Marine Applications for Fuel Cell Technology

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MARINE APPLICATIONS FOR FUEL CELL TECHNOLOGY

A TECHNICAL MEMORANDUM

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Foreword

Fuel cell technology is one of the most promising of the new electric power technologies currently undergoing development. Fuel cell power systems have attracted attention because of their potential for high efficiency, low emissions, flexible use of fuels, and quietness. The Federal Government and the private sector have been funding fuel cell R&D for more than *20* years. The state-of-the-art has advanced to the point that fuel cell manufacturers hope to begin marketing fuel cells in just a few years. Full-scale demonstration plants are currently being designed.

Much of the available R&D funding has been targeted for phosphoric acid fuel cell research, and this is the type of fuel cell technology most nearly ready for commercialization. However, other types of fuel cells are also undergoing development, and these hold promise for even greater efficiency of power production. The electric and gas utility industries have been most interested in using fuel cell technologies. The electric utility industry hopes to be able to use fuel cells for peak-shaving, load-following, and, eventually, baseload powerplants. The gas industry, on the other hand, would like to employ fuel cells to generate onsite electricity and heat for residential, commercial, and small industrial applications.

To date, almost no attention has been given to the potential marine applications for fuel cell technologies. Nevertheless, some of the benefits that fuel cells may offer to the utility industry may also apply to some marine uses. Recognizing this possibility, the Senate Committee on Commerce, Science, and Transportation asked OTA's Oceans and Environment Program to evaluate the likely benefits and problems of using fuel cells for propulsion and auxiliary power at sea. As part of its investigation, OTA held a 1 day workshop on Sept. 5, 1985, inviting fuel cell manufacturers and participants from the Department of Energy, Maritime Administration, Navy, Army, and industry research organizations. OTA found that fuel cells may offer advantages for some marine uses, including applications requiring quiet operations, applications where throttle settings are constantly changed, and for small submarines. However, the marine market is not in itself large enough to drive fuel cell technology developments. Fuel cells are not expected to penetrate marine markets until they become firmly established in the commercial utility sector.

JOHN H. GIBBONS
Director

OTA Marine Applications for Fuel Cell Technology Workshop, Sept. 5, 1985

Gary Baham
Baham Corp.

Dick L. Bloomquist
David Taylor Naval Ship R&D Center

Frank Critelli
Maritime Administration

Lloyd Fink
Maritime Administration

Sigurd Folstad
International Fuel Cells Corp.

Don Glenn
Energy Research Corp.

Douglas Jewell
U.S. Department of Energy
Morgantown Energy Technology Center

Johann Joebstl
U.S. Army Belvoir R&D Center

Art Kaufman
Engelhard Corp.

William Kumm
Arctic Energies Ltd.

Shirley Morales
Legislative Assistant
Congresswoman Helen Bentley

James E. Nivin
American Commercial Barge Lines

Ted Stanford
U.S. Navy, NAVSEA

Percival Wilson
Consultant

Joe Woener
David Taylor Naval Ship R&D Center

Richard R. Woods
Gas Research Institute

OTA Marine Applications for Fuel Cell Technology Project Staff

John Andelin, *Assistant Director, OTA*
Science, Information, and Natural Resources Division

Robert W. Niblock, *Oceans and Environment Program Manager*

Project Staff

Peter A. Johnson, *Project Director*

William E. Westermeyer, *Policy Ahalyst*

Administrative Staff

Kathleen A. Beil Jacquelynne R. Mulder

Contractor

Denzil Pauli

Other OTA Contributors

Peter D. Blair Thomas E. Bull

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OVERVIEW

A fuel cell is a device for directly converting 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. Small, specialized fuel cells were first successfully used in the Gemini space program. Recent technological advances with other types of fuel cells and small-scale demonstrations have encouraged the development of fuel cell technology for commercial land-based use.

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 the National Aeronautics and Space Administration's (NASA) program. The Department of Energy (DOE) began funding fuel cell research in 1976. Although fuel cells are still under development for commercial use, these efforts are beginning to bear fruit. Several types of fuel cells are being investigated, but phosphoric acid fuel cells are nearly ready for commercial use in sizes ranging from a few kilowatts to a few megawatts.

The most promising near-term uses for fuel cell technology are for applications in the electric and gas utility industries. However, fuel cells have also been considered for automobile, train, and marine applications. The use of non-petroleum-fueled fuel cells in transportation is most desirable from the standpoint of oil displacement, but 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.

For marine applications, it has been suggested that fuel cells be employed to provide propulsion or auxiliary power for cruise ships, powered barges, ferry boats, offshore supply boats, push-tow boats, oceangoing tugs, submersibles, and even submarine tankers. Fuel cells have also been suggested for use as power sources for offshore oil platforms, for underwater facilities, and for refrigerated containers on containerships. Some of these possible applications may be technically feasible and cost-effective in a decade or so. Other potential applications (e.g., fuel-cell-powered submarine tankers) may take much longer to develop. In any case, successful development for commercial needs will depend on economic factors in addition to technical feasibility; likewise, successful development for military uses will also depend on mission requirements.

If fuel cells prove technically and economically feasible, they could conceivably replace many electrical generating systems in use today in a myriad of applications, from small transportation units to large power stations. Their advantages over existing systems could include higher efficiencies, lower cost, reduced emissions, and fewer maintenance problems. Many of the benefits fuel cells could provide to the utility industry could also apply in the marine field. Of special interest is the potential of fuel cells for high efficiency, since this efficiency may translate into fuel cost savings. Moreover, fuel cell efficiency is relatively constant over a broad range of power settings. Such a characteristic suggests that fuel cells might be efficiently employed in ships that frequently vary power demand—e. g., towboats, ferries, or offshore supply boats. Capability of using a variety of fuels is another potential advantage. In addition to the potential for providing main propulsion, fuel cells could also supply auxiliary power and other heat needs.

Several other characteristics of fuel cells could provide benefits for specific applications. The fact that fuel cell systems are of modular design enables flexibility in the arrangement of plant components and could lead to a more cost-effective layout of power and cargo spaces and of basic ship structure. However, overall space and volume requirements of the fuel cell system and fuel will probably be greater than for present systems. As with other electrical powerplants, the maneuvering problems of ships and tugs might be mitigated by the advantage fuel cells provide in enabling electric power to be quickly switched to various locations to reverse main propellers or to activate side thrust propellers or water jets. Fuel cells have few moving parts, suggesting minimal manning requirements. Since they produce little noise, they may have possible uses on anti-submarine warfare ships and seismic survey vessels.

Finally, fuel cells offer greater endurance than batteries for some types of submerged operation.

Despite these potential benefits, commercial marine applications for fuel cells are a long way off. None of the advantages stated above have been demonstrated for marine fuel cells, and a number of present problems constrain private development today. The marine market is not in itself large enough to drive fuel cell technology developments. Hence, it is not expected that fuel cells will penetrate marine markets before they become firmly established in the commercial utility sector. Even then, fuel cell systems will have a difficult time capturing a large share of the market, given competition from other systems. Shipbuilders will need to use and adapt products developed first either for the utility industry or for the Department of Defense (DOD). Moreover, potential cost advantages to onsite shore users due to large-scale production may not accrue to the marine industry.

Given these constraints, Federal assistance will be required if the Federal Government wishes to accelerate the development of fuel cells for the commercial marine sector. Though OTA has not evaluated the rationale for such Federal assistance, many reasons to do so have been advanced. For example, the Federal Government may wish to stimulate commercial development of marine fuel cells in order to reduce dependence on traditional fuels (e.g., diesel oil), to help ensure the transition to alternative fuels as traditional fuels become scarce, to help reduce pollutant emissions, or for other reasons. It has also been suggested that if the United States does not push development of fuel cells, as the Japanese are doing, a developing market in which the United States now has a technical lead will be lost.

Fuel cell technology may offer benefits to the military as well. However, development of fuel cell technology for military purposes can best be considered separate from development for commercial purposes. If fuel cells prove to be the best technology for specific military applications, cost constraints that would slow development in the commercial sector would be a less limiting factor.

Some Options for the Federal Government

The outlook for using fuel cells in the electric and gas utility industry appears promising. The Federal Government has supported private sector research and development (R&D) efforts since the 1960s. Continued Federal support of fuel cell development programs is probably necessary to advance the introduction of fuel cell technology into the land-based utility industry.

The use of fuel cells in the marine industry in the next 15 to 20 years is far less certain. When and if the commercial maritime industry decides that fuel cell power systems would provide significant cost and/or other advantages over competing power systems, these fuel cell systems must be adapted to the unique demands of the marine environment. Very little R&D on fuel cells for marine applications is currently underway inside or outside the government. Since the R&D program for land-based applications is so large in comparison, some believe that the proper course for the marine industry is just to monitor closely that R&D and select developments and applications as they may occur in the future. Others believe that unique marine requirements warrant specialized R&D efforts.

Specific research and development could be supported by the Federal Government and/or industry to improve the potential of fuel cells in the marine market. For example, the near-term use of fuel cells in the marine industry could be stimulated by developing technology capable of reforming diesel oil. Other research that could be undertaken includes: laboratory testing, followed by shipboard analysis and testing, of fuel cell components to determine their suitability and/or vulnerability to the marine environment; basic electrochemical studies to improve catalysts and electrolytes that would not be contaminated by fuel processed from fuel oil; and accelerated investigation of molten carbonate fuel cells and of the vulnerability of this type of fuel cell to the marine environment. The Federal Government's investment in molten carbonate technology could concentrate on those developments needed to support a demonstration of this fuel cell's higher efficiency and fuel flexibility. The private sector could focus on the technology and processes needed to manufacture these fuel cells at a cost competitive with conventional power generators.

The Maritime Administration, and perhaps other agencies within the Department of Transportation, and DOE might be able to offer some assistance for applications more directly relevant for the commercial transportation sector. For instance, funding could be provided to demonstrate and evaluate use of a fuel cell system on a commercial ship or locomotive. One suggestion is that future fuel cell research for heavy-duty transportation applications focus on developing the more efficient molten carbonate fuel cells. Once a small (i.e., 50 kilowatts (kW)) molten carbonate system has been demonstrated, these agencies could coordinate a demonstration of a 2 to 4 megawatt (MW) powerplant for the heavy-duty transportation sector. Different types of incentives to private industry might also be used, such as tax benefits for those who use non-petroleum-based fuels or accelerated depreciation.

The Federal Government may also wish to encourage the Navy, Army, Air Force, and Coast Guard to become more involved in developing fuel cells for their mission requirements, OTA's analysis indicates potential benefits of marine fuel cell use in naval applications, and suggests that more in-depth analysis of the potential applicability of fuel cell technologies for Navy missions is needed.

The Navy is currently monitoring fuel cell developments, but it may be useful for the Navy to consider supporting specialized research into marine fuel cell development as well. At present, for example, very little work has been done on developing fuel cells for "quiet" ship operation aboard certain vessels where noise emissions from conventional engines are a major problem. If fuel cells could match these and other unique Navy missions, then naval fuel cell research, independent of private sector efforts, may be justified.

Recognizing that research funds are limited and must be carefully targeted to the most productive avenues of research, it may be best to begin by encouraging the military to develop small fuel cell systems for auxiliary power on naval surface ships, As experience is gained, larger fuel cells (on the order of a megawatt) might be used for naval and Coast Guard auxiliary power. Finally, beyond 2000, the Navy or Coast Guard could be encouraged to focus on developing larger fuel cell powerplants for primary propulsion power. The Navy and Coast Guard have different missions than the civilian sector and some applications developed by them may not be directly useful for the private sector. On the other hand, some applications first developed for military purposes might stimulate development of applications for commercial use.

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.

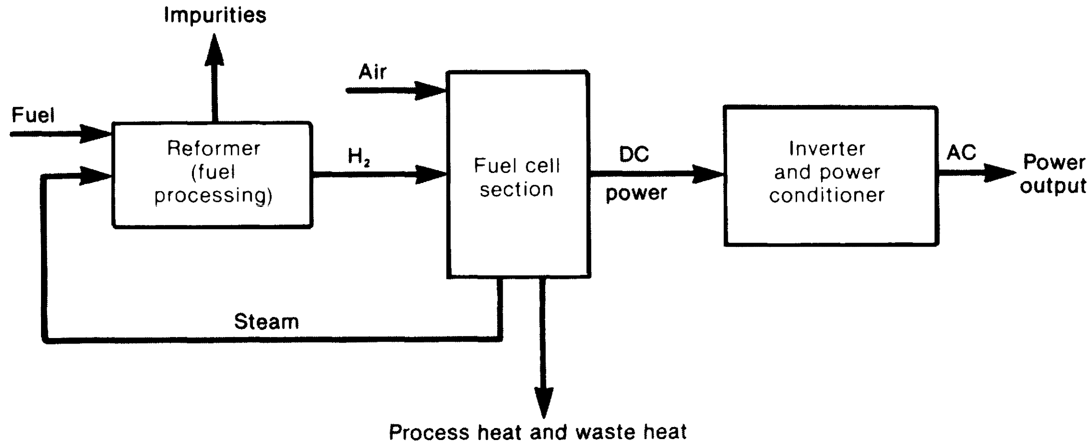
Description of Phosphoric Acid Fuel Cell Systems

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

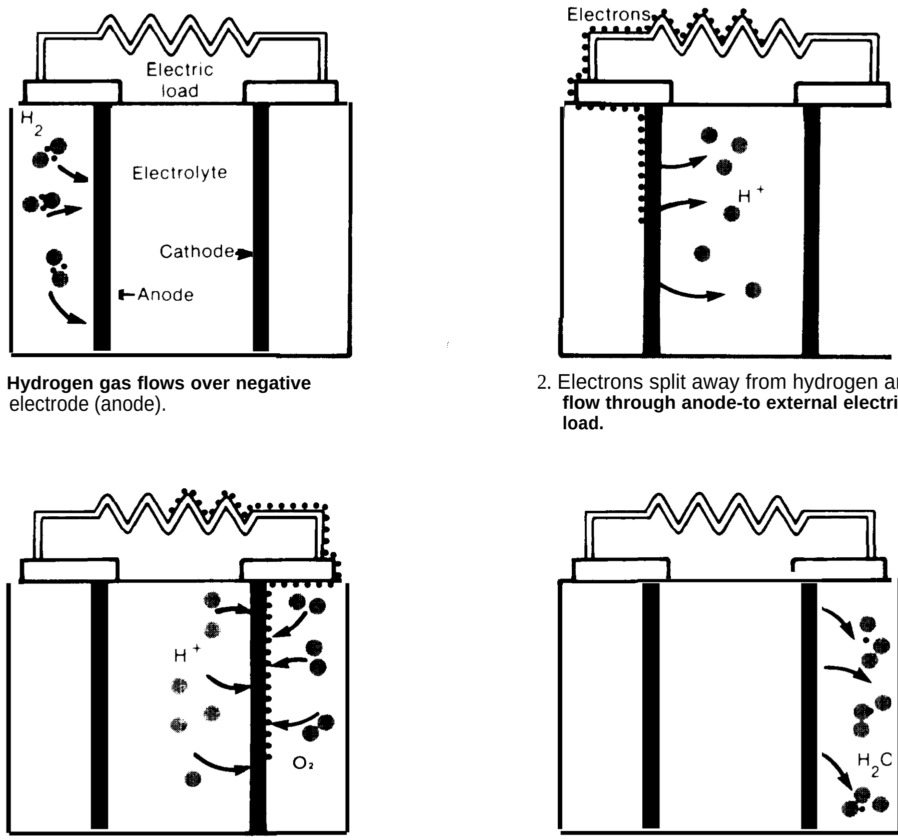
Fuel cells are composed of two electrodes, a cathode and an anode, separated by an electrolyte (see figure 2). In the typical PAFC, fuel (a hydrogen-rich gas reformed from natural gas or another fossil fuel) is delivered to the porous anode element. The anode is coated with a catalyst, such as platinum, 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.

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

'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 Spark Utilities' 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

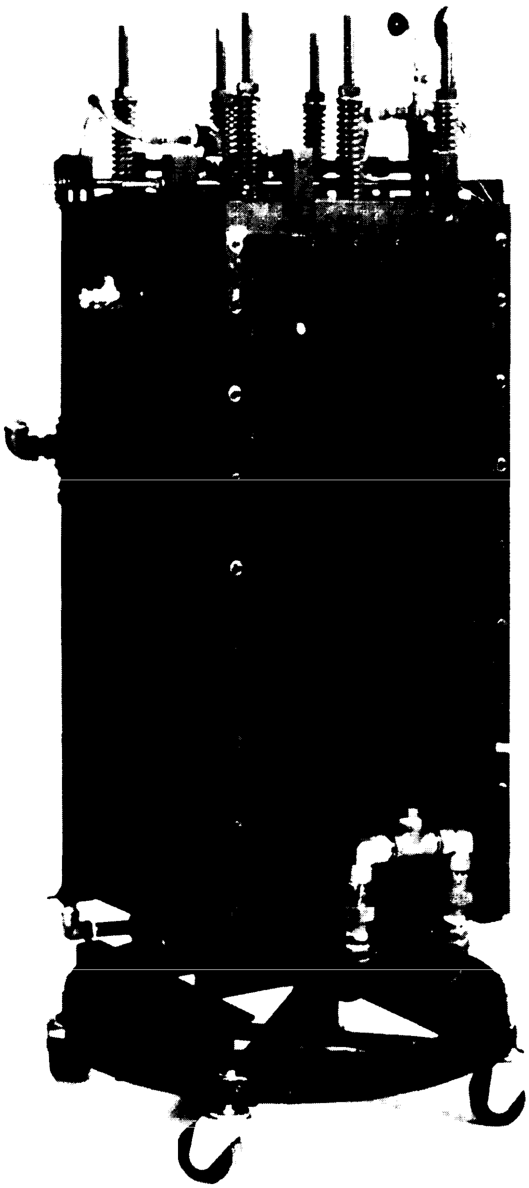


Photo credit Engelhard Corp

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,

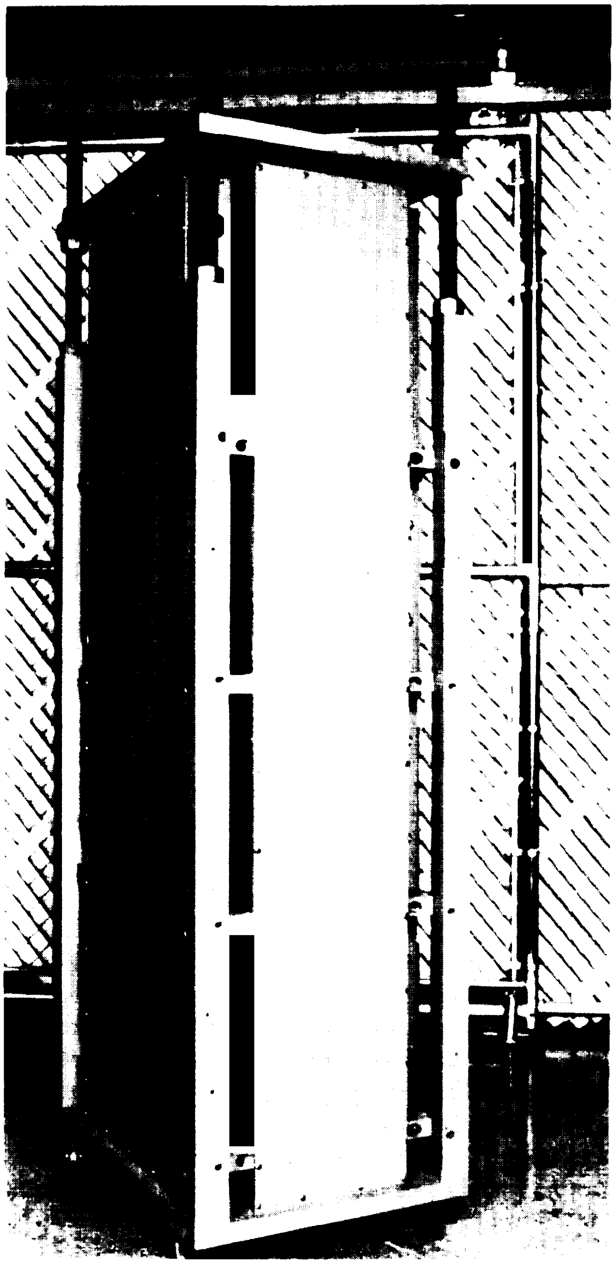


Photo credit" Engelhard Corp

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.

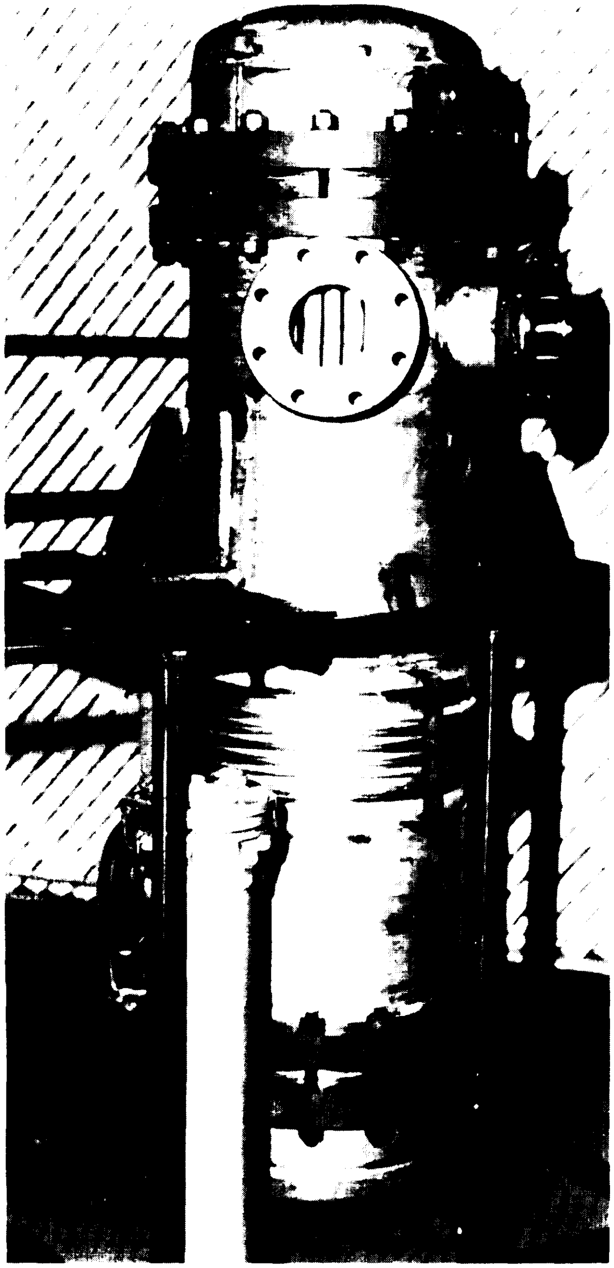


Photo credit Engelhard Corp

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 powerplant 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:

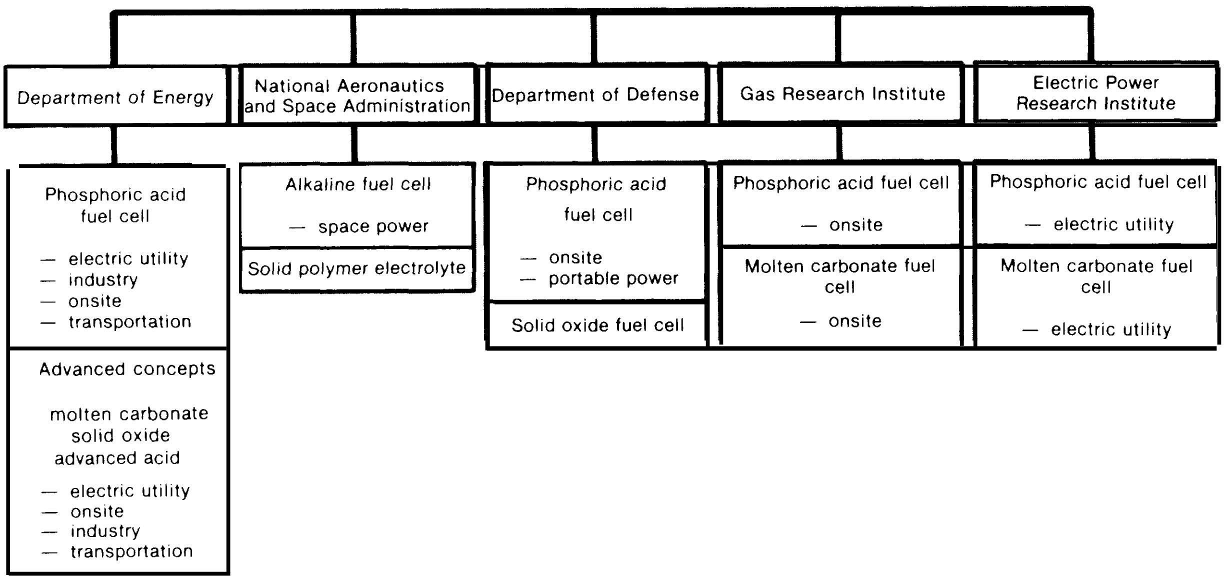
> . . . to establish, in concert with the activities of other funding organizations and fuel cell manu-

[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.

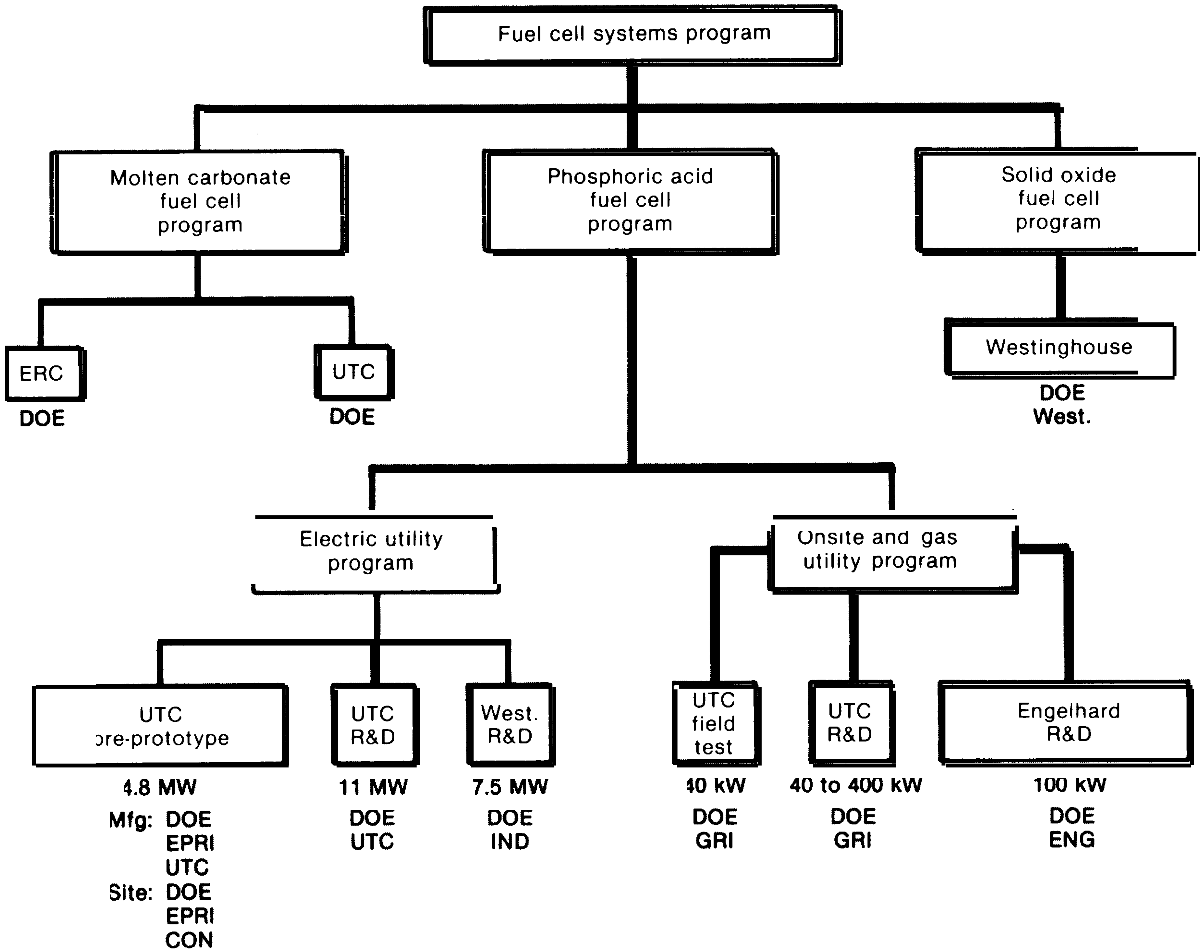
DOE is currently supporting development of three types of fuel cells that may be used in both multi-megawatt and multi-kilowatt systems—phosphoric acid, molten carbonate, and solid oxide fuel cells (see figure 4). DOE began funding fuel cell research in 1976. To date, most of the research it has funded 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]

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-

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

"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 by 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] Ibid., 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]	I0.50[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

PART TWO: MARINE USES OF FUEL CELLS

Introduction

Why consider fuel cells for marine applications? As with land-based applications, economic factors drive the search for improved commercial marine power generation. These factors include capital and operating costs of propulsion and auxiliary power systems, cost and availability of fuel, and powerplant efficiency and reliability. Each of these factors has a strong influence on the design of ships and other equipment and powerplants. Fuel cells have been considered as one of several alternative propulsion systems for the ships of the future. Baham, for instance, has evaluated nontraditional propulsion systems for the commercial shipping industry (under contract to the Maritime Administration), and concluded that four systems show merit worthy of further investigation: nuclear, closed Brayton cycle, Stirling cycle, and fuel cells.[39]

Some of the benefits fuel cells would provide to the utility industry could also apply in the marine field. Of special interest is the potential of fuel cells for high efficiency, since this efficiency may translate into fuel cost savings. Moreover, fuel cell efficiency is relatively constant over a broad range of power settings. Such a characteristic suggests that fuel cells might be efficiently employed in ships that frequently vary power demand—e.g., towboats, ferries, offshore supply boats, or icebreakers. In addition to the potential for providing main propulsion, fuel cells could also supply auxiliary power and other needs.

Several other characteristics of fuel cells could provide benefits for specific applications. The fact that fuel cells are of modular design enables flexibility in the arrangement of plant components and could lead to a more cost-effective layout of power and cargo spaces and of basic ship structure. However, overall space and volume requirements of the fuel cell system and fuel will be greater than for present systems. As with other electrical powerplants, the maneuvering problems of ships and tugs might be mitigated by the advantage fuel cells provide in enabling electric power to be quickly switched to various locations to reverse main propellers or to activate side thrust propellers or water jets. Fuel cells have few moving parts, suggesting minimal manning requirements. Fuel cells are quiet, suggesting possible uses on anti-submarine warfare ships and seismic vessels. Finally, fuel cells offer greater endurance over batteries for some types of submerged operation.

Despite potential benefits, the marine market is not in itself large enough to drive fuel cell technology developments. Hence, it cannot be expected that fuel cells will penetrate marine markets before they become firmly established in the commercial utility sector, and shipbuilders will need to use and adapt products developed first either for the power industry or for DOD. In addition, cost advantages to onsite shore users due to large-scale production may not accrue to the marine industry.

Technical barriers, of course, also remain to be resolved. Barriers relating to the commercialization of fuel cells for transportation have been noted by Walsh and Rajan.[40] Most bear directly on cost, and include:

- high cost of platinum and other catalysts;
- thermal control problems;
- difficult fuel processing requirements;
- system complexity;
- startup time, especially in PAFCs;
- high reformer cost, especially in small systems;
- low volumetric power density;
- carbon monoxide intolerance of electrodes;
- high cost of membranes (for solid polymer electrolyte fuel cells);
- low efficiency of the oxygen electrode;
- deterioration of the cost/performance ratio in small systems; and
- need to replace cells periodically.

Required Characteristics

Fuel cells must be competitively priced, reliable, and durable if they are to be accepted by the maritime industry, They will be competing with other types of powerplants, especially with well-established diesel-electric plants, for a share of the

[39] Baham, op. cit,

[40] Walsh and Rajan, op. cit., P. 8.

marine market. Current low-speed diesels operating on residual fuel are very nearly as efficient as present PAFC powerplants, and the efficiency of the conventional powerplants of the future is expected to improve (see table 3). For example, diesel manufacturers are continuing their efforts to improve the heavy fuels capability of their engines. Shipowners will not likely try new propulsion systems without some very clear and convincing reasons to do so. Substantial advantages must be demonstrated, not just incremental improvements in efficiency in order to induce potential buyers to switch from a long-established powerplant to a new and relatively untested type of unit,

What would it take in order for the fuel cell to become competitive in the commercial marine industry? One view is that, for applications such as tugboat propulsion, total efficiency improvements of 10 to 20 percent would be required, that installed capital costs would have to be on the order of $300 to $500 (1985 dollars) per kilowatt (to compete with direct drive diesels), that power densities (kW/cubic foot and kW/lb) would have to be reasonably close to those of the diesel engine, and that the fuel cell (in the near term, at least) must be capable of running on distillate petroleum-type fuels customarily widely available.

Table 3.—Possible Marine Powerplants

	Fuel	Efficiency (o/o)
Current:		
Steam turbine with reheat steam (1,450 psig, 150 F)	Residual	32-36
Low-speed diesel	Residual	39-41
Future conventional:		
Steam turbine with heat pressure, high temperature reheat (2,400 psig, 1,050' F)	Residual	35-39
Adiabatic diesel	Diesel	49
Naval Academy heat balance engine	Diesel	43
Heavy-duty gas turbine, combined cycle	Residual	36-40
Closed-cycle combustion turbine	Residual	40-41
Fuel cells.[a]		
Phosphoric acid	Naphtha	41
Molten carbonate	Distillate	***50***
Alkaline	Hydrogen	60

[a]Without combined cycle or other forms of heat recovery

SOURCE U S Department of Energy, *Alternative Energy Sources for Non-Highway Transportation*, DOE/CS/05438-T 1, June 1980

Requirements for specific uses could vary considerably, but these will be difficult targets to reach.

The major factor inhibiting fuel cell usage for commercial marine applications is high cost. For military applications—e. g., for submersibles, small surface ships, and other specialized vehicles—mission requirements rather than cost are generally more important. Thus, if fuel cell technology is determined to have unique advantages for a defined mission, high cost may not be the major concern.

Other important factors to consider in selecting a fuel cell or other unconventional powerplant include compatibility with salty air and water; system and fuel safety; ability to withstand the shocks, vibrations, and ship motions commonly encountered at sea; ability to withstand and/or control transient thermal shocks due to rapid changes in load; training and manning requirements; and constraints on weight and volume of the powerplant, auxiliary systems, and fuel. The questions of fuel storage and possible additional en route refueling time, as well as other elements related to fueling along the transportation route, have not been considered in most studies. The volume of fuel required to travel between two points may be much greater for certain types of fuel (e.g., methanol). This may either place additional space and therefore size requirements on the vessel or necessitate additional refueling stops.

The ability to burn less expensive, widely available fuel would be advantageous, as would the capability to cogenerate steam, since, typically, ships have well-established uses for steam. Finally, fuel cells, like any other marine propulsion system, will need to be certified by the U.S. Coast Guard and/or ship classification societies (e.g., the American Bureau of Shipping or Lloyd's of London) that they are safe, durable, and perform to acceptable specifications. Listed below are five significant issues that will affect future marine fuel cell use.

Capital, Operating, and Maintenance Costs

There is no question that it is technically feasible to propel a ship and/or generate auxiliary power using fuel cells. The issue is whether and/or when fuel cells will be economical to purchase, install, operate, and maintain. Manufacturers of fuel cells for the utility industry maintain that $1,000/kW (1985 dollars) is a realistic installed capital cost goal for a mature fuel cell system. As technical improvements are made (e.g., by improving power density, cell stack cooler arrays, catalyst material, electrolyte management, and/or inverter efficiency) and as automated production techniques improve, the capital costs may be reduced further. However, in order for fuel cells to be competitive with direct drive diesel powerplants in the commercial marine industry, capital costs may have to be considerably lower than $1,000/kW.

Several studies of specific marine applications have considered the question of capital costs in detail. Notably, the Los Alamos National Laboratory (LANL) did a levelized life-cycle cost study of a typical 7,000-horsepower (hp) vessel capable of operating on inland or coastal waters. LANL concluded that such a vessel powered by an advanced PAFC using methanol costing $12.30/MMBtu could not compete with a similar vessel powered by a medium- to high-speed diesel powerplant, even if the capital costs for the fuel cells were zero. They then considered the case of fuel cells capable of using less expensive fuels, residual bunker fuel and coal, noting that handling and processing technology for these fuels has not yet been developed. Although their conclusions are tentative, they suggest that the capital costs necessary to make fuel cells competitive for this application would be significantly below $500/kW, even when using low-cost coal.[41] One of OTA's workshop participants estimated the total cost of a fuel cell system for a 5,000-hp vessel, assuming it can be installed for $500/kW, at $2 million.[42] The cost for a comparable diesel would be about $800,000.

The duty cycles and specific requirements of other potential marine applications could vary considerably. Thus, it is not suggested that the required competitive capital cost per kilowatt will be as low for all potential marine fuel cell applications. However, what little evidence there is suggests that fuel cells will have a difficult time capturing a large share of the market for most marine propulsion systems.

The relatively small size of the marine market will not likely encourage volume-based cost reductions; nor is the marine market large enough, by itself, to stimulate development of alternative fuels. For example, it has been estimated that, at best, the U.S. domestic towboat industry might acquire **50** fuel cell powerplants per year.[43] Even if all potential Navy applications utilized fuel cells, the domestic market could still not be considered large. Moreover, there are other reasons why development of marine fuel cells may be difficult. Baham notes that it is possible that competing powerplants could enter the market first and establish long-term commitments with major customers; that ship operators and builders tend to be conservative in their attitude toward changes in propulsion machinery and would likely be skeptical about changes that involve unknown risks; and that potential PAFC users may wish to wait for development of molten carbonate fuel cells, which may offer better performance and cost.[44]

Fuel Costs and Supply

Methanol has been identified in several studies of the possible marine applications for fuel cells as one of the most practical fuels for marine transportation applications. Among its advantages, methanol can be derived from a number of sources (including natural gas and coal, and wood and other renewable resources), it is clean and relatively easy to store (although it takes up more space per unit energy than hydrocarbon fuels), it is easily reformed at low temperatures using conventional heat exchangers, and methanol reforming technology is in a relatively advanced stage. Nevertheless, there are some significant problems and uncertainties associated with the use of methanol as a fuel cell fuel.

It is apparent from the few studies that have been commissioned that the competitiveness of

[41] J.H. Altseimer and J.A. Frank, "An Assessment of Fuel Cell Propulsion Systems," Los Alamos National Laboratory, LA-9954-MS, November 1983.

[42] Francis X. Critelli, Maritime Administration, OTA workshop comment, Sept. 5, 1985.

[43] James Niven, American Commercial Barge Lines, OTA workshop comment, Sept. 5, 1985.

[44] Baham, op. cit., p. 6-6.

fuel cells in the marine industry will be sensitive to the cost of fuel. Researchers who have assumed methanol will be used for marine fuel cells have reached both optimistic and pessimistic conclusions about the future competitiveness of fuel cells .45 The assumed price of methanol in these studies varied widely. The price of methanol during the mid-1990s—the earliest time that fuel cells could be expected to enter the marine market—is highly uncertain. A 1983 study by FCUG estimated that by **1990** methanol would cost $16.00/MMBtu (1983 dollars)." Recently, the same group lowered their estimate to approximately $10.00/MMBtu (1983 dollars). (The current price is about $7.30/MMBtu.) Although FCUG's estimate has been reduced, methanol is still expected to be more expensive than No. 2 diesel, propane, and naphtha (see table 2). Moreover, fuel cost is not the only important factor. Experience has shown that improvements to reduce fuel costs are not acceptable if poor reliability is a consequence.

Perhaps as significant as the issue of cost is the fact that methanol and other alternative fuels (e.g., naphtha) are not widely available as transportation fuels and that no network exists to distribute these at present. It is not a simple matter to shift from a well-established fuel to a new fuel, and residual fuel, bunker C, and diesel will likely be available for at least another 20 years. The U.S. Navy considers the fuel availability problem so important that it has all but eliminated methanol from consideration as a potential fuel for its fleet. Similarly, the U.S. Army has major reservations about using methanol as a fuel cell fuel in the field. All Army vehicles use diesel fuel. Thus, the logical fuel to use with the portable fuel cell generators the Army is developing is also diesel. It is not surprising that the Army has initiated development of reformer technology capable of processing No. 2 diesel fuel.

For the short term, methanol appears to suffer from a chicken-and-egg problem. Automotive and vessel manufacturers are hesitant to produce methanol-powered vehicles because the fuel distribution network does not exist. Fuel suppliers, on the other hand, will not be motivated to provide methanol until there are enough vehicles on the road or at sea that require it. From an economic point of view, the future cost of methanol has been estimated to be twice as much as gasoline, on a mileage equivalent basis, if new methanol plants must be built to satisfy U.S. demands.[47] However, methanol may well deserve a much closer look when the traditional fuels, such as No. 2 diesel, become scarcer and more expensive. It is the least expensive high-grade liquid fuel that can be produced from abundant U.S. coal resources, and can be derived from other sources as well. Some automotive industry people believe that a methanol distribution network for automobiles could evolve naturally from the present distribution system, since methanol is already used in small quantities in some places as a gasoline additive .48 It is not too far-fetched, then, to envision the distribution system expanding to include small boat marinas and eventually to facilities for larger ships, but the costs of establishing such a network are very difficult to estimate.

Several additional concerns have been noted. Methanol has a low flashpoint, which could be particularly troublesome for some military applications. Thus, special precautions would likely need to be taken in handling methanol. Second, a safety problem could arise because methanol burns without a visible flame; hence, a methanol fire cannot be easily detected. And finally, very little information is available on the effects of low concentration, chronic exposure to methanol.

Reformer Technology

Development of reformer technologies capable of using logistic fuels could be an important breakthrough for the acceptance of fuel cells for transportation. The logistic fuel of choice appears to be No, 2 diesel. It is currently widely available and relatively inexpensive. However, currently available reformers are not capable of efficiently

[45]See, for example, Arctic Energies Ltd., op. cit.; and Los Alamos National Laboratory, "Assessment of Fuel Cell Propulsion Systems, " November 1983.

[46]The Fuel Cell Users Group, "Report on the Availability and Prices of Alternative Fuels to Supply Fuel Cell Power Plants, " July 1983.

[47]Chevron, U. S. A., Inc., op. cit., pp. 4-5.

[48]Gene Helms, Allison Gas Turbine Division, General Motors, telephone conversation, Nov. 6, 1985.

producing the hydrogen needed by the fuel cell from No. 2 diesel fuel. If efficient reformer technology could be developed enabling fuel cells to use No. 2 diesel, the fuel logistics and safety problems associated with methanol and some other fuels would be moot for the near term. The key challenge is to develop a reformer for liquid hydrocarbon fuels that works for relatively small to medium capacities. As noted above, the U.S. Army has initiated work on this significant problem. Specific development needs include stable catalysts, the reduction of the water-to-carbon ratio, and desulfurization.

Survivability in Marine Environment

For the most part, fuel cells have been designed for terrestrial use and have not had to cope with the special problems related to the marine environment—presence of salty air and water, vibrations, shocks, corrosion, etc. The durability of fuel cells under harsh marine conditions is not known. However, the design of fuel cell systems that can withstand these elements is not expected to be a major challenge. For instance, although it is not yet known how salt will affect fuel cell operation, the filtering system designed for a marine gas turbine might reasonably be expected to remove salt in the air so fuel cells and reformers are not contaminated. Similarly, it is likely that fuel cells can be "hardened" to withstand marine shocks. The Navy, for instance, designed their alkaline fuel cell to withstand the stress associated with a 5G landing in a C5A transport plane, and NASA designed its alkaline fuel cell for use in space. Still, no long-term testing of commercial fuel cells under typical marine conditions has been conducted. The specific mission will control design requirements.

Transient Energy Response

Little is currently known about the response of marine fuel cells to abrupt changes in temperature due to sudden, very large changes in load. It has been suggested[49] that present fuel cells may not be able to withstand the temperature changes associated with abrupt power changes (i. e., changing from full load to "all stop") that occur aboard ships. If this is true, fuel cell durability may be significantly decreased. Problems resulting from temperature changes could include fuel cell fires and acid leaks, either of which would render the fuel cell inoperative. Long-term testing, under controlled conditions, of responses to electrical and thermal transients is needed to determine the nature of the problem.

If design changes of marine fuel cells are required to address this potential problem, the cost of fuel cells for marine applications may increase. Thus, a more sophisticated control system may be needed, requiring the development of quick response sensors imbedded in the cell stack and gas control system. Electrodes, electrolytes, and fuel processors may also need modification.

PAFCs have been the type of fuel cell investigated in most studies of marine applications for fuel cells. Other types of fuel cells offer the potential for greater efficiency than PAFCs, and these may be considered for use as marine powerplants in the more distant future. Molten carbonate fuel cells using distillate fuel, for instance, may be more than so percent efficient, and in addition, have the capability to cogenerate high-quality steam, for which ships have well-established uses. In a 1980 study done for DOE, the Exxon Research & Engineering Co. concluded that future molten carbonate systems will be very close to being competitive with diesel engines and therefore deserved closer examination.[50] Alkaline fuel cells using pure hydrogen fuel, although expensive, have already demonstrated efficiencies in excess of 60 percent in the space program.

Potential Applications

The marine industry may have a wide variety of applications for fuel cells of various power outputs. To date, however, virtually all of the fuel cell development efforts undertaken by manufacturers and funded by government agencies and

[49] Gene Helms, Allison Gas Turbine Division, General Motors, personal communication, Oct. 9, 1985,

[50] U. S. Department of Energy, "Alternative Energy Sources for Non-Highway Transportation, " prepared by Exxon Research & Engineering Co., DOE/CS/05438-T1, June 1980, pp. 6-27. Exxon also concluded that a coal-fired steam boiler/turbine should be able to undercut the molten carbonate system by $100/hp-yr, given coal priced at $0.90 to $1.60/MMBtu.

industry have been associated with advancing the state-of-the-art of fuel cell technology for land-based gas and electrical utility applications. Thus far, the only fuel cell designed and tested specifically for marine use has been an alkaline fuel cell built by UTC for a very specialized Navy deep-sea search mission (this application is described in some detail below). Other than this one project, studies of fuel cell applications in the marine field have been confined to a handful of conceptual and planning studies initiated by DOE, the Maritime Administration, and the Navy.

Given the sparse information available, the Office of Technology Assessment recently invited some industry and government experts to brainstorm about some of the possible marine uses for fuel cells. The suggestions may be broadly placed into seven major categories:

1. Applications in which quiet operation is useful or desired:
   - research ship propulsion and auxiliary power,
   - seismic vessel propulsion and auxiliary power, and
   - anti-submarine warfare vessel propulsion and auxiliary power.
2. Applications in which power settings are constantly changing:
   - tow boat propulsion,
   - Coast Guard cutter propulsion,
   - ferry propulsion, and
   - supply vessels for the offshore oil and gas industry.
3. Submarines and submersibles:
   - submersible propulsion (military or commercial),
   - submarine tanker propulsion, and
   - remote underwater vehicles.
4. Commercial transport ship propulsion:
   - tankers,
   - bulk carriers,
   - containerships, and
   - cruise ships.
5. Naval ship propulsion power.
6. Commercial and naval ship auxiliary power.
7. Other applications:
   - offshore platform auxiliary power;
   - power for remote navigation, radar, or oceanographic data acquisition and transmission systems; and
   - power for refrigerated containers.

Very little effort has been devoted to the specific requirements of the above (or any other) possible marine applications for fuel cells relative to their mission cycles, or to the physical and operating constraints that must be considered for each application and how fuel cells measure up to these constraints relative to competing power systems. Until mission requirements and physical and operating constraints are determined for potential applications, it will be impossible to reach definitive conclusions about the applicability of fuel cells to specific cases.

Quiet Operation Applications

One of the most logical potential applications for fuel cells is for propulsion and/or auxiliary power for ships that require or could benefit from quiet operations. Fuel cells appear to offer a distinct advantage over other powerplants for this purpose. Moreover, cost considerations are not as severe a constraint if quiet operation significantly improves the ability to accomplish the vessel's mission. This is particularly true for the Navy's Anti-Submarine Warfare vessels, where the mission requirement, and not cost, is the main factor controlling selection of the powerplant. It may also be true, but perhaps to a lesser degree, for commercial seismic vessels and for oceanographic acoustic research ships, both of which would be able to collect better quality data if the powerplant made less noise. In addition to propulsion, the fuel cell system could be used for the auxiliary power and hotel load requirements on such vessels.

Applications in Which Power Settings Are Constantly Changing

Some vessels are constantly changing speed and/or varying load requirements. Push= tow boats are a prime example. This type of application may deserve a close look given the capability of fuel cells to maintain their efficiency over a broad range (30 to 100 percent) of power fraction. This capability translates into significant operational savings—in some instances—over diesel powerplants, which lose efficiency unless operated at full power. However, as noted above, sudden large changes in power loads may have negative consequences for marine fuel cell operation. Several conceptual studies of these types of applications have been done.

Inland Waterways Push-Tow Boats .—The Los Alamos National Laboratory (LANL) began studying possible transportation applications for fuel cells in 1981 when it began a fuel cell R&D program jointly funded by DOE's Division of Energy Storage and Office of Vehicle and Engine Research and Development. In particular, Huff and Murray of LANL have investigated the feasibility of using fuel cells for propelling inland-water, 5,000 to 6,000 hp push-tow boats .51 The push-tow boats now operating on the Ohio and Mississippi Rivers are currently powered by two locomotive diesel engines with direct coupling from each engine to the propeller through a gear reduction and reversing gearbox. The usual tow consists of 15 barges, arranged in 5 rows of 3. With this arrangement the boat can move a 22,500 ton payload at speeds of 5 mph upstream and 11 mph downstream. The Los Alamos researchers determined that it is technically feasible to use fuel cells fueled by methanol to power push-tow boats. Fuel cell systems meet weight and volume constraints, are compatible with existing propulsion components, and provide adequate performance relative to operational requirements.

However, while technically feasible, the researchers concluded that using fuel cells for this application is not particularly attractive. Although the efficiency of both PAFC and SPE powerplants for push-tow boat use was determined to be greater than diesel power efficiency (see table 4), diesels are considered to be very efficient for this application. Methanol was chosen as the likely most practical fuel cell fuel for this application. However, the researchers noted that "the addition of electrical systems reduces the fuel cell system efficiency to the point where the energy cost disadvantage of methanol cannot be overcome. " Moreover, fuel consumption (in gallons/hour) was calculated to be greater in both fuel cell systems considered than in the current diesel system, so that the range possible before refueling is much reduced. In the case considered, two fueling stops would be required for the PAFC-powered vessel to travel the **1,890** mile distance from New Orleans to Pittsburgh. Additional onboard fuel storage could be a problem.

Table 4.—Push-Tow Boat Powerplant Comparisons

	PAFC	SPEFC	Diesel
Total power (hp)	5,760	5,760	5,140
Powerplant efficiency	0.55	0.50	0.36
Fuel consumption (gal/h) (methanol/diesel)	411	457	273
Upstream energy consumption (Btu/net ton mile)	294	327	401
Downstream energy consumption (Btu/net ton mile)	126	140	172
Average energy consumption (Btu/net ton mile)	210	234	286
Upstream range (miles for 120,000 gal tank)	832	1,182	1,976

SOURCE J R. Huff and H.S Murray, "Feasibility Evaluation of Fuel Cells for Selected Heavy-Duty Transportation Systems, " Los Alamos National Laboratory, October 1982, p 28

Coast Guard Cutters.–Arctic Energies, Ltd. (AEL) reached a more optimistic conclusion in a study of the potential fuel cost savings that use of PAFCs on Coast Guard cutters might bring. 52 AEL combined data on fuel usage and duty cycles to determine fuel consumption at various throttle positions. They concluded that for this application fuel cost savings (over diesel-powered cutters) of between **32** and **51** percent were obtainable by methanol-fueled fuel cells and DC propulsion drive. The price of methanol used in calculations was $0.42/gal. It should be pointed out that this study was limited to consideration of fuel cost savings only, and that other factors, such as range, availability of fuel, etc., were not considered. The conclusions reached do suggest, however, that fuel cells used for this application may eventually deserve a closer look.

[51] J.R. Huff and H.S. Murray, "Feasibility Evaluation of Fuel Cells for Selected Heavy-Duty Transportation Systems, " Los Alamos National Laboratory, March 1982.

[52] Arctic Energies, Ltd., "Evaluation of the Ship Fuel Cost Savings Potential of Phosphoric Acid Fuel Cell Power Plants and DC Drive for Coast Guard Cutters," AEL/CGORD 85-1, May 1985. The Coast Guard provided the data for this study but did not sponsor the research and does not necessarily agree with the study's conclusions.

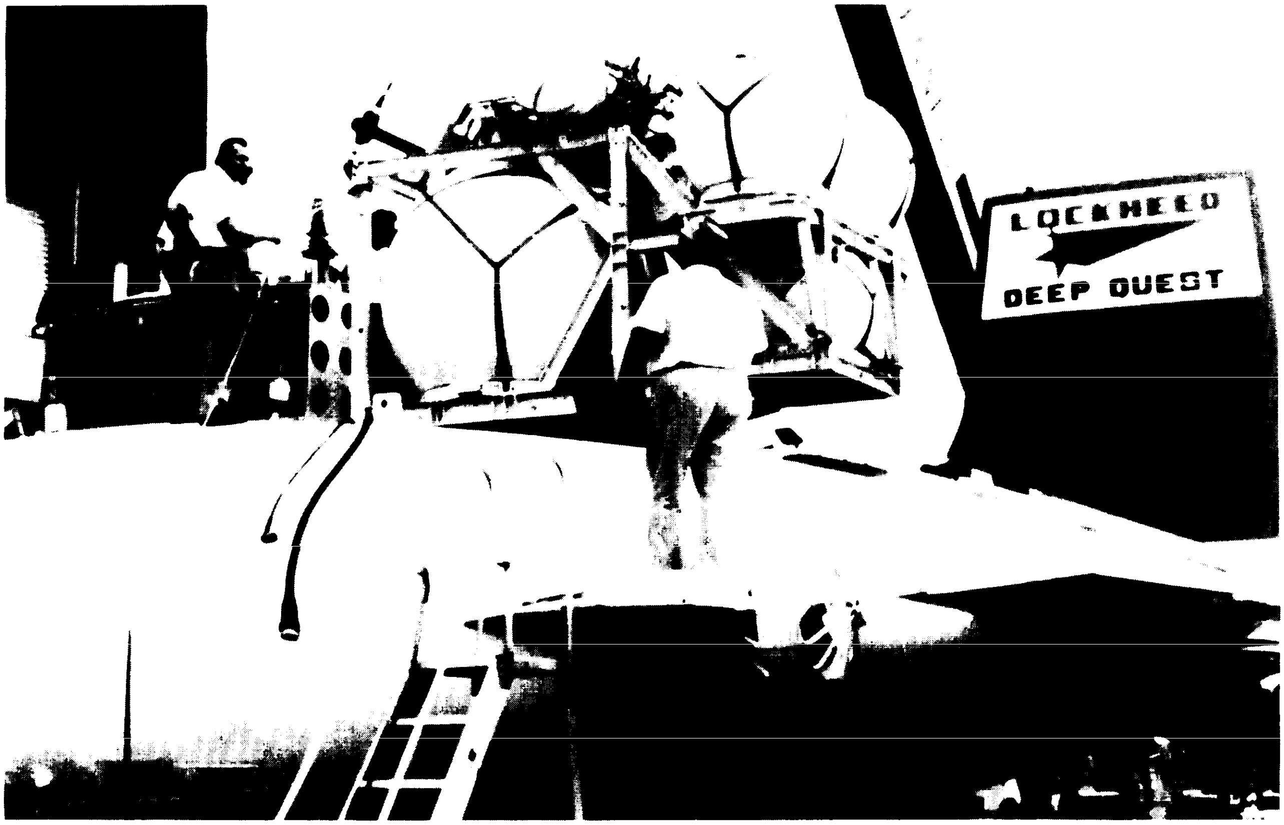


Photo credit U S Navy

Fuel cell being installed in submersible *Deep Quest*

Submarines and Submersibles

A major constraint faced by submerged vessels, whether submarines or submersibles, is endurance. Fuel cells have been considered for submerged operations because they enable undersea vessels to remain submerged for a greater length of time than the batteries that typically propel small submersibles.

The Deep Submergence Search Vehicle (DSSV) and the Deep Submergence Rescue Vehicle (DSRV). —The only fuel cell system developed thus far for a marine application has been the one designed by UTC, using the alkaline fuel cell technology developed by NASA, for use in a deep submergence search vehicle for the U.S. Navy, In 1978, Lockheed installed and tested the UTC 30 kW alkaline fuel cell on board its deep submergence search vehicle, Deep Quest. *Deep Quest* made about **50** successful dives with its fuel cell power system. Nevertheless, the U.S. Congress terminated the program, and the alkaline fuel cell no longer had a mission. The fuel cell was reconfigured for possible application on the DSRV; however, the mission requirements for the DSRV were sufficiently different from those of the DSSV that it did not require a fuel cell propulsion system. The DSRV is designed to be carried piggy-back on a nuclear submarine, so it could get its batteries recharged by the mother submarine, Thus, the initial power supply was more than adequate for the submersible's rescue mission. Moreover, although the fuel cell was technically satisfactory, doubts persisted about reliability and system safety in a real rescue situation. High pressure hydrogen and oxygen to fuel the alkaline fuel cell would have to be stored aboard the mother submarine and transferred to the DSRV for refueling, a potential safety problem. In addition, if large quantities of hydrogen and oxygen were stored on board, it would be necessary to take off a weapons system. In other words, the alkaline fuel cell, technically adequate though it was, did not fill the mission requirement.[53] This example illustrates the fact that for military applications, the mission requirement, and not cost, is the major consideration.

The Navy has no current effort to develop submersible/submarine fuel cell power systems. However, some believe that small submarines are one type of naval vessel for which fuel cells would be well-suited, providing, perhaps, a less expensive alternative to nuclear-powered submarines. For instance, SPE technology is currently being investigated in West Germany as an alternative to diesel power for submarines.

Submarine Tankers. —Several conceptual engineering and economic studies have been done investigating the feasibility of building large submarine tankers to transport oil or products such as methanol and liquefied natural gas from Alaska's North Slope under Arctic Ocean ice to Europe or the U.S. East Coast. In 1982 Arctic Enterprises, Inc., prepared a report for DOE on the feasibility of building a fuel cell propelled submarine tanker system.[54] Although the report concluded that no engineering or R&D breakthroughs were required to build such a vessel, neither technical nor economic feasibility have yet been demonstrated. No oil company at this time is seriously considering transporting oil or oil products under Arctic ice, and the idea is considered by most to be ahead of its time.

Remote Underwater Vehicles.—Remote underwater vehicles used for search, salvage, inspection, and scientific purposes are also constrained by onboard energy sources. The principal users of these vehicles are the oil industry, the Navy, other government agencies such as the National Oceanic and Atmospheric Administration, and the scientific community. It is expected that as the needs arise within the industry and the Navy, systems similar to the DSRV system will be built. The scientific community will probably first ride "piggy-back" on industry or Navy fuel cell equipped remote vehicles until it becomes clear that sufficient need and funding can be identified for such equipment to become a part of the community's University National Oceanographic Laboratory System fleet.

Commercial Transport Ships

Fuel cells have been considered as well for commercial transport ships. The competition with alternative systems is likely to be even stiffer for tankers, containerships, bulk carriers, and the like. This is because these ships operate at constant speeds and currently use high efficiency, low-rpm diesel engines. Use of fuel cells will be limited by industry reluctance to change from a propulsion system that is reliable and efficient. In general, commercial applications for fuel cells, unlike military applications, must prove cost effective. Unless there are clear and significant economic advantages for fuel cells, they are unlikely to be used. These advantages have not yet been demonstrated.

Naval Ships

Cost is not necessarily the major concern in building naval surface ships. Fuel cells will be used if they prove to be the best technology for a particular application. The Navy has not yet determined that there are any missions for which fuel cells are uniquely suited, although some analytical work has been done.[55] Limited availability of fuel cell fuel and the low power density are the biggest constraints in developing fuel cells for naval ships. As presented above, it is no easy task for a fleet to switch to a new fuel. In the Navy's case, before it would do so, the fuel would have to be available worldwide. Thus, the Navy will likely continue to depend on traditional logistic fuels as long as they are available and fulfill mission requirements. A second special military problem concerns the use of low flashpoint fuels such as methanol. A low flashpoint increases the potential for fires, and fuels with low flashpoints

[53] Ted Stanford, U.S. Navy, NAVSEA, discussion in OTA workshop, Sept. 5, 1985.

[54] U.S. Department of Energy, *Fuel Cell Propelled Submarine Tanker System Study*, prepared by Arctic Enterprises Inc., DOE/FE I 15086, June 1982.

[55] For example, Naval Sea Systems Command, *A Total Ship Analysis of Future Candidate Naval Fuel Alternatives*, report No. 313-011-81, July 1981.

could be particularly dangerous in a battlefield situation, where fires are to be expected. Thus, methanol-fueled fuel cells probably would not fit some Navy missions even if fuel cells offered other significant advantages. A different logistic fuel would have to be found, or reformer technology would have to be developed for No. 2 diesel.

Auxiliary Ship Power

Auxiliary power units provide electricity to all systems aboard a ship except main propulsion. These systems include hotel services (lighting, plumbing, and pumps for water); bilge and ballast pumps; fuel transfer systems; cargo-handling systems; navigation systems; etc. Fuel cells could provide electricity for these auxiliary systems. Less capital investment, and hence, less risk would be required than would be the case for investment in main propulsion systems. Hence, the outlook for near-term testing of fuel cells for auxiliary purposes may be better than the outlook for the use of fuel cells as main propulsion units. However, there are some potential drawbacks to be considered. One would not want to have one fuel for the main power units and another fuel for auxiliary power units. Generally, the simpler the fuel logistic system, the better. In addition, although fuel cell auxiliary systems may be more efficient than alternative powerplants, the potential savings possible are not very large compared to savings potentially achievable by switching to more efficient main propulsion units. Cruise ships may be an exception to this rule, because they have big hotel loads; hence, quiet, unobtrusive fuel cell auxiliary power units may be particularly suited for this type of ship.

Other Potential Applications

Several other potential marine applications have been considered. Fuel cells could be used as a power source on offshore oil platforms. Commercial diesel engines and gas turbines provide power at present. Fuel cells could also be used to power remote navigation, radar, or oceanographic data acquisition and transmission systems. As with other marine uses, the long-term reliability of fuel cells used for these purposes has never been tested. Another possibility is to use fuel cells as an auxiliary power source for refrigerated containers. Such containers are transferred from shore to ship and must be kept refrigerated at all times. Sea-Land Corp. has investigated the use of fuel cells for this application and concluded that the idea is not economically attractive at the present time. Finally, large, floating fuel cell power generation systems can be envisioned. Such floating plants might provide power for overseas markets and could be an export opportunity for U.S. companies; however, development of this application is not likely at any time soon.

Other Transportation Applications

Train Applications

Investigations of the application of fuel cells to train transportation systems have been conducted by DOE's Los Alamos National Laboratory. Comparisons were made of phosphoric acid and solid polymer electrolyte fuel cell systems with a conventional General Motors' SD40-2 diesel electric locomotive. The simulation results show that performance goals can be met and that overall energy consumption of heavy-duty fuel cell powerplants can be substantially improved over diesel operation of locomotives. If development of fuel cells for locomotives is pursued, it may eventually stimulate more interest in fuel cells on the part of marine operators. Powerplants developed for locomotives have many of the features and performance characteristics required for a number of marine uses.

Automotive Applications

Potential applications of fuel cell technology for land vehicles have ranged from automobiles to buses and trucks. For automobiles, estimates have been made that the fuel cell equipped auto might be able to achieve 60 miles per gallon. However, the use of a fuel cell alone for automotive propulsion leads to a serious deficiency. In the automotive field, fast acceleration and changing power requirements place quick response requirements on the power system. While fuel cell systems are generally considered good load following systems for industrial applications, they are too slow to respond to fast and often unpredictable car, bus, and truck power changes. Research is underway to combine heavy-duty battery power sources with the fuel cell system to obtain the response needed to accommodate the almost instantaneous peak power increases required by on-road and off-road vehicles. The fuel cell would be used to recharge the battery during steady, low demand driving periods.

Walsh and Rajan are not optimistic about the use of fuel cells in the automotive industry. They note that transportation economics demand radical reductions in the cost of fuel cell systems. PAFCs are currently about 10 times too expensive to be considered for transportation markets.[56] For fuel cells to become competitive with heat engines, major cost breakthroughs must be achieved. Significantly, heat engines can be modified to burn nonpetroleum fuels such as methanol, and therefore, fuel cells will be in direct competition with heat engines. "Present fuel cell technology is grossly inadequate for most transportation applications, and quantum advances are needed. In our opinion, 10 or 20 years of intensive R&D with strenuous attempts at invention will be required."[57] Other factors, such as higher fuel efficiency, reduced maintenance costs, and reduced pollution may compensate, to some degree, for production costs. General Motors, on the other hand, is more optimistic, and is currently investigating the potential of phosphoric acid and SPE fuel cells for land transportation uses. 'g

Some Options for the Federal Government

The outlook for using fuel cells in the electric and gas utility industry appears promising. The Federal Government has supported private sector R&D efforts since the 1960s. Continued Federal support of fuel cell development programs is probably necessary to advance the introduction of fuel cell technology into the land-based utility industry.

The use of fuel cells in the marine industry in the next 15 to **20** years is far less certain. When and if the commercial maritime industry decides that fuel cell power systems would provide significant cost and/or other advantages over competing power systems, these fuel cell systems must be adapted to the unique demands of the marine environment. Very little R&D on fuel cells for marine applications is currently underway inside or outside the government. Since the R&D program for land-based applications is so large in comparison, some believe that the proper course for the marine industry is just to monitor closely that R&D and select developments and applications as they may occur in the future. Others believe that unique marine requirements warrant specialized R&D efforts.

Specific research and development could be supported by the Federal Government and/or industry to improve the potential of fuel cells in the marine market. For example, the near-term use of fuel cells in the marine industry could be stimulated by developing technology capable of reforming diesel oil. Other research that could be undertaken includes: laboratory testing, followed by shipboard analysis and testing, of fuel cell components to determine their suitability and/or vulnerability to the marine environment; basic electrochemical studies to improve catalysts and electrolytes that would not be contaminated by fuel processed from fuel oil; and accelerated investigation of molten carbonate fuel cells and of the vulnerability of this type of fuel cell to the marine environment. The Federal Government's investment in molten carbonate technology could concentrate on those developments needed to support a demonstration of this fuel cell's higher efficiency and fuel flexibility. The private sector could focus on the technology and processes needed to manufacture these fuel cells at a cost competitive with conventional power generators.

The Maritime Administration, and perhaps other agencies within the Department of Transportation, and DOE might be able to offer some assistance for applications more directly relevant for the commercial transportation sector. For instance, funding could be provided to demonstrate and evaluate use of a fuel cell system on a commercial ship or locomotive. One suggestion is that future fuel cell research for heavy-duty transportation applications focus on developing the more efficient molten carbonate fuel cells. Once a small (i.e., 50 kW) molten carbonate system has been

[56]Walsh and Rajan, op. cit., p. 6.

[57]Walsh and Rajan, op. cit., p. 9.

"Gene Helms, Allison Gas Turbine Division, General Motors, telephone conversation, Nov. 6, 1985, demonstrated, these agencies could coordinate a demonstration of a 2 to 4 MW powerplant for the heavy-duty transportation sector. Different types of incentives to private industry might also be used, such as tax benefits for those who use non-petroleum-based fuels or accelerated depreciation.

The Federal Government may also wish to encourage the Navy, Army, Air Force, and Coast Guard to become more involved in developing fuel cells for their mission requirements. OTA's analysis indicates potential benefits of marine fuel cell use in naval applications, and suggests that more in-depth analysis of the potential applicability of fuel cell technologies for Navy missions is needed.

The Navy is currently monitoring fuel cell developments, but it may be useful for the Navy to consider supporting specialized research into marine fuel cell development as well. At present, for example, very little work has been done on developing fuel cells for "quiet" ship operation aboard certain vessels where noise emissions from conventional engines are a major problem. If fuel cells could match these and other unique Navy missions, then naval fuel cell research, independent of private sector efforts, may be justified.

Recognizing that research funds are limited and must be carefully targeted to the most productive avenues of research, it may be best to begin by encouraging the military to develop small fuel cell systems for auxiliary power on naval surface ships. As experience is gained, larger fuel cells (on the order of a megawatt) might be used for naval and Coast Guard auxiliary power. Finally, beyond 2000, the Navy or Coast Guard could be encouraged to focus on developing larger fuel cell powerplants for primary propulsion power. The Navy and Coast Guard have different missions than the civilian sector and some applications developed by them may not be directly useful for the private sector. On the other hand, some applications first developed for military purposes might stimulate development of applications for commercial use.

GLOSSARY

alkaline fuel cell: Fuel cell using alkali (a type of soluble salt) as the electrolyte. Operates at 650 C. First developed for NASA. Uses pure hydrogen and oxygen.

anode: The negative electrode or terminal of a fuel cell.

base load: The normal, relatively constant demand for energy on a given system.

bottoming cycle: A means to increase the thermal efficiency of an electric generating system by converting some waste heat into electricity rather than discharging all of it to the environment.

British thermal unit (Btu): The amount of heat required to raise the temperature of 1 pound of water 10 F under stated conditions of temperature and pressure. It is the standard unit for measuring quantity of heat energy.

Carnot cycle: An ideal heat engine cycle in which the sequence of operations forming the working cycle consists of isothermal expansion, adiabatic expansion, isothermal compression, and adiabatic compression back to its initial state. An ideal Carnot cycle engine converts heat into work with the maximum theoretical efficiency.

catalyst: A substance that changes the rate of a reaction without itself undergoing any net change; a substance that induces catalysis.

cathode: The positive electrode or terminal of a fuel cell.

carbon monoxide shifter: Used in processing fuel. Transforms carbon monoxide (CO) to carbon dioxide (CO_2).

closed Brayton cycle: An external combustion gas turbine engine. Potential propulsion system for future ships.

cogeneration: Production of electrical (or mechanical) energy and thermal energy from the same primary energy source.

controller: In a fuel cell system, controls supplemental power during the startup operations, stack cooling and **gas** flow during power and hold operations, and close-down operations. Uses temperature, gas flow, and other sensors and microprocessors to perform its functions.

distillate fuel: The lighter fuels distilled off during the refining process. Includes Nos. 1 and 2 heating oils, diesel fuels, and No. 4 fuel oil.

electrochemical: Chemical action employing a current of electricity to cause or to sustain the action.

electrode: Reactive materials, such as metals and metal oxides, attached to grids that conduct electricity.

electrolyte: A conducting medium in which the flow of electric current takes place by the migration of ions.

flashpoint: The lowest temperature at which the vapors arising from a liquid surface can be ignited by an open flame.

fuel processor: Same as reformer. Converts a stock fuel to a hydrogen-rich gas for use in fuel cells. Also removes impurities.

fuel cell **stack: A** stack of individual fuel cells connected in parallel to provide the desired total power.

heat rate: A measure of thermal efficiency, generally expressed as Btu per kilowatt-hour.

inverter: A device for converting direct current to alternating current.

kilowatt: A unit of power equal to 1,000 watts.

life-cycle cost: The accumulation of all funds spent for the purchase, installation, operation, and maintenance of a system over its useful life. The accumulation generally includes a discounting of future costs to reflect the relative value of money over time.

load: The energy tapped from any power source. In the electric industry, the amount of electric power delivered or required at any specified point or points in the system.

load following: A utility power generator used to cope with swings in the load.

megawatt: One million watts, or 1,000 kilowatts.

molten carbonate fuel cell: Fuel cell using molten carbonate as the electrolyte. Operating at from 6000 to 7000 C. Able to use a variety of fuels. Internal reforming potential.

oxidant: A chemical element or compound that is capable of gaining electrons, i.e., of being reduced.

peak-shaving: A type of utility powerplant operated only when the need for additional power is temporarily high.

phosphoric acid fuel cell: Fuel cell using phosphoric acid as the electrolyte. Operates at 1500 to 200° C.

power conditioner: Receives electrical power from the fuel cell stack and converts it to match the required output .

power density: The amount of power per unit of cross-sectional area.

reformer: Same as fuel processor. Converts a stock fuel to a hydrogen-rich gas for use in fuel cells. Also removes impurities.

sintering: The agglomeration of solids at temperatures below their melting point, usually as a consequence of heat and pressure.

solid oxide fuel cell: Fuel cell using solid oxide as the electrolyte. Operates at temperatures close to 1,000° C. Less developed than phosphoric acid fuel cells.

solid polymer electrolyte fuel cell: Fuel cell using solid polymer as the electrolyte.

steam turbine: A machine powered by high pressure steam and used to drive mechanical apparatus. It has a rotary motion in contrast to a reciprocating motion.

Stirling cycle: An external combustion engine under development. Has the ability to use any heat source. Prospects for high efficiency. A potential propulsion system for future ships.

thermal inertia: The tendency for a heat machine to generate heat at the same level at all times.

thermal signature: The heat trace that may be detected from an energy source, such as a submarine.

thermal transient: Abrupt changes in temperature due to sudden changes in load.

watt: A unit of power that equals 1 absolute joule per second. It is analogous to horsepower or foot-pounds per minute of mechanical power. One horsepower is equivalent to approximately **746** watts.

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