Firing Up Fuel Cells

Has a space-age technology finally come of age for civilians?

By Richard Lipkin

In January 1994, a new type of bus will hit the American road.

Unlike conventional diesel buses, whose growling engines spew coarse black fumes, this 30-foot prototype should, if all goes well, leave little trace of its passage. No thick exhaust. No engine grind. No diesel grime. Just the thrum of its electric drive, powered by a phosphoric acid fuel cell that converts airborne oxygen and methanol-derived hydrogen into electricity and water, while emitting negligible amounts of pollutants.

The Department of Energy (DOE) will road test this bus as part of a special project that aims to reduce vehicle emissions and dependence on fossil fuels while promoting a practical form of renewable energy. The first three buses, products of H Power Corp. in Belleview, N.J., will undergo trials in Los Angeles, Chicago, and Washington, D.C., next year, signaling a move to bring hydrogen-powered propulsion systems from government-sponsored research labs to the civilian world. Compared to diesel buses, the DOE maintains, the fuel-cell-powered buses will run with 50 percent higher fuel economy, 10 to 20 decibels less noise, and 99 percent lower emissions, spewing out carbon monoxide, nitrogen, and sulfur compounds – depending on the fuel source for the hydrogen – in amounts below the stringent standards set for ultra-low-emission vehicles in California.

The fuel cell – which generates electricity, heat, and water by combining hydrogen and oxygen – has been around conceptually for more than 150 years. Since the 1960s, NASA and the Defense Department have used fuel cells to supply electricity and hot water for the Gemini, Apollo, and space shuttle missions and to keep troops powered up in remote locations. But only recently have technical advances made commercial uses look feasible. Now, with companies plugging fuel cells into cars, buses, and power plants, the long-term vision of a cleaner, hydrogen-powered nation – considered unrealistic even five years ago – seems less farfetched.

"This is the first time since fuel cells were invented that their performance has been high enough and their price low enough to build demonstration plants," says Edward Gillis, fuel-cell program manager for the Electric Power Research Institute in Palo Alto, Calif. "We're finally seeing commercial fuel cells, and that just happened in the last year."

Fuel cells have enormous potential. Hydrogen could easily displace fossil fuels as an energy source, if only a simply engineered system could generate electricity cheaply, safely, and reliably for homes and vehicles. In theory, fuel cells can achieve that goal. But the question is when.

An answer should surface soon. In transportation, for instance, Canada is road testing a fuel-cell-powered bus built by the Ballard Corp. of North Vancouver, British Columbia. Varying slightly from the H Power bus, this 32-foot demonstration vehicle, operating since March 1993, runs on compressed hydrogen, which fuels a proton exchange membrane (PEM) fuel cell. By 1998, under the auspices of the government of British Columbia, Ballard plans to build a fleet of 75-passenger, 350-mile-range commercial buses for use in transit systems.

Among car companies, General Motors Corp., at its Indianapolis-based Allison Gas Turbine Division, is working on several fuel-cell-powered passenger vehicles, ranging from compact cars to minivans. In West Palm Beach, Fla., Energy Partners, Inc. is showing off its fuel-cell-powered Green Car. To boot, the Mazda Motor Corp. is at work on an electric prototype, powered by an 8-kilowatt PEM cell that draws its hydrogen from a metal hydride storage tank.

The United States will see fuel-cell testing in 1994 in power plants as well as buses. The Southern California Gas Co. plans to have 10 fuel-cell plants on-line in California by mid-1994, lighting up a hotel in Irvine, hospitals in Anaheim and Riverside, and even the Santa Barbara county jail. California's Pacific Gas & Electric Co. is gearing up for a 125-kilowatt system. And Southern California Edison's Rosemead facility will plug in a 20-kilowatt unit early next year. Other fuel-cell tests are under way in Buffalo, Pittsburgh, and Atlanta.

Only Japan surpasses California in large fuel-cell systems, with an 11-megawatt plant operating on Tokyo Bay.

A fuel cell's basic principles are rather simple. Electricity breaks down water into hydrogen and oxygen gases; a fuel cell runs the reaction in reverse, forming water from hydrogen and oxygen, liberating energy. In a sense, a fuel cell is just a battery that generates a charge when fed a hydrogen-rich diet. With no moving parts, a fuel cell converts chemical energy directly into electric current without intermediate mechanical steps.

The best cells are about twice as efficient as steam and internal combustion engines. With cogeneration systems – which recover excess heat to warm buildings, boil water, or even drive additional steam generators – fuel cells can reach 65 to 80 percent efficiency, compared to 35 percent for a typical internal combustion engine. The catch, though, is to iron out engineering bugs and build a system that holds up under real-world stresses.

Fuel cells offer other advantages. They are modular, coming in sizes that suit demand. Typically, each flat, disk-shaped cell produces less than a volt of electric potential. When stacked up like a tower of dinner plates and plugged into a system, however, the cells quickly mount in power output, from the few watts required for a flashlight to the many megawatts needed for a big city. Clean and silent-running, a major power plant could hide in a basement or a trailer in a parking lot – its output of potable water, useful heat, and minuscule emissions suiting it perfectly to urban life.

Since Sir William Grove built the first fuel cell in 1839, many varieties have come along, each distinguished by the electrolyte – or chief chemical conductor – used to promote the hydrogen oxidation reaction. Today, five cell types dominate research, each with strengths and weaknesses that best suit it for a particular application.

The phosphoric acid fuel cell is the furthest developed for commercial use. With platinum electrodes sandwiching a silicon carbide matrix, which holds the phosphoric-acid electrolyte, each cell generates two-thirds of a volt – with an efficiency of roughly 40 percent – running at 200°C. Scaling up for a power plant or down for a bus, these fuel cells perform well with readily available carbon-containing fossil fuels. On the other hand, they generate less power per cell than other types of cells, run at lower efficiencies, and require heating to operate. Also, fuels other than pure hydrogen – such as natural gas, ethanol, or methanol – must be reformed, a process that extracts hydrogen from the organic blend of compounds.

Still, the phosphoric acid fuel cell is the cell of choice for uses as diverse as H Power's bus and Tokyo's 11-megawatt Goi power station, which serves 4,000 households. In fact, a phosphoric acid test facility at the South Coast Air Quality Management District on the outskirts of Los Angeles did so well that Southern California Gas bought 10 additional units — and is considering 10 more. Since then, International Fuel Cells, Inc. of South Windsor, Conn., which built the facility, has picked up orders for another 50 200-kilowatt stations.

In contrast, PEM fuel cells use a solid polymer membrane as the electrolyte sandwiched between platinum electrodes. Many types of membranes are in development, mostly variations of a Teflon-based film called Nafion. The chief advantages of these cells are their high power density, high efficiency, and low-temperature operation. The membranes deliver more current per square centimeter of cell, handle rapid power demands, and start up quickly at a mere 80°C. They are lighter and more compact than other fuel cells, which makes them well-suited for use in small machines — whether a tape recorder or family vehicle.

Their chief weaknesses are a need to be kept moist and a tendency to perform poorly when carbon monoxide taints the fuel supply. Currently, PEMs cost more than phosphoric acid fuel cells but show great long-term promise for anything that runs on batteries.

Ballard powers its bus with PEM fuel cells because of their light weight, low operating temperature, and strong output. For similar reasons, Energy Partners placed a 24-kilowatt stack of PEM cells in its Green Car and a 2-kilowatt stack in a prototype submersible, called PC 14, whose fuel cell powered it on 16 test dives. Mazda, too, will go with PEMs.

So agreeable are the PEM fuel cells to small applications that H Power sells a 12-volt NoCad power pack to replace batteries in video cameras and in March 1994 will offer a spin-off version to run laptop computers. Snap a hydrogen cartridge into the fuel cell, drop the power pack into a computer's battery compartment, and the laptop gets juice for 16 hours.

"We're also working on a 200-watt unit the size of my fist," says Joseph Maceda, vice president of H Power, calling it "the Power Brick." An entrepreneur and fuel-cell guru, Maceda sees a future of 1-kilowatt fuel cells, no larger than microwave ovens, supplying all the electricity, heat, and hot water for single-family homes.

Maceda is not alone in his quest to make fuel cells easy to use. "We must find better ways to put fuel cells into simple packages," says John Appleby, a fuel-cell researcher at Texas A&M University in College Station. "If you need a new engine for a light plane, you don't scale down a marine diesel engine. That makes no sense. It's the same for fuel cells. When you scale down, you must be innovative."

Among the hottest, cutting-edge designs today is the solid-oxide fuel cell. It is also literally the hottest, operating at close to 1,000°C. When raised to this glowing temperature, yttrium-doped zirconium oxide conducts oxygen ions, serving as a good electrolyte. The solid oxide is sandwiched between a cathode, made of strontium-doped lanthanum manganite, and an anode, made of nickel-zirconia cermet.

The result: a potential powerhouse. Solid oxides offer the advantage of long-lasting, reliable electric supplies without the problems associated with corrosive liquid acids or fragile membranes. Overall, the system is simpler, with only three major components: a fuel preheater, a fuel cell, and an air preheater. Its solid ceramic structures need less maintenance than other cells. The high temperature obviates the need for precious metal catalysts — such as expensive platinum — and special fuel pretreatment.

At the same time, the high temperature also creates a problem, requiring long warm-up periods and careful monitoring. Solid-oxide cells will probably fare best in large industrial power plants — though they may one day power large ships and submarines. Today, they cost thousands of dollars per kilowatt to build. But researchers at the Electric Power Research Institute contend that material costs could fall below $20 per kilowatt, with cell life exceeding 10 years.

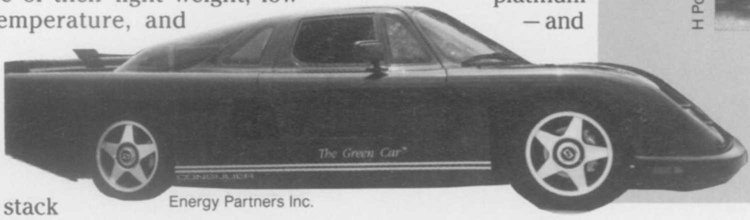
To improve solid-oxide cells, three designs are in the works: tubes, planes, and monoliths. In each, the goal is to shape the electrodes to maximize the hydrogen-oxygen reaction. Westinghouse Electric Corp. has taken its long, thin tube-shaped cells the furthest, with test units running continuously for 40,000 hours, two 25-kilowatt units on-line in Japan, and a 100-kilowatt cogeneration unit set for 1995 plug-in by Southern California Gas in Los Angeles.

Testing planar electrodes are two U.S. companies — Ceramatec, Inc. in Salt Lake City, and Ztec, Inc. in Waltham, Mass. — and several Japanese firms, including Fuji, Mitsubishi, and Murata. Here, thin, plate-like cells 10 to 15 centimeters in diameter form compact, slender stacks. Though lower in power density than the tubes, the plates appear easier to make and operate.

For higher power densities, monolithic blocks of layered solid oxide show great promise. Allied-Signal Corp. is developing these many-layered fuel-cell sandwiches, which could surpass tubes and planes as the most efficient design.

Molten carbonate fuel cells offer another direction for large-scale industrial use. More extensively developed than solid oxides, they use a solid carbonate electrolyte — held in a ceramic and sandwiched between nickel electrodes — that becomes molten during its 650°C operation. The cells' main advantage is high efficiency — 50 to 60 percent before heat recovery for cogeneration. The high temperature, too, means little fuel pretreatment.


H Power Corp.


Energy Partners Inc.

Energy Partners' Green Car (left) carries a PEM fuel cell in its trunk for power, while H Power's prototype bus (above) draws juice from a phosphoric acid fuel cell stacked in the bus' rear.

Molten carbonate cells can run directly on natural gas. On a large scale, this approach appears quite cost-effective to build and install — per-kilowatt prices may be as low as $1,000, competitive with those of fossil-fuel turbines.

With two 125-kilowatt stacks being tested on-site, Energy Research Corp. in Danbury, Conn., is preparing a 2-megawatt plant that by 1995 will power 2,000 homes in Santa Clara, Calif. Trial runs of a 70-kilowatt Energy Research unit at the Pacific Gas and Electric plant in San Ramon, Calif., have gone well enough to convince the utility to try a bigger system.

Union Oil of California is readying a 250-kilowatt molten carbonate system, built by Chicago-based M-C Power, Inc. Kaiser Permanente, a health maintenance organization with headquarters in Oakland, Calif., is trying out four 200-kilowatt phosphoric acid systems while preparing a 250-kilowatt molten carbo-

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rious signals that are larger than the signals Svoboda sought — namely, the 8-nanometer strides of kinesin.

Moreover, airborne vibrations proved notorious troublemakers, Block recounts. Since the interferometer is sensitive enough to pick up the sound waves of a conversation, the researchers conducted many of their experiments at night, when the lab was quieter, he says.

Once everything was still, they could record the gait of one kinesin molecule, but only after shifting it into first gear. In a cell, kinesin speeds at about 1 micrometer per second, the equivalent of a person running at 55 miles per hour. To measure its movement reliably, the investigators had to slow it down to about 0.01 micrometer per second, Block explains.

While the Rowland researchers stayed up late with their laser beam, Spudich's group across the country also spent nightly vigils with lasers. They devised a method of stretching a normally floppy actin filament taut between two laser beams and then lowering the filament to touch a single myosin molecule, Spudich explains. With the two laser beams holding the ends of the actin filament fast, the researchers could measure the force exerted on the actin by the myosin molecule. They did so by adding a feedback loop to the laser trap. That allowed them to record the force with which the actin filament tried to escape the grip of the laser beams, says Spudich.

Optical tweezers "seem to be the way to go to answer many questions," says Vale. But, he adds, "they do not tell us the entire story. They reveal nothing about the structural changes in the motor molecules that accompany the steps. That area is extremely important but still a black box for kinesin."

Again, researchers studying myosin have made some headway in assembling data from structural biology and optical tweezers into a complete picture. The crystal structure of myosin — its three-dimensional makeup—has been unveiled recently and imaged with near-atomic resolution, summing up what Block calls "20 years of biochemistry on myosin."

In a report accompanying the publication of myosin's crystal structure, a team of researchers collaborated to produce a detailed model of the sequence of events that brings about myosin's power stroke. It involves the alternate opening and closing of myosin's several clefts and pockets. To develop the model, the researchers also used the previously discovered structure of actin and computer models illustrating how myosin and actin bind (and function) together in the elaborate superstructure of a muscle filament.

To understand how myosin moves past actin filaments, one needs to know how "the high-resolution crystal structures of actin and myosin fit together to form the large assembly of a muscle filament," says Ronald A. Milligan, a partner in the collaboration.

To find that out, Milligan, a cell biologist at Scripps Research Institute in La Jolla, Calif., began with electron-microscopic images of a muscle filament. Processing these images with computerized image-analysis techniques yielded "three-dimensional maps," which show the assembly's contours, complete with all its bulges and grooves.

Into these contours Milligan and his coworkers then docked the crystal structure of myosin. Marking reference points on the proteins with the element gold, they were able to see in which orientation myosin slips into actin. With that information, they constructed an image of how all the individual proteins come together to form the working assembly found in the cell, he explains. Armed with such detailed knowledge of how actin and myosin interact, the team was able to draw up a step-by-step scenario for myosin's power stroke.

That scenario isn't entirely proved, nor do the new mechanical measurements make an airtight case. But with motor research on the move, "the pieces of the puzzle may soon be put together," says Spudich. "For us, that is a dream come true." □

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nate plant for a San Diego medical center.

For the highest efficiencies of all—up to 70 percent — alkaline fuel cells have proved the winners so far. Yet these cells, which use alkaline potassium hydroxide as the electrolyte, are also the most expensive to make. NASA and the Defense Department have spent heartily on these lean, pricey systems.

Until recently, civilian applications for alkaline fuel cells looked preposterous. But several companies are seeking to slash production costs and design better methods for storing pure hydrogen, given the alkaline's intolerance to impurities. Soon, even alkaline cells may jockey for position in the commercial fuel-cell market.

The problem of storing hydrogen has plagued fuel-cell advocates from the start. A highly reactive, explosive gas, hydrogen does not lend itself to safe containment. Engineering advances, though, have improved that picture. Other than compressing hydrogen in canisters or cooling it to a liquid, the gas can be extracted as needed from hydrogen-rich compounds, such as methane or ethanol.

Newer systems attempt to hold hydrogen in a metal hydride matrix or activated carbon. As water holds hydrogen well, a more venturesome tack tried by H Power involves controlling the oxidative reduction — rusting — of sponge iron in a cycle that liberates hydrogen as needed. Meanwhile, at the University of California, Riverside, researchers are splitting water molecules with sunlight, using a 12-cell electrolysis unit hooked to a 3.5-kilowatt photovoltaic array.

The major disadvantage of fuel cells — this seeming panacea for energy production — stems from engineering hurdles rather than inherent system weaknesses. Economics, too, have held fuel cells back. Until recently, they've been too expensive to build and operate, costing upwards of $3,500 per kilowatt versus the $1,000 to $2,000 cost of conventional fossil-fuel turbines.

But lately, the economic picture has changed. Better materials and production methods now make fuel cells competitive with gas and oil generators, especially if the expense of an electric grid figures into the equation. Overhead power lines cost $50,000 to $1 million per mile to build, plus maintenance expenses. Fuel cells could potentially make power lines obsolete, with small modular systems running neighborhoods and individual homes.

In fact, DOE is studying the feasibility of fuel cells for commercial and residential buildings, according to Ronald J. Fiskum, a DOE fuel-cell program manager. "We're not looking to reinvent the wheel," he says, "but to see the best way to integrate fuel cells into residential and commercial buildings. Micro-cogeneration — supplying heat and power — is a natural."

Lest fuel cells seem like the final answer to U.S. energy needs, it's worth keeping in mind the technical hurdles researchers must still leap. Cells still suffer material degradation. The life span of commercial stacks must exceed five — sometimes 10 — years to offset the initial capital expense. Current output must hold up steadily for long stretches. And consumers must get accustomed to a hydrogen-based power supply.

Fuel-cell advocates have heralded their solution before. However, where big talk once provoked skepticism, it now calls forth construction contracts.

"Virtually everyone agrees we should move from fossil-fuel dependence toward renewable energy sources," says Martin Gutstein, director of the Fuel Cell Institute in Washington, D.C. "But with fuel cells there's a vicious circle. You can't get cost down until production comes up, and you can't get production up until the cost comes down. The Japanese have taken action here. We've done very little. Now, perhaps, we'll see a turnaround in this country." □