefit of reducing atmospheric concentrations."

He points out, however, that the current situation is creating its own environmental problems by warming the climate. What's more, the oceans are already sopping up a net 7 billion tons of the carbon dioxide emitted by human activities each year. The gas seeps from the air directly into the surface waters around the world and is gradually making the upper ocean more acidic. Scientists recently reported that the shifting chemistry has already started to stunt the growth of coral reefs (SN: 4/3/99, p. 214).

By pumping carbon dioxide directly into the deep sea, nations could reduce the amount inadvertently entering the sunlit waters near the surface, where much of marine life makes its home. Though anathema to environmentalists, this kind of trade-off may seem more promising in the future as the effects of greenhouse-gas pollution grow more obvious, say sequestration advocates.

"There's no soft landing here," says Herzog. "There's no perfect solution. And it's going to involve some hard choices eventually." □

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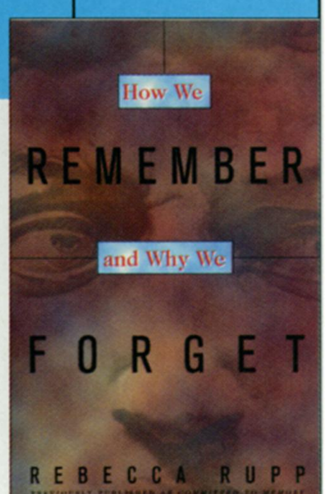

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