WORLD·WATCH

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FEATURES

American Electric Power's coal-fired power plant in Putnam County, West Virginia, USA.

Photo Courtesy Vivian Stockman and the Ohio Valley Environmental Coalition

FRONT COVER: illustration by Wesley Bedrosian.

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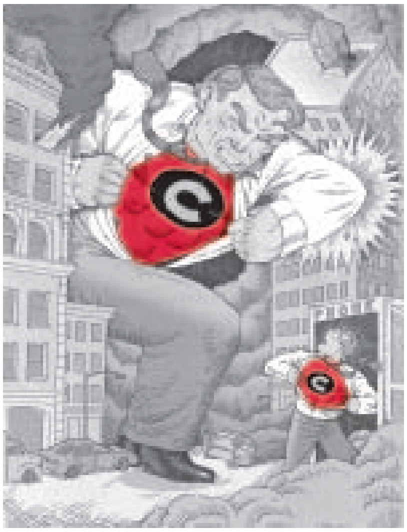


Portraits in Carbon

Forget oxygen—carbon may be the most important element on the planet.

by Todd Neff

Illustrations by Wesley Bedrosian

It's hard to avoid the number six in talking about carbon: It's the sixth element in the periodic table, and normally has six protons and six neutrons in its nucleus and six electrons hovering in loose formation around it. This form, called carbon 12, accounts for 99 percent of all carbon (carbon 13 and 14 account for the rest). As a substance, pure carbon comes in several guises, but among the most important are graphite (which is typically soft, black, slippery, and flaky); diamonds (which can be any of several colors, or colorless, and are as hard as elements come); and amorphous carbon (such as coal and soot). Carbon is abundant in the Earth's crust and biosphere, and as coal costs as little as 1.2 U.S. cents per kilogram. As natural diamonds, however, it can cost thousands or even millions of dollars per gram. The name derives from the Latin *carboneum*, but is rendered *kohlenstoff* in German, *uhlik* in Czech, and *sekitan* in Japanese.

Oh, and carbon is the basis of more than 20 million chemical compounds and thus of life as we know it.

Those are the raw, actuarial facts, perhaps carbon's dullest mugshot face. But carbon is more interesting than these facts suggest, and like a quick-change artist has many faces. Here are five more:

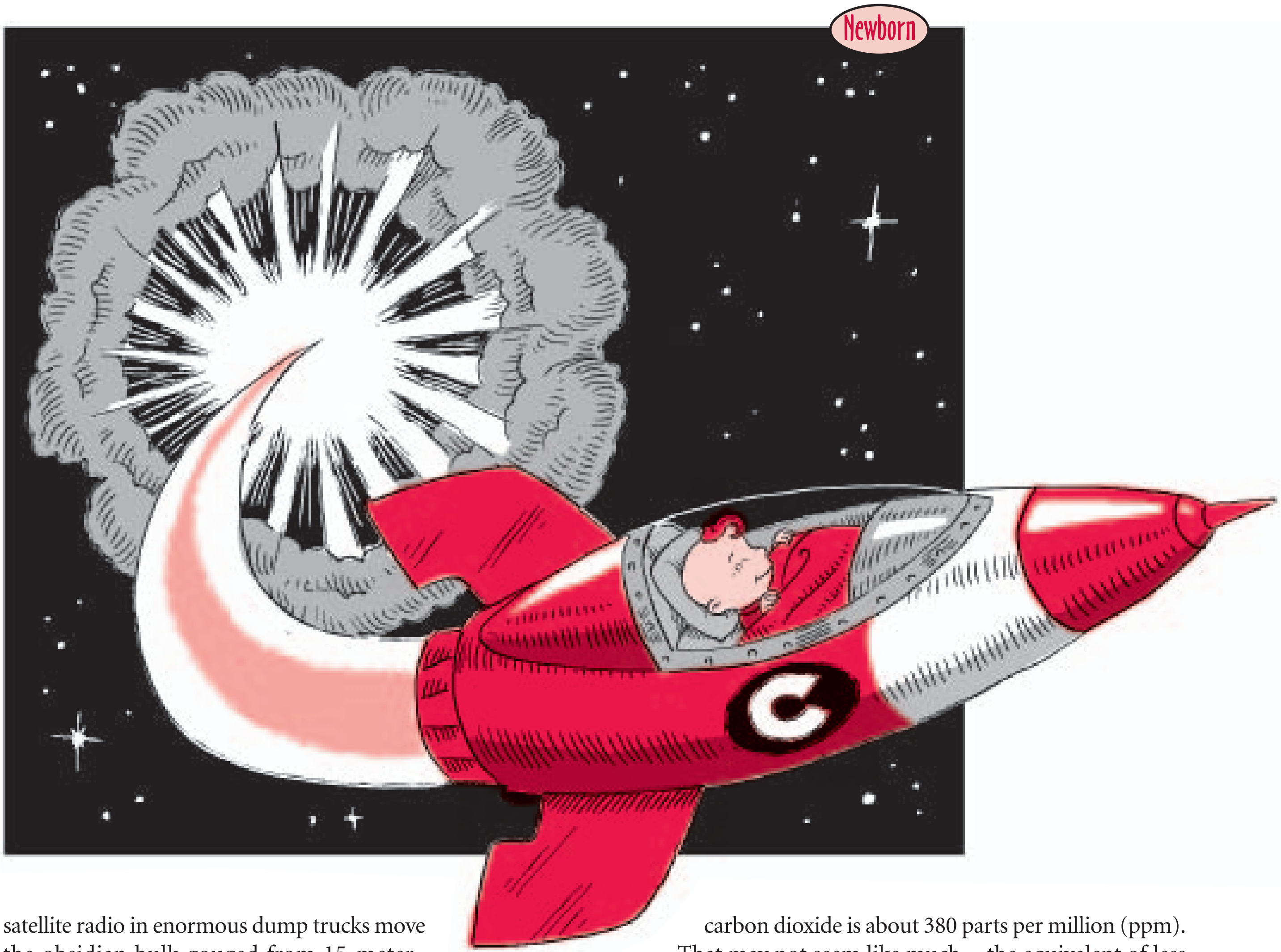
Newborn

Carbon is born in dying stars and scattered when they explode. Our own solar system formed from such remnants, a collector hoarding from interstellar estate sales. Carbon represents less than one-tenth of the Earth's crust by mass, but is the only element capable of forming robust single bonds with other atoms at ambient temperatures, which is why it is the chemical backbone of the living world. "Organic chemistry" is carbon chemistry. Carbon is proteins, carbohydrates, hydrocarbons, and DNA. Shakespeare was mostly carbon, and so were his quill, ink, and the paper on which he scratched *Hamlet*. It's perfume and plastic, trash bags and tennis balls and tree stumps.

It's also natural gas and oil and coal—the fossil fuels that modern civilization runs on.

Much of this was formed during the aptly named Carboniferous Period, a part of the Paleozoic Era from 354 to 290 million years ago. That period saw untold millions of swamp trees with two-meter-diameter trunks die but not rot—in part, some believe, because herbivores, termites, and certain bacteria had not yet evolved to eat lignin (a new plant innovation at the time), which is the glue differentiating wood from leaves. Unable to decompose, the resulting peat piled up in northern Europe, parts of Asia, and in the eastern and midwestern United States. Seas rose and fell, covering the swamps intermittently and cutting off the oxygen that would otherwise fuel organic decay. Pressure and heat over millions of years converted the material to coal, specifically anthracite, the hardest and most energy-rich form, composed of up to 98 percent carbon.

Bituminous coal, softer and younger, is only about 60 percent carbon, but it's lower in sulfur too, and thus emits less acid-rain-forming pollutants when burned. This coal, from places like the Powder River Basin, began as giant ferns and other plants flourishing in the lush effluvial plains of what is now Wyoming about 55 million years ago. Men listening to



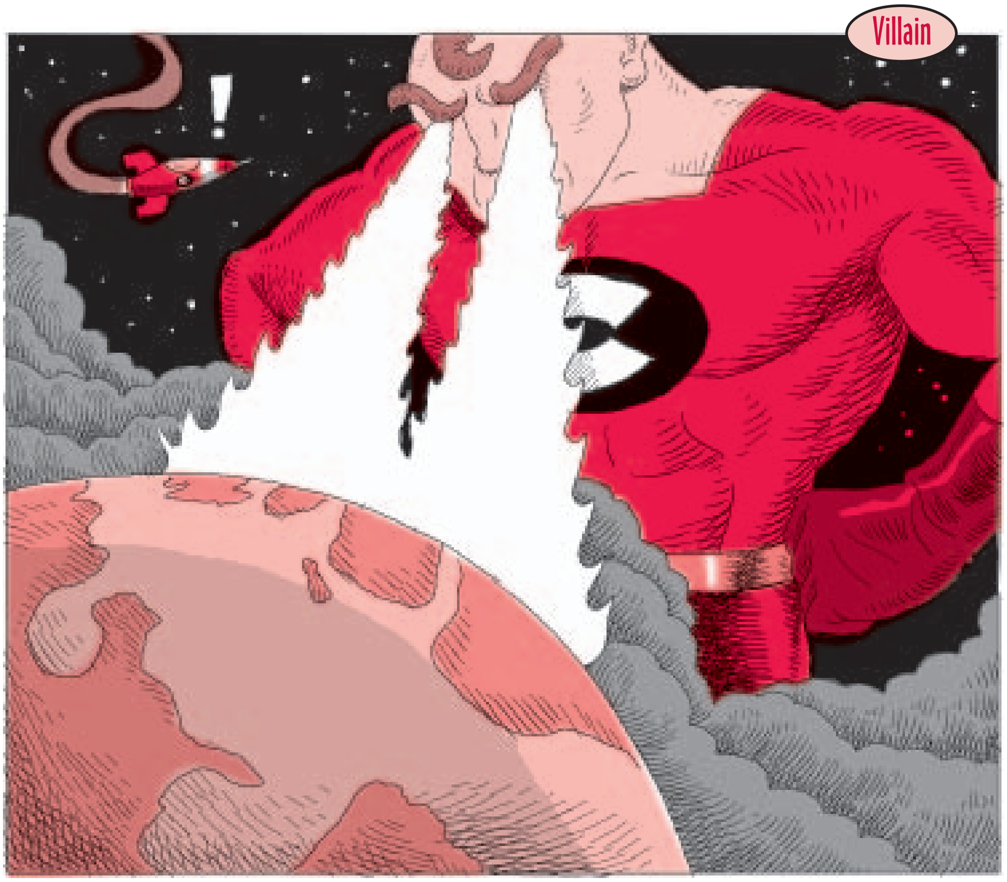
satellite radio in enormous dump trucks move the obsidian bulk gouged from 15-meter-thick seams to railheads, dispatching 400 million tons every year—40 percent of the coal burned in the United States—to power plants around the country.

Villain

Which brings us to carbon's dark side. Atmospheric carbon likes to run with pairs of oxygen atoms like some celebrity with arms around identical twins—carbon dioxide (CO_2). It is an association born in fire, through the combustion of trees, dung, and fossil fuels. The fossil fuels are the main culprits. Their carbon, largely buried and sequestered until James Watt came up with the steam engine, is being unlocked and flung into the atmosphere at a rate of 7 billion metric tons of carbon every year. (That's just the carbon; the CO_2 gas weighs more like 27 billion tons. The United States emits nearly 6 billion tons of that total.) The weight of 7 billion tons of carbon is roughly equal to that of a concrete block as tall as the Empire State Building and covering 450 hectares.

The current global average atmospheric concentration of carbon dioxide is about 380 parts per million (ppm). That may not seem like much—the equivalent of less than a nickel in $100—but it's 36 percent more than the 280 ppm present in the air before the industrial revolution. Even such trace concentrations of CO_2 help keep Earth from a state of ice-age frigidity by creating the greenhouse effect, in which carbon is, with water vapor, methane, and a host of other trace gases, a key player.

Carbon dioxide's heat-trapping properties are a matter of chance, the product of the molecule's affinity for certain bands of infrared light. Infrared waves, which radiate invisibly from a good campfire or a sunlight-warmed Earth, make carbon and its escort oxygen atoms dance. As Steve Montzka, an atmospheric chemist with the National Oceanic and Atmospheric Administration's Earth System Research Laboratory in Boulder, Colorado, describes it, oxygen and nitrogen, the dominant atmospheric gases, pay the infrared light no heed. But the bonds in carbon dioxide "have a certain frequency, like two balls on a spring. If you hit the balls, they'll start vibrating back and forth in a nice, coherent way. That's kind of what happens when infrared light hits carbon dioxide molecules, and that's why it adds energy to the molecule." The carbon dioxide molecules vibrate, rotate, and



stretch for an instant, then spit the infrared light—heat—back out in all directions.

So while 280 ppm was cozy, 380 ppm (and rising) looks like trouble. The U.S. National Center for Atmospheric Research's top climate model has estimated that a doubling of current concentrations—a real possibility by century's end unless we temper our use of coal and other fossil fuels—will raise global average temperatures nearly 6 Fahrenheit degrees by 2100 (3.3 Celsius degrees).

Jailbird

Coal's outsized global-warming footprint has led the U.S. Department of Energy to commit hundreds of millions of dollars to carbon capture and storage research. This is suddenly the Holy Grail of the fossil energy industry. The idea is to sequester CO_2 emissions from coal-fired power plants in underground reservoirs. The carbon came from beneath the Earth, after all—why not just put it back?

Well, for one thing, it would require the extremely expensive scrapping of conventional coal-burning plants and their replacement with plants using integrated gasification combined cycle technology. IGCC plants convert coal to a gas of carbon dioxide and hydrogen. The hydrogen is burned to run a turbine, and then the exhaust generates steam to run a second turbine. Such plants are about 10 percent more efficient than conventional coal-fired plants, which convert less than a third of their coal energy into electrical energy, and also scrub pollutants such as mercury and sulfur dioxide more effectively. The carbon dioxide would be injected directly into deep saline aquifers or other geological formations, or even pumped down to the sea floor, where the enormous pressures and frigid temperatures would liquefy it and allow it to pool forever on the bottom. In theory.

There are challenges. Only four IGCC power plants exist in the world, including two in the United States. Contrast that with 5,000 large coal plants, with many more proposed or being built (See "Coal Rush," page 8, and "China and Her Coal," page 14). Of the roughly 150 new U.S. coal plants currently planned, only a handful would use IGCC technology, and just one (proposed for Colorado by Xcel Energy) is slated to actually sequester the CO_2. It won't become operational before about 2013, Xcel officials say.

Nor is sequestration itself a thoroughly known quantity, although oil companies have been injecting CO_2 underground to force more petroleum out of existing fields for decades. At Chevron's Rangely oil field in western Colorado, for instance, they go through 36 million cubic feet of CO_2 a day, piped 260 kilometers from Wyoming's Green River Basin. It comes with a financial and energy cost. Chevron engineer R.J. Wackowski estimates that the company has spent "hundreds of millions of dollars" on CO_2 injection. It takes 33,000 kilowatts distributed across 11 howling compressors to squeeze the gas into the 2,100 pounds per square inch pressure needed for injection.

That's not cheap, but consumers seem ready to pay almost anything for oil and it fetches high prices. But coal's historic benefit is its cheapness, and the Intergovernmental Panel on Climate Change's *Special Report on Carbon Dioxide Capture and Storage*, released in September 2005, estimates that a new IGCC plant with carbon storage would be from 20 percent to 100 percent more expensive per kilowatthour than a new conventional coal-fired plant, assuming no carbon taxes.

And will carbon forced into sequestration actually stay put? Only our descendants will know for sure. There is just one production facility in the world, run by Norway's Stadtoil, that is sequestering CO_2 for sequestration's sake, and it's only been operating for 10 years. The U.S. Department of Energy is spending more than $100 million through 2009 to understand the technical feasibility of storing billions of tons of carbon dioxide under U.S. soil.

Jeff Goodell, author of *Big Coal*, has his doubts about geologic sequestration. He questions the electric power industry's will to implement carbon capture and storage on any significant scale. "They like to pretend it's a really simple thing—pump it down there and cap it off," Goodell says. "But the Earth is like a giant pincushion, and this CO_2 can migrate for miles and come up through fissures." The IPCC report, on the other hand, concludes that 99 percent of sequestered CO_2 would likely stay put for a millennium. Ken Caldeira of the Carnegie Institution of Washington's Department of Global Ecology, a co-author of the IPCC report, says sequestration needs to play a role in future energy portfolios, but that there will be political challenges. "It implies you're going to have some sort of globally coordinated carbon police, part of some incorruptible squad," he said. "My brother works in a food plant that makes kosher food. When the rabbi walks away, they keep putting the label on it even when no one is blessing it."

Displaced Person

Anyone aspiring to carbon neutrality can take action immediately. Drive a mid-sized car 20,000 kilometers a year? A one-time payment of $72 to CoolDriver.org will let you release the resulting six tons of CO_2 skyward with a clean conscience. Flying from New York to Los Angeles? TerraPass.org's Puddle Jumper package can make up for the ton of CO_2 emissions for $9.95.

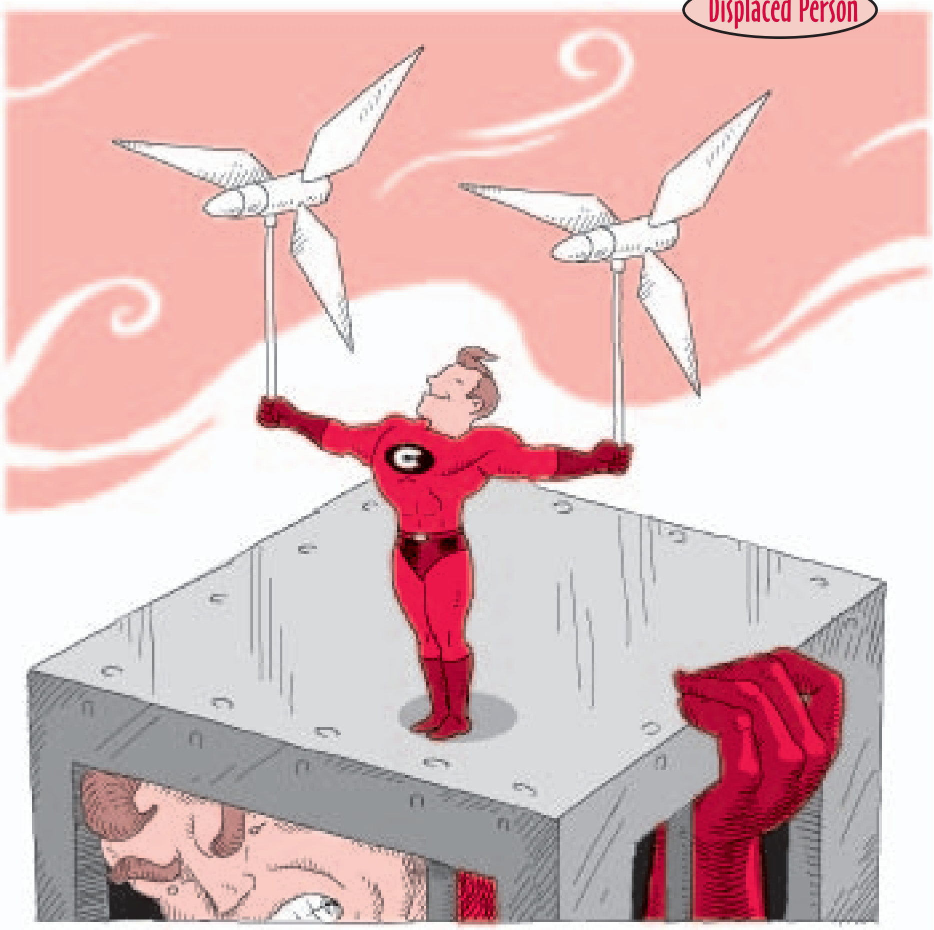
Both programs deal in carbon offsets, in which fossil fuel burners indirectly pay someone else to make up for their combustion. CoolDriver and TerraPass send the money to renewable energy projects and are among many organizations offering consumers, businesses, and municipal and state governments ways to ease their carbon load by investing in everything from groves of trees to new wind farms.

This is still an unregulated and confusing business. To offset six tons of carbon emissions costs $72 at CoolDriver.org, $40 at DriveNeutral.org and $49.95 at TerraPass.org, where you also get a free luggage tag. There also have been questions about the accountability of outfits promising to offset flights to Singapore by planting trees in Central America. "What was on the land before those trees in Costa Rica and so on were planted? Did they cut other trees down and get paid to replant?" asks Russ Schnell, director of the U.S. National Oceanographic and Atmospheric Administration's global atmospheric gas sampling network. Done properly, Schnell said, such projects do have the benefit of sequestering the weight of the tree in carbon.

Carbon-offset equivalents of companies like PriceWaterhouseCoopers have emerged to assuage such fears. The San Francisco-based Center for Resource Solutions runs the Green-e verification program, and the Climate Neutral Network has its Climate Cool program to make sure it's all on the up-and-up.

How much impact carbon offsets are having on the market remains a question. Kevin Rackstraw, North American development leader for Clipper Windpower, says it's hard to convince lenders on $200 million wind-farm projects that 100,000 people buying green power today will do the same in

Displaced Person



15 years. Even major buys of renewable energy credits by companies or municipalities wanting to offset their electricity use have a limited effect compared to federal tax subsidies. "If renewable-energy credits go away, we can still do business. If the production tax credit goes away, we're at a standstill, practically," he says.

Superhero?

In the wrong form or place, carbon can be troublesome. But it also has remarkable properties that might be valuable. Consider carbon fiber, for instance.

Spun at high temperature from strands of the polymer polyacrylonitrile, carbon fiber's combination of strength, lightness, and relative imperviousness to heat and cold has landed it a role in the Space Shuttle's nosecone and countless satellites. It is coveted by military aircraft designers and, lately, by those designing warships. Massive wind turbines would be impossible without it. Voices as diverse as former CIA director James Woolsey (now an energy efficiency champion) and Amory Lovins of the Rocky Mountain Institute want to see carbon fiber auto bodies, which could weigh a third less than steel. Given the U.S. automakers' financial situation and the fact that carbon fiber bodies would cost at least 10 times more than steel, that might be a stretch. But then, the new boss at Ford Motor Company was formerly CEO of Boeing Commercial Airplanes, and Boeing has certainly seen the carbon fiber light.

Fully half of the wings and fuselage of the efficient, $150-million Boeing 787 Dreamliner, due to fly in 2008, is made of carbon-fiber composites. The move lightens the aircraft enough to boost fuel efficiency 3 percent, but also allows for bigger windows, higher cabin air pressure, and higher cabin humidity because corrosion isn't an issue. Boeing archrival Airbus is also using carbon fiber extensively in its gargantuan new A380.

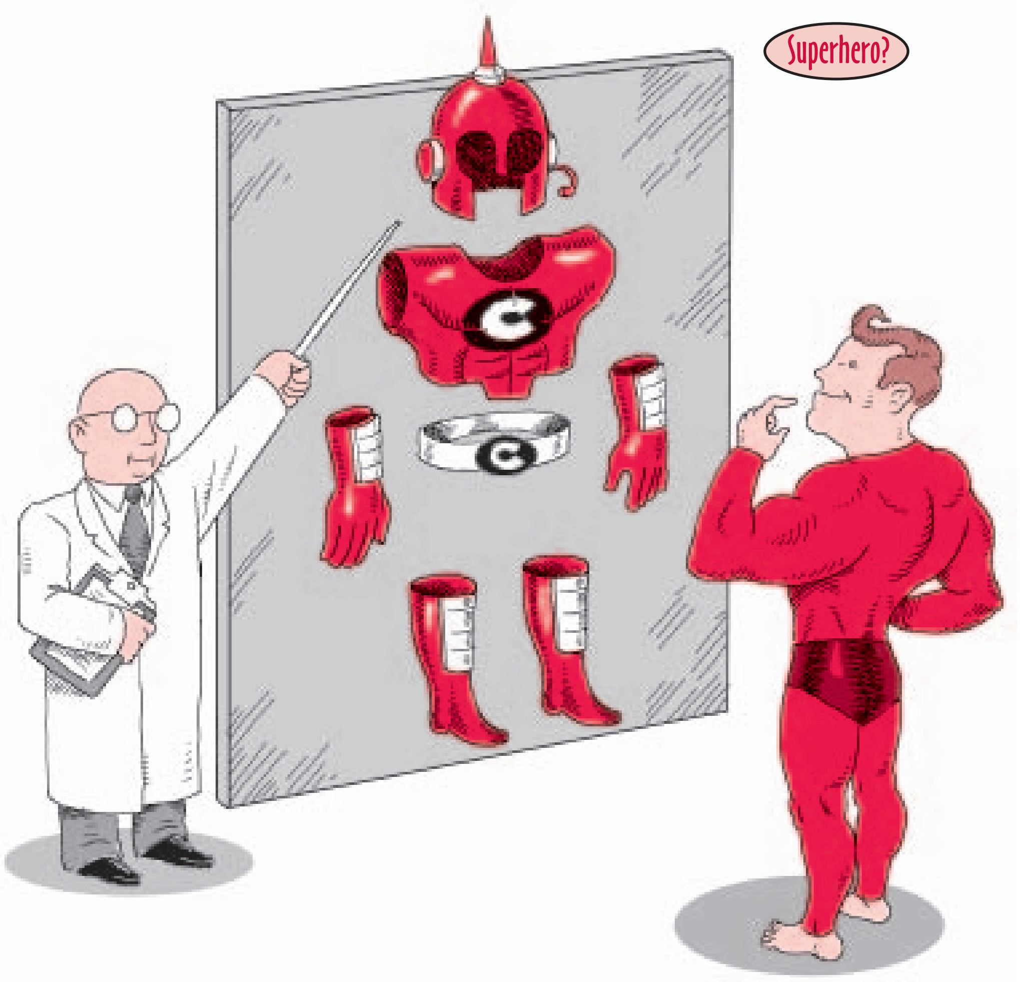
Carbon fiber is so hot that it's hard to come by. Toray Carbon Fibers America, Inc., which is supplying carbon fiber for the Boeing 787, has been running at 100 percent capacity for three years straight, according to sales manager Buster Tipton. The company opened a new U.S. plant last year and has three more planned in Japan and Europe. "Make no mistake, there's a global shortage," Tipton said—which may explain why high-end carbon fiber bicycles can cost as much as small cars did 10 years ago.

Then there are nanotubes.

In 1985, scientists at Rice University created a new form of carbon, consisting of 60 atoms vaguely resembling a soccer ball. The Buckminsterfullerene, or "buckyball," launched the field of carbon nanotechnology and won its co-discoverers the 1996 Nobel Prize in chemistry. Six years later, Japanese scientist Sumio Iijima reported his creation of carbon nanotubes—cylindrical fullerenes.

Carbon nanotubes are an entirely new and potentially miraculous material, 60 times stronger than steel and capable of conducting electricity 1,000 times better than copper. Carbon nanotube research is among the hottest areas of research in nanotechnology, which refers to engineered structures less than 100 nanometers in size. (A nanometer is a billionth of a meter, or the same part of a meter as the length of your thumbnail is of the Earth's diameter.)

Nanotubes are as thin as one nanometer wide, but can be thousands of nanometers long. Potential applications range



from next-generation transistors and solar cells to artificial muscles and blast-resistant clothing. Some firms are using nanotubes in the electrodes of experimental fuel cells, as electron guns in field-emission displays, and in radiation-hardened computer memory for military and space applications. Commercial applications include nanotube-infused plastic that dissipates static electricity, an attractive feature in automotive fuel lines and microelectronics manufacturing, where a spark can be costly.

Ken McElrath, vice president at Carbon Nanotubes Inc. in Houston, says that if the first half of the 20th century was the age of steel and the latter half the age of polymers, then the coming decades belong to carbon nanotubes: "We're on the ground floor of a new material."

Can nanotubes possibly live up to the hype? Dean Aslam, director of the Micro and Nano Technology Laboratory at Michigan State University, thinks they will. Aslam is most bullish on nanotubes for use in miniaturized chemical or biological sensors. His group and a University of Michigan team are collaborating in an effort to use carbon nanotubes to make a microchip-based gas chromatograph, or airborne chemical detector. Carbon nanotubes have a huge surface area per unit volume, which is perfect for capturing molecules as they float by. Heat the nanotubes and they drop their contents into a tiny chamber for analysis. Such a system embedded in a watch could enable the equivalent of food labeling for air. "We know what kind of food we're eating. We don't know what kind of air we're breathing," Aslam says.

What's the downside? So far, nanotubes don't come cheap: Research grades of the tubes cost up to $2,000 per gram, though commercial varieties are far less pricey. Kalman Migler, a scientist at the U.S. National Institute of Standards and Technology who is working on developing nanotube standards, says nanotubes remain poorly characterized and that the market remains nascent. Another issue, he says, is understanding the possible environmental and human health impacts before nanotubes become the next plastic: "I believe there's a need for a much greater effort to understand the effects of nanotubes and nanomaterials on safety, health, and the environment, and it's clearly an area of concern to great numbers of people thinking about nanotechnology."

Rice University's Center for Biological and Environmental Nanotechnology focuses on health impacts and medical applications of nanotubes. Kristen Kolinowski, the center's executive director for policy, says nanotubes pried apart in solution have been shown to kill cell cultures, and that nanotubes forced into the lungs of rats and mice caused irritation. A University of Michigan study has shown nanotubes to accumulate in living cells and with that, potentially, food webs.

"We have to think about the impacts of putting these things in the body. There are people who think that carbon nanostructures are not going to be the best materials in the human body unless we can isolate them or they turn out to be pretty nontoxic," Kolinowski said. "I think the jury's still out on that."

Todd Neff *covers science for the* Daily Camera *in Boulder, Colorado. He is writing a book about NASA's Deep Impact mission to strike a carbon-carrying comet.*

For more information about issues raised in this story, visit **www.worldwatch.org/ww/carbon**.