Washing CARBON OUT OF THE AIR

Machines could absorb carbon dioxide from the atmosphere, slowing or even reversing its rise and reducing global warming

By Klaus S. Lackner

The world cannot afford to dump more carbon dioxide into the atmosphere. Yet it is not cutting back. All indications are that the concentration of CO_2 will continue to rise for decades. Despite great support for renewable energy, developed and developing countries will probably burn more oil, coal and natural gas in the future.

For transportation, the alternatives to petroleum appear especially far off. Onboard energy storage for electric vehicles is difficult; for a given mass, batteries hold less than 1 percent of the energy stored in gasoline. Carrying hydrogen on vehicles requires 10 times the storage volume of gasoline, and the high-pressure tank needed to hold it is very heavy. Although a few maiden flights of airplanes powered by jet fuel derived from biomass have taken place, it is unclear that biofuels can be produced at the quantities and low prices required by airliners … or by ships for that matter.

So how are we to keep the CO_2 concentration from rising beyond its current level of 389 parts per million? Unless we ban carbon-based fuels, one option is to pull CO_2 out of the air. Allowing forests to expand in area could absorb some of the gas, but humans produce so much that we simply do not have the land available to sequester enough of it. Fortunately, filtering machines—think of them as synthetic trees—can capture far more CO_2 than natural trees of a similar size.

Several research groups are studying prototype machines, among them the Georgia Institute of Technology, the University of Calgary in Canada, the Swiss Federal Institute of Technology in Zurich, and my own teams at Columbia University and Global Research Technologies in

JOE ZEFF DESIGN

Tucson, Ariz. [*see "Competing Processes" on page 71*]. All the designs involve variations on the same theme: as air breezes through a structure, it contacts a "sorbent" material that chemically binds the CO_2, leaving the nitrogen, oxygen and other elements to waft away.

Carbon dioxide would have to be captured on a grand scale to curtail climate change, but the basic concept is already well established. For decades scrubbers have removed CO_2 from the air breathed inside submarines and spaceships and from air used to produce liquid nitrogen. Various chemical processes can accomplish this scrubbing, but machines with solid sorbents promise to trap the most gas per unit of energy required. Early, small prototype units suggest that wide dissemination of solid-sorbent machines could stop or even reverse the rise of atmospheric CO_2.

One Big Filter

Like their leafy counterparts, air capture machines come in different shapes and sizes. Demonstration units intended to go beyond the laboratory prototypes should each trap from a ton to hundreds of tons of CO_2 per day. The design being developed by Columbia and Global Research Technologies offers an example of how the technology can work. Thin fibers of sorbent material are arranged into large, flat panels akin to furnace filters, one meter wide and 2.5 meters high. The upright filter panels will revolve around a circular, horizontal track that is mounted on top of a standard 40-foot (12.2 meters) shipping container [*see illustration on next page*]. The panels will be exposed to the air. Once they are loaded with CO_2, they will move off the track and down into a regeneration chamber inside the container. There the

KEY CONCEPTS

- Machines with filters made from sorbent materials can bind carbon dioxide, extracting it from the air.
- With mass production, machines might capture CO_2 at $30 a ton, less than the $100 or more charged for commercial CO_2 supply.
- With improved sorbents, 10 million machines across the planet could reduce CO_2 concentration by five parts per million a year, more than the rate of global increase right now.

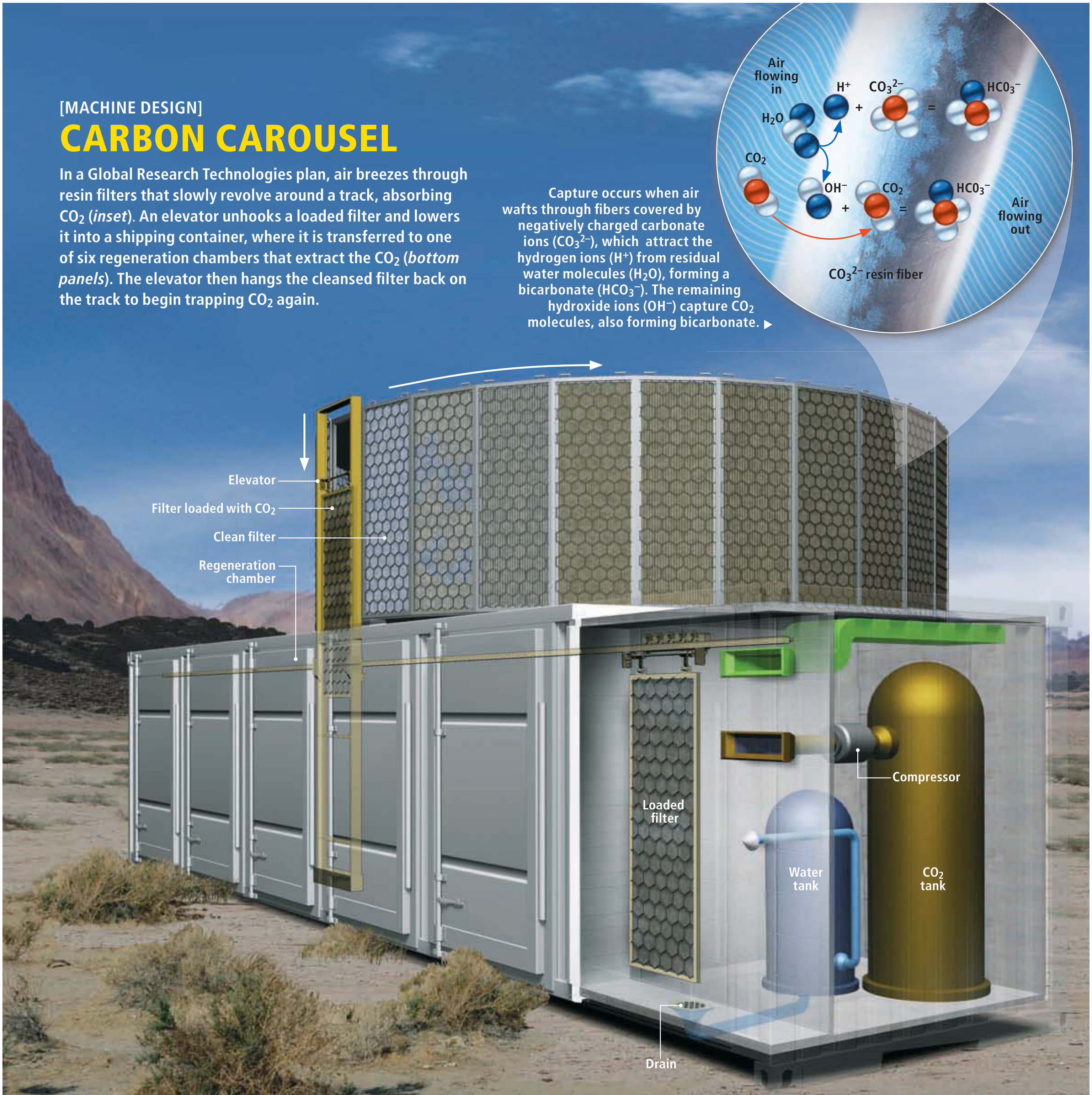
—The Editors

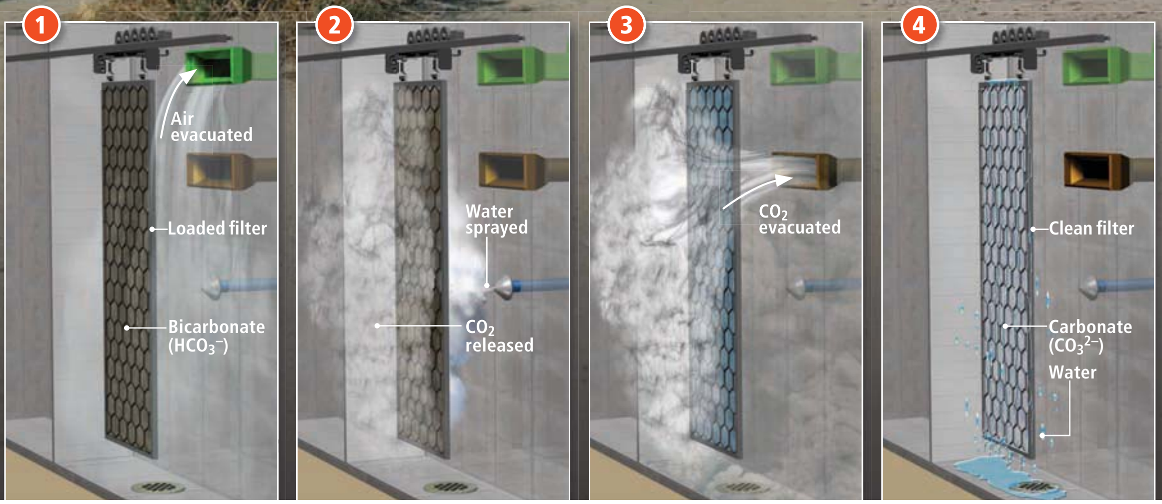
[MACHINE DESIGN]

CARBON CAROUSEL

In a Global Research Technologies plan, air breezes through resin filters that slowly revolve around a track, absorbing CO_2 (*inset*). An elevator unhooks a loaded filter and lowers it into a shipping container, where it is transferred to one of six regeneration chambers that extract the CO_2 (*bottom panels*). The elevator then hangs the cleansed filter back on the track to begin trapping CO_2 again.

Capture occurs when air wafts through fibers covered by negatively charged carbonate ions (CO_3^{2-}), which attract the hydrogen ions (H^+) from residual water molecules (H_2O), forming a bicarbonate (HCO_3^-). The remaining hydroxide ions (OH^-) capture CO_2 molecules, also forming bicarbonate. ▶





Cleaning a filter begins by evacuating air from the chamber ①. Water is then sprayed to dissolve the bicarbonate on the fibers, which reverts to carbonate and CO_2 ②. The CO_2 is evacuated and compressed into a liquid, for storage or use by industry ③. Water is collected through a drain ④.

trapped gas will be freed from the sorbent and compressed to a liquid. The refreshed panel will be moved back up onto the track to pull more gas from the wind.

The CO_2 collected by air capture machines could be used profitably by industry or be piped underground, as is done in experimental carbon capture and storage systems, intended largely for use at coal-fired power plants. As an enticing alternative, however, the gas could serve as the feedstock for synthetic liquid fuels for transportation. Electricity would break one oxygen atom off a CO_2 molecule and one off a water molecule (H_2O). The resulting mixture of CO and H_2 is known as synthesis gas, which, made by other means, has been used for almost a century as a feedstock for fuels and plastics. For years the South African energy company Sasol has been making synthetic gasoline and diesel with synthesis gas produced from coal. Air capture could therefore offset the emissions from vehicles that burn fossil fuels or help replace those fuels with synthetic liquids that do not require mining or drilling of coal, oil or natural gas.

Of course, air capture must not only work chemically; it must be practical, cost-effective and energy-efficient. To be practical, the equipment required to snatch CO_2 from the air would have to be compact. In one day more than 700 kilograms of CO_2 passes through a door-size opening, at ground level or altitude, that is exposed to a wind speed of six meters per second, common for a windmill site. That amount is equivalent to the CO_2 output of 13 people in the U.S. across the same period. Although air collectors might not see such high wind speeds, and the filtering will slow the flow, and even though trapping 100 percent of the gas is unlikely, the collectors would still be compact.

When assessing cost, two basic steps have to be considered: absorbing the CO_2 from the air and recovering the carbon from the sorbent. Based on a comparison with windmills, I concluded early on that the cost of filtering the air with a sorbent can be small. The subsequent act of liberating the CO_2 from the sorbent dominates the cost of the overall process. Nevertheless, air capture is still a significantly more practical alternative to scrubbing the tailpipes of millions of vehicles, because a large volume of CO_2 would have to be stored onboard each vehicle and returned to a collection point (every kilogram of gasoline burned by an engine produces three kilograms of CO_2). Washing the ambient air is more viable.

Wet Sorbent or Dry

From a chemist's point of view, a successful sorbent has to bind CO_2 strongly enough to absorb the gas but not hold it so strongly that subsequently freeing the gas for storage is expensive. The concentration in ambient air is about 0.04 percent, compared with 10 to 15 percent in a coal plant's flue gas. But the required strength of the sorbent varies only slightly with the carbon dixoide concentration, so sorbents for air capture can be similar in strength to those for flue-gas scrubbing.

Sorbents can be constructed as solids or liquids. Liquids are appealing because they can be transferred between collector and regenerator easily. Maintaining good surface exposure of a liquid to ambient air is challenging, but chemical engineering methods for this task are well understood. For example, David Keith, working at the University of Calgary and a new start-up company called Carbon Engineering, is using a sodium hydroxide solution that is trickled into a bed of plastic surfaces, through which air is blown by a fan. Moving the liquid is easy, but the strong binding of carbon dioxide to sodium hydroxide makes removal from the sorbent relatively difficult.

Solid sorbents are desirable because their surfaces can be roughened, creating more binding sites for CO_2 molecules, which raises uptake rates. Moving solid sorbents to and from a regeneration chamber is more difficult than it is for liquids, however. A commercial partnership called Global Thermostat, based on work at the Georgia Institute of Technology, is investigating solid sorbents that are heated to release the CO_2 they capture.

Both solid and liquid sorbents rely on acid-base chemistry. Carbon dioxide is an acid, and most sorbents are bases. They react with one another to form a salt. As an example, sodium hydroxide, known as caustic soda, is a powerful sorbent that binds carbon dioxide by forming sodium carbonate (soda ash). Sodium carbonate is still basic and can absorb additional carbon dioxide, transforming into sodium bicarbonate (baking soda), which is also a base. Similar chemistry occurs with other sorbents.

It should in principle be possible to remove CO_2 from a bicarbonate and return the sorbent to its hydroxide state, thereby continually recycling the sorbent. But in practice, regeneration methods seem to work well only for a half-step: they either remove carbon dioxide from a bicarbonate, resulting in a carbonate, or they remove

PLANETARY PLAN

One vision for slowing global warming:

10 million
air capture machines worldwide

10 tons
of CO_2 a day pulled from the air by each machine, after accounting for emissions related to energy consumed by the machines

36 gigatons
a year of CO_2 captured overall

5 parts per million
shaved annually from the CO_2 concentration in the earth's atmosphere, now at 389 ppm and rising

[THE AUTHOR]

Klaus S. Lackner, a professor of geophysics, is chair of the department of earth and environmental engineering at Columbia University, where he is also a member of the Earth Institute. Lackner is co-founder of Global Research Technologies, a company that Gary Comer, the late owner of Lands' End, funded to demonstrate air capture technology.

KEVIN HAND (*illustration*); COURTESY OF COLUMBIA UNIVERSITY (*Lackner*)

carbon dioxide from a carbonate, resulting in a hydroxide. Cycling back and forth between bicarbonate and carbonate is preferable because less energy is required to free the CO_2 once it has bound to the sorbent.

Several classes of innovative sorbents can swing between carbonates and bicarbonates. One class comprises so-called anion exchange resins. These plasticlike carbonate polymers are employed in a variety of chemical processes, including the preparation of deionized water. The positive ions in the resin are fixed in place, and negative ions are mobile. One set of negative ions can be exchanged for another by washing the resin in a solution that offers different negative ions.

Global Research Technologies has devised one such carbonate resin. Filters made from dry resin and exposed to the wind load up with carbon dioxide until the resin reaches the bicarbonate state. Wetting the resin releases the captured carbon dioxide, and the resin reverts to carbonate. Once the resin dries, it can begin absorbing carbon dioxide again.

In our planned system, a loaded filter will descend into a regeneration chamber housed inside the shipping container. The air will be pumped out, and water, perhaps in the form of mist, will be added. The moist resin will release the CO_2, which will be pumped out and compressed into a liquid. Compression also will force any residual water vapor to condense into pure water, which will be withdrawn and reused. The cleansed filter will rise back above the regeneration chamber to dry and then resume absorbing carbon dioxide above the shipping container.

Energy consumption by such machines is dominated by two steps. The first is pumping the air out of the regeneration chamber. The second, which demands far more energy, is compressing the carbon dioxide from a fraction of an atmosphere to the pressure required to liquefy it (several tens of atmospheres, depending on temperature). The total process for collecting 1.0 kilogram of carbon dioxide from our design will require 1.1 megajoules of electricity. For comparison, when power plants across the U.S. are averaged, generating 1.1 megajoules of electricity produces 0.21 kilogram of carbon dioxide. Therefore, the air capture process collects far more carbon dioxide than it creates through energy consumption.

Realistic cost for the energy required is around \$15 per ton of carbon dioxide collected—not much greater than the cost of scrubbing the gas from a flue stack. Right now, however, most of the expense for deploying units would be in manufacturing and maintenance, costs that would decrease as production numbers rose. I expect the initial cost of air capture to be around \$200 per ton of carbon dioxide, with prices dropping dramatically as more collectors are built.

Use It, Store It

Aside from being stored, what can be done with all the CO_2 that would be collected? Several options present themselves.

Many industries use carbon dioxide—to carbonate beverages, freeze chicken wings and make dry ice. The gas is also used for stimulating the growth of indoor crops and as a nonpolluting solvent or refrigerant. Few industrial sources exist, so the price is driven by the cost of shipping. In the U.S., CO_2 usually sells for more than \$100 a ton, but in remote locations the price can double or triple. The world market approaches 30 million tons annually, some of

SELLING CO_2

Carbon dioxide sucked from the air could be sequestered underground, or it could be sold as a processing agent or raw material for existing and future industries.

EXISTING APPLICATIONS

- Pressurizing agent to force oil from enhanced oil recovery fields.
- Carbonation for beverages.
- Freezing agent for chicken wings.

FUTURE APPLICATIONS

- Feedstock for synthetic gasoline.
- Nutrient for algae farms that produce biofuel.
- Raw material for carbonate-based cement.


OIL RECOVERY


ALGAE FARM


CEMENT

[TERMINOLOGY]

Not Geoengineering

Some people label the extraction of carbon dioxide from the air as geoengineering. I do not, because the process does not change the natural dynamics of the earth or create a potential environmental risk. Geoengineering schemes do: lofting aerosols into the upper atmosphere to absorb sunlight alters the chemistry of the atmosphere and the radiation balance across the globe. Spreading iron particles over the ocean surface to speed growth of algae that can absorb CO_2 alters the ocean's chemistry and biology. Air capture simply withdraws the excess CO_2 from the atmosphere that humans are putting there. *—K.S.L.*

which could be serviced by air capture units.

Niche markets such as food processing can provide a toehold. As more air capture units are made, prices will come down, increasing market size. Once the price of a ton of captured CO_2 has dropped well below $100, extraction could also be sold as a carbon credit, like those traded on the Carbon Exchange in London.

Emerging markets could accelerate the technology's maturity. Since the 1970s petroleum companies have purchased CO_2 for enhanced recovery; the gas is pumped underground to force more oil or natural gas from dwindling fields. If the CO_2 came from air capture, the companies could claim a carbon credit for the gas that stays underground; typically about half of the injected gas stays there naturally. Enhanced oil recovery is a potentially large market, but many oil fields are far away from CO_2 sources. Installing capture units right above a field could change that dynamic.

With the advent of clean energy sources, however, the prize for air capture would be the production of fresh liquid fuel from CO_2 feedstock. As noted earlier, well-established technologies such as electrolysis and reverse water-gas shift reactions can produce synthesis gas from CO_2 and water, leading to fuel synthesis. The big cost is the electricity needed.

Until fuel synthesis becomes affordable, humankind will have to dispose of all the emissions it generates. Technologies such as geologic sequestration and mineral sequestration are being developed for storing CO_2 collected at power plants. Air capture can work with the same storage approaches, and machines could be installed at the same disposal sites.

Global Cooling

Until clean transportation technologies become significantly more efficient, extracting carbon from the air would allow cars, planes and ships to continue burning liquid fuels, with their emissions captured by faraway air collectors. And "far away" is the case. Unlike ozone or sulfur dioxide, CO_2 remains in the atmosphere for decades to centuries, giving it ample time to travel extensively. The atmosphere mixes so thoroughly that it is legitimate to remove CO_2 from the air in Australia and take credit against emissions in North America. An equivalent amount of the gas could even be removed before emissions are released; a car could be made carbon-neutral by collecting its estimated lifetime emission of 100 tons before the vehicle rolls off the assembly line.

Air capture could also be a cheaper way to sequester emissions from power plants, especially older ones not easily retrofitted with flue-stack scrubbers or those located far from storage sites. And in a future world in which atmospheric CO_2 concentrations have already been stabilized, air capture could even drive levels down. In effect, air capture can deal with past emissions.

In addition to cost, critics argue that numerous air capture machines would consume lots of energy, and they note that the filters are made of plastics derived from oil. A more substantial hurdle, in my mind, is that for each ton of CO_2 collected, several tons of water would evaporate to the atmosphere, as wet filters dried. But if air capture were implemented on a large scale, it could start to correct climate change. Transportable units could collect about one ton apiece a day. Ten million such units could collect 3.6 gigatons a year, which would reduce atmospheric levels by about 0.5 ppm a year. If over time the units could handle 10 tons a day (which would require improved sorbents), the annual reduction would be 5 ppm a year, which is more than the rate of global increase right now. Note that even though 10 million units may seem large, the world produces about 71 million cars and light trucks *every year.*

Initially the cost to capture CO_2 would be high, about $200 per ton as noted. If the technology follows standard learning and manufacturing curves, however, we could end up with costs that are dominated by materials and energy, which puts capture in the $30 per ton range. At that point the cost added to a gallon of gasoline to pay for capturing the CO_2 it creates would be 25 cents—a price well worth paying. ■

COMPETING PROCESSES

Various organizations are investigating dry and wet sorbents that could lead to commercial air capture machines. A sampling:

DRY SORBENTS

Columbia University and Global Research Technologies: Carbonate polymer

Georgia Institute of Technology and Global Thermostat: Carbonate polymer

WET SORBENTS

Brookhaven National Laboratory: Hydroxide solution

University of Calgary and Carbon Engineering: Hydroxide solution

Xerox PARC: Hydroxide solution

Swiss Federal Institute of Technology, Zurich: Hydroxide solution, lime

Paul Scherrer Institute: Hydroxide solution, lime

➡ MORE TO EXPLORE

Climate Strategy with CO_2 Capture from the Air. David W. Keith et al. in *Climatic Change,* Vol. 74, pages 17–45; January 2006.

Fixing Climate: What Past Climate Changes Reveal about the Current Threat—and How to Counter It. Wallace S. Broecker and Robert Kunzig. Hill and Wang, 2008.

Capture of Carbon Dioxide from Ambient Air. Klaus S. Lackner in *European Physical Journal: Special Topics,* Vol. 176, No. 1; pages 93–106; September 2009.

BLOOMBERG/GETTY IMAGES *(oil well)*; COURTESY OF JIM DEMATTIA *(algae farm)*; WAVE/CORBIS *(cement)*