

# Understanding Fuel Cells

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**F**uel cells are likely to replace internal combustion engines in the next century. Internal combustion (IC) engines and fuel cells are both energy converters which transform chemical energy into a more usable form of energy. Fuel cells are electrochemical devices which efficiently convert chemical energy into DC electricity and some heat (thermal energy). IC engines transform chemical energy into mechanical energy and a substantial amount of heat.

## Energy Converters

Coupling a fuel cell to an electric motor produces mechanical energy. Similarly, an IC engine produces electrical energy if we couple it to an alternator or dynamo. Fuel cells offer an incredible efficiency advantage over IC engines, especially gasoline engines in stop-and-go service. Atmospheric pollution could be greatly reduced with the use of fuel cells. These clear advantages may ultimately cause the bell to toll for the internal, infernal combustion engine.

## All Fuel Cells are not the Same

Typically, fuel cells are categorized according to the kind of electrolyte which is utilized within these devices. The electrolyte may consist of a liquid solution or a solid membrane material. In any case the electrolyte serves the vital function of ionic transfer of electrical charge. Some of the technologies are relatively advanced while others are still in their infancy. There are basically five fuel cell versions:

- Phosphoric acid fuel cells (PAFC)
- Alkaline fuel cells (AFC)
- Molten carbonate fuel cells (MCFC)
- Solid oxide fuel cells (SOFC)
- Proton exchange membrane fuel cells (PEMFC)

The proton exchange membrane fuel cell is a promising candidate for stand-alone home power generation.

## PAFCs: The Most Mature Approach

*Phosphoric acid fuel cells* (PAFCs) probably represent the most mature fuel cell technology. Westinghouse, International Fuel Cells, and at least a trio of Japanese manufacturers have been refining the design of mid-sized PAFC cogeneration plants. They are intended to fill the niche for stand-alone power generation for utility substations, factories, restaurants, hotels, and hospitals.

The fuel choice for PAFCs is not restricted to pure hydrogen. Typically, these near-term plants will use natural gas, methanol, or light distillates derived from fossil fuel sources. These cells operate at moderate temperatures (less than 200°C) with auxiliary reformers. Reformers convert the hydrocarbons to a mixture of hydrogen and carbon dioxide gases for the cells. The requirement for the initial reformation step sacrifices some efficiency, but the advantage of PAFCs is that they are tolerant of CO<sub>2</sub> and other reformat impurities. The overall efficiency improves above the 40–50% range if the installations are used as cogeneration plants, and the waste heat is used to make hot water and/or steam.

## AFCs: Extraterrestrial & Terrestrial Applications

Another fuel cell technology which has been with us since the 1960s is the *alkaline fuel cell* (AFC) system. AFCs were first developed for spaceflight applications as part of the Gemini program to produce reliable on-board power and fresh water for the astronauts. International Fuel Cells and Siemens are currently major players in this field.

AFCs operate at relatively low temperatures, and don't require noble metal catalysts, strong advantages in their favor. Highly purified hydrogen, such as electrolytic hydrogen, is required as the fuel source. Unfortunately, AFCs also require pure oxygen as the oxidant, not air. AFCs are intolerant of even meager amounts of CO<sub>2</sub> which effectively poisons them. If air is to be used as the oxidant, expensive CO<sub>2</sub> scrubbers would have to be used to prevent a degradation of AFC performance.

The use of AFCs in transportation applications is doubtful; it is generally assumed that oxygen will not be stored on-board light vehicles. In home systems with solar hydrogen production, oxygen will also be produced in most cases, so this may not be a problem.

## MCFCs: The New Hot Shots on the Block

Little will be said here about *molten-carbonate fuel cells* (MCFCs) and *solid-oxide fuel cells* (SOFCs). These second generation fuel cell strategies require

very high temperatures for operation, (600–1200°C). This allows for the internal reformation of fuels such as natural gas, methanol, petroleum, and coal. These devices tolerate CO<sub>2</sub> without requiring any further treatment and are possible substitutes for large to mid-sized thermal power plants, substations, or as cogenerators for factories. MCFCs and SOFCs are less likely to be utilized for remote home power generation by you or me, even in the distant future.

### PEMFCs: Promise for Home Power Generation

One remaining fuel cell design approach has been saved for last. It is the solid polymer fuel cell, perhaps more commonly referred to as the *proton exchange membrane fuel cell* (PEMFC). This technology deserves the most careful scrutiny by advocates of decentralized renewable energy and alternative transportation.

Proton exchange membrane fuel cells (PEMFCs) appear to be the “new kids on the block”. In reality they represent a technology that was virtually “forgotten” for about a decade. This was an area of fuel cell research that languished in relative obscurity, and which received minimal R&D funding until only recently.

General Electric pioneered the early work. The interest really revived in the last few years when Ballard Power Systems of Vancouver B.C., Canada went public with their results. Other private organizations which have gotten into the act in recent years include: H-Power, Ergenics, Energy Partners, Lynntech, Siemens, and Billings (International Academy of Science). United States educational and public institutions which have on-going laboratory research in this field include the Schatz Fuel Cell Project at California State University at Humboldt, the Center for Electrochemical and Hydrogen Research at Texas A&M, and Los Alamos National Laboratory. New players are entering and exiting this field so frequently that this lineup may already be out of date.

### Elegant Simplicity

One can hardly examine PEMFCs without being impressed with their elegantly simple design concept. Yet, closer study reveals their complexities and potential pitfalls in operation. Although PEMFCs are currently available commercially from a few vendors on special order, don't rush for your checkbooks unless you have deep pockets and a strong heart. PEMFCs are currently in the prototype development stage, although laboratory research continues as well.

So most of us must exercise a little patience for the vast promise of these devices to be fulfilled. Unless, that is, you're an impatient do-it-yourselfer, and choose to follow in the footsteps of others like Walt Pyle, Reynaldo Cortez, Alan Spivak, and Jim Healy who

have built an operational single cell PEMFC. A detailed description of their procedures can be found on page 42 of this issue.

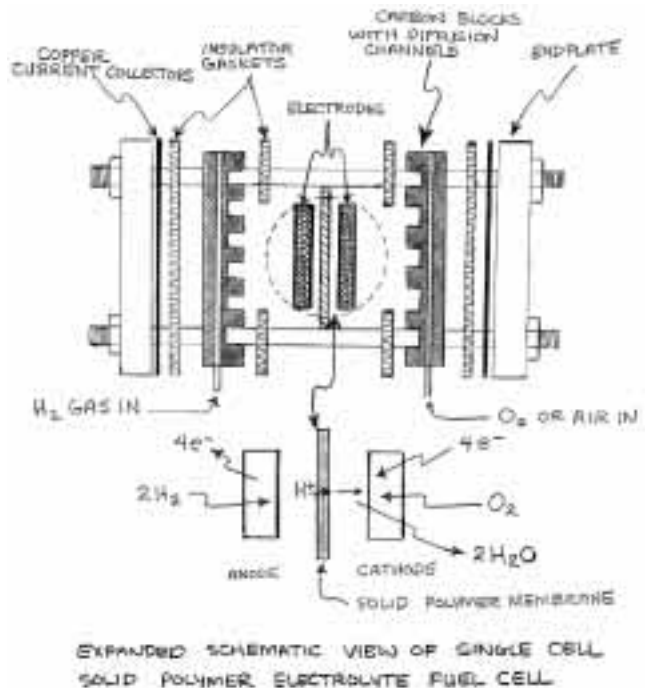
### A Look Inside PEMFCs

The similarity between fuel cells and electrolyzers may be apparent from the illustration below. As Rob Wills pointed out in *HP #23*, fuel cells are essentially electrolyzers operating in reverse. Both of these electrochemical cells share certain internal elements along with batteries. They all have negatively charged electrodes, positively charged electrodes, and an electrolyte that conducts charged ions between the electrodes.

Hydrogen is introduced into a PEMFC through a porous conductive electrode, which is frequently composed of graphite (carbon). The porous conductors may consist of special carbon paper. They may be graphite blocks milled with many gas delivery channels. The porous conductors may even be formed by pressing a carbon powder with a binder into a die with sufficient heat and pressure. The particular type of porous conductor construction is determined by the size and complexity of the cell or cell stack.

### Gas Separator and Ion Conductor

The solid polymer electrolyte membrane makes the PEMFC unique. Most current prototypes of PEMFCs use either a Nafion membrane from DuPont or one that is simply referred to as the “Dow membrane”. Each is a perfluorinated sulfonic acid polymer, but the Dow membrane is said to have more sulfonate side chains. There are even other versions by Asahi Chemical and



Chloride Engineers, Inc. The simple beauty of this design is that the membrane acts both as a conductor of hydrogen protons, and as a separator to keep the reacting gases from mixing and combusting. This feature allows for compact, lightweight cells, because the membranes themselves are very thin (0.007–0.015 inches).

A sheet of Nafion 117 doesn't look much different than a thick sheet of polyethylene or Saran Wrap. Onto this Nafion substrate is deposited a dispersed coating of platinum, a noble metal catalyst. This facilitates the chemical reactions, so they proceed at lower temperatures. Approaches which have been used with success for depositing the platinum include: thin film vacuum processes, brushing or precipitating a dilute solution of chloroplatinic acid, and hot pressing powders (carbon, platinum, and teflon). Significant reductions in the amount of expensive platinum have apparently been achieved, from 20 mg/cm<sup>2</sup> to 0.4 mg/cm<sup>2</sup>, without sacrificing performance.

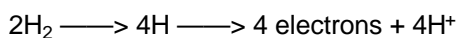
#### Seen from a Molecules Point-of-View

Okay, now we're ready to travel the inner journey traversed by individual hydrogen and oxygen molecules on the path to their new union (see figure). If we introduce pure hydrogen through the porous conductive hydrogen electrode, it arrives as a diatomic gas, H<sub>2</sub>. Each molecule is dissociated into two hydrogen atoms and stripped of two electrons as it interacts with the catalytic surface of the membrane. Devoid of their electrons they exist as two H<sup>+</sup>, hydrogen protons. The membrane itself will not conduct electrons. However, the electrons will flow readily via the conductive hydrogen electrode through the external circuit to the opposite oxygen electrode. Along this path, the current may flow through an external load accomplishing work.

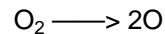
Meanwhile, the protons are moving their way through the solid polymer electrolyte on their way to meet oxygen ions. Simultaneously, diatomic oxygen molecules, O<sub>2</sub>, are diffusing through the oxygen electrode where they contact the platinized surface on the opposite side of the membrane. Here we would find that oxygen molecules separate into oxygen atoms which are held momentarily in a "receptive" state on the active platinum. Once electrons coming from the load meet the two protons arriving at this site, they combine with the oxygen atom in a spontaneous union. Voila! This results in the formation of one molecule of water, H<sub>2</sub>O.

Only one half as much oxygen is needed in this process as is needed of hydrogen. A chemist might write a synopsis of the entire process as shown below.

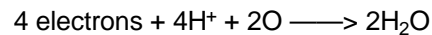
The reaction at the hydrogen electrode of a PEMFC:



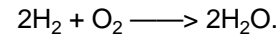
The reaction at the oxygen electrode of a PEMFC:



then,



The overall reaction within a PEMFC is simply



#### What's the Rub?

Well this works very well in theory, but there is a little more to the story. In actual practice there are some additional complications involved in PEMFC operation. First, the hydrogen which is introduced into the cell must be saturated with H<sub>2</sub>O vapor or else the membrane will dry out on the hydrogen side hindering performance markedly. Second, on the opposite side of the membrane a delicate balance must be struck with humidification also. Water is continually forming on the oxygen side which aids hydration of the membrane. But if droplets of water condense on the active surfaces, the reaction rate can slow to a halt as the cell literally drowns in its end product. Some waste heat is also building up simultaneously, even though the process is usually between 55–80% efficient. It is primarily the need for moisture and thermal management of both sides which has plagued a number of the PEMFC designs. Leakage of gases around gaskets or O-rings is another difficulty. As series cell stacks are built up of adjacent cells in a bipolar configuration to produce useful output voltages, these problems may magnify several fold.

#### So What is the Prognosis?

There is every reason to believe that the operational difficulties encountered in PEMFCs will be solved in the near future. The progress needed to make these fuel cells viable should not require any major "technological breakthroughs". PEMFCs hold great promise for automotive and other transportation applications, because they should prove to be both light and compact as well as extremely efficient compared to internal combustion engines.

When transportation energy analysts compare various drive train systems for future automobile designs, they frequently speak of criteria such as energy density and power density. Energy density is commonly expressed in units such as kWhr/kg, whereas power density pertains to the ability of a system to deliver performance quickly, and is expressed as kW/kg. Since fuel cells themselves do not produce torque, they would need to be coupled with highly efficient electrical motors. The coupling of hydrogen stored on-board an automobile as a liquid, hydride, or compressed gas with PEMFCs would seem to have superior energy density as an integral system than any battery electric vehicle

configuration on the horizon. However, in order for these fuel cell vehicles to come close to matching the power of today's internal combustion engine vehicles, perhaps the best configuration would be a hybrid one. These hybrids would likely use a "base load" fuel cell for cruising with a quick discharging battery for the higher instantaneous demands of acceleration. This is exactly the conclusion arrived at by three independent research analysts, and published in two scientific papers which have recently been published (see references).

### **The Pregnant Promise of Fuel Cells**

We can only hope that fuel cell research coupled with engineering refinements continues at an accelerated pace. The inefficiency of the internal combustion engine cannot be tolerated much longer. Atmospheric pollution, global warming resulting from greenhouse gas emissions, and the steadily declining reserves of petroleum are all part of the legacy left us by dependence on fossil fueled IC engines. Many scientists and energy analysts believe that a solar based hydrogen energy system is the answer to these problems. The timely maturity of hydrogen fuel cell technologies will be of critical significance, if the world is going to successfully wean itself from fossil fuels. An

appropriate analogy might be made between the development of integrated circuits and fuel cells. The first integrated circuits were a landmark advance that ushered in the electronic and information age. As fuel cells replace IC engines, I believe a Solar Hydrogen Age will blossom from the dust of the passing fossil fuel era.

### **Access**

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### **Further reading**

*Hydrogen Fuel-Cell Vehicles*, Mark DeLuchi, Institute of Transportation Studies, University of California, Davis, CA 95616

*The International Journal of Hydrogen Energy*, Permagon Press. Contact P.O. Box 248266, Coral Gables, FL 33124

*Hydrogen-Fueled Vehicles Technology Assessment Report* for California Energy Commission, Dr. David Swan and Debbi L. Smith, Technology Transition Corporation and Center for Electrochemical Systems and Hydrogen Research, Texas A&M University, 238 Wisenbaker ERC, College Station, TX 77843

