# PART ONE: FUEL CELL TECHNOLOGY: DESCRIPTION AND STATUS

## Introduction

A fuel cell converts the chemical energy of a fuel, such as hydrogen or a hydrogen-rich gas, and an oxidant into electrical energy. It also produces heat, which in some applications may be a useful byproduct. Invented and demonstrated by Sir William Grove, the principles governing fuel cell operation have been known for about 150 years. Fuel cells were first successfully used in the Gemini space program. However, these solid polymer electrolyte fuel cells were far too expensive for commercial land use. Recent technological advances with other types of fuel cells and small-scale (40 kW) demonstrations have encouraged the development of fuel cell technology for commercial use. Increased efficiency and low emissions are important advantages that fuel cells are expected to have over most conventional powerplants.

The private sector has been conducting fuel cell research in the United States for more than 20 years. Federal funding also began more than 20 years ago with NASA's program. DOE began funding fuel cell research in 1976. These efforts are beginning to bear fruit. Several types of fuel cells are being investigated, but phosphoric acid fuel cells (PAFC) are most nearly ready for commercial use.

The PAFC development effort has proceeded primarily along two tracks. The gas industry, with the assistance of DOE, has installed and is testing 46 natural gas fueled 40 kW PAFC demonstration units at various locations (including four at military installations) around the country. These are designed to provide onsite electricity and heat for residential, commercial, and small industrial applications. The electric utility industry, on the other hand, is interested in developing fuel cells for use at central stations as peak-shaving, load-following, and—eventually—base-load powerplants. To date, two 4.8 MW demonstration plants have been built, one in New York City and the other in Japan. Much was learned from the New York facility, but it was plagued by numerous startup problems and was shut down before it began generating electricity. The Japanese prototype 4.8 MW PAFC facility, which also uses U.S. technology, has been tested and remains in operation. U.S. companies are currently designing 7.5 and 11 MW commercial demonstration plants.[1]

Fuel cells have been considered for automobile, train, and marine applications. However, application of fuel cell technology to the transportation field in general and to the marine transportation area in particular is still in the early exploratory stage. The future use of nonpetroleum-fueled fuel cells in transportation is most desirable from the standpoint of oil displacement, but transportation applications are also a difficult target market. One limitation could be the need to set up a new fuel distribution network for fuel cell fuels. A unique problem related to transportation applications is the need for quick startup and rapid, large power variations during operations.[2]

Two bills regarding fuel cells have recently been introduced in the U.S. Senate. The effect of S. 1687, the Fuel Cells Energy Utilization Act of 1985, would be to promote development of fuel cell technology. S. 1686, the Renewable Energy/Fuel Cell Systems Integration Act of 1985, seeks to promote research on technologies that will enable fuel cells to use nontraditional fuels.

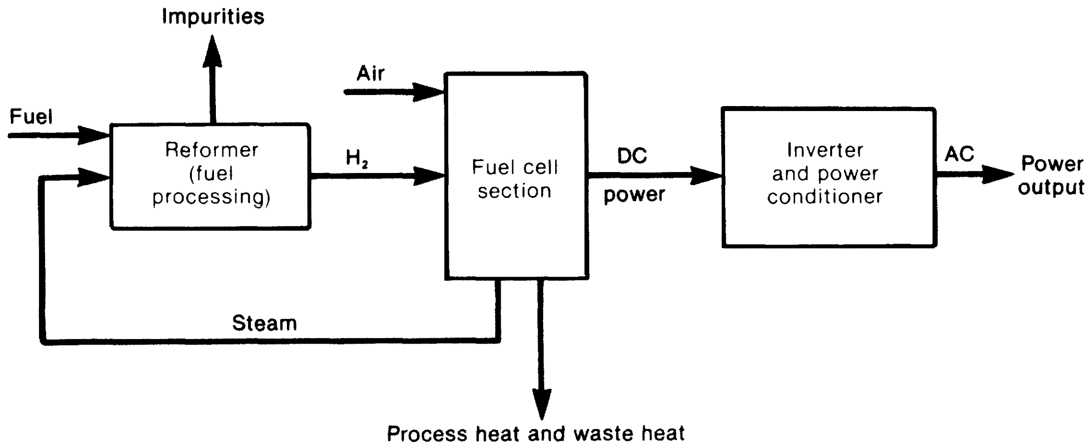
## Description of Phosphoric Acid Fuel Cell Systems

Fuel cell systems are composed of three basic elements, the heart of which is the fuel cell itself (figure 1). The fuel supply subsystem, usually a processor for producing hydrogen gas, and an electrical converter, for providing electrical power in a form acceptable to the user, make up the two other elements. Fuel cell characteristics and performance typically vary depending on the mate-

[1]For a more detailed discussion of fuel cell applications in the electrical utility industry, see U.S. Congress, Office of Technology Assessment, New *Electric Power Technologies: Problems and Prospects for the* 1990s, OTA-E-246 (Washington, DC: U.S. Government Printing Office, July 1985).

[2]The Los Alamos National Laboratory has conducted studies of fuel cells for such transportation applications as locomotives and tugboats. General Motors has also sponsored R&D on fuel cell powerplants that could be used in both land and marine vehicles.

**Figure 1.—Diagram of Major Components of a Fuel Cell**




SOURCE National Fuel Cell Coordinatlng Group

rials used for electrodes, electrolytes, and catalysts. PAFCs are the most developed of the fuel cell systems currently being considered, but other types, such as molten carbonate, solid oxide, alkaline, and solid polymer electrolyte fuel cells (classified by the electrolyte used in the cell) are also receiving research attention.

## The Fuel Cell Stack

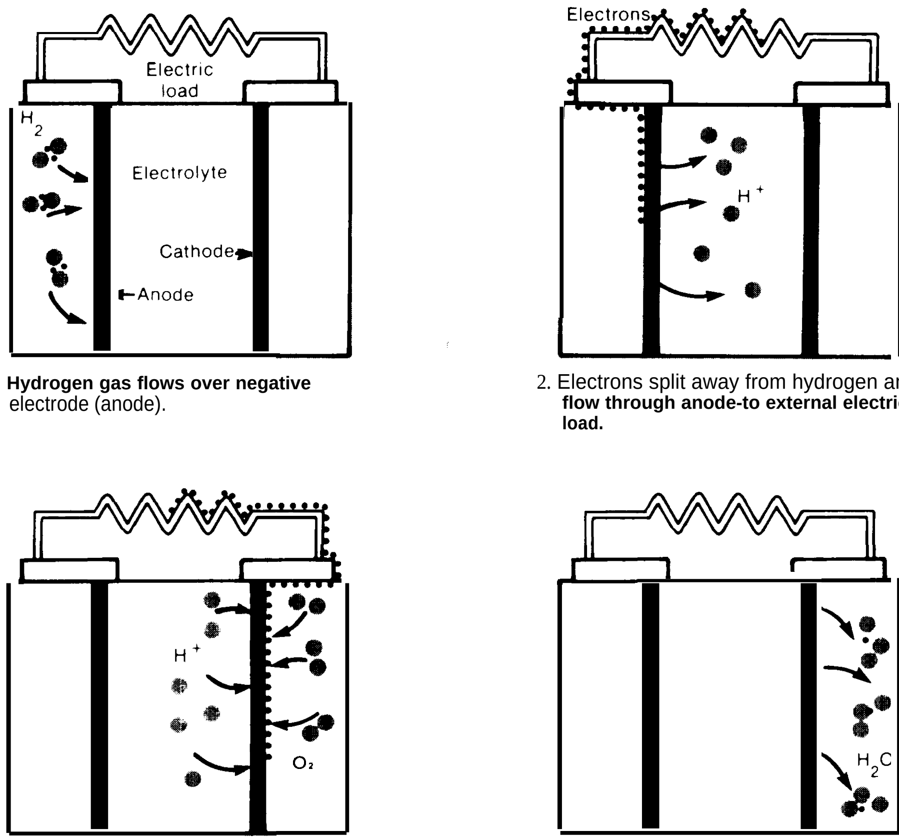
Fuel cells are composed of two electrodes, a cathode and an anode, separated by an electrolyte (see figure 2). In the typical PAFC, fuel (a hydrogen-rich gas reformed from natural gas or another fossil fuel) is delivered to the porous anode element. The anode is coated with a catalyst, such as platinum, which causes the hydrogen molecules to dissociate into hydrogen ions and electrons. The hydrogen ions pass through the phosphoric acid electrolyte to the cathode. A current is created as the electrons, unable to move through the electrolyte, pass instead through a conductor attached to both electrodes. When a load is attached to this circuit, electrical work is accomplished. At the cathode, oxygen (generally in the form of air) is introduced. The oxygen combines with the hydrogen ions, which have migrated from the anode, and with the electrons arriving via the external circuit to produce water.[3] The nitrogen and carbon dioxide components of the air are discharged. Unlike a battery, a fuel cell does not have a fixed amount of chemical supply, and thus does not run down. It continues to operate as long as fuel and oxidant are supplied to it and an adequate level of electrolyte is maintained.[4]

The individual PAFCs being developed for commercial use are flat sandwich structures, with size ranging from about 0.1 to approximately 1 square meter. One to two kW are produced per square meter. The voltage produced by a single cell is low, between 0.6 and 0.85 volts, after allowing for losses within the cell. However, these small voltages add up when cells are connected in series. A high voltage output is created by stacking the individual cells. A typical 200 kW "stack" of 500 fuel cells would result in about a 325 volt output, each cell producing about 400 watts of power. Stacks may then be connected in parallel to provide the desired total power. The current produced is proportional to the rate at which the electrochemical reactions proceed and to the surface area available for the reactions.

[3] Arnold P. Fickett, "Fuel-Cell Power Plant s," *Scientific American, vol.* **239, No, 6,** December 1978, p. 70,

[4] U.S. Department of Energy and National Aeronautics and Space Administration, *Assessment of the Environmental Aspects of the DOE Phosphoric Acid Fuel Cell Program,* DOE NASA 12703-3, May 1983, p. 3.

**Figure 2.—Schematic Representation of How a Fuel Cell Works**




1. **Hydrogen gas flows over negative** electrode (anode).

2. Electrons split away from hydrogen and **flow through anode-to external electric load.**

3. **Hydrogen ions move through electrolyte to cathode. Electrons stream into cathode from load. Cathode is bathed with oxygen.**

4. **Hydrogen, electrons, and oxygen combine to form water (steam).**

SOURCE Ernest Raia,"Fuel Cells SparkUtilities' Interest, " *High Technology*, December 1984

The temperatures at which these reactions occur vary with the type of fuel cell. The choice of phosphoric acid as the electrolyte in PAFCs determines an operating temperature of between 1500 and 2000 Celsius. Other types of fuel cells operate at much higher temperatures. Below 1500 C the phosphoric acid is not a good hydrogen ion conductor. Above 2500 C, the electrode materials become unstable. Heat is given off in this electrochemical reaction, some of which is used to maintain the temperature of the electrolyte. However, most of the heat is transported away by air or liquid coolants and, if it can be used in the fuel processor and/or for other heating needs, it improves the overall conversion efficiency of the fuel cell.

An important characteristic by which fuel cells are compared with other powerplants is the heat rate. Heat rate refers to the amount of thermal energy required to produce a unit of electric power, and is measured in terms of British thermal units per kilowatt-hour (Btu/kWh). Presently available PAFC systems providing alternating current have heat rates of about 8,500 Btu/kWh, The most efficient power generator now available, the oil-fired powerplant operating on a combined cycle, also requires about 8,500 Btu/kWh. Commercialization of fuel cells depends in part on reducing heat rates, thereby improving cell power output and efficiency. Realistic future goals for PAFC heat rates are thought to be about 7,500

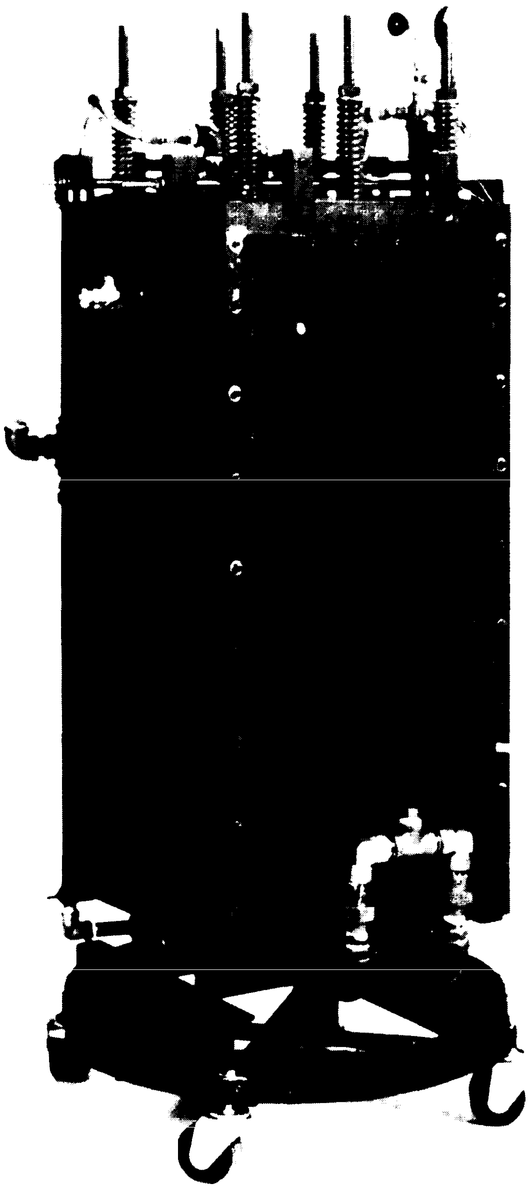


Photo credit Engelhard Corp

5 kW Fuel Cell Stack

Btu/kWh. One way to achieve these rates is by developing cells that can run at higher operating temperatures and pressures, Another is by using advanced “super acids” that are more active electrochemically than phosphoric acid. Such acids may be able to lower the heat rate to about 7,000 Btu/kWh. Phosphoric acid, for example, may in principle be substituted directly for phosphoric acid without having to change the design of present cells. However, super acids cannot yet be synthesized in great quantities, and they remain laboratory curiosities. [5]

## The Fuel Processor

The fuel processor or reformer performs two important functions. One is to convert the stock fuel to a hydrogen-rich gas for use in the fuel cell stacks. The second is to remove impurities, To minimize contamination of the fuel cell electrodes, sulfur and carbon monoxide are removed by the fuel processor through the use of special desulfurizers and carbon monoxide shifters (the shifters transform CO to $CO_2$). Water vapor produced by the reforming process is also removed from the hydrogen-rich gas prior to its delivery to the fuel cell stack. Fuel processing requires different technology for each stock fuel. Since no power or heat is available from the fuel cell stack when the system is initially started, a separate source of power is required to start both the reformer and the stack. This power source must be able to generate steam for the reformer and to preheat the stock fuel. Startup times of several hours or more are required for 40 kW and larger systems, a factor that could affect the use of fuel cells for some forms of marine transportation.

## The Power Conditioner

The power conditioner receives electrical power from the fuel cell stack and converts it to match the required output. Fuel cells produce direct current (DC), and if the application uses DC current, as may be the case for some marine applications, the current may be used as it comes from the fuel cell stack after providing for voltage and power monitors and controls, and power cutoff devices. If alternating current (AC) is required, an inverter is incorporated into the power conditioner. This conversion device is about 90 percent efficient with present designs. In many cases the cost of AC motors and the inverter is less expensive than the equivalent DC system, and it is therefore likely that the AC conditioner would be incorporated.

‘Ernest Raia, “Fuel Cells Spark Utilities’ Interest, ” *High Technology,* December 1984, p. 56,

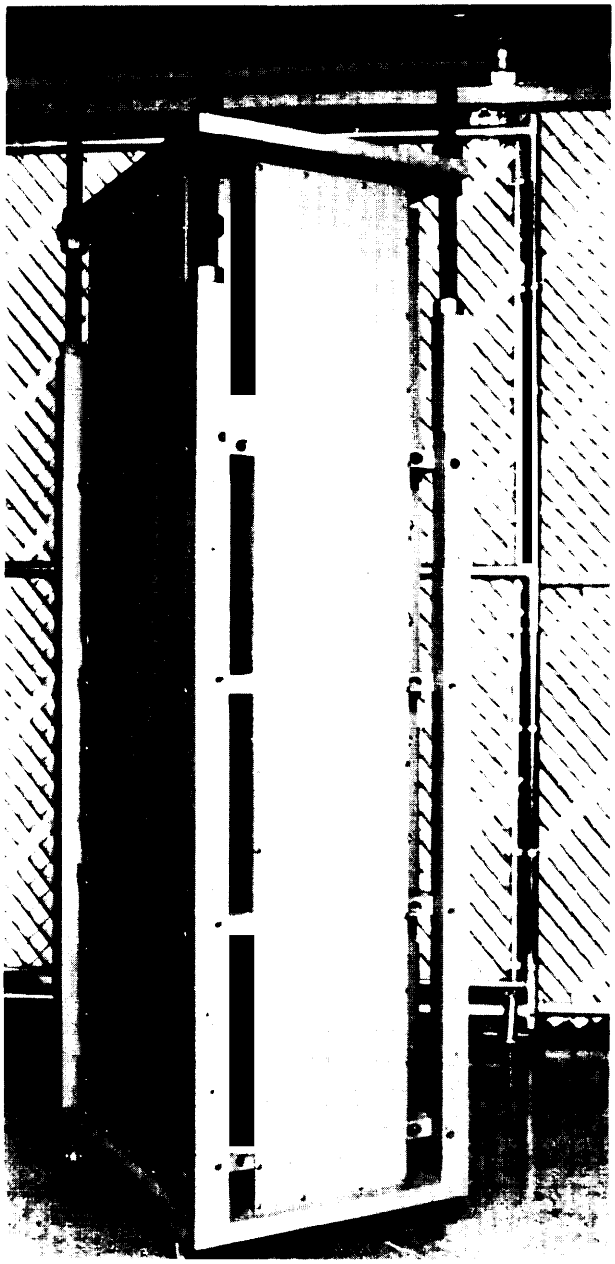


Photo credit" Engelhard Corp

25 kW Fuel Cell Stack

### The Controller

The fuel cell controller has a number of functions. It must control supplemental power during the startup operations, stack cooling and gas flow during power and hold operations, and finally control the close-down operations. Numerous temperature, gas flow, and other sensors and microprocessors are used by the controller in performing its functions.

## Other Types of Fuel Cells

Although the PAFC is the most developed and closest of the various types of fuel cells to becoming commercially available, several other promising development approaches are being pursued by government and private industry. Each of the fuel cell types discussed below requires considerable technological advances before commercialization, but these other approaches promise to be even more efficient than PAFCs, as well as provide other benefits. Since each operates at a different temperature, each has different advantages and limitations.

### Molten Carbonate Fuel Cells (MCFC)

Development of MCFCs is still at a relatively early stage. The program is about 5 to **10** years behind the state-of-the-art of phosphoric acid systems. Therefore, MCFCs will probably not be commercial before the late 1990s. However, MCFCs are appealing for several reasons. Since MCFCs operate at temperatures of from 6000 to 7000 C, a catalyst is not needed to speed up the chemical reactions; expensive platinum use can be eliminated. Moreover, this type of fuel cell is even more efficient than the PAFC. MCFCs also appear to be able to use more types of fuels. Furthermore, it may be possible to use the waste steam to convert hydrocarbon fuel into hydrogen within the fuel cell itself, thereby eliminating the need for an external reformer. This may increase efficiency and lower costs, but the feasibility of this process has not yet been verified.

The high operating temperatures that MCFCs require and the corrosive electrolyte create materials problems. For example, the present nickel oxide cathodes do not have an adequate operating life. Technical challenges include developing anodes with improved dimensional stability during operation; maintaining the desired electrolyte distribution during cell operation; and maintaining adequate corrosion resistance at a reasonable cost. In addition, some investigators of transportation applications have noted that thermal inertia may be a problem in operations with rapid load fluctuations.

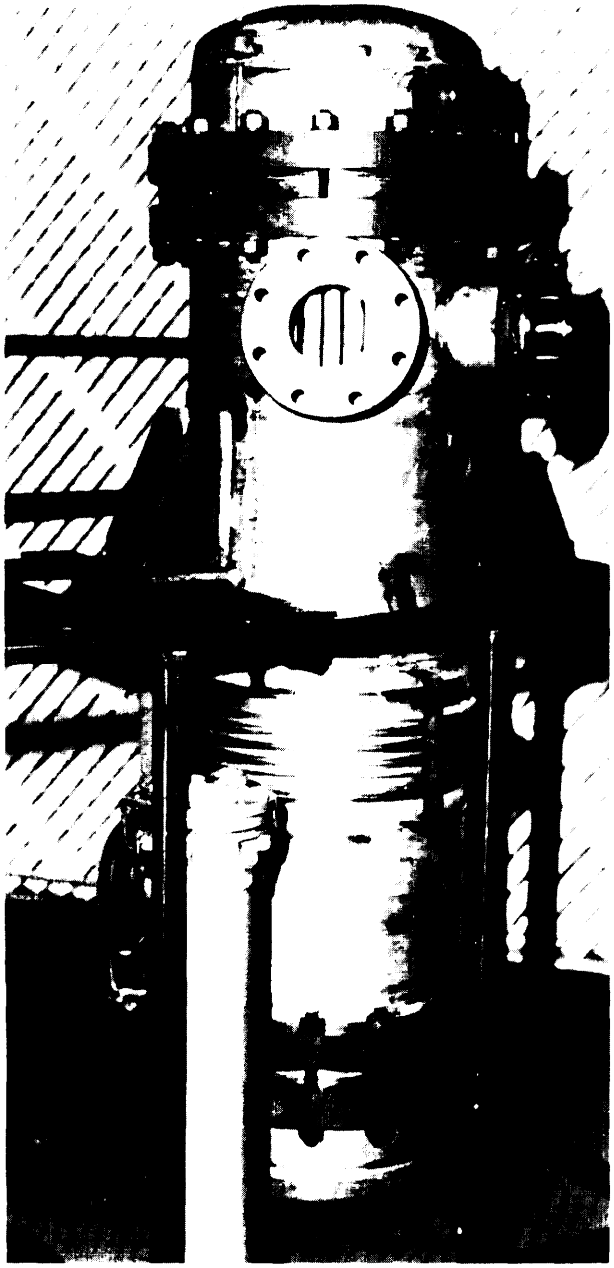


Photo credit Engelhard Corp

50 kW Methanol Reformer

MCFCs are now under development principally for large industrial or central power-generating plants. It is believed that heat rates can be as low as 6,500 Btu/kWh, and that eventually molten carbonate heat rates may be reduced to as little as 5,900 Btu/kWh, whereas the present PAFC heat rate is about 8,500 Btu/kWh. The ability to use traditional marine fuels may also make MCFCs attractive for marine applications.

### Solid Polymer Electrolyte (SPE)

SPE technology is still highly exploratory. Theoretically, however, this technology could provide greater performance than PAFC technology. The advantages could be high efficiency and almost instantaneous startup and shutdown. However, at present the electrolyte, a proton-exchange membrane, is intolerant to high temperatures. This means there are limited cogeneration applications and that control problems could be severe.' The Los Alamos National Laboratory has evaluated the feasibility of using SPE fuel cells for selected heavy-duty transportation systems, and believes further R&D of SPE fuel cells to be potentially very important.[7] Likewise, General Motors is investigating the possible use of SPE fuel cells for land transportation.

### Solid Oxide

Solid oxide fuel cells are theoretically highly efficient and are at about the same stage of development as molten carbonate systems, at least 5 to 10 years from commercial use. A major attraction is that these fuel cells are conceptually simple. Since they are solid state, there should be fewer maintenance problems, no liquids to contain, no migrating electrolyte, and no corrosion problems. Compared to other fuel cell technologies, sulfur tolerance is high. In addition, since solid oxide fuel cells operate at close to 1,0000 C, high-quality heat for bottoming cycles and internal reforming is generated. High temperature operation also eliminates the need for special catalysts. However, at these high temperatures, stability of materials is a problem. Materials must also have closely matched thermal expansion coefficients to prevent delamination of ceramic layers, and not many materials meet these requirements. All such

[6]Peter S, Hunt, "Analysis of Equipment Manufacturers and Vendors in the Electric Power Industry for the 1990s as Related to Fuel Cells, " prepared for the Energy and Materials Program, Office of Technology Assessment, U.S. Congress, Washington, DC, Dec. 15, 1984, p. 34.

[7]W. J. Walsh and J.B.Rajan, "Advanced Batteries for Electric Vehicles, " Argonne National Laboratory, April 1985, p. 7. See also J.R. Huff and H.S. Murray, "Feasibility Evaluation of Fuel Cells for Selected Heavy-Duty Transportation Systems, " Los Alamos National Laboratory, March 1982.

materials currently being investigated are rather exotic. In addition, solid oxide fuel cells currently under development are small, so the power output is low. Hundreds of thousands of these would be needed to construct a multi-megawatt powerplant, and this could be a major problem for a system designer.[8] The National Fuel Cell Coordinating Group sees the initial market for solid oxide fuel cells in electric utilities and industrial cogeneration applications using natural gas fuel. Eventually coal-fueled powerplants might become practical.[9] Solid oxide fuel cells may also have some transportation applications because they could be small and light.

Alkaline

Alkaline fuel cells, which operate at about 65° C, were first developed by NASA for use in the space program. First used on Gemini 5 to supply electricity and drinking water, they have subsequently been used on Apollo, Skylab, and Space Shuttle missions. The most advanced alkaline fuel cells used on the Space Shuttle provide about eight times as much power as the first versions developed. Alkaline fuel cells are highly efficient, with a heat rate of about 5,000 Btu / kWh, but given their high expense, industry sees few applications for them. Alkaline fuel cells do not tolerate carbon in the fuel stream, so must rely on pure hydrogen and oxygen. Producing high purity fuels is very expensive, and therefore alkaline fuel cells are not considered commercially practical at the present time for other than very specialized applications (e.g., in the chlor-alkali industry where pure hydrogen is produced as a byproduct). NASA is more concerned with weight, however, not fuel cell expense.

## Advantages and Disadvantages of Fuel Cells

Generation of electricity by fuel cells promises numerous benefits. General advantages are likely to include:

1. *High efficiency*. The fuel cell converts the chemical energy of a fuel directly to electrical energy without combustion. Thus, its theoretical efficiency is not limited by the Carnot cycle. The conversion efficiency of PAFC stacks, from input fuel to output electricity, is between **40** and 44 percent. Since the efficiency of a fuel cell stack is determined largely by the characteristics of the individual cell, the efficiency of the fuel cell power system is (to a degree) independent of the size of the plant. Overall, the greater efficiency that fuel cells may provide could mean a significant fuel conservation potential.
2. Low emissions. Since most undesirable constituents are stripped from the fuel in the reformer, emissions from the fuel cell itself are negligible, consisting mostly of water, which is emitted as a result of reactions within the reformer. Water is emitted as a result of the reduction of oxygen at the cathode. Carbon dioxide is emitted as a result of the reduction of oxygen at the cathode. Carbon dioxide emissions may contribute to world climate warming (the "greenhouse effect"), but the quantities of carbon dioxide produced are not greater than quantities produced by conventional fossil fuel powerplants.

   The major source of undesirable emissions is in the preparation (reformation) of hydrocarbon fuels for use in the fuel cell. In reforming petroleum or coal for use in fuel cell powerplants, sulfur dioxide and nitrogen oxides are produced. However, sulfur dioxide emissions are expected to be about 0.0001 pound per million Btu (lb / MMBtu), almost nonexistent when compared to emissions from oil- and coal-fired powerplants, and nitrogen oxide emissions about 0.2 lb / MMBtu, about three times lower than present Federal standards for new coal-fired powerplants.[10] In the environmental assessment they conducted for DOE and NASA, Lundblad and Cavagrotti concluded that "sizable improvements in national air quality can be expected when fuel cells penetrate the energy supply market in substantial quantities."[11]
3. Quiet. Fuel cell powerplants are quiet compared to conventional powerplants. Because the fuel cell has no moving parts, the only

[8] Raia, op. cit., p. 56.
[9] Irwin Stambler, "Fuel Cell Systems Aiming at 5,000 Btu/kWh Heat Rates, " *Cogeneration*, November December 1984, p. 26.

[10] Fickett op. cit., p. 73. Present Federal standards are discussed in U.S. Congress, Office of Technology Assessment, *Acid Rain and Transported Air Pollutants: Implications for Public Policy*, OTA-0-204 (Washington, DC: U.S. Government Printing Office, June 1984).
[11] U.S. Department of Energy and National Aeronautics and Space Administration, "Phosphoric Acid Fuel Cell Platinum Use Study, " DOE / NASA / 2701 / 2, May 1983, p. 156,

noises are those produced by the pumps and fans of the fuel cells auxiliary equipment. This fact means that investments in noise control equipment can be reduced and that fuel cell plants can be sited closer to the loads they serve.

4. *Ease of siting.* Low emissions and quietness are qualities that are likely to make siting of utility fuel cell powerplants easier than siting of conventional powerplants. Hence, fuel cells are more easily located in urban areas where construction of conventional powerplants would be difficult. This same quality may be important for some marine applications—e. g., on cruise ships.
5. *Opportunities for cogeneration.* The fuel utilization efficiency of fuel cells can be further increased by utilizing the waste heat generated by the electrochemical process. When PAFCs are used to produce both electricity and heat, overall efficiencies of **80** percent or more maybe reached. The economics for cogeneration systems look much better than for those systems producing only electricity. A shipboard system could also take advantage of cogeneration.
6. Modularty. Fuel cells can be manufactured in modules. Unlike restrictions on conventional powerplants, the size of a fuel cell powerplant can be easily increased in electric utility applications to match load requirements. By increasing capacity incrementally as needed, utilities may be able to avoid some of the initial capital investments otherwise required of steam or nuclear plants, which are sized for some distant year's consumption. The conventional large plant is not operated at its most efficient level for many years. For shipboard applications, adding capacity incrementally probably does not apply. However, the fuel cells can be distributed to points of load concentration, which offers advantages in certain military and specialized vessel applications.
7. *Short construction lead time.* Because fuel cells can be factory mass-produced, lead times necessary to construct a fuel cell powerpIant can be significantly reduced, Whereas a conventional coal or nuclear plant may require 10 to 12 years to license, design, and construct, it is estimated that once a fuel cell manufacturing plant is operating, a fuel cell powerplant could be installed in less than 3 years. These short construction lead times in turn will reduce utility reliance on frequently inaccurate long-term demand projections, thereby reducing business risk and improving utility economics. For certain naval operations, short construction lead time may also be a substantial advantage.
8. *Flexible fuel usage.* Fuel cell systems can be designed to use a variety of fuels. The fuel usually selected for commercial onsite PAFCs is natural gas. Other fuels that could be used include waste site methane, naphtha, liquid hydrocarbon fuels such as butane or propane, low and medium Btu coal gas, methanol or ethanol, coal-derived liquid fuels, biomass derived fuels, and hydrogen or hydrogen-rich byproduct gases from industrial processes. However, the fuel processor must be specially designed for each fuel. Since fuel cells will, to some degree, displace conventional powerplants, their capability to use alternative fuels could reduce dependence on premium oil and gas used in conventional powerplants.

   Fuel usage for a particular type of fuel cell is largely dependent on the characteristics of the electrodes, electrolyte, and catalyst used in the cell. Since these components may be sensitive to contamination by "poisons," the fuel processor must be designed to eliminate contaminants. For example, the cathodes of PAFCs can be readily contaminated with any sulfur in the enriched hydrogen fuel. Thus, fuels containing significant amounts of sulfur must undergo considerable desulfurization to be usable. An alkaline fuel cell can tolerate only pure hydrogen and oxygen and is readily poisoned even by carbon dioxide.
9. *Efficient part load application.* Fuel cells have the ability to maintain efficiency through a range of loads—i. e., at loads between **30** to 100 percent of rated output. Conventional systems, on the other hand, are less efficient at the lower end of this range.
10. *Easy to operate and maintain.* Fuel cells are simple to operate because there are few moving parts. Fuel cells could potentially oper-

ate unmanned. Hence, operation and maintenance costs are likely to be low.

Assuming fuel cells function as desired, there would still be several potential drawbacks to their widespread use. These include:

1. *Capital cost.* Relatively high cost for a new and unproven technology is the principal deterrent to early, widespread commercial use of fuel cells, especially in the marine industry where difficult economic conditions prevail and no one is taking large risks.
2. F'reduction *of carbon dioxide* in amounts similar to those emitted by conventional fossil fuel plants (when a fossil fuel is used as an input fuel). Thus, like use of conventional powerplants, fuel cell use could contribute to global climate warming.
3. Possible *material vulnerability.* Some of the materials used in fuel cells are in scarce supply in the United States. Among these are platinum, used as a catalyst in PAFCs. Domestic platinum deposits are capable of supplying only about 10 percent of annual U.S. requirements today.[12] If fuel cells gain wide acceptance, demand for these materials could increase significantly, and, consequently U.S. dependence on sometimes unstable foreign sources of supply would grow. Cumulative U.S. platinum demand for PAFC market penetration of **20,000** to **40,000** MW is estimated to be between 1.1 and 2,2 million troy ounces. '3 The world supply of platinum appears sufficient to handle the estimated increased demand, and platinum prices are expected to rise only moderately, '4
4. *Some public exposure to fuels.* If fuel cell powerplants were located in urban areas, there could be more exposure to fuels transported through populated areas than would be the case with conventional powerplants located away from densely populated areas.
5. *Fuel supply.* Wide availability of fuel for transportation applications could be a problem. Use of some fuels considered appropriate for fuel cells would require emplacement of an entirely new distribution network. This issue is considered in more detail below.
6. *Fuel cell life.* Periodic replacement of fuel cell stacks is required for some systems after as little as 5 years of use; thus, life-cycle costs may be a negative factor.

## Fuel Cell Development Programs: Current and Future Emphasis

Fuel cell research is funded by the Federal Government, by industry research institutes, and by private manufacturers and utility companies. Since 1960, total expenditures for government-sponsored R&D have exceeded $500 million. Within the Federal Government, most of the research money comes from DOE, but DOD and NASA also have active fuel cell programs. The two major industry research institutes funding research are the Electric Power Research Institute (EPRI) and the Gas Research Institute (GRI). These five entities comprise the National Fuel Cell Coordinating Group (see figure 3). This group provides an ad hoc forum for coordinating the national fuel cell development effort. The costs of many fuel cell technology development projects are often shared between two or more of these organizations. Several fuel cell users groups, established to assist members in the development and commercialization of fuel cells, have also been formed. The Onsite Fuel Cell Users Group is comprised primarily of gas utilities, while the Electric Utility Fuel Cell Users Group is comprised mostly of electric utilities.

### U.S. Department of Energy

The Department of Energy's Office of Fossil Energy runs the Federal Government's most extensive fuel cell R&D program. DOE's overall goal in funding fuel cell research is to foster the development of environmentally acceptable technologies that will help reduce the Nation's use of oil and natural gas. In general, DOE does this by supporting high-risk, high-payoff technology development. Thus, a major objective is:

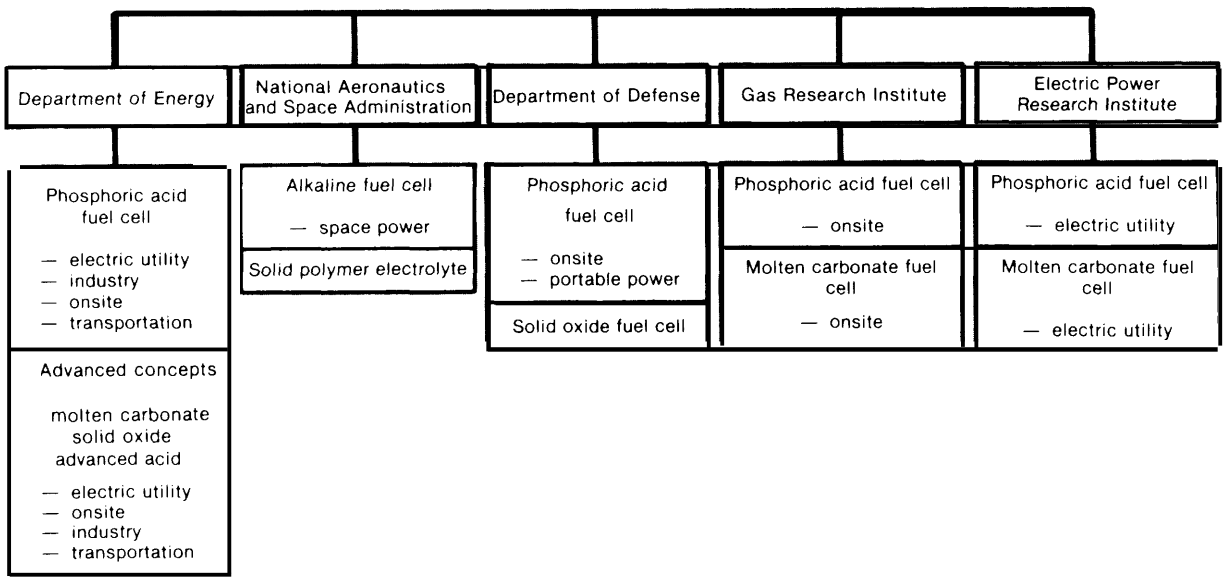
> . . . to establish, in concert with the activities of other funding organizations and fuel cell manu-

[12] T. F, Anstett, D.I. Bleiwas, and C. Sheng-Fogg, "platinum Availability—Market Economy Countries, " U.S. Department of the Interior, Bureau of Mines, information circular 8897, p. 12.

[13] DOE and NASA, DOE/NASA/2701/2, op. cit., pp. 109 and 110.

[14] DOE and NASA, DOE/NASA/2701 /2, op. cit., p. 155.

**Figure 3.—National Fuel Cell Coordinating Group**




SOURCE U S Department of Energy

> facturers, a verified technology base upon which the private sector can, at lower risk, develop and commercialize [fuel cell systems] for early entry into U.S. markets. 15

DOE's fuel cell program is divided into two major subprograms. The objective of one is to develop multi-megawatt fuel cell powerplants for electric utility and large industrial applications; of the other, to develop multi-kilowatt powerplants for onsite use by residences, light industry, and small businesses, Many research projects may help foster commercialization of both types of systems.

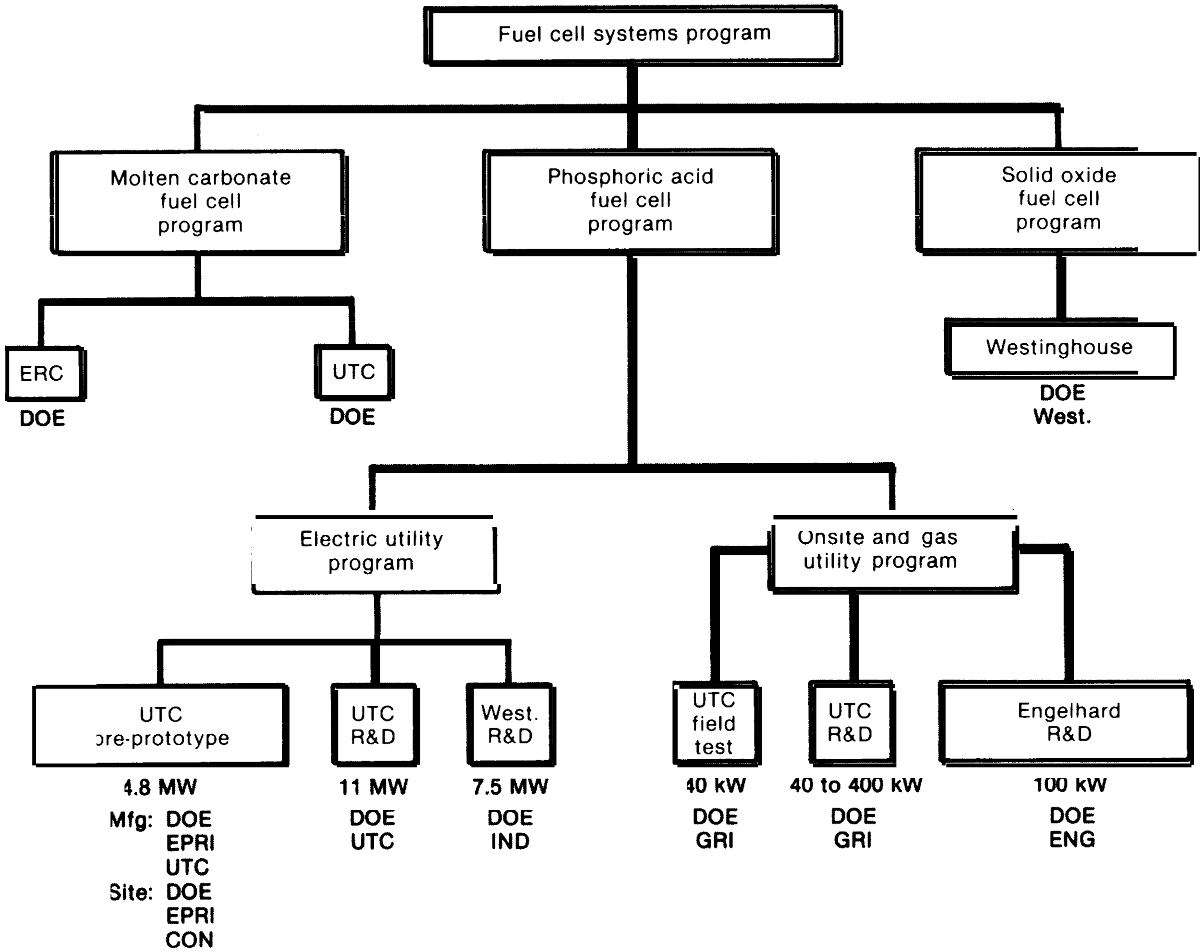
DOE is currently supporting development of three types of fuel cells that may be used in both multi-megawatt and multi-kilowatt systems—phosphoric acid, molten carbonate, and solid oxide fuel cells (see figure 4). DOE began funding fuel cell research in 1976. To date, most of the research it has funded has been for development of PAFC technology. However, DOE now believes that phosphoric acid research is sufficiently advanced that the private sector no longer needs as much support.

[15] DOE and NASA, DOE NASA / 2703-3, op. cit., p. 7.

Most DOE funding for fuel cell research has gone to four private contractors for electric utility and onsite fuel cell development. These include United Technologies Corp. and its subsidiary, the recently established International Fuel Cells Corp.; Westinghouse; Engelhard Corp.; and Energy Research Corp. There has been very little funding of the possible transportation applications for fuel cell technologies, but DOE has funded the Los Alamos National Laboratory to evaluate the potential of fuel cells for selected heavy-duty transportation systems. DOE has also funded one commercial ocean transport system study. This was a feasibility study for submarine tankers propelled by PAFCs.

Between 1976 and 1984, DOE spent about **$260** million on fuel cells, Since 1978 funding for DOE's fuel cell program has averaged about $35 million per year. Of this, the bulk of funds (over 65 percent) have been expended on phosphoric acid research. Molten carbonate systems have received about 28 percent of DOE's funding support, and solid oxide systems about 7 percent. DOE has preferred to focus program effort on phosphoric acid development, since this technology is most advanced and since commercialization of a specific

**Figure 4.—Participants in DOE's Fuel Cell Program**




SOURCE U S Department of Energy

fuel cell technology is likely to be necessary before potential users are likely to become very interested in fuel cell technologies that, however promising, are not yet very advanced. Success of PAFC systems will likely stimulate industry competition to further advance alternative fuel cell technologies. The present administration has repeatedly sought to reduce funding for the fuel cell program. However, Congress has been a strong supporter of fuel cell research and has consistently reinstated research funds that the present Administration has sought to cut.[16]

[16] Hunt, op. cit., p. 19

## National Aeronautics and Space Administration

In the 1950s and 1960s, NASA funded the development of alkaline fuel cell powerplants for use in spacecraft. The current NASA program is directed toward development of low temperature, hydrogen-oxygen fuel cells for regenerative and primary space mission applications, and toward development of advanced concepts for future space applications.[17] Fuel cells developed for use in outer space are not cost-effective for terrestrial transportation uses. In addition to its other activ-

[17] U.S. Department of Energy, Office of Fossil Energy, "Fuel Cell Systems Program Plan," October 1984, p. 11.

ities, NASA (Lewis Research Center) has been designated by DOE to implement DOE-funded PAFC projects.

### U.S. Department of Defense

The armed services are interested in the possible applications of fuel cell technology primarily as a means to support field operations. Characteristics of fuel cells that make them particularly useful for the military include low noise, low thermal signature, and high efficiency. The Belvoir Research and Development Center of the U.S. Army has had a fuel cell program since the mid-1960s, and is currently sponsoring the development of fuel cells for mobile applications to support troop operations. Phosphoric acid units have been designed for power ranges between 1.5 and 5 kW. Thus far, the Army's portable fuel cell powerplants have been designed to run on methanol; however, future units will be developed to run on diesel fuel, since it is both less expensive and (since all Army vehicles use it) readily available in the field. Work on developing reformers for diesel-powered fuel cells is in progress.[18]

The Army also manages a fuel cell program for the U.S. Air Force. The Air Force is primarily interested in using fuel cells in remote areas, such as at Distant Early Warning radar sites in the Arctic. Currently, diesel drive electric generators are used at these sites, but because the cost of providing fuel and maintenance services is high, PAFCs are being considered as an alternative.

The U.S. Navy does not have a significant fuel cell R&D program. However, several of its research offices monitor other agency and industrial programs and occasionally conduct reviews to keep abreast of fuel cell developments that may be applicable for Navy missions. Several small SPE fuel cells are currently being tested at the David Taylor Naval Ship Research and Development Center in Annapolis. In the past, the Navy has supported development of fuel cells for powering small submersibles and submarines, but it has no plans at the present time for using fuel cells for main or auxiliary ship power.

[18] Allayne Adams, U.S. Army, Ft. Belvoir, interview, July 8, 1985.

### U.S. Department of Transportation

The Maritime Administration (MARAD), within DOT, has funded a small amount of work investigating the potential marine applications for fuel cells. One study assessed a broad range of advanced merchant vessel power systems and concluded that fuel cells are one of four contenders with some potential.[19] Another MARAD-sponsored study examined a plan to evaluate at sea a methanol-fueled PAFC used as an auxiliary power system,[20] MARAD has decided not to proceed with the proposed test.

### Gas Research Institute

GRI is the gas industry research organization. Its budget of about $170 million per year is generated by an R&D surcharge on natural gas consumption of 1.35 mills/MMBtu, as approved by the Federal *Energy* Regulatory Commission (FERC). Much of the research it funds is coupled with Federal and private efforts. A primary objective of GRI is to promote the development of fuel cells that can use pipeline gas.[21] Hence, GRI has focused its effort on developing and demonstrating fuel cells that can be operated independent of an electric utility grid. The size of these onsite fuel cell powerplants will likely be between 40 and 500 kW. Since a 40 kW plant generates about 150,000 Btu/hr of heat, these units can be used as cogenerators to maximize net efficiency. Commercialization of these onsite units would mean load losses (and thus direct competition) for the electric utility industry.

A major facet of GRI's onsite program is field testing of phosphoric acid units. The program is jointly sponsored by DOE, GRI, and a number of participating utilities. Customers of the utility user group include hospitals, stores, restaurants, etc., and are spread all over the country. No marine users, however, are in the user's group. To-

[19] Gary J. Baham, "Merchant Vessel Advanced Power Systems," final report to the Maritime Administration, U.S. Department 01 Transportation, NTIS #PB-82-185240, January 1982.

[20] Arctic Energies Ltd., "Development of Marine Rated Phosphoric Acid Fuel Cells," final report to MARAD, NTIS #1' B-85-164879, September 1984.

[21] Gas Research Institute, *1985-1989 Five-yedr Research and Development Plan and 1985 Research and Development Program*, April 1984, pp. 135-142.

tal project costs for the 1981-85 period have been about $60 million. The purpose of the field test project is to verify performance, demonstrate installation and maintenance, and stimulate user acceptance. The onsite field test program has progressed from tests in the 1960s of some sixty 12.5 kW fuel cell powerplants to the present testing of over forty 40 kW PAFC powerplants. The present installations began operating in 1983. Performance data will continue to be collected through mid-1986. At the present time, 46 powerplants have been placed in the field and over 215,000 operating hours have been obtained. Primary problems seem to relate to supporting equipment, such as pumps, and to the coolant system. It is expected that the 40 kW field tests will be followed by the design, development, and commercial introduction of an approximately 200 kW capacity unit in the future.

GRI is also helping to fund PAFC technology development by the private sector (primarily United Technologies Corp. (UTC)). The objectives of the technology development project are to improve onsite components, system performance, reliability, and maintainability; and to reduce fuel cell manufacturing costs, thereby promoting early commercialization.

### Electric Power Research Institute

EPRI is the major electric utility industry research organization. Like GRI, EPRI fuel cell programs are coordinated with Federal and private efforts. EPRI funding is also derived from a levy on ratepayers approved by FERC. However, unlike GRI, EPRI interest focuses more on large, multi-megawatt central power generating systems. With DOE, UTC, and a utility consortium led by Continental Edison, EPRI participated in developing a 4.8 MW pre-prototype phosphoric acid powerplant located in New York City.[22] EPRI is also contributing funds to the UTC effort to develop an 11 MW PAFC and to the Westinghouse effort to build a 7.5 MW powerplant.

In addition to promoting phosphoric acid research, EPRI promotes R&D of advanced fuel cell concepts that may prove useful for the electric utility industry. Thus, EPRI has a program whose major goals are to develop molten carbonate fuel cells capable of 25,000 hours of operation under a wide range of conditions, and to verify an advanced stack concept that can reform natural gas or methanol within the fuel cell stack and produce power at approximately 60 percent efficiency. Achievement of this latter goal initially could result in a relatively small (2 MW), modular, highly efficient (50 to 60 percent), and very simple powerplant that does not require an external fuel processor.[23] Such a powerplant could have potential marine transportation applications.

EPRI budgeted $9.6 million for fuel cell and hydrogen technology research in 1985, and it has budgeted a total of $81.6 million for the 1985-89 period.[24]

### Major Company Efforts

There are relatively few companies involved in fuel cell research, development, and manufacturing. All are, to some degree, supported by DOE and/or other Federal agencies. Industry estimates that the ratio of private sector spending to Federal funding has been historically approximately 2 to 1,[25] but this figure is very difficult to verify. Perhaps the company with the longest involvement in fuel cell R&D is UTC. UTC is involved in development and manufacturing of PAFCs for both the electric utility multi-megawatt program and the gas utility onsite program. UTC and the Toshiba Corp. recently established a joint venture, the International Fuel Cells Corp., to design, develop, and market an 11 MW fuel cell powerplant for electric utility use. UTC is also funded by DOE to conduct research on MCFCs, and it has an ongoing program to develop alkaline fuel cells for military and space applications.

Westinghouse is developing a multi-megawatt PAFC system independent of the UTC effort. It has received funding support from DOE and EPRI

[22] The New York facility cost $85 million, of which 57 percent was contributed by DOE, 20 percent by EPRI, 16 percent by UTC, and 7 percent b, Consolidated Edison of New York and its partners.

[23] Electric power Research Institute, *1985-1989 Research & Development Plan*, EPRI P-3930-SR, January 1985, pp. 474-475.

[24] 1 bid., p. 469.

[25] Sidney Law, Statement of Sidney Law, member, Fuel Cell Users Group, before the Subcommittee on Energy Research and Development of the Committee on Energy and Natural Resource, U.S. Senate, May 3, 1983, p. 745.

for the design of two 7.5 MW DC air-cooled PAFCs, which it hopes to have operating in **1987** and 1988, However, as of October 1985 no utilities had offered sites for a commercial demonstration of these units. Both UTC and Westinghouse expect to have multi-megawatt commercial PAFC powerplants for sale before 1990. Westinghouse is also conducting research on solid oxide systems, and as a result of recent technical accomplishments, believes that commercial introduction of solid oxide systems may become available as soon as 1990.[26]

The Engelhard Corp. is designing an integrated onsite energy system, which includes a PAFC powerplant; a heating, ventilating, and air-conditioning subsystem; and an energy storage subsystem. The overall plan is to develop a full-size 100 kW system made up of four 25 kW fuel cell stacks, two 50 kW fuel conditioners, and two 50 kW power processors to provide adequate reliability and redundancy .27 DOE funding for the project has been applied to improve the state-of-the-art of fuel cell stack and fuel processor technologies.

The Energy Research Corp. (ERC) is primarily involved in developing molten carbonate fuel cells for large-scale industrial cogeneration applications. ERC has licensed its PAFC technology to Westinghouse.

Finally, and perhaps most significantly with respect to transportation applications for fuel cell technologies, the Allison Gas Turbine Division of General Motors has an ongoing program to study the feasibility y of using fuel cells as a power source for automobiles and other transportation applications.

### Japan

Japan can be expected to be a major U.S. competitor in the future fuel cell market. [28] Five Japanese firms are involved in an ambitious R&D program, and Japan's New Energy Development Organization is supporting efforts aimed at having full-sized phosphoric acid plants on utility grids by about 1990. The goal of Japan's Moonlight Program is to develop a 1 MW commercial system in 1986. Research is also progressing on development of other types of fuel cells. All but one of the Japanese firms has an operating alliance with a U.S. company: Toshiba with United Technologies, Mitsubishi with Westinghouse, Engelhard with Fuji, and Sanyo with Energy Research Corp. Only Hitachi currently lacks a partner. 29 The Tokyo Electric Power Co. has been successfully operating a **4.8** MW PAFC powerplant designed by UTC since late 1983. This plant is similar to the one UTC installed in New York, but it is an improved version that takes advantage of several of the lessons learned at the New York site.

Japan is also one of the world's leading maritime nations, and Japanese developers are aware that if high efficiency fuel cells can be developed, they could possibly be used for shipboard applications. 30

## Cost Considerations

The installed capital costs of the first commercial demonstration PAFC powerplants are currently expected to be about $3,000/kW. However, no manufacturer has made a public offering, and without any commercial units in place, cost estimates should not be considered firm. With maturing technology and mass production of fuel cells, capital costs for both large and small powerplants have been projected to fall below $1,000/kW (1985 dollars) by **1995.**[31] Estimates of the installed capital cost that will enable fuel cells to compete with other utility and cogeneration alternatives vary, but are between **$750** and $1,500/kW, depending on the specific application .32 These figures

[26] G. W. Weiner and J.T. Brown, "Solid Oxide Fuel Cell Power Plants–The New Perspective for Commercialization, " 1985 *Fuel Cell Seminar: Abstracts,* sponsored by the National Fuel Cell Coordinating Group, Tucson, AZ, Ma, 19-22, 1985.

[27] DOE and NASA, DOE/NASA 2703-3, op. cit., p. 16.

[28] Irwin Stambler, "Fuel Cell Outlook Brightens as Technical Obstacles Fall, " *Research and Development,* December 1984, p, 52

29 Hunt, Op, cit., p. 9.

[30] U.S. Department of Energy, "Japanese Research and Development of Fuel Cells, " DOE/SF/10538, T6, prepared under the direction of Dr. Chico Fujishima of Galaxy NJM, February 1981, p. 22,

[31] U.S. Congress, Office of Technology Assessment, *New Electric Power Technologies: Problems and Prospects for the 1990s,* OTA-E-246 (Washington, DC: U.S. Government Printing Office, July 1985), pp. 107, 313,

[32] " Electric Utility and Gas Industry's Fuel Cell Models in Research Racer" *Electric Utility Week,* Mar, 4, 1985, p. 13; and Lee Catalano, "Can Fuel Cells Survive the Free Market in the 1990s?" *Power,* February 1984, p. 61,

do not take into account various benefit values, which, if taken together, could reduce present and projected costs per kilowatt by an estimated $200 (1985 dollars), Among these potential benefits are savings related to air emission offsets, spinning reserve and load following, transmission and distribution, and most importantly, cogeneration potential.[33] Cost and performance parameters comparing large and small PAFC powerplants with two conventional technologies are presented in table 1.[34]

A number of factors influence the overall costs of fuel cells. These include:

1. the state-of-the-art of fuel cell technology,
2. the cost to manufacture the cells and build the powerplant,
3. the cost to operate and maintain the powerplant,
4. cell replacement frequency, and
5. the cost of fuel.

Naturally, in order for fuel cell powerplants to be competitive with other alternatives, these costs must be minimized.

"Electric Power Research Institute, "System Planner's Guide for Evaluating Phosphoric Acid Fuel Cell Power Plants, " EPRI EM-3512, July 1984, p. 4-3.

[34]OTA, *New Electric Power Technologies,* op. cit., pp. 142, 313.

Although PAFC technology is well-advanced, incremental technical improvements of fuel cell and related-system components can still help reduce costs. For example, development of:

1. inexpensive, corrosion resistant cell structural materials;
2. less expensive and more effective catalysts that can operate at higher temperatures and pressures;
3. improved automated fabrication and handling processes for large area cells;
4. cheap, reliable, and efficient fuel processing units; and
5. techniques for reducing electrolyte consumption, as well as improvements in various other standard components,[35] will lower costs and enhance the ability of fuel cell units to compete with other powerplants.

One of the advantages that fuel cells will have over conventional alternatives for producing electricity is that they can be factory mass-produced. Thus, quality control can be maintained, and fuel cell stacks can be prefabricated, enabling reduction of the expensive onsite work required of other types of powerplants. Improvements in the manufacturing process will enable further reduction

[35]1 bid., p. 108,

**Table 1 .—Cost and Performance Comparisons for Land-Based Electrical Powerplants That Use Technologies Similar to Marine Propulsion Units**

| | Combustion turbine | Slow-speed diesel | PAFC large | PAFC small |
|---|---|---|---|---|
| ***General:*** | | | | |
| Reference year | 1990 | 1990 | 1995 | 1995 |
| Reference-plant size (MWe) | 150 | 40 | 11[a] | 0.2 |
| Lead-time (years) | 2-3 | 2 | 3-5 | 2 |
| ***Performance parameters:*** | | | | |
| Operating availability (o/o) | 90 | 95 | 80-90 | 80-90 |
| Duty cycle | Peaking | Intermediate | Variable | Variable |
| Plant lifetime (years) | 20 | 30 | 30 | 20 |
| Plant efficiency ('/0) | 30 | 39 | 40-44[b] | 36-40[b] |
| ***costs.***[c] | | | | |
| Capital costs ($/kWe) | 350 | 1,200 | 700-3,000[d] | 950-3,000[d] |
| O&M costs (mills/kWh) | 4-4.7 | 5.1-8.2 | 4.2-1 1.5e | 4.2-1 1.5e |
| Fuel costs (mills/kWh) | 48.6 | 42 | 27-30[f] | 30-33' |

aA typical Commercial powerplant will be much larger than 11MW.
bDoes not include cogeneration potential. Cogeneration efficiency could be as high as 85 percent
cAll cost figures are reported in mid-1983 dollars
dLower end of range assumes mature technology and mass production; high end represents the estimated cost of the first commercial units
eIncluding cell replacement costs
'Natural gas fuel

SOURCE U S Congress, Off Ice of Technology Assessment, New *Electric* Power *Technologies Problems and Prospects for the 1990s*, OTA-E-246 (Washington, DC: U S. Government Printing Off Ice, July 1985), pp 142, 313.

of total costs, However, one "chicken-and-egg" type problem is that cost savings from mass production cannot be realized until utilities and other potential users begin ordering fuel cells, but the current cost of fuel cells is still too high for most potential users to be willing to invest. This situation, according to fuel cell manufacturers and potential users, may warrant continued strong government participation in helping to bring costs down and in demonstrating fuel cell technologies.[36]

The cost to build certain plants, however, compares favorably with competing technologies because modular construction permits incremental capacity to be added only as needed. Therefore, funds do not have to be tied up in expensive, many-year construction projects. Moreover, it is frequently years before the capacity of a newly constructed conventional powerplant is fully utilized. Fuel cell powerplants can be built to closely match load needs, adding capacity only as needed.

Several costs are associated with operating and maintaining (O&M) fuel cell powerplants. The cost of labor is one such cost. Smaller plants are being designed to operate unmanned; plants in the multi-megawatt range may require manning for safety. A second important O&M cost occurs because fuel cells must periodically be replaced, Fuel cell voltage and efficiency decrease with time because the platinum catalyst undergoes a reduction in surface area and performance due to sintering (agglomeration of a solid by heating without melting) as the cells operate. In addition, the heat rate slowly increases over time if cells are not replaced, and as a result, the amount of fuel required increases .37 The cost of producing electricity can be minimized by optimizing the fuel cell module reloading frequency.

The most important variable cost is the cost of fuel. As noted above, fuel cells are capable of using a variety of fuels. Moreover, since fuel cells convert fuel to electricity with high efficiency, they have an advantage over many competing technologies in that the cost of fuel per kilowatt-hour can be substantially less. Present and projected fuel prices for six potential fuel cell fuels are given in table 2, and table 1 compares the estimated cost of fuel for competing power supply systems in terms of mills per kilowatt-hour. The Fuel Cell Users Group (FCUG) believes that natural gas will remain the preferred fuel cell fuel for utilities at least through the mid-1990s, but they also predict that propane will eventually become the less expensive and preferred fuel. Methanol, typically made from natural gas, continues to be priced above most other fuels suitable for fuel cell application, and the FCUG predicts that its high price per Btu will continue into the foreseeable future,[38]

[36]Brian E. Curry, "The Fuel Cell: Electric Utility Planning Perspectives, " address before the New England Conference of Public Utilities Commissioners, Farmington, CT, June 14, 1983, The Fuel Cell Users Group, p. 16.

[37]J.R. Lance, B.L. Pierce, and M.S. Barrett, "Economics and Performance of Utilit y Fuel Cell Power Plants, " Westinghouse Electric Corp., Advanced Energy Systems Division, Pittsburgh, PA, 1984, p. 825.

[38]The Fuel Cell Users Group, "Report on the Availability and Prices of Alternative Fuels to Supply Fuel Cell Power Plants, " July 1983, pp. 8-9; see also, Chevron U. S. A., Inc., "The Outlook for Use of Methanol as a Transportation Fuel, " January 1985,

**Table 2.—Potential Fuels for Use in Marine Fuel Cells**

| | Heat content (Btu/gal) | Extent of distribution infrastructure and availability | Ease of processing for fuel cell use | Complexity of storage | Recent price ($/MMBtu) | Estimated 1990 price (1985$/MMBtu) | Volume per unit energy (compared to diesel) |
|---|---|---|---|---|---|---|---|
| Methanol . . . . . . . . . | 64,000 | Medium | Easy | Moderate | 7.00[a] | l0.50[b] | 2.2 |
| LNG . . . . . . . . . . . . | 78,000 | Low | Easy | Complex | 5.00' | 5.20[c] | 1.8 |
| LPG . . . . . . . . . . . . . | 91,000 | Medium | Difficult | Moderate | 7.00[d] | 7.00[d] | 1.5 |
| Diesel No. 2. ..., . . . | 138,000 | High | Difficult | Simple | 6.20[e] | 6.50[d] | 1.0 |
| Naphtha . . . . . . . . . . | 125,000 | Medium | Difficult | Simple | 6.60[e] | 6.60[e] | 1.1 |
| JP-5 (Jet fuel) . . . . . . | 122,000 | Medium | Difficult | Simple | 6.00[d] | 6.75[d] | 1.1 |

[a]DeWitt & C. , Inc , *Methanol Newsletter*, Oct 18, 1985
[b]Electric Power Research Institute, "Fuel Forecast Review, Energy Resources Program, No 1," March 1985
[c]Phillips petroleum Phillips is currently exporting LNG to Japan This is the only active LNG operation in the United States The price of LNG has recently fluctuated between $470 and $5 30/MMBtu
[d]U s Department of Energy, 1984 *Annual Energy Outlook*
'The Fuel Cell Users Group "Report on the Availability and Prices of Alternative Fuels to Supply Fuel Cell Power Plant s," July 1983