FUEL CELLS

SYNOPSIS

This Tech Data Bulletin provides an overview of current fuel cell technology and its applications.

INTRODUCTION

In recent years, energy conservation and environmental issues have prompted researchers and the electric power industry to search for more efficient and environmentally friendly electric generation technologies. As a result, alternative energy resources, such as photovoltaics and chemical conversion systems, have assumed greater significance. Chemical conversion systems, such as batteries and fuel cells, directly convert chemical energy to electricity. Fuel cell technology has received increasing attention because of its high efficiency (~40-50 percent) and negligible emissions.

The theoretical concepts governing the development of fuel cell technology have been well understood for over a century. However, the American space program benefited from the first practical applications of this technology. Fuel cells supporting the space programs use pure hydrogen and oxygen for fuel and oxidant, respectively. Fuel cell power plants were used for the Gemini and Apollo programs; and, in the 1980s, a fuel cell power plant was built for the space shuttle incorporating many significant technological and design advances. These space applications are considered very successful.

The initial transfer of fuel cell technology to terrestrial applications proved difficult. The major obstacle was the switch from pure hydrogen and oxygen to impure hydrogen and air. However, use of phosphoric acid and molten carbonate has overcome this problem.

THEORY

A fuel cell is an electromechanical device that combines a hydrogenrich fuel with an oxidant (normally air) and converts the chemical energy of the mixture directly to electricity without intermediate combustion steps. A fuel cell is constructed with a cathode (negatively charged electrode), an anode (positively charged electrode), an electrolyte, and an external electrical circuit connecting the cell to the load (Figure 1). The electrolyte mixture is capable of conducting electric current from the movement of its positive and negative ions. A typical fuel cell generates low voltage, direct current (dc) electrical power. Desired voltages are obtained by connecting several fuel cells into a cell stack (Figure 2). In essence, the construction of a fuel cell is similar to that of the ordinary storage battery. However, the main difference lies in the ability of the fuel cell to produce energy continuously while fuel is supplied. In a storage battery, the fuel and oxidant are self-contained and therefore a battery must be replaced once the fuel and oxidant are consumed. In a fuel cell, the fuel and oxidant are supplied continuously.

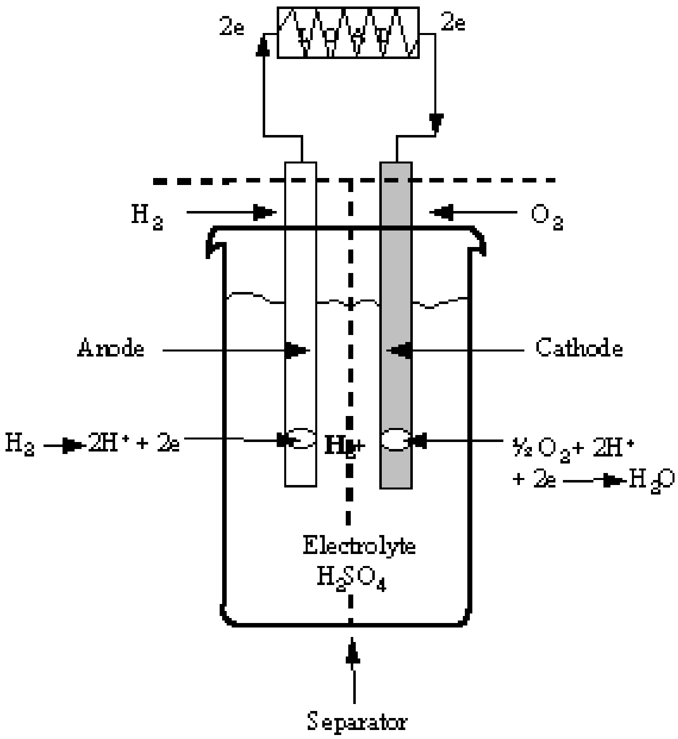

Figure 1. Operation (reaction mechanism) of the Fuel Cell

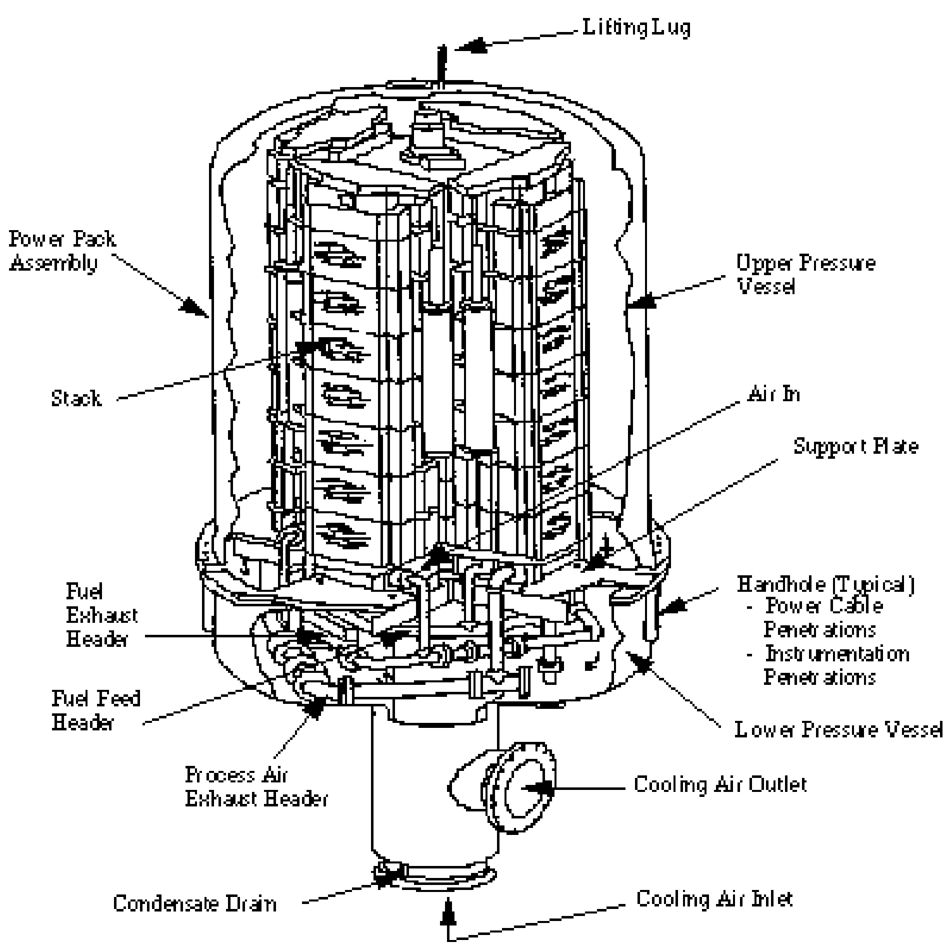

Figure 2. 375 kW to 400

kW Air-Cooled Demonstration Module

A brief description of the roles of these components follows.

- The anode (fuel electrode) provides an interface between the fuel and the electrolyte, catalyzes the fuel reaction, and provides a path through which free electrons are conducted to the load via the external circuit.
- The cathode (oxygen electrode) provides an interface between the oxygen and the electrolyte, catalyzes the oxygen reaction, and provides a path through which the electrons are conducted from the load to the oxygen electrode via the external circuit.
- The electrolyte acts as a gas separator between the hydrogen (fuel) and the oxygen (oxidant) to prevent mixing and direct combustion. The electrolyte also completes the electrical circuit of transporting ions between the electrodes.

To illustrate the operation of fuel cells, consider the simple acid electrolyte cell shown in Figure 1. In this fuel cell, two catalyzed carbon electrodes are immersed in an acid electrolyte and separated by a gas barrier. As fuel (hydrogen) and oxidant (air/oxygen) are fed into the fuel cell, hydrogen and oxygen bubbles are formed across the surfaces of the fuel and oxygen electrodes, respectively. The hydrogen fuel reacts with the catalytic surface of the fuel electrode, forming hydrogen ions and electrons. The hydrogen ions move across to the surface of the cathode, passing through the electrolyte and the gas barrier.

Simultaneously, the electrons flow through the external electrical circuit to the cathode. At this point, the oxygen, hydrogen ions, and free electrons combine on the surface of the oxygen electrode (cathode) to form water.

FUEL CELL TECHNOLOGY

Currently, three major fuel cell types are considered for possible commercialization: the phosphoric acid fuel cell (PAFC); the molten carbonate fuel cell (MCFC); and the solid oxide fuel cell (SOFC).

PHOSPHORIC ACID FUEL CELL. The PAFC uses phosphoric acid as an electrolyte. The PAFC system operates at temperatures ranging from 150C to 200C. Operation beyond this range is inefficient, as phosphoric acid is a poor ionic conductor at lower temperatures, while other materials used in the system (carbon and platinum) may become unstable at higher temperatures. PAFC's advantages include electrolyte stability; the ability to highly concentrate phosphoric acid (~100 percent); and the high efficiency of anode performance even in the presence of fuels containing carbon monoxides. The main disadvantage is the sluggish performance of the cathode (Reference 1).

MOLTEN CARBONATE FUEL CELL. Molten carbonate fuel cells are the second generation after the PAFCs. MCFCs use an alkali metal carbonate (Lib, NA, K) as the electrolyte. However, an alkali metal carbonate must be in the liquid phase to function as an electrolyte. Therefore, the MCFC must operate at temperatures above the melting point of the electrolytes. MCFC operating temperatures range from 600C to 700C. MCFCs provide the highest electrical efficiency among existing fuel cell technologies. MCFCs offer several attractive advantages, especially for the industrial sector. MCFCs use carbon monoxide and impure hydrogen as fuel and eliminate the use of noble metals. Further, the MCFC produces high-quality waste heat available for cogeneration to improve overall system efficiency. The high operating temperatures, however, impose limitations and constraints on choosing materials suitable for long lifetime operations (Reference 1).

SOLID OXIDE FUEL CELL. This type of fuel cell uses solid, nonporous metal oxide electrolytes. The metal electrolyte normally used in manufacturing SOFCs is stabilized zirconia. Operating temperatures of SOFCs range from 900C to 1000C. SOFCs offer advantages similar to MCFCs; the yield of highquality waste heat available for cogeneration; and use of nonnoble metals. In comparison with MCFCs, SOFCs have similar drawbacks, namely the constraints on materials suitable for long lifetime operations (Reference 1).

Of the three major fuel cell technologies, the PAFC is the most advanced; currently, 200 kw PAFC units are available in the market (Reference 2). MCFC technology is considered to be about five years behind the PAFC (Reference 3).

FUEL CELL ENERGY SYSTEM

A practical fuel cell power plant system consists of at least three basic sections: a fuel processor, a fuel cell power section, and the power conditioning unit. Figure 3 presents a block diagram of a typical fuel cell power plant. A brief functional description of each subsystem follows.

FUEL PROCESSOR UNIT. This subsystem is responsible for managing the fuel supply to the power section. The fuel processor's function can vary from simple control of fuel flow to complex chemical processing. In the latter case, the fuel processor unit converts hydrocarbon fuel to hydrogen. Hydrocarbon fuels include natural gas, light and heavy oils, coal, industrial off-gases, and biomass (Reference 4). The fuel processor is also responsible for filtering the fuel, because small amounts of sulfur compounds may cause a drastic, unacceptable drop in power production. Fuel cells with high operating temperatures have the capability to process fuel internally within the cell stacks.

FUEL CELL POWER UNIT. This section is the heart of the fuel cell power plant. In this subsystem, the chemical reactions responsible for producing electric power take place. The power unit converts the mixture of hydrogen fuel and the oxidant (air) into direct current (dc) power. The power subsystem consists of one or more cell stacks. Each stack contains many individual fuel cells arranged in a series to provide the desired voltage.

POWER CONDITIONING UNIT. This unit converts the output power of the fuel cell to the type of power required by the application, from a simple voltage controller to a complex dc-ac inverter.

ADDITIONS. Stand-alone fuel cells may require auxiliary systems (e.g., coolers, heaters, controls, or a secondary power supply). For example, water treatment systems may be needed to remove excess water produced by the fuel cell.

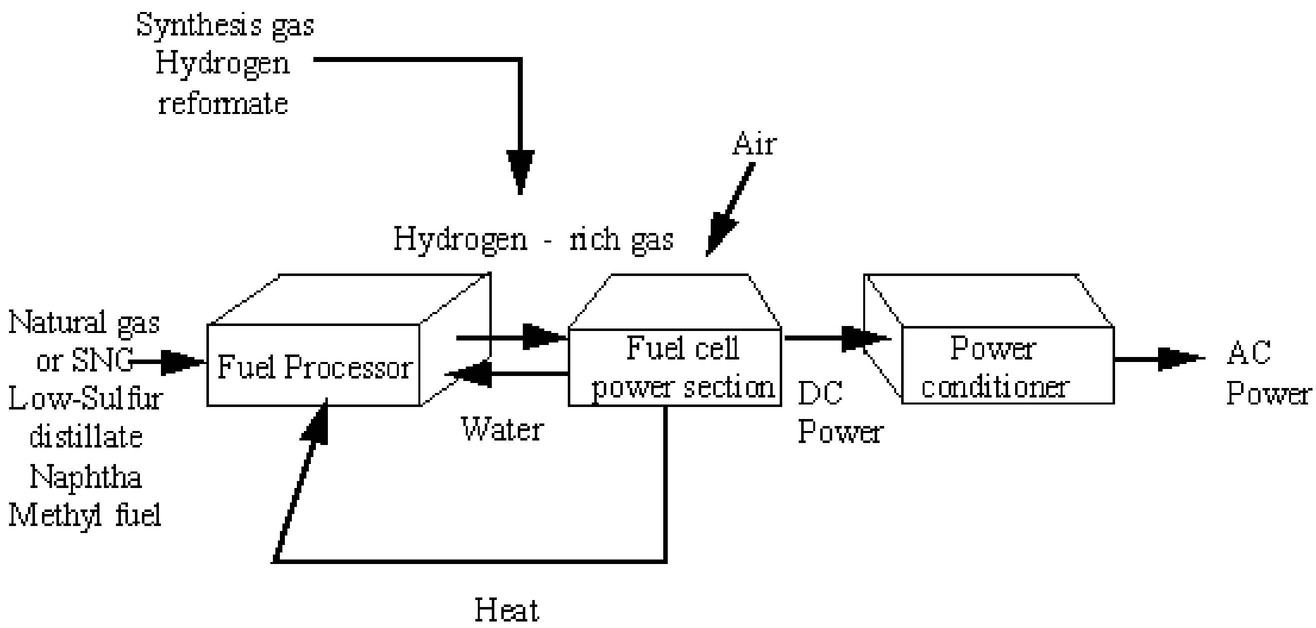

Figure 3. Generalized Schematic of a Fuel Cell Power Plant

APPLICATIONS AND FIELD TESTS

Many applications and field tests involving fuel cell power plants have been completed. Life-cycle cost comparisons between fuel cells and conventional power resources were conducted by the Air Force (References 5-9). Recently, field tests of precommercial PAFC power plants with capacities ranging from 12 kW to 4.5 mW have been completed. In these tests, 46 pipeline gas-fueled 40 kW fuel cell units were used. The units achieved electric efficiency of about 36 percent. With waste heat recovery (cogeneration), the efficiency of the units could reach 70 percent. This point was demonstrated recently in another field test of a 50 kW unit (Reference 4). Air Force applications and field tests include central power stations on military bases, remote power supplies, dispersed power supplies, and cogeneration. A brief description of such applications follows.

- A 20-year life-cycle cost (LCC) analysis was developed to assess the possible use of fuel cells to replace diesel-driven generators at Seek Igloo radar sites. This study concluded that an estimated $5 million savings could be realized over a 20-year period with the use of fuel cells.
- Under the category of dispersed power supplies, a study was conducted of replacing the existing gas turbine-powered generators at Forward Air Controller radar sites with fuel cells (Reference 7). The main advantages of the gas turbine system were its light weight, capability to operate in rough environments, and fast startup characteristics. However, the gas-turbine consumed about 17.5 gallons per hour at full load (an efficiency of about 10 percent). Fuel cells offer higher electrical efficiency, but are much larger and heavier.

In this study, a 60 kW fuel cell was designed to supply the necessary power to perform the radar mission. In the application, two 60 kW gas turbines and two 60 kW fuel cells were used to increase available power. Each fuel cell unit weighed 8,100 pounds; each gas turbine unit weighed 1,900 pounds. However, if a comparison includes the fuel required to complete a two-week mission, then the fuel cell system's weight is comparable to the gas turbine unit (Table 1). The study revealed that a 65 percent reduction in fuel consumption could be achieved by using fuel cell power plants.

A 20-year LCC comparison of the two systems is shown in Table 2. Using fuel cells could yield as much as $440,000 in savings for the 20-year period. Note that the LCC provided in Table 2 is a comparison of single units .

Table 1 Total System Weight Needed to Complete a 2-Week Forward Air Controller Mission Source: Reference 5

	Gas Turbine	Fuel Cell
R.T. Unit(lbs)	4,000	16,000
Fuel Wt.(lbs)	36,400[1]	12,800[2]
Total Wt.(lbs)	40,400	28,800

[1]17 gals./hr
[2]6 gals./hr

Table 2 LCC of Power Plants for Forward Air Controller Radar Source: Reference 5

	Gas Turbine	Fuel Cell
Unit Capacity	$60	$60
Intial Cost	$0	$360,000
Replacement Cost	$32,400	$0
Operating Personnel	$286,000	$286,000
Maintenance and Supplies	$149,000	$93,200
Fuel	$1,279,600	$451,500
Operations Transport and Special Equipment	$75,600	$187,600
Total LCC	**$1,822,600**	**$1,378,300**

FUEL CELL ADVANTAGES

In addition to being very efficient electrical power generators, fuel cells are also considered an excellent alternative energy resource from the environmental standpoint. Fuel cells are quiet, employ no moving parts, and produce negligible emissions. Emission tests conducted on the International Fuel Cell 200 kW PAFC preproduction power plant fueled by pipeline gas revealed all emissions were far below Federal, state or air quality district standards. The test's emissions were 3.58 mg/Nm^3 of NOx, 35.82 mg/Nm^3 of CO, and 25.79 mg/Nm^3 of total hydrocarbons (Reference 4). Sulfur emissions were nonexistent. The excess water produced by fuel cells was at a temperature and quality to permit discharge to sanitary sewer systems (Reference 2).

It is clear that fuel cell use will have a positive impact on the environment. If fuel cells replace the combustion engine in transportation, CO2 emissions could be reduced by one-half and CO emissions virtually eliminated.

Further, fuel cells can successfully meet local thermal loads, leading to an increase in power plant efficiency to about 85 percent.

THE FUTURE

The first generation of commercial on-site fuel cell units, the PAFC, recently reached the market. Many ideal applications for fuel cells exist in the civilian and military sectors. While the on-site PAFC operates at temperatures near 200C, other technologies under development operate in the range of 600-700C (MCFC) and 900-1000C (SOFC). These advancements, expected to reach the commercial stage about 1998, will provide higher quality heat (an especially attractive feature for industrial applications). In addition to being cost-effective, field tests have demonstrated that fuel cells provide superior environmental performance.

Fuel cells offer silent operation; modular construction; optional fuels; high efficiency over a wide load range; and minimum siting restrictions. Future fuel cell technology will employ a wide range of domestic fuels, including coalderived gases. Experts are convinced this can be achieved without a significant decrease in efficiency or environmental performance.

Although PAFC technology currently is the most advanced, many important issues must be further addressed, particularly cost and lifetime. The current cost of a multi-kilowatt plant is approximately $6000/kW installed. The established goal of $2000/kW may be achieved by the year 2000. The cost goal of individual stacks is $500/kW.

The lifetime of PAFCs remains an unknown. Many field tests have proven that the expected lifetime of PAFCs is greater than 10,000 hours. However, the operating life goal is 40,000 hours. To date, no field test has resulted in operating life close to the desired goal.

The future of fuel cells looks bright. Each year, more than $200 million is spent on development and commercialization of fuel cells. Low noise and reduced electromagnetic pulse (EMP) make fuel cells a very attractive solution to many energy problems in the military sector. Some of the applications under consideration include electric power production, cogeneration,and motive power.

The Air Force Civil Engineer Support Agency through the U. S. Army Construction Engineering Research Laboratory is placing fuel cells at selected locations as demonstrations. Congressionally mandated and funded, installations have already occurred at the 934th Air Reserve Base, MN, Kirtland AFB NM, and Nellis AFB, NV. These have availability rates of 84 to 91 percent. Future locations include the 911th Air Reserve Station PA, Little Rock AFB AR, and Laughlin AFB TX. For more information on this program contact Mr. Larry Strother, HQ AFCESA/CESE, 139 Barnes Dr, Suite1, Tyndall AFB FL 32403-5319.

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