THE NEW YORKER

ANNALS OF SCIENCE

THE CLIMATE FIXERS

Is there a technological solution to global warming?

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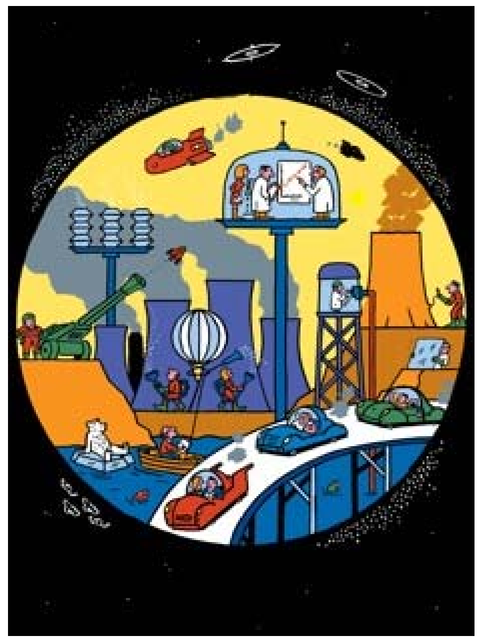
MAY 14, 2012



Geoengineering holds out the promise of artificially reversing recent climate trends, but it entails enormous risks.

Late in the afternoon on April 2, 1991, Mt. Pinatubo, a volcano on the Philippine island of Luzon, began to rumble with a series of the powerful steam explosions that typically precede an eruption. Pinatubo had been dormant for more than four centuries, and in the volcanological world the mountain had become little more than a footnote. The tremors continued in a steady crescendo for the next two months, until June 15th, when the mountain exploded with enough force to expel molten lava at the speed of six hundred miles an hour. The lava flooded a two-hundred-and-fifty-square-mile area, requiring the evacuation of two hundred thousand people.

Within hours, the plume of gas and ash had penetrated the stratosphere, eventually reaching an altitude of twenty-one miles. Three weeks later, an aerosol cloud had encircled the earth, and it remained for nearly two years. Twenty million metric tons of sulfur dioxide mixed with droplets of water, creating a kind of gaseous mirror, which reflected solar rays back into the sky. Throughout 1992 and 1993, the amount of sunlight that reached the surface of the earth was reduced by more than ten per cent.

The heavy industrial activity of the previous hundred years had caused the earth's climate to warm by roughly three-quarters of a degree Celsius, helping to make the twentieth century the hottest in at least a thousand years. The eruption of Mt. Pinatubo, however, reduced global temperatures by nearly that much in a single year. It also disrupted patterns of precipitation throughout the planet. It is believed to have influenced events as varied as floods along the

Mississippi River in 1993 and, later that year, the drought that devastated the African Sahel. Most people considered the eruption a calamity.

For geophysical scientists, though, Mt. Pinatubo provided the best model in at least a century to help us understand what might happen if humans attempted to ameliorate global warming by deliberately altering the climate of the earth.

For years, even to entertain the possibility of human intervention on such a scale—geoengineering, as the practice is known—has been denounced as hubris. Predicting long-term climatic behavior by using computer models has proved difficult, and the notion of fiddling with the planet's climate based on the results generated by those models worries even scientists who are fully engaged in the research. "There will be no easy victories, but at some point we are going to have to take the facts seriously,'' David Keith, a professor of engineering and public policy at Harvard and one of geoengineering's most thoughtful supporters, told me. "Nonetheless,'' he added, "it is hyperbolic to say this, but no less true: when you start to reflect light away from the planet, you can easily imagine a chain of events that would extinguish life on earth."

There is only one reason to consider deploying a scheme with even a tiny chance of causing such a catastrophe: if the risks of not deploying it were clearly higher. No one is yet prepared to make such a calculation, but researchers are moving in that direction. To offer guidance, the Intergovernmental Panel on Climate Change (I.P.C.C.) has developed a series of scenarios on global warming. The cheeriest assessment predicts that by the end of the century the earth's average temperature will rise between 1.1 and 2.9 degrees Celsius. A more pessimistic projection envisages a rise of between 2.4 and 6.4 degrees—far higher than at any time in recorded history. (There are nearly two degrees Fahrenheit in one degree Celsius. A rise of 2.4 to 6.4 degrees Celsius would equal 4.3 to 11.5 degrees Fahrenheit.) Until recently, climate scientists believed that a six-degree rise, the effects of which would be an undeniable disaster, was unlikely. But new data have changed the minds of many. Late last year, Fatih Birol, the chief economist for the International Energy Agency, said that current levels of consumption "put the world perfectly on track for a six-degree Celsius rise in temperature. . . . Everybody, even schoolchildren, knows this will have catastrophic implications for all of us."

Tens of thousands of wildfires have already been attributed to warming, as have melting glaciers and rising seas. (The warming of the oceans is particularly worrisome; as Arctic ice melts, water that was below the surface becomes exposed to the sun and absorbs more solar energy, which leads to warmer oceans—a loop that could rapidly spin out of control.) Even a two-degree climb in average global temperatures could cause crop failures in parts of the world that can least afford to lose the nourishment. The size of deserts would increase, along with the frequency and intensity of wildfires. Deliberately modifying the earth's atmosphere would be a desperate gamble with significant risks. Yet the more likely climate change is to cause devastation, the more attractive even the most perilous attempts to mitigate those changes will become.

"We don't know how bad this is going to be, and we don't know when it is going to get bad,'' Ken Caldeira, a climate scientist with the Carnegie Institution, told me. In 2007, Caldeira was a principal contributor to an I.P.C.C. team that won a Nobel Peace Prize. "There are wide variations within the models,'' he said. "But we had better get ready, because we are running rapidly toward a minefield. We just don't know where the minefield starts, or how long it will be before we find ourselves in the middle of it."

The Maldives, a string of islands off the coast of India whose highest point above sea level is eight feet, may be the first nation to drown. In Alaska, entire towns have begun to shift in the loosening permafrost. The Florida economy is highly dependent upon coastal weather patterns; the tide station at Miami Beach has registered an increase of seven inches since 1935, according to the National Oceanic and Atmospheric Administration. One Australian study, published this year in the journal *Nature Climate Change*, found that a two-degree Celsius rise in the earth's temperature would be accompanied by a significant spike in the number of lives lost just in Brisbane. Many climate scientists say their biggest fear is that warming could melt the Arctic permafrost—which stretches for thousands of miles across Alaska, Canada, and Siberia. There is twice as much CO_2 locked beneath the tundra as there is in the earth's atmosphere. Melting would release enormous stores of methane, a greenhouse gas nearly thirty times more potent than carbon dioxide. If that happens, as the hydrologist Jane C. S. Long told me when we met recently in her office at the Lawrence Livermore National Laboratory, "it's game over."

The Stratospheric Particle Injection for Climate Engineering project, or SPICE, is a British academic consortium that seeks to mimic the actions of volcanoes like Pinatubo by pumping particles of sulfur dioxide, or similar reflective chemicals, into the stratosphere through a twelve-mile-long pipe held aloft by a balloon at one end and tethered, at the other, to a boat anchored at sea.

The consortium consists of three groups. At Bristol University, researchers led by Matt Watson, a professor of geophysics, are trying to determine which particles would have the maximum desired impact with the smallest likelihood of unwanted side effects. Sulfur dioxide produces sulfuric acid, which destroys the ozone layer of the atmosphere; there are similar compounds that might work while proving less environmentally toxic—including synthetic particles that could be created specifically for this purpose. At Cambridge, Hugh Hunt and his team are trying to determine the best way to get those particles into the stratosphere. A third group, at Oxford, has been focussing on the effect such an intervention would likely have on the earth’s climate.

Hunt and I spoke in Cambridge, at Trinity College, where he is a professor of engineering and the Keeper of the Trinity College clock, a renowned timepiece that gains or loses less than a second a month. In his office, dozens of boomerangs dangle from the wall. When I asked about them, he grabbed one and hurled it at my head. “I teach three-dimensional dynamics,’’ he said, flicking his hand in the air to grab it as it returned. Hunt has devoted his intellectual life to the study of mechanical vibration. His Web page is filled with instructive videos about gyroscopes, rings wobbling down rods, and boomerangs.

“I like to demonstrate the way things spin,’’ he said, as he put the boomerang down and picked up an inflated pink balloon attached to a string. “The principle is pretty simple.” Holding the string, Hunt began to bobble the balloon as if it were being tossed by foul weather. “Everything is fine if it is sitting still,’’ he continued, holding the balloon steady. Then he began to wave his arm erratically. “One of the problems is that nothing is going to be still up there. It is going to be moving around. And the question we’ve got is . . . this pipe”—the industrial hose that will convey the particles into the sky—“is going to be under huge stressors.’’ He snapped the string connected to the balloon. “How do you know it’s not going to break? We are really pushing things to the limit in terms of their strength, so it is essential that we get the dynamics of motion right.’’

Most scientists, even those with no interest in personal publicity, are vigorous advocates for their own work. Not this group. “I don’t know how many times I have said this, but the last thing I would ever want is for the project I have been working on to be implemented,’’ Hunt said. “If we have to use these tools, it means something on this planet has gone seriously wrong.’’

Last fall, the SPICE team decided to conduct a brief and uncontroversial pilot study. At least they thought it would be uncontroversial. To demonstrate how they would disperse the sulfur dioxide, they had planned to float a balloon over Norfolk, at an altitude of a kilometre, and send a hundred and fifty litres of water into the air through a hose. After the date and time of the test was announced, in the middle of September, more than fifty organizations signed a petition objecting to the experiment, in part because they fear that even to consider engineering the climate would provide politicians with an excuse for avoiding tough decisions on reducing greenhouse-gas emissions. Opponents of the water test pointed out the many uncertainties in the research (which is precisely why the team wanted to do the experiment). The British government decided to put it off for at least six months.

“When people say we shouldn’t even explore this issue, it scares me,’’ Hunt said. He pointed out that carbon emissions are heavy, and finding a place to deposit them will not be easy. “Roughly speaking, the CO_2 we generate weighs three or four times as much as the fuel it comes from.” That means that a short round-trip journey—say, eight hundred miles—by car, using two tanks of gas, produces three hundred kilograms of CO_2. “This is ten heavy suitcases from one short trip,’’ Hunt said. “And you have to store it where it can’t evaporate.

“So I have three questions, Where are you going to put it? Who are you going to ask to dispose of this for you? And how much are you reasonably willing to pay them to do it?” he continued. “There is nobody on this planet who can answer any of those questions. There is no established place or technique, and nobody has any idea what it would cost. And we need the answers now.”

Hunt stood up, walked slowly to the window, and gazed at the manicured Trinity College green. “I know this is all unpleasant,’’ he said. “Nobody wants it, but nobody wants to put high doses of poisonous chemicals into their body, either. That is what chemotherapy is, though, and for people suffering from cancer those poisons are often their only hope. Every day, tens of thousands of people take them willingly—because they are very sick or dying. This is how I prefer to look at the possibility of engineering the climate. It isn’t a cure for anything. But it could very well turn out to be the least bad option we are going to have.’’

The notion of modifying the weather dates back at least to the eighteen-thirties, when the American meteorologist James Pollard Espy became known as the Storm King, for his (prescient but widely ridiculed) proposals to stimulate rain by selectively burning forests. More recently, the U.S. government project Stormfury attempted for decades to lessen the force of hurricanes by seeding them with silver iodide. And in 2008 Chinese soldiers fired more than a thousand rockets filled with chemicals at clouds over Beijing to prevent them from raining on the Olympics. The relationship between carbon emissions and the earth’s temperature has been clear for more than a century: in 1908, the Swedish scientist Svante Arrhenius suggested that burning fossil fuels might help prevent the coming ice age. In 1965, President Lyndon Johnson received a report from his Science Advisory Committee, titled “Restoring the Quality of Our Environment,” that noted for the first time the potential need to balance increased greenhouse-gas emissions by “raising the albedo, or the reflectivity, of the earth.” The report suggested that such a change could be achieved by spreading small reflective particles over large parts of the ocean.

While such tactics could clearly fail, perhaps the greater concern is what might happen if they succeeded in ways nobody had envisioned. Injecting sulfur dioxide, or particles that perform a similar function, would rapidly lower the temperature of the earth, at relatively little expense—most estimates put the cost at less than ten billion dollars a year. But it would do nothing to halt ocean acidification, which threatens to destroy coral reefs and wipe out an enormous number of aquatic species. The risks of reducing the amount of sunlight that reaches the atmosphere on that scale would be as obvious—and immediate—as the benefits. If such a program were suddenly to fall apart, the earth would be subjected to extremely rapid warming, with nothing to stop it. And while such an effort would cool the globe, it might do so in ways that disrupt the behavior of the Asian and African monsoons, which provide the water that billions of people need to drink and to grow their food.

"Geoengineering" actually refers to two distinct ideas about how to cool the planet. The first, solar-radiation management, focusses on reducing the impact of the sun. Whether by seeding clouds, spreading giant mirrors in the desert, or injecting sulfates into the stratosphere, most such plans seek to replicate the effects of eruptions like Mt. Pinatubo's. The other approach is less risky, and involves removing carbon directly from the atmosphere and burying it in vast ocean storage beds or deep inside the earth. But without a significant technological advance such projects will be expensive and may take many years to have any significant effect.

There are dozens of versions of each scheme, and they range from plausible to absurd. There have been proposals to send mirrors, sunshades, and parasols into space. Recently, the scientific entrepreneur Nathan Myhrvold, whose company Intellectual Ventures has invested in several geoengineering ideas, said that we could cool the earth by stirring the seas. He has proposed deploying a million plastic tubes, each about a hundred metres long, to roil the water, which would help it trap more CO_2. "The ocean is this giant heat sink,'' he told me. "But it is very cold. The bottom is nearly freezing. If you just stirred the ocean more, you could absorb the excess CO_2 and keep the planet cold." (This is not as crazy as it sounds. In the center of the ocean, wind-driven currents bring fresh water to the surface, so stirring the ocean could transform it into a well-organized storage depot. The new water would absorb more carbon while the old water carried the carbon it has already captured into the deep.)

The Harvard physicist Russell Seitz wants to create what amounts to a giant oceanic bubble bath: bubbles trap air, which brightens them enough to reflect sunlight away from the surface of the earth. Another tactic would require maintaining a fine spray of seawater—the world's biggest fountain—which would mix with salt to help clouds block sunlight.

The best solution, nearly all scientists agree, would be the simplest: stop burning fossil fuels, which would reduce the amount of carbon we dump into the atmosphere. That fact has been emphasized in virtually every study that addresses the potential effect of climate change on the earth—and there have been many—but none have had a discernible impact on human behavior or government policy. Some climate scientists believe we can accommodate an atmosphere with concentrations of carbon dioxide that are twice the levels of the preindustrial era—about five hundred and fifty parts per million. Others have long claimed that global warming would become dangerous when atmospheric concentrations of carbon rose above three hundred and fifty parts per million. We passed that number years ago. After a decline in 2009, which coincided with the harsh global recession, carbon emissions soared by six per cent in 2010—the largest increase ever recorded. On average, in the past decade, fossil-fuel emissions grew at about three times the rate of growth in the nineteen-nineties.

Although the I.P.C.C., along with scores of other scientific bodies, has declared that the warming of the earth is unequivocal, few countries have demonstrated the political will required to act—perhaps least of all the United States, which consumes more energy than any nation other than China, and, last year, more than it ever had before. The Obama Administration has failed to pass any meaningful climate legislation. Mitt Romney, the presumptive Republican nominee, has yet to settle on a clear position. Last year, he said he believed the world was getting warmer—and humans were a cause. By October, he had retreated. "My view is that we don't know what is causing climate change on this planet," he said, adding that spending huge sums to try to reduce CO_2 emissions "is not the right course for us." China, which became the world's largest emitter of greenhouse gases several years ago, constructs a new coal-burning power plant nearly every week. With each passing year, goals become exponentially harder to reach, and global reductions along the lines suggested by the I.P.C.C. seem more like a "pious wish," to use the words of the Dutch chemist Paul Crutzen, who in 1995 received a Nobel Prize for his work on ozone depletion.

"Most nations now recognize the need to shift to a low-carbon economy, and nothing should divert us from the main priority of reducing global greenhouse gas emissions,'' Lord Rees of Ludlow wrote in his 2009 forward to a highly influential report on geoengineering released by the Royal Society, Britain's national academy of sciences. "But if such reductions achieve too little, too late, there will surely be pressure to consider a 'plan B'—to seek ways to counteract climatic effects of green-house gas emissions.''

While that pressure is building rapidly, some climate activists oppose even holding discussions about a possible Plan B, arguing, as the Norfolk protesters did in September, that it would be perceived as indirect permission to abandon serious efforts to cut emissions. Many people see geoengineering as a false solution to an existential crisis—akin to encouraging a heart-attack patient to avoid exercise and continue to gobble fatty food while simply doubling his dose of Lipitor. "The scientist's focus on tinkering with our entire planetary system is not a dynamic new technological and scientific frontier, but an expression of political despair," Doug Parr, the chief scientist at Greenpeace UK, has written.

During the 1974 Mideast oil crisis, the American engineer Hewitt Crane, then working at S.R.I. International, realized that standard measurements for sources of energy—barrels of oil, tons of coal, gallons of gas, British thermal units—were nearly impossible to compare. At a time when these commodities were being rationed, Crane wondered how people could conserve resources if they couldn't even measure them. The world was burning through twenty-three thousand gallons of oil every second. It was an astonishing figure, but one that Crane had trouble placing into any useful context.

Crane devised a new measure of energy consumption: a three-dimensional unit he called a cubic mile of oil. One cubic mile of oil would fill a pool that was a mile long, a mile wide, and a mile deep. Today, it takes three cubic miles' worth of fossil fuels to power the world for a year. That's a trillion gallons of gas. To replace just one of those cubic miles with a source of energy that will not add carbon dioxide to the atmosphere—nuclear power, for instance—would require the construction of a new atomic plant every week for fifty years; to switch to wind power would mean erecting thousands of windmills each month. It is hard to conceive of a way to replace that much energy with less dramatic alternatives. It is also impossible to talk seriously about climate change without talking about economic development. Climate experts have argued that we ought to stop emitting greenhouse gases within fifty years, but by then the demand for energy could easily be three times what it is today: nine cubic miles of oil.

The planet is getting richer as well as more crowded, and the pressure to produce more energy will become acute long before the end of the century. Predilections of the rich world—constant travel, industrial activity, increasing reliance on meat for protein—require enormous physical resources. Yet many people still hope to solve the problem of climate change just by eliminating greenhouse-gas emissions. "When people talk about bringing emissions to zero, they are talking about something that will never happen,'' Ken Caldeira told me. "Because that would require a complete alteration in the way humans are built."

Caldeira began researching geoengineering almost by accident. For much of his career, he has focussed on the implications of ocean acidification. During the nineteen-nineties, he spent a year in the Soviet Union, at the Leningrad lab of Mikhail Budyko, who is considered the founder of physical climatology. It was Budyko, in the nineteen-sixties, who first suggested cooling the earth by putting sulfur particles in the sky.

"In the nineteen-nineties, when I was working at Livermore, we had a meeting in Aspen to discuss the scale of the energy-system transformation needed in order to address the climate problem,'' Caldeira said. "Among the people who attended was Lowell Wood, a protégé of Edward Teller. Wood is a brilliant but sometimes erratic man . . . lots of ideas, some better than others." At Aspen, Wood delivered a talk on geoengineering. In the presentation, he explained, as he has many times since, that shielding the earth properly could deflect one or two per cent of the sunlight that reaches the atmosphere. That, he said, would be all it would take to counter the worst effects of warming.

David Keith was in the audience with Caldeira that day in Aspen. Keith now splits his time between Harvard and Calgary, where he runs Carbon Engineering, a company that is developing new technology to capture CO_2 from the atmosphere—at a cost that he believes would make it sensible to do so. At the time, though, both men considered Wood's idea ridiculous. "We said this will never happen,'' Caldeira recalled. "We were so certain Wood was nuts, because we assumed you can change the global mean temperature, but you will still get seasonal and regional patterns you can't correct. We were in the back of the room, and neither of us could believe it."

Caldeira decided to prove his point by running a computer simulation of Wood's approach. Scenarios for future climate change are almost always developed using powerful three-dimensional models of the earth and its atmosphere. They tend to be most accurate when estimating large numbers, like average global temperatures. Local and regional weather patterns are more difficult to predict, as anyone who has relied on a five-day weather forecast can understand. Still, in 1998 Caldeira tested the idea, and, "much to my surprise, it seemed to work and work well," he told me. It turned out that reducing sunlight offset the effect of CO_2 both regionally and seasonally. Since then, his results have been confirmed by several other groups.

Recently, Caldeira and colleagues at Carnegie and Stanford set out to examine whether the techniques of solar-radiation management would disrupt the sensitive agricultural balance on which the earth depends. Using two models, they simulated climates with carbon-dioxide levels similar to those which exist today. They then doubled those concentrations to reflect levels that would be likely in several decades if current trends continue unabated. Finally, in a third set of simulations, they doubled the CO_2 in the atmosphere, but added a layer of sulfate aerosols to the stratosphere, which would deflect about two per cent of incoming sunlight from the earth. The data were then applied to crop models that are commonly used to project future yields. Again, the results were unexpected.

Farm productivity, on average, went up. The models suggested that precipitation would increase in the northern and middle latitudes, and crop yields would grow. In the tropics, though, the results were significantly different. There heat stress would increase, and yields would decline. "Climate change is not so much a reduction in productivity as a redistribution,'' Caldeira said. "And it is one in which the poorest people on earth get hit the hardest and the rich world benefits"—a phenomenon, he added, that is not new.

"I have two perspectives on what this might mean,'' he said. "One says: humans are like rats or cockroaches. We are already living from the equator to the Arctic Circle. The weather has already become .7 degrees warmer, and barely anyone has noticed or cares. And, yes, the coral reefs might become extinct, and people from the Seychelles might go hungry. But they have gone hungry in the past, and nobody cared. So basically we will live in our gated communities, and we will have our TV shows and Chicken McNuggets, and we will be O.K. The people who would suffer are the people who always suffer.

"There is another way to look at this, though,'' he said. "And that is to compare it to the subprime-mortgage crisis, where you saw that a few million bad mortgages led to a five-per-cent drop in gross domestic product throughout the world. Something that was a relatively small knock to the financial system led to a global crisis. And that could certainly be the case with climate change. But five per cent is an interesting figure, because in the Stern Report''—an often cited review led by the British economist Nicholas Stern, which signalled the alarm about greenhouse-gas emissions by focussing on economics—"they estimated climate change would cost the world five per cent of its G.D.P. Most economists say that solving this problem is one or two per cent of G.D.P. The Clean Water and Clean Air Acts each cost about one per cent of G.D.P.," Caldeira continued. "We just had a much worse shock to our banking system. And it didn't even get us to reform the economy in any significant way. So why is the threat of a five-per-cent hit from climate change going to get us to transform the energy system?"

Solar-radiation management, which most reports have agreed is technologically feasible, would provide, at best, a temporary solution to rapid warming—a treatment but not a cure. There are only two ways to genuinely solve the problem: by drastically reducing emissions or by removing the CO_2 from the atmosphere. Trees do that every day. They "capture" carbon dioxide in their leaves, metabolize it in the branch system, and store it in their roots. But to do so on a global scale would require turning trillions of tons of greenhouse-gas emissions into a substance that could be stored cheaply and easily underground or in ocean beds.

Until recently, the costs of removing carbon from the atmosphere on that scale have been regarded by economists as prohibitive. CO_2 needs to be heated in order to be separated out; using current technology, the expense would rival that of creating an entirely new energy system. Typically, power plants release CO_2 into the atmosphere through exhaust systems referred to as flues. The most efficient way we have now to capture CO_2 is to remove it from flue gas as the emissions escape. Over the past five years, several research groups—one of which includes David Keith's company, Carbon Engineering, in Calgary—have developed new techniques to extract carbon from the atmosphere, at costs that may make it economically feasible on a larger scale.

Early this winter, I visited a demonstration project on the campus of S.R.I. International, the Menlo Park institution that is a combination think tank and technological incubator. The project, built by Global Thermostat, looked like a very high-tech elevator or an awfully expensive math problem. "When I called chemical engineers and said I want to do this on a planetary scale, they laughed,'' Peter Eisenberger, Global Thermostat's president, told me. In 1996, Eisenberger was appointed the founding director of the Earth Institute, at Columbia University, where he remains a professor of earth and environmental sciences. Before that, he spent a decade running the materials research institute at Princeton University, and nearly as much time at Exxon, in charge of research and development. He believes he has developed a system to capture CO_2 from the atmosphere at low heat and potentially at low cost.

The trial project is essentially a five-story brick edifice specially constructed to function like a honeycomb. Global Thermostat coats the bricks with chemicals called amines to draw CO_2 from the air and bind with it. The carbon dioxide is then separated with a proprietary method that uses low-temperature heat—something readily available for free, since it is a waste product of many power plants. “Using low-temperature heat changes the equation,’’ Eisenberger said. He is an excitable man with the enthusiasm of a graduate student and the manic gestures of an orchestra conductor. He went on to explain that the amine coating on the bricks binds the CO_2 at the molecular level, and the amount it can capture depends on the surface area; honeycombs provide the most surface space possible per square metre.

There are two groups of honey-combs that sit on top of each other. As Eisenberger pointed out, “You can only absorb so much CO_2 at once, so when the honeycomb is full it drops into a lower section.” Steam heats and releases the CO_2—and the honeycomb rises again. (Currently, carbon dioxide is used commercially in carbonated beverages, brewing, and pneumatic drying systems for packaged food. It is also used in welding. Eisenberger argues that, ideally, carbon waste would be recycled to create an industrial form of photosynthesis, which would help reduce our dependence on fossil fuels.)

Unlike some other scientists engaged in geoengineering, Eisenberger is not bothered by the notion of tinkering with nature. “We have devised a system that introduces no additional threats into the environment,’’ he told me. “And the idea of interfering with benign nature is ridiculous. The Bambi view of nature is totally false. Nature is violent, amoral, and nihilistic. If you look at the history of this planet, you will see cycles of creation and destruction that would offend our morality as human beings. But somehow, because it’s ‘nature,’ it’s supposed to be fine.’’ Eisenberger founded and runs Global Thermostat with Graciela Chichilnisky, an Argentine economist who wrote the plan, adopted in 2005, for the international carbon market that emerged from the Kyoto Climate talks. Edgar Bronfman, Jr., an heir to the Seagram fortune, is Global Thermostat’s biggest investor. (The company is one of the finalists for Richard Branson’s Virgin Earth Challenge prize. In 2007, Branson offered a cash prize of twenty-five million dollars to anyone who could devise a process that would drain large quantities of greenhouse gases from the atmosphere.)

"What is fascinating for me is the way the innovation process has changed,'' Eisenberger said. "In the past, somebody would make a discovery in a laboratory and say, 'What can I do with this?' And now we ask, 'What do we want to design?,' because we believe there is powerful enough knowledge to do it. That is what my partner and I did." The pilot, which began running last year, works on a very small scale, capturing about seven hundred tons of CO_2 a year. (By comparison, an automobile puts out about six tons a year.) Eisenberger says that it is important to remember that it took more than a century to assemble the current energy system: coal and gas plants, factories, and the worldwide transportation network that has been responsible for depositing trillions of tons of CO_2 into the atmosphere. "We are not going to get it all out of the atmosphere in twenty years,'' he said. "It will take at least thirty years to do this, but if we start now that is plenty of time. You would just need a source of low-temperature heat—factories anywhere in the world are ideal." He envisions a network of twenty thousand such devices scattered across the planet. Each would cost about a hundred million dollars—a two-trillion-dollar investment spread out over three decades.

"There is a strong history of the system refusing to accept something new," Eisenberger said. "People say I am nuts. But it would be surprising if people didn't call me crazy. Look at the history of innovation! If people don't call you nuts, then you are doing something wrong."

After leaving Eisenberger's demonstration project, I spoke with Curtis Carlson, who, for more than a decade, has been the chairman and chief executive officer of S.R.I. and a leading voice on the future of American innovation. "These geoengineering methods will not be implemented for decades—or ever," he said. Nonetheless, scientists worry that if methane emissions from the Arctic increase as rapidly as some of the data now suggest, climate intervention isn't going to be an option. It's going to be a requirement. "When and where do we have the serious discussion about how to intervene?" Carlson asked. "There are no agreed-upon rules or criteria. There isn't even a body that could create the rules."

Over the past three years, a series of increasingly urgent reports—from the Royal Society, in the U.K., the Washington-based Bipartisan Policy Center, and the Government Accountability Office, among other places—have practically begged decision-makers to begin planning for a world in which geoengineering might be their only recourse. As one recent study from the Wilson International Center for Scholars concluded, "At the very least, we need to learn what approaches to avoid even if desperate."

The most environmentally sound approach to geoengineering is the least palatable politically. "If it becomes necessary to ring the planet with sulfates, why would you do that all at once?'' Ken Caldeira asked. "If the total amount of climate change that occurs could be neutralized by one Mt. Pinatubo, then doesn't it make sense to add one per cent this year, two per cent next year, and three per cent the year after that?'' he said. "Ramp it up slowly, throughout the century, and that way we can monitor what is happening. If we see something at one per cent that seems dangerous, we can easily dial it back. But who is going to do that when we don't have a visible crisis? Which politician in which country?''

Unfortunately, the least risky approach politically is also the most dangerous: do nothing until the world is faced with a cataclysm and then slip into a frenzied crisis mode. The political implications of any such action would be impossible to overstate. What would happen, for example, if one country decided to embark on such a program without the agreement of other countries? Or if industrialized nations agreed to inject sulfur particles into the stratosphere and accidentally set off a climate emergency that caused drought in China, India, or Africa?

"Let's say the Chinese government decides their monsoon strength, upon which hundreds of millions of people rely for sustenance, is weakening," Caldeira said. "They have reason to believe that making clouds right near the ocean might help, and they started to do that, and the Indians found out and believed—justifiably or not—that it would make their monsoon worse. What happens then? Where do we go to discuss that? We have no mechanism to settle that dispute."

Most estimates suggest that it could cost a few billion dollars a year to scatter enough sulfur particles in the atmosphere to change the weather patterns of the planet. At that price, any country, most groups, and even some individuals could afford to do it. The technology is open and available—and that makes it more like the Internet than like a national weapons program. The basic principles are widely published; the intellectual property behind nearly every technique lies in the public domain. If the Maldives wanted to send airplanes into the stratosphere to scatter sulfates, who could stop them?

"The odd thing here is that this is a democratizing technology,'' Nathan Myhrvold told me. "Rich, powerful countries might have invented much of it, but it will be there for anyone to use. People get themselves all balled up into knots over whether this can be done unilaterally or by one group or one nation. Well, guess what. We decide to do much worse than this every day, and we decide unilaterally. We are polluting the earth unilaterally. Whether it's life-taking decisions, like wars, or something like a trade embargo, the world is about people taking action, not agreeing to take action. And, frankly, the Maldives could say, 'Fuck you all—we want to stay alive.' Would you blame them? Wouldn't any reasonable country do the same?" ♦

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