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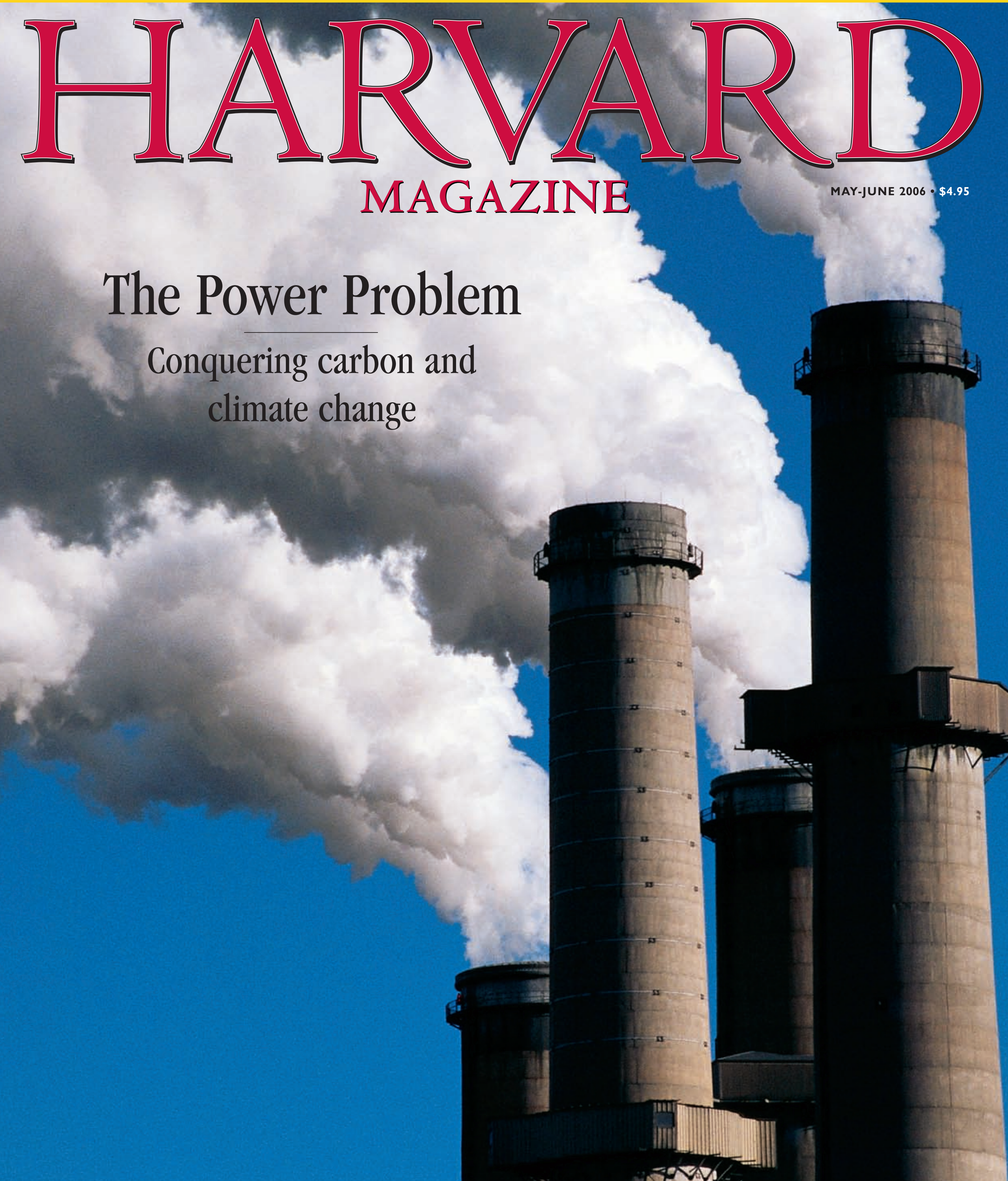

The Power Problem

Conquering carbon and climate change

Fueling Our Future

Climate warming is accelerating as energy use soars. Nuclear power won't close the gap. We need to learn to live with coal. Here's one elaborate engineering solution.

by JONATHAN SHAW

Our demand for energy, on which we depend for health and prosperity, rises all the time: oil and natural gas to heat our homes; electricity for lights, refrigeration, computers, and televisions; gasoline and diesel for our cars and trucks. Fossil fuels provide 80 percent of the energy that powers civilization. The more fuel we burn, the more heat-trapping greenhouse gases we produce, principally carbon dioxide (CO_2). We know the carbon is coming from fossil-fuel combustion because, as Iain Conn, executive director of British Petroleum, said in a recent visit to Harvard, isotopic fingerprinting of the carbon tells us so. The consequent global warming is already linked to a pattern of record floods, droughts, heat, and other extreme weather events around the globe, and is expected to lead to extinctions of some plants and animals. But such news from the natural world has done little to galvanize political will. Even forecasts of disastrous effects for the human sphere—severe drought in parts of Africa and Europe in the next century, and rising sea levels worldwide that will someday drown major cities—have thus far failed to mobilize public action in the United States. The time to act is running short.

"It's a grand problem," says professor of earth and planetary sciences Daniel Schrag. "One that most people haven't even thought about." Even within universities, he says, "research on energy has basically decayed away to almost nothing over the last 30 years. Around the country, there just isn't that much intellectual capital, and the reason for that is really quite simple: the cost of oil has been low for a very long time." Harvard, however, is lucky to still have a few scholars—"survivors," Schrag calls them—who got their start during the oil crisis of the 1970s. On Wednesday mornings, they gather for a weekly "energy breakfast" that Schrag, who is also director of the Harvard University Center for the Environment, hosts near his Hoffman Laboratory office. Heinz professor of environmental policy John Holdren of the Kennedy School of Government (KSG), an energy adviser in the Clinton White House, spends every Wednesday morning in the earth and planetary sciences department, where he is also a professor, and co-hosts the discussion with Schrag. Former U.S. senator Timothy Wirth and President Lawrence H. Summers have attended. Global economist Jeffrey Sachs was a regular when he taught at Harvard.

THE NUCLEAR OPTION

One morning last fall, the discussion turned to nuclear power. Because nuclear plants are carbon-free sources of electricity, some scientists concerned about climate change have embraced them as a way to help end the accumulation of atmospheric CO_2 (see "The Great Global Experiment," November-December 2002, page 34). The recent rise in the price of fossil fuels has made nuclear energy more competitive with plants fired by coal, oil, and natural gas. And federal energy legislation passed in mid 2005 provides new incentives for nuclear power: tax breaks, protections from legal challenges, a streamlined approval process for new, so-called "cookie-cutter reactors" (older plants were independently designed and engineered, expensively, from the ground up), and funds for research into advanced technologies.

But even Holdren, director of the program on science, technology, and public policy at the KSG and a proponent of nuclear power, acknowledges that there are obstacles to increasing its contribution to the global energy supply. Worldwide, 440 aging reactors now produce one-sixth of the world's electricity. Just to *main-*

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tain this level over the next century, those reactors will need to be replaced and several thousand more added. Doubling nuclear's share, to help address climate change, would require 5,000 new reactors. But large-scale deployment multiplies the classic problems of waste storage and nuclear proliferation—as well as the newer problem of terrorism (see "Is Nuclear Power Scalable?" page 44). And then there is the risk of accident. "Think about a world with 10,000 nuclear reactors," says Schrag, who envisions a quintupling of capacity to address climate change. "We have only a few hundred today. What is the probability of a big accident? It's going to happen." After Chernobyl, 4,000 children developed thyroid cancer, some 350,000 people were displaced, and a whole region was blighted. A 2005 UN report on the disaster pointed out that far fewer people have died as a result of radiation poisoning than had been expected (just 50 so far). But "the impact of Chernobyl is not measured in terms of deaths," Schrag says. "The world got scared of nuclear power."

Nor is there any evidence that climate change has made the public more receptive to nuclear energy. As Holdren and colleagues from MIT wrote in a 2003 report, *The Future of Nuclear Power*, "people [in the United States] do not connect concern about global warming with carbon-free nuclear power. There is no difference in support for building more nuclear power plants between those who are very concerned about global warming and those who are not."

Daniel Schrag

That may change as the public dialogue moves from questions about whether global warming is real, to its increasing impacts on our lives, to possible solutions. But even in that context, nuclear power is only a partial solution. A tenfold increase in nuclear capacity during the next 100 years—faster rates of construction may not be realistic—would supply only about one-third of world electricity consumption. That, says Schrag, represents "just one-tenth of the carbon problem," which is not only about electricity; it includes transportation, home heating, and industrial emissions, too.

Even so, says nuclear-security expert Graham Allison, Dillon professor of government and director of the KSG's Belfer Center for International Affairs, "If you are serious about anthropogenic contributions to global warming (and I would say that 99.9 percent of scientists and informed citizens who look at the problem are), and if you believe that power is the engine of economic growth (which it is, as a first approximation), then nuclear has to be part of the portfolio of [future] energy sources…if we are not to have a huge impact on the environment. Nuclear power

Photograph by Stu Rosner

> **Scientists know that when the ice in Greenland and West Antarctica melts or collapses completely, the rise in sea level will drown coastal civilizations around the world.**

should not be regarded as an alternative to cleaner energy fuels or biomass or windmills. We are going to need everything—and then over time we will see how the economics sort out."

CO_2 AND THE SEA

The imperative to embrace nuclear power—despite all its problems and limited usefulness—hints at the severity and irreversibility of some climate impacts. Though whole regional ecosystems are forecast to fail, unable to provide basic necessities such as water and food crops, Schrag has found that one dimension of climate change, in particular, gets people's attention: rising seas.

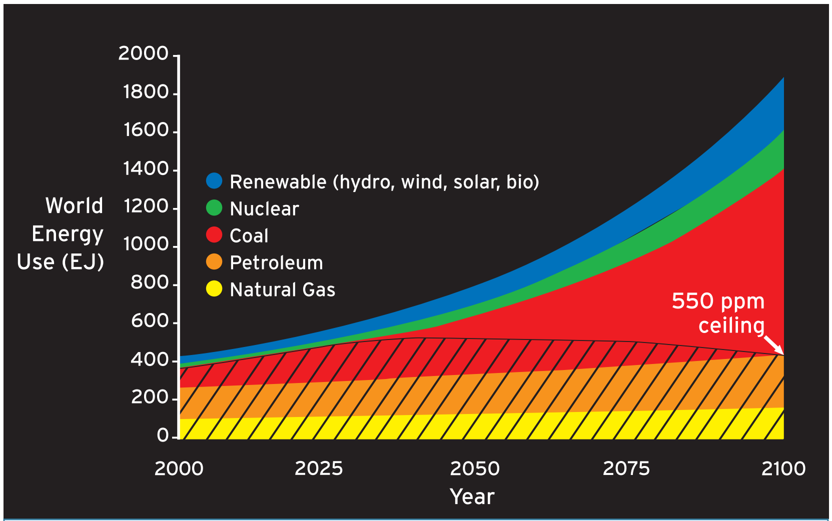
On the geologic time scale, sea levels rise and fall in inverse relation to land-based glaciation. The end of the last ice age, for example, 14,000 to 12,000 years ago, was punctuated by a meters-per-decade rise in sea level (totaling nearly 53 feet). Ever since then, the earth's climate has been good to us. An unprecedented period of climate stability began 11,600 years ago, about the time when archaeologists date the dawn of human civilization. Had the climate continued to cycle between periods of warm and cold as it had during the previous 400,000 years, when atmospheric concentrations of carbon dioxide fluctuated between 180 and 280 parts per million (ppm)—closely tracking the changes in temperature—we would be in the midst of a 20,000-year-long cooling trend.

Instead, atmospheric concentrations of CO_2 remained near 280 ppm (the established upper range) through the early 17th century, and then began to rise steadily with the advent of the Industrial Revolution. When one American scientist began measuring the gas in 1958, the concentration was still just 315 ppm, only about 12 percent higher than the historic norm. But by 2005, it had reached 380 ppm, a level not seen in at least 650,000 years (the farthest back that ice cores with embedded bubbles can currently be extracted). Last year was reportedly the warmest in at least several thousand years (statistically tied with 1998), and the previous 10 included the nine warmest years since record-taking began in the late nineteenth century.

Images commissioned by Schrag show what would happen to South Florida (top) and Manhattan (below) if sea levels rose 3.5 meters—equivalent to the volume of water produced if half the Greenland ice sheet melted. Nobody knows how long that will take, he says, but "100 years is possible."

"The effect of CO_2 on temperature is not theoretical," says Schrag. "Just look at Venus." Venus is closer to the sun, but its surface is so reflective that if it shared our atmosphere, it would be much colder than Earth. In fact, temperatures on the Venusian surface reach 900 degrees Fahrenheit. The planet's CO_2-rich atmosphere traps heat, causing a runaway greenhouse effect.

Schrag has done a lot of thinking about the effects of CO_2 on planets, including Earth. More than a decade ago, working with Hooper professor of geology Paul Hoffman, he developed evidence to support a theory that the earth has been completely encased in ice several times in its history. Though the geological evidence for glaciers at the equator is widespread and convincing, an explanation for how Earth could have emerged from total glaciation was missing at first. After all, a frozen planet is a white globe that would reflect most of the sun's heat-energy back into space, locking its own surface perpetually in ice. The frigid embrace might have lasted forever—except for CO_2. Volcanic eruptions release the gas in abundance. Today, photosynthesis and rain and ocean waters absorb much of that CO_2 and some of it even becomes trapped in sediments at the bottom of the sea. But when the oceans were frozen and plant life was suspended, CO_2 could not be absorbed. Slowly, over millions of years, CO_2 from volcanic eruptions built up in the atmosphere, raising temperatures until the ice began to melt.



One scenario of world energy use over this century (expressed in exajoules) that Schrag uses to explain the carbon problem assumes annual growth in demand of 1.5 percent. Dwindling reserves of petroleum and natural gas suggest that their contribution to global energy supply by century's end will show modest growth at best. If we used energy only at the level provided by those two sources in 2100, atmospheric concentrations of carbon dioxide could be held below 550 parts per million. Any new demand would then have to be met partly by carbon-free energy sources (such as nuclear and renewables), but mostly by coal, which releases more CO_2 per unit of energy than any other source. If this scenario played out, CO_2 would reach 900 ppm by the end of the century. Through 2100, summarizes Schrag, "The climate problem is a coal problem."

That same process, now caused primarily by emissions from fossil fuels, has set in motion an increase in temperature with effects that won't be fully felt for thousands of years. That is because the ocean acts as an enormous brake on climate change, absorbing half the man-made CO_2 and much of the heat. The top 10 to 15 feet of water alone, a small fraction of the total volume, store as much energy as the entire atmosphere. (Hurricanes, whose increased frequency and intensity have been linked to higher sea-surface temperatures, feed off this energy.) Even if we could stabilize atmospheric concentrations of greenhouse gases at current levels, the earth would continue to warm.

The losses caused by Katrina, the costliest hurricane in U.S. history, pale by comparison to what might come. If just one-fourth of the land-based ice in Greenland and the western part of Antarctica were to melt, sea level would rise three and a half meters and all of South Florida, as far north as Lake Okeechobee, would be under water. "South Florida alone must be worth a few trillion dollars at least," notes Schrag, whose opinion about spending billions to rebuild New Orleans in the same spot using dikes and levees ("a very dangerous strategy") appeared recently in the *New York Times*. "I can't tell you if it is going to happen in 500 years or 100 years. But a hundred years is possible," he says. "Our understanding of glaciers is so bad, we don't know how fast they are going to melt." We do know that before 2050, atmospheric CO_2 will cross the 500 ppm threshold, a level last seen during the Eocene, 55 million to 36 million years ago. There were palm trees in Wyoming and crocodiles in the Arctic then. Antarctica was a coniferous forest. Because there were no continental ice sheets, sea level was 100 meters (328 feet) higher than it is today.

Already, glaciers in Greenland and West Antarctica have begun to melt. Two separate studies published in *Science* early in 2006 showed that these ancient ice sheets were shrinking faster than expected, implying that estimates of global sea-level rise in this century are too low. Scientists know that when the ice in Greenland and West Antarctica melts or collapses completely, the rise in sea level will drown coastal civilizations all around the world. Each one has the potential to raise global sea level by about six or seven meters, or if combined, approximately 42 feet. That is nothing compared to what would happen if vast East Antarctica, which is poorly understood, also lost mass. The submarine portion of that ice sheet, which is vulnerable to melting from below due to warm ocean water, is itself as large as the West Antartic. The *entire* East Antarctic ice sheet represents more than 200 feet of potential sea level change. Just slowing the rate at which continental ice sheets melt is clearly in humanity's best interests.

The latest revelations from Greenland and the West Antarctic surprised scientists because atmospheric CO_2 today is only about a third higher than its historic upper range of 280 ppm during the last 400,000 years. By 2050, CO_2 concentrations—which are increasing 200 times faster than they ever have naturally—will be double the historic level. If a small increase in CO_2 can trigger the new ice-mass losses that scientists have recently observed, finding a solution to the carbon problem is urgent.

SEEKING A SOLUTION

Schrag has found that a quantitative approach to the problem guides the way to a solution, because such a tactic strips away the illusion that nuclear power, or any other alternative energy source alone, can solve the problem. First, a difficult but achievable target level of atmospheric CO_2 is chosen: he uses 550 ppm—45 percent above the current level. Stabi-

Sea-level-rise simulations by Jared T. Williams.

During the next 100 years, "The climate problem is a coal problem."

lizing CO_2 at lower levels is probably not realistic. But even to hold the atmospheric concentration to 550 ppm, he says, "emissions over the century have to be 70 percent less than what we predict business as usual is going to be. The scale of what we are talking about is huge." Undergraduates in his environmental science and public policy seminar, "Technological Approaches to Mitigation of Climate Change" (ESPP 90m), co-taught with Agassiz professor of biological oceanography James J. McCarthy, each choose an energy source in which they will become expert during the semester: nuclear power, coal, oil, natural gas, or a renewable such as wind, hydropower, solar energy, or biomass. Eventually, each student must devise a plan, using *all* these energy sources, to stabilize atmospheric concentrations of CO_2 below 550 ppm by the year 2100 (an allowance is made for improved energy efficiency).

Then the class and the professors critique the student models. Because each participant is by now well versed in one form of energy, they can point out flaws in each other's work. On this first attempt, none of the students is able to reach the CO_2 target without making at least one highly optimistic assumption—a sobering outcome. "It is a difficult problem," Schrag reassures them. "Staying under 550 ppm is not easy."

With his graduate students, who gather once a week in an "energy-journal club" to critique the scientific literature on energy and climate change, Schrag is less gentle. At a meeting last fall, the group discussed a paper on climate change by Stephen Pacala and Robert Socolow '59, Ph.D. '64, both professors at Princeton. The authors attack the climate-change problem with "stabilization wedges": actions or existing technologies that can make a small contribution to reducing CO_2 output—equal to one billion tons of carbon per year by 2050. The 15 wedges Pacala and Socolow consider are not all equally plausible, but only seven good ones are needed to put us on a path to stabilizing atmospheric CO_2 at a reasonable level by 2050, according to the article.

The graduate students adopt a "take no prisoners" approach. Each casts a vote for or against the viability of each wedge. Reduced use of vehicles, improved soil management, increased forestation, solar power: few of the wedges pass muster. Energy efficiency meets their approval, but only as a short-term fix that will buy the world time to make the switch to carbon-free

Is Nuclear Power Scalable?

HEINZ PROFESSOR OF ENVIRONMENTAL POLICY John Holdren, who holds a joint appointment in the Faculty of Arts and Science's department of earth and planetary sciences, counts himself among the environmentalists who believe a contribution from the expansion of nuclear power—if its drawbacks can be overcome—would help meet the need for carbon-free electricity in a climate-constrained world. "Nuclear power provides about one-sixth of the world's electricity today," generated by 440 reactors, he notes. In the near future, as older power stations are taken off-line, nuclear's share of global electricity production will fall precipitously unless new plants are built.

In response to this forecast, Holdren and a group of colleagues from MIT asked the question, "If we are going to need nuclear power, what is the safest, most cost-effective way to retain the option to use this resource?" Their answer, outlined in a 2003 report called *The Future of Nuclear Power,* identifies four key challenges to the industry: high cost, waste disposal, safety (which in a post-9/11 world includes the possibility of terrorism), and weapons proliferation.

Nuclear power has always been expensive because of the capital costs associated with starting up a plant. "Coal eats nuclear's lunch over 20 to 30 years unless the carbon output of fossil-fuel-burning power plants is taxed at something like $100 per ton," Holdren says. Today, electricity generated by a nuclear power plant costs about 6.4 cents per kilowatt hour (kwh), as compared to 4.5 to 5 cents per kwh for coal and 3.5 to 4 cents per kwh for natural gas, Holdren explains. Carbon taxes would induce the market to control carbon-dioxide emissions, and many energy producers are already preparing for the day when those taxes arrive. But even if costs were equivalent, a renaissance in nuclear power would face obstacles. In 1983, Graham Allison, then dean of the Kennedy School of Government, and Albert Carnesale, then professor of public policy there, wrote an essay describing the dilemma faced by a utility director weighing whether to build a coal or a nuclear power plant. In their hypothetical scenario, even when nuclear power is cheaper, the director chooses a coal plant because of the political uncertainties surrounding the nuclear alternative. But today, Allison believes that the balance has changed. "The combination of liability relief, fast-tracking of the regulatory approval process, and the introduction of standardized reactor designs in the energy legislation passed last summer make it likely that we are going to have some new nuclear power plants," he says.

Holdren notes that cost-competitiveness is not the whole story, however. "What we do with nuclear radioactive waste is not a solved problem," he says. There are engineering questions about the massive storage repository proposed for the Nevada desert. Certainty about its ability to keep groundwater supplies safe falls off after 10,000 years—while the facility needs to function as planned for several hundred thousands of years. And the space is already too small to accommodate even the lifetime output of this country's *existing* 104 nuclear power plants.

Holdren believes the toughest problem facing nuclear power today is not waste storage, but breaking the energy/terrorism link. Though modern reactors are operationally 10 to 100 times safer than the designs at Three Mile Island or Chernobyl, he says, nuclear power plants were not built with terrorists in mind. Allison, perhaps the world's leading expert on nuclear security, agrees: "The idea that suicidal terrorists would come in groups of 20 was not the basis on which nuclear power plants and their security systems were designed," he points out. "Nevpower. Land-based wind turbines are an economically competitive power source right now. But as Schrag asks of each wedge, "Is it scalable?" Scalability is the ultimate test, because energy demand keeps growing and power sources must be able to keep pace. "End-use" efficiency—making our cars, appliances, and homes more energy efficient—is not scalable, he notes, "because you can't reduce demand to zero; you are always going to need some energy." Neither is wind power. Even if all the viable sites in the world were covered with wind turbines, the energy problem couldn't be solved. In the end, six or perhaps seven wedges are left standing, but they are fraught with real-world obstacles. Nuclear power, even though it may not be scalable for practical and political reasons, is one of them.

Later, in his office, Schrag reveals the nub of the problem, pointing to a graph that plots global energy demand in the next hundred years (see page 43). Beneath the curve, the graph is shaded to show the relative contributions to supply of each and every possible energy source as it grows during the century or, as in the case of oil and natural gas, peaks and then tails off slightly. Presented in such a graph—the one he uses happens to assume a mid-range 1.5 percent annual growth in global energy demand—what immediately jumps out is the enormous contribution of coal by 2100. By then, nearly half the world's energy supply is projected to come from coal alone. As Schrag puts it, during the next 100 years, "The climate problem is a coal problem."

COAL COMFORT

Constraints on supply, he says, will dictate this outcome. Known global reserves of oil (based on current, not future, consumption) will last 41 years; natural gas, 67 years; and coal 164 years. Some people believe that a peak for oil production will come much sooner. Natural gas, once thought to be abundant and cheap, has become harder to find. But coal remains abundant. The United States has some of the largest coal reserves in the world, notes Schrag, adding, "If we are serious about developing domestic energy sources, and weaning ourselves of foreign sources of oil and gas, coal will have to play a large role."

Meanwhile, energy demand will increase precipitously worldwide, partly due to a global population growth of 50 percent by century's end, but largely because per capita energy use in populous countries such as China and India—which also have tremendous coal reserves—will rise toward the levels seen in developed nations. "Economic growth"—on the order of 500 percent—"dominates the equation," says Schrag.

ertheless, the chances of an aircraft penetrating the dome of a reactor and causing a meltdown are pretty slim because it has got to hit in just the right spot." But Al Qaeda looked into targeting nuclear plants with airplanes, he says, and has never taken them off their lists.

An act of terrorism at a nuclear power plant would be analogous to a big dirty bomb, says Allison. "A dirty bomb is a blast in which some radioactive material gets pulverized and then spewed into the atmosphere. Mostly what this does is cause panic." Some people will get a dose of radiation at a level that would increase the risk of cancer in 25 years, and a few might suffer radiation poisoning, which at high doses can be fatal. Dirty bombs make big messes, and may require massive relocations, as at Chernobyl, but they pale by comparison to the primary threat that Allison has written about in *Nuclear Terrorism: The Ultimate Preventable Catastrophe*—the possibility that terrorists might get hold of and detonate a nuclear bomb in a major city. "What does a nuclear power plant like Seabrook [in New Hampshire] have to do with that?" asks Allison. "Essentially zero. Not zero, but essentially zero."

Not all nuclear power plants are light-water reactors like Seabrook, however, and Holdren and others have warned that their nuclear fuels and wastes do present a security risk, especially as they are handled in some foreign countries. Unfortunately, any country that can enrich natural uranium to 2 to 3 percent (the concentration needed to fuel a power plant) can easily use those same machines to enrich the U-235 to 80 or 90 percent, the concentration needed for a nuclear bomb.

A similar vulnerability surrounds the spent fuel that comes out of a reactor. Plutonium in the spent fuel is easily separated from other waste through chemical processing and, like the uranium, can be used to make a nuclear bomb. France and Japan, on the other hand, routinely extract and reprocess plutonium for reuse as reactor fuel, but the dual-use potential of this process has led Holdren and his coauthors to recommend a "once-through fuel cycle" in which the spent fuel is not reprocessed, but instead goes directly into a storage repository.

Keeping bomb-making material out of the hands of all but the existing nuclear states has been a guiding principle in diplomatic efforts to restrain North Korea's and Iran's nuclear programs, for example, without denying those countries the right to operate nuclear power plants peacefully. "If the world is going to have a lot more nuclear power plants," says Allison, "you are going to have to have some arrangement for supplying fuel credibly and for taking it away that doesn't require everybody getting into the business [of making it] themselves." He points out that Mohamed ElBaradei, director general of the International Atomic Energy Agency (IAEA) "is trying to create a neutral fuel bank…that would guarantee countries like Iran their fuel." This proposed international arrangement is called the assured nuclear fuel cycle. Allison notes that the United States and Russia "have agreed to donate several tons of uranium as the first installment of this fuel bank."

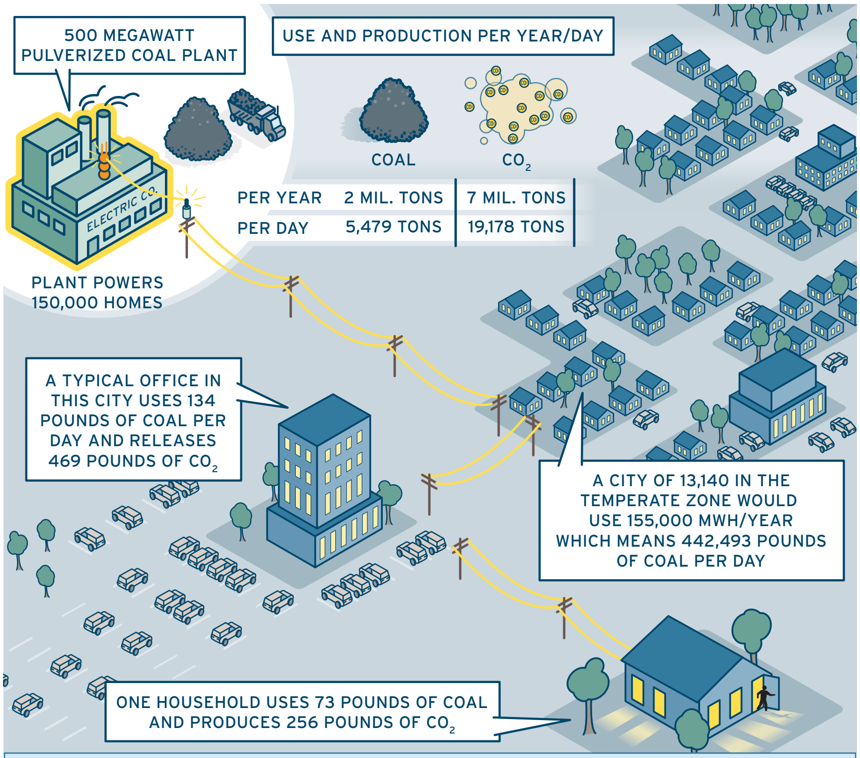
Could terrorists actually acquire enough material to build a bomb? ElBaradei, who with the IAEA was awarded the 2005 Nobel Peace Prize, was asked this question on a recent visit to Harvard. "In the last 10 years," he replied, "I've seen 200 cases of nuclear material being smuggled across borders. So far, not enough to build a nuclear bomb." Yet it could happen, he said. "This is a world in denial."

From the wider environmental perspective, meanwhile, even a tenfold expansion in nuclear capacity by 2100 would by itself barely reduce the atmospheric burden of CO_2—from a projected 900 ppm (parts per million) to 820 ppm, both catastrophically higher than today's concentration of 380 ppm, according to Daniel Schrag. But the options for addressing climate change—nuclear power, renewable energy sources, carbon sequestration, and increased energy efficiency—are few. As Holdren and his coauthors wrote, "In our judgment, it would be a mistake to exclude any of these four options at this time."

There is enough deep-water capacity within 200 miles of the U.S. coastline to hold thousands of years of current U.S. carbon emissions.

To power that growth, we will have to burn the coal. Nuclear, hydropower, geothermal, wind, solar, and biomass energy sources will be important, but won't be able to close the gap. In order to meet demand while keeping atmospheric CO_2 in check, we must burn the coal with advanced technologies that allow its carbon content to be captured.

Coal is the dirtiest fossil fuel. Beyond its effects on human health, burning coal produces *twice* as much CO_2 as natural gas. Researchers have come up with a two-part engineering solution to this problem. First, gasify the coal by heating it to temperatures so high that it breaks down into a variety of petroleum products. This gasification process can be engineered to separate out the CO_2. Second, sequester the CO_2 by directing it into underground reservoirs where engineers anticipate that it will remain buried forever.



A 500-megawatt, coal-fired power plant burns two million tons of coal per year and releases seven million tons of carbon dioxide to the atmosphere. Such a plant could provide electricity for 11 small cities like Escanaba (population 13,140), in Michigan's Upper Peninsula. This typical city in the temperate zone uses nearly 450,000 pounds of coal daily to meet its electrical needs, releasing more than 1.5 million pounds of CO_2. Electricity use in a single average household in Escanaba releases 256 pounds of CO_2 to the atmosphere every day; a typical small business there releases 469 pounds.

Many pulverized-coal plants are fitted with pollution controls that filter sulfur or bag particles and other pollutants. Such plants could be retrofitted with an additional layer of controls to remove the CO_2 from the exhaust. But because these plants burn the coal in regular air (which is mostly nitrogen), separating the CO_2 from the other exhaust (again, mostly nitrogen) is difficult. Alternatively, traditional coal plants could burn the coal in pure oxygen, so that the exhaust stream would be mostly CO_2 that could be captured along with all the other regulated pollutants and buried underground. Both these approaches appear economically challenging, however, because they would require the plant to expend at least 30 percent of its energy just to filter the CO_2 or generate the pure oxygen.

"Even with the cost," says Schrag, "burning the coal with advanced technology that captures the CO_2 and then sequesters it may actually be the way to go, at least as a bridge to renewable energy sources in the future." Long term, that means replacing the existing capital stock of coal plants with coal-gasification (clean coal) plants. Short-term, it means *not* building more dirty coal plants, in this country or anywhere else. But none of the countries with massive coal reserves—China, India, and the United States—has a carbon policy. The stakes are high, because rapidly developing countries are building new power plants all the time. China plans to build 168 traditional coal plants in the next two years alone. The economic lifetime of those plants might be 50 years or more. Acting soon to ensure that the right kind of coal plants are built now is therefore critical.

Coal-gasification plants are more efficient than traditional plants and can be engineered to produce a variety of liquid and gaseous fuels, including methanol, diesel, hydrogen, and natural gas (methane). Making diesel fuel for use in transportation (as South Africa has done), generates lots of CO_2, which makes capturing it especially critical; even so, some CO_2 is still released when the diesel is burned. Making electricity, using a gasification process called integrated gasification combined cycle, allows almost all the CO_2 to be captured. The IGCC plants gasify coal in the presence of extreme heat to create a synthesis gas (syngas) that is mostly hydrogen and carbon monoxide. The syngas is burned in a turbine to generate electricity and the hot exhaust is then used to create steam, which turns a second turbine. The process generates electricity about 15 percent more efficiently than a traditional pulverized-coal plant. By conventional pollution standards, such plants are as clean as natural-gas plants and compete directly with them. One such plant, located in Polk County, Florida, is reportedly the cheapest and most reliable power source on its regional grid, but the CO_2, which is unregulated at the moment, goes up the stack and into the atmosphere.

Burying the CO_2 instead, the second part of the solution, has already been tested. A government-financed coal-gasification plant in Beulah, North Dakota, designed in the 1970s to produce synthetic gas, failed when the price of natural gas dropped in the 1980s. Subsequently sold to a private company, it now operates profitably, selling almost all its byproducts—including its CO_2, which is piped to an oil company across the Canadian border, where it is pumped underground in order to enhance oil recovery.

Infographics by Funnelinc.com

Oil companies have for decades been pumping CO_2 from natural underground reservoirs into old oil wells in order to squeeze out more petroleum from fields with declining production. British Petroleum currently plans oil-field sequestration of CO_2 that it will capture from a new IGCC plant in Carson City, California. And the federal government is planning a new experimental coal-gasification plant called FutureGen that will both generate electricity and sequester CO_2 in an underground geological basin formation (a site has not been chosen). Schrag agrees that these are fine places to start proving the concept of carbon sequestration with the first tens of millions of tons of CO_2, but sees problems of scale ahead. "In the long run, the amount of space in oil wells is tiny compared to the amount of carbon we need to put underground," he says. "By the middle of the century, we are talking about several billion tons of carbon per year, and by century's end, more than 10 billion tons."

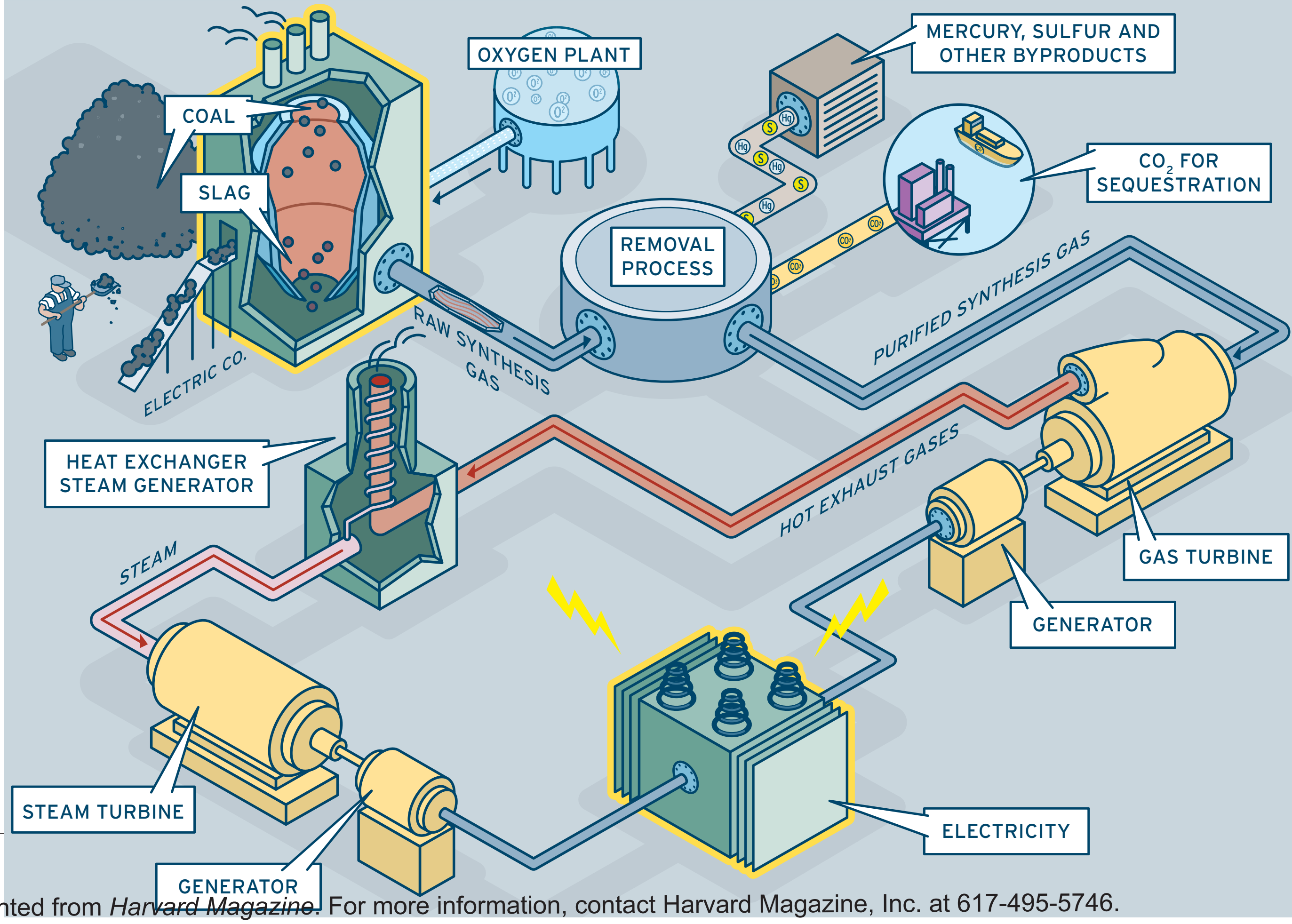
Another problem with land-based geological sequestration is also one of scale: multiple small and scattered storage sites could develop leaks and so would need to be monitored. "A lot of people think that the leaks will be small," says Schrag, "but there is a persistent worry that, because CO_2 is buoyant, it will want to come back"—and someday, perhaps hundreds of years from now, escape into the atmosphere.

Schrag and graduate student Kurt House have instead proposed a permanent, large-scale solution, one especially suited to coastal areas like the eastern United States, where there are few suitable land-based geological basins. "Under high pressure and low temperature," he says, "CO_2 is denser than seawater." It sinks. Their innovative idea is to inject the CO_2 into deep-water sediments that have accumulated on the ocean floor. In these sediments—think of tiny shells and clay that have sunk to the bottom—water makes up more than half the total volume. "At the top, they are almost all water," says Schrag, "and as you go down, the sediment gets more dense." The compressed CO_2 would be shipped to offshore platforms, similar to those used to drill for oil, and then pumped to the bottom of the sea. A drilling rig could easily penetrate the loose collection of detritus that has accumulated over eons on the ocean floor, allowing the CO_2 to be injected into the sediment. At depths greater than 3,000 meters, the temperature is so low, and the pressure so great, that the CO_2 would form an ice-like cap over a spreading liquid plume and eventually dissolve, diffusing slowly into the oceans over millions of years at a rate that would not affect marine ecology. Schrag's lab continues to refine the idea, but says the CO_2 will not require long-term monitoring the way most other sequestration schemes certainly will. There is enough deep water capacity within the 200-mile economic zone of the U.S. coastline, they estimate, to hold thousands of years of current U.S. carbon emissions.

A SOLUBLE PROBLEM

THE FACT THAT there may be a solution to the carbon problem—Schrag estimates the cost to be about 1 percent of GDP, or an

In an integrated gasification combined cycle (IGCC) plant, the coal reacts with oxygen and steam to produce a synthesis gas that is primarily hydrogen and carbon monoxide. Carbon dioxide and other pollutants can be efficiently separated from the raw synthesis gas, which is then burned in a high-temperature gas turbine that drives an electric generator. The exhaust from the gas turbine is then piped through a heat exchanger that boils water into steam, which is used to drive a second turbine. Though 20 percent more costly to build, IGCC plants can achieve efficiencies far exceeding those of traditional coal plants. More important, they allow the carbon-dioxide waste stream to be captured.



"Five hundred and fifty parts per million of atmospheric CO_2 may be the best we can do, but it is still a disaster."

amount equal to annual government spending on the Iraq war—nevertheless comes hand in hand with a disquieting realization. Imagine if people everywhere start to grasp the magnitude of the problem and demand that governments respond, so that we actually succeed in stabilizing atmospheric CO_2 at 550 ppm. How can that represent success? At the current level, just 380 ppm, glaciers and sea ice are already slowly melting, changing the earth's reflectivity and causing it to absorb more heat. The earth will continue to grow warmer, and sea levels will continue to rise, even if atmospheric concentrations of CO_2 stabilized at the current level.

Schrag has thought of all this. He has even created an interactive video that allows visitors to an exhibit in the Harvard Museum of Natural History to vote whether they would be willing to spend hundreds of dollars per family each year to control domestic carbon emissions. The video then asks if they would be willing to spend even more to control emissions abroad, subsidizing the technology to enable clean-energy growth in rapidly developing countries such as China or India. (Readers can see the video and vote themselves on-line at www.harvardmagazine.com/globalwarming.)

Even if the answer to both questions is yes, the earth is clearly in trouble. The last time it experienced what Schrag considers a safe level of atmospheric CO_2—which he defines as 300 ppm—was around 1900. "Five hundred and fifty may be the best we can do," he says, "but it is still a disaster." Yet he remains optimistic. Given time, he says, the ocean has a tremendous capacity to absorb CO2 directly from the atmosphere. If we can reduce our emissions substantially before most of the continental ice sheets melt, we might be able to prevent or at least postpone the most extreme climate impacts. Inertia will be our worst enemy: the inertia that has built up in the climate system, on the one hand, and political inertia on the other. The only thing missing from a solution to the carbon problem, Schrag says, is the will to act.

Jonathan Shaw '89 is managing editor of this magazine.

Two versions of carbon sequestration. Carbon dioxide from a power plant or refinery could be piped underground and sequestered beneath a dome of rock in a geological basin formation. But because the CO_2 is buoyant and billions of tons will have to be stored, some scientists worry that the gas will leak back into the atmosphere. A potentially permanent solution, well-suited to coastal areas, would involve transporting the CO_2 to tanker ships that would carry it to offshore platforms, where it would be injected into deep-ocean sediments. Under high pressure and low temperature, the CO_2 becomes a liquid that is heavier than water, and slowly dissolves. Tests indicate the CO_2 will remain there permanently.