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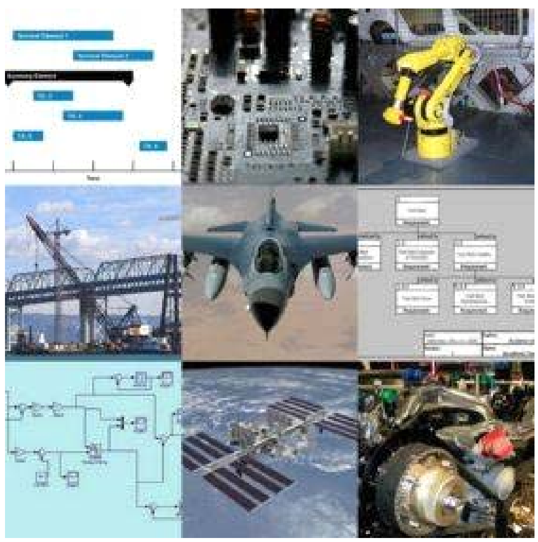

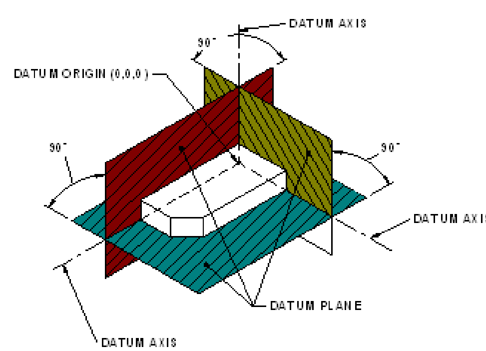

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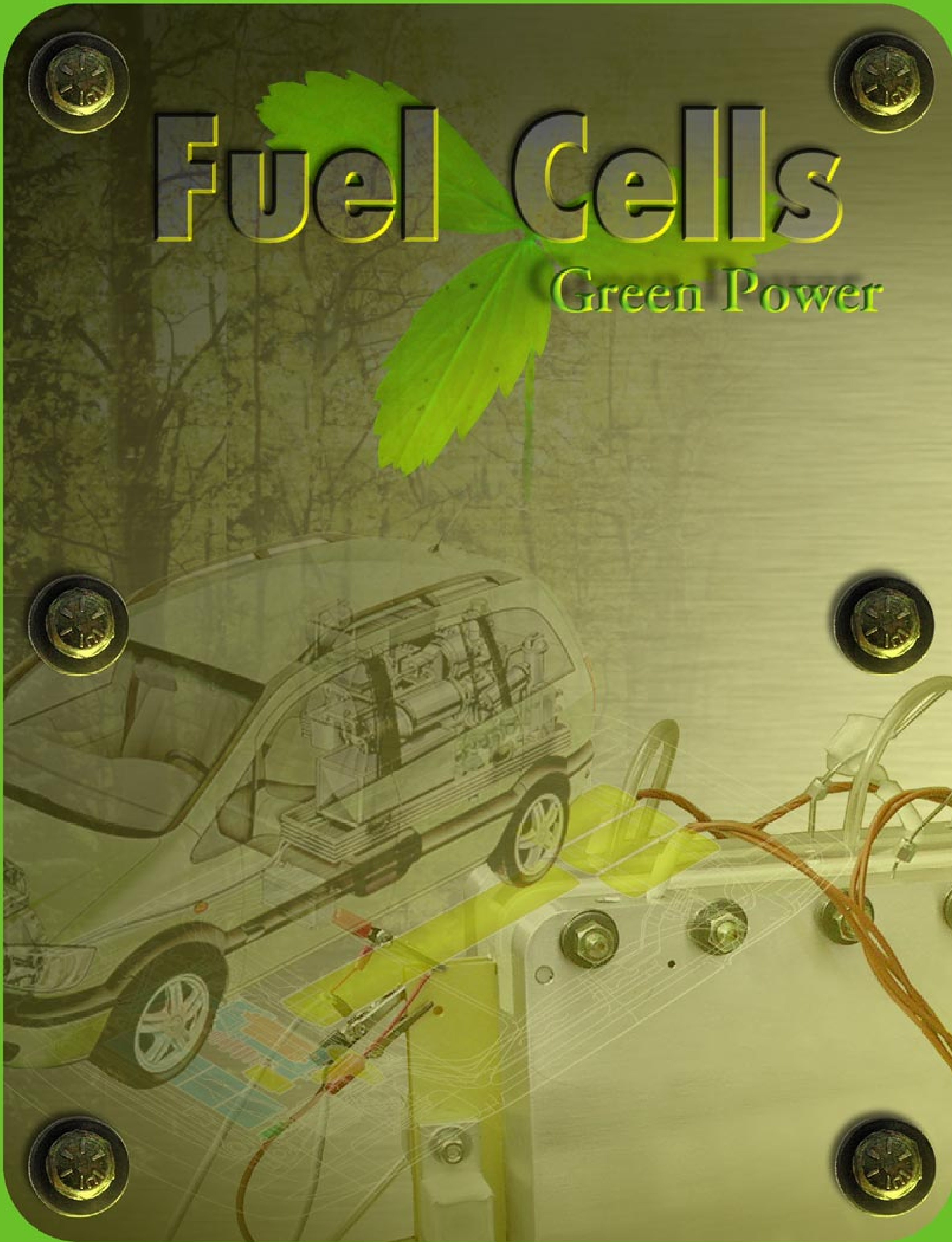
Fuel Cells
Green Power

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Fuel Cells
– Green Power

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What's Inside

Lamps, burning coal oil and coal gas, lit the living rooms of most homes of the early 1900's. But when electric light bulbs replaced those smoky, smelly sources of illumination, homes became brighter, cleaner, and safer. At first only the wealthy could afford electric lights. But as the demand went up and the cost went down, more and more of the population were able to afford electric lighting even though there was plenty of coal to continue lighting buildings in the usual way. The better technology won.

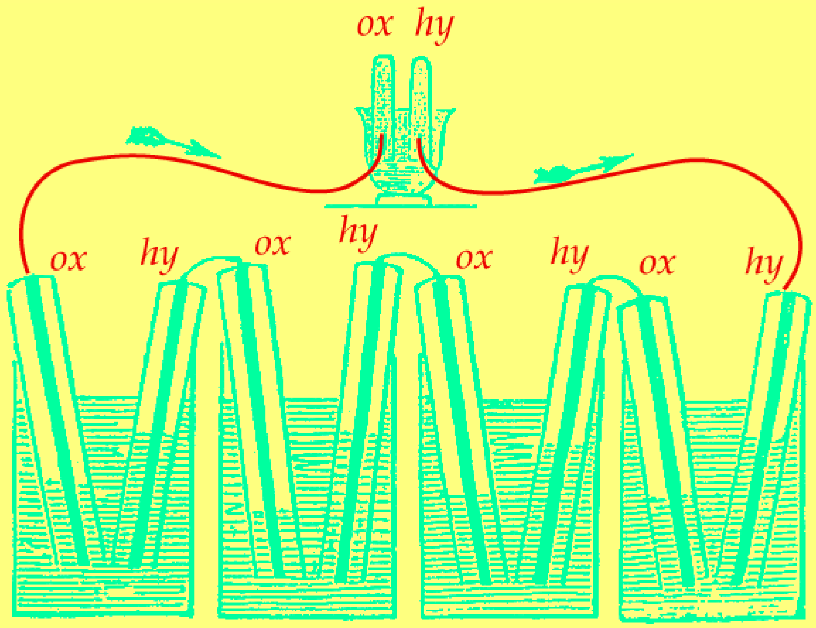
D.S. Scott and W. Hafele. "The Coming Hydrogen Age: Preventing World Climate Disruption." International Journal of Hydrogen Energy. Vol. 15, No. 10, 1990.

"I cannot but regard the experiment as an important one..."

William Grove writing to Michael Faraday, October 22, 1842

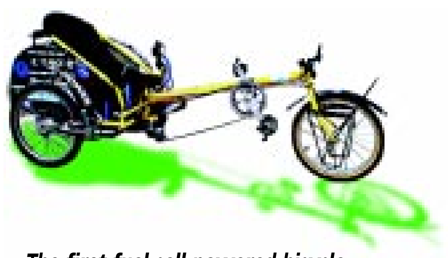
A Brief History

Although fuel cells have been around since 1839, it took 120 years until NASA demonstrated some of their potential applications in providing power during space flight. As a result of these successes, in the 1960s, industry began to recognize the commercial potential of fuel cells, but encountered technical barriers and high investment costs — fuel cells were not economically competitive with existing energy technologies. Since 1984, the Office of Transportation Technologies at the U.S. Department of Energy has been supporting research and development of fuel cell technology, and as a result, hundreds of companies around the world are now working towards making fuel cell technology pay off. Just as in the commercialization of the electric light bulb nearly one hundred years ago, today's companies are being driven by technical, economic, and social forces such as high performance characteristics, reliability, durability, low cost, and environmental benefits.



In 1839, William Grove, a British jurist and amateur physicist, first discovered the principle of the fuel cell. Grove utilized four large cells, each containing hydrogen and oxygen, to produce electric power which was then used to split the water in the smaller upper cell into hydrogen and oxygen.

In March 1998, Chicago became the first city in the world to put pollution-free, hydrogen fuel cell powered buses in their public transit system.
(Courtesy: Ballard Power Systems)



The first fuel cell powered bicycle to compete in the American Tour-de-Sol.
(Courtesy: H-Power)

The FutureCar Challenge, sponsored by the U.S. Department of Energy, presents a unique assignment to students from North America's top engineering schools: convert a conventional midsize sedan into a super efficient vehicle without sacrificing performance, utility, and safety. In 1999, the Virginia Tech team entered the competition with a fuel cell vehicle.

The automobile, it is fair to say, changed the industrial and social fabric of the United States and most countries around the globe. Henry Ford epitomized "Yankee ingenuity" and the Model T helped create the open road, new horizons, abundant and inexpensive gasoline...and tailpipe exhaust. More people are driving more cars today than ever before — more than 200 million vehicles are on the road in the U.S. alone. But the car has contributed to our air and water pollution and forced us to rely on imported oil from the Middle East, helping to create a significant trade imbalance. Today many people think fuel cell technology will play a pivotal role in a new technological renaissance — just as the internal combustion engine vehicle revolutionized life at the beginning of the 20th century. Such innovation would have a global environmental and economic impact.

"In today's world, solving environmental problems is an investment, not an expense."

William Clay Ford, Jr.
Chairman and CEO, Ford Motor Company,
September 1998

Fuel cells are not just laboratory curiosities. While there is much work that needs to be done to optimize the fuel cell system (remember, the gasoline internal combustion engine is nearly 120 years old and still being improved), hydrogen fuel cell vehicles are on the road — *now*. Commuters living in Chicago and Vancouver ride on fuel cell buses. You can take a ride around London in a fuel cell taxi and even compete in the American Tour de Sol on a fuel cell bicycle. Every major automobile manufacturer in the world is developing fuel cell vehicles. To understand why fuel cells have received such attention, we need to compare them to existing energy conversion technologies.

"The mission of our global fuel cell project center is nothing less than to make us the leader in commercially viable fuel cell powered vehicles."

Harry J. Pearce, Vice Chairman,
Board of Directors, General Motors.
May 1998

Where the Action in Fuel Cells is Today

Allied Signal
Volvo
Ballard
DaimlerChrysler
Detroit Edison
DuPont
Shell
Ford
General Motors
Honda
Mazda
Georgetown University
Case Western Reserve University
Los Alamos National Laboratory
Motorola
Penn State University
Princeton University
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Toyota
University of California
Exxon
Westinghouse
Renault
3M
Nissan
BMW
PSA Peugeot Citroën
Texaco
University of Florida
Tokyo Electric Power

(This is just a partial list)

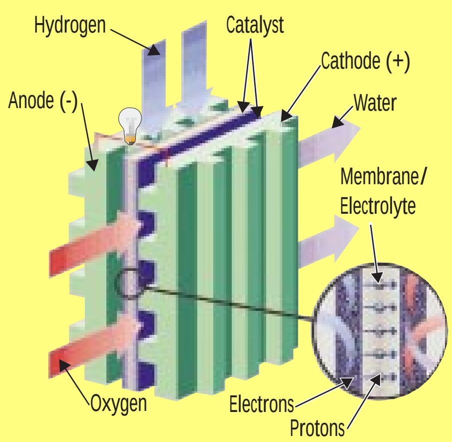
Carnot Cycle vs. Fuel Cells

The theoretical thermodynamic derivation of Carnot Cycle shows that even under ideal conditions, a heat engine cannot convert all the heat energy supplied to it into mechanical energy; some of the heat energy is rejected. In an internal combustion engine, the engine accepts heat from a source at a high temperature (T_1), converts part of the energy into mechanical work and rejects the remainder to a heat sink at a low temperature (T_2). The greater the temperature difference between source and sink, the greater the efficiency,

$$\text{Maximum Efficiency} = (T_1 - T_2) / T_1$$

where the temperatures T_1 and T_2 are given in degrees Kelvin. Because fuel cells convert chemical energy directly to electrical energy, this process does not involve conversion of heat to mechanical energy. Therefore, fuel cell efficiencies can exceed the Carnot limit even when operating at relatively low temperatures, for example, 80°C.

The Very Basics



- A fuel cell is an electrochemical energy conversion device. It is two to three times more efficient than an internal combustion engine in converting fuel to power.
- A fuel cell produces electricity, water, and heat using fuel and oxygen in the air.
- Water is the only emission when hydrogen is the fuel.

As hydrogen flows into the fuel cell on the anode side, a platinum catalyst facilitates the separation of the hydrogen gas into electrons and protons (hydrogen ions). The hydrogen ions pass through the membrane (the center of the fuel cell) and, again with the help of a platinum catalyst, combine with oxygen and electrons on the cathode side, producing water. The electrons, which cannot pass through the membrane, flow from the anode to the cathode through an external circuit containing a motor or other electric load, which consumes the power generated by the cell.

The voltage from one single cell is about 0.7 volts – just about enough for a light bulb – much less a car. When the cells are stacked in series, the operating voltage increases to 0.7 volts multiplied by the number of cells stacked.

How do Fuel Cells Compare to Internal Combustion Engines and Batteries?

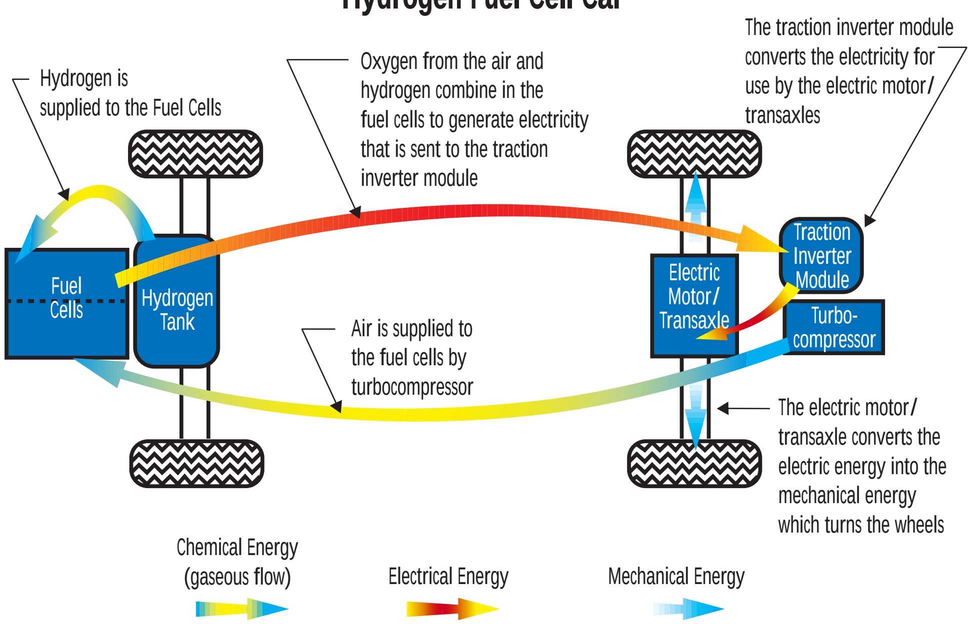
What internal combustion engines, batteries, and fuel cells have in common is their purpose: all are devices that convert energy from one form to another. As a starting point, let's consider the internal combustion engine — used to power virtually all of the cars driven on U.S. highways today. These engines run on noisy, high temperature explosions resulting from the release of chemical energy by burning fuel with oxygen from the air. Internal combustion engines, as well as conventional utility power plants, change chemical energy of fuel to thermal energy to generate mechanical and, in the case of a power plant, electrical energy. Fuel cells and batteries are electrochemical devices, and by their very nature have a more efficient conversion process: chemical energy is converted directly to electrical energy. Internal combustion engines are less efficient because they include the conversion of thermal to mechanical energy, which is limited by the Carnot Cycle.

If cars were powered by electricity generated from direct hydrogen fuel cells, there would be no combustion involved. In an automotive fuel cell, hydrogen and oxygen undergo a relatively cool, electrochemical reaction that directly produces electrical energy. This electricity would be used by motors, including one or more connected to axles used to power the wheels of the vehicle. The direct hydrogen fuel cell vehicle will have no emissions even during idling — this is especially important during city rush hours. There are some similarities to an internal combustion engine, however. There is still a need for a fuel tank and oxygen is still supplied from the air.

Many people incorrectly assume that all electric vehicles (EVs) are powered by batteries. Actually, an EV is a vehicle with an electric drive train powered by either an on-board battery or fuel cell. Batteries and fuel cells are similar in that they both convert chemical energy into electricity very efficiently and they both require minimal maintenance because neither has any moving parts. However, unlike a fuel cell, the reactants in a battery are stored internally and, when used up, the battery must be either recharged or replaced. In a battery-powered EV, rechargeable batteries are used. With a fuel cell powered EV, the fuel is stored externally in the vehicle's fuel tank and air is obtained from the atmosphere. As long as the vehicle's tank contains fuel, the fuel cell will produce energy in the form of electricity and heat. The choice of electrochemical device, battery or fuel cell, depends upon use. For larger scale applications, fuel cells have several advantages over batteries including smaller size, lighter weight, quick refueling, and longer range.

The polymer electrolyte membrane (PEM) fuel cell is one in a family of five distinct types of fuel cells. The PEM fuel cell, under consideration by vehicle manufacturers around the world as an alternative to the internal combustion engine, will be used to illustrate the science and technology of fuel cells.

Hydrogen Fuel Cell Car



The P2000, from Ford Motor Company, is a zero-emission vehicle that utilizes a direct hydrogen polymer electrolyte fuel cell. (Courtesy of Ford Motor Co.)

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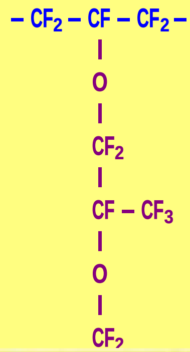
Structure of Polymer Electrolyte Membranes



The polymer electrolyte membrane is a solid, organic polymer, usually poly[perfluorosulfonic] acid. A typical membrane material, such as Nafion™, consists of three regions:

(1) the Teflon-like, fluorocarbon backbone, hundreds of repeating $-CF_2-CF-CF_2-$ units in length,

(2) the side chains, $-O-CF_2-CF-O-CF_2-CF_2-$, which connect the molecular backbone to the third region,

(3) the ion clusters consisting of sulfonic acid ions, $SO_3^-\ H^+$.

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