Polymer electrolyte fuel cells: a review of recent developments

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Abstract

The very high power density available from proton-exchange membrane (PEM) fuel cells combined with the potential for very low cost suggests the PEM fuel cell as the most probable power plant for the next generation, non-polluting automobile engine. The demonstrated capability of the PEM fuel cell to produce power from available hydrocarbon fuels opens the possibility of reliable, efficient, power generation located near the user. This review summarizes the operating principles of the fuel cell stack and power systems, describes the current status of the technology, focusing on recent developments, and discusses the technical challenges and commercial prospects for this fuel cell technology.

Introduction

The proton-exchange membrane or PEM fuel cell [1], like other fuel cells [2], consists of two electrodes separated by an electrolyte. It is the choice of electrolyte which distinguishes the PEM fuel cell from others. The unique physical and operational properties of the polymer membrane electrolyte provide significant advantages over liquid and high temperature solid electrolytes in materials selection, component design and manufacturing, and power plant systems design.

The very high power density available from PEM fuel cells [3, 4], combined with the potential for very low cost, has led many in the field to identify the PEM fuel cell as the most probable power plant for the next generation, non-polluting automobile engine.

The demonstrated capability of the PEM fuel cell to produce power from hydrocarbon fuels, such as methanol [5] and natural gas [6], opens the possibility of reliable, efficient, low-cost power generation located near the user — even to the siting of power generation in the home.

This paper first presents a generalized overview of the operating principles of PEM fuel cell systems and PEM fuel cell stacks. This is followed by a summary of the present status of the various aspects of this technology. The technical challenges remaining to be addressed are described as well as the probable commercial impact of this technology.

Operating principles

The proton-exchange membrane fuel cell (also known as the solid polymer fuel cell) uses as its electrolyte one of several ion-exchange polymers. These polymers are

electronic insulators, but excellent conductors of hydrogen ions. The materials used to date consist of a fluorocarbon polymer backbone, similar to Teflon, to which sulfonic acid groups have been chemically bonded. The acid molecules are fixed to the polymer and cannot leak out, but the protons on these acid groups are free to migrate through the electrolyte.

The electrolyte is used in the form of a thin membrane, typically 0.05 to 0.18 mm thick. This membrane electrolyte can be handled easily and safely. The anode and cathode are prepared by applying a small amount of catalyst, typically platinum black or a supported platinum, to one surface of a thin sheet of a porous, electrode support material. The electrolyte is then sandwiched between the anode and cathode, and the three components are sealed together to produce a single 'membrane/electrode assembly' (MEA). This assembly, which is the heart of the fuel cell, is less than a millimeter thick.

The anode and cathode are contacted on the back side by fluid flow field plates in which channels have been formed. The ridges between the channels make electrical contact with the backs of the electrodes and conduct the current to the external circuit. The channels supply fuel to the anode and oxidant to the cathode. To obtain useful voltages, several cells are generally assembled together and connected electrically in series to produce a fuel cell stack.

The electrode reactions in the PEM fuel cell are analogous to those in the other acid electrolyte fuel cells, such as the phosphoric acid fuel cell. Hydrogen from the fuel gas stream is consumed at the anode, yielding electrons to the anode and producing hydrogen ions which enter the electrolyte. At the cathode, oxygen combines with electrons from the cathode and hydrogen ions from the electrolyte to produce water. The water does not dilute the polymer electrolyte but is, instead, generally rejected from the back of the cathode into the oxidant gas stream.

Figure 1 represents a typical PEM fuel cell system. The system consists of a fuel supply which may include a fuel processor, an oxidant supply which may include a compressor, the fuel cell stack, and a water/heat management system.

Fuel system

If the fuel cell is to be supplied with pure hydrogen as the fuel, the fuel system consists simply of a pressurized supply of hydrogen and a constant pressure regulator to supply hydrogen as required for the current being drawn by the load. In the typical operating system, using pure hydrogen as the fuel, excess hydrogen will be passed through the fuel cell, as part of the water balance system. This excess hydrogen is recirculated to the fuel entry port of the fuel cell using a recirculation pump or preferably an ejector. In this way, all the hydrogen is ultimately consumed in the fuel cell to produce electricity.

The PEM fuel cell can also operate on hydrocarbon fuels. This requires the presence of a fuel processor which converts the fuel or a fuel water mixture into a gas stream containing hydrogen, carbon dioxide, water, and traces of carbon monoxide. Depending upon the choice of fuel processor, nitrogen may also be present. In any fuel cell, the presence of inert, diluent gases in the fuel stream will reduce the fuel cell output voltage.

As the PEM fuel cell generally operates at temperatures below 100 °C, carbon monoxide adsorbs strongly on the platinum catalyst typically used in this fuel cell. For operation on hydrocarbon fuels, the fuel processor must produce a gas stream which limits the carbon monoxide content of the fuel stream to something below 100 ppm, depending upon the choice of the catalyst and operating conditions. This is
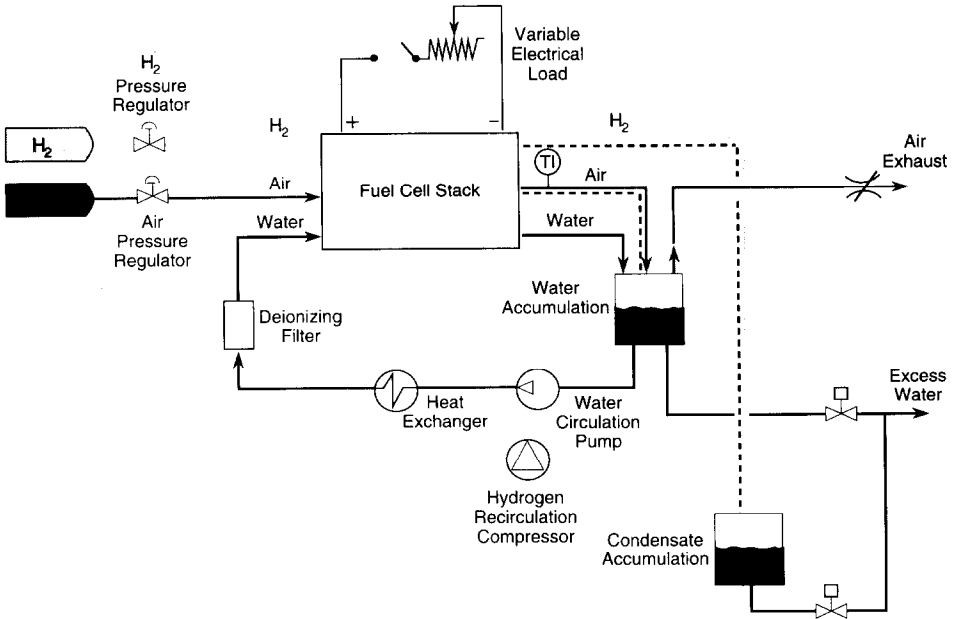
Fig. 1. Typical PEM fuel cell system design.

usually accomplished by the incorporation of a shift reactor and a selective oxidizer into the fuel processor. With these small, inexpensive units in the system, carbon monoxide levels well below 10 ppm can be maintained.

At Ballard and elsewhere, PEM fuel cells have demonstrated thousands of hours of stable operation on fuels derived from such hydrocarbon sources as methanol and pipeline natural gas.

Oxidant system

For those unusual applications in which pure oxygen is available, the oxidant system is analogous to the pure hydrogen system described above, consisting of a simple pressure regulator and, usually, a recirculation loop.

For most practical, commercial operations, the fuel cell will operate on air as the oxidant. The choice of air has many implications for fuel cell electrode and stack design, but the ultimate design choices will be dictated by the commercial realities of each particular application. Two distinct approaches are possible — the use of ambient air or operation at elevated pressures.

In principle, using ambient pressure air as the oxidant would seem to be desirable from the point of view of system simplicity. But fuel cell performance increases as oxidant pressure is increased. In general, then, the size and cost of the fuel cell stack necessary to provide a given power level increases as the operating pressure decreases.

The use of ambient air also complicates the heat and water management requirements for fuel cell operation. While dealing with these issues is relatively simple for small, low-power fuel cell stacks, it becomes more of a challenge for designing commercial power plants in the multi-kilowatt power range.

For many commercial applications, it may be desirable to supply the fuel cell with pressurized air, even though this means increasing the complexity of the air

delivery system. Typically, such a system will consist of a motor-driven compressor powered by the fuel cell in conjunction with a turbocompressor which recovers some of the energy available from the exhaust air stream. Such a system has been demonstrated on Ballard's fuel cell powered bus.

Ultimately, the decision on operating air pressure will be made on the basis of the balance between overall system efficiency, weight, and cost for a particular commercial application.

Water/heat management

The water/heat management system shown in Fig. 1 is typical of that for a fuel cell operating on pressurized air. Most of the product water from a PEM fuel cell is traditionally removed from the cathode, where it is produced, by excess flow of oxidant gas. Typically, the oxidant flow represents twice the stoichiometric amount of oxygen required by the fuel cell.

As the PEM fuel cell typically operates in the range of 70 to 90 °C, much of the product water condenses as it exits the fuel cell and can easily be collected in simple gravity collection devices. This avoids the condensers needed in phosphoric acid systems and dramatically simplifies the water management system. In some systems, it may be desirable to collect water from the anode exhaust as well.

In most systems, the pure product water is then used in the cooling system and to humidify the incoming fuel and oxidant gases. Humidification may be required to prevent dehydration of the electrolyte membrane, as discussed below. In the system represented in Fig. 1, product water is first passed through the active, power-generating section of the fuel cell stack to cool the stack and warm the water stream to the operating temperature of the stack. The warmed water is then exposed to the incoming fuel and oxidant streams, often after those gas streams have passed through manifolds adjacent to the active power-generating section of the fuel cell, warming the incoming gases. The incoming gases may be humidified in a direct contact humidifier or the water stream and gas streams may be separated by a water-transport membrane.

While the gas humidification process cools the water stream somewhat, a further heat exchange process is required to remove the remaining heat generated by the fuel cell. This is typically accomplished by a water/air heat exchanger, though in some applications, the excess heat could be used to provide space heating or residential hot water.

Fuel cell stack

As described above, the heart of the PEM fuel cell is the membrane/electrode assembly or MEA. This unit consists of the polymer electrolyte membrane, a layer of catalyst on each side of the electrolyte, and a gas-porous electrode support material. This electrode support material, typically porous carbon paper or cloth, provides physical strength and electrical contact to the catalyst layer while also providing a path for reactants to reach the catalyst and product water to be removed.

To enhance the strength of commercial electrode support materials and to control the tendency of water to condense in the interstices of these materials, they are typically treated with a hydrophobic material, such as a polytetrafluoroethylene emulsion, before use in the fuel cell.

The catalyst, which may consist of platinum black or platinum supported on carbon as well as other materials, may be coated on the membrane or on the electrode support. The catalyst layer usually includes a binder, such as polytetrafluoroethylene. A soluble form of the polymer electrolyte may also be infused into the catalyst layer to produce a more intimate contact between the catalyst and the electrolyte.

The membrane electrolyte and two electrode supports are usually bonded together to form an integrated unit. This is generally accomplished by heating the components under pressure to a temperature at which the electrolyte softens.

The nature of the membrane and the support structure provided by the electrode support allows the PEM fuel cell to sustain a significant pressure differential across the cell in operation. At Ballard, pressure differentials of at least 6 atm (90 psi) have been demonstrated. This ability of the PEM fuel cell to operate with the fuel and oxidant at different pressures is not shared by liquid electrolyte fuel cells, which often require complex and expensive systems to assure minimal pressure differential across the electrolyte. The ability to withstand a pressure across the electrolyte is one of the important features of the PEM fuel cell which allows simpler control systems and the flexibility of optimizing the operating pressure at each electrode to the requirements of the application.

In addition to the MEA, the fuel cell requires a structure to distribute the fuel and oxidant gases over the backs of the electrode support structures and to provide a path for the removal of the product water. This function is generally accomplished with separator or flow field plates. These plates are formed with grooves or channels in their surface. The remaining ridges make electrical contact with the electrode support while the channels provide paths for the reactant gases and the product water. The design of the flow channels can be critical to the effective operation of the fuel cell, particularly when operating on air. In commercial fuel cells, these separator plates are made of low-cost materials such as carbon or carbon composites. For military and aerospace applications, such materials as titanium have been used.

In a commercial fuel cell, a number of single cells must be combined in series to produce useful voltages. Such a combination is called a fuel cell stack. In most commercial fuel cell stacks, the separator plates are designed to be bipolar, with one side of the plate being the anode of one cell and the other side being the cathode of the adjacent cell. The series electrical connection between cells is made through the electrically conducting separator plate.

The separator plates are also often used in the stack-cooling system. Thus, some plates will have cooling water channels on one side to allow the removal of heat from the electrochemically active section of the fuel cell stack.

Because the electrolyte is confined, due to its solid nature, PEM fuel cell stacks are often designed with gas and liquid manifolds passing through the outer edges of the separator plates and sometimes through regions surrounded by the electrolyte. Figure 2 shows an example of a flow field plate designed for operation on air. The openings at the corners of the plate are manifolds for the dry gases, the humidified gases, the cooling and humidifying water.

Figure 3 presents the MEA corresponding to the separator plate shown in Fig. 2. In this design, the sealing materials necessary to isolate the gases and liquids from each other and from the external environment are built into the MEA.

A typical PEM fuel cell stack is shown in Fig. 4. This stack produces about 5 kW of power when supplied with hydrogen and air at 3 atm (30 psig). The stack is 25 cm × 25 cm × 46 cm in size and weighs 45 kg.

Current status

Prototype products/system demonstrations

The PEM fuel cell is rapidly approaching commercialization. Hundreds of the stacks illustrated in Fig. 4 have been manufactured by Ballard Power Systems. These
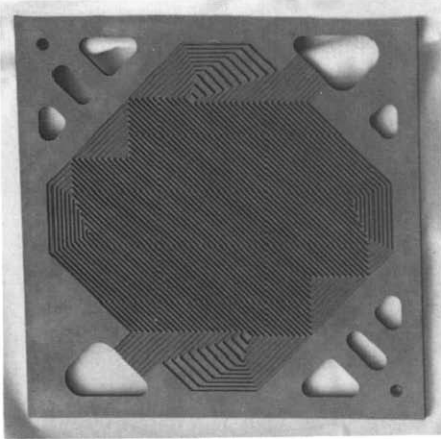
Fig. 2. Cathode flow field plate for Ballard MK 5 fuel cell. Openings in the corners are fluid manifolds for cell-to-cell gas and liquid transport.
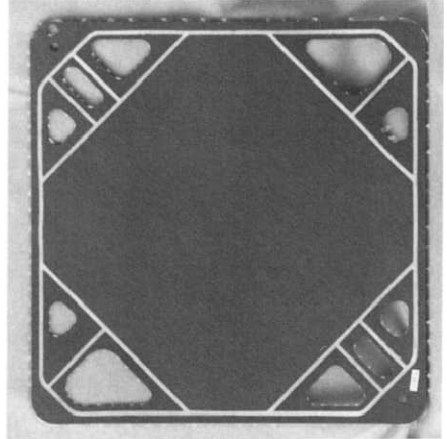
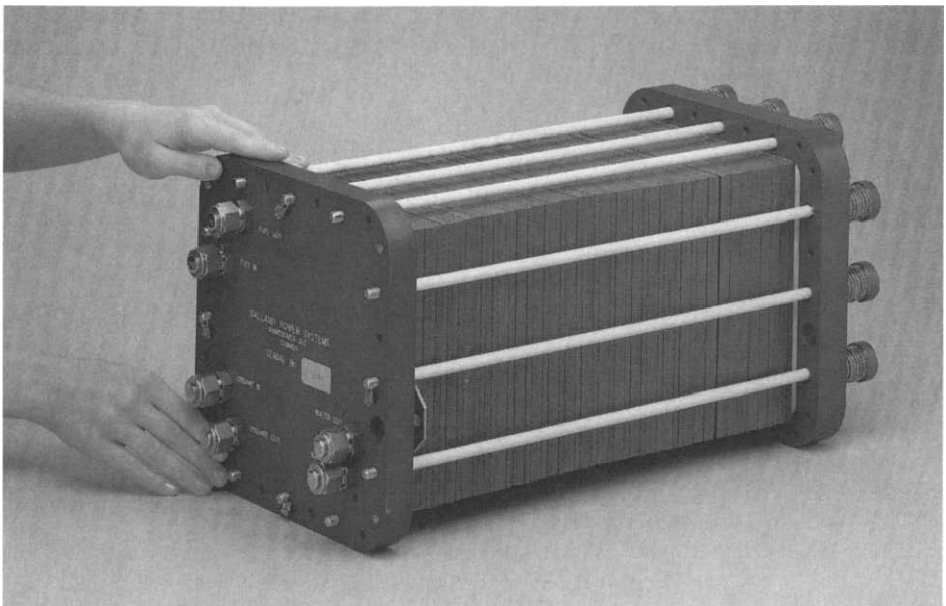Fig. 3. Membrane/electrode assembly for Ballard MK 5 fuel cell.

Fig. 4. Ballard MK 5 fuel cell stack.

stacks have been tested by organizations around the world and have also been used to power a fuel cell bus and a 35 kW stationary power plant demonstration unit. A commercial transit bus based upon PEM fuel cells is planned for 1998. In the same year, a commercial natural gas power plant will be available. Automobiles powered by PEM fuel cells are expected to be important early in the next decade.

In 1993, Ballard unveiled the first transit bus powered entirely by fuel cells [7]. The light duty transit bus, shown in Fig. 5, was chosen to demonstrate that even the

Fig. 5. Zero-emission fuel cell powered transit bus.

unoptimized stacks in Fig. 4 were sufficiently developed to provide full power for such a bus. The objective of the program was to demonstrate the same drive performance as the diesel equivalent.

The bus power plant consists of 24 of the 5 kW stacks arranged in a series-parallel string providing 120 kW of gross power. Air is supplied by a combination of a motor-driven automotive supercharger and a turbocharger driven by the air exhaust stream. The fuel is compressed hydrogen stored in transportation-approved natural gas cylinders under the bus frame.

This bus has now driven over 2000 km in Vancouver, in Los Angeles, and in Sacramento, California. As the fuel cell is fuelled with hydrogen, this bus produces absolutely no pollution. The only exhaust is moist air. In California, the zero-emission vehicle status of this bus was verified.

A program is now under way at Ballard to construct a full size transit bus also entirely powered by PEM fuel cells and operating on hydrogen fuel. This bus will be operational in 1995. The power plant for this bus will be based upon an improved stack, shown in the foreground of Fig. 6, which delivers twice the power of the earlier stack, shown in the background. The 250 kW bus power plant will fit into the same space as is presently allocated to the diesel engine on the equivalent diesel bus. Hydrogen, stored on the roof, will provide a range of over 400 km. The commercial bus, scheduled for introduction in 1998, will have a range of over 550 km.

In other PEM fuel cell motive demonstrations, Energy Partners has exhibited a battery/fuel cell powered automobile, the so-called 'Green Car' [8]. Mazda has shown a fuel cell powered golf cart [9], operating on the stack in Fig. 4.
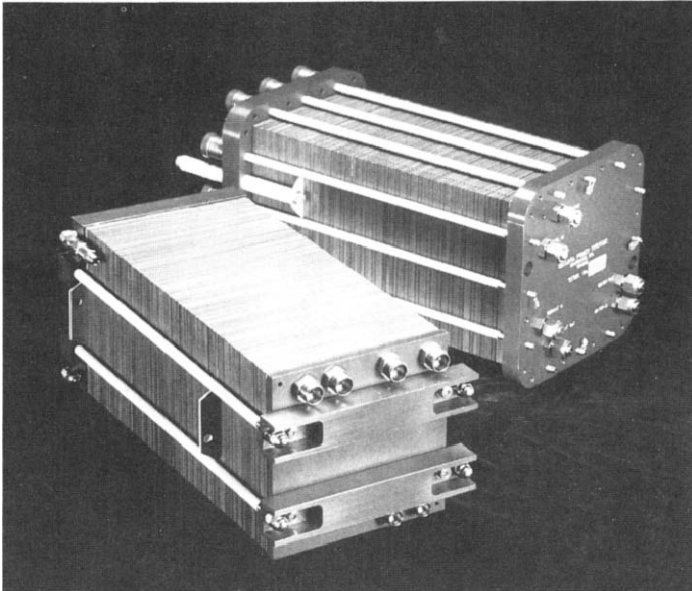
Fig. 6. Fuel cell stack improvements. Foreground: 10 kW Ballard series 510 stack; background: 5 kW Ballard MK 5 stack.

Daimler–Benz has recently demonstrated a Mercedes–Benz MB 180 van [10], shown in Fig. 7. This personal vehicle-size van is entirely powered by the first generation Ballard fuel cell stack shown in Fig. 4. Fuelled with gaseous hydrogen, the vehicle is totally non-polluting.

PEM fuel cells are also being developed for stationary utility applications. Ballard has just installed the 35 kW grid-connected power plant shown in Fig. 8 at a commercial site in Vancouver. This unit operates on by-product hydrogen from a nearby chlor-alkali plant.

In Japan, Mitsubishi Heavy Industries has demonstrated a 5 kW PEM fuel cell system operating on natural gas [6]. Dow Chemical Company and Ballard have recently announced an agreement [11, 12] to commercialize natural gas fuelled power plants based upon Ballard's and Dow's technology.

Fuel system

Several organizations are reported to be working on hydrocarbon fuel processors for PEM fuel cell systems. The work at Ballard [5], Los Alamos [13] under the General Motors/US Department of Energy (DOE) program, CJB Developments [14] and Mitsubishi [6] have been publicly acknowledged.

Ballard has demonstrated a load-following, methanol fuel processor [5]. PEM fuel cells have been successfully operated on fuel gas from the unit. The reformer system produces sufficient hydrogen for a 20 kW fuel cell. It includes a selective oxidizer which reduces carbon monoxide levels to below 30 ppm.

The Mitsubishi natural gas demonstration unit [6] appears to include a reformer and a palladium diffuser to provide purified hydrogen to the fuel cell. The Los Alamos methanol fuel processor has not been publicly described, but it is believed to include a reformer and a selective oxidizer.

Fig. 7. Daimler–Benz fuel cell powered Mercedes MB 180 van.

Ballard has also been working on a natural gas fuel processor under a program designed to demonstrate utility applications for PEM fuel cells. This fuel processor produces enough hydrogen-rich gas to support a 20 kW fuel cell. PEM fuel cells have operated reliably on the resulting fuel stream.

Water/heat management

Essentially all recent work on PEM fuel cells has been based upon acid electrolytes. In such systems, the product water formed as a result of the generation of power appears at the cathode. In addition to product water, some water will also be transported across the electrolyte membrane from the anode with the proton flux [15]. This electro-osmotic water transport has been shown to depend upon the nature of the polymer electrolyte and the water content of the membrane [15–20]. There may also be a tendency for water to diffuse from the cathode to the anode to some extent, depending upon the relative humidities of the anode and cathode gas streams [18, 21].

The objective in designing and operating a PEM fuel cell is that the membrane should not be dehydrated, as this increases ionic resistance and may ultimately lead to membrane failure. A parallel objective is to remove the water being formed at the cathode as effectively as possible to minimize flooding effects on cathode performance. Several papers have recently reported models for the transport of water in PEM fuel cells [16, 17, 21–27].

The accepted procedure for minimizing membrane dehydration has been to saturate the incoming fuel and oxidant gases with water at or above the stack-operating temperature. Water produced from the power generation process or condensed in the reactant gas streams is swept out by excess gas flow. Systems are designed to remove essentially all of the product water from the cathode gas stream.

While such an approach can be made to work well, with proper design of the gas flow fields and manifolds, it does require substantial flow of oxidant in excess of
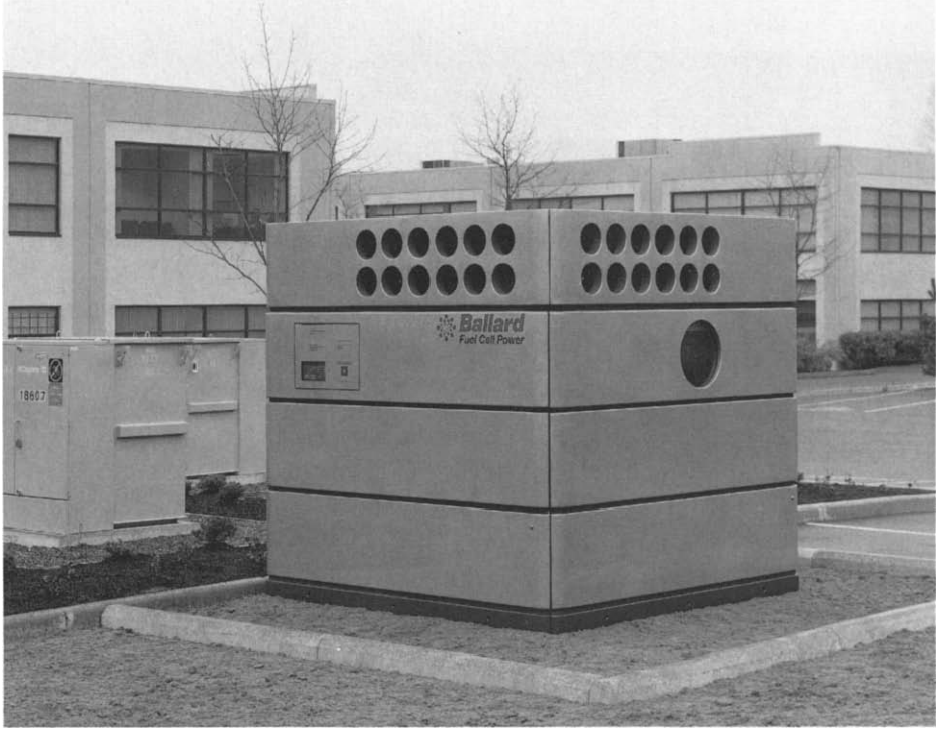
Fig. 8. PEM fuel cell stationary power plant, operating on by-product hydrogen and air; this unit produces 35 kW net grid quality a.c. power.

the stoichiometric amount in order to remove product water. This is disadvantageous when air is being used as the oxidant and energy must be used to compress the air.

Recently it has been shown that by proper adjustment of the pressure and/or temperature drop across a fuel cell, all product water can be removed from the anode side of the PEM fuel cell [28, 29]. In such a circumstance, it is found that the characteristic drop-off in voltage at high current, due to mass-transport limitations at the cathode, is eliminated. This approach results in higher peak power and improved stability at peak power [28, 29].

The choice of water removal and gas humidification techniques for a PEM fuel cell system will depend largely on the constraints placed upon the system by the application. There are a number of ways in which water balance can be maintained to provide good performance and long membrane life.

Fuel cell stack

The design of the fuel cell stack is determined in large part by the application and the constraints placed upon the stack by the remainder of the power plant system. In particular, the distinctly different requirements of a stationary/utility power plant and an automobile engine are driving stack development in two different directions. The utility power plant must be highly efficient and operate for as long as 40 000 h. Size and weight are of secondary concern. The stack cost must be in the range of US$ 500/kW.

In the automobile application, size, weight, and cost are of primary concern. The target cost for the fuel cell in this application is in the range of US$ 50/kW. The efficiency and lifetime requirements can be relaxed, however. For the automobile application, an operating lifetime of 4000 h is adequate.

To date, only Mitsubishi and Ballard have announced programs to develop PEM fuel cells for stationary applications. While Mitsubishi has exhibited a small natural gas system, little is known about the design of their stack.

Ballard has assembled a four-stack unit, shown in Fig. 9, as the basis of a 10 kW natural gas-fuelled demonstration unit. For the utility application, the stack is operated at 0.8 V/cell. The peak power from this stack, however, is over 40 kW. Stacks for a 250 kW power plant are being designed.

A number of programs are under way to develop PEM stack technology for motive applications. Siemens is developing a hydrogen/oxygen system for powering submarines [30]. The US Department of Energy (DOE) is funding a program [13], led by General Motors and including Ballard, to develop a PEM fuel cell car operating on reformed methanol as the on-board fuel. DOE also has announced a program to develop a hydrogen-fuelled, PEM fuel cell powered automobile [31].

Ballard and Daimler–Benz are working on a joint program to develop a lightweight PEM fuel cell power plant for an automobile while a number of Japanese and other European automakers are evaluating the technology in various programs. Other organizations, such as International Fuel Cells and Allied Signal, have stated their intention to develop PEM fuel cells for automotive applications, but little has been published about their programs.

The target of all of these automotive programs is the development of fuel cell stacks with higher power density, in the range of 500 to 1000 W/kg, which are manufacturable in quantity at low cost. While no results have been reported from these efforts to date, a recent patent by Ballard [32] indicates one of the directions being followed. In this patent, Ballard discloses a stack design in which flow fields are cut into the porous electrode structure, eliminating the need for the heavy gas flow field plates.

Most of the stack development activities for the automotive application assume that the operating pressure will be somewhat elevated, between 2 and 4 atm (15 to 45 psig). This elevated pressure increases the power density and reduces the cost of the stack, but requires the addition of a compressor.

Some groups, such as Lynntech, Inc. [33], BCS Technology Inc. [34], H Power Corporation [35], and Texas A&M University [35], are pursuing technology for fuel cell designs intended to operate at essentially ambient pressure. These designs generally incorporate passive water and thermal management as well, further reducing the complexity of the fuel cell system. H Power is now marketing small, ambient pressure fuel cell stacks for low power applications. It remains to be seen whether compact ambient pressure systems can be developed for multi-kilowatt applications.

While many of the automotive programs, presently under way, envision using methanol reformed on board of the vehicle as fuel, several groups are attempting to avoid the necessity of the reformer by developing PEM fuel cells which directly oxidize methanol at the anode. Significant progress has been reported recently [37], but, to date, the sustained current density available from 'direct methanol' fuel cells remains one to two orders of magnitude less than that obtained from hydrogen fuel cells. The two main issues appear to be poisoning of the anode catalyst by reaction intermediates and the crossover of methanol through the electrolyte membrane from the anode to the cathode.
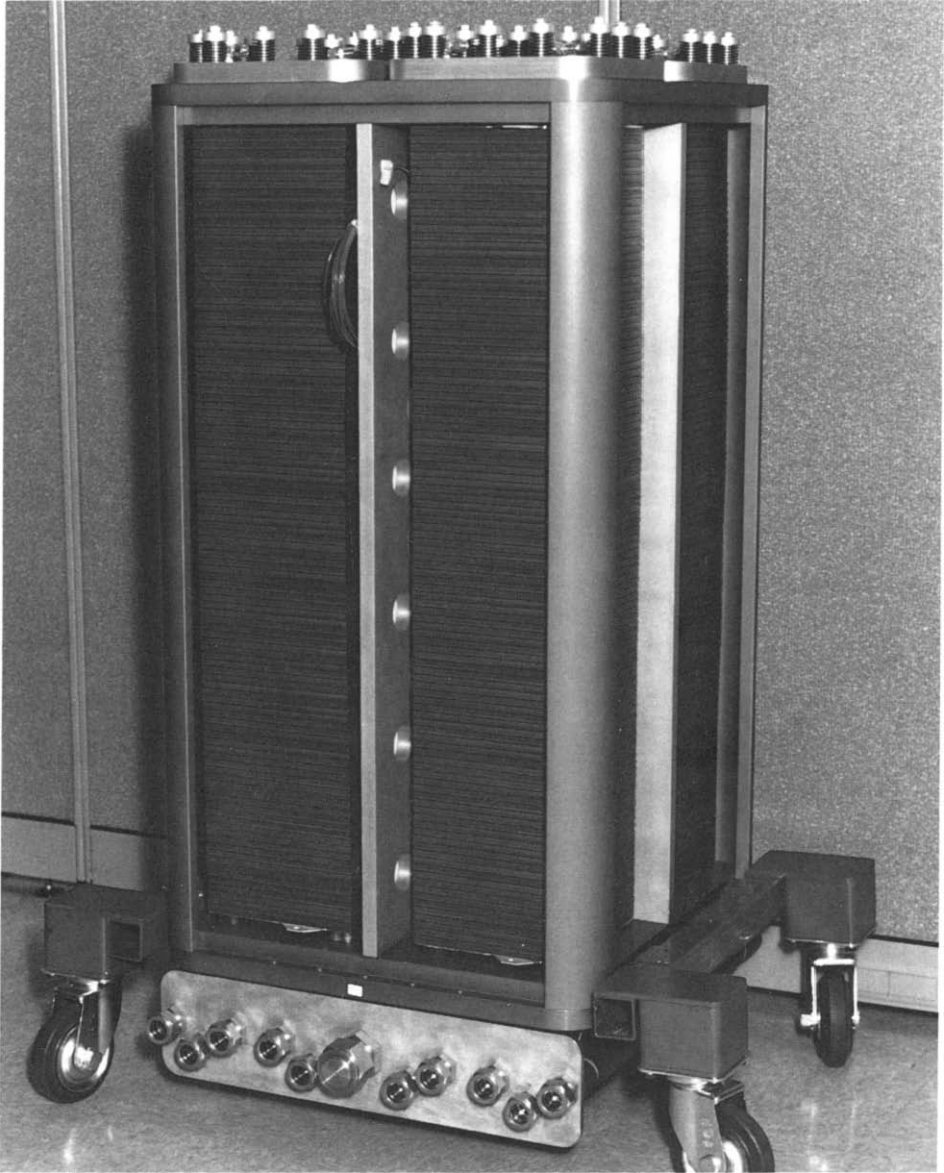
Fig. 9. PEM fuel cell stack for natural gas power plant.

Substantial progress has been made in reducing the cost of PEM fuel cells, largely by reducing the catalyst, membrane, and flow field costs. Several groups have demonstrated good performance from PEM fuel cells with substantially lower platinum loading [38–49] than the traditional 4 mg/cm^2. Baseline performance has been demonstrated by PSI Technology [41] on electrodes produced by electro-depositing the platinum at loadings as low as 0.05 mg/cm^2. Groups at Los Alamos National Laboratories [42, 43, 46–48] and Texas A&M University [39, 40, 45] have each shown excellent

performance at low catalyst loadings by incorporating soluble forms of the electrolyte membrane into the catalyst layer.

Membrane cost can be reduced by increasing the areal power density, reducing the areal cost, or both. The various membrane electrolyte suppliers (Dow, Dupont, Ashai Chemical, CEC, among others) are working to develop improved membrane electrolytes and to provide reliable, thinner materials. Up to a point, a thinner electrolyte provides improved power by reducing electrolyte resistance. Very thin membranes can be subject to unacceptable high gas transfer rates which lower performance. Thin membranes are also more difficult to use reliably in high volume manufacturing processes.

Most of the membrane electrolytes in present use are perfluorinated materials. These materials provide long life, but are costly to manufacture. Ballard Advanced Materials Corporation has recently developed a membrane material which is not perfluorinated [50]. The objective of this program is to obtain electrochemical performance equivalent to the perfluorinated materials in a lower cost membrane, while possibly sacrificing some lifetime. To date, the Ballard membrane has demonstrated excellent performance for over 4000 h [50], more than sufficient for the automotive application.

The Ballard fuel cell stacks shown in Fig. 6 include gas flow field plates machined from non-porous carbon plate blanks. Both the material and the machining process are too expensive for a commercial product. Two alternative approaches have been identified by various manufacturers to substantially reduce flow field plate cost. International Fuel Cells [51] holds a patent covering moulded graphite–fluoropolymer composite flow fields. Others are reportedly working with thin metal flow fields.

Technical challenges

The remaining technical challenges to be overcome before the large-scale commercialization of PEM fuel cell technology is possible are: (i) the reduction of component cost; (ii) the development of stack designs and manufacturing processes for economic, high volume production; (iii) the demonstration of the required lifetimes in manufactured products, and (iv) the development of economical, efficient fuel cell systems incorporating PEM stacks.

Substantial progress has been made in the laboratory in reducing catalyst loading. These advances must now be converted into useful, high-volume production techniques and the required product lifetimes demonstrated for mass-produced fuel cells. Further improvement in catalyst technology, such as better tolerance to carbon monoxide and other poisons, improved oxygen reduction performance, or the development of improved catalysts for direct hydrocarbon oxidation would be desirable, but are not mandatory for the commercialization of PEM fuel cells.

A reduction in membrane electrolyte cost is desirable to meet the stationary/utility market cost targets and absolutely necessary to penetrate the automotive market. These cost reductions can be achieved through the development of lower cost and/or higher performance materials as well as through the reductions in cost expected with higher volumes and increased competition.

Fuel cell stacks and components must now be designed for low-cost, high-volume manufacture. Fortunately, the nature of the polymer membrane electrolyte and the porous electrode structures lend themselves to mass production. But mass production and the resulting lower costs will only be achieved with proper design of the fuel cell.

Fuel cell design also contributes significantly to operating lifetime. The design of sealing structures and the selection of sealing materials may be as important as the selection and handling of catalyst and membrane electrolytes in achieving adequate lifetimes in cost-effective fuel cells.

Finally, and perhaps most important, appropriate fuel cell systems must be developed for each application. Unless the systems are well designed and manufactured cost effectively, the benefits inherent in the PEM fuel cell will not be translated into a desirable product. In this regard, improvements in air-delivery systems, fuel processing and storage techniques and power conditioning and control systems will be necessary, particularly for the automotive application.

Commercial impact

Over the past decade, there has been growing recognition that mankind cannot continue to ignore the impact our use of energy has on the environment. This has led to a number of initiatives around the world to reduce the pollution associated with the generation and use of energy. Fuel cells are seen by many as a very important component in the future energy systems because of their inherent efficiency and low environmental impact.

Two major markets are seen for fuel cells — engines for vehicles and power plants for stationary electrical requirements. The vehicle market is being driven almost entirely by environmental concerns. The stationary power market is being driven by economic as well as environmental issues.

In the USA, these concerns have led to the enactment of two major laws. The Clean Air Act Amendment of 1990 reduced the volume of the allowable emissions of pollutants and imposed strict regulation on pollution sources. The Energy Policy Act of 1992 set energy efficiency standards for industrial equipment and specifically calls for DOE programs to develop fuel cells.

The state of California has taken the lead in environmental regulation. It has imposed a requirement that beginning in 1998 a growing fraction of automobiles sold in California must be totally non-polluting. The emissions of the remaining fleet must also be progressively reduced. In spite of resistance from the North American automobile manufacturers, the Ozone Transport Commission, consisting of representatives of 12 northeastern states recently voted to request the US Environmental Protection Agency to mandate rules similar to the California regulations for the entire northeastern region.

While the nature and timing of environmental regulations may be subject to modification, there is little doubt that increasingly stringent regulations will be put in force and that this need for transportation power will lead to the introduction of more efficient, less-polluting vehicle engines. The fuel cell, and specifically the PEM fuel cell, appears to the only likely candidate for such a power plant.

The growing demand for efficient, non-polluting sources of utility electric power and the growing perception that siting power generation near the user is desirable from economic and reliability points of view has led to the creation of a number of programs designed to develop and commercialize fuel cell power plants for stationary applications.

While several fuel cell types are being developed for these applications, the PEM fuel cell appears to have significant advantages for the relatively small power plants, in the range of a few kilowatts to a few megawatts, which might be sited near the

user. The advantages of small size, simplicity, rapid start-up and quick response to changing load characteristics of the PEM fuel cell are particularly desirable in these applications.

Significantly, the PEM fuel cell is likely to be the only fuel cell type which can expect significant markets in both transportation and stationary markets. The synergy of the two markets and the cost reductions which will arise due to the large volume of manufacture expected for both applications will allow the PEM fuel cell to compete with existing technologies more quickly than would be the case if only one market were available.

Summary

The PEM fuel cell is poised for early commercial introduction in both transportation and stationary markets. Substantial progress has been made in fuel cell design and cost reduction. Additional developments are required in low-cost manufacturing and systems engineering.

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