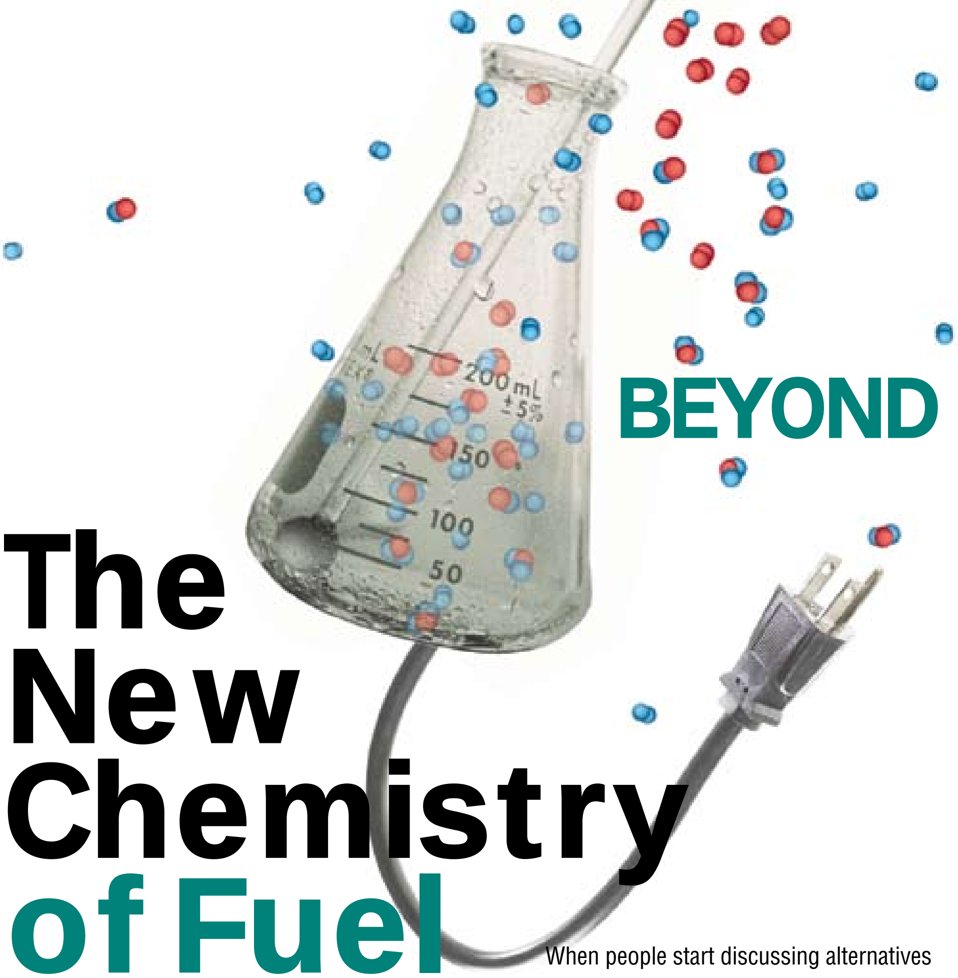


BEYOND HYDROGEN: The New Chemistry of Fuel Cells

GETTY IMAGES

By Mark Michalovic

For the past one-hundred years, burning gasoline has been a very convenient way to make cars move. However, times have changed. You need crude oil to make gasoline, and crude oil is getting harder to find. Although the earth isn't out of oil just yet, the oil that is still out there is often hiding in places where drilling is difficult, like underneath the ocean floor. What's more, much of the world's oil is in places that are politically unstable. All of this tends to drive the price of gasoline higher.

Even when gasoline is cheap, burning it still produces carbon dioxide, a greenhouse gas. The Swedish chemist Svante Arrhenius first predicted back in 1896 that burning fossil fuels could cause global warming. Today, with gas prices and global temperatures both going up, some people are starting to think it might be time to find other ways to make cars, trucks, and buses go.

When people start discussing alternatives to the internal combustion engine, the discussion almost always includes the hydrogen fuel cell. There are good reasons for this. Hydrogen fuel cells don't pollute; their only exhaust gas is water vapor. They are also very efficient. In some ways, hydrogen fuel cells seem like the answer to all of our gasoline problems.

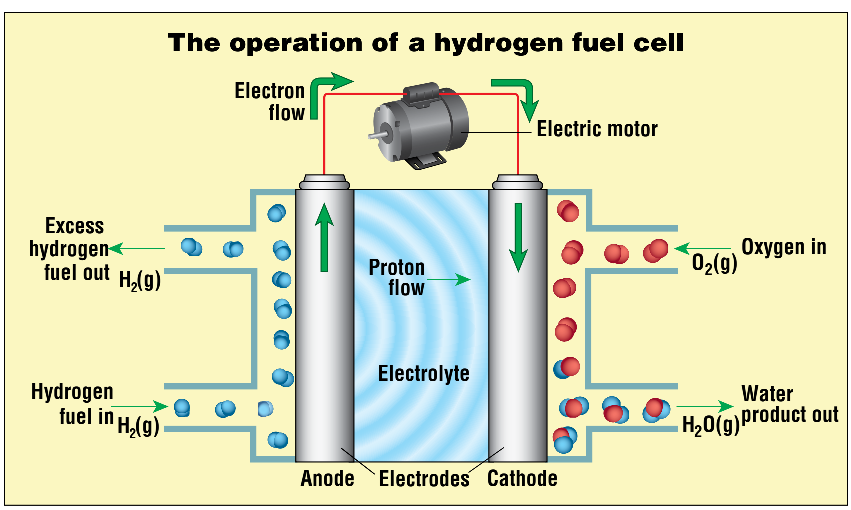
What fuel cells do

In a fuel cell, hydrogen and oxygen are converted into water, and in the process, electricity is generated. In an automobile, this electricity is used to run an electric motor that makes the car go. The chemical reaction between hydrogen and oxygen that powers the fuel cell is the same as when you simply burn hydrogen:

$$2\ H_2 + O_2 \rightarrow 2\ H_2O$$

Why bother with a fuel cell then? Why not just burn the hydrogen? The answer is efficiency. If we burn hydrogen in an internal combustion engine, like the ones in normal cars, the reaction is rapid and uncontrolled and only turns about 20% of the energy in a fuel into useful work. The rest of the energy is wasted as heat or spent overcoming all of the friction between all the moving parts of a gasoline engine. In a fuel cell the reaction between hydrogen and oxygen is very controlled and happens at a much slower rate. Fuel cells don't generate much waste heat. This means a fuel cell can convert about 50% of the energy in hydrogen to useful work.

So how does it all work? A fuel cell has three main parts: a membrane, an anode cata-



CESAR CAMINERO

Hydrogen ions are formed when electrons are removed from H_2. The electrons move through the circuit to the cathode–causing the motor to work in the process. The hydrogen ions combine with O_2 gas to form water.

lyst, and a cathode catalyst. In a hydrogen fuel cell, hydrogen is fed into the cell and flows over the anode catalyst. When hydrogen molecules hit the anode catalyst, the H_2 molecule separates into two hydrogen ions (that is, two protons) and two electrons by the following chemical reaction:

$$H_2 \rightarrow 2\,H^+ + 2\,e^-$$

The hydrogen ions and the electrons part ways at this point. The electrons flow through the wire toward the other side of the fuel cell. Meanwhile, the hydrogen ions are headed toward the other side of the fuel cell, but they get there a different way. The hydrogen ions pass through the membrane to get to the other side. The membrane is made of a special polymer called Nafion that allows positively charged ions to pass through.

COURTESY OF GEORGIA TECH: GARY MEEK

Thomas Bradley and Reid Thomas go through the procedure of starting up the fuel cell aircraft during a test flight at the Atlanta Dragway.

When the hydrogen ions and the electrons both get to the other side of the fuel cell, they don't just reform a hydrogen molecule again. At the cathode catalyst, oxygen from the air gets involved. The cathode catalyst separates oxygen molecules into oxygen atoms. As electrons arrive at the cathode catalyst, they increase the negative charge on the oxygen atom, inducing it to pick up hydrogen ions that are arriving via the membrane:

$$O_{2\,(g)} \rightarrow 2\,O_{(adsorbed)}$$
$$O_{(adsorbed)} + e^- + H^+ \rightarrow OH_{(adsorbed)}$$

When hydrogen ions reach the cathode catalyst, they react with the oxide ions to form water molecules:

$$OH_{(adsorbed)} + e^- + H^+ \rightarrow H_2O$$

The most important step in this whole process happens when the electrons flow through the wire from one side of the fuel cell to the other. Remember that an electrical current is just electrons flowing through a wire. Just like the flow of water in a river can be used to turn a water wheel, the flow of moving electrons can be used to do real work, like turning an electric motor in a car.

Some problems with hydrogen

For all its efficiency, hydrogen fuel has some serious drawbacks. Hydrogen is a gas, and gases are hard to store. One solution could be a car with a pressurized tank to hold hydrogen, and fuel stations would need pressurized tanks, too. Transporting the hydrogen fuel isn't easy, either. Since gases aren't very dense, a truck wouldn't be able to haul very much of it at a time.

An even bigger problem is making the hydrogen. You don't often find hydrogen gas on earth. You have to separate hydrogen from some hydrogen-containing compound. For example, you can separate it from water by passing an electric current through the water in a process called electrolysis (electro referring to electricity, lysis meaning "to break").

$$2H_2O \rightarrow 2H_2 + O_2$$

As this requires electricity, you have to generate that electricity somehow. Because most of our electricity comes from coal, that doesn't really help us cut down our use of fossil fuels. Burning coal generates carbon dioxide just like burning gasoline does.

Some scientists have proposed separating hydrogen from methane, the main compound in natural gas, using the following "steam reforming" chemical process:

$$CH_4 + H_2O \rightarrow CO + 3\,H_2$$

More H_2 can be made from the CO by the "water-gas shift" reaction:

$$CO + H_2O \rightarrow CO_2 + H_2$$

but reaction produces carbon dioxide, the same greenhouse gas we're trying *not* to make by using hydrogen as a fuel in the first place, plus you also have to worry about traces of CO remaining in the H_2, since CO can poison the Pt catalyst used in the fuel cell.

Because making hydrogen is still a tricky proposition, many scientists are looking into other fuels that might work just as well or better in fuel cells. Two alcohols, methanol and ethanol, are showing promise.

Methanol

Methanol is the simplest alcohol, with a formula of CH_3OH. It has already been used as a fuel in ordinary internal combustion engines. For example, methanol was once the race car fuel used in the Indianapolis 500, until the race organizers switched to ethanol a few years ago. Methanol is a liquid, so it is easier to store and transport than hydrogen is. You can store it and sell it in the same tanks and pumps that gas stations already have. Everything we need to store, ship, and use methanol is already in place, except the cars. Even the cars are in the works, as Daimler-Chrysler recently drove an experimental car powered by a methanol fuel cell across the United States.

In a fuel cell, methanol would react with oxygen by the following chemical reaction:

$$2\,CH_3OH + 3\,O_2 \rightarrow 4\,H_2O + 2\,CO_2$$

But wait! Isn't this reaction producing carbon dioxide? Again, one advantage of alternative fuels is the opportunity to reduce the amount of carbon dioxide we put into the atmosphere. However, it turns out there is more to the story than meets the eye.

Methanol is normally made from methane (CH_4) in a complicated process with several steps. However, you can also make methanol using a fuel cell. How does this work? Normally, when you run a methanol fuel cell, methanol and oxygen react to make water and carbon dioxide, and in the process an electrical current is generated. However, you can make the whole process run in reverse. By simply running electrical current through the cell, you can make the cell convert carbon dioxide and water vapor from the air back into methanol. In this way, the methanol fuel cell can generate its own fuel.

Making the methanol removes carbon dioxide from the air when carbon dioxide is converted into methanol. When you use the methanol as fuel, you convert it back into carbon dioxide. This means you are only adding the same amount of carbon dioxide to the air than you removed from the air in the first place, provided you only use methanol made by a fuel cell. Because of this, we say that the system is "carbon neutral."

COURTESY OF HONDA

Actress Q'orianka Kilcher has become the youngest customer to lease Honda's environmental status symbol, the hydrogen-powered and zero-emissions FCX fuel cell vehicle. Kilcher is the first person ever whose first car runs on hydrogen. She took possession of the FCX on March 7, 2007, in Universal City, California.

This system isn't perfect, though. You still need a source of electricity if you want to use the fuel cell to make methanol fuel. This is the same problem scientists run into when they try to make hydrogen fuel from water.

One answer might be to use electricity generated by wind power to run methanol fuel cells. A big problem with wind power is you can only transmit electricity a few hundred miles using transmission wires due to the resistance to the flow of electricity in the wires. Unfortunately, the windiest places, the best places to put windmills, aren't always close to where people live and use electricity.

The Great Plains of the United States and the open ocean are some of the best and windiest places for windmills, but not many people live on the Great Plains, and even fewer live out on the open sea. Using windmills and fuel cells to generate methanol fuel could provide us with a way to transport the energy of windmills to places where it can be used. In this scheme, methanol fuel cells might be used not only for powering cars, but also for providing electricity to homes.

Another problem is that even though carbon dioxide levels in the earth's atmosphere are getting higher and higher, CO_2 still only makes up less than 1% of the earth's atmosphere. This means making methanol from atmospheric CO_2 would be a slow process. Fuel cells might not be able to produce methanol quickly enough to meet demand.

Ethanol

Ethanol is the alcohol that people are most familiar with, since it is the alcohol in mouthwash, certain medicines, and alcoholic beverages. An ethanol molecule is a little bit more complicated than a methanol molecule, with a formula of C_2H_5OH. Ethanol is already used in plain-old internal combustion engines, usually mixed with gasoline in blends like E85. However, using ethanol in a fuel cell would be more efficient. Ethanol fuel cells would work a lot like methanol fuel cells, using the following chemical reaction to produce power:

$$C_2H_5OH + 3\ O_2 \rightarrow 3\ H_2O + 2\ CO_2$$

There is a serious problem with ethanol fuel cells. The Pt catalyst used in hydrogen fuel cells is really excellent, giving basically perfect efficiency in hydrogen oxidation. (The cathode, for oxygen reduction, is less efficient.) Already switching to methanol results in lower efficiencies, since it's trickier to oxidize a C–H bond than an H–H bond. This reduces the power you can get from methanol, so current thinking is that you can't run a car using a direct methanol fuel cell, because the power is too low. Ethanol is infinitely worse, because the C–C bond is very difficult to oxidize. So ethanol fuel cells are not currently practical.


MIKE CIESIELSKI

The good news is that these conclusions are all dependent on the nature of the currently used catalysts, not the intrinsic properties of the fuels. We face a great challenge to develop new, more efficient catalysts that could revolutionize how we drive, and reduce global warming! Perhaps one of you reading this article will go on to study chemistry and be the one to find this new catalyst.

Beyond alcohols

Both methanol and ethanol have their advantages and drawbacks. Right now, neither of them is ready to solve our energy needs. It's possible that in the end, both may find some important use. In fact, other fuels are also being studied, like diesel and hydrides. We may end up with a variety of substances making our fuel cells run. Whatever happens, it will be the result of interesting chemistry waiting to be discovered.

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ChemMatters

December 2007
Teacher's Guide

"Beyond Hydrogen"

Student Questions

Beyond Hydrogen: The New Chemistry of Fuel Cells

1. What are two compounds that might be used to produce hydrogen?
2. How many carbon atoms are there in a methanol molecule?
3. How many carbon atoms are there in an ethanol molecule?
4. What atmospheric gas can be converted into methanol using a fuel cell?
5. What main part of a fuel cell is made out of a polymer?
6. What metal is found in both the anode and cathode of most fuel cells?
7. At which electrode does oxidation take place in a fuel cell?
8. At which electrode does reduction take place in a fuel cell?
9. Fuels are oxidized in fuel cells. What substance is reduced in a fuel cell?
10. What type of ions pass through the membrane between the anode and the cathode?
11. Very little of the chemical energy released from the fuel used in a fuel cell is released as heat. In what form is the fuel's chemical energy released?

Answers to Student Questions

Beyond Hydrogen: The New Chemistry of Fuel Cells

1. **What are two compounds that might be used to produce hydrogen?**
   Water and methane are two compounds that might be used to produce hydrogen.
2. **How many carbon atoms are there in a methanol molecule?**
   A methanol molecule contains one carbon atom.
3. **How many carbon atoms are there in an ethanol molecule?**
   An ethanol molecule contains two carbon atoms.
4. **What atmospheric gas can be converted into methanol using a fuel cell?**
   Carbon dioxide from the atmosphere can be converted to methanol using a fuel cell.
5. **What main part of a fuel cell is made out of a polymer?**
   The membrane is made of polymer.
6. **What metal is found in both the anode and cathode of most fuel cells?**
   Platinum is found in both anodes and cathodes of most fuel cells.
7. **At which electrode does oxidation take place in a fuel cell?**
   Oxidation in fuel cells takes place at the anode.
8. **At which electrode does reduction take place in a fuel cell?**
   Reduction in fuel cells takes place at the cathode.
9. **Fuels are oxidized in fuel cells. What substance is reduced in a fuel cell?**
   Oxygen is reduced in a fuel cell.
10. **What type of ions pass through the membrane between the anode and the cathode?**
    Cations or positively-charged ions pass through the membrane.
11. **Very little of the chemical energy released from the fuel used in a fuel cell is released as heat. In what form is the fuel's chemical energy released?**
    The chemical energy of the fuel cell is released in the form of electrical current.

NSES Correlation

National Science Education Content Standard Addressed

National Science Education Content Standard Addressed As a result of activities in grades 9-12, all students should develop understanding	**Beyond Hydrogen: The New Chemistry of Fuel Cells**
Science as Inquiry Standard A: and abilities to do scientific inquiry.	
Science as Inquiry Standard A: about scientific inquiry.	
Physical Science Standard B: of the structure and properties of matter.	✔
Physical Science Standard B: of chemical reactions.	✔
Physical Science Standard B: of interaction of energy & matter.	✔
Science and Technology Standard E: about science and technology.	✔
Science in Personal and Social Perspectives Standard F: of personal and community health.	
Science in Personal and Social Perspectives Standard F: about natural resources.	✔
Science in Personal and Social Perspectives Standard F: of environmental quality.	✔
Science in Personal and Social Perspectives Standard F: of natural and human-induced hazards.	
Science in Personal and Social Perspectives Standard F: of science and technology in local, national, and global challenges.	✔
History and Nature of Science Standard G: of science as a human endeavor.	

History and Nature of Science Standard G: of the nature of scientific knowledge.	✔
History and Nature of Science Standard G: of historical perspectives.	✔

Anticipation Guides

Anticipation guides help engage students by activating prior knowledge and stimulating student interest before reading. If class time permits, discuss their responses to each statement before reading each article. As they read, students should look for evidence supporting or refuting their initial responses.

Directions for all Anticipation Guides: In the first column, write "A" or "D" indicating your agreement or disagreement with each statement. As you read, compare your opinions with information from the article. In the space under each statement, cite information from the article that supports or refutes your original ideas.

Beyond Hydrogen: The New Chemistry of Fuel Cells

Me	Text	Statement
		1. Global warming was not foreseen by chemists until the late 20th century.
		2. Hydrogen fuel cells produce water vapor and methanol.
		3. Fuel cells generate much more waste heat than gasoline engines.
		4. Most fuel cells contain platinum catalysts.
		5. Producing hydrogen from hydrogen-containing compounds generates greenhouse gases.
		6. Race cars have used methanol fuel cells for many years.

		7. Methanol fuel cells can produce their own fuel.
		8. Finding new catalysts for fuel cells is a challenge for future chemists.

Content Reading Guides

These matrices and organizers are provided to help students locate and analyze information from the articles. Student understanding will be enhanced when they explore and evaluate the information themselves, with input from the teacher if students are struggling. Encourage students to use their own words and avoid copying entire sentences from the articles. The use of bullets helps them do this. If you use these reading strategies to evaluate student performance, you may want to develop a grading rubric such as the one below.

Score	Description	Evidence
4	Excellent	Complete; details provided; demonstrates deep understanding.
3	Good	Complete; few details provided; demonstrates some understanding.
2	Fair	Incomplete; few details provided; some misconceptions evident.
1	Poor	Very incomplete; no details provided; many misconceptions evident.
0	Not acceptable	So incomplete that no judgment can be made about student understanding

Beyond Hydrogen: The New Chemistry of Fuel Cells

Directions: In the chart below, compare and contrast hydrogen fuel cells with methanol fuel cells.

	Hydrogen Fuel Cell	**Methanol Fuel Cell**
Membrane		
Anode Catalyst		
Cathode catalyst		
Chemical reactions		
Advantages		
Disadvantages		

Beyond hydrogen: The New Chemistry of Fuel Cells

Background Information

More on the inefficiencies of internal combustion engines

Fuels cells are much more efficient than internal combustion engines, that is, they convert more of the energy available in the chemical bonds of a fuel into useful kinetic energy that actually ends up moving a car down the road. There are three main sources of inefficiency in internal combustion engines. The first is that most of the energy released in an internal combustion engine is released as heat. Some of this heat makes gases in the cylinders expand, pushing the pistons, and ultimately, turning the wheels of the car. However, pushing the pistons doesn't use nearly all the heat produced. When the gases are through pushing, they are sill very hot, and much of the heat is sent out the tailpipe of the car with the hot exhaust gases. What's more, a lot of the heat released doesn't do any useful work at all, but just makes the metal in the engine hot. This is the nature of heat, to flow from hot objects to cold objects, so containing it requires a fight against the second law of thermodynamics. A fuel cell releases most of its energy as electrical current rather than heat, reducing this kind of inefficiency.

The second source of inefficiency is friction. An internal combustion has lots of moving parts. Pistons slide up and down in cylinders, the crankshaft moves in its bearings, and so forth. Every time moving parts move in contact with non-moving surfaces, the moving parts must overcome friction. There is plenty of friction in an internal combustion engine, cutting its efficiency. Fuel cells, on the other hand, have few moving parts, and therefore little loss of energy due to friction.

The third source of inefficiency in an internal combustion engine has to do with the way pistons move. In an internal combustion engine, pistons are constantly moving back and forth, accelerating to very high speeds, coming to a stop, and then accelerating in the opposite direction. When the fast-moving piston comes to a stop, a lot of its kinetic energy is converted to heat rather than being used for work. Some clever designs, like the Wankel rotary engine used by Mazda in several models, eliminate this problem. Needless to say, fuel cells have no pistons and no such energy losses.

More on the drawbacks of methanol

For all their advantages, methanol fuel cells do have two serious drawbacks. The first is a property of the fuel itself. Methanol is much more toxic than gasoline and other alternative fuels like ethanol. In the body, methanol attacks the optic nerve and can cause permanent blindness if ingested in small doses. Larger doses can be fatal.

The second drawback has to do with the operation of methanol fuel cells. Methanol molecules can sometimes pass through the polymer membrane which separates the anode catalyst from the cathode catalyst. The methanol molecules are then oxidized into CO_2 and H_2O, but without producing any useful electrical current. This is called crossover oxidation, and it results in a reduction in the amount of useful energy obtainable from a given amount of methanol fuel.

More on the drawbacks of ethanol

Ethanol fuel cells aren't as efficient as methanol fuel cells because ethanol molecules contain carbon-carbon bonds, which don't oxidize as efficiently in fuel cells as, say, carbon-oxygen bonds do. However, bigger disadvantages may revolve around the production of ethanol. Depending on the source, ethanol may or may not be a "green" fuel. Corn-based ethanol still requires fossil fuel use, once growing the corn, fermentation, and distillation have been taken into account, so the decrease in greenhouse gas emission is much smaller than you would expect. Ethanol from sugar cane is somewhat less energy-intensive to produce. On the other hand, sugar cane ethanol is less energy-intensive to produce. Many other plants are currently being investigated as ethanol sources. Furthermore, the use of corn-based ethanol as a fuel has driven up corn prices world-wide, leading to increased food prices. In February of 2007, there were even street protests in Mexico City over the high price of corn tortillas, a direct result of the use of corn-based ethanol fuels.

More on other fuels

Alcohols aren't the only fuels being considered as alternatives to hydrogen for use in fuel cells. Ammonia, dimethyl ether, and formic acid are also under investigation. In ammonia fuel cells, ammonia essentially acts as a medium for delivering hydrogen to the fuel cell. First, the ammonia is heated to decompose it into hydrogen gas and nitrogen gas. Then the hydrogen gas is oxidized into water as in a normal hydrogen fuel cell. The main advantage of ammonia as a fuel is that it can be liquefied at moderate pressures, and therefore is easier to handle, store, and transport than hydrogen. Dimethyl ether (DME) offers this same advantage. DME is less toxic than methanol, and DME fuel cells don't suffer from crossover oxidation the way methanol fuel cells do. Formic acid also offers the advantages of lower toxicity and reduced crossover oxidation.

There is an important difference between fuel cells that use fuels like ammonia and those that use fuels like formic acid or dimethyl ether. Ammonia is not itself electrolyzed in an ammonia fuel cell. Rather, ammonia is decomposed into N_2 gas and H_2 gas, and the H_2 gas is electrolyzed as in a normal hydrogen fuel cell. Fuel cells that convert their fuels into hydrogen are called *reforming* fuel cells. Formic acid and DME, on the other hand, are themselves electrolyzed in fuel cells. Fuel cells that do not convert their fuels into hydrogen or other substances are called *direct* fuel cells. Ethanol and methanol fuel cells are usually direct fuel cells.

More on fuel cell electrode materials

Traditionally, platinum has been the metal of choice in both the anode and the cathode of polymer-electrolyte fuel cells, regardless of the fuel used. Recently, a new platinum-nickel alloy called $Pt_3Ni(III)$ has been developed which is ten times as catalytically active as platinum alone when used as a cathode material. For the cathode catalyst to work, molecular oxygen from the air must be adsorbed on the surface of the catalyst. However, when platinum cathodes are used, hydroxide ions produced as intermediates in the production of water molecules adsorb tightly to platinum atoms at the surface of the catalyst, blocking those surface platinum atoms. Hydroxide ions adsorb much less strongly on $Pt_3Ni(III)$, meaning fewer surface platinum atoms will be blocked, and more will be available onto which O_2 can adsorb.
The greater catalytic activity increases the efficiency of fuel cells, which is important in the case of methanol fuel cells which already suffer from losses of efficiency due to crossover oxidation.

More on polymer electrolyte membranes

Most experimental fuel cells for automotive use involve polymer electrolyte membrane fuel cells. These are fuel cells in which the electrolyte which separates the anode and the cathode is a thin layer of a special polymer designed to conduct cations, but not electrons. Polymers are giant molecules containing thousands of atoms, usually arranged in a chain-like structure. Many polymers are made up of a main backbone chain, with small side chains of atoms attached to the atoms in the backbone chain. In polymer electrolytes, these side chains contain ionizable groups. Nafion, a polymer often used for making fuel cell electrolyte membranes, is a polymer containing mostly carbon and fluorine atoms, but with side chains containing sulfonate groups, usually with sodium as the counterion. The anionic sulfonate groups are bound to the polymer chain, but cations are freely conducted through the material. This allows the material to conduct hydrogen or other cations between the anode and the cathode.

Other types of materials are used as electrolytes in fuel cells for non-automotive applications. For example, phosphoric acid is used an electrolyte in larger stationary fuel cells. Other stationary fuel cells use solid oxides as electrolyte membranes.

More on the history of fuel cells

Electrochemical cells were invented in the late 1700s. The connection between electricity and chemical reactions provided a fruitful field for researchers of the early 1800s. Scientists like Humphry Davy improved cell designs while using their current to decompose compounds by electrolysis to discover new elements like sodium, potassium, magnesium, calcium, strontium, and barium. Meanwhile, William Nicholson and Anthony Carlisle discovered that water could be decomposed by electrolysis into hydrogen and oxygen. In 1839, Sir William Grove experimented with reversing the process to generate electricity while synthesizing water from hydrogen and oxygen. Even so, it would be another fifty years before the first practical fuel cell was built by Charles Langer and Ludwig Mond in 1889, powered by methane. Francis Bacon worked to develop better fuel cells from the 1930s through the 1950s. Fuel cell development really took off with the birth of the space age, when NASA needed compact and efficient sources of electricity for spacecraft.

Connections to Chemistry Concepts

1. **Oxidation and reduction**—All the reactions that power fuel cells are redox processes, regardless of the fuel involved.
2. **Half reactions**—Fuel cells are a real-world application in which it makes sense to describe the chemical reaction taking place as two half-reactions. In fuel cells, oxidation and reduction take place in different locations. Half-reactions provide a realistic description of the chemistry.
3. **Energy and chemical reactions**—The chemical reactions in fuel cells are necessarily exothermic, just as combustion reactions are exothermic.
4. **Ions**—All fuel cells involve the passage of cations through a membrane while electrons travel separately through a wire to the same destination at the cathode catalyst on the far side of the fuel cell.
5. **Atomic structure**—The nature of atoms as being made of protons, neutrons, and electrons is central to understanding how ions form and convert to neutral molecules again in fuel cells.
6. **Electrochemical cells**—To understand fuel cells, students will apply concepts familiar from other electrochemical cells and reinforce those concepts.
7. **Polymers**—The membrane separating the anode and cathode of a fuel cell is usually made of a polymer electrolyte of some sort.
8. **Catalysis**—The anode and cathode of a fuel cell not only conduct electrons from one side of the fuel cell to the other, but they also catalyze the oxidation of the fuel molecules and the reduction of the resulting ions to form waste products.
9. **Gases and liquids**—The fact that there is a lot of empty space between the molecules of a gas becomes important when the economics of transporting hydrogen need to be evaluated. The fact that liquid fuels have much less empty space in between their molecules makes them more economical to transport.

10. **Atmospheric chemistry**—The carbon dioxide content of the atmosphere is a major concern in this story, not only the fact that human activity is raising atmospheric CO_2 levels, but ironically that CO_2 levels might not be high enough to make methanol production from atmospheric CO_2 feasible.

11. **Surface and interphase chemistry**—In a fuel cell, both oxidation and reduction take place when gas-phase reactant molecules are adsorbed onto the surface of a solid-phase catalyst. A lot of interesting chemistry takes place on surfaces, from sophisticated catalysis to the simple spreading of water on a piece of glass. Even though this topic usually gets little attention in high school chemistry classes, it is important enough that the 2007 Nobel Prize for Chemistry was awarded to German scientist Gerhard Ertl for his work in surface chemistry.

12. **Elements and compounds**—Hydrogen is the most abundant element in the universe, and there is plenty of it on planet Earth—but it is locked up in compounds with other elements, mostly water, and to a lesser extent methane. Obtaining elemental hydrogen, H_2, requires decomposing water or other hydrogen containing compounds.

Possible Student Misconceptions

1. **"Fuel cells burn fuels"** "Burning" implies combustion, which is mechanistically, and kinetically different from the way fuels are oxidized in fuel cells. A major consequence of the different mechanisms of oxidation in fuel cells is that energy is released as electric current rather than heat, as is the case with combustion.

2. **"The electrodes in a fuel cell absorb ions."** The difference between absorption and adsorption is one that high school students may not be familiar with. They should be made aware that adsorption is merely the attachment of molecules or ions to a surface through chemical interaction of some sort, and not the same thing as absorption.

3. **"Hydrogen, methanol, and ethanol are energy sources."** Any fuel is just a means of storing energy. (Even fossil fuels are merely storing solar energy from millions of years ago.) Energy is required to produce hydrogen, methanol, and ethanol. That energy must come from somewhere. The energy used to produce hydrogen, methanol, or ethanol, may be that stored in fossil fuels, or it may come from a renewable source like solar or wind power. Either way, the fuels are only as green as the energy used to produce them.

4. **"Ethanol is non-toxic."** Ethanol is toxic, just not as toxic as methanol. While (most) adults can safely and responsibly consume it is small doses, people have died from ingesting enough of it.

Demonstrations and Lessons

1. The electrolytic decomposition of water can be accomplished using a Hoffman's apparatus or with simpler set-ups using batteries and pencil-lead electrodes. Fuel cells combine hydrogen and oxygen to generate electricity. The reverse process, using electricity to decompose water into hydrogen and oxygen, demonstrates the connection between electricity and chemical transformation, and underscores the thermodynamics of the reactions involved in fuel cells (i.e. producing water releases energy, while converting water into hydrogen and oxygen absorbs energy). What's more, it reinforces the understanding that generating hydrogen for fuel requires energy of some sort.

2. Constructing a simple galvanic cell is another way to reinforce the concept that chemical reactions can produce electricity. Also, there are enough similarities between fuel

cells and galvanic cells that concepts learned in one are applicable to the other, and one can be used to reinforce understanding of the other.
3. You can set up an electroplating apparatus to reinforce the connection between electricity and chemical changes.
4. Simple reforming fuel cells can be made that use HCl and HNO_3 as hydrogen sources. A description and procedure is found in Bilash, Borislaw; Gross, George R.; and Koob, John K., *A Demo A Day: A Year of Chemical Demonstrations*. Batavia, IL: Flinn Scientific, 1995, p. 240.
5. A description of how to build a direct methanol fuel cell for classroom demonstration use can by found in Zerbinati, Orfeo, “A Direct Methanol Fuel Cell,” *Journal of Chemical Education*, July 2002, **79(9)**, *829*.
6. A low-cost apparatus for studying gas adsorption on solid-surfaces for use in teaching is described in Macedo, Hugo; Aguiar-Ricardo, Ana ; and Sotomayor, João, “Construction of a Low-Cost Apparatus for Gas Adsorption on Solids, *Journal of Chemical Education*, June 2006, **83(6)**, *915*.

Student Projects

1. Students can research other fuels; they can be assigned fuels, other than methanol and ethanol, which are being investigated for use in fuel cells. Students should investigate the advantages, disadvantages, and potential applications of their assigned fuel. You might choose to have them report their findings as written reports, posters, or class presentations. This project might be done in groups so you don’t have to find a different fuel for each individual student in your class.
2. Have a debate/discussion in which students have been assigned to argue for either methanol or ethanol fuel cells as a better alternative for automotive use.
3. Assign students or groups to research and report on other important electrochemical processes, such as aluminum refining, galvanic corrosion protection, the reactions in rechargeable batteries, photovoltaic cells, etc.
4. Assign students or groups to research and report on non-automotive uses of fuel cells. Fuel cells are used in aerospace applications, portable electronic devices, and stationary power sources, among other things. Student reports, in whatever format you choose, should include information about the technical constraints of the application, the fuel used in a particular application, and the limits of the technology used, and outlook for future development.

Anticipating Student Questions

1. **“Why can’t water be used as a fuel?”** *Fuels release their energy by reaction with oxygen (which is relatively abundant). Water cannot react further because it is already oxidized as much as it can be. (Any further oxidation with oxygen would consume, not release energy.)*
2. **“Why can’t electricity from windmills be transmitted over long distances?”** *Electrical current is the motion of electrons moving through a wire or some other conducting material. Although the copper wire in transmission lines conducts electricity very well, it does resist the flow of electrons a little bit. Overcoming that resistance uses up some of the energy of the moving electrons. The longer the distance the electrons have to travel through the transmission lines, the more energy will gradually be used up overcoming resistance. After a few hundred miles, the flowing electrons will have lost so much energy that they won’t have*

enough energy left to do things like turn electric motors or make bulbs light up. For this reason, electric power plants have to be built relatively close to where the electricity they produce will be used.

3. **"Why are we worried about the effect of CO_2 in the atmosphere if it only makes up less than 1% of the atmosphere?"** *Carbon dioxide is a potent enough greenhouse gas that even small amounts can have an effect on global temperatures. Currently CO_2 levels are at about 370 ppm. It's thought that an increase to only 450 ppm may cause irreversible and possibly catastrophic climate change.*

References

McFarlan, A.; Pelletier, L.; and Maffei, N. "An Intermediate-Temperature Ammonia Fuel Cell Using Gd-Doped Barium Cerate Electrolyte," *Journal of the Electrochemical Society*, 2004, **151**, *A930*.

J.T. Muller, P. M. Urban, and W. F. Holderich, "Electro-oxidation of Dimethyl Ether in a Polymer-Electrolyte-Membrane Fuel Cell," *Journal of the Electrochemical Society*, 2001, **147**, *4058*.

Jiang, Ruichun; Kunz, H. Russell; and Fenton, James M. "Comparison of Several Research Approaches for Direct Methanol Fuel Cell Membranes,"
Abstract of a paper presented at the 210th Electrochemical Society Meeting, October 29-November 3, 2006, Cancun, Quintana Roo, Mexico.
<http://ecsmeet2.peerx-press.org/ms_files/ecsmeet2/2005/06/01/00021841/00/21841_0_art_file_0_1117673543.pdf>

Jeong, Kyoung-Jin, et al. "Fuel crossover in direct formic acid fuel cells," *Journal of Power Sources*, 2007, **168 (1)**, *119*.

Stamenkovic, V. R., et al. "Improved Oxygen Reduction Activity on $Pt_3Ni(111)$ via Increased Surface Site Availability," *Science*, 2007, **315**, *493*.

"Mexicans Stage Tortilla Protest," BBC News Online, February 1 2007. http://news.bbc.co.uk/2/hi/americas/6319093.stm

Ehsani, Mehrdad. *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design*. CRC Press, 2005, p. 17-18.

Websites for Additional Information

More on the History of Fuel Cells

"Collecting the History of Fuel Cells" —an impressive online exhibit from the Smithsonian Institution. http://americanhistory.si.edu/fuelcells/

More on Ethanol as a Fuel

“Green Dreams,” Joel K. Bourne, Jr. This feature story also available in the print edition of *National Geographic* magazine, October 2007, explores the promises and pitfalls of ethanol and biodiesel produced from a variety of plant sources, from corn and sugar cane to switch grass and algae. This insightful and in-depth story looks at the various sources in terms of their environmental, economic, and human impacts.
http://magma.nationalgeographic.com/ngm/2007-10/biofuels/biofuels.html

General Web References

“Fuel Cells”—from the U.S. Department of Energy. This site contains basic information on a wide variety of fuel cells using different technologies and for different applications.
http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html

“Fuel Cells” —video segment from the PBS television series *NOVA ScienceNow*, which originally aired in July of 2005. The segment features a particularly entertaining explanation of how fuel cells work by Tom and Ray Magliozzi, hosts of National Public Radio’s *Car Talk*. The site also includes web extras.
http://www.pbs.org/wgbh/nova/sciencenow/3210/01.html

“How Fuel Cells Work” —from HowStuffWorks. http://auto.howstuffworks.com/fuel-cell.htm

More websites on Teacher Information and Lesson Plans

“Discovering the principle of the fuel cell at home or in school” —An involved student laboratory activity on electrolysis, created by Dr. Martin Schmidt, from Fuel Cells 2000.
http://www.fuelcells.org/ced/career/scienceproject.pdf

“Bonneville Power Administration Energy Efficiency Education Program” —This site features free downloadable curriculum materials on fuel cells and other energy-related topics.
http://www.bpa.gov/Energy/N/projects/fuel_cell/education/index.cfm