Hydrogen Fuel Cell Automobiles

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With gasoline now more than $2.00 a gallon, alternate automobile technologies will be discussed with greater interest and developed with more urgency. For our government, the hydrogen fuel cell-powered automobile is at the top of the list of future technologies. This paper presents a simple description of the principles behind this technology and a brief discussion of the pros and cons. It is also an extension on my previous paper on the physics of the automobile engine.[1]

There have been numerous articles on the hydrogen fuel cell automobile. Strong supporters of the hydrogen fuel cell automobile include Amory Lovins[2] and Joan Ogden.[3] A more balanced approach comes from Mathew Wald[4] and the American Physical Society.[5] Robert Service[6] and Steven Ashley[7] take a more skeptical position. I probably fall in the skeptical camp, but I leave it to the reader to make his or her own evaluation.

The hydrogen fuel cell is fundamentally a battery that operates with H_2 and air (O_2) as its fuel, electricity as its output, and water and heat as its exhaust. This article will focus on the proton-exchange membrane (PEM) fuel cell, which is the type most readily usable and currently being road tested in automobiles.[8] Each PEM fuel cell has a sandwich structure with five layers, as seen in Fig. 1.[9] The two outer layers are the backing layers. They are both porous to gases and electrically conducting, and are usually made of carbon paper or carbon cloth. The anode-backing layer allows hydrogen gas to reach the anode and collects electrons from the anode. The cathode-backing layer allows air (oxygen) to reach the cathode, water vapor to leave the cathode, and electrons to flow to the cathode. Layers two and four are the anode and cathode, which usually consist of platinum nanoparticles embedded in a carbon substrate. On the platinum surfaces in the anode, the hydrogen molecules are split into two protons and two electrons. On the platinum surfaces of the cathode, the oxygen molecules, protons, and electrons combine to form water molecules. The middle layer is a thin polymer electrolyte membrane, similar

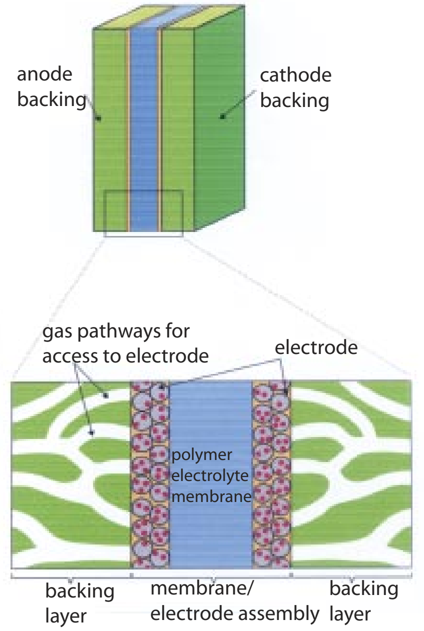

Fig. 1. Schematic drawing of the membrane/electrode assembly with backing layers of a PEM hydrogen fuel cell, courtesy of S. Thomas and M. Zalbowitz.[9] The electrodes consist of platinum nanocrystals (red dots) embedded in a porous carbon matrix (gray circles).

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to Teflon, that allows protons to diffuse from the anode to the cathode but is electrically insulating and also impermeable to hydrogen gas and air. A single cell will develop 0.7 V across the electrodes, and the current is proportional to the cross-sectional area of the cell. The cell generates heat as well as electrical energy, which must be removed to keep the cell at a temperature of about 80°C. A more theoretical explanation of the operation of the hydrogen fuel cell can be found in the appendix.

Hydrogen fuel cell automobiles are cars powered by electric motors that get their electrical energy from hydrogen fuel cells. They clearly have a number of important advantages. First, it is an automobile that does not run on gasoline; this technology would dramatically reduce the amount of oil consumed by this country, which in turn, would also reduce our dependence on foreign oil. Second, the technology exists and is currently being field-tested.[7,10] Third, the conversion of hydrogen potential energy to kinetic energy of the automobile is very efficient, around 37%; in contrast, for the gasoline-powered internal combustion engine it is about 15%.[4] Fourth, the only waste product from the hydrogen fuel cell is water; it does not pollute.

However, there are a number of disadvantages. First, there is the question: Where does all this hydrogen come from? There are no significant underground sources of hydrogen gas. Currently, more than 90% of the hydrogen gas used in this country is produced by reforming methane gas. This is done by heating methane and water to very high temperatures, generating hydrogen gas and the waste products of carbon dioxide and carbon monoxide. In Norway, where they have a surplus of electricity generated from hydroelectric plants, they use that excess electricity to hydrolyze water into hydrogen gas and oxygen gas.

In this country we do not have a surplus of electric power, and natural gas, which is primarily methane, is also in short supply. Consequently, there are at present no viable means to produce large quantities of hydrogen gas. The one fossil fuel that is plentiful in this country is coal, so it has been suggested that a new technology be developed that generates hydrogen gas from coal. The use of coal creates another serious environmental problem. Given that coal is primarily carbon, any process that generates hydrogen from coal will also generate large amounts of carbon dioxide—the major greenhouse gas. So this new technology must also capture the carbon dioxide and store it someplace—a process called sequestration. Simply put, this coal gasification and sequestration technology does not exist and faces huge technical problems.

Second, currently the cost to manufacture a hydrogen fuel cell to power an automobile is about $50,000.[5] The major reason for the high cost is the need for large quantities of platinum, a material currently more expensive than gold.[5] Unfortunately, mass production of fuel cells will not bring down the price of platinum; most likely, the increased demand for this rare metal will drive the price up. So until there is a major technological breakthrough in finding an alternative catalytic material or in using much less platinum, the cost of the hydrogen fuel cell is prohibitive.[11]

Third, there is the question of the safety of this technology. Unlike gasoline, which is a flammable liquid, hydrogen is an explosive gas, which can be ignited easily by a spark. How open will the public be to housing a potential bomb in their garage? And what about the possibility of a major hydrogen explosion during an automobile crash? These risks are at present unknown.

Fourth, the range of a hydrogen fuel cell automobile is limited by the amount of hydrogen that can be stored in a cylinder in the rear of the car. With present technology, that range is now about 100 miles. Again, a significant technological improvement in hydrogen storage is needed before this car is marketable.[5,12]

Fifth, there is the problem of developing a hydrogen infrastructure.[10] Simply put, the consumer will not purchase a hydrogen fuel cell automobile until there are hydrogen gas stations around the country, and the energy companies will not erect these hydrogen gas stations around the country until there is a sizable fleet of hydrogen-powered cars on the road. This is probably the least serious problem facing the hydrogen fuel cell technology. One possible approach is to start with fleets of taxis or government cars in a few cities and build hydrogen gas stations in those few cities. Then expand this approach to more cities and eventually to more suburban and rural locations.

Clearly, a viable hydrogen fuel cell automobile industry faces a number of major technological problems before it is ready for "prime time." In my opinion, it would be a grave mistake to rely on this technology to decrease our dependence on foreign oil or to solve the global warming problem. It is a technology worth investigating, but it should be viewed as a long shot. It should not be used to avoid seriously considering alternate approaches to our energy, transportation, and environmental problems. If anything, the current status of the hydrogen fuel cell automobile should reinforce the importance of energy conservation as the only viable response this country really has for the next 20 years to a future energy or environmental crises.

References

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8. There are hydrogen fuel cells other than the PEM fuel cell such as the phosphoric acid fuel cell and the alkaline acid fuel cell, either one of which could be used to power vehicles.
9. A more detailed description of the construction and operation of hydrogen fuel cells by S. Thomas and M. Zalbowitz from the Los Alamos National Laboratory can be found at http://www.education.lanl.gov/resources/fuelcells.
10. F. Markus, "Driving impression: GM Hy-wire," *Car and Driver* **48**, 77 (March 2003) and J. Dunne, "Fuel cells from sea to shining sea," *Pop. Mech.* **180**, 78 (Jan. 2003). The article by Dunne describes a hydrogen fuel cell automobile that uses methanol as the source of the hydrogen gas; this may be a way to introduce hydrogen fuel cell technology without initially developing a hydrogen distribution system.
11. The technological problem of the cost of platinum in hydrogen fuel cells may have already been solved. Firoz Rasul, former CEO of Ballard Power Systems, which is the world's largest manufacturer of hydrogen fuel cells, stated in a private conversation that the hydrogen fuel cells manufactured by his company use as much platinum as catalytic converters use in gasoline-powered automobiles. Rasul is convinced that the cost of hydrogen fuel cells will dramatically drop when they are mass produced. Also, platinum could be recycled from discarded fuel cells, which would increase the supply of platinum and reduce its cost.
12. Research is now being conducted in developing both high-pressure gas cylinders and solid-state storage materials that can absorb and release large amounts of hydrogen. In particular, metal hydride and carbon nanotube materials can store very large amounts of hydrogen in a way that minimizes the possibility of an explosion.

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Appendix

The chemical and thermodynamic principles behind the operation of the hydrogen fuel cell are easy to understand. On the anode, the following catalytic reaction occurs:

$$2H_2 \rightarrow 4H^+ + 4e^- . \qquad (1)$$

The H^+ diffuse from the anode through the permeable electrolyte layer to the cathode, where they react with the O_2 in the air in the following manner:

$$4H^+ + 4e^- + O_2 \rightarrow 2H_2O . \qquad (2)$$

Chemical batteries and electrical diodes work on identical principles. In all these devices, the flow of charge is controlled by the sum of a built-in electric field and an external electric field. Depending on the external electric field, the direction of charge diffusion can be switched and in principle the reactions at the anode and cathode reversed.

Consider three cases:

- **Case 1. Open circuit (zero bias).** Since no current is flowing between the anode and cathode, reaction 1 leaves the anode negative and reaction 2 leaves the cathode positive. As reactions 1 and 2 continue, negative charge continues to build up on the anode and positive charge on the cathode, creating an electric field between the anode and cathode that opposes the diffusion of H^+. In short order, this built-in electric field will grow until the diffusion of H^+ stops. In turn, reactions 1 and 2 cease.

- **Case 2: Closed circuit (forward bias).** When the circuit is closed, electrons flow from the anode through the external circuit to the cathode reducing the built-in electric field. H^+ start diffusing from the anode to the cathode and reactions 1 and 2 start up.
- **Case 3: Hydrolysis (reverse bias).** If an external positive voltage is put on the cathode, it increases the electric field between the anode and cathode driving H^+ in the opposite direction. In principle, the reverse reactions to 1 and 2 occur at the anode and cathode, creating H_2 at the anode and O_2 at the cathode. In practice this does not occur in a hydrogen fuel cell since there is no source of H_2O at the cathode. However, the reverse process does occur in a hydrolysis system.

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