# Fuel Cells Gather Steam

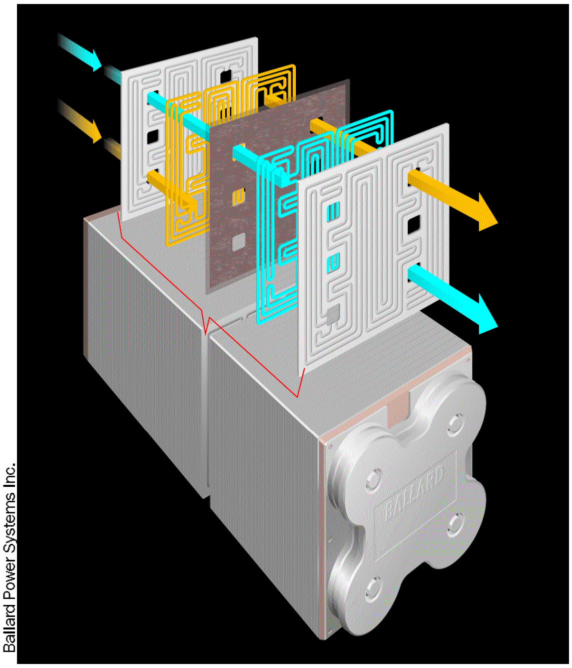
Having languished in relative obscurity since their invention 160 years ago, fuel cells appear well poised to cash in on their oft-touted potential as a clean and efficient alternative power source. Thanks to key technological advances and a corresponding resurgence of investment in fuel-cell R&D by major corporations, the stage is set for lucrative commercial opportunities in transportation and electric-power generation. Paradoxically, electric-power generation in the 21st century may find itself reliant on a device that dates well back into the 19th century, if current development efforts succeed.

Sometimes called "cold combustion," fuel cells convert chemical energy directly into electricity using an electrochemical reaction (Figure 1). The reaction is similar to that of a battery, except that fuel cells rely on a continuous supply of fuel from an external storage tank rather than storing their energy internally with chemicals. Fuel cells create energy without the high emissions commonly associated with internal combustion, and with a much higher rate of conversion efficiency—60% to 70%, depending on the system's complexity.

The first hydrogen–oxygen fuel cell was discovered in 1839 by Sir William Grove. The British chemist was studying the electrolysis of water, in which water is broken down into hydrogen and oxygen by passing an electrical current through it. Fuel cells operate in reverse, combining hydrogen and oxygen ions to form electricity, water, and heat. The advent of the internal combustion engine shortly after Grove's discovery hindered further fuel-cell development. The devices did not find significant application until the National Aeronautics and Space Administration decided to use fuel cells to supply on-board power for its Gemini and Apollo spacecraft in the 1960s, and more recently on the Space Shuttle.

Only in the last decade has fuel-cell technology advanced sufficiently to make commercialization a reality. "The issue always came down to cost," says Bill Hahn, vice president of new business development for International Fuel Cells (IFC), a division of United Technologies and a leading manufacturer of fuel-cell systems based in South Windsor, Connecticut.

Modern fuel cells typically fall into five categories, based on the choice of electrolyte used. The categories are alkaline (AFC), proton-exchange membrane (PEM), solid oxide (SOFC), phosphoric acid (PAFC), and molten carbonate (MCFC) fuel cells. Of the five, the most promising are PEM fuel cells for transportation and SOFCs for portable and stationary power applications, according to Paul Grant of the Electric Power Research Institute (EPRI) in Palo Alto, California. EPRI is developing PAFCs for electric-power generation.




Ballard Power Systems Inc.

**Figure 1. In this fuel-cell stack, hydrogen (orange) flows through channels formed in flow-field plates to the central anode, where a platinum catalyst promotes its separation into protons and electrons. The electrons are conducted as usable current through an external circuit. Air (blue) flows to the central cathode, where its oxygen attracts the protons to form water and heat.**

PAFCs of about 10 MW have been demonstrated for power generation at utilities in Japan. Their high price and small market, however, which prevent the cost reductions usually achieved with mass production, have hampered broad commercialization. Because they use platinum as a catalyst, PEMs, PAFCs, and AFCs long appeared prohibitively expensive for commercial applications; a typical passenger car would have required $30,000 worth of platinum to generate enough power from a PEM fuel cell to operate.

This situation changed in the early 1990s, when researchers at Los Alamos National Laboratory and other groups developed fabrication processes for fuel-cell membrane electrode assemblies that reduced the amount of platinum needed and dropped the cost of the required platinum by as much as 90%. "Only now have we reached a point where products are coming onto the market," says Robert Rose, executive director of Fuel Cells 2000, a nonprofit educational organization based in Washington, DC. "Demand is sort of infinite at the moment because the supply is zero, but fuel cells are no longer mythical."

## A future in autos

The immediate driving force behind fuel-cell development is the enormous potential market in the transportation industry. Passenger vehicles represent the largest market, with annual worldwide sales of about 30 million vehicles—1 million in California alone—although it is generally agreed that mass commercial production is unlikely before 2004. The urban bus market boasts worldwide annual sales of 17,000 vehicles, 30% of which are sold in North America.

Environmental issues favor alternative technologies such as fuel cells. Cars and trucks account for approximately half of the volatile organic compounds and nitrogen oxides, and most of the carbon monoxide, emitted in of most major U.S. cities, according to the U.S. Department of Energy.

In addition to low emissions, PEM-powered vehicles offer such advantages as two to three times greater energy density—and, thus, superior range—and better overall fuel economy than battery-powered vehicles, according to Ross. More important, fuel cells can now use fossil fuels to operate, and they have the potential to be refueled like today's internal combustion cars.

Major automotive manufacturers are increasing their fuel-cell R&D efforts accordingly. In 1997, Germany's Daimler-Benz invested $145 million in Ballard Power Systems (Vancouver, BC), a leading developer of PEM fuel-cell technology. Ford has since joined the alliance, and the firms expect to produce 100,000 fuel-cell engines a year by 2005. Chrysler, now part of Daimler-Benz, is collaborating with A. D. Little (Cambridge, MA) to create an operational prototype fuel-cell vehicle by the end of this year. The automaker has said that fuel cells could be the primary power source for its Concorde/Intrepid class of cars by 2015.

General Motors hopes to have its first fuel-cell-powered vehicle in production by 2004. Toyota is testing two versions of a hybrid fuel-cell electric vehicle. Mercedes-Benz introduced its third-generation prototype fuel-cell vehicle in September 1997, and Volkswagen and Volvo expect to introduce fuel-cell prototypes by 1999. IFC has formed a joint venture with Toshiba to develop PEM fuel cells for automotive applications. Zero Emissions Vehicle Co. (London, England) put the world's first taxi powered by AFCs on the streets last July.

John F. Cooper, a researcher at Lawrence Livermore National Laboratory, has developed a zinc–air fuel cell that operates by feeding zinc fuel pellets from an external hopper into fixed electrochemical cells. Cooper's technology has been successfully tested on an electrically powered municipal bus; PEM-based prototype buses are already in operation. The Chicago Transit Authority began testing three Ballard fuel-cell buses on regular service routes in mid-1998, and Ballard subsequently placed three additional fuel-cell buses in Vancouver.

## Power-generation

Investors are looking to emerging markets in the power industry to help defray development costs of the technologies. Chief among these are portable, low-power applications (10 kW or less), particularly for replacing small generators and for powering cellular telecommunications.

Hahn divides the market for stationary power applications into three segments: industrial, with power levels of 250 kW or more; commercial, for small stores and restaurants requiring power levels of about 50 kW; and residential, with average power levels of between 1 and 6 kW. ONSI (South Windsor, CT), another United Technologies division, currently produces 200-kW PAFC units that run off natural gas.

Energy Partners (West Palm Beach, FL) has formed a partnership with NUI Corp. (Bedminster, NJ) to develop a line of stationary PEM fuel cells using natural gas and propane for residential and commercial power applications. Energy Research Corp. (Danbury, CT) is focusing on PEM fuel cells, and Westinghouse Electric Corp. (Pittsburgh, PA) is focusing on SOFCs; both technologies are intended for stationary power applications.

Early last year, Cinergy Technology, Inc. (Vancouver, BC) committed $1.625 million to the purchase of a 250-kW, natural-gas fuel-cell power plant from Ballard, scheduled for delivery later this year. Ballard also completed an agreement with GEC Alsthom in Basel, Switzerland, and Ebara Corp. in Tokyo to establish joint ventures for the eventual manufacture of fuel-cell power plants in Europe and Japan.

## Challenges

Despite the excitement generated by recent technological breakthroughs, further cost reductions are needed before fuel cells can penetrate potential markets. For example, Energy Partners' prototype 20-kW fuel cells retail for $150,000, and its 5-kW demo unit retails for $37,500. "The really big issue is whether these markets will be large enough to support production volumes of sufficient magnitude to achieve competitive costs," says EPRI's Fritz Kalhammer. "The interested parties are counting on the automotive market, with its large numbers of units, to 'pull' PEM technology toward lower costs of $60 to $80 per kilowatt." Other niche markets, such as space missions and military applications, may also help increase manufacturing volumes.

According to EPRI's Grant, the principal impediment to cost reduction and widespread use of fuel cells for transportation and electrical generation is the necessity for reforming, or converting, one fuel to another, prior to its electrochemical oxidation. "Whereas early space applications were able to use premanufactured hydrogen, large-scale terrestrial use requires direct extraction of gaseous hydrogen from fossil fuels as part of the fuel cell operation," he says.

Fuel processing technology is still in its infancy, but some important advances have been made. A. D. Little has created a fuel reformer capable of extracting hydrogen from gasoline for use in a PEM fuel cell, and the process also works with methanol and ethanol. Energy Partners expects to introduce a flexible PEM fuel-cell stack this year that will allow the device to operate on either a pure hydrogen stream or a reformate created by converting natural gas, propane, methanol, or gasoline.

Equally important, the ideal proton-exchange membrane for use in PEM fuel cells has yet to be developed. Chief among the desired properties is high protonic conductivity. Currently, DuPont's Nafion membranes, made of sulfonated fluorocarbon polymers, are the most widely used in PEM technology. Although the cost of membranes has declined, less expensive alternatives are still desired. Researchers at Rensselaer Polytechnic Institute have developed a new membrane material of sulfonated styrene/ethylene–butylene/styrene copolymers, which they claim provides 15% higher conductivity than other materials at 40% lower cost.

Improvements in overall system design and the existing fuel distribution infrastructure are also needed. Rose cites such issues as pump design, electronic control systems, carbon monoxide sensors, and new manufacturing processes as among the obstacles requiring resolution if fuel cells are to achieve widespread commercial viability. Grant expresses concern about the potential stress that extensive use of fuel cells might place on the existing gas-distribution system, which was not designed to carry the additional load.

However, "if not fuel cells, what?" says Rose. Although he foresees fierce competition between conventional and emerging alternative-energy technologies, he adds: "I don't know of anybody who doesn't believe that the car of the future will be electric or electrochemical in nature." Ω