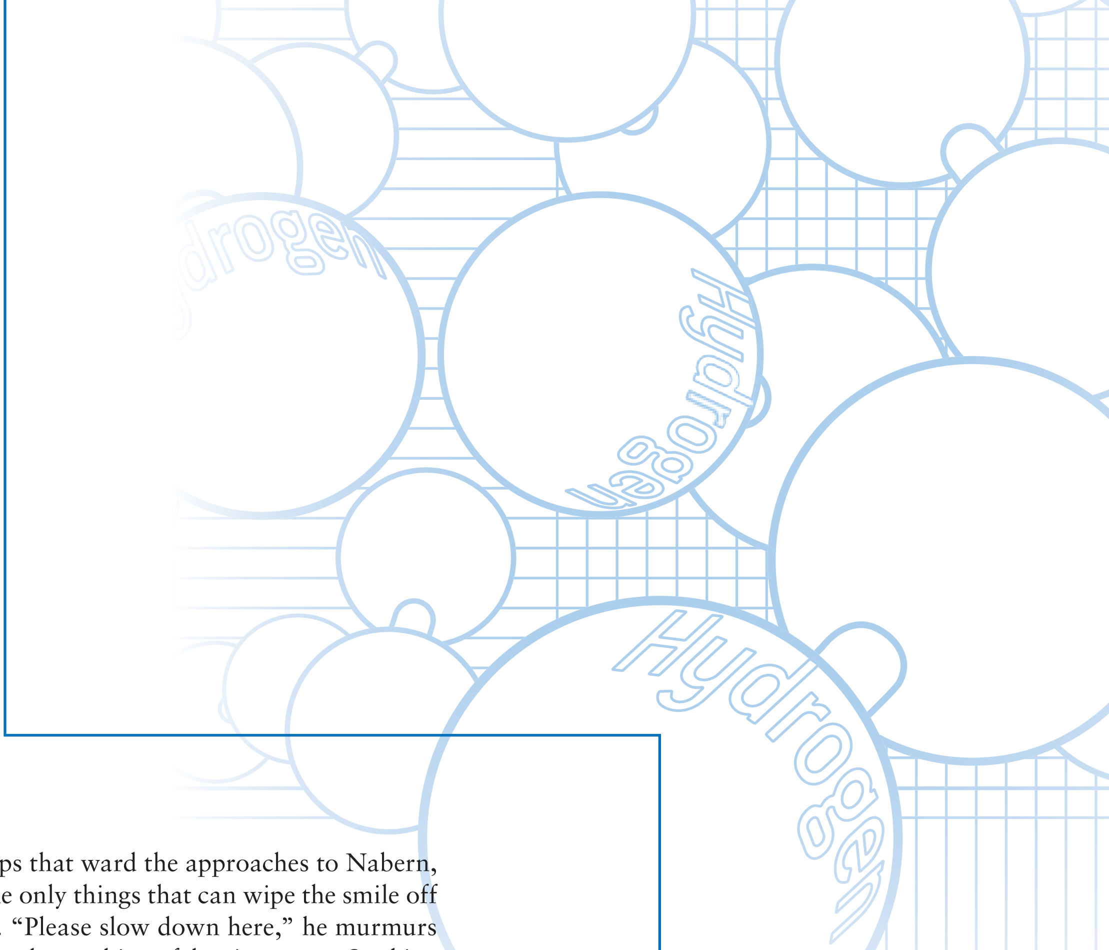
TEST FLEETS of DaimlerChrysler F-Cell hydrogen fuel-cell cars are now undergoing driving trials.

On the road to FUEL-CELL CARS

DAIMLERCHRYSLER



Although fleets of fuel-cell prototypes are hitting the streets, basic technical and market obstacles must be hurdled before the clean, hydrogen-powered cars reach dealer showrooms

By Steven Ashley

The automated speed traps that ward the approaches to Nabern, Germany, seem to be the only things that can wipe the smile off Rosario Berretta's face. "Please slow down here," he murmurs darkly as our vehicle nears the outskirts of the picturesque Swabian village. Berretta leads a team that is preparing a fleet of 60 of DaimlerChrysler's latest hydrogen fuel-cell car, the F-Cell, for testing worldwide. The aim is to allow automakers to evaluate the pollution-free, energy-efficient vehicles in diverse driving conditions. The curly-headed engineer is eager for visitors to try out the F-Cell's quick pickup off the line, one of the benefits of having an electric motor under the hood. But such maneuvers have to wait until the sharp eyes of the camera traps get small in the rearview mirror.

Despite its high-tech propulsion system, the F-Cell looks, performs and handles like a Toyota Corolla, a Ford Focus or any other conventional small car. Thus, the F-Cell seems less like a next-generation prototype and more like a real-world car. The sole clue of anything out of the ordinary is the unfamiliar whir of a compressor—a noise that Berretta vows company engineers will soon muffle.

DaimlerChrysler is not alone in its quest for the ultimate clean vehicle. After a decade of focused research and development, the auto industry worldwide has passed a milestone with the arrival of the first test fleets of seemingly roadworthy fuel-cell cars. Twenty of Honda's latest FCX and 30 of Ford's Focus FCV fuel-cell-powered compacts will soon be on the highways. General Motors plans to provide 13 fuel-cell-powered vehicles to the New York City metropolitan area for evaluation next year. Already 30 DaimlerChrysler-built fuel-cell buses are plying the streets of 10 European cities, and three more will shortly each be servicing Beijing and Perth.

Meanwhile nearly every other car company—particularly, Toyota but also Nissan, Renault, Volkswagen, Mitsubishi and Hyundai, among others—is operating at least a few prototype vehicles as well, one indication of the substantial funds carmakers are investing to perfect the technology. Today between 600 and 800 fuel-cell vehicles are reportedly under trial across the globe. And suppliers have emerged to develop and provide the components needed to build the prototypes. If all goes well, these developments will mark a midway milestone on the road to the initial commercialization of the fuel-cell car by the early part of the next decade.

Faced with ever tighter governmental regulatory limits on exhaust emissions, forecasts of impending oil shortages and a potential global warming catastrophe caused by greenhouse gases, the motor vehicle industry and national governments have invested tens of billions of dollars during the past 10 years to bring to reality a clean, efficient propulsion technology that is intended to replace the venerable internal-combustion (IC) engine [see "Vehicle of Change," by Lawrence D. Burns, J. Byron McCormick and Christopher E. Borroni-Bird; Scientific American, October 2002]. Critics, however, still question the industry's actual interest in producing a truly green car and whether this R&D effort is really enough to yield success anytime soon. Suspicions linger that work on fuel-cell vehicles is a smokescreen intended to shield business as usual long into the future. Car company executives reply that they foresee no better option to the hydrogen fuel-cell vehicle in the long run, because all alternatives, such as hybrid vehicles (which combine IC engines with electrochemical batteries), still burn petrochemical fuels and produce carbon dioxide and pollutants.

> Tens of billions of dollars have been spent on fuel-cell vehicles during the past 10 years.

Overview/*Green Machines*

- The motor vehicle industry recently passed a milestone when it fielded test fleets of reasonably practical fuel-cell cars some 10 years after the first prototypes hit the road. During that period, carmakers and governments spent several tens of billions of dollars on research and development, but much more will be needed before initial commercialization can take place.
- Despite stricter pollution limits, potential oil shortages and the threat of global warming, volume production of fuel-cell vehicles is not expected before midway through the next decade and, perhaps, much later.
- Significant improvements in onboard hydrogen storage capacity, fuel-cell durability and power as well as substantially lower costs will be required before fuel-cell cars can approach marketability. A hydrogen production and distribution system must also be built.

Stumbling Blocks

A two-hour drive, say, the 140 or so miles from Nabern to Frankfurt am Main on the German autobahn, would be enough to reveal the most telling distinction between the F-Cell and your typical IC engine car. In something less than 90 minutes, you would be stuck on the roadside out of fuel and with little prayer of finding a fill-up. Neither the F-Cell nor any of its hydrogen-powered kindred carries enough fuel to get anywhere near the 300-mile minimum driving range that car owners expect. And because hydrogen service stations are still few and far between, refueling would be problematic at best. So despite bright hopes and the upbeat pronouncements by automakers, considerable technical and market challenges remain that could delay introduction of the fuel-cell family car for years, if not decades.

Before early adopters can trade in their Toyota Priuses and Honda Accord Hybrids for something even greener, car manufacturers and their suppliers must somehow figure out how to do several things: boost onboard hydrogen storage capacity substantially, cut the price tags of fuel-cell drive trains to a hundredth of the current costs, increase the power plants' operating lifetimes fivefold, and enhance their energy output for SUVs and other heavy vehicles. Finally, to operate these vehicles, a hydrogen fueling infrastructure will be required to replace the international network of gas stations.

Even some of the automakers remain unconvinced that all this will happen soon: "High-volume production could be 25 years off," says Bill Reinert, national manager for Toyota's advanced technology group. "I'm less than hopeful about reducing costs sufficiently, and I'm quite pessimistic about solving hydrogen storage issues and packaging these large systems in a marketable vehicle." One telling sign that fuel-cell vehicles are still works in progress: nearly all car company representatives call for more government investment in basic research and hydrogen distribution systems to help overcome these roadblocks.

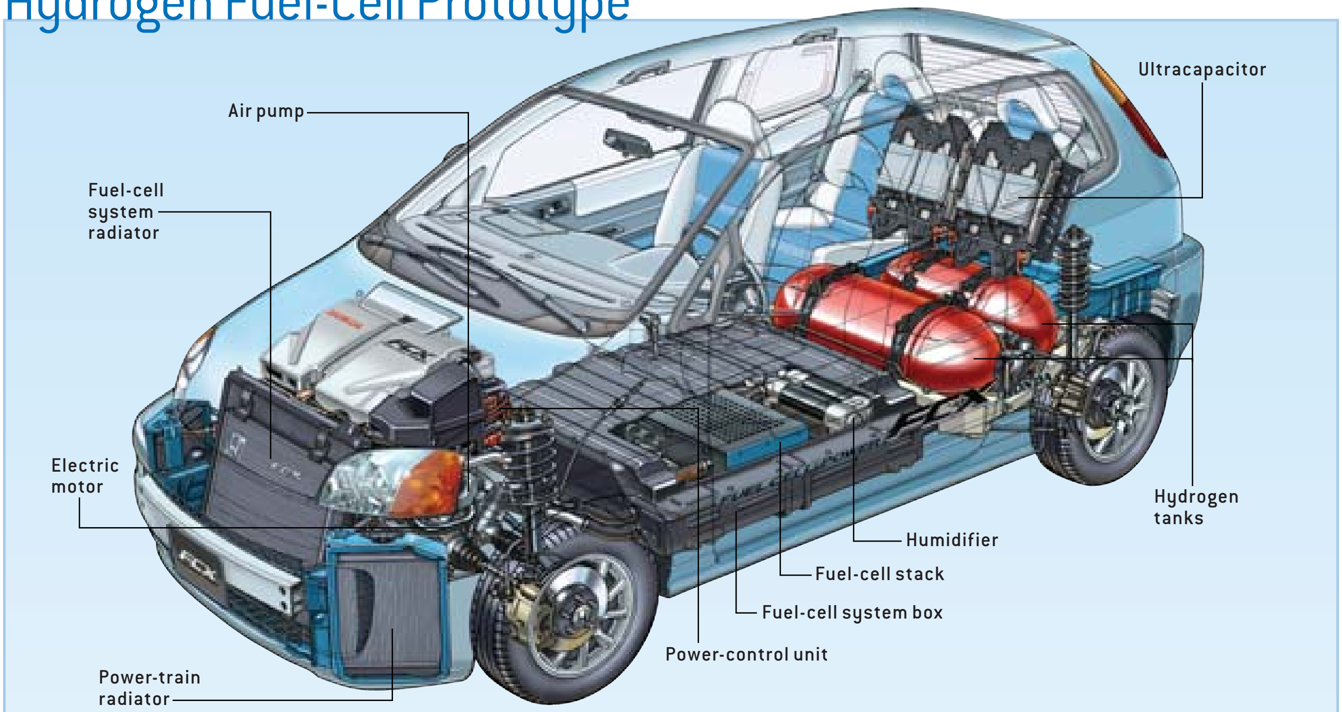
Stack Issues

A fuel-cell car, bus or truck is essentially an electric vehicle powered by a device that operates like a refuelable battery. Unlike a battery, though, a fuel cell does not store energy; it uses an electrochemical process to generate electricity and will run as long as hydrogen fuel and oxygen are fed to it [*see box on page 66*].

At the core of the automotive fuel cell is a thin, fluorocarbon-based polymer—a proton-exchange membrane (PEM)—that serves as both the electrolyte (for charge transport) and a physical barrier to prevent mixing of the hydrogen fuel and the oxygen. Electricity for powering a fuel-cell car is produced when electrons are stripped from hydrogen atoms at catalysis sites on the membrane surface. The charge carriers—hydrogen ions or protons—then migrate through the membrane and combine with oxygen and an electron to form water, the only exhaust produced. Individual cells are assembled into what are called stacks.

Engineers chose PEM fuel cells because they convert up to

Hydrogen Fuel-Cell Prototype



Honda's 2005 FCX model is typical of current hydrogen fuel-cell technology. The four-seat compact, which has a top speed of 93 miles per hour, offers a driving range greater than 200 miles. Equivalent fuel economy is 62 miles per gallon in city driving and 51 mpg on the highway. The FCX's fuel-cell stack, which was designed by Honda for low-cost manufacturing, features a hydrocarbon polymer membrane that offers improved durability. An ultracapacitor—a device that stores energy in the fields between electrically charged plates—provides extra power during passing maneuvers or hill climbing. Reclaimed energy from a regenerative braking system is stored by the ultracapacitor.

55 percent of the fuel energy put into them into work output; the efficiency figure for an IC engine is approximately 30 percent. Other benefits include relatively low-temperature operation (80 degrees Celsius); reasonably safe, quiet performance; easy operation; and low maintenance requirements.

The prospect of a commercial fuel-cell car by 2015 will depend on improvements in membrane technology, which makes up as much as 35 percent of the cost of a fuel-cell stack. Researchers list several needed enhancements such as low fuel crossover from one side of a membrane to the other, augmented chemical and mechanical stability of the membrane for greater durability, control over undesired by-reactions, and higher tolerance to contamination by fuel impurities or from unwanted reaction by-products such as carbon monoxide. Most of all, what is required is an across-the-board reduction in costs.

News of a "breakthrough" in membrane technology created a considerable stir in fuel-cell research circles last fall. PolyFuel, a small company in Mountain View, Calif., announced that it had created a hydrocarbon polymer membrane that it says offers superior performance and lower costs than current perfluorinated membranes. "It looks like a piece of sandwich wrap," James Balcom says, chuckling. The PolyFuel chief executive boasts a variety of reasons why his cellophanelike film performs better than the more common perfluorinated membranes, notably DuPont's Nafion material. The hydrocarbon membrane can run at higher temperatures than current membranes—up to 95 degrees C, which allows the use of smaller radiators to dissipate heat. It lasts 50 percent longer than fluorocarbon versions, he claims, while generating 10 to 15 percent more power and operating at lower (less troublesome) humidity levels. And whereas fluorocarbon membranes cost about $300 per square meter, the PolyFuel materials potentially cost half the price [*see box on next page*]. Although many other researchers remain skeptical about hydrocarbon membranes, Honda's newest FCX fuel-cell cars incorporate them.

Catalyst Conundrum

THE OTHER KEY to the operation of a PEM membrane is the thin layer of platinum-based catalyst that coats both of its sides and that represents 40 percent of the stack cost. The catalyst prepares hydrogen (from the fuel) and oxygen (from the air) to take part in an oxidation reaction by assisting both molecules to split, ionize, and release or accept protons and electrons. On the hydrogen side of the membrane, a hydrogen molecule (containing two hydrogen atoms) must attach to two adjacent catalyst sites, thereby freeing positive hydrogen ions (protons) to travel across the membrane. The complex reaction on the oxygen side occurs when a hydrogen ion and an electron mate with

HONDA MOTOR COMPANY

oxygen to produce water. This latter sequence must be finely controlled because it can yield destructive by-products such as hydrogen peroxide, which degrades fuel-cell components.

Because of the high cost of the precious metal ingredients, researchers are searching for ways to lower the platinum content. Their efforts include not only finding methods to raise the activity of the catalyst so less can be used for the same power output but also determining how to form a stable catalyst structure that does not degrade over time and avoiding side reactions that contaminate the membrane. One recent success in boosting catalytic activity was achieved by 3M Corporation researchers, who created nanotextured membrane surfaces covered with "forests of tiny columns" that significantly increased the catalysis area. Other work has concentrated on materials ranging from nonprecious metal catalysts such as cobalt and chromium to catalysts consisting of fine dispersions of particles embedded in porous composite structures.

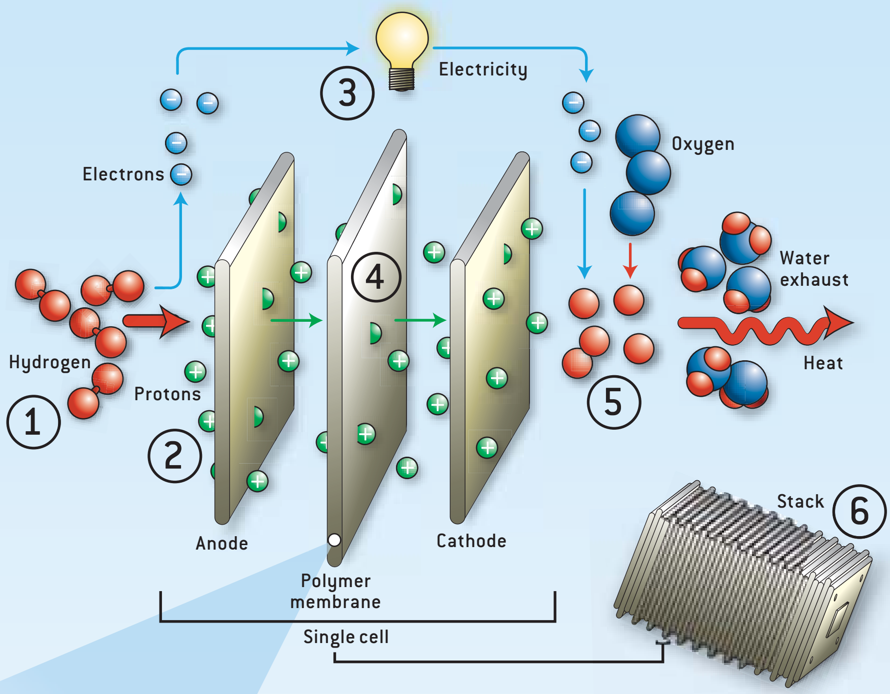
Onboard Storage

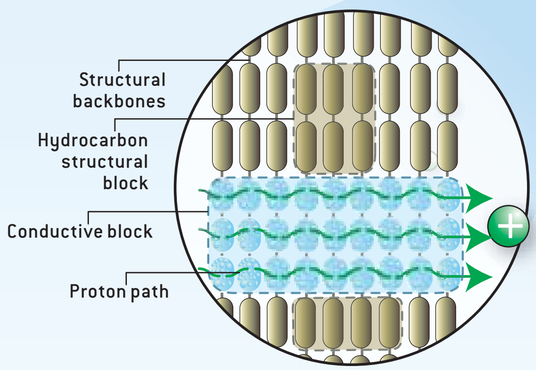
ONE OF THE BIGGEST WORRIES among proponents of fuel-cell vehicles is how engineers will manage to stuff enough hydrogen onboard to provide the driving range that consumers demand. Five to seven kilograms will take a car up to 400 miles, but current fuel-cell prototypes hold from 2.5 to 3.5 kilograms. "Nobody really knows how to store twice that amount in a reasonable volume," says Dennis Campbell, chief executive of Ballard Power Systems in Vancouver, the dominant fuel-cell-stack maker.

Typically hydrogen is stored in pressure tanks as a highly compressed gas at ambient temperature. Many engineering teams are working on doubling the pressure capacity of today's 5,000-psi (pounds per square inch) composite pressure tanks. But twice the pressure does not increase the storage twofold. Liquid-hydrogen systems, which store the fuel at temperatures below −253 degrees C, have been tested successfully

INSIDE FUEL CELLS

A fuel cell operates like a refuelable battery; it will generate electricity as long as it is supplied with hydrogen and oxygen. A proton-exchange membrane (PEM) fuel cell (*right*) is composed of two thin, porous electrodes, an anode and a cathode, separated by a solid polymer membrane electrolyte. Platinum-based catalysts coat one side of each electrode. After hydrogen atoms enter the cell (*1*), the anode catalyst splits them into electrons and protons (*2*). The electrons move along an external circuit to power a drive motor (*3*), while the protons migrate through the membrane (*4*) to the cathode. The catalyst on that side combines the protons with returning electrons and with oxygen from the air to generate water and heat (*5*). Many cells are piled in stacks to produce higher voltages (*6*).



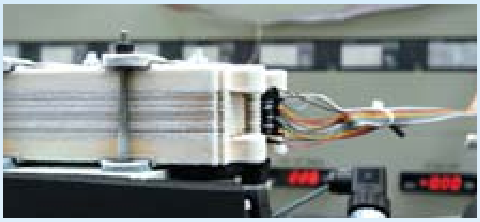


Hydrocarbon membranes last longer, generate more energy and cost less than current fluorocarbon types, maker PolyFuel claims. The company's concept incorporates blocks of highly conductive polymer species to promote the passage of protons, increasing energy production. These conductive materials are tied to blocks of high-strength polymers that reinforce the membrane's structure, improving durability. Because the two types of polymers have a low chemical affinity for each other, they segregate themselves during processing into the different functional blocks, easing manufacture.

LUCY READING-IKKANDA

Freeze-Proof Fuel Cells

Resistance to subzero temperatures has long been a key goal for developers of fuel-cell stacks. When stacks freeze, the water inside turns to ice, which can puncture membranes and block pipes. Last year Honda engineers demonstrated that the fuel-cell power plant in its latest FCX hatchback (*right*) will start up repeatedly at –20 degrees Celsius. Researchers at DaimlerChrysler and General Motors have shown similar results with frozen stacks in the laboratory (*below*). The trick seems to lie in keeping all water inside the system in the vapor state.



DAIMLERCHRYSLER (*left*); HONDA MOTOR COMPANY (*right*)

but suffer from significant drawbacks: about one third of the energy available from the fuel is needed to keep the temperature low enough to preserve the element in a liquid state. And despite bulky insulation, evaporation through seals robs these systems every day of about 5 percent of the total stored hydrogen.

Several alternative storage technologies are under development, but no surefire advances have occurred. "There's quite a good distance between what can be demonstrated in the lab and a fully engineered storage system that's affordable, long-lasting and compact," says Lawrence Burns, vice president for research and development and planning at GM.

Probably the foremost candidates for a storage technology are metal hydride systems in which various metals and alloys hold hydrogen on their surfaces until heat releases it for use. "Think of a sponge for hydrogen," explains Robert Stempel, chairman of ECD Ovonic, a part of Texaco Ovonic Hydrogen Systems, the leader in this area. The hydrogen gas is fed into the storage tank under pressure and chemically bonds to the crystal lattice of the metal in question through a reaction that absorbs heat. The resulting compounds are called metal hydrides. Waste heat from the stack is used to reverse the reaction and release the fuel. In January, GM and Sandia National Laboratories launched a four-year, $10-million program to develop metal hydride storage systems based on sodium aluminum hydride.

Because metal hydride storage systems tend to be heavy (about 300 kilograms), researchers at Delft University of Technology in the Netherlands have developed a way to store hydrogen in water ice—as a hydrogen hydrate, in which hydrogen is trapped in molecule-size cavities in ice. Water, of course, is significantly lighter than metal alloys. This approach is unexpected because hydrogen hydrates are notoriously difficult to make, typically requiring low temperatures and extremely high pressures, on the order of 36,000 psi. Working with scientists at the Colorado School of Mines, the Delft team came up with a "promoter" chemical—tetrahydrofuran—that stabilizes gas hydrates under much less extreme pressure conditions, only 1,450 psi. Theoretically, it should be possible to get about 120 liters (120 kilograms) of water to store about six kilograms of hydrogen.

Freezing Stacks

SEVERAL HUNDRED people gathered behind the state capitol building in Albany, N.Y., to hear Governor George E. Pataki welcome the lease by New York State of a pair of Honda FCX hydrogen fuel-cell cars one cold, blustery late November morning in 2004. What made the event notable was the temperature of the air. All previous fuel-cell vehicle demonstration programs had been situated in warmer climes to ensure that the fuel-cell stacks would not freeze up. In previous designs, subzero temperatures could convert any liquid water into expanding ice crystals that can puncture membranes or rupture water lines. Early in the year Honda engineers demonstrated that their fuel-cell units could withstand winter conditions, an important engineering achievement for the fuel-cell research community.

> Nobody really knows how to store enough hydrogen fuel in a reasonable volume.

After the speech, Ben Knight, vice president of R&D for American Honda, explained that the new freeze-resistant 2005 FCX models will start up repeatedly at –20 degrees C. Other car companies, including DaimlerChrysler and GM, have also claimed success with cold-starting test stacks in the lab [*see box on preceding page*].

Besides its ability to start up in midwinter temperatures, the 2005 version of Honda's FCX fuel-cell car—a four-seat compact hatchback—showcases other technical advances over the model released two years earlier. The new FCX is unusual, for example, because it employs an ultracapacitor—a device that stores energy in the electric fields between charged electrode plates—to provide short bursts of supplementary power for passing and hill climbing. Most other automakers use batteries for this purpose.

Infrastructure Issues

LATER ON that November day an even more enthusiastic crowd assembled for the second half of the planned ceremonies at the nearby headquarters of Plug Power, the Latham, N.Y.–based maker of stationary hydrogen fuel-cell energy units for backup power applications. The cheering group of mostly Plug Power workers were there to celebrate the opening of a hydrogen fueling station that they had co-developed with Honda engineers. The Home Energy Station II contains a miniature chemical plant—a steam reformer—that extracts hydrogen fuel from piped-in natural gas using a steam-based process. "It's half the size of the previous version," said Roger Saillant, CEO of Plug Power. "Besides refueling vehicles, the system feeds some of the hydrogen into a fuel-cell stack to produce electricity for our headquarters building, which is also warmed in part by waste heat generated by the unit."

The hydrogen infrastructure is the classic chicken-and-egg dilemma.

With great fanfare, one of the FCXs wheeled up to the fuel-dispensing pump—a metal box the size of a luxury kitchen stove that had been installed in the company parking lot. A state official first grounded the car by attaching a wire to the vehicle. He then dragged the fuel hose from the pump to the FCX's refueling port, inserted the nozzle and locked it into place. The unit finished filling the car's tank after about five or six minutes. Knight explained that the pump produces enough purified hydrogen to refill a single fuel-cell vehicle a day.

Afterward, Knight discussed the problems facing the development of a hydrogen infrastructure: "It's the classic chicken-and-egg dilemma," he said. "There's no demand for cars and trucks with limited fueling options, but no one wants to make the huge investment to create a fueling infrastructure unless there are fleets of vehicles on the road. So the question is: How do we create demand?" [see "Questions about a Hydrogen Economy," by Matthew L. Wald; SCIENTIFIC AMERICAN, May 2004].

A study by GM has estimated that $10 billion to $15 billion would pay to build 11,700 new fueling stations—enough so a driver would always be within two miles of a hydrogen station in major urban areas and so there would be a station every 25 miles along main highways. That concentration of mostly urban hydrogen stations would support an estimated one million fuel-cell vehicles, it says. "Twelve billion dollars, that's chump change when cable operators are plunking down $85 billion for cable system installations," exclaims Ballard's Campbell.

The Latham filling station—along with several dozen others scattered from Europe to California to Japan—embodies the first halting steps toward the construction of an infrastructure. Soon, Campbell says, about 70 hydrogen refueling stations will be operating worldwide, and California's Hydrogen Highway program has set a goal of 200 stations.

A National Academy of Sciences committee recently estimated that the transition to a "hydrogen economy" will probably take decades, because tough challenges remain. These include how to produce, store and distribute hydrogen in sufficient quantities and at reasonable cost without releasing greenhouse gases that contribute to atmospheric warming. Unfortunately, the extraction of hydrogen from methane generates carbon dioxide, a major greenhouse gas. If the energy sources for electrolysis (the splitting of water into hydrogen and oxygen using electricity) burn fossil fuels, they, too, would generate carbon dioxide. And hydrogen is a highly leak-prone gas that could escape from cars and production plants into the atmosphere,

Hydrogen Gas Stations

Filling stations that dispense hydrogen fuel are still rare. Currently about 70 hydrogen refueling units are operating worldwide: two dozen each in the U.S. and Europe, a dozen in Japan and 10 elsewhere. Filling up a car with pressurized hydrogen, demonstrated above by a Ford Focus FCV fuel-cell car, typically takes about five minutes. An electrical ground wire must be attached to the car beforehand to avoid sparks. At its Torrance, Calif., headquarters, American Honda has built a service station (*below*) that splits water into hydrogen fuel and oxygen using power generated by a solar photovoltaic array. This would be the ultimate in green hydrogen production.

FORD MOTOR COMPANY (*top*); HONDA MOTOR COMPANY (*bottom*)

FUEL-CELL-DRIVEN DESIGN FREEDOM

General Motors's new Sequel fuel-cell concept vehicle (*right*) contains enough fuel to drive 300 miles, the minimum acceptable range. It does so by fitting about seven kilograms of hydrogen into its 11-inch-thick "skateboard" chassis (*bottom left*), which also contains almost all the crossover SUV's operating systems. The Sequel demonstrates how all-electric power trains will free auto designers to rethink the configuration of future models. Because strictly mechanical components can be replaced by fully electronic counterparts, interior layouts can be opened up (*bottom right*). "Look at all the space you get when you don't need to work around a big steering column," says Robert Bonaface, GM's director of advanced design. "We even had enough space to place a good-size storage bin in the dashboard, which is unheard of. Parents are going to love this."

GENERAL MOTORS CORPORATION

which could set off chemical reactions that generate greenhouse gases. Finally, using fossil fuels to make hydrogen takes more energy than that contained in the resulting hydrogen itself.

Researchers at the Idaho National Engineering and Environmental Laboratory and Cerametec in Salt Lake City have developed a way to electrolyze water and produce pure hydrogen with far less energy than other methods. The team's work points to the highest-known production rate of hydrogen by high-temperature electrolysis. Their new method involves running electricity through water that has been heated to about 1,000 degrees C. As the water molecules break up, a ceramic sieve separates the oxygen from the hydrogen. The resulting hydrogen has about half the energy value of the energy put into the process, which is better than competing processes.

Hydrogen proponents contend that arguments over infrastructure constitute a red herring. "U.S. industry currently produces 50 million to 60 million tons of hydrogen per year, so it's not like there's no expertise in handling hydrogen out there," Campbell notes. But automakers have a somewhat different perspective. "Fifty to 60 percent of the problems we have with our fuel cells arise from impurities in the hydrogen we buy from industry," complains Herbert Kohler, vice president of body and power-train research at DaimlerChrysler. "The chemical industry needs to do their homework."

Byron McCormick, GM's executive director of fuel-cell activities, likens investment in building a hydrogen infrastructure in the 21st century to the investment in railroads in the 19th century or to the creation of the interstate highway system in the 20th century: "There'll be a point relatively soon at which these kinds of how-do-you-get-it-funded decisions will be more important than the technology," he predicts.

Resolution of the myriad remaining technical and market issues will determine whether the transportation linchpin of the proposed hydrogen economy, the commercial fuel-cell vehicle, arrives in 10 years or 50. SA

Steven Ashley is a staff technology writer and editor.

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