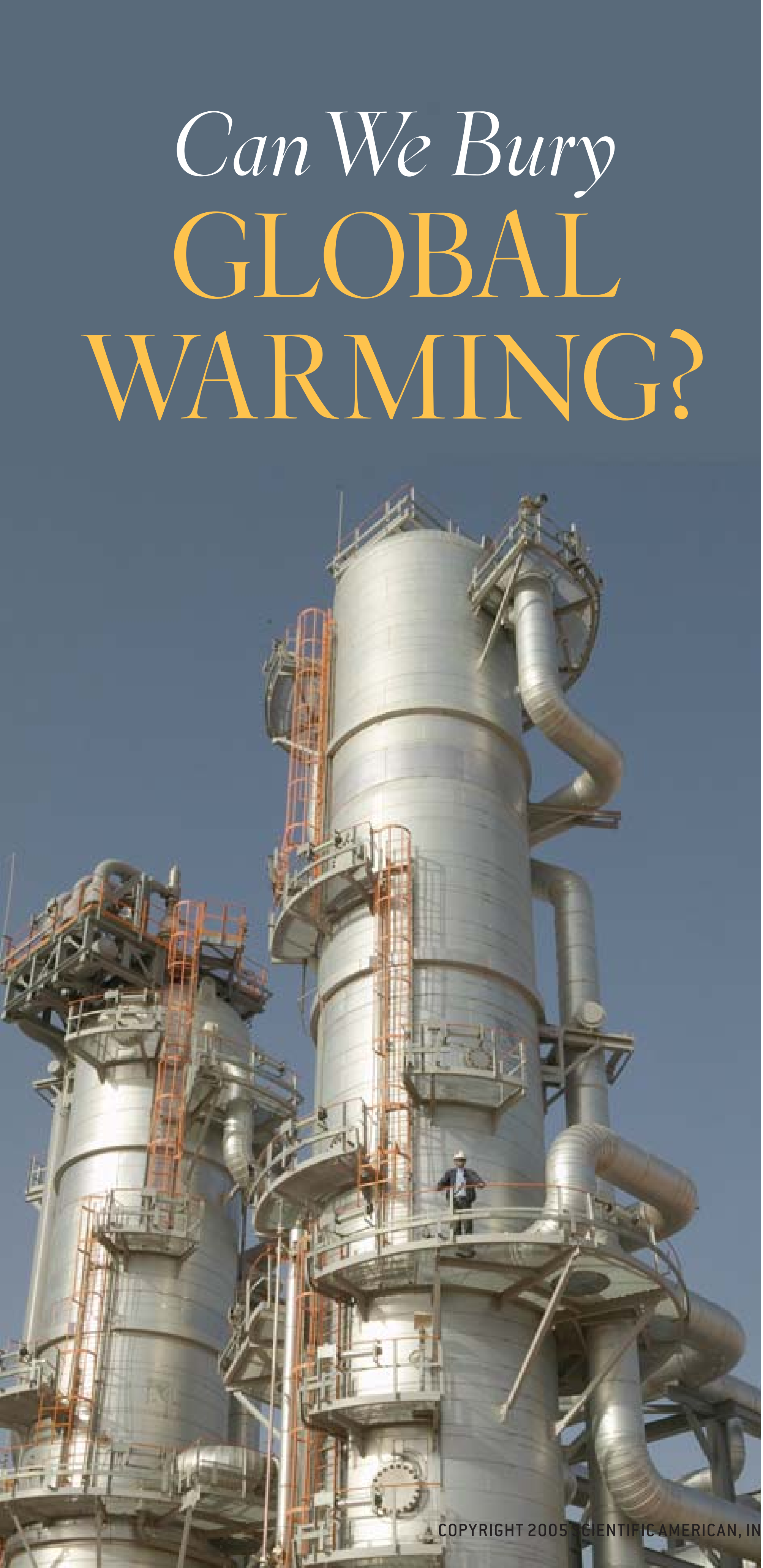
Can We Bury GLOBAL WARMING?

Pumping carbon dioxide underground to avoid warming the atmosphere is feasible, but only if several key challenges can be met

By Robert H. Socolow



STRIPPER TOWERS at an Algerian gas-extraction facility deep in the Sahara Desert chemically separate carbon dioxide from natural gas bound for European markets. The CO_2 is then pumped two kilometers below ground.

When William Shakespeare took a breath, 280 molecules out of every million entering his lungs were carbon dioxide. Each time you draw breath today, 380 molecules per million are carbon dioxide. That portion climbs about two molecules every year.

No one knows the exact consequences of this upsurge in the atmosphere's carbon dioxide (CO_2) concentration nor the effects that lie ahead as more and more of the gas enters the air in the coming decades—humankind is running an uncontrolled experiment on the world. Scientists know that carbon dioxide is warming the atmosphere, which in turn is causing sea level to rise, and that the CO_2 absorbed by the oceans is acidifying the water. But they are unsure of exactly how climate could alter across the globe, how fast sea level might rise, what a more acidic ocean could mean, which ecological systems on land and in the sea would be most vulnerable to climate change and how these developments might affect human health and well-being. Our current course is bringing climate change upon ourselves faster than we can learn how severe the changes will be.

If slowing the rate of carbon dioxide buildup were easy, the world would be getting on with the job. If it were impossible, humanity would be working to adapt to the consequences. But reality lies in between. The task can be done with tools already at hand, albeit not necessarily easily, inexpensively or without controversy.

Were society to make reducing carbon dioxide emissions a priority—as I think it should to reduce the risks of environmental havoc in the future—we would need to pursue several strategies at once. We would concentrate on using energy more efficiently and on substituting noncarbon renewable or nuclear energy sources for fossil fuel (coal, oil and natural gas–the primary sources of man-made atmospheric carbon dioxide). And we would employ a method that is receiving increasing attention: capturing carbon dioxide and storing, or sequestering, it underground rather than releasing it into the atmosphere. Nothing says that CO_2 must be emitted into the air. The atmosphere has been our prime waste repository, because discharging exhaust up through smokestacks, tailpipes and chimneys is the simplest and least (immediately) costly thing to do. The good news is that the technology for capture and storage already exists and that the obstacles hindering implementation seem to be surmountable.

Carbon Dioxide Capture

THE COMBUSTION of fossil fuels produces huge quantities of carbon dioxide. In principle, equipment could be installed to capture this gas wherever these hydrocarbons are burned, but some locations are better suited than others.

If you drive a car that gets 30 miles to the gallon and go 10,000 miles next year, you will need to buy 330 gallons—about a ton—of gasoline. Burning that much gasoline sends around three tons of carbon dioxide out the tailpipe. Although CO_2 could conceivably be caught before leaving the car and returned to the refueling station, no practical method seems likely to accomplish this task. On the other hand, it is easier to envision trapping the CO_2 output of a stationary coal-burning power plant.

It is little wonder, then, that today's capture-and-storage efforts focus on those power plants, the source of one quarter of the world's carbon dioxide emissions. A new, large (1,000-megawatt-generating) coal-fired power plant produces six million tons of the gas annually (equivalent to the emissions of two million cars). The world's total output (roughly equivalent to the production of 1,000 large plants) could double during the next few decades as the U.S., China, India and many other countries construct new power-generating stations and replace old ones [*see illustration on page 52*]. As new coal facilities come online in the coming quarter of a century, they could be engineered to filter out the carbon dioxide that would otherwise fly up the smokestacks.

Today a power company planning to invest in a new coal plant can choose from two types of power systems, and a third is under development but not yet available. All three can be modified for carbon capture. Traditional coal-fired steam power plants burn coal fully in one step in air: the heat that is released converts water into high-pressure steam, which turns a steam turbine that generates electricity. In an unmodified version of this system—the workhorse of the coal power industry for the past century—a mixture of exhaust (or flue) gases exits a tall stack at atmospheric pressure after having its sulfur removed. Only about 15 percent of the flue gas is carbon dioxide; most of the remainder is nitrogen and water vapor. To adapt this technology for CO_2 capture, engineers could replace the smokestack with an absorption tower, in which the flue gases would come in contact with droplets of chemicals called amines that selectively absorb CO_2. In a second reaction column, known as a stripper tower, the amine liquid would be heated to release concentrated CO_2 and to regenerate the chemical absorber.

The other available coal power system, known as a coal gasification combined-cycle unit, first burns coal partially in the presence of oxygen in a gasification chamber to produce a "synthetic" gas, or syngas—primarily pressurized hydrogen and carbon monoxide. After removing sulfur compounds and other impurities, the plant combusts the syngas in air in a gas turbine—a modified jet engine—to make electricity. The heat in the exhaust gases leaving the gas turbine turns water into steam, which is piped into a steam turbine to generate additional power, and then the gas turbine exhaust flows out the stack. To capture carbon from such a facility, technicians add steam to the syngas to convert (or "shift") most of the carbon monoxide into carbon dioxide and hydrogen. The combined cycle system next filters out the CO_2 before burning the remaining gas, now mostly hydrogen, to generate electricity in a gas turbine and a steam turbine.

The third coal power approach, called oxyfuel combustion, would perform all the burning in oxygen instead of air. One version would modify single-step combustion by burning coal in oxygen, yielding a fuel gas with no nitrogen, only CO_2

Overview/*Entombing CO_2*

- A strategy that combines the capture of carbon dioxide emissions from coal power plants and their subsequent injection into geologic formations for long-term storage could contribute significantly to slowing the rise of the atmospheric CO_2 concentration.
- Low-cost technologies for securing carbon dioxide at power plants and greater experience with CO_2 injection to avoid leakage to the surface are key to the success of large-scale CO_2 capture and storage projects.
- Fortunately, opportunities for affordable storage and capture efforts are plentiful. Carbon dioxide has economic value when it is used to boost crude oil recovery at mature fields. Natural gas purification and industrial hydrogen production yield CO_2 at low cost. Early projects that link these industries will enhance the practitioners' technical capabilities and will stimulate the development of regulations to govern CO_2 storage procedures.

COURTESY OF BP plc (*preceding page*)

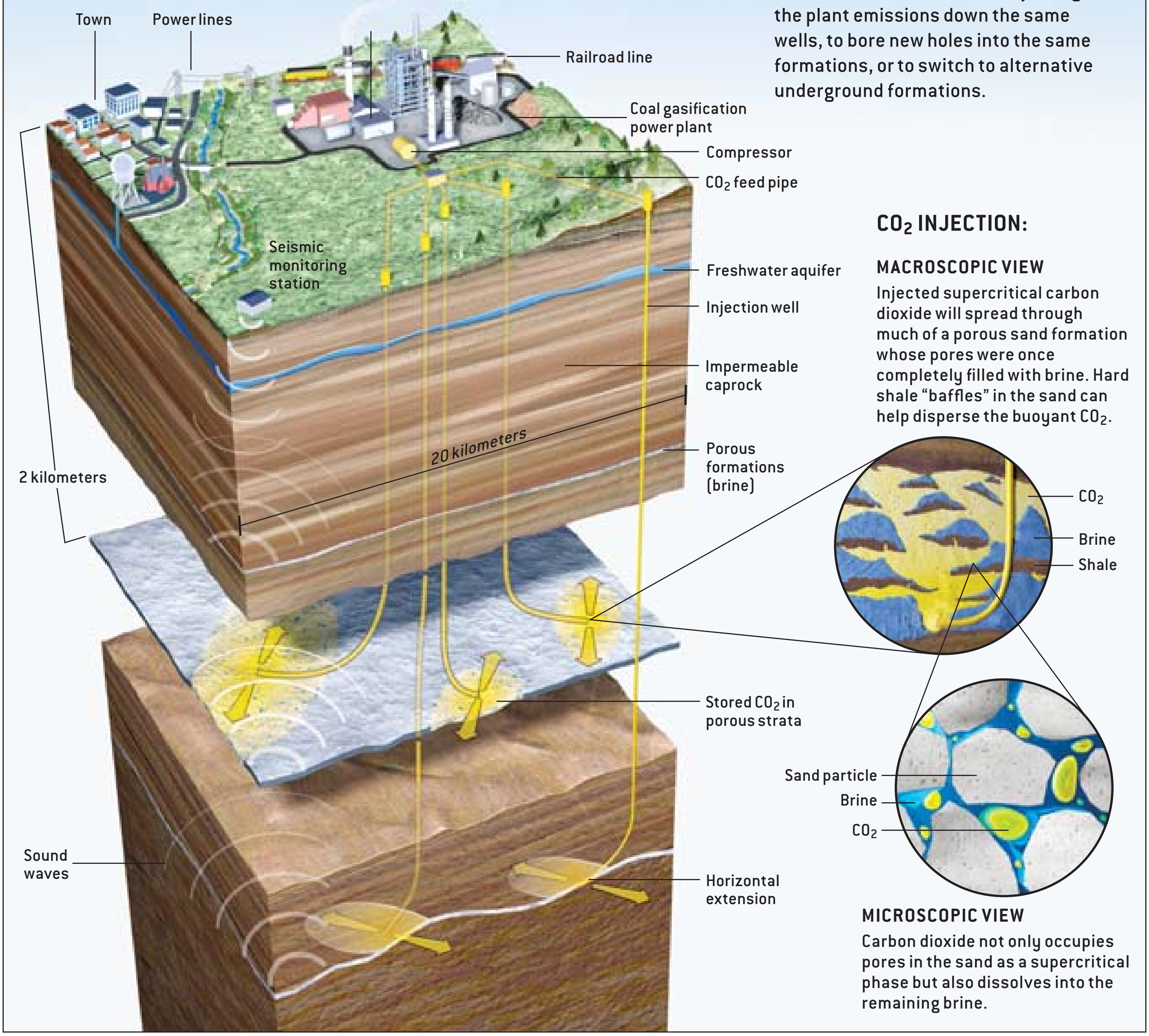
FUTURE FOSSIL-FUEL POWER PLANT

Consider a hypothetical town near a future 1,000-megawatt coal gasification power plant that has been sequestering carbon dioxide for 10 years. The town receives water from a shallow aquifer, unaffected by the CO_2 injection. The rail line transports coal to the plant, and the power lines carry away the electricity it generates.

Some 60 million tons of CO_2 have been captured during the plant's first 10 years of operation, and by now very large pancake-shaped deposits of CO_2 sit in the porous subterranean strata. The carbon dioxide was injected through horizontal wells into two deep brine (saltwater) formations, each located under impermeable caprock more than two kilometers below the surface. At seven tenths the density of water, the high-pressure "supercritical" CO_2 occupies almost 90 million cubic meters. In both formations, 10 percent of the volume is pore space, and a third of the pores are filled with CO_2 [*see insets for detailed views of the porous strata*]. Two thirds of the injected gas has been pumped into the 40-meter-thick upper formation, and one third has been sent into the 20-meter-thick lower formation. As a result, the total (horizontal) area of porous rock soaked with supercritical carbon dioxide in each formation is about 40 square kilometers.

Note that the horizontal and vertical scales depicted here differ. The depth of each injection well and the length of their horizontal extensions are really about equal in length, around two kilometers. Nor are the building structures to scale.

Technicians at a seismic monitoring station keep track of the CO_2 locations by beaming sound waves into the ground. During the power station's initial decade of operation, utility managers learned many details about the local geology by observing how the CO_2 spread through the area. This information will help them decide whether to continue injecting the plant emissions down the same wells, to bore new holes into the same formations, or to switch to alternative underground formations.



CO_2 INJECTION:

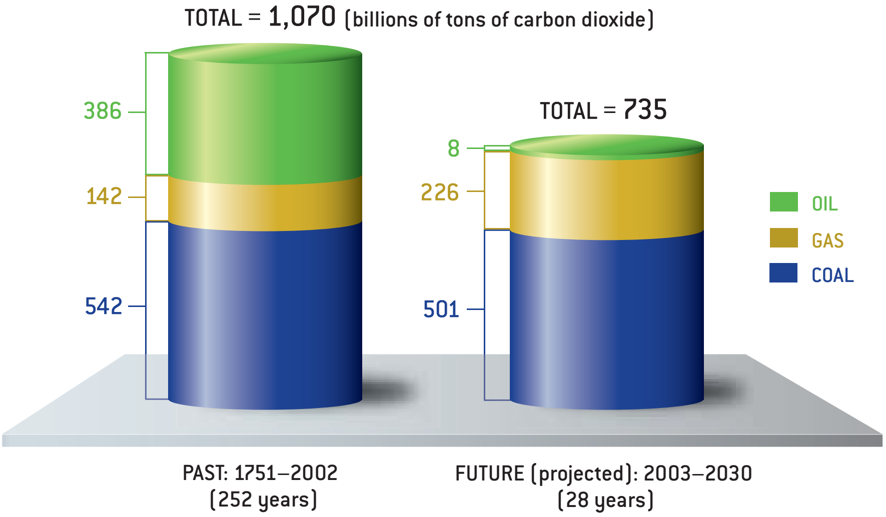
MACROSCOPIC VIEW

Injected supercritical carbon dioxide will spread through much of a porous sand formation whose pores were once completely filled with brine. Hard shale "baffles" in the sand can help disperse the buoyant CO_2.

MICROSCOPIC VIEW

Carbon dioxide not only occupies pores in the sand as a supercritical phase but also dissolves into the remaining brine.

ILLUSTRATION BY DAVID FIERSTEIN; CONCEPT BY JULIO FRIEDMANN *Lawrence Livermore National Laboratories*



LIFETIME FOSSIL-FUEL EMISSIONS from power plants projected to be built during the next quarter of a century will be comparable to all the emissions during the past 250 years. The left column shows the cumulative carbon dioxide emissions produced by burning coal, oil and natural gas for all uses (including transportation and building heating) from 1751 to 2002, whereas that on the right depicts the lifetime CO_2 emissions from fossil-fuel power generation plants projected by the International Energy Agency to come online between 2003 and 2030. Coal-fired power plants are assumed to operate for 60 years and gas-fired power stations for 40 years.

and water vapor, which are easy to separate. A second version would modify the coal gasification combined-cycle system by using oxygen, rather than air, at the gas turbine to burn the carbon monoxide and hydrogen mixture that has exited the gasifier. This arrangement skips the shift reaction and would again produce only CO_2 and water vapor. Structural materials do not yet exist, though, that can withstand the higher temperatures that are created by combustion in oxygen rather than in air. Engineers are exploring whether reducing the process temperature by recirculating the combustion exhaust will provide a way around these materials constraints.

Tough Decisions

MODIFICATION FOR carbon dioxide capture not only adds complexity and expense directly but also cuts the efficiency of extracting energy from the fuel. In other words, safely securing the carbon by-products means mining and burning more coal. These costs may be partially offset if the plant can filter out gaseous sulfur simultaneously and store it with the CO_2, thus avoiding some of the considerable expense of sulfur treatment.

Utility executives want to maximize profits over the entire life of the plant, probably 60 years or more, so they must estimate the expense of complying not only with today's environmental rules but also with future regulations. The managers know that the extra costs for CO_2 capture are likely to be substantially lower for coal gasification combined-cycle plants than for traditional plants. Removing carbon dioxide at high pressures, as occurs in a syngas operation, costs less because smaller equipment can be employed. But they also know that only a few demonstration gasification plants are running today, so that opting for gasification will require spending extra on backup equipment to ensure reliability. Hence, if the management bets on not having to pay for CO_2 emissions until late in the life of its new plant, it will probably choose a traditional coal plant, although perhaps one with the potential to be modified later for carbon capture. If, however, it believes that government directives to capture CO_2 are on their way within a decade or so, it may select a coal gasification plant.

To get a feel for the economic pressures the extra cost of carbon sequestration would place on the coal producer, the power plant operator and the home owner who consumes the electricity, it helps to choose a reasonable cost estimate and then gauge the effects. Experts calculate that the total additional expense of capturing and storing a ton of carbon dioxide at a coal gasification combined-cycle plant will be about $25. (In fact, it may be twice that much for a traditional steam plant using today's technology. In both cases, it will cost less when new technology is available.)

The coal producer, the power plant operator and the home owner will perceive that $25 cost increase quite differently. A coal producer would see a charge of about $60 per ton of coal for capturing and storing the coal's carbon, roughly tripling the cost of coal delivered to an electric utility customer. The owner of a new coal power plant would face a 50 percent rise in the cost of power the coal plant puts on the grid, about two cents per kilowatt-hour (kWh) on top of a base cost of around four cents per kWh. The home owner buying only coal-based electricity, who now pays an average of about 10 cents per kWh, would experience one-fifth higher electricity costs (provided that the extra two cents per kWh cost for capture and storage is passed on without increases in the charges for transmission and distribution).

First and Future Steps

RATHER THAN WAITING for the construction of new coal-fired power plants to begin carbon dioxide capture and storage, business leaders are starting the process at existing facilities that produce hydrogen for industry or purify natural gas (methane) for heating and power generation. These operations currently generate concentrated streams of CO_2. Industrial hydrogen production processes, located at oil refineries and ammonia plants, remove carbon dioxide from a

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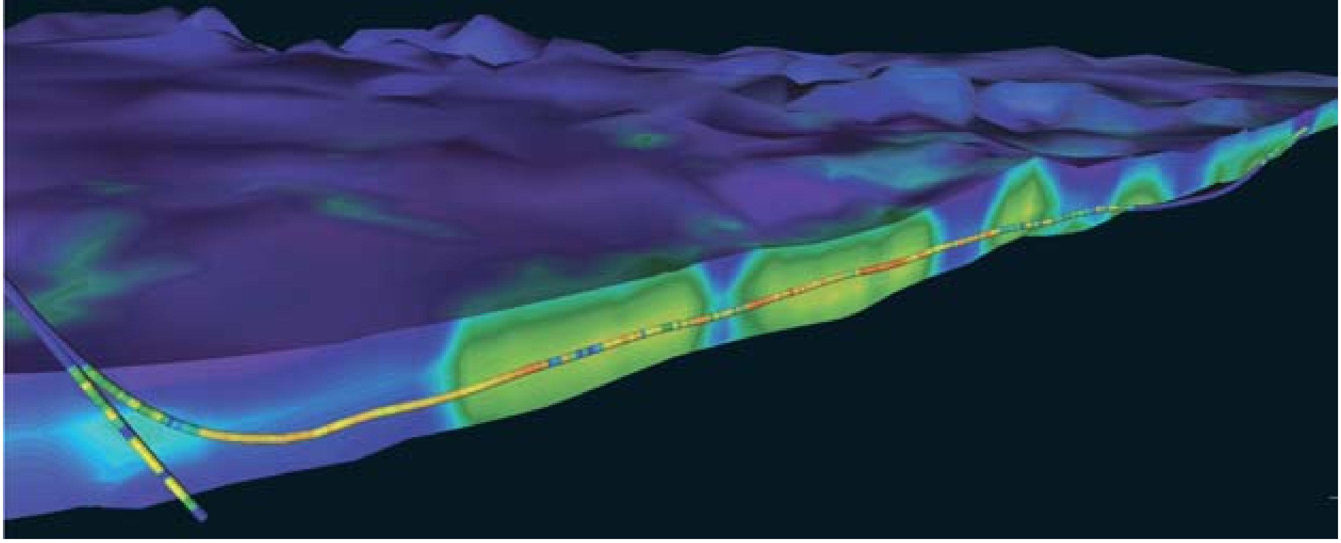
ILLUSTRATION BY ALISON KENDALL; CONCEPT BY DAVID HAWKINS *Natural Resources Defense Council*; PAST DATA FROM GREGG MARLAND *Oak Ridge National Laboratory*



POROSITY OF A GEOLOGIC FORMATION near a carbon dioxide injection well (*thin tubing*) at the Krechba field in the Algerian desert was revealed by two sets of measurements. (Red and yellow represent high porosity regions of the 20-meter-thick reservoir; blue indicates low porosity areas.) BP engineers used the coarse mapping of the geologic layers, which was derived from seismic echolocation soundings, to determine where best to place the well. A down-hole electric sensor probe, which gave a finer depiction of porosity (looking like colored beads), revealed porosity within a few centimeters of the well. Engineers employed these more accurate readings to hunt for and steer the drilling apparatus toward regions of high porosity.

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high-pressure mix of CO_2 and hydrogen, leaving behind carbon dioxide that is released skyward. Natural gas purification plants must remove CO_2 because the methane is heading for a liquefied natural gas tanker and must be kept free of cold, solid carbon dioxide (dry ice) that could clog the system or because the CO_2 concentration is too high (above 3 percent) to be allowed on the natural gas distribution grid.

Many carbon dioxide capture projects using these sources are now under consideration throughout the oil and gas industry. Hydrogen production and natural gas purification are the initial stepping-stones to full-scale carbon capture at power plants; worldwide about 5 percent as much carbon dioxide is produced in these two industries as in electric power generation.

In response to the growing demand for imported oil to fuel vehicles, some nations, such as China, are turning to coal to serve as a feedstock for synthetic fuels that substitute for gasoline and diesel fuel. From a climate change perspective, this is a step backward. Burning a coal-based synthetic fuel rather than gasoline to drive a set distance releases approximately double the carbon dioxide, when one takes into account both tailpipe and synfuels plant emissions. In synthetic fuels production from coal, only about half the carbon in the coal ends up in the fuel, and the other half is emitted at the plant. Engineers could modify the design of a coal synfuels plant to capture the plant's CO_2 emissions. At some point in the future, cars could run on electricity or carbon-free hydrogen extracted from coal at facilities where CO_2 is captured.

Electricity can also be made from biomass fuels, a term for commercial fuels derived from plant-based materials: agricultural crops and residues, timber and paper industry waste, and landfill gas. If the fossil fuels used in harvesting and processing are ignored, the exchanges between the atmosphere and the land balance because the quantity of carbon dioxide released by a traditional biomass power plant nearly equals that removed from the atmosphere by photosynthesis when the plants grew. But biomass power can do better: if carbon capture equipment were added to these facilities and the harvested biomass vegetation were replanted, the net result would be to scrub the air of CO_2. Unfortunately, the low efficiency of photosynthesis limits the opportunity for atmospheric scrubbing because of the need for large land areas to grow the trees or crops. Future technologies may change that, however. More efficient carbon dioxide removal by green plants and direct capture of CO_2 from the air (accomplished, for example, by flowing air over a chemical absorber) may become feasible at some point.

Carbon Dioxide Storage

CARBON CAPTURE is just half the job, of course. When an electric utility builds a 1,000-megawatt coal plant designed to trap CO_2, it needs to have somewhere to stash securely the six million tons of the gas the facility will generate every year for its entire life. Researchers believe that the best destinations in most cases will be underground formations of sedimentary rock loaded with pores now filled with brine (salty water). To be suitable, the sites typically would lie far below any source of drinking water, at least 800 meters under the surface. At 800 meters, the ambient pressure is 80 times that of the atmosphere, high enough that the pressurized injected CO_2 is in a "supercritical" phase—one that is nearly as dense as the brine it replaces in geologic formations. Sometimes crude oil or natural gas will also be found in the brine formations, having invaded the brine millions of years ago.

The quantities of carbon dioxide sent belowground can be expressed in "barrels," the standard 42-gallon unit of volume employed by the petroleum industry. Each year at a 1,000-megawatt coal plant modified for carbon capture, about 50 million barrels of supercritical carbon dioxide would be secured—about 100,000 barrels a day. After 60 years of operation, about three billion barrels (half a cubic kilometer) would be sequestered below the surface. An oil field with a capacity to produce three billion barrels is six times the size of the smallest of what the industry calls "giant" fields, of which some 500 exist. This means that each large modified coal plant would need to be associated with a "giant" CO_2 storage reservoir.

Alternative CO_2 Storage Schemes

Captured carbon dioxide might be stored not only in depleted oil and gas reservoirs and subterranean brine formations but also in minerals that form carbonate compounds, in coal seams and in the deep ocean.

Minerals that can become carbonates could potentially sequester even more carbon dioxide on the earth's surface than brine formations could store underground. The magnesium oxide in two abundant iron-magnesium minerals, serpentine and olivine, combines with CO_2 to produce highly stable magnesium carbonate. The big challenge is to get CO_2 to react quickly with bulk quantities of these rocks, perhaps by grinding them into fine powders to increase the surface area at which the chemical reactions occur.

The pore surfaces within coal formations adsorb methane. During mining, some of this methane can be released, too often causing underground explosions and, consequently, the deaths of miners. Pressurized carbon dioxide could be introduced into unexploited coal seams where it would replace the adsorbed methane, which could then be recovered and sold as fuel.

Ocean injection of carbon dioxide is controversial. Advocates of storage in the deep ocean point out that atmospheric CO_2 passes continuously into the ocean surface, as the air and ocean system seeks chemical equilibrium. Slowing the increase of CO_2 levels in the air will reduce the amount dissolving into the surface water. Thus, deep-ocean injection would shift some CO_2 from the surface waters to the lowest layers, reducing environmental impacts near the surface, where most marine life is found. Opponents of ocean storage cite international law that protects the oceans from certain kinds of industrial uses and the difficulties of monitoring carbon dioxide transport after injection. In many parts of the world, opponents tap into a strong cultural preference for leaving the oceans alone. *—R.H.S.*

About two thirds of the 1,000 billion barrels of oil the world has produced to date has come from these giant oil fields, so the industry already has a good deal of experience with the scale of the operations needed for carbon storage.

Many of the first sequestration sites will be those that are established because they can turn a profit. Among these are old oil fields into which carbon dioxide can be injected to boost the production of crude. This so-called enhanced oil recovery process takes advantage of the fact that pressurized CO_2 is chemically and physically suited to displacing hard-to-get oil left behind in the pores of the geologic strata after the first stages of production. In this process, compressors drive CO_2 into the oil remaining in the deposits, where chemical reactions result in modified crude oil that moves more easily through the porous rock toward production wells. In particular, CO_2 lowers crude oil's interfacial tension—a form of surface tension that determines the amount of friction between the oil and rock. Thus, carbon dioxide injects new life into old fields.

In response to British government encouragement of carbon dioxide capture and storage efforts, oil companies are proposing novel capture projects at natural gas power plants that are coupled with enhanced oil recovery ventures at fields underneath the North Sea. In the U.S., operators of these kinds of fields can make money today while paying about \$10 to \$20 per ton for carbon dioxide delivered to the well. If oil prices continue to rise, however, the value of injected CO_2 will probably go up because its use enables the production of a more valuable commodity. This market development could lead to a dramatic expansion of carbon dioxide capture projects.

Carbon sequestration in oil and gas fields will most likely proceed side by side with storage in ordinary brine formations, because the latter structures are far more common. Geologists expect to find enough natural storage capacity to accommodate much of the carbon dioxide that could be captured from fossil fuels burned in the 21st century.

Storage Risks

TWO CLASSES of risk must be addressed for every candidate storage reservoir: gradual and sudden leakage. Gradual release of carbon dioxide merely returns some of the greenhouse gas to the air. Rapid escape of large amounts, in contrast, could have worse consequences than not storing it at all. For a storage operation to earn a license, regulators will have to be satisfied that gradual leakage can occur only at a very slow rate and that sudden leakage is extremely unlikely.

Although carbon dioxide is usually harmless, a large, rapid release of the gas is worrisome because high concentrations can kill. Planners are well aware of the terrible natural disaster that occurred in 1986 at Lake Nyos in Cameroon: carbon dioxide of volcanic origin slowly seeped into the bottom of the lake, which sits in a crater. One night an abrupt overturning of the lake bed let loose between 100,000 and 300,000 tons of CO_2 in a few hours. The gas, which is heavier than air, flowed down through two valleys, asphyxiating 1,700 nearby villagers and thousands of cattle. Scientists are studying this tragedy to ensure that no similar man-made event will ever take place. Regulators of storage permits will want assurance that leaks cannot migrate to belowground confined spaces that are vulnerable to sudden release.

Gradual leaks may pose little danger to life, but they could still defeat the climate goals of sequestration. Therefore, researchers are examining the conditions likely to result in slow seepage. Carbon dioxide, which is buoyant in brine, will rise until it hits an impermeable geologic layer (caprock) and can ascend no farther.

Carbon dioxide in a porous formation is like hundreds of helium balloons, and the solid caprock above is like a circus tent. A balloon may escape if the tent has a tear in it or if its surface is tilted to allow a path for the balloon to move sideways and up. Geologists will have to search for faults in the caprock that could allow escape as well as determine the amount of injection pressure that

UNDERGROUND STORAGE of carbon dioxide is being performed today at the In Salah gas project in the Algerian desert. The raw natural gas produced at this site by BP, Statoil and Sonatrach contains too much CO_2 for commercial use, so the excess is removed by chemical absorbers (*two pairs of stripper towers at center of plant*), compressed and then injected under pressure into a brine formation two kilometers below the surface. Subterranean injection proceeds at a rate that is only about six times less than what would be required at a 1,000-megawatt coal gasification plant fitted for CO_2 capture and storage.

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could fracture it. They will also evaluate the very slow horizontal flow of the carbon dioxide outward from the injection locations. Often the sedimentary formations are huge, thin pancakes. If carbon dioxide is injected near the middle of a pancake with a slight tilt, it may not reach the edge for tens of thousands of years. By then, researchers believe, most of the gas will have dissolved in the brine or have been trapped in the pores.

Even if the geology is favorable, using storage formations where there are old wells may be problematic. More than a million wells have been drilled in Texas, for example, and many of them were filled with cement and abandoned. Engineers are worried that CO_2-laden brine, which is acidic, could find its way from an injection well to an abandoned well and thereupon corrode the cement plug and leak to the surface. To find out, some researchers are now exposing cement to brine in the laboratory and sampling old cements from wells. This kind of failure is less likely in carbonate formations than in sandstone ones; the former reduce the destructive potency of the brine.

The world's governments must soon decide how long storage should be maintained. Environmental ethics and traditional economics give different answers. Following a strict environmental ethic that seeks to minimize the impact of today's activities on future generations, authorities might, for instance, refuse to certify a storage project estimated to retain carbon dioxide for only 200 years. Guided instead by traditional economics, they might approve the same project on the grounds that two centuries from now a smarter world will have invented superior carbon disposal technology.

The next few years will be critical for the development of carbon dioxide capture-and-storage methods, as policies evolve that help to make CO_2-emission reduction profitable and as licensing of storage sites gets under way. In conjunction with significant investments in improved energy efficiency, renewable energy sources and, possibly, nuclear energy, commitments to capture and storage can reduce the risks of global warming.

MORE TO EXPLORE

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Intergovernmental Panel on Climate Change (IPCC): **www.ipcc.ch/index.html** (Look for the "Special Report on Carbon Dioxide Capture and Storage" expected in late 2005.)

International Energy Agency (IEA) Greenhouse Gas R&D Program: **www.ieagreen.org.uk/index.html**

Office of Fossil Energy, U.S. Department of Energy: **www.fe.doe.gov/programs/sequestration/**

CO_2 Capture Project: **www.co2captureproject.org**