FUEL CELLS

Fuel cells are electrochemical devices that convert the chemical energy of a fuel directly into electrical and thermal energy. In a typical fuel cell, gaseous fuels are fed continuously to the anode (negative electrode) compartment, and an oxidant, eg, oxygen or air, is fed continuously to the cathode (positive electrode) compartment. The electrochemical reactions take place at the electrodes to produce an electric (direct) current. The fuel cell theoretically has the capability of producing electrical energy for as long as the fuel and oxidant are fed to the electrodes. In reality, degradation or malfunction of components limits the practical operating life of fuel cells.

Besides the direct production of electricity, heat is also produced in fuel cells. This heat can be effectively utilized for the generation of additional electricity or for other purposes, depending on the temperature. A practical consideration for fuel cells is compatibility with the available fuels and oxidants. As of this writing the electrochemical reactions involving hydrogen and oxygen (or air) are the only practical ones. The oxygen (qv) is usually derived from air. Hydrogen (qv) is available from several fuel sources, eg, steam-reformed fossil fuels (see COAL; PETROLEUM), coal gasification (see COAL CONVERSION PROCESSES), steam-reformed methanol (qv), etc (see FUELS, SYNTHETIC–GASEOUS FUELS). Very little practical success has been achieved using the direct electrochemical oxidation of hydrocarbon-based liquids or gases in fuel cells operating at 200°C or lower.

General Characteristics

One of the main attractive features of fuel cell systems is the expected high fuel-to-electricity efficiency. This efficiency, which runs from 40–60% based on the lower heating value (LHV) of the fuel, is higher than that of almost all other energy conversion systems (see POWER GENERATION). In addition, high temperature fuel cells produce high grade heat which is available for cogeneration applications. Because fuel cells operate at near constant efficiency, independent of size, small fuel cells operate nearly as efficiently as large ones. Thus fuel cell power plants can be configured in a wide range of electrical levels from watts to megawatts. Fuel cells are quiet and operate with virtually no noxious emissions, but they are sensitive to certain fuel contaminants, eg, CO, H_2S, NH_3, and halides, depending on the type of fuel cell. These contaminants must be minimized in the fuel gas. The two primary impediments to the widespread use of fuel cells are high initial cost and short operational lifetime. These two aspects are the focus of research.

Types of Fuel Cells

A variety of fuel cells has been developed for terrestrial and space applications. Fuel cells are usually classified according to the type of electrolyte used in the cells as polymer electrolyte fuel cell (PEFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), and solid oxide fuel cell (SOFC). These fuel cells are listed in Table 1 in the approximate order of increasing operating temperature, ranging from ~80°C for PEFCs to ~1000°C for SOFCs. The physicochemical and thermomechanical properties of materials used for the cell components, ie, electrodes, electrolyte, bipolar separator, current collector, etc, determine the practical operating temperature and useful life of the cells. The properties of the electrolyte are especially important. Solid polymer and aqueous electrolytes are limited to temperatures of ca 200°C or lower because of high water-vapor pressure and/or rapid degradation at higher temperatures. The operating temperature of high temperature fuel cells is determined by the melting point (MCFC) or ionic-conductivity requirements (SOFC) of the electrolyte. The operating temperature dictates the type of fuel that can be utilized.

Table 1. Fuel Cell Components and Operating Conditions[a,b]

Characteristic	PEFC	AFC[c]	AFC[d]	PAFC	MCFC	SOFC[e]
anode	Pt black or Pt/C	80% Pt-20% Pd	Ni	Pt/C	Ni–10% Cr	Ni–ZrO_2 cermet
cathode	Pt black or Pt/C	90% Au–10% Pt	Li-doped NiO	Pt/C	Li-doped NiO	Sr-doped $LaMnO_3$
pressure, MPa[f]	0.1–0.5	0.4	~0.4	0.1–1	0.1–1	0.1
temperature, °C	80	80–90	260	200	650	1000
electrolyte, wt %	Nafion[g]	35–45% KOH	85% KOH	100% H_3PO_4	62% Li_2CO_3–38% $K_2 2CO_3$[h]	yttria-stabilized ZrO_2

[a] AFC = alkaline fuel cell; MCFC = molten carbonate fuel cell; PAFC = phosphoric acid fuel cell; PEFC = polymer electrolyte fuel cell; and SOFC = solid oxide fuel cell.

[b] All cells are bipolar having a filter-press or flat-plate construction, except where otherwise indicated.

[c] Used in the space shuttle *Orbiter*.

[d] Used in the *Apollo* program.

[e] Tubular cells.

[f] To convert MPa to psi, multiply by 145.

[g] Fluorinated sulfonic acid, registered trademark of E. I. du Pont de Nemours & Co., Inc.

[h] In mol %.

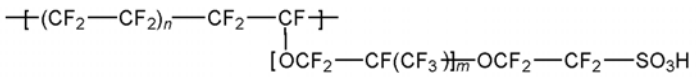
The low temperature fuel cells utilizing aqueous electrolytes are, in most practical applications, restricted to hydrogen as the fuel. The presence of carbon monoxide (qv) and sulfur-containing gases are detrimental to fuel cell performance because these poison the anode in low temperature fuel cells. In high temperature fuel cells, the list of usable fuels is more extensive for two reasons: the inherently rapid electrode kinetics and the lessened need for high electrocatalytic activity at high temperature. In addition, there are options for hydrocarbon fuels which can be utilized either directly or indirectly (see HYDROCARBONS).

In low temperature fuel cells, ie, AFC, PAFC, PEFC, protons or hydroxyl ions are the principal charge carriers in the electrolyte, whereas in the high temperature fuel cells, ie, MCFC, SOFC, carbonate and oxide ions are the charge carriers in the molten carbonate and solid oxide electrolytes, respectively. Fuel cells that use zirconia-based solid oxide electrolytes must operate at about 1000°C because the transport rate of oxygen ions in the solid oxide is adequate for practical applications only at such high temperatures. Another option is to use extremely thin solid oxide electrolytes to minimize the ohmic losses.

Polymer Electrolyte Fuel Cell. The electrolyte in a PEFC is an ion-exchange (qv) membrane, a fluorinated sulfonic acid polymer, which is a proton conductor (see MEMBRANE TECHNOLOGY). The only liquid present in this fuel cell is the product water; thus corrosion problems are minimal. Water management in the membrane is critical for efficient performance. The fuel cell must operate under conditions where the by-product water does not evaporate faster than it is produced because the membrane must be hydrated to maintain acceptable proton conductivity. Because of the limitation on the operating temperature, usually less than 120°C, H_2-rich gas having little or no (<a few ppm) CO is used, and higher Pt loadings than those used in PAFCs are usually required in both the anode and cathode.

The advantages of PEFCs are no free corrosive liquid in the cell, simple fabrication of the cell, ability to withstand large pressure differentials, materials corrosion problems are minimal, and demonstrated long life, ie, membrane life exceeds 100,000 h. On the other hand, the disadvantages of PEFCs are that the fluorinated polymer electrolyte is traditionally expensive, water management in the membrane is critical for efficient operation, and long-term high performance with low catalyst loadings in the electrodes needs to be demonstrated.

The use of organic cation-exchange membrane polymers in fuel cells was conceived in the 1950s. The early membranes tested in PEFCs include the hydrocarbon-type polymers such as cross-linked polystyrene–divinylbenzene–sulfonic acids and sulfonated phenol–formaldehyde. The U.S. Gemini Space Program in the 1960s used a fuel cell module which had the dimensions: 31.7-cm diameter, 63.5-cm high, 30 kg, 1 kW at 23.3–26.5 V; the cell operated at 37 mA/cm^2 at 0.78 V on pure H_2 and O_2 at 138–207 kPa (20–30 psi) and ~35°C. Membranes were polystyrene–divinylbenzene–sulfonic acid cross-linked within an inert fluorocarbon film. The life of PEFCs was limited by oxidative degradation of the polymer electrolyte. When these polystyrenes were replaced with fluorine-substituted polystyrenes, eg, polytrifluorostyrene sulfonic acid, the life of PEFCs was extended by four to five times. However, the operating temperature of PEFCs using fluorinated polystyrenes was limited to less than 75°C. The development of Nafion (Du Pont), ie, perfluorocarbon sulfonate sulfonic acid, membranes yielded electrochemical stability in PEFCs at temperatures up to about 100°C. This polymer consists of the ionomer units shown where $n = 6–10$ and $m \geq 1$.



Nafion and its derivatives all have two features in common. The polymer chains consist mainly of a poly(tetrafluoroethylene) (PTFE) backbone, which statistically forms segments several units in length, and perfluorinated vinyl polyether, a few ether links long. The latter joins the PTFE segments to form a flexible branch pendent to the main perfluoro-chain and carries a terminal acidic group to provide the cation-exchange capacity. These perfluorinated ionomer membranes with sulfonic acid groups meet all the required characteristics of ion-exchange membranes for use in fuel cells, as well as for use in H_2O and alkali hydroxide electrolysis cells. Nafion, first used in fuel cells in 1966, is the most widely used ion-exchange membrane in PEFCs (see also ALKALI AND CHLORINE PRODUCTS; ELECTROCHEMICAL PROCESSING).

The Nafion membranes, fully fluorinated polymers, exhibit exceptionally high chemical stability in strong bases in strong oxidizing and reducing acids, H_2O_2, Cl_2, H_2, and O_2 at temperatures up to 125°C. A high degree of dissociation and a high (>4 molal) concentration of mobile H^+ ions ensure good ionic conductivity in Nafion. A conductivity of >0.05(ohm·cm)$^{-1}$ at 25°C is considered to be acceptable for use in fuel cells. A review on the conductivity properties of Nafion is available (1). The range of equivalent weights for Nafion that is of greatest interest in PEFCs is 1100 to 1350. This provides a highly acidic environment, ie, comparable to a 10 wt % H_2SO_4 solution, in a hydrated membrane.

The porous electrodes in PEFCs are bonded to the surface of the ion-exchange membranes which are 0.12- to 0.25-mm thick by pressure and at a temperature usually between the glass-transition temperature and the thermal degradation temperature of the membrane. These conditions provide the necessary environment to produce an intimate contact between the electrocatalyst and the membrane surface. The early PEFCs contained Nafion membranes and about 4 mg/cm^2 of Pt black in both the cathode and anode. Such electrode/membrane combinations, using the appropriate current collectors and supporting structure in PEFCs and water electrolysis cells, are capable of operating at pressures up to 20.7 MPa (3000 psi), differential pressures up to 3.5 MPa (500 psi), and current densities of 2000 mA/cm^2.

Very substantial advances have been made in terms of improvements in electrode structures and increases in the Pt utilization as illustrated in Figure 1. It appears that Pt loadings of less than 0.2 mg Pt/cm^2 are adequate to obtain acceptable performance in PEFCs using pure H_2 as the fuel (see THIN FILMS). Whereas early electrodes contained 4 mg Pt/cm^2, the most recent developments in electrode fabrication have permitted Pt loadings to be reduced to 0.13 mg Pt/cm^2 in a thin-film structure, while maintaining high performance.

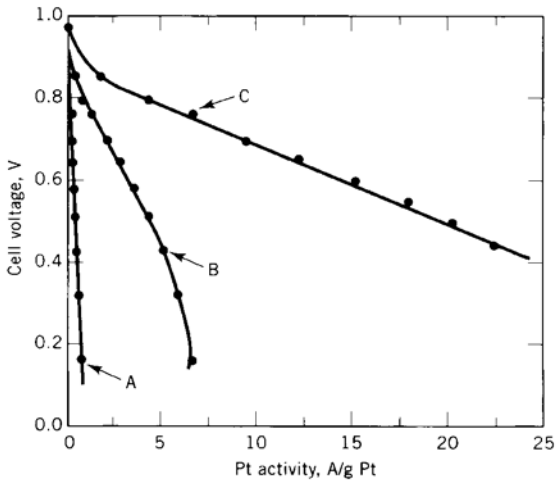


Fig. 1. Increase in Pt utilization in PEFCs, where A represents the GE space technology fuel cell, 4 mg Pt/cm^2; B represents Prototech, 0.45 mg Pt/cm^2; and C represents thin film, 0.13 mg Pt/cm^2 (2).

In a H_2/O_2 PEFC, H_2 is oxidized at the anode to H^+ ions, which are transported through the membrane to the cathode. During operation of the fuel cell, water is transported through the Nafion membrane with the H^+ ions because of the electroosmotic effect. At 100°C, 3.5 to 4 H_2O molecules are transported with each H^+ ion (3). The transport of water through the membrane presents a water-management problem. There is a tendency for the anode side to dehydrate, resulting in a reduction in ionic conductivity and a decrease in the power output from the cell. One solution to this problem is to humidify the fuel gas entering the cell, but the addition of too much H_2O can be detrimental because it may form a liquid film on the electrocatalyst which interferes with the transport of H_2 to the electrocatalyst. At the cathode H_2O is produced which must be rapidly removed to avoid flooding of the electrode.

As of this writing, the primary focus of research and development in PEFC technology is a fuel-cell system for terrestrial transportation applications requiring the development of low cost cell components. Reformed methanol is expected to be a principal fuel source for PEFCs in transportation applications. Because the operating temperature of PEFCs is much lower than that of PAFCs (see Table 1), poisoning of the anode electrocatalyst by CO from steam-reformed methanol is a problem.

A newer series of perfluorinated ionomers (qv), developed by Dow Chemical Co., provides an attractive alternative to Nafion in PEFCs (4,5). This newer polymer has a PTFE-like backbone similar to those of Nafion, but the pendent side chain containing the sulfonic acid group is shorter. Instead of the long side chain of Nafion, the side chain of the Dow polymer consists of $OCF_2–CF_2–SO_3H$. This polymer possesses ion-exchange properties similar to that of Nafion, and it is also available with higher acid strength and lower equivalent weights, ie, 600–950. Even at these low equivalent weights the Dow membrane has good mechanical strength and does not hydrate excessively, whereas Nafion of comparable equivalent weight would form a highly gelled polymer, having poor or no mechanical integrity. The physical and transport properties of ion-exchange membranes are largely determined by the amount of absorbed H_2O. For a given equivalent weight, the Dow polymer absorbs less water (~50%) than Nafion, but it has comparable ionic conductivity and lower permeability. This polymer has a higher glass transition temperature (165 vs 110°C for Nafion); thus PEFCs containing this material should be capable of operating at temperatures above 100°C where poisoning of the electrocatalyst by CO is less problematic and electrode kinetics are more rapid.

Alkaline Fuel Cell. The electrolyte in the alkaline fuel cell is concentrated (85 wt %) KOH in fuel cells that operate at high (~250°C) temperature, or less concentrated (35–50 wt %) KOH for lower (<120°C) temperature operation. The electrolyte is retained in a matrix of asbestos (qv) or other metal oxide, and a wide range of electrocatalysts can be used, eg, Ni, Ag, metal oxides, spinels, and noble metals. Oxygen reduction kinetics are more rapid in alkaline electrolytes than in acid electrolytes, and the use of non-noble metal electrocatalysts in AFCs is feasible. However, a significant disadvantage of AFCs is that alkaline electrolytes, ie, NaOH, KOH, do not reject CO_2. Consequently, as of this writing, AFCs are restricted to specialized applications where CO_2-free H_2 and O_2 are utilized.

The most successful application of AFC technology was in the U.S. space programs, ie, *Apollo* and the Space Shuttle. The AFC used in the U.S. *Apollo* space program was based on technology originally developed in the 1930s (6). This original fuel cell operated at 200 to 240°C, 45 wt % KOH, and pressure maintained at 4 to 5.6 MPa (580–810 psi) to prevent the electrolyte from boiling. The anode consisted of a dual-porosity Ni electrode, ie, a two-layer structure having porous Ni of 16-μm maximum pore diameter on the electrolyte side and 30-μm pore diameter on the gas side. The cathode consisted of a similar dual-layer porous structure of lithiated NiO. The three-phase boundary in the porous electrodes was maintained by a differential gas pressure across the electrode because at that time a wetproofing agent was not available.

The AFC fuel-cell module for the U.S. *Apollo* space program (57-cm diameter, 112-cm high, ~110 kg, 1.42 kW at 27–31 V, 0.6-kW average power) utilized pure H_2 and O_2 and concentrated electrolyte (85 wt % KOH) to permit cell operation at lower (ca 400 kPa (58 psi) reactant gas pressure) pressure without electrolyte boiling. Using this concentrated electrolyte, cell performance is not as high as in the less concentrated electrolyte; thus the operating temperature was increased to 260°C. The typical performance of this AFC was 0.85 V at 150 mA/cm^2, which compared favorably to the performance of the original cell operating at about 10 times higher pressure.

The alkaline fuel cells in the space shuttle *Orbiter* (fuel-cell module: 35-cm high, 38-cm wide, 101-cm long, 91 kg, 12 kW at 27.5 V, 7-kW

average power) operate in the same pressure range as for the *Apollo* program but at a lower (80 to 90°C) temperature and a higher (470 mA/cm^2 at 0.86 V) current density. The electrodes contain high loadings of noble metals (anode: 10 mg of 80% Pt–20% Pd/cm^2 on a Ag-plated Ni screen, cathode: 20 mg of 90% Au–10% Pt/cm^2 on a Ag-plated Ni screen) that are bonded with PTFE to achieve high performance at lower temperatures. A wide variety of materials (eg, potassium titanate, ceria, asbestos, zirconium phosphate gel) have been used to retain the alkaline solution in the microporous electrolyte separators for AFCs. A brief survey of the advanced-technology components in AFCs for space applications is available (7).

Phosphoric Acid Fuel Cell. Concentrated phosphoric acid is used for the electrolyte in PAFC, which operates at 150 to 220°C. At lower temperatures, phosphoric acid is a poor ionic conductor (see PHOSPHORIC ACID AND THE PHOSPHATES), and CO poisoning of the Pt electrocatalyst in the anode becomes more severe when steam-reformed hydrocarbons (qv) are used as the hydrogen-rich fuel. The relative stability of concentrated phosphoric acid is high compared to other common inorganic acids; consequently, the PAFC is capable of operating at elevated temperatures. In addition, the use of concentrated (~100%) acid minimizes the water-vapor pressure so water management in the cell is not difficult. The porous matrix used to retain the acid is usually silicon carbide SiC, and the electrocatalyst in both the anode and cathode is mainly Pt.

In the mid-1960s, the conventional porous electrodes were PTFE-bonded Pt black, and the loadings were about 9 mg Pt/cm^2. As of the early 1990s, Pt supported on carbon black has replaced Pt black in porous PTFE-bonded electrode structures as the electrocatalyst. A dramatic reduction in Pt loading has also occurred. Platinum loadings are about 0.25 mg/cm^2 in the anode and about 0.50 mg/cm^2 in the cathode, although at both electrodes, Pt may be combined with other metals. The operating temperature, and correspondingly the acid concentration, of PAFCs has increased to achieve higher cell performance. Temperatures of about 200°C and acid concentrations of 100% H_3PO_4 are commonly used. In addition, the operating pressure of PAFCs has surpassed 0.5 MPa (70 psi) in many tests, and commercial electric utility systems are planned to operate at ~0.8 MPa (115 psi).

Molten Carbonate Fuel Cell. The electrolyte in the MCFC is usually a combination of alkali (Li, Na, K) carbonates retained in a ceramic matrix of $LiAlO_2$ particles. The fuel cell operates at 600 to 700°C where the alkali carbonates form a highly conductive molten salt and carbonate ions provide ionic conduction. At the operating temperatures in MCFCs, Ni-based materials containing chromium (anode) and nickel oxide (cathode) can function as electrode materials, and noble metals are not required.

In MCFCs there are no materials that can serve to wet-proof a porous structure against ingress by molten carbonates. Consequently, the technology to obtain a stable three-phase interface in MCFC porous electrodes is different from that of PAFCs. In the MCFC, the stable interface in the electrodes is achieved by carefully tailoring the pore structures of the electrodes and the electrolyte matrix ($LiAlO_2$) so that the capillary forces establish a dynamic equilibrium in the different porous structures to prevent the electrodes from flooding with electrolyte, particularly the cathode. On the other hand, the anode is relatively insensitive to the degree of filling by the electrolyte.

In a conventional fuel cell system, a carbonaceous fuel is fed to a fuel processor where it is steam-reformed to produce H_2 as well as such other products as CO, CO_2, and H_2O. The hydrogen (qv) is then introduced into the fuel cell and electrochemically oxidized. Efforts are underway to develop a fuel-cell system that eliminates the need for a separate fuel processor by providing for the reforming of carbonaceous fuels in the fuel cell, ie, internal reforming, and near the electrochemically active sites. This technique appears practical in high temperature fuel cells such as MCFCs where stream-reforming of hydrocarbons to produce hydrogen can be sustained using catalysts at the cell operating temperatures. By integrating the reforming reaction and the electrochemical oxidation reaction of hydrogen in the fuel cell, the internal-reforming MCFC (IRMCFC), as illustrated schematically in Figure 2, is realized. The IRMCFC eliminates the need for the external fuel processor and its ancillary equipment, and provides a highly efficient, simple, reliable, and potentially cost-effective alternative to the conventional MCFC system.

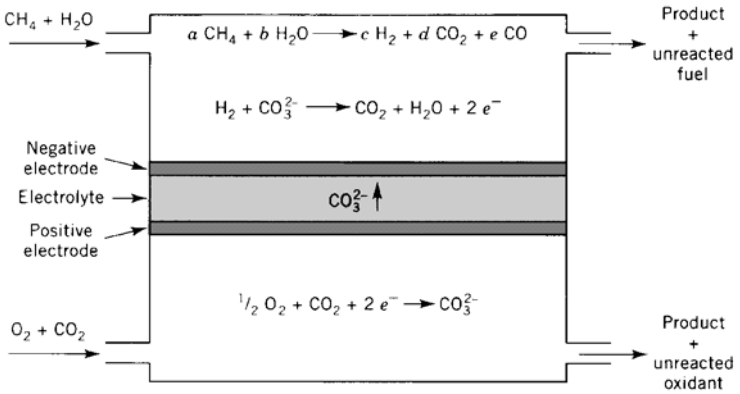


Fig. 2. Internal reforming in MCFCs.

Steam reforming of CH_4 is commonly carried out at 750 to 900°C, thus at the lower operating temperature of MCFCs a high activity catalyst is required. The internal reforming of methane in IRMCFCs, where the steam-reforming reaction

$$CH_4 + H_2O \rightarrow CO + 3\,H_2 \quad (1)$$

occurs simultaneously with the electrochemical oxidation of hydrogen in the anode compartment, has been demonstrated. The steam-reforming reaction is endothermic, whereas the overall fuel cell reaction is exothermic. In an IRMCFC, the heat required for reaction 1 is supplied by the waste heat from the fuel cell reaction eliminating the need for an external heat exchanger, required by a conventional fuel processor. In addition, the

product steam produced during the oxidation of hydrogen can be used to drive the reforming reaction and the water gas shift reaction to produce additional H_2. The forward direction of reaction 1 is favored by high temperature and low pressure, thus an IRMCFC is best suited to operate near atmospheric pressure. A supported Ni catalyst, eg, Ni supported on MgO or $LiAlO_2$, provides sufficient catalytic activity to sustain the steam-reforming reaction at 650°C to produce H_2 at the necessary rate.

Two manifold concepts have been developed to direct the reactant fuel and oxidant gases to the MCFC stack and to remove the exhaust gases. These are illustrated schematically in Figure 3, and are referred to as internally and externally manifolded stacks. The external manifold (Fig. 3**b**) is commonly used in fuel cell stacks formed by repeated stacking of thin flat-plate cells. The reactant fuel and oxidant gases are directed into and out of the stack by using a manifold that is connected to the sides of the thin cells, and cross flow of the two gases is the common flow pattern. On the other hand, the gases used in the internally manifolded stack (Fig. 3**a**) are directed into and out of the stack through openings that are formed in the stack components, and not through an external manifold. The gas flow patterns with the internally manifolded stack are more complex, and examples involving both cross flow and parallel flow have been described (8). The advantage of an internal manifold is that electrolyte migration along the length of the stack does not occur because the stack has no porous manifold gaskets in contact with the electrolyte. Furthermore this design permits easy stack assembly and scale-up without the need for a heavy external manifold. On the other hand, stacks having internal manifolds have a more complicated design, and fabrication of components is more complex.

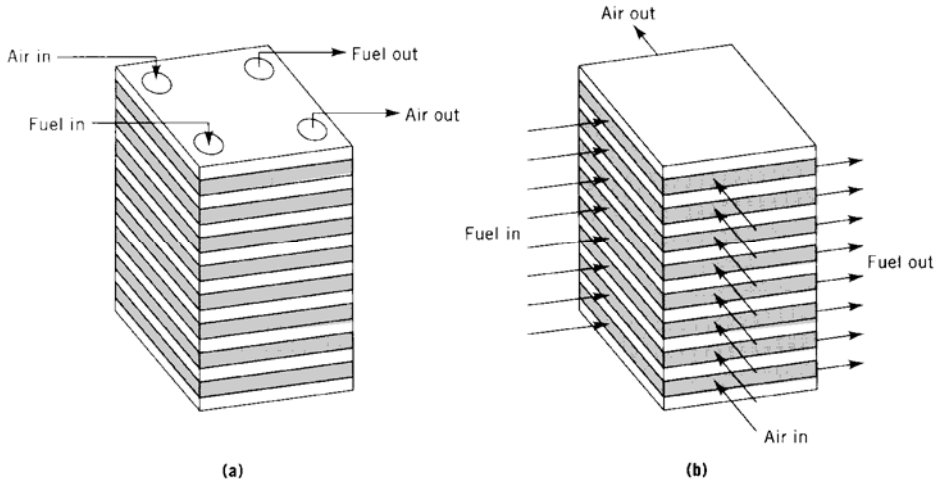


Fig. 3. Schematics of gas manifolds for MCFC stacks: (**a**) internally manifolded fuel cell stack; (**b**) externally manifolded fuel cell stack.

Solid Oxide Fuel Cell. In a SOFC, there is no liquid electrolyte present that is susceptible to movement in the porous electrode structure, and electrode flooding is not a problem. Consequently, the three-phase interface that is necessary for efficient electrochemical reaction involves two solid phases (solid electrolyte/electrode) and a gas phase. A critical requirement of the porous electrodes for the SOFC is that they are sufficiently thin and porous to provide an extensive electrode/electrolyte interfacial region for electrochemical reaction. Because of the high (typically 1000°C) operating temperatures of SOFCs, the materials used in the cell components are limited by chemical stability in oxidizing and/or reducing environments, chemical stability of contacting materials, acceptable conductivity, and thermomechanical compatibility. The principal effort to date has been on demonstrating the viability of a tubular structure (Fig. 4) in SOFCs. The tubular design uses a porous ceramic support tube of about 100-cm length and 1.27-cm diameter. However, more recently the development of planar electrolyte structures has received considerable attention.

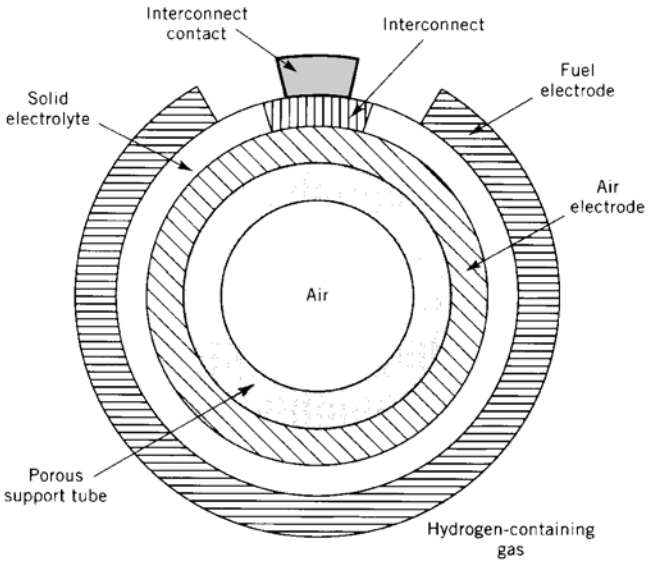


Fig. 4. Schematic representation of the cross section of tubular configuration for SOFC.

An electrochemical vapor deposition (EVD) technique has been developed that produces thin layers of refractory oxides that are suitable for the electrolyte and cell interconnection in SOFCs (9). In this technique, the appropriate metal chloride ($MeCl_x$) vapor is introduced on one side of a porous support tube, and H_2/H_2O gas is introduced on the other side. The gas environments on both sides of the support tube act to form two galvanic couples, ie,

$$MeCl_x + y\ O^{2-} \rightarrow MeO_y + \frac{1}{2}x\ Cl_2 + 2y\ e^- \quad (2)$$

and

$$H_2O + 2\ e^- \rightarrow H_2 + O^{2-} \quad (3)$$

The result is the formation of a dense and uniform metal oxide layer in which the deposition rate is controlled by the diffusion rate of ionic species and the concentration of electronic charge carriers. This procedure is used to fabricate the thin layer of solid electrolyte (yttria-stabilized zirconia) and the interconnection (Mg-doped lanthanum chromite).

The anode consists of metallic Ni with a Y_2O_3-stabilized ZrO_2 skeleton, which serves to inhibit sintering of the metal particles and to provide a thermal expansion coefficient comparable to those of the other cell materials. The anode structure is fabricated, having a porosity of 20 to 40% to facilitate mass transport of reactant and product gases. The Sr-doped lanthanum manganite, $La_{1-x}Sr_xMnO_3$, where $x = 0.10–0.15$, that is most commonly used for the cathode material is a *p*-type semiconductor. Similar to the anode, the cathode is a porous structure that must permit rapid mass transport of reactant and product gases. The cell interconnection material (Mg-doped lanthanum chromite, $LaCr_{1-x}Mg_xO_3$, $x = 0.02–0.10$), on the other hand, must be impervious to fuel and oxidant gases and must possess good electronic conductivity. In addition, the cell intergases and must possess good electronic conductivity. In addition, the cell interconnection is exposed to both the cathode and anode environments, thus it must be chemically stable under O_2 partial pressures of about 10^5 Pa (14.5 psi) down to 10^{-13} Pa at 1000°C. The solid electrolyte, commonly Y_2O_3-stabilized ZrO_2, must be free of porosity that permits gas to permeate from one side of the electrolyte layer to the other, and it should be thin to minimize ohmic loss. In addition, the electrolyte must have a transport number for O^{2-} as near to unity as possible, and a transport number for electronic conduction as near to zero as possible. Zirconia-based electrolytes are suitable for SOFCs because these exhibit pure anionic conductivity over a wide range of O_2 partial pressures ($10^5–10^{-15}$ Pa ($14.5–10^{-13}$ psi)). The solid electrolyte in SOFCs must be only about 25–50 μm thick if its ohmic loss at 1000°C is to be comparable to that of the electrolyte in PAFCs. Fortunately, thin electrolyte structures of about 40-μm thickness can be fabricated by EVD, as well as by tape casting and other ceramic processing techniques (see CERAMICS). The other cell components should permit electronic conduction, and interdiffusion of ionic species in these components at 1000°C should not have a significant effect on their electronic conductivity. Other severe restrictions placed on the cell components are that they must be stable to the gaseous environments in the cell, they must be capable of withstanding thermal cycling, and the thermal expansion coefficients of the cell components must be compatible.

Applications

Fuel cells operating on pure H_2 and O_2 provide a useful power source in remote areas such as in space or under the sea where system weight and volume are important parameters. On the other hand, fuel cell power plants operating on fossil fuels and air offer the potential for environmentally acceptable, highly efficient, and low cost power generation. Thus fuel cells can be considered for terrestrial applications where environmental pollution or noise would be objectionable, and they can be located near the point of use of the electricity such as on an urban site, rather than at a

remote location. An analysis (10), summarized in Table 2, describes the minimum technical requirements for fuel cells for four different types of applications, ie, for buildings, industry, transportation, and utilities. The fuel cell technologies which are most likely to be used in the various applications, and their anticipated capacities are given. The life of the power plants listed in Table 2 are longer than the projected life for the fuel cell stacks; thus periodic stack replacement is required. Larger fuel cell units utilized by the utility and industrial sectors are likely to be operated at high temperatures where the excess heat can be utilized to generate additional electrical energy. On the other hand, fuel cells for transportation applications are more convenient if they operate near ambient temperatures where the time to reach operating conditions is shorter.

Table 2. Minimum Technical Requirements for Fuel Cell Applications[a]

Characteristic	Buildings	Industry	Transportation	Utility
technology	PEFC/PAFC	SOFC	PEFC	MCFC
efficiency, %	35	40	35	45
system life, yr	2/15	15	2+	20
capacity, kW	5–200	200–2000	5–200	2000+
operating temperature, °C	90/194	1000	90	700
heat recovery	important	important		important

[a] Ref. 10.

An excellent summary of the development of fuel cells from the work carried out in 1839 (11) to the pioneering efforts in the 1930s (6) is available (12) as are other notable reviews (13–15) that document the historical development of fuel cells. Development of fuel-cell stacks and integration to other supporting equipment increased with the advent of the U.S. Space Program. At the same time, efforts were underway to demonstrate the feasibility of fuel cells for terrestrial applications (13,14). For example, in the mid-1950s Union Carbide Corp. demonstrated several terrestrial-type systems. Then in the 1960s a serious attempt to demonstrate fuel-cell technology for utility-related applications was initiated with the Team to Advance Research on Gas Energy Transformation (TARGET) Program, which resulted in the test of 12.5 kW PAFCs at 35 sites in the United States, Japan, and Canada. Further advances toward commercialization of PAFCs have been relatively slow. The demonstration of multimegawatt PAFC power plants occurred in the 1980s and early 1990s at Tokyo Electric Power Company (Goi, Japan).

In 1981 a national program, called the Moonlight Project, was initiated for energy conservation in Japan. A primary part of this strategy has been to develop fuel cell technologies, and as of this writing Japan is believed to have the largest commercialization program for fuel cells in the world. The Japanese government started a project to demonstrate a 1-MW unpressurized PAFC (Tokyo Gas Co.) and a 5-MW pressurized PAFC (Kansai Electric Power Co.) at utility sites. In addition, the installation of PAFC power plants totaling 20 MW at various sites in Japan should be completed by 1994. More modest efforts are underway to demonstrate MCFC and SOFC technologies in Japan. A survey of fuel-cell development and demonstration activities can be found in Reference 16.

Phosphoric Acid Fuel Cell. Tests of 4.8 MW and 11 MW power plants using PAFCs have been successfully completed in Japan. The fuel cell stacks (PC23) of the latter, built by International Fuel Cells, Inc. (IFC), began operation in March 1991. Eighteen 700-kW stacks were used. IFC designed the power conversion section and Toshiba Corp. provided the rest of the power plant system, ie, fuel reformer, thermal management, balance-of-plant equipment. This, the largest PAFC built and operated as of this writing, achieved full-rated output in April 1991. At its rated power, a gross a-c power efficiency of 43.6% (41.8% net) was obtained, and the measured NO_x exhaust was <3 ppm. By the end of August 1992, the total electricity generated exceeded 23, 435 MW·h, having a power generation time of 4041 h. Another demonstration of a smaller (1 MW) power plant using two PAFC stacks manufactured by IFC is planned for Milan, Italy. The manufacture of IFC's 200-kW PAFC power plants in Europe is to be carried out by CLC srl, Genoa, Italy and Ansaldo SpA (Italy).

A subsidiary of IFC and Toshiba Corp. called ONSI Corp. was formed for the commercial development, production, and marketing of packaged PAFC power plants of up to 1-MW capacities. ONSI is commercially manufacturing 200-kW PAFC systems for use in a PC25 power plant. The power plants are manufactured in a highly automated facility, using robotic techniques to assemble the repeating electrode, bipolar separator, etc, units into the fuel cell stack.

The PC25 power plant, 2.5 – m wide × 7.6 – m long × 3.2 – m high, is capable of remote unattended operation using pipeline gas. This power plant has a rated power output of 200 kW, operates at ambient pressure, and has achieved an electrical efficiency of over 40% (LHV). It is capable of operating in the cogeneration mode, producing 222 kW (760,000 Btu/h) of hot (74°C) water, and an overall energy efficiency of 85%. The first PC25 power plant, tested at IFC, accumulated over 12,000 h of operation, starting in 1991. The initial stack voltage was ~200 V, whereas the long-term voltage remained steady at ~190 V. As of this writing, the longest continuously operating PC25 (5400 h) is located in Japan, and has a total operating time of 7900 h.

The availability of both electric power and useful thermal energy makes these power plants attractive for dispersed locations for small commercial and industrial buildings. The applications of 200-kW PAFC power plants are summarized in Table 3. By July 1993, 29 out of a total of 52 planned power plants were installed. The first of these power plants was operated by the South Coast Air Quality Management District (SCAQMD) in Diamond Bar, California. The measured emissions from the PAFC were low. The NO_x was 0.5 ppmv, CO 2 ppmv, and total hydrocarbons (THC) 4 ppmv. There was no SO_2, smoke, or particulates. The SCQAMD was able to drastically curtail the institutional issues of siting, licensing, and permitting for installing PAFC power plants in their jurisdiction encompassing the Los Angeles basin area.

Table 3. Applications and Locations of 200-kW PAFCS[a,b]

	Location	
	North America	Asia

Application/type	United States	Canada	Japan	South Korea	Europe	Total number of plants
hospital	6					6
nursing home	1					1
hotel	2					2
office	2	1	4	1		8
education	2					2
public safety	1					1
district heating system			3		4	7
light industrial	4		6		3	13
R&D[c] facility			7		2	9
special application	2		1			3
Total	*20*	*1*	*21*	*1*	*9*	*52*

[a] PC25 power plants.

[b] Ref. 17.

[c] R&D = research and development.

The performance characteristics of several versions of PAFC stacks developed by IFC for utility (Configuration A) and on-site (Configuration B) applications are summarized in Table 4. These stacks are water-cooled. Cooling plates are located at five-cell intervals in the stack for utility applications and at seven-cell intervals in stacks for on-site applications. The cell voltage and efficiency of the PAFC power plant are clearly enhanced by operating at elevated pressures. The PAFC (Configuration B) for on-site applications such as hospitals, hotels, and the light industry, operates at atmospheric pressure. Increasing the operating pressure to 0.82 MPa (120 psi) and electrode area to 0.93 m^2 of the PAFC stack designated as Configuration B results in enhanced power density. Configuration A, which is used in the 11-MW demonstration program in Japan, operates at 0.82 MPa (120 psi).

Table 4. Performance Characteristics of IFC PAFC Powerplants[a]

Stack configuration[b]	Electrode area, m^2	Pressure, kPa[c]	Current density, mA/cm^2	Cell voltage, V	Power density, mW/cm^2	Remarks[d]
B	0.45	100	215	0.650	140	SNG/air
B	0.45	820	215	0.740	159	SNG/air
B	0.93	820	431	0.715	307	fuel NS
A	0.93	820	215	0.760	164	fuel NS

[a] Ref. 18.

[b] A = utility application; B = on-site application.

[c] To convert kPa to psi, multiply by 0.145.

[d] SNG = simulated natural gas; NS = not specified.

Westinghouse Electric Corp. initiated a program to develop air-cooled PAFC stacks, containing cooling plates at six-cell intervals. Full size 100-kW stacks (468 cells, 0.12-m^2 electrode area) were built, and a module containing four of these stacks was tested. An air-cooled stack operated at 0.480 MPa yielded a cell voltage of 0.7 V at 267 mA/cm^2 (187 mW/cm^2). Demonstration of this technology is planned for a site in Norway.

There are several organizations in Japan that are actively involved in PAFC demonstration programs. Fuji Electric Co. is taking the lead in the commercialization of PAFCs in Japan, with units ranging from 50 kW to 5 MW. Over 65 PAFC power plants having total capacity of greater than 10 MW are on order. 50-kW units having a capability for cogeneration, electrical efficiency of 40% and total efficiency of 80% (LHV), using town gas are being developed. The larger fuel cell power plants are being sited at gas and electric utilities, as well as industrial companies in Japan. In addition, Fuji is involved in the United States Department of Energy (DOE) program to demonstrate the viability of PAFCs for powering city buses. Other Japanese companies involved in the development of PAFCs are Mitsubishi Electric Co. (MELCO) and Toshiba Corp. MELCO was involved with a demonstration test of a 200-kW PAFC stack that operated for over 13,000 h, and a short stack that operated for 16,000 h with no acid addition. The company is planning additional tests of 200-kW PAFC stacks, starting in 1994 at Osaka Gas (Japan). Toshiba Corp. is collaborating with IFC to market the 200-kW PAFC (PC25), as well as supporting the development of improved PAFC stacks (200 kW, 50 kW) based on the PC25, and much larger units (670 kW, 1 MW).

The Office of Transportation Technologies of the U.S. DOE is supporting programs to develop fuel cells for transportation applications. As of this writing, the viability of a PAFC-powered bus (9-m long) operating on an urban route is being investigated. This program is coordinated by H-Power (Belleville, N.J.) in collaboration with subcontractors Bus Manufacturing USA, Inc. (bus design and fabrication), Booz Allen & Hamilton (bus system integration), Fuji Electric Co. Ltd. (50-kW PAFC hardware), Soleq Corp. (power train and controls), and Transportation Manufacturing Corp. (transit bus industry guidance and 12-m bus conceptual design). The PAFC (0.2 m^2 electrode area, 175 cells) is designed to operate at 240 mA/cm^2 (0.66 V/cell) and 190°C on H_2 from steam-reformed CH_3OH. The overall design efficiency is 38% (based on LHV CH_3OH). Delivery of the buses for dynamometer testing began in 1993. Demonstration runs are planned for Washington, D.C. and Los Angeles.

Molten Carbonate Fuel Cell. The MCFC is well-suited to utilize fuels that are produced in coal gasifiers or from other sources. In one

approach, Energy Research Corp. (ERC) is steam-reforming natural gas to form H_2 and CO_2 in the fuel cell (internal reforming), eliminating the need for a dedicated fuel processor. The reaction is carried out using a catalyst that is located in the fuel manifold near the anode inlet and in the fuel cell stack itself. Because the steam reforming reaction is endothermic, heat that is generated during the production of electrical energy is utilized. The MCFC stacks developed by ERC operate at atmospheric pressure and utilize external gas manifolds.

The MCFC appears to be in the final stages of prototype testing, and a 234-cell MCFC stack (0.37 m^2 cell area, 70 kW) tested at ERC operates with a cross-flow gas distribution pattern (see Fig. 3). A 70-kW stack from ERC was also tested, starting in the fall of 1991, at a site of Pacific Gas and Electric Co. in San Ramon, California. In addition, ERC has tested a 120-kW, 244-cell MCFC stack (0.56 m^2 electrode area). The purpose of these tests was to demonstrate the feasibility of the technology for scaling up to large size MCFC stacks. A large demonstration plant utilizing the ERC technology in large fuel cell stacks (125 kW stacks, 0.56 m^2 electrode area) to produce a 2-MW power plant in Santa Clara, California is expected to be operational by late 1994 or early 1995.

In 1987 M-C Power (Burr Ridge, Illinois) was formed to commercialize the MCFC technology developed by the Institute of Gas Technology (IGT), Chicago, in partnership with Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI) of Japan. In 1991 M-C Power demonstrated the largest stack to date (70 cells) using an internally manifolded heat exchanger (IMHEX) fuel-cell-stack (19,20) in a 1580-h test. The gas flow field in this design is illustrated in Figure 5. This configuration has large manifolds for the gas inlets and outlets and an octagonal flow field. Both cross and parallel flow occur in different areas of the electrode. This design permits heat to flow more efficiently in the stack and minimizes the tendency of the cells to shrink over operating time, which occurs because of structural changes in the cell components, eg, sintering of porous electrodes. In 1992, M-C Power began a test of the first full-area commercial IMHEX 20-cell, 20-kW stack (0.93 m^2 cell area), and exceeded 2500 h of operation. A demonstration of MCFC technology using a 250-kW power plant in 1994 at the UNOCAL Science and Technology Center in Brea, California and one at a hospital in San Diego are planned.

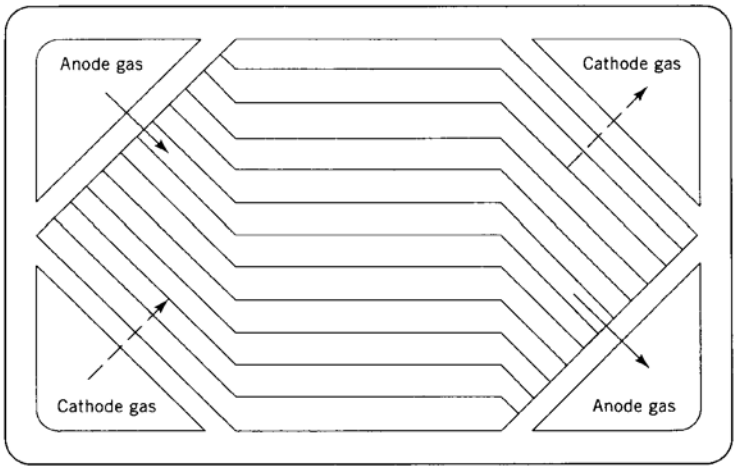


Fig. 5. Schematic representation of gas flow pattern in the IMHEX design.

A summary of the MCFC technologies is presented in Table 5. Both ERC and MCP have developed pilot continuous manufacturing facilities to produce MCFC cell components. Based on the results of an analysis to define the optimum operating pressure, ERC selected 0.1 MPa (14.5 psi) to obtain the lowest cost of electricity and longest cell life in MCFC stacks operating with internal fuel reforming. On the other hand, the goal of the MCP program is to operate at pressures above ambient, ie, 0.3 MPa (43.5 psi), using externally reformed fuels. The demonstrated lifetimes of MCFC stacks are short of the goal of 40,000 h. Efforts to extend the life include minimizing voltage-induced electrolyte migration in the stack, which appears to be a principal reason for performance degradation.

Table 5. Performance Status of Continuous MCFC Technologies.[a,b]

Parameter	Energy Research Corp.	M-C Power Corp.
module size, m^2	0.37	0.93
cells, number	234	20
current density, mA/cm^2	172	172
power density, mA/cm^2	113 (151)	129 (215)
operating pressure, MPa[c]	0.1 (0.1)	0.1 (0.3)
electrical efficiency, %[d]	(60–65)	(60–65)
stack lifetime, h	10,000 (40,000)	2,500 (40,000)

[a] Ref. 18.

[b] Data in parentheses are the goal.

[c] To convert MPa to psi, multiply by 145.

[d] 2-MW natural gas cell.

The Japanese Government is actively involved with Hitachi, Ltd., IHI, and MELCO to develop 100-kW MCFC power plants and systems. A target for this program is to develop a 1-MW class MCFC power plant leading to a test at a utility site by 1997. Hitachi is exploring a concept that revolves around the use of 25-kW blocks of cells (22 cells, 1.2 m^2 electrode area), which are integrated to form large stacks, ie, four 25-kW blocks to form a 100-kW stack. Performance of these stacks at both 0.1 MPa (14.5 psi) and 0.59 MPa (87 psi) has been demonstrated for over 5000 h. Large (1.4 m^2) cells have been tested by IHI for 9700 h, and tests of a 100-kW stack are under way as of this writing. MELCO is involved in the development of both direct internal-reformed (DIR) and indirect internal-reformed (IIR) MCFC technologies. The distinction between these involves the location of the steam-reforming catalyst such as Ni supported on MgO. In the DIR MCFC, the catalyst is located in the anode gas channels, and simultaneous reforming and electrochemical oxidation of hydrogen occur in close proximity. In the IIR MCFC, the reforming catalyst is located in separate and independent reaction chambers in the cell stack. Because the catalyst is located in the anode compartment of the DIR MCFC, it is susceptible to contamination and deactivation by the molten carbonate electrolyte. A successful demonstration of 4500 h showing 99% CH_4 conversion with a DIR 5-kW MCFC (ten 5000 cm^2 cells) was completed. MELCO also demonstrated a 100-kW IIR MCFC stack (192 cells) in a test lasting more than 2000 h.

Programs to develop MCFC technology are also under way in Europe. Ansaldo SpA (Italy) is setting up facilities to produce 1-m^2 cells in an automated process, and their goal is to test 100-kW stacks in 1994. The 100-kW stack is also to be tested by IBERDROLA in Spain as part of a complete power plant system. Two Dutch companies, Stork and Royal Schelde, have joined with the Dutch government to form Brandstofcel Nederland (BCN), which plans to test a 50-kW MCFC and two 250-kW MCFC stacks in 1994.

Solid Oxide Fuel Cell. A comprehensive review of the SOFC technology can be found in the literature (21). A tubular or cylindrical configuration was adopted for SOFCs to alleviate problems with gas seals experienced in the initial, planar design. A tubular design having a porous support tube of about 30-cm length and 1.27-cm diameter (active area of about 110 cm^2) developed by Westinghouse Electric Corp. (WEC) produced about 18 W. The manifolding of the oxidant and fuel gases for these types of tubular cells is illustrated in Figure 6. The oxidant gas is introduced via a central Al_2O_3 tube, and the fuel gas is supplied to the exterior of the closed-end tube. In this arrangement, the Al_2O_3 tube extends to the proximity of the closed end of the support tube, and the oxidant flows back past the cathode surface to the open end. The fuel gas flows past the anode on the exterior of the cell, and in a parallel direction (co-flow) to the oxidant gas. The spent gases are exhausted into a common plenum where the remaining active gases react, and the generated heat serves to preheat the incoming oxidant stream. One attractive feature of this arrangement is that it eliminates the need for leak-free gas manifolding of the fuel and oxidant streams.

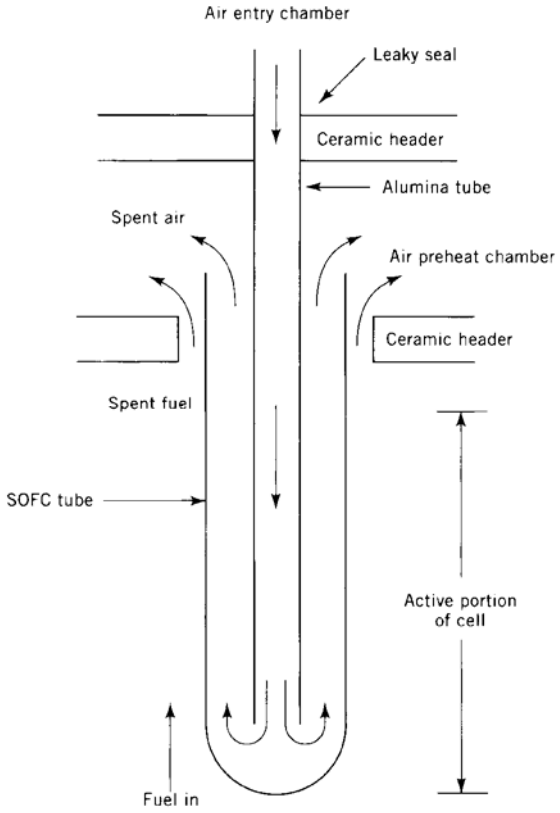


Fig. 6. Gas-manifold design for a tubular SOFC.

The tubular design is the most advanced SOFC technology. Tests of a nominal WEC 25-kW SOFC unit were started in 1992 at Rokko Island near Osaka, Japan in a joint program by Kansai Electric Co., Osaka Gas, and Tokyo Gas Co. This unit consists of 1152 cells, 50-cm length, which are contained in two independently controlled and operated sections. The SOFC has surpassed 2500 h of operation, and achieved d-c power of 36

kW of steady output and a peak of 44 kW. The WEC technology was originally based on the use of a porous support tube (see Fig. 4). Tubular cells 100-cm long are now standard, but commercial cells are expected to be 200 cm in length. A cell has been operated at 875°C for more than 28,000 h at 250 mA/cm^2 and with a performance degradation of about 1%/1000 h of operation. The average performance from a test matrix of 12 SOFC cells was an average cell voltage of 0.516 V at 377 mA/cm^2. An effort is under way to eliminate the support tube, and instead utilize a self-supported air electrode (SSAE), which should decrease the materials and fabrication costs, and improve cell performance. Tubular cells employing SSAE (36-, 50-, and 77-cm long) have been tested for up to 6800 h.

Efforts are under way to develop SOFCs that have a bipolar, planar design. The planar design permits a more efficient utilization of the weight and volume in the fuel cell stack. The effort at AlliedSignal Aerospace Co. (Torrance, California), for example, is to build a monolithic SOFC capable of achieving high power densities because of its compact design (Fig. 7). This planar design resembles the corrugated structure found in cardboard. The typical layer thicknesses are 100 μm, and cell-to-cell distances are 1 to 2 mm. Both co-flow and cross-flow of the reactant gases have been considered. The monolithic structure was fabricated in the green state and then the complete structure was co-fired to obtain small (100 and 50 W) SOFC stacks. Other options for fabricating monolithic structures have also been considered (21). Using a single cell (5 cm^2), a performance of 0.75 V at 500 mA/cm^2 was obtained at 1000°C on 97% H_2/3% H_2O and air. More recently, AlliedSignal has shifted effort to evaluate the flat-plate planar design. Cell components of up to 23 cm × 23 cm have been produced, and thin electrolyte layers (1–10 μm) on NiO/ZrO_2 have been fabricated by tape calendering. Because of the thin electrolyte layers, a lower operating temperature can be used. A power density of 0.3 W/cm^2 was obtained using a small (<10 cm^2) planar cell at 800°C using 97% H_2/3% H_2O and air, and no significant performance degradation was observed for more than 1000 h.

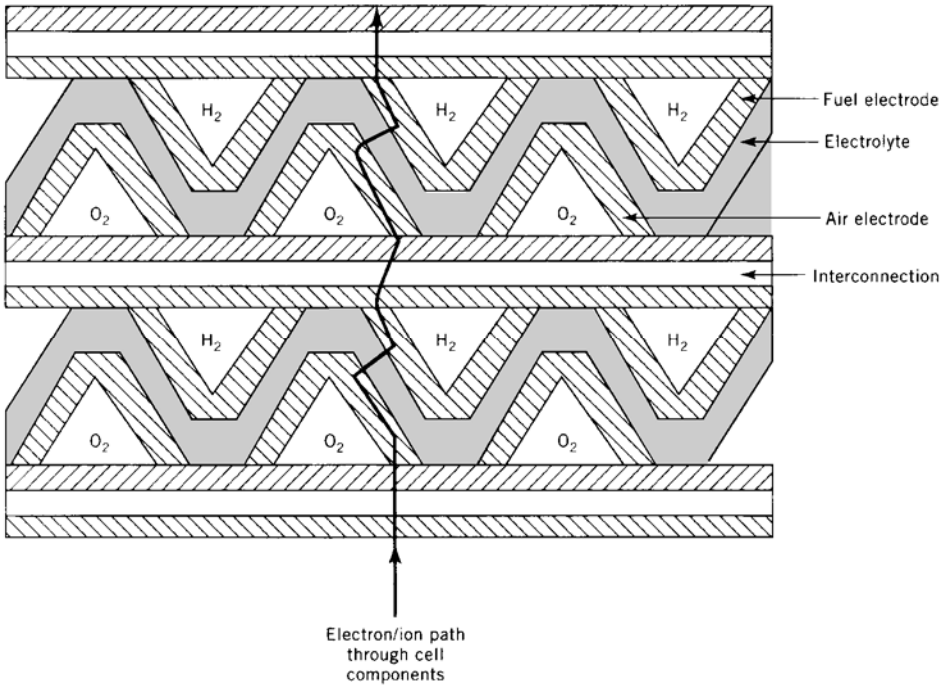


Fig. 7. Schematic representation of the cross section of monolith structure for SOFCs.

Ceramatec, Inc. (Salt Lake City, Utah) and Ztek Corp. (Waltham, Massachusetts) are also pursuing the development of planar SOFCs. Ceramatec has obtained performance of ~300 mA/cm^2 at 0.5 V/cell in 5-cell stacks and 200 mA/cm^2 at 0.5 V/cell in 40-cell stacks. Ceramatec is collaborating with SulzerInnotec (Switzerland) to develop planar SOFC power plants for cogeneration applications by 1996. Ceramatec is integrating cells of 12-cm diameter into an internally manifold stack designed by Sulzer. Ztek has fabricated compact (16 cells/2.54 cm) SOFC stacks of the planar design. Single cells achieved power densities of 250 mW/cm^2, and 25 W was obtained using a 10-cell stack, which was tested for 1000 h.

Research into SOFC programs in Japan was started in 1981 under the Moonlight Project. Japanese companies such as Fuji Electric Corp., Mitsubishi Heavy Industries, Ltd., Tonen Corp., and Sanyo Electric Co. are participating in the program. This effort is in its early stages and is concentrating on cell components and small cell development.

Several research and development (R&D) programs on SOFCs are under way in Europe. Siemens AG (Germany) is developing a planar SOFC having metallic bipolar plates using, eg, Cr-based alloys, and internal gas manifolding. Several sizes of stacks were manufactured, and a 10-cell stack delivered 103 W at 235 mA/cm^2. Soft-glass seals developed by Dornier GmbH (Germany) demonstrated over 3000 h of operation without suffering gas leaks. They also obtained over 3000-h operation using a 5-cell stack (25 cm^2 cell area) without experiencing gas leaks through the seals in planar SOFCs, and observed a performance of 350 mA/cm^2 at 0.6 V on H_2 and air. Research on cell components, such as the solid electrolyte and anode materials, is being pursued at the Riso National Laboratory (Denmark) and Imperial College (United Kingdom).

Polymer Electrolyte Fuel Cell. The PEFC is being developed in the United States primarily for transportation applications. The cost

of the Nafion membrane, traditionally very high, may present a barrier to the acceptance of PEFCs in the consumer sector. Ion-exchange membranes developed by Dow Chemical and Chlorine Engineering (Japan) in the latter 1980s have, however, shown encouraging results in tests of PEFCs. These developments and the potential market for PEFCs in the transportation sector should help to lower the cost of the polymer electrolyte.

A team consisting of Allison Gas Turbine Division of General Motors Corp. (prime contractor) and Los Alamos National Laboratory, Dow Chemical Co., Ballard Power Systems (Vancouver, Canada), and GM Research Laboratories (subcontractors), are developing PEFCs as a midterm option for transportation applications. These fuel cells are expected to offer significant advantages, ie, reduced weight and size, over PAFCs. State-of-the-art 5-kW PEFCs are under test, and technical issues on component development, fuel processing, water and thermal management, electronic controls, start-up, and transient operations are being addressed. This program, which is sponsored by the U.S. DOE, has a goal of developing a 50-kW PEFC power plant utilizing steam-reformed CH_3OH for vehicular applications.

Ballard Power Systems, the leader in the manufacture of PEFC stacks, has sold at least fifty 3- to 5-kW units worldwide. Ballard is involved in a program in Canada to demonstrate a 120-kW PEFC stack to power a transit 20-passenger, 9752-kg bus. For this demonstration, on-board compressed hydrogen, sufficient for 150-km range, is the fuel.

Energy Partners, Inc. (West Palm Beach, Florida), acquired fuel cell technology from Treadwell Corp. (Thomaston, Connecticut), which supplied electrochemical equipment to the U.S. Navy. Energy Partners, Inc. are involved in developing PEFCs for propulsion applications in transportation and submersible vehicles. A 20-kW PEFC stack was designed for demonstration tests.

A 15-kW PEFC power plant and power system for the supply of primary power in an unmanned underwater vehicle (UUV) is being developed by IFC to replace the Zn–AgO battery stacks that are used as of this writing. The 112-cm diameter UUV is expected to operate with high reliability for more than 5000 h in an enclosed environment. A 20-cell stack was built and tested for 2100 h, and achieved an initial performance level of 0.82 V at 280 mA/cm^2 using pure H_2/O_2. Based on the successful results of the 20-cell stack, 80-cell PEFC stacks were built and tested. Plans are also under way at IFC to develop PEFC technology to provide auxiliary power in a nuclear submarine, with a baseline design consisting of a 1-MW power plant.

The Japanese Government initiated a program in 1992 to promote the development of PEFCs for both portable and stationary applications. The goal is to demonstrate a 1-kW module having a power density of 0.3 W/cm^2 at a cell voltage greater than 0.75 V by 1995. A few research projects are under way in Japan.

Siemens AG has been involved in R&D on PEFCs, and Vickers Shipbuilding & Engineering Ltd. (United Kingdom) is evaluating PEFCs from Ballard Power Systems for power generation. A 35-cell stack was successfully tested for more than 300 h. Plans are under way to test a 20-kW PEFC.

Because of the low operating temperature and ease of fabrication for low power units, PEFCs are the most likely fuel cell to be introduced in portable power packs. PEFCs in sizes of 300–500 W are being considered as a power source, eg, 4-h duration, 300 W, 1.2 kW, for the modern soldier operating in the enclosed environment of a self-contained protective suit, which has facilities for air conditioning, radio communication, etc. Analytic Power Corp. (Boston) is assessing the use of PEFCs for this application.

Alkaline Fuel Cell. Commercial development of AFCs outside of the aerospace and military sector has not been vigorously pursued in the United States. Regenerative fuel cells, ie, those capable of producing electricity by consumption of oxygen and hydrogen, as well as generating these gases by electrolysis, utilizing both AFC and PEFC technologies, have been proposed for space applications. High performance AFC cells based on lightweight cell hardware were developed by IFC. A 4-cell stack (~470 cm^2 cell area) operated at power densities of up to 3.4 W/cm^2. The specific mass was 0.56 kg/kW compared to ~6.5 kg/kW for the AFC in the Space Shuttle. This dramatic improvement was achieved by changing the cell operating conditions to ~150°C and 1.4 MPa (203 psi), as well as by developing improved materials and structures for cell components.

There is an effort in Belgium, spearheaded by Elenco NV, to demonstrate the viability of AFCs in transportation applications. The focus is to develop low cost components for AFCs. A 78-kW AFC stack which operates at about 70°C and uses pure H_2 fuel and recirculating KOH for the electrolyte has been developed. Elenco is collaborating with Ansaldo Richerche (Italy) to supply the electric drive train, Air Products Nederland (the Netherlands) to supply the hydrogen storage capability, and SAFT (France) to supply the Cd/NiOOH batteries for a power source. Demonstrations (Eureka Bus Program) of this technology in city buses (18-m long) in Amsterdam and Brussels are planned in 1994.

The development of AFC technology is also being pursued in Sweden for potential application in utility power generation and transportation. A strong research effort on gas diffusion electrodes and electrocatalysis for AFCs has been undertaken. An analysis performed by the Royal Institute of Technology concluded that CO_2 can be economically scrubbed from fuel gases obtained by coal gasification, thus making large, low cost AFC power plants attractive for utility power generation.

Economic Aspects

From the standpoint of commercialization of fuel cell technologies, there are two challenges: initial cost and reliable life. The initial selling price of the 200-kW PAFC power plant from IFC was about $3500/kW. A competitive price is projected to be about $1500/kW or less for the utility and commercial on-site markets. For transportation applications, cost is also a critical issue. The fuel cell must compete with conventional mass-produced propulsion systems. Furthermore, it is not clear if the manufacturing cost per kilowatt of small fuel cell systems can be lower than the cost of much larger units. The life of a fuel cell stack must be five years minimum for utility applications, and reliable, maintenance-free operation must be achieved over this time period. The projection for the PAFC stack is a five year life, but reliable operation has yet to be demonstrated for this period.

Several activities, if successful, would strongly boost the prospects for fuel cell technology. These include the development of (*1*) an active electrocatalyst for the direct electrochemical oxidation of methanol; (*2*) improved electrocatalysts for oxygen reduction; and (*3*) a more CO-tolerant electrocatalyst for hydrogen. A comprehensive assessment of the research needs for advancing fuel cell technologies, conducted in the 1980s, is available (22).

A viable electrocatalyst operating with minimal polarization for the direct electrochemical oxidation of methanol at low temperature would strongly enhance the competitive position of fuel cell systems for transportation applications. Fuel cells that directly oxidize CH_3OH would eliminate

the need for an external reformer in fuel cell systems resulting in a less complex, more lightweight system occupying less volume and having lower cost. Improvement in the performance of PEFCs for transportation applications, which operate close to ambient temperatures and utilize steam-reformed CH_3OH, would be a more CO-tolerant anode electrocatalyst. Such an electrocatalyst would reduce the need to pretreat the steam-reformed CH_3OH to lower the CO content in the anode fuel gas. Platinum–ruthenium alloys show encouraging performance for the direct oxidation of methanol.

For high temperature fuel cells, there is still a strong need to develop lower cost materials for cell components. In the case of SOFCs, improved fabrication processes and materials that permit acceptable performance in fuel cells at lower operating temperatures are also highly desirable.

One factor contributing to the inefficiency of a fuel cell is poor performance of the positive electrode. This accounts for overpotentials of 300–400 mV in low temperature fuel cells. An electrocatalyst that is capable of oxygen reduction at lower overpotentials would benefit the overall efficiency of the fuel cell. Despite extensive efforts expended on electrocatalysis studies of oxygen reduction in fuel cell electrolytes, platinum-based metals are still the best electrocatalysts for low temperature fuel cells.

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