Introduction to the Future's Energy: Fuel Cells

Fuel cells are often described as being continuously operating batteries, but this is an incomplete idea. Like batteries, fuel cells produce power without combustion or rotating machinery. They produce electricity by utilizing an electrochemical reaction to combine hydrogen ions with oxygen atoms. Hydrogen ions are obtained from hydrogen-containing fuels. Fuel cells, unlike batteries, use an external and continuous source of fuel and produce power continuously, as long as the fuel supply is maintained.

Two electrodes, an anode, and a cathode form an individual cell. They are sandwiched around an electrolyte in the presence of a catalyst to accelerate and improve the electrochemical reaction.

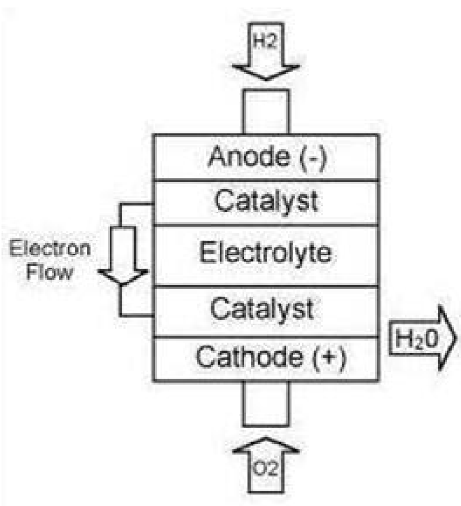

Figure 1 shows a fuel cell that uses fuel to create chemical reactions that produce either hydrogen- or oxygen-bearing ions at one of the cell's two electrodes. These ions then pass through the electrolyte, such as phosphoric acid, and react with oxygen atoms. The result is an electric current flowing between both electrodes plus the generation of waste heat and water vapor. This current is proportional to the cross sectional area of the electrodes. The voltage is limited electrochemically to about 1.23 volts per electrode pair, or cell. These cells then can be "stacked" until the desired power level is reached.

Figure 1: A scheme of a fuel cell

There are many types of fuel cells, differing only in their design, but they all function the same way. The type of electrolyte used classifies fuel cells. The table below summarizes the most popular fuel cells used today.

	FUEL CELL TYPE			
	Polymer Electrolyte Membrane	**Phosphoric Acid**	**Carbonate**	**Solid Oxide**
Electrolyte	Ion Exchange Membrane	Phosphoric Acid	Alkali Carbonates Mixture	Yttria Stabilized Zirconia
Operating Temp. °C	80	200	650	1,000
Charge Carrier	H^+	H^+	$CO_3^=$	$O^=$
Electrolyte State	Solid	Immobilized Liquid	Immobilized Liquid	Solid
Cell Hardware	Carbon- or Metal-Based	Graphite-Based	Stainless Steel	Ceramic
Catalyst	Platinum	Platinum	Nickel	Perovskites
Cogeneration Heat	None	Low Quality	High	High
Fuel Cell Efficiency, %LHV	<40	40-45	50-60	50-60

As previously stated, the type of electrolyte used not only defines the fuel cell but also gives the fuel cell its name. For example, the three major electrolytes used for stationary power generation are phosphoric acid, carbonate, and solid oxide and therefore, they are called the Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC), respectively.

The PAFC is the oldest technology used today. The electrodes are metal-based but require a platinum catalyst to convert ("reform") a natural gas fuel to a hydrogen-rich gas that is used in the chemical reaction. Due to system complexity, capital costs are higher and efficiencies are lower than what can be achieved using other types of fuel cells such as MCFC and SOFC.

Compared to the PAFC, the MCFC operates at higher temperatures, can operate at or slightly above ambient pressure, and uses less expensive, nickel-based electrodes. Reforming can occur inside the fuel cell stacks. Technologies using internal reforming are called Direct Fuel Cells and are inherently more efficient compared to external reforming fuel cell systems. DFCs can generate power at 50 to 60 percent efficiency in a single cycle. This far surpasses conventional generation technologies such as gas turbines, internal combustion engines, and steam turbines, which generate power at a maximum efficiency of 33 or 35 percent, limited by Carnot the cycle.

The SOFC approach is the least mature of the three. It uses a coated zirconia ceramic as the electrolyte the electrochemical conversion process occurs at very high temperatures that support internal reforming. The cells themselves may be either flat plates or tubular. There are basic manufacturing challenges still to be overcome if SOFC technology is to become commercially viable. SOFC promises to operate at moderately high efficiencies with a high-grade recoverable heat product.

Molten Carbonate Fuel Cell

The following describes in detail how fuel cell technology works. As previously mentioned, all fuel cells operate the same and differ only in the electrolyte used. To facilitate our discussion, the MCFC technology, which uses natural gas as a fuel, will be profiled.

The operating principles for a carbonate fuel cell are simple in concept. The reactants — fuel and an oxidant (in this case, air)— are fed to the cell's electrodes. Ions are transported through the electrolyte sandwiched between the electrodes, creating a current equal to the amount of electric energy needed by the system connected to the fuel cell (also called load). The basic reactions are as follows:

Internal reforming (using a methane):

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

With hydrogen now available, we have the following electrochemical reactions.

At the anode:

$$H_2 + CO_3^{=} \rightleftharpoons H_2O + CO_2 + 2\,e^-$$

At the cathode:

$$\tfrac{1}{2}\,O_2 + CO_2 + 2\,e^- \rightleftharpoons CO_3^{=}$$

and the overall reaction is:

$$H_2 + \tfrac{1}{2}\,O_2 + CO_2\,(\text{cathode}) \rightleftharpoons H_2O + CO_2\,(\text{anode})$$

(Notice that the CO molecules do not directly participate in the fuel cell reactions, but act to produce more H_2 by reacting with H_2O in the reforming reactions, commonly called the water shift reaction).

While natural gas is the primary fuel, with appropriate cleanup, any hydrogen-rich gas — including gas from landfills, digesters, coalmines, or liquid fuels — can be used in the fuel cell. Note that electricity, heat, water vapor, and carbon dioxide are the products of these basic reactions. Carbon dioxide is a greenhouse gas, but less toxic than CO and others. Waste heat and steam can be used for heating and auxiliary services.

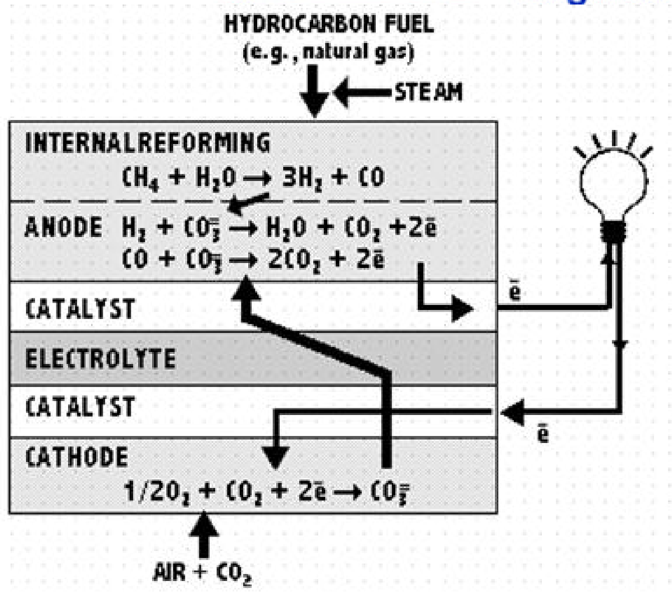

Figure 2: Schematic of MCFC process

Besides the reaction involving H_2 and O_2 to produce H_2O, the equations show a transfer of CO_2 from the cathode gas stream to the anode gas stream. One mole of CO_2 is transferred along with two Faradays of charge or 2 gram moles of electrons. The reversible potential for a MCFC, taking into account the transfer of CO_2, is given by the equation

$$E = E^{\circ} + \frac{RT}{2F} \ln \frac{P_{H_2} P_{O_2}^{1/2}}{P_{H_2O}} + \frac{RT}{2F} \ln \frac{P_{CO_{2,c}}}{P_{CO_{2,a}}}$$

where the subscripts a and c refer to the anode and cathode gas compartments, respectively. When the partial pressures of CO_2 are identical at the anode and cathode, and the electrolyte is invariant, the cell potential depends only on the partial pressures of H_2, O_2 and H_2O. Typically, the CO_2 partial pressures are different in the two electrode compartments and the cell potential is affected accordingly.

It is usual practice in an MCFC system to recycle the CO_2 generated at the anode to the cathode where it is consumed. This will require some type of device that will either (i) transfer the CO_2 from the anode exit gas to the cathode inlet gas ("CO_2 transfer device"), (ii) produce CO_2 by combustion of the anode exhaust gas, which is mixed with the cathode inlet gas, or (iii) supply CO_2 from an alternate source.

The Cell

The construction of an individual fuel cell resembles a sandwich. In the DFC, fuel and oxidant are fed through separate manifolds to the anode and cathode compartments of the cells, divided by a bipolar separator plate. The anode is bathed with fuel, the cathode with oxidant (air and carbon dioxide). These electrodes consist mainly of porous, sintered nickel (anode) or nickel oxide (cathode). Layered between the electrodes is the carbonate electrolyte contained in a porous (ceramic) matrix.

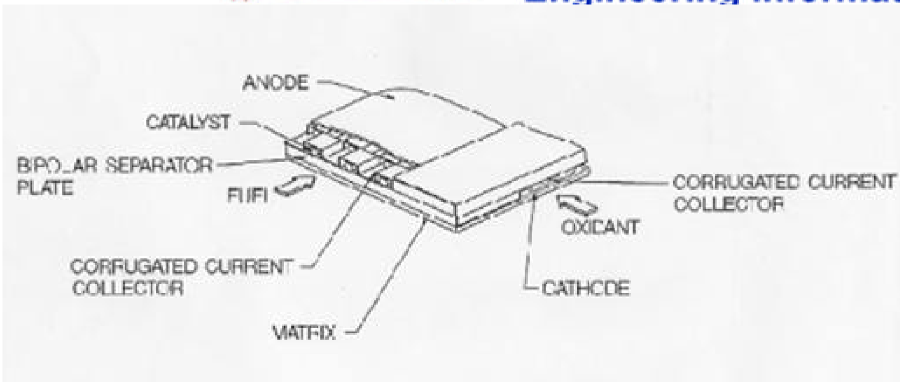

Figure 3: A cell itself

Individual cells generate a relatively small voltage, on the order of 0.7 to 1.0 volts each (after accounting for resistance losses).

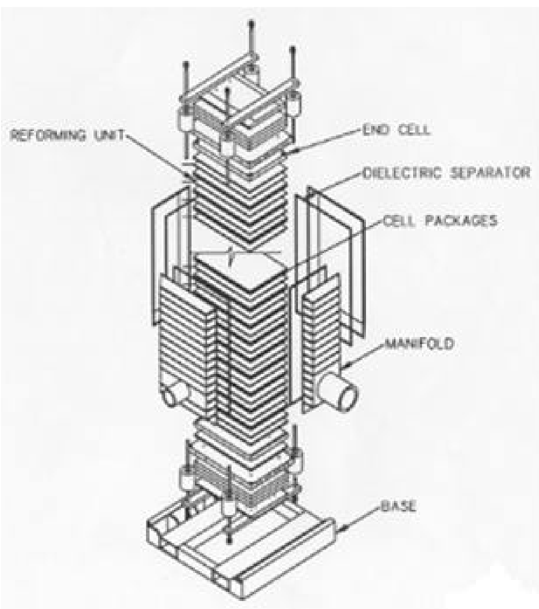

Figure 4: A FC stack

The current produced by an individual fuel cell is approximately a linear function of cell surface area. For commercial cells, the cell area is a trade-off between acceptable current (amperage) levels and manufacturing and transportation constraints. The most common dimensions are two by four feet area.

To develop higher voltages, cells are "stacked" and connected in series. As the diagram indicates, stack design considerations include manifolds for uniform gas distribution to each cell and to maintain cell compression and mechanical integrity at the stack's high operating temperatures. For Energy Research Corporation's (ERC) commercial megawatt-class power plants, individual stacks contain about 340 cells. Between each 10-cell grouping is a special catalyst-containing cell to improve internal reforming. Each stack has interconnections for fuel, air, and electricity.

At the factory, several stacks are combined into a truck-transportable "module" fabricated with all relevant connections, and shipped for installation at the site. The desired output from the power plant is obtained by combining a number of modules at the site. Megawatt-class power plants will contain one or two modules, each containing four stacks.

<u>Fuel Cell Power Plant</u>

The following describes a Direct Fuel Cell, so named because fuel is reformed to hydrogen-rich gas internally in the stack. This eliminates the fuel-processing unit required by phosphoric acid fuel cells and other designs. Three significant advantages result from internal reforming:

- Elimination of costly, separate fuel processing equipment, leading to lower overall capital costs.

- A reduction in the amount of equipment required, leading to simpler operation and higher reliability.
- Increased system efficiency.

Figure 5 shows a "simplified" power plant design:

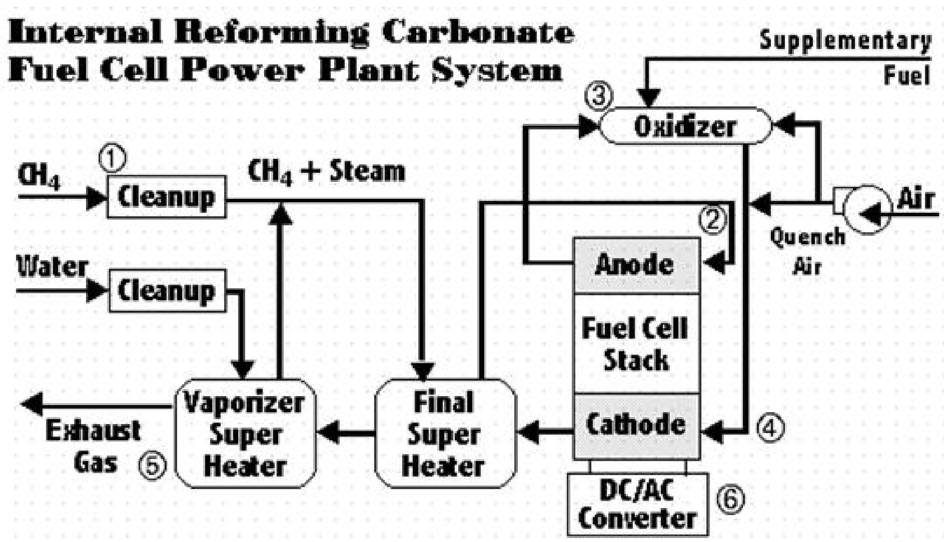

Figure 5: Fuel cell power plant layout

(1) Sulfur and other impurities are removed from the natural gas (CH_4) in a cleanup bed.

(2) Fuel and steam are fed to the cell's anode section. The fuel is internally reformed and electrochemically oxidized by carbonate ions formed at the cathode by the reaction of oxygen and carbon dioxide.

(3) The anode exhaust stream is mixed with air and fed to the cathode. This is the source of the oxygen and carbon dioxide in (4). The cathode exhaust, resembling flue gas, is cooled with the extracted heat used to preheat and vaporize the water. Thermal energy at ~800°F is available for cogeneration (5).

(6) DC power produced by the fuel cells is conditioned by a high-efficiency inverter to meet AC electrical grid requirements.

Power output is controlled by varying fuel and oxidant feeds to the fuel cells. The inverter controls real and reactive power output.

The stacks have a projected commercial life of 40,000 hours. They gradually degrade over their projected life and must be replaced periodically. Stack replacement is more of an economic decision than a process decision as one trades off performance loss versus fuel costs. The degree of stack or module flanging or valving dictates how much of the plant needs to be taken off-line when a stack is replaced.

<u>Advantages of this technology</u>

Environmental Acceptability - Because fuel cells are so efficient, CO_2 emissions are reduced for a given power output. The fuel cell is quiet, emitting only 60 decibels at 100 feet. Emissions of SO_x and NO_x are 0.003 and 0.0004 pounds/megawatt-hour respectively. Fuel cells can be designed as water self-sufficient.

Efficiency - Dependent on type and design, the fuel cells direct electric energy efficiency ranges from 40 to 60 percent. Fuel cell operates at near constant efficiency. Independent of size and load, fuel cells are not limited by the Carnot Cycle. For hybrid fuel cell/gas turbine systems, electrical conversion efficiencies are expected to achieve over 70 percent. When by-product heat is utilized, the total energy efficiency of the fuel cell systems approach 85 percent. The fuel cell is very responsive - cold starting within hours and achieves full load in minutes.

Distributed Capacity - Distributed generation reduces the capital investment and improves the overall conversion efficiency of fuel to end use electricity by reducing transmission losses. In high growth or remotely located areas, distributed generation could reduce or eliminate transmission and distribution problems by reducing the need for new capacity or laying new power lines. Presently 8-10 percent of the generated electrical power is lost between the generating station and the end user. Also many smaller units are statistically more reliable than one larger generating unit since the probability of all distributed units failing at one time is negligible.

Permitting - Permitting and licensing schedules are short due to the ease in sitting. In fact, natural gas fuel cell power plants have been exempt from many of California's environmental regulations known to be one of the most environmentally protective places on the face of the earth.

Modularity - The fuel cell is inherently modular. The fuel cell power plant can be configured in a wide range of electrical outputs, ranging from a nominal 0.025 to greater than 50-megawatt (MW) for the natural gas fuel cell, to greater than 100-MW for the coal gas fuel cell.

Fuel Flexibility - The primary fuel source for the fuel cell is hydrogen, which can be obtained from natural gas, coal gas, methanol, landfill gas, and other fuels containing hydrocarbons. This fuel flexibility means that power generation can be assured even when a primary fuel source is unavailable.

Cogeneration Capability - High-quality heat is available for cogeneration, heating, and cooling. Fuel cell exhaust heat is suitable for use in residential, commercial, and industrial cogeneration applications.

The challenge in fuel cell development for practical applications has been to improve the economics through the use of low-cost components with acceptable life and performance. Pure hydrogen and oxygen reactants have been replaced with common fossil fuels and air. Low-cost electrodes and electrolytes have been developed. Engineering, materials improvements, and manufacturing processes are now being developed to produce fuel cells with sufficiently high power, acceptable lifetimes, and affordable costs.

As each of these challenges is met, the promise of a factory-fabricated power generator, scalable to virtually any size, with highly automated operation can be realized. Achieving these goals can help the dream of cleaner energy become a reality.

<u>Finally</u>

What about the present state of operating fuel cells? Below are several photographs of existing fuel cells currently in operation. Fuel cell technology is continually developing but it is delivering results right now!

200kW PAFC power plant built by ONSI Corporation

Energy Research Corporation's 250kW Molten Carbonate Fuel Cell power plant (also called Direct Fuel Cell power plant)

References:

Graphicals courtesy of http://www.ifc.com/index_fl.shtml

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