far they have flunked a key emissions test: They produce more nitrogen oxides and soot particles than proposed standards allow.

Diesel-engine designers have always faced a perplexing Catch-22. Because of the way the engines burn fuel, techniques that reduce NO_x emissions—such as recirculating exhaust gases back into the engine to be burned again—increase soot production, while reducing soot ratchets up NO_x. To address the problem, PNGV-funded scientists are tinkering with fuel variations and a filter that can sop up twice as much NO_x before it leaves the tailpipe. It's a daunting challenge: To meet NO_x standards, for instance, sulfur may have to be virtually eliminated from fuel, cut from 500 to 50 parts per million.

Critics are skeptical that CIDI engines can clean up their act. Under proposed California low-emission standards that would take effect in 2004, for instance, even CIDI-based hybrids "might be virtually illegal to sell in California," the nation's largest car market, says Jason Mark of the Union of Concerned Scientists in San Francisco. He would rather see the $40 million a year spent on the diesel program go toward developing cleaner technologies such as fuel cells.

Other critics are calling for an end to PNGV. Taxpayers "should not be forced to help private companies," says Moore, who supports the efforts of some budget hawks in Congress to trim the program. The opponents got some new ammunition last year, after Chrysler merged with Daimler, Germany's car giant, prompting Kasich and others to question whether the United States was funding research that would benefit foreign competitors. PNGV skeptics also seized on Toyota's 1997 introduction of Prius, a hybrid gas-electric car, noting that the Japanese company built the car on its own dime (see sidebar).

Such complaints have done little to erode PNGV support, however. In recent testimony before Congress, Administration officials dismissed concerns about foreign companies siphoning intellectual property from the project, and they hold up Toyota's supercar as a reminder that PNGV is necessary to keep U.S. automakers competitive. Supporters also note that low gas prices provide little incentive to invest in developing high-mileage cars. "This field would be asleep without federal funds," says a Senate aide.

But with low gas prices and no requirement to market cars based on the PNGV prototypes, observers express skepticism that supercars—at least those made by U.S. firms—will roll into showrooms anytime soon. Jokes one industry official: "You've probably got about a decade to save up for a downpayment."

–DAVID MALAKOFF

NEWS

Bringing Fuel Cells Down to Earth

Automakers are banking on fuel cells, used to run equipment aboard spacecraft, to power the first zero-emission vehicles; the type of fuel that supplies the cells could determine how deeply these cars penetrate the market

Hydrogen has long been touted as the fuel of the future. Combine it with oxygen in a fuel cell, and it will give you electricity and a little heat, with one byproduct: water. Trouble is, the future never quite seems to arrive. Although fuel cells helped the Apollo astronauts make it to the moon, they have never made much of an impact on Earth. But if you listen to automakers these days, you may think they've seen the future—and that the future is on its way to a showroom near you.

Electricity generation gap. Fuel cells powered the Gemini spacecraft; now they are ready to hit the road, in DaimlerChrysler's NECAR 4.

CREDITS: (LEFT TO RIGHT) NASA; DAIMLERCHRYSLER

In a bid to keep up with ever tighter air pollution standards, automakers are pushing hard to introduce fuel cells to mundane family sedans and pickup trucks. Virtually every major car company is now working on the technology. Early demonstration vehicles running on hydrogen and methanol are already on the road. The California Fuel Cell Partnership, a new collaboration between car- and fuel cell–makers, oil companies, and government agencies, plans to put some 50 demo cars and buses through their paces in the next 4 years. And DaimlerChrysler is so confident the partnership will like one of the early designs that it has promised to roll out 40,000 fuel cell vehicles by 2004. If fuel cells, as expected, become cheaper and can match the performance of traditional car engines, they "will be the most prominent power source in the next century," predicts Ron Sims of Ford's research lab in Dearborn, Michigan.

Those are brave words, considering that the internal combustion engine—thanks to a stream of technological advances since Henry Ford's day—has managed to beat back challenges from every upstart alternative for powering automobiles. And the fuel cell's challenge could be blunted by a bruising battle over which fuel should provide the hydrogen the cells will consume. It's a battle that could undermine the technology before it ever gets up to speed.

Engineers and clean-air experts say the simplest and cleanest option is hydrogen gas itself. But it would cost tens of billions of dollars to outfit all the filling stations in the United States to supply hydrogen—not to mention an intense marketing campaign to convince the public of the safety of a fuel still associated with the fiery demise of the Hindenburg, a hydrogen-filled zeppelin, in 1937. Car and oil companies would prefer to equip vehicles with miniature chemical factories to convert liquid fuels, such as gasoline or methanol, into hydrogen gas that can be fed into fuel cells. Critics, meanwhile, argue that the converters likely will be expensive and prone to breaking down. "Everybody is pushing their own version of the technology," says Reinhold Wurster, a fuel cell expert at LB Sustain Technique in Ottobunn, Germany.

The outcome of this battle will set the course for fuel cell technology—and perhaps alter the world's energy map—well into the next century. Because the United States uses over 40% of the gasoline produced globally, "it's the gorilla that drives the rest of the world," says John Turner, a fuel cell expert at the U.S. Department of Energy's (DOE's) National Renewable Energy Lab in Golden, Colorado. "What we do here will have a lot of influence on future energy use."

Space-to-Earth odyssey. Fuel cells didn't start nipping at the heels of traditional car engines overnight. The technique was invented in 1839—more than 20 years before the first internal combustion engine—by Sir William Grove, a Welsh judge who began his career as a physicist. He shot an electric current through water, splitting the molecules into oxygen and hydrogen. When the gases recombined in his experimental cell, Grove noted, they produced a current.

The technology remained little more than a curiosity until the late 1950s, when General Electric developed proton-exchange membrane (PEM) fuel cells as a lightweight solution for providing onboard electricity to the Gemini spacecraft that put some of the first U.S. astronauts in orbit. Around that time, other firms developed alkaline fuel cells, which use a liquid electrolyte instead of a membrane to control the flow of charged ions in the cell. Alkaline cells proved more efficient for cosmic voyages: Space shuttles still use them to generate about 45 kilowatts (kW) of power. But this electricity comes at a pretty penny. The shuttle's alkaline cells typically cost more than $500,000 per kW, about 10,000 times the price—roughly $50 per kW—that would start to interest carmakers.

To avoid fuel cell sticker shock, firms are revisiting GE's PEM technology as a rough blueprint for making fuel cells for cars (see sidebar, p. 683). Since first starting to tinker with this design in the mid-1980s, Ballard Power Systems of Burnaby, Canada, for one, has developed fuel cell assemblies that generate 25 kilowatts of power (a trio of which can power a family sedan) and run at a cool 85 degrees Celsius. Along the way Ballard has lowered the price 100-fold, to about $275 per kilowatt. Based on this success, and the belief that the price will be right when fuel cells are made en masse, Ballard has inked investment and research deals with major automakers totaling more than $1 billion.

Ballard projects that, by converting hydrogen to electricity directly, fuel cell engines could make productive use of up to 60% of the power generated; internal combustion engines, by comparison, squander about 75% of the power they generate. That should allow hydrogen vehicles to travel about 87 miles per gallon (37 kilometers per liter), without the tailpipe pollutants of today's cars. What's more, according to Wurster, fuel cell engines—thanks to a simpler design—should be cheaper than combustion engines when mass-produced. Such attributes, says Sims, make fuel cell vehicles the leading contender to meet California's strict clean air rules, which require that 10% of cars sold in the state after 2003 produce zero emissions. Maine, Massachusetts, New York, and Vermont are all mulling over similar zero-emissions laws, too.

Nagging questions. Despite the impressive achievements at Ballard and other fuel cell–makers, many observers say the technology has a bumpy road ahead. Looming over the industry is the question of which fuel will power tomorrow's cells—a "major topic that will drive fuel cells for the next 5 years," says Neil Rossmeissl, who manages the hydrogen research program at DOE in Washington, D.C.

Gasoline is the obvious default option, as the infrastructure for delivering it to cars is already in place. But gasoline has a big strike against it: It is composed of a broad mix of hydrocarbons that must be converted—or in industry parlance, "reformed"—to hydrogen. That makes the onboard conversion plant, or reformer, very difficult to design and has put gasoline reformer technology "at least a decade behind" reformers that work with methanol, a simpler hydrocarbon, says C. E. "Sandy" Thomas, who analyzes fuel cell economics at Directed Technologies Inc. in Arlington, Virginia. Oil companies would also have to create a new grade of gasoline purged of impurities that can ruin reformer catalysts.

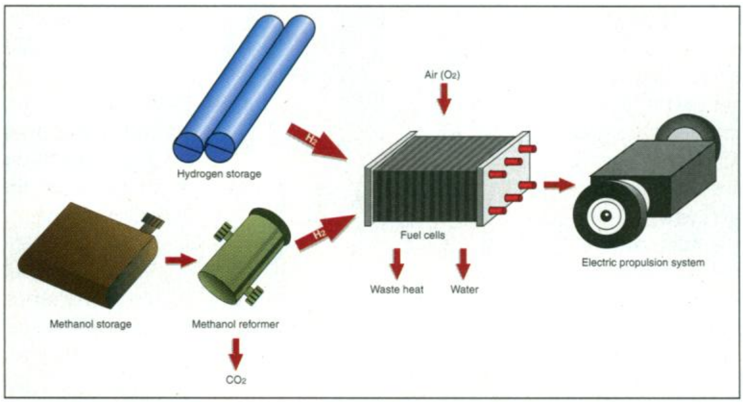
With gasoline thus trammeled, methanol has sprinted ahead. Although only half as energy-dense as gasoline—cars would need nearly a double-sized fuel tank for a similar cruising range—methanol is a liquid at room temperature, which means that it can be handled and transported more easily than gaseous hydrogen. According to a recent analysis by Thomas and others, U.S. chemical companies now have the capacity to produce enough methanol to support 1.5 million fuel cell vehicles. A study financed by the American Methanol Institute in Washington, D.C., concluded last year that each gas station that wants to sell the highly corrosive fuel would have to install a new type of underground tank that costs about $50,000. Vehicles too would have to be equipped with special tanks. Still, DaimlerChrysler, Honda, and others say they are betting on methanol. "For the everyday conventional car, methanol seems to be the fuel of choice," says Wurster.

A second look. But others argue that the economics, environmental concerns, and science favor a dramatic shift in car fuels to hydrogen gas. "As you go from direct hydrogen to methanol to gasoline, you increase the levels of emissions," explains Sims. "Many people think hydrogen is a dark horse," adds Thomas. "But if you look at all the different costs, it comes out ahead."

Perhaps the biggest impediment facing hydrogen-powered vehicles is building from scratch an infrastructure for distributing the gas. Today, U.S. chemical plants make hydrogen gas and ship it nationwide by chilling it to 20 degrees above absolute zero, at which point it becomes a liquid. Because that takes a lot of energy, Thomas argues that it would be better for each filling station to make its own hydrogen and store the gas in underground tanks. Gas stations could run electrolysis machines at night, when electricity is cheaper, turning water into hydrogen and oxygen. Or existing natural gas pipelines could deliver hydrocarbons such as methane, which can be reformed easily to hydrogen. Either scheme would cost less than $1 to create an amount of hydrogen equivalent to a gallon of gasoline, Thomas contends.

Big savings would also come from doing away with the need for reformers in cars. "The typical automobile is used less than 2 hours a day," and even then its engine is rarely working at full capacity, says Thomas. "If I take the onboard reformer from one fuel cell vehicle and put it on the curb, it could serve 110 vehicles" by churning out hydrogen continuously, he says. With all the costs factored in, Thomas calculates that creating the infrastructure to power fuel cells with methanol would cost roughly $1300 to $2800 per vehicle. Gasoline comes in at around $2350 to $5200, largely due to a more complex reformer. And hydrogen would add about $990 to $1150. The extra expense for reformer-based systems, along with the likelihood of the complex devices breaking down, says Turner, could sour consumers on fuel cell cars early on. "If that happens, everybody loses," he says.

Critics, however, contend that hydrogen is impractical for long hauls. Because of the gas's low density, even a pressurized steel tank would have to be about four times the size of a conventional one to give a hydrogen-



Fuel fight. Hydrogen or methanol "reformed" to hydrogen are the leading contenders for powering fuel cell cars.

SOURCE: HUMBOLDT STATE UNIVERSITY

powered car the same 560-kilometer range as a 1999 Ford Taurus, says Sims. Rossmeissl and others note that experimental lightweight carbon-fiber tanks and other improvements could extend the driving range of hydrogen-powered cars.

The dominant fuel should emerge in the next few years, say Sims and others. Hydrogen is poised to sprint to an early lead: In the next 2 years the California Fuel Cell Partnership plans to build two hydrogen fueling stations in the state which will pump hydrogen gas into onboard fuel tanks. As for methanol, it could take a few years before reformers are reliable enough to mass-produce. "Until then, we've got this window to prove the [hydrogen] technology" and to devise better ways to make it and store it, says Sigmund Gronich, a DOE hydrogen specialist. But unless hydrogen blows away the field, it is unlikely to conquer the passenger car arena. "As onboard fuel processing reaches maturity in the middle of the next decade, you're probably going to see methanol become a fuel of choice," says Sims.

Whatever version of the technology gets the checkered flag will have a long reign, says Turner. Even if gasoline wins, it could provide a hydrogen source until fossil fuels become scarce decades or even centuries from now. But at that point, Turner predicts, consumers will need to switch to hydrogen, which is easier than methanol to generate from solar power and other renewable energy sources. "Ultimately we will get there," says Turner. "The question is, do we generate an interim infrastructure and then 50 years from now do it all over again?"

–ROBERT F. SERVICE

NEWS

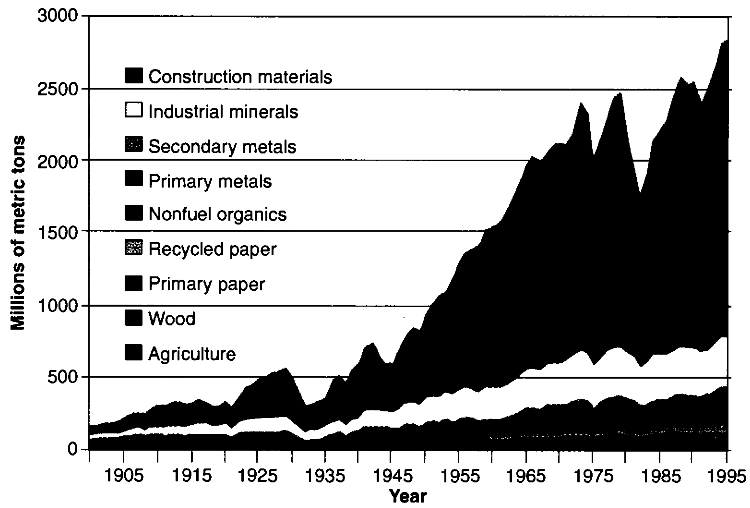
Turning Engineers Into Resource Accountants

A new discipline is trying to persuade companies that tracking the flow of materials and energy over a product's lifetime makes good business sense

To Robert Frosch, a computer is like a frog. Both are made of energy-intensive materials: organic molecules for the amphibian, plastics and metals for the computer. Both use energy as they operate. And, like a dead frog decomposing in a marsh, an obsolete computer will decay somewhere, maybe in a landfill. But Frosch, an industrial ecologist at Harvard University's Kennedy School of Government, believes their life cycles could be made even more similar: Before the computer is junked, he would like to see it picked over by a scrap dealer—someone, he says, "a little like the microorganisms that turn waste into fertilizer."

This view of organisms and consumer goods leading parallel lives is gaining a wider audience thanks to Frosch and like-minded scientists, whose goal is to scrutinize every gram of material and joule of energy going into and out of a product. "It's a way of organizing and systematically studying the built environment," explains Iddo Wernick, a physicist at Columbia University. The philosophy has begun to pay off—mainly in Europe—in everything from appliances designed with reusable parts to schemes for capturing precious metals that may otherwise end up in landfills or riverbeds.

However, a cradle-to-grave approach to doing business hasn't yet caught fire in the United States. Efforts to get U.S. companies to feed off each other's waste, for instance, have sputtered (see sidebar), and only a handful of corporate titans have embraced the concept of scrutinizing their products' material and energy flows. That irks Frosch, who decries the consumption in developed countries, which deplete natural resources at a prodigious rate: about 1000 times the body weight of each inhabitant per year, according to a 1997 study led by the nonprofit World Resources Institute in Washington, D.C. "You find amazing amounts of things being thrown away that are perfectly useful," Frosch says. Industrial ecologists hope to curb this compulsion by convincing companies—and people—to make the most of every iota of energy and substance. But that may happen only if governments end policies that embrace waste, such as cheap landfills and tax subsidies that skew the real costs of virgin materials.



All-consuming. The United States' appetite for many raw materials shows no sign of tapering off.

SOURCE: USGS

What goes in must come out. Industrial ecology was born in the late 1980s, when Frosch and Nicholas Gallopoulos, then at General Motors, described in a *Scientific American* article how to analyze a factory the same way you might an ecosystem, by assessing its energy cycles and decay and reuse. "A key question is, where did this stuff come from and where is it gonna end up?" Frosch says. The budding field, a mix mainly of social scientists, engineers, physicists, and ecologists, got a boost 2 years ago from the debut of the *Journal of Industrial Ecology* (mitpress.mit.edu/JIE).

Fueling the academic push is a wave of regulations and voluntary targets aimed at cutting back on waste. Since the early 1990s, several European countries and Japan have begun to mandate that companies use less packaging and take back old consumer appliances. In the United States, the Clinton Administration has pushed voluntary initiatives, including a program in which the Environmental Protection Agency (EPA) works with companies to help them "design for the environment"—for example, by finding alternatives to lead solder to make computer circuit boards. Some European countries, such as Germany, are even discussing an ambitious goal to curtail their consumption of natural resources by 90% by 2040.

One way to reach these targets might be to employ the principles of industrial ecology. In its most reductionist form, the discipline involves life-cycle assessment—drawing a circle around, say, a television or a toaster, then tallying the materials and energy that go into their parts, manufacture, and use and the waste and pollution that come out. "You go as far back in the chain as the coal coming out of the ground," says H. Scott Matthews of Carnegie Mellon University in Pittsburgh. The next step is to design a