# FUEL CELL POWER PLANTS

Fuel cell power plants offer the potential for ultrahigh-efficiency energy conversion and the enhancement of the quality of our environment. Because of this, organizations in several countries are sponsoring the development of fuel cells for stationary power generation market applications.

Concerns for the global environment are driving future power generation systems toward technologies that produce extremely low environmental emissions. Because of their high efficiencies, fuel cell power plants will help in reducing carbon dioxide emissions. Since combustion is not utilized in the process, fuel cells generate very low amounts of nitrogen oxide ($NO_x$). Fuel cell power plants have been exempt from air permitting requirements in northern and southern California and in Massachusetts. Relying on electrochemistry instead of combustion, the fuel cell is attractive for both heavily polluted urban areas and remote applications. Not only will it emit none of the smog-causing pollutants associated with conventional powerplants, it is ideal as a distributed power source; that is, it can be sited at or near the electricity user—for example, at electrical substations, at shopping centers or apartment complexes, or in remote villages—minimizing long-distance transmission lines.

The U.S. Stationary Power Fuel Cell Program is a market-driven program which has over 40% cost-sharing from the private sector. The U.S. program is being implemented by the U.S. DOE Federal Energy Technology Center (FETC). The stationary power fuel cell developers enjoy the support of user groups with over 75 utility and other end-user members. In addition, DOE cooperates with the Gas Research Institute (GRI) and the Electric Power Research Institute (EPRI) to fully and efficiently leverage funding for the U.S. Stationary Power Fuel Cell Program.

Because of investment in the 1980s and early 1990s, first-generation fuel cells are now crossing the commercial threshold. DOE and predecessor agencies have funded the development of fuel cell systems since the 1970s. Initially, phosphoric acid fuel cells (PAFCs) were the primary focus, and these units, operating on natural gas, are now in the initial stage of commercialization. In the last few years, focus in the United States has shifted to the advanced fuel cell types, including molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs). These systems offer higher efficiencies and the potential for lower capital cost, and because of higher operating temperatures they are more suitable for cogeneration than lower-temperature fuel cells.

## FUEL CELL TECHNOLOGY

Fuel cells generate electricity and heat using an electrochemical process similar to that of a battery. A fuel cell will continuously produce power as long as a fuel, such as natural gas, and an oxidant, air, are supplied to the system. Present early market systems are achieving over 40% lower heating value (LHV) cycle efficiency. The next-generation systems are expected to achieve 55% and eventually 70% LHV cycle efficiencies.

As shown in Table 1, several different types of fuel cells are being developed for stationary power applications. The electrolyte controls the operating temperature of the cells, which in turn determines the materials of construction. PAFCs are now becoming commercially available, while MCFCs and SOFCs promise even higher efficiencies for the future (1).

A basic fuel cell (Fig. 1) consists of two electrodes, with the anode and cathode separated by an electrolyte. Fuel cell types are characterized by their electrolyte. For example, PAFCs utilize a phosphoric acid electrolyte in a matrix between anode and cathode electrodes. To produce a useable quantity of electric power, individual cells are assembled into a vertical "stack" of repeating components which are electrically interconnected. A fuel cell power plant (Fig. 2) consists of the stack or power section integrated with a fuel processor and a power conditioner to convert the power from direct current to alternating current.

**Table 1. Types of Fuel Cells**

| Characteristic | PAFC | MCFC | SOFC |
|---|---|---|---|
| Electrolyte | Phosphoric acid | Lithium carbonate/potassium carbonate | Stabilized zirconia |
| Operating temperature | 200°C | 650°C | 1000°C |
| Electrical conversion efficiency (LHV) | 45–50% | 50–65% | 50–60% |
| Materials | Carbon platinum | Nickel stainless steel | Ceramic |

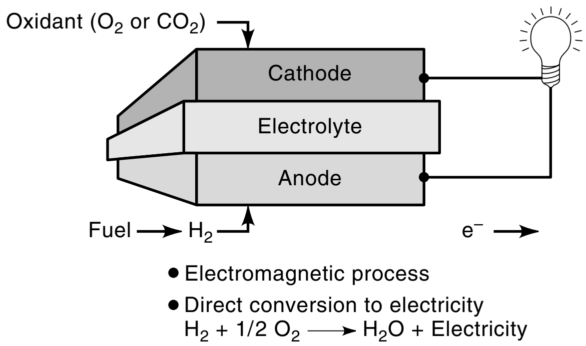

**Figure 1.** Basic fuel cell.

The fuel cell is inherently modular. Constructed as an assembly of individual cells, stacks ranging from 100 to 250 kW form a modular building block. Depending on the generating capacity required, 10 to 20 stacks can be grouped with a fuel processor and a power conditioner to create a 1 to 2 MW power plant. Larger plants will use a larger number of stacks. In high-growth areas or remote sites, modular power plants located near the demand can offset the cost of right-of-way access and transmission lines.

## PHOSPHORIC ACID FUEL CELLS STATUS

In the PAFC technology, the electrochemical reactions occur on highly dispersed electrocatalyst particles supported on carbon black. Platinum or platinum alloys are used as the catalyst for both electrodes. The platinum is supported on carbon black for both electrodes. The electrodes also use a polymeric binder and a carbon paper substrate. The separator plates are all graphite (1).

DOE and GRI, beginning in the late 1970s, supported an on-site PAFC effort that included an R&D program and a manufacturing and field test program with international fuel cells (IFCs). The program resulted in the production and testing of over fifty 40 kW, on-site cogeneration power plants distributed to sites throughout the United States and Japan. This program was successfully completed in 1986 and formed the technology base for the current 200 kW, on-site work. The PAFC is a proton-conducting fuel cell, which has routinely reached an operating performance level of 200 $W/ft^2$ (2150 $W/m^2$) at ambient pressure.

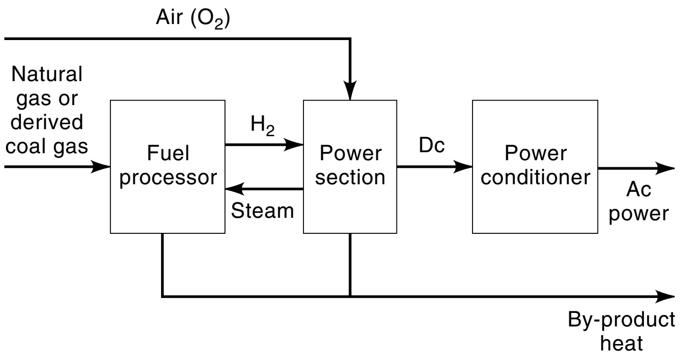

**Figure 2.** Fundamentals of a power plant.

The DOE/FETC-sponsored PAFC development work at IFC was completed in 1992. ONSI Corporation, located in South Windsor, Connecticut, has been actively involved in the development and marketing of on-site PAFC systems and has a 40 MW/year manufacturing facility. In their PAFC commercialization, the ONSI Corporation, a subsidiary of IFC, is offering a complete packaged phosphoric acid fuel cell power plant for $3000/kW. Named PC25, over one hundred 200 kW units are in operation in the United States and around the world. An additional 22 units were added in the United States through the Climate Change Fuel Cell Program. Operating experience has been excellent, with availabilties of over 90%. The PAFC is so reliable that it is being considered for uninterrupted power supply (UPS) applications.

Although PAFC technology is the most mature of the fuel cell types being developed and cell-and-stack performance exhibited by all designs is close to acceptable for early commercial operation, cost remains as an issue. Power-plant costs must be reduced to be competitive with other advanced technologies. A current goal is to reduce these costs to less than $1500 to $2000/kW. An operating life of 40,000 h is desired and may not be an issue. In fact, 70,000 h of life is now thought to be attainable. IFC is currently developing 1 MW class units based on a five-stack design and developing the PC25C, which is lower in size and cost. The major improvement represented by the PC25C was the smaller, lighterweight invertor whose smaller size helped lower the PC25's weight by 20,000 pounds (9091 kg).

ONSI claims several things about its large 1.2 MW PAFC plants it is offering: The PAFC is not a strandable asset since it is movable; repackaging of the PAFC into 1.2 MW plants will lower cost and footprint; availability is increased by using multiple, high-reliability units, making it a natural for UPS applications; and the PAFC can provide high power availability with low reserve margins.

In its premium power application, IFC uses a static switch to switch to grid only when the fuel cell, which is baseloaded, is to be maintained. The grid is the UPS. This is quite unlike the applications where the reciprocating engine is used as a UPS. The engine is not baseload run and is used only in an emergency, being tested daily.

## MOLTEN CARBONATE FUEL CELLS STATUS

Overall system efficiencies of 50 to 60% are forecast for natural gas and coal gasification MCFC power plants. The MCFC operates at 650°C. The MCFC, like other fuel cells and unlike turbines and diesels, offers high efficiency at small size and at part load. Furthermore, an MCFC power plant can operate on coal or natural, refinery, or processed gas. MCFC stack designs incorporate either internal or external fuel and oxidant manifolding and either internal or external reforming. All MCFC designs include flat cell components in the cell package (i.e., anode, matrix to hold carbonate, cathode, current collector, and separator plate).

The main components of an individual cell are the anode, the cathode, and the molten carbonate electrolyte. Electrode materials are usually porous nickel alloys for reducing atmospheres (anode) and nickel oxide for oxidizing atmospheres (cathode). The electrolyte, typically a combination of molten, alkali (lithium, potassium, sodium) carbonates, is contained within a porous ceramic matrix, commonly made of lithium aluminate. An individual cell is approximately 6 mm thick. The electrolyte is about 1 mm thick.

Figure 3 illustrates the structure of an MCFC stack. Conductive, bipolar separator plates connect the individual cells in a stack, both structurally and electrically. The bipolar separator plate is made of stainless steel, and each plate physically separates the fuel gas stream of one cell from the oxidant gas stream of the adjacent cell. One side of each separator plate channels a fuel stream so that it flows over a porous anode, while the flip side channels an oxidant stream over a porous cathode. Each bipolar separator plate also collects current, thus, electrically connecting adjacent cells of a stack in series. Electrons are conducted from the anode through the bipolar separator plate and into the cathode of the adjacent cell. There they react with the oxidant gas stream and form carbonate ions. The carbonate ions diffuse through the electrolyte and into the anode, where they react with the fuel gas stream, releasing electrons into the anode. Electrons are conducted in this manner through all the cells, thus establishing direct current through the stack. An external circuit connects a load between the two end plates of the stack, completing the circuit.

Figure 4 depicts an MCFC with the fuel and oxidant streams flowing perpendicular to each other within the cell. This internal flow geometry is known as *cross-flow*. Other possible internal flow geometries are cocurrent and countercurrent. In general, a countercurrent internal flow geometry produces the most uniform current densities and temperature distributions within a cell. A cocurrent internal flow geometry, in general, results in the least uniform current densities and temperature distributions.

At least two MCFC developers, Energy Research Corporation (ERC) and M-C Power (MCP), have conceptual designs of efficient integrated MCFC power plants. Operating conditions for these MCFCs are projected to be in the range of 150–250 A/ft$^2$ (160–270 mA/m$^2$), at 0.60–0.80 V, with 50–85% fuel utilization (2–9).

The goal of the U.S. MCFC program is to develop and commercialize low-cost, packaged, simple, and modular fuel cell systems. DOE is accelerating the drive for private sector commercialization of multifuel, MCFC power plants.

The two MCFC developers have collected impressive stack test performance data under the 1990 program R&D announcement (PRDA). ERC is developing an externally manifolded, externally reforming MCFC and has constructed a 2 to 17 MW/year MCFC manufacturing plant. ERC has constructed a 100 kW test facility in Danbury, Connecticut, and has scaled up to a 6 ft$^2$ (0.56 m$^2$) area stack.

MCP is developing an internally manifolded, externally reforming MCFC and has constructed a 4 to 12 MW/year MCFC manufacturing plant. MCP has constructed a 250 kW acceptance test facility in Burr Ridge, Illinois, and has scaled up to an 11.4 ft$^2$ (1.06 m$^2$) full-area stack.

DOE, in conjunction with EPRI, GRI, and the Department of Defense (DOD), is also funding product development tests (PDTs) concurrently with system development at ERC and MCP. A successful demonstration track record will enhance support for MCFC technology from utilities and other end users in the distributed, repowering industrial and commercial markets.

The initial MCFC PDTs was in California in 1996–1997. ERC is conducting a 2 MW PDT in Santa Clara, California, funded by the Santa Clara Demonstration Group, EPRI, and DOE. MCP will conduct a 250 kW PDT in San Diego, California, funded by DOE, GRI, and San Diego Gas and Electric at the Miramar Naval Air Station.

DOE/FETC recently competed a Product Design and Improvement (PDI) PRDA to resolve technology, system, and network issues. There remain major issues in MCFC operation, such as cathode corrosion (3,4,10). Major network and system issues are cost, heat loss management, footprint,

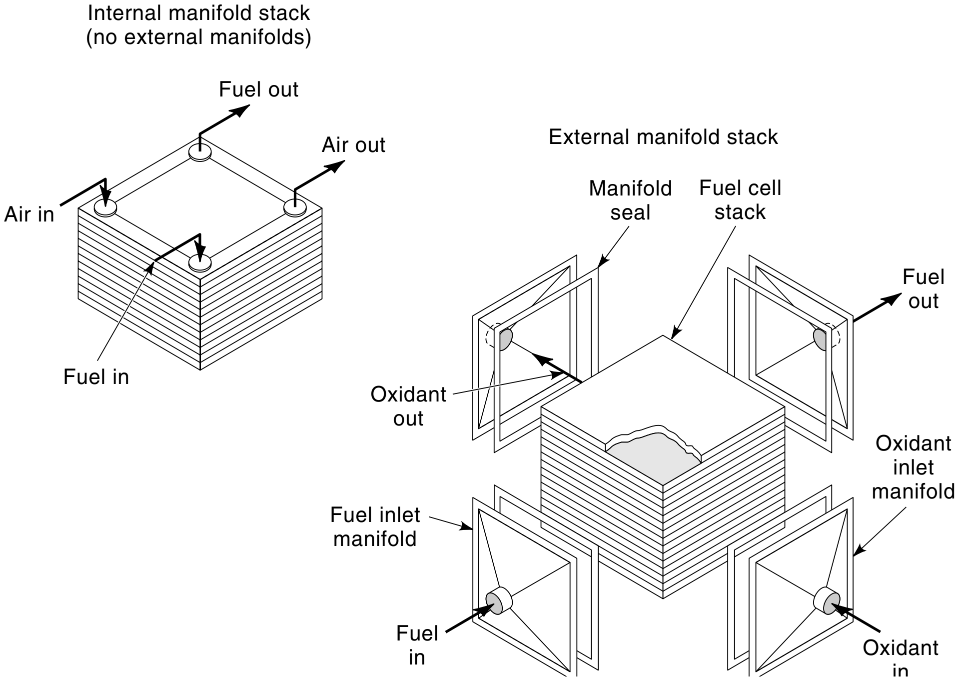

**Figure 3.** MCFC stack structural designs.

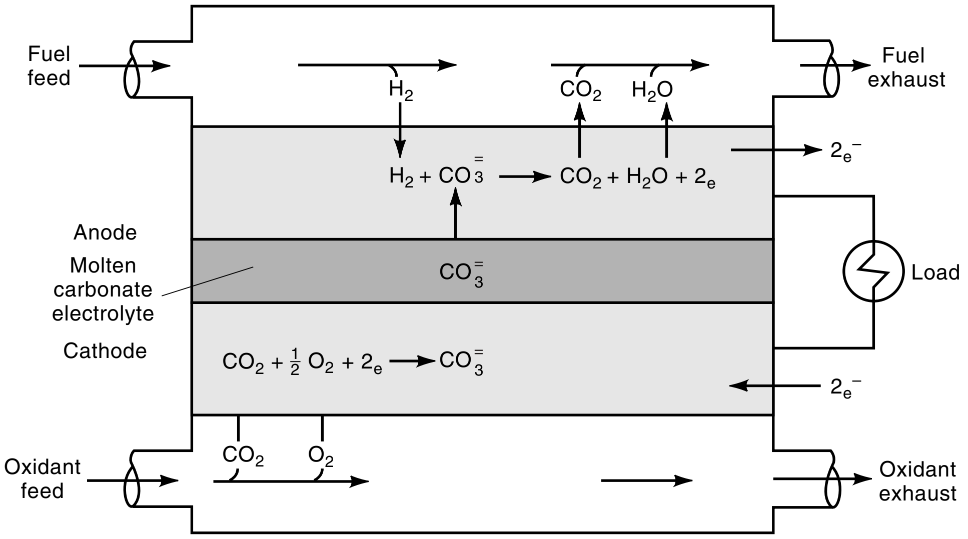

**Figure 4.** Operation of an MCFC.

packaging and integration, parasitic power losses, pressurization, and reforming. The objective of this work is to aim current MCFC stack development toward the development of a packaged, commercializable MCFC product. The PRDA will bring a multifueled, integrated, simple, low-cost, modular, market-responsive MCFC power plant to the marketplace. The development program will be based on a commercialization plan to manufacture and package, demonstrate, and aggressively market MCFC power plants. The PDI PRDA will culminate in the manufacture and construction of high-performance, low-cost, 500 to 2000 kW MCFC power-plant modules.

## SOLID OXIDE FUEL CELLS STATUS

Some general characteristics appear to be shared by many of the SOFC technologies being developed. While there is variability in materials being used for various components, the SOFC is an oxygen ion-conducting, solid-state device composed of a nickel–zirconia cermet anode, an yttria-stabilized zirconia electrolyte, a strontium-doped lanthanum manganite cathode, and a doped lanthanum chromite interconnect (1). The solid-state electrolyte of yttria-stabilized zirconia oxide is characterized by ionic conduction. The solid-state character of the SOFC electrolyte means there are few constraints on design. There is no problem of electrolyte containment, hence the flexibility and the wide variety of designs or forms being pursued.

The flexible SOFC may be operated over a wide range of temperatures. The theoretical thermodynamic efficiency (73% based on the hydrogen oxidation reaction at 927°C) is slightly lower for the SOFC than for the MCFC and the PAFC. However, the overall efficiencies of SOFC systems are more than those of the PAFC and certainly rival those of MCFC system configurations.

Power densities for SOFCs are promising. Power densities of 2.0 W/cm$^2$ on hydrogen at 1000°C have been reported for SOFCs. The high-power density with thin-layered components could make the SOFC an attractive power-plant alternative. However, packaging and cost reduction will be required to make the SOFC promise a reality.

The high-temperature (1000°C) SOFC can provide greater fuel flexibility than lower temperature fuel cells, since the reforming reaction is favored at higher temperatures. Reforming heat requirements with low-temperature fuel cells can actually lower overall system efficiency for some fuel cells. Reforming is an important system consideration which will remain important in the absence of a low-cost hydrogen supply. In addition, a higher-quality heat produced by the high-temperature SOFCs results in better bottoming cycle performance in some system configurations.

Westinghouse Electric is the acknowledged world leader in tubular SOFC technology. The Westinghouse Electric tubular configuration is shown in Fig. 5. Several completely packaged and self-contained generators, up to nominal 25 kW size, have been manufactured and tested by Westinghouse Electric. A pre-pilot manufacturing facility currently produces the cells (tubes), bundles, and generators. The length of the tubes has been scaled up to a nominal 2 m in length. The porous air support tube has recently been eliminated. The cell is now supported by the air electrode. The Westinghouse Electric technology has been validated to a far greater extent than any other SOFC technology. Multiple tube tests have been successfully conducted for more than 65,000 h, with less than 1% per 1000 h degradation. Pressurized operation of the tubular SOFC has recently been demonstrated at Ontario-Hydro.

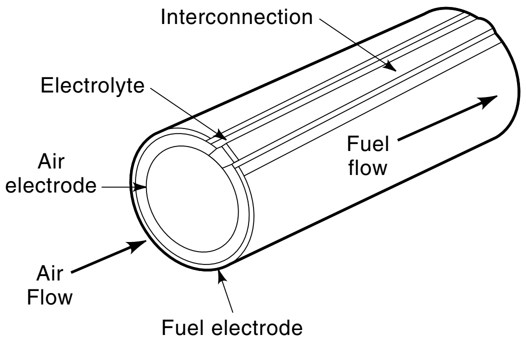

**Figure 5.** Westinghouse SOFC design.

A 100 kW generator test, in the Netherlands, is also planned for the 1996–1997 timeframe (12–16).

Several planar designs are also under development. Organizations developing planar designs include the Institute of Gas Technology (IGT), Ceramatec, Ztek, Technology Management Incorporated, and Allied Signal Aerospace Corporation. These developers hold strong patent positions on cell designs, which is essential for low-cost manufacturing.

IGT is developing an 800°C, intermediate-temperature, internally manifolded planar design. This trilayer IGT design, shown in Fig. 6, has, according to IGT, the advantages of more effective gas flow patterns, more compact design and cell stacking, more efficient current and voltage transfer from cell to cell, and more cost-effective manufacture (17). The IGT design is an internally manifolded fuel cell design using pressed metallic plates called IMHEX®. Because the IMHEX® design has no external gaskets and seals, only compression seals are necessary to obtain good sealing. The ceramic bipolar separator plates in the SOFCs currently under development are the single most expensive component. These make up more than 80% of the total materials and fabrication costs of the cell components (18). IGT replaces the ceramic separator plates with nickel-based metallic separator plates, thus lowering cost significantly. Since at 800°C the zirconia electrolyte will have high-internal-resistance losses, IGT is using the provskite gadolinium-doped barium cerium oxide. IGT may utilize the Argonne National Laboratory glass/ceramic composite seals, which could sidestep most of the problems associated with glass-only or cement-only manifold seals.

The Ceramatec design, CPn®, consists of stacks and a fuel processor, and it places some cells in a series rather than in parallel to obtain greater efficiency. Ceramatec has attained a power density of 0.18 W/cm$^2$ (167 W/ft$^2$) and a current density of 250 mA/cm$^2$ (230 A/ft$^2$). Ceramatec has tested a 1.4 kW module and has a limited partnership with Babcock and Wilcox (19,20) for the commercialization of the technology. Ztek uses a radial design stacked into two-stack modules which are then combined into arrays. Ztek, along with EPRI and Tennessee Valley Authority, has completed testing a 1 kW stack (21,22). Technology Management Incorporated uses an Interscience Radial Flow design in which each cell is made up of four layers, with sealing being achieved through the use of rings which also form the internal fuel and air manifolds. Small stack testing from one to ten cell stacks has been performed. Power densities around 0.08 W/cm$^2$ (75 W/ft$^2$) have been attained (23). Allied Signal Aerospace Corporation is developing the monolithic and flat planar designs and is now using tape-calendaring to produce a thin-electrolyte, reduced-temperature fuel cell with a potentially low manufacturing cost (24,25).

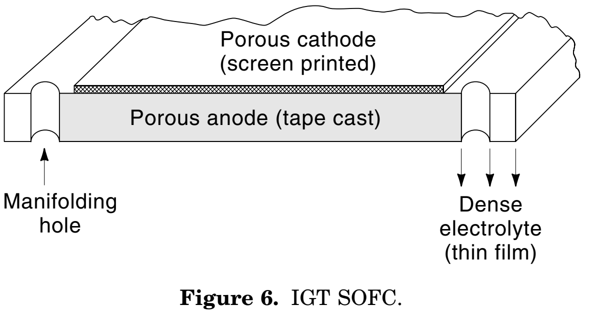

**Figure 6.** IGT SOFC.

It is often difficult to determine if the SOFC materials and their electrochemical and physical properties, per se, or if the individual SOFC designs contribute more to performance, as measured by power density, efficiency, longevity (or durability), cost, packagability, and system integrability. A variety of both material and design-related issues are being addressed.

## NETWORKS

In conventional fuel cell systems, multiple stacks have been arranged in parallel with regard to the flow of reactant streams. Networking (26–30) improves upon conventional MCFC system designs in which multiple stacks are typically arranged in parallel with regard to the flow of reactant streams. As illustrated in Fig. 7(a), the initial oxidant and fuel feeds are divided into equal streams which flow in parallel through the fuel cell stacks.

In an improved design, called an MCFC network, reactant streams are ducted such that they are fed and recycled among multiple MCFC stacks in series. Figure 7(b) illustrates how the reactant streams in a fuel cell network flow in series from stack to stack. By networking fuel cell stacks, increased efficiency, improved thermal balance, and higher total reactant utilizations can be achieved. Networking also allows reactant streams to be conditioned at different stages of utilization. Between stacks, heat can be removed, streams can be mixed, and additional streams can be injected.

MCFC stack networks produce more power than conventional configurations because they more closely approximate a reversible process. The Nernst potential is the voltage which drives reversible electrode reactions. This reversible voltage, generated by the overall cell reaction, is a function of the local temperature, pressure, and reactant concentrations. As reactants are utilized, their concentrations change. Since Nernst potential is dependent upon the concentrations of reactants, it varies with the degree of utilization.

In a conventional power plant, the fuel is utilized in a single stack, and all the current is generated at a single voltage. In networks, stacks in series each utilize only part of the fuel. The network can produce more power because most of the total charge is transferred at increased voltages. When the total fuel utilization of each system is optimized for maximum efficiency, the efficiency of the fuel cell stacks networked in series can be nearly 10% greater than that of the stacks arranged in parallel.

Arranging fuel cell stacks in series offers several other advantages over conventional fuel cell powerplates. Placing stacks in series also allows reactant streams to be conditioned at different stages of utilization. Between stacks, heat can be consumed or removed (methane injection, heat exchange), which improves the thermal balance of the system. The composition of streams can be adjusted between stacks by mixing exhaust streams or by injecting reactant streams.

## HIGH-EFFICIENCY FUEL CELL GAS TURBINE SYSTEMS

One of the most promising developments in fuel cell power plants is the conceptual development of very high efficiency fuel cell gas turbine power plants (31–40). Studies have indi-

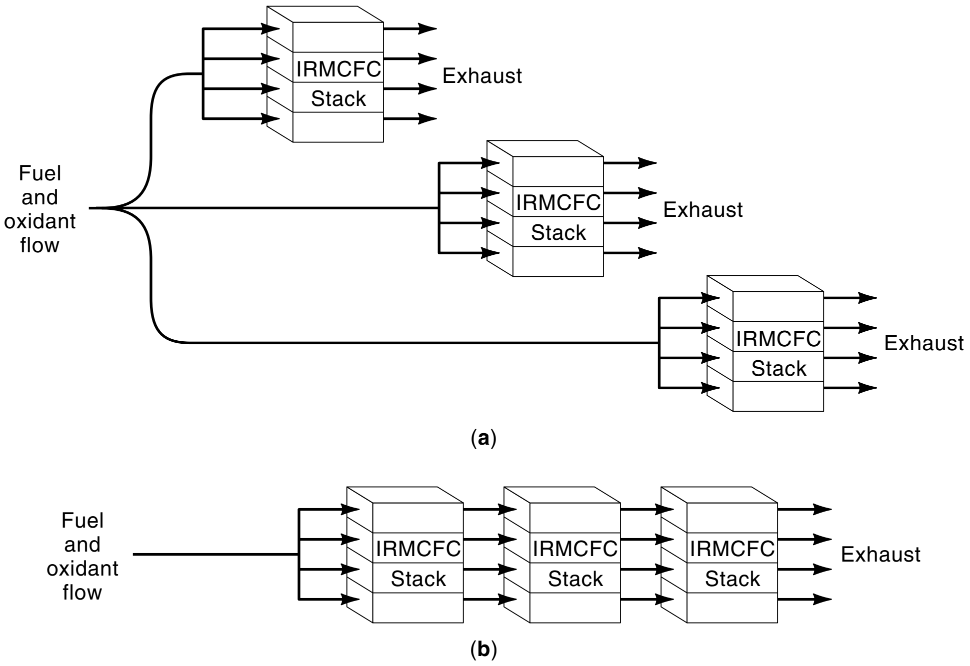

**Figure 7.** (a) Parallel flow of reactant streams through stacks. (b) Series flow of reactant streams through stacks.

cated that this combination has the potential to increase the overall efficiency for the conversion of natural gas into electricity to over 70%.

Because of the synergistic effects leading to the higher efficiencies and lower emissions achieved by combining a fuel cell and a gas turbine into a power generation system, many potential system configurations have been developed (39). These include the natural gas, indirect-fired, carbonate fuel cell bottomed, combined cycle and the topping natural gas/solid oxide fuel cell combined cycle for distributed power and on-site markets in the 20 to 200 MW size range. Most of these large fuel cell/gas turbine systems utilize a steam cycle to achieve high thermal efficiency. The latter is shown in Fig. 8. In addition, smaller systems not incorporating a steam turbine are ideal for the distributed power and on-site markets in the 1–5 MW size range. Table 2 summarizes some of these fuel cell gas turbine power plants (40).

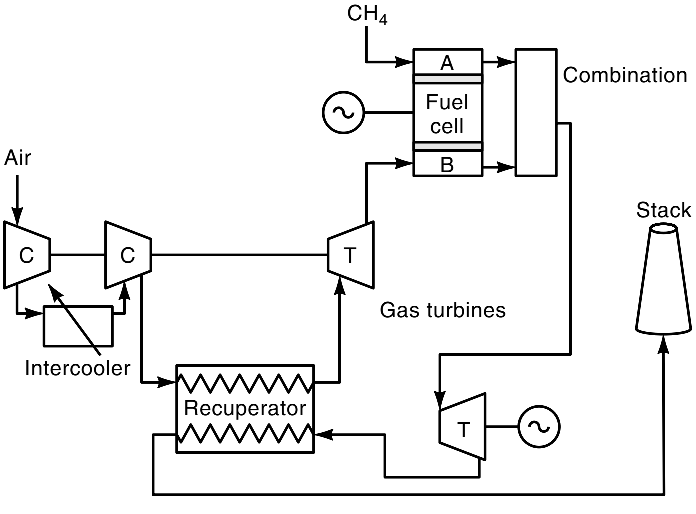

**Figure 8.** Gas turbine/fuel cell.

The combination of the fuel cell and turbine has the potential for enormous synergies, in that it offers a solution to two important problems: (1) the low efficiency and relatively high $NO_x$ emissions of small gas turbines and (2) the high cost of small fuel cell power plants.

Small gas turbines, with capacities of less than 10 MW, typically have efficiencies in the 25 to 30% (LHV) range. Small high-temperature solid oxide and molten carbonate fuel cell power plants are predicted to cost \$1000 to \$1500/kW, when commercially available in the years after 2000. By combining the two systems, and in effect allowing the fuel cell to serve as the combustor for the gas turbine and the gas turbine to serve as the BOP for the fuel cells, the combined efficiency is raised to the 58 to 63% range even at sizes of less than 3 to 10 MW, and $NO_x$ emissions are essentially eliminated. The capital cost of the combined system is markedly reduced relative to the cost of a stand-alone fuel cell power plant of that size and is equal to or less than that of a gas turbine power plant of that size. The combined efficiency is much higher than either stand-alone plant of either technology.

If the early efforts are successful in commercializing these combination cycle products, the foundation will be laid for scaling up the technology to large-scale powerplants. This is important, in that the combination at the scale of 200 MW or more can achieve efficiencies of 75% or more. This is significantly higher relative to other technologies for generating electricity from natural gas, and as a result, has the potential to significantly reduce carbon dioxide emissions. In comparison, the best currently available, large-scale, gas-fired, combined cycle power plants have an efficiency of about 58%. That level will likely increase to 60 to 62% over the next decade. The highest efficiencies currently projected for several fuel cell technologies, which are now under development, are in the range of 55 to 65% for stand-alone fuel cell power plants.

**Table 2. Potential Power Plants**

| Vendor | Product Size (MW) | Efficiency (LHV) | Fuel Cell | Gas Turbine | Availability | Mature Price Target ($/kW) |
|---|---|---|---|---|---|---|
| Westinghouse | 3 | 61 | Pressurized | Heron | 1999 Prototype | 1200–800 |
| | 5 | 69 | Tubular SOFC | Heron | | |
| | 10 | 60 | One 1.8 MW unit | Allison | | |
| | | | Two 1.8 MW units | | | |
| | | | Multiple 1.8 MW units | | | |
| Solar | 1–2 | 58–63 | Pressurized Planar SOFC | 4 : 1 PR Turbo-expander | 1999 Prototype | <650 |
| ERC | 3.3 | 65 | Direct MCFC | Steam bottoming gas turbine topping and steam bottoming | 1250 | |
| | 3.8 | 68 | | | | |
| Ztek | 0.2 | | Pressurized | 50–100 kW | 1998 Prototype | 1000–1500 |
| | 50 | | Planar SOFC | | | |
| Allison | 10–25 | 59–62 | Unspecific | Allison 501 KB/KM or ATS | ATS engine in 1998–2002 | 425–450 for engine only |

## THE WORLD POWER MARKET

Fuel cell technology is expected to play a role in the world power market. By the year 2010, it is estimated that approximately 130 gigawatts (GW) of new generating capacity will be installed in the United States, while in world markets and within a much closer timeframe, nearly 550 GW of generating capacity will be added (41). Fuel cell commercialization opportunities in the U.S. market are focused in several areas: repowering, central power plants, industrial generators, and commercial/residential generators.

The worldwide market for additional electric generation capacity dwarfs the domestic market. Nearly 550,000 MW of new capacity will be added by 2002. Estimates of plant repowering installations between 1999 and 2010 range from 15% to approximately 65% of the installed generating capacity. Most repowering will occur in central power plants: Fuel cell installations of 100 MW or more are targeted to this market, powered initially by natural gas and later by coal gas.

New generating capacity of approximately 100 GW will be required in the central powering market by 2010. Coal gas-powered fuel cell power plants are targeted to this market, with plants sized at 100 MW or more.

The market for additional industrial capacity by 2010 is estimated at 3 GW, and the market for additional commercial/residential capacity is estimated at 6 GW. These markets are targeted for early entry and will be a proving ground for natural-gas fuel cell power plants sized from 500 kW to 20 MW.

## THE CHANGING FACE OF ELECTRICITY GENERATION

Fuel cell power plants should provide a significant share of our electrical power in this decade and well into the next century (42–45). They are set to play a major role in a deregulated power industry. Large-scale plants will compete in the baseload power generation market, while smaller plants will penetrate the distributed power and cogeneration markets.

Baseload generation currently relies on coal-fired, nuclear, or natural-gas-fired technologies. The natural-gas-fired fuel cell is more efficient, more environmentally friendly, and potentially more cost-effective than the current technologies in the baseload market segment.

Some utilities consider that the success of fuel cells and some other technology hinges on the emergence of dispersed power generation. Dispersed power generation is one of the phenomena accompanying the deregulation or disruption of the electric power industry. Hence, fuel cells are viewed by some as a disruptive technology since it is helping "introduce customer choice" and offers a set of attributes suitable for dispersed power generation.

Deregulation of the electric industry is about capturing system economies and efficiencies down to a point where the payout/return is not worth the investment/trouble. Self-dispatching of fuel cells in the deregulated industry would be done to minimize cost or maximize profit—that is, make the most money or save the most money. However, economics cannot control decisions such as frequency control, voltage control, and spinning reserve since decision-making takes too long. These control decisions will probably not be economic ones.

Fuel cells should be able to capture economies in a deregulated industry. The more aggressive, nonpassive decision-making which will accompany deregulation will lead to opportunities for fuel cells. However, utilities need help in determining where fuel cells would benefit them; passive decision-making by utilities, not looking at other economic alternatives, just going ahead and doing the standard substation upgrade—trashing power quality and raising costs for all customers—hurts fuel cells and other new technologies.

Technologies for the distributed power and cogeneration market segment include gas turbines, diesel engines, hydroelectric plants, solar and wind generation, and already commercialized PAFC. In this market, MCFC and SOFC plants also hold distinct advantages: The smaller applications favor fuel cells for their high-efficiency, low-emission, and load-following capabilities. In addition, the attractiveness of economical and reliable on-site power generation may significantly expand the market for small-scale commercial and industrial power plants. The Clean Air Act mandates significantly reduced emissions of sulfur and nitrogen compounds from existing power plants and sets strict limits on emissions from new sources. In the short term, these restrictions may encourage the use of underutilized fuels, particularly natural gas, by electric power producers.

## SPECIFIC FUEL CELL ATTRIBUTES AND MARKET APPLICATIONS

Fuel cells have many attributes which make them suitable for distributed generation applications (42). These include low emissions, high efficiency, production of high-grade waste heat, modularity, reliability, unmanned operation, and fuel flexibility, to name a few.

Increasing power generation without increasing emissions is the challenge facing power producers today, and fuel cells are a key approach to balancing our energy needs with our desire for a cleaner, healthier environment. Fuel cell power plants produce dramatically fewer emissions; and their byproducts, primarily water and carbon dioxide, are so environmentally friendly that natural-gas fuel cell power plants have a blanket exemption from regulations in California's South Coast Air Quality Management District—possibly the strictest in the nation.

Fuel cells convert a remarkably high proportion of the chemical energy in fuel to electricity. Even without cogeneration, fuel cell power plants promise to be nearly twice as efficient as conventional power plants, and efficiency is not a function of plant size or load: Small-scale fuel cell plants are just as efficient as large ones, and operation at partial load is as efficient as at full load. Higher efficiencies mean fuel savings for the producer and cost savings for the consumer.

High-grade waste heat from fuel cell systems is perfect for use in commercial, industrial, and residential applications, including cogeneration, heating, and air-conditioning. When by-product heat is used, the total energy efficiency of fuel cell systems approaches 85%.

The fuel cell stack is the basic component of a fuel cell power plant. Stacks are combined into modules, and plant capacity is determined by the number of modules. Individual modules can go from idle to full load in minutes. Modular plants can help planners overcome many difficult expansion problems. Mass-assembly construction techniques and shorter lead times for installation reduce the capital risk in adding generating capacity. Capacity can be better matched to load, and the high costs of large new plants with underutilized capacity can be avoided.

Modularity also produces a flat economy of scale: The cost per kilowatt is about the same in small plants as in large ones; and because electrical efficiency is determined by individual cell performance, the number of modules in the power plant has little or no effect on overall efficiency. As a result, fuel cell power plants offer the same advantages at 25 kW as they do at 50 MW.

The modular nature of fuel cells allows power capacity to be added wherever it is needed. In the typical central power configuration, additional capacity is sited at the central plant or at substations. In a distributed power configuration, capacity is placed close to the demand. In high-growth or remote areas, distributed placement offsets the high costs of acquiring rights-of-way and installing transmission and distribution lines. A distributed configuration also eases public concerns about exposure to electromagnetic fields from high-voltage lines.

Smaller-scale distributed configuration power plants are perfect for commercial buildings, prisons, factories, hospitals, telephone switching facilities, hotels, schools, and other facilities. In these applications, consumers get the best of all worlds: high-quality power that is economical and reliable. On-site power conditioning eliminates the voltage spikes and harmonic distortion typical of utility grid power, making fuel cell power plants suitable even for sensitive electronic loads like computers and hospital equipment; and in many cases, utility grid backup reduces the need for expensive UPS systems.

Fuel cells promise to be one of the most reliable, if not the most reliable, power generation technology. They are now being used by hospitals, hotels, and telephone companies as part of critical UPS systems.

Unmanned fuel cell operation may mean big savings in some applications. This is especially true for dangerous and metropolitan areas. Fuel cell designs with small footprints and easy installation are a must in cities. The footprint of the fuel cell is currently higher than that of turbines.

Fuel cells need hydrogen, which can be generated internally from natural gas, coal gas, methanol landfill gas, or other fuels containing hydrocarbons. Although most market-entry fuel cell plants are fueled by natural gas, fuel flexibility means that power generation can be assured even when the primary fuel source is unavailable.

Potential customers have also identified premium power, grid support, voltage control, reliability improvement, VAR control, frequency control (fuel cell is a smart transformer), spinning reserve, incremental (modular) load growth (small incremental cost), emission offset, transmission and distribution (T&D) deferral, and customer retention as uses for the fuel cell. Fuel cell's value is dependent on "what it does, where it does it, and when it does it."

The ideal fuel cell application would be for a new prison, hospital, or orphanage, that is, something with bed and requiring heat, electricity, and a UPS in an area with no T&D infrastructure, so credit could be given for deferment of a substation upgrade; the fuel cell could be owned and operated by a "utility entity" having a distributorship taking credits for environmental benefits. The point is that the right application needs to be a high-value application which can take credit for many quantifiable benefits.

The building application is potentially important for fuel cells. It is obvious that fuel cells can compete only on a life-cycle cost basis. The longer the life, the better. Building operators do not want to get into the power business. One opportunity is to own and lease power plants for the operators. New ownership modes need to be explored. The retrofit market is important for buildings. Developers must be patient. It will take many years for fuel cells to penetrate any market.

## INTERNATIONAL MARKET APPLICATIONS

Some countries, such as Japan and the European community, are firmly committed to the entire gamut of fuel cell development, as is evidenced by their funding commitment from both government and private industry, extensive research facilities, and commitment of personnel (46).

Large companies, such as Fuji, Mitsubishi Electric Company, Mitsubishi Heavy Industries, Toshiba, and Hitachi are involved in fuel cell development in Japan. This contrasts with the situation in the United States, where several of the fuel cell developers are smaller, entrepreneurial companies. The capital investment required for establishing manufacturing and distribution infrastructure should be easier to obtain for these large Japanese corporations than it will be for the small U.S. corporations.

Japan's electric industry has very high capital and operating costs and might be an excellent place to introduce new, higher-cost technologies like the PAFC. This high cost may be attributable, in part, to both high fuel costs and inefficiencies in the Japanese goods and services distribution system. Some Japanese companies favor the deregulation of the electric industry, which is occurring in the United States and promises to lower electricity costs.

There is a PAFC unit in Japan at a Nippon Telegraph and Telephone switchboard in Yokohama, Japan. The waste heat is also used to cool the equipment, using absorption chillers. This is a large market in Japan, where 0.5% of electricity is consumed by telephone switchboards. Also, Tokyo Gas will be selling heat-recovery-type absorption chillers as a future product.

Due to low capital costs, Tokyo Gas considers the natural gas engine to be the primary competition of the PAFC, especially in peak shaving and UPS applications.

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