Fuel Cells

Trends in Research and Application

A. J. Appleby

FUEL CELLS: TRENDS IN RESEARCH AND APPLICATIONS

Edited by

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Preface

This volume (Volume II) completes the records of the Proceedings of the Workshop "Fuel Cells: Trends in Research and Applications," held in Ravello, Italy, 10–14 June, 1985. The meeting, organized by UNESCO in cooperation with the Commission of the European Communities and the Council of Europe, brought together approximately 30 specialists from 17 countries. It was the first major international conference on this subject.

Volume I, a summary of the Proceedings of this Workshop, was issued by UNESCO in late 1985. In addition to such ancillary items as the agenda and list of participants, it includes the summary of the discussions of the three working groups into which the Workshop was subdivided, abstracts of the papers presented, as well as an introductory paper prepared for this meeting by Mr. B. Birnbaum under a contract to UNESCO. Copies of this Summary Volume can be obtained from UNESCO upon request.

Volume II compiles the full texts of the presentations prepared for this Workshop without any changes, except for some minor modifications introduced by the Editor. It contains an overview paper by Dr. F. Sissine, which was not prepared for this Workshop. It is included since it was distributed with his permission to participants at the beginning of the Workshop, and it provided valuable background information for the discussions. Certain presentations at the Workshop are not included in Volume II, since they have already appeared in complete form in Volume I or elsewhere. These include the paper by B. Birnbaum cited earlier, as well as papers by P. Gelin (France), E. Gileadi (Israel), V. S. Kublanovskii (USSR) and R. Vellone (Italy), which were only available in the form of extended abstracts that were published in their entirety in Volume I. In addition, the paper by D. S. Cameron (United Kingdom) was published complete in the *Platinum Metals Review,* **29** (3), pp. 107–112 (1985), and that by S. Abens and M. Farooque (USA) appeared in very similar form as S. Abens, M. Farooque and R. Jacobs, in *Proceedings of the 1984 Intersociety Energy Conversion Engineering Conference,* Paper 849208, San Francisco, CA, American Nuclear Society, Washington, D.C., 1984, p. 838. In addition, the two papers by A. Ascoli, and A. Ascoli and G. Redaelli (Italy), have been combined here into a single paper.

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Contents

Fuel Cells for Electric Power Production: Future Potential, Federal Role and Policy Options

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INTRODUCTION

Over the past 10 years, the Federal Government has invested nearly $260 million in research and development (R&D) on fuel cells for electric power production. The goal of this research is to develop a highly energy efficient technology that has some very desirable characteristics for electric power planning: low environmental impact, fuel flexibility, high performance, small size and spinning reserve capability. The primary national payoffs expected from the fuel cell research effort are increased fuel use efficiency, substitution of alternate fuels for conventional fuels and an improved balance of trade. However, the prospect of siting fuel cells in urban areas has increased the scrutiny of possible environmental and safety concerns. Fulfilling regulations that address these concerns has caused significant delays in the operation of a major demonstration facility.

As phosphoric acid fuel cell developments have progressed, Congress and the Reagan Administration have adopted distinctly different views about how near this system is to commercial readiness. Consequently, Administration budget requests for R&D and congressional appropriations have differed sharply for four consecutive fiscal years. In any case, realization of national payoffs from the Federal investment in fuel cells could depend primarily on policy actions yet to be taken. In addition to continued R&D support, other key policy actions may involve research or technologies that enable fuel cells to use alternate fuel sources and consideration of technology transfer, export potential and regulations affecting facility siting and power production.

The first part of this paper describes the technical capabilities of fuel cells, environmental considerations for their use and utility characteristics that influence their market potential. The remaining parts examine the status of Federal R&D and funding, private sector perceptions of risk and technical barriers, and policy options for research- and implementation-related actions.

TECHNOLOGY DESCRIPTION

General Operation

A fuel cell combines a hydrogen-rich gas with air and converts the chemical energy of this mixture into electricity directly--with no intermediate combustion step. Its construction is similar to the familiar dry-cell battery. Unlike a battery, however, a fuel cell does not undergo a material change. Consequently, it does not run down or require recharging--it operates as long as fuel and air are supplied. A typical fuel cell produces a high current and low voltage. Practical voltages are obtained by connecting many individual cells into what is referred to as a cell stack. A fuel cell produces direct current (DC power), which usually requires a power conditioning unit, called an inverter, to convert the output to alternating current (AC power). Depending on the type of fuel that is to be used, the fuel cell system may also require a fuel processing unit, known as a reformer, to convert the input to a hydrogen-rich gas.

Because a fuel cell transforms fuel directly to electricity without an intermediate conversion to heat, less waste heat is produced, and very high conversion efficiencies--in the range from 40 to 60 percent--are achieved. Additionally, the constant temperature operation of a fuel cell allows the heat liberated by the electrochemical reaction to be used for space heating, water heating or industrial heat. When a fuel cell is used in this cogeneration mode, producing both power and heat, it can achieve overall efficiencies as high as 80 percent.

Types of Fuel Cells

Fuel cells are characterized by the type of electrolyte (conductive material) used for the chemical conversion process. Fuel cells that use a phosphoric acid electrolyte have been studied more intensively than others and are the nearest to commercial use. Other types of fuel cells currently being studied are those with molten carbonate, solid oxide, alkaline and solid polymer electrolytes. Each type of fuel cell operates at a different temperature, and consequently, it may achieve different efficiencies and have different applications.

Perhaps the most important of the advanced fuel cell concepts is the direct fuel cell. A direct fuel cell does not require a fuel reformer but inputs fuel directly to the cell stack. By eliminating the fuel reformer, it may attain a higher conversion efficiency and a lower plant cost than other fuel cell designs. Another possible advantage may be an ability to operate at somewhat lower temperatures than other designs, making technology easier to develop. Present research on the direct fuel cell is focused on the development of a 2-megawatt (millions of watts, MW) molten carbonate system. Researchers project that this system could attain a 15 percent higher fuel efficiency than other molten carbonate cells, and a 40 percent higher efficiency than phosphoric acid fuel cells[1].

TECHNICAL CAPABILITIES

Fuel cells appear to offer several technical capabilities in addition to their prospect of high fuel efficiency and possible environmental advantages. These characteristics follow:

Fuel Flexibility

A fuel cell employs a hydrogen rich gas to produce electricity. Thus, it can use any fuel source that can supply this gas. At present, sources of such gas include petroleum, naphtha, natural gas, and methanol. Several other sources may be developed to varying degrees. In places where biomass and solid waste produce natural gas economically, they can be used as fuel sources[2]. Researchers expect that medium-BTU (British thermal unit, measure of heat-energy content) gas from coal gasification or other synthetic fuels will also become an acceptable fuel. Additionally, where hydrogen storage is feasible, renewable power sources could drive an electrolysis process to produce hydrogen during off-peak periods that can be used to operate fuel cells during peak demands[3].

High Performance

Fuel cells are expected to attain a performance reliability near 85 percent. Furthermore, their modular construction should facilitate repair when they are scheduled for maintenance or are forced out of service by a technical difficulty. Consequently, a utility that installs a substantial number of them may be able to reduce its reserve margin capacity requirements while maintaining a constant level of system reliability. By reducing the need for capacity construction, cost savings may be realized[4].

Small Size

The fuel cell's compact design enables it to be added in small, discrete increments of capacity, which allows better matching of capacity to expected load growth. In contrast, the installation of a single large conventional power plant can produce excess capacity for several years, especially if the load growth rate is low. Fuel cells' small size also enables them to be located close to the load, which can reduce energy losses and costs associated with transmission and distribution equipment. Fuel cell sitings near load centers may also reduce the likelihood of system blackouts[5].

Spinning Reserve and Load Following

One of the fuel cell's most important characteristics is its ability to operate efficiently at part-load and to respond rapidly to sudden increases or decreases in power demands. The fuel cell's ability to increase output quickly is known as its spinning reserve capability, and its ability to decrease output quickly is known as its load following capability. These capabilities make fuel cells attractive as peak-load facilities. In addition to meeting changes in power demand, the fuel cell's spinning reserve and load following capabilities also enable it to complement effectively the variable output from windfarms and other renewable power sources.* The combined output of these complementary facilities may enable them jointly to defer or displace some conventional power plant construction before the year 2000.

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* This possibility could be enhanced even further if off-peak power from renewable sources is used to produce hydrogen for operation of the fuel cell during peak periods. For example, photovoltaic systems reach their peak output in the early afternoon, but utility peak loads usually occur during the early evening.

FUEL CELL INDUSTRY

Presently, United Technologies Corporation (UTC) and Westinghouse Electric Corporation are the major U.S. companies that are involved in the design and manufacture of fuel cells. UTC has the longest history of private sector involvement with fuel cells. With financial assistance from DOE and the Electric Power Research Institute (EPRI), it is currently developing the technology for an 11-MW water-cooled phosphoric acid demonstration plant. Westinghouse has only recently become involved in fuel cell activities. With DOE and EPRI assistance, it is currently developing the technology for a 7.5-MW air-cooled phosphoric acid demonstration plant. Interest in the capabilities and potential of fuel cells has also sparked the formation of fuel cell user groups representing electric utilities and industry.*

UTILITY INTEREST AND MARKET POTENTIAL

Utility Interest

Electric utility market potential is influenced by an interest in fuel cells' ability to reduce business risk and improve finances. Many utilities believe that their investment risk would be reduced by: (1) mass production, which improves quality control and reduces on-site assembly time, and (2) shorter construction lead times, which allow decisions to be made on the basis of load forecasts that are far more accurate than the 10 to 15 year forecasts that must be used to plan conventional facilities. Utilities also expect that the short time required to place fuel cells in-service would create immediate cash flow benefits and lower interest costs on borrowed capital[5].

Utility Market Potential

EPRI recently completed a study of the potential+ for fuel cell use in 25 utility systems[6]. The systems included a cross-section of investor-owned, publicly-owned and rural cooperative utilities that represent approximately 20 percent of the 1986 projected U.S. peak demand. The study found that fuel cells were more attractive to utilities that already have sufficient or excess base-load nuclear or coal capacity and appear to need new cycling or peaking capacity. Most of these utilities are located in the North Central, Southeastern and Western regions of the country. In these utility systems,

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* For information about the Fuel Cell Users Group (FCUG) of the Electric Utility Industry, contact Mr. Jeffrey Serfass, 1101 Connecticut Ave., N.W., Suite 705, Washington, DC, (202) 457-0868; and for information about the Industrial Fuel Cell Association, contact Mr. Joe Anderson, P.O. Box 5871, Lake Charles, LA, (318) 477-7905.

\+ The potential was studied with 20-year least cost capacity expansion plans covering the period from 1986 to 2005. Break-even capital costs varied with utility generation mix, ranging from \$400/kW to \$1,000/kW. The study assumed that fuel cells would employ an expensive fuel (assumed to be the same cost as distillate oil) that created a relatively high operating cost. The least cost method dispatched the fuel cells after base-load and intermediate steam units, but before any fossil-fired peaking units.

however, fuel cells will have to compete against other peak-load technologies such as combustion turbines, combined cycles, pumped energy storage and compressed-air energy storage.

The EPRI study projects that fuel cells will be added at a slow rate through 1992 because of high reserve margins, low growth projections and substantial construction in progress. After 1992, the study projects that fuel cells will be added at a higher rate due to falling reserve margins and reduced fuel cell costs. EPRI concludes that the 25 utilities studied would add about 8,220 MW of fuel cells through the year 2005, and that a national market potential of 45,000 MW exists for fuel cells during the period from 1986 to 2005. EPRI notes that several desirable planning characteristics and financial benefits of fuel cells--arising from their modularity, short lead times, less restricted siting and lower financial risk than conventional plants--were not built into the projection, and could make the potential market even larger. However, the study also notes that energy storage, load management and other advanced technologies were not considered and could reduce the market potential.

A more recent report by the Fuel Cell Users Group (FCUG) suggests three reasons why the market potential for fuel cells may be considerably larger than the estimate made by the EPRI report[7]. One, the EPRI study does not address the international market potential outside the United States.* Additionally, the FCUG report notes that the EPRI study does not assess the possible market impacts of fuel cell cost reductions or performance improvements during the period from 1986 through 2005. The FCUG concludes that fuel cells market potential could be as large as 65,000 MW for the period 1986 through 2005.

TECHNICAL PROBLEMS

There are some uncertainties about whether fuel cells can achieve technical, performance and cost objectives. Although technical and operational feasibility have been established, there are still concerns about water purity, durability, heat rates and alternative fuel use that may be difficult to attain. Ensuring that water of an acceptable purity and quality is fed into the system may pose one technical barrier for phosphoric acid fuel cell commercialization. Another hardware concern, according to Russel Thompson of UTC, involves durability improvements that require extending the life of fuel cell stacks and other commercially available components used in the fuel cell system[8]. Also, private sector commercialization goals depend on expected reductions in fuel cell heat rates, which would translate into improved fuel efficiency and, thus, reduced operating costs.+ Perhaps the most important technical barrier involves the use of alternative fuels. At hearings held by the House Science and Technology Committee, William Podolny of UTC testified

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* For example, fuel cells may have an even greater value in land-limited areas like Japan and Europe than they do in the United States.

+ Heat rates indicate the amount of fuel required to produce a unit of electric power. The 4.8-MW facility has achieved a heat rate of 9,300 BTU/kWh, but high market penetrations require a reduction to about 7,000 BTU/kWh.

that the major barrier to using coal gas in fuel cells involves the cost and performance of coal gasification technology[1].

ENVIRONMENTAL CONSIDERATIONS

Environmental Advantages

The Department of Energy (DOE) funded, and the National Aeronautics and Space Administration (NASA) administered, an assessment of the environmental effects expected from the use of phosphoric acid fuel cells[9]. It concludes that these fuel cells would have fewer environmental impacts than conventional fossil-fueled power plants. The importance of the environmental benefits are expected to vary with locations but are expected to be substantial on a national basis. The findings related to air quality, water quality and noise follow.

Air quality. Because fuel cells do not rely on a fuel-burning process, their air pollution emissions are projected to be 1,000 to 10,000 times smaller than those of new fossil-fueled plants--even if the fossil plants employ the most advanced pollution control equipment. Air quality benefits would be improved further when the fuel cell is operated as a cogeneration facility.* Fuel cells' low emissions enable them to be sited close to the load in urban areas of poor air quality, where the benefits are most needed. Also, the expected reductions in sulfur and nitrogen oxides could enable fuel cells to reduce suggested acid rain conditions[10].

Water quality. The use of fuel cells is also expected to provide significant benefits related to water use and water quality. Because the fuel cell's electrochemical reaction produces water as a byproduct, little, if any, external water is required for its operation. In contrast, conventional power plants require massive amounts of water for system cooling. The impacts of these water demands on aquatic ecosystems and water supplies may be reduced greatly with use of fuel cells. Additionally, fuel cells' limited water demands may allow them to be located in remote sites[11]. Fuel cells may also reduce or eliminate water quality problems created by conventional plants' thermal discharges and the disposal of residues from air pollution control equipment[12].

Noise level. The quiet electrochemical conversion process of fuel cells eliminates many of the noise sources associated with conventional steam power plants. This feature reduces community concerns, enabling siting close to the load, and decreases the cost of noise control. It also improves the work environment[12].

Environmental Disadvantages

In three respects, fuel cells will likely have some undesirable impacts on the environment that parallel those of conventional fossil power plants. One, on an energy use basis, they produce similar quantities of carbon dioxide emissions which may contribute to world climate warming (the greenhouse

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* This improvement results from cogeneration's higher fuel use efficiency.

effect). Also, the solid wastes created by fuel cells are expected to be similar in quantity and hazard potential to those generated by conventional fossil plants[13].

Many of the fuels employed by fuel cells are inflammable, explosive and may contain organic components that are toxic or otherwise dangerous. The transport, on-site storage and use of these fuels create environmental and safety concerns. These concerns are especially important because fuel cell deployment is more likely to occur in residential, commercial and industrial areas than in the more isolated areas where conventional plants are located[14].

MATERIALS VULNERABILITY CONSIDERATION

The only strategic concern related to phosphoric acid fuel cell use is that high levels of market penetration could increase platinum demand significantly. In these systems, platinum is used as a catalyst in the cell stack electrodes. Assuming a 92 percent recycling rate, the DOE/NASA report projects that a 20,000-MW fuel cell market penetration could increase U.S. platinum demand by 4 percent, and a 50,000-MW penetration could increase demand by 11 percent. The report concludes that it is likely that the increased demand would have to be met by increased imports rather than expanded domestic production[15].

HISTORY AND FEDERAL PROGRAM

The fuel cell was invented by Sir William Grove in 1839, but its first practical application occurred during the U.S. space program's Gemini V flight in August 1965. The fuel cell fulfilled the Gemini spacecraft's need for an efficient and reliable power generator with a very high energy density[16]. The success of fuel cells in the space program encouraged private sector efforts to develop them for utility power generation. The private sector effort began with UTC and a group of several electric utilities in 1972 and culminated with the successful operation of a 1-MW pilot plant in 1977[17]. In 1973, this group started design work on a 4.8-MW phosphoric acid plant and later appealed to ERDA (which later became part of DOE) for assistance. The Office of Coal Utilization under the Assistant Secretary for Fossil Fuels at DOE currently directs the primary Federal effort to help utilities develop fuel cells for stationary power production. However, NASA and the Department of Defense are also conducting fuel cell R&D programs in related areas.

DOE PROGRAM

DOE is pursuing two related, but different, developments of fuel cells. One is focused on multi-kilowatt (thousands of watts, kW) cogeneration systems for dispersed uses, and the other is aimed at developing multi-megawatt systems for utility grid applications.

The Multi-Kilowatt System

This effort is of interest primarily to gas and gas-electric (combination) utilities. It is focused on cogeneration systems ranging from 40 to 300 kW in size, for use in commercial buildings, light industry and multifamily residential buildings. These relatively small plants could use pipeline gas as a fuel and would supply both electric and thermal energy while consuming no more fuel than that which is now required for thermal demand alone. During FY83 and FY84, 45 phosphoric acid plants of 40-kW size were installed for field testing throughout the United States and Japan. The goal of this effort is to produce adequate experience to allow manufacturers and users to make commercial decisions.

The Multi-Megawatt Systems

The other application is of interest primarily to electric utilities. It involves the siting of multi-megawatt, dispersed plants on the utility grid with the potential for waste heat recovery. The ultimate goal of DOE's multi-megawatt program is to develop modular, factory-assembled units with capacities of 7 to 11 MW for use in urban areas where environmental regulations prevent utilities from siting conventional power plants.

The ConEd 4.8-MW demonstration plant. In 1979, DOE, EPRI and UTC began a cost-shared program to build a 4.8-MW demonstration plant in the service area of Consolidated Edison of New York (ConEd). Development of the ConEd 4.8-MW facility cost a total of $85 million. Of this total, DOE contributed $48 million, EPRI spent $17 million, UTC spent $14 million, and ConEd spent $6 million[18]. The primary purpose of this program was to enable the utility industry to determine the operational, environmental and siting advantages that fuel cells appeared to offer.

The southernmost tip of Manhattan Island was selected for the site, and development of the facility began in early 1980. However, nearby residents became concerned about possible fire hazards from on-site processing and storage of the naphtha fuel.* A community debate over the fire safety concerns led the New York Fire Department to require that the fuel be embedded in concrete storage tanks, all welds in the system be subjected to radiographic examination, and that piping be given stringent hydrostatic pressure tests.

During the ensuing years of reviews and special tests, the primary technical problems to emerge involved undersized heat exchangers and inadequate space between system components for repair and maintenance. In April 1984, ConEd attempted to operate the facility, but the effort was foiled by migrating acid from the cell stack: the unexpected delay in operation had exceeded the designed lifetime of the prototype cells[19]. Despite the failure to produce power, DOE and UTC feel that the experience has fulfilled their original research goals, along with providing unanticipated information about cell storage life. Additional experience has been obtained from a second 4.8-MW facility built with advanced components and tested successfully by the Tokyo Electric Power Company (TEPCo) in 1983 and 1984. DOE considers the 4.8-MW program to be complete as of the end of FY84.

The 7.5- and 11-MW demonstrations. The data and experience gathered from the 4.8-MW Tokyo facility has provided a basis for DOE and EPRI to begin a cost-shared effort with UTC to develop an 11-MW water-cooled phosphoric acid plant and with Westinghouse to develop a 7.5-MW air-cooled system. The

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* Naphtha is a light petroleum distillate.

contributions for the 11-MW system will be: DOE, 53 percent; EPRI, 35 percent; and UTC, 12 percent. The contributions for the 7.5-MW system will be: DOE, 40 percent; EPRI and Westinghouse, 60 percent. The purpose of these efforts is to demonstrate that modular, factory-assembled units of this size can achieve the performance, efficiency and cost-effectiveness necessary for peak-load use and also, where cogeneration opportunities exist, for base-load use. Furthermore, there is increasing interest in the prospect of integrating these systems with coal gasifiers for base-load service in sizes ranging from 50 to 250 MW[20].

Research on Advanced Systems for Utility Applications

While phosphoric acid systems move closer to demonstrating technical readiness for commercial service, DOE is also supporting R&D on molten carbonate and solid oxide fuel cell systems. Research on these systems is motivated by their higher operating temperatures, which create the potential for increased efficiency and reduced costs. However, these high temperatures also demand more R&D on materials and electrolytes before they can begin to approach the stage of technical and commercial readiness that has been achieved by phosphoric acid systems[21].

DOE FUNDING

History

From FY76 through FY84, DOE spent a total of nearly $260 million on fuel cells, as shown in Table 1.

TABLE 1. DOE Funding (1976-1984)
($ in millions)

FY76	FY77	FY78	FY79	FY80	FY81	FY82	FY83	FY84
$3.0	17.8	33.0	41.0	26.0	32.0	34.5	29.9	42.6

However, since the Reagan Administration took office, there has been a dramatic difference between Administration budget requests and Congressional appropriations, as shown in Table 2.

Congressional Action on the FY85 Budget

In its FY85 budget request, the Administration recommended no further funding or either the 4.8-MW demonstration facility or the 40-kW on-site field tests, arguing that work on these projects has been completed. Also, it recommended that one of the molten carbonate development efforts be eliminated because it involves unnecessary duplication.

The House Science and Technology Committee recommended that the FY85 fuel cells authorization be increased by $27.9 million over the Administration's request[22]. The largest part of this addition, $22.2 million, was earmarked for phosphoric acid systems--primarily for technology development of the 11-MW and 7.5-MW systems. The Committee also recommended that $5.7 million be added