YEAR 12 CHEMISTRY EXTENDED RESPONSE TASK WEEK 1
ELECTROCHEMICAL CELLS

Spontaneous redox reactions can be used as a source of electrical energy, including primary, secondary and fuel cells. Fuel cells are a potential lower-emission alternative to the internal combustion engine and are already being used to power various modes of transport. Organisations such as the International Partnership for Hydrogen and Fuel Cells in the Economy, have been created to foster global cooperation on research and development, common codes and standards, and information sharing on infrastructure development.

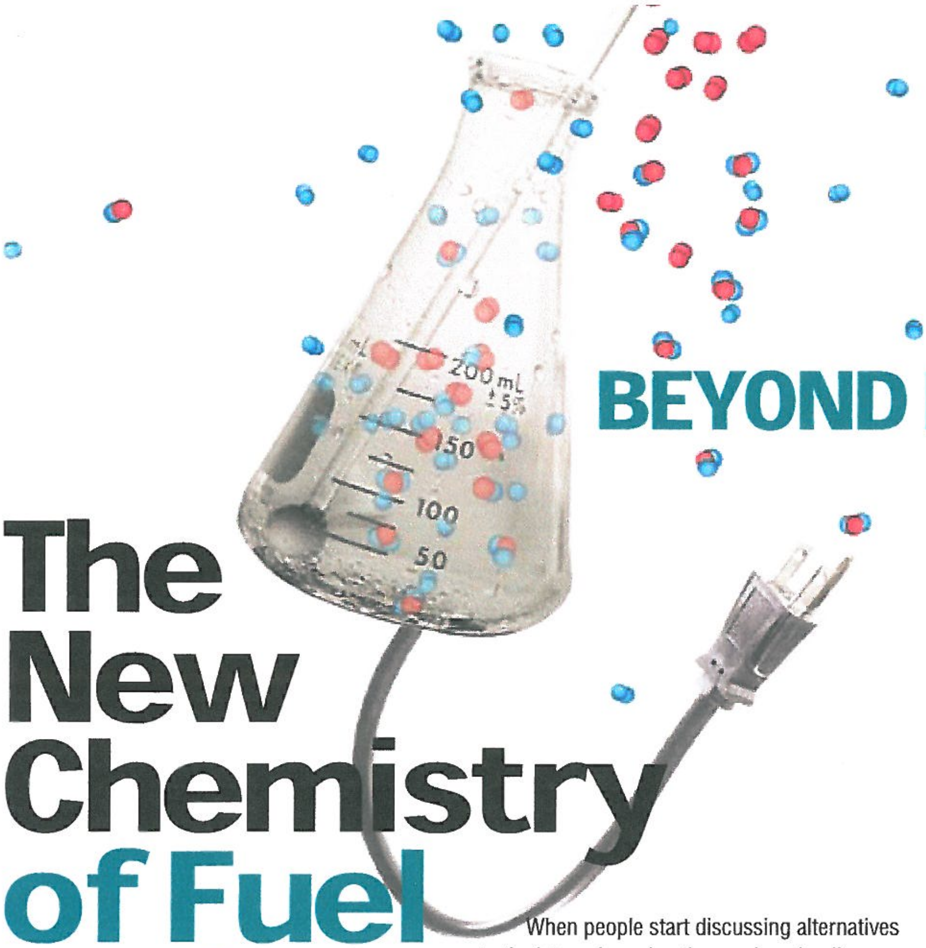
The Extended Response task will assess your understanding of redox chemistry, electrochemical cells, the operation of fuel cells, the latest developments in fuel cell technology including materials/catalysts used to decompose water in the formation of hydrogen gas, and a comparison of the combustion engine to the hydrogen fuel cell.

Suggested readings include;

- https://www.acs.org/content/dam/acsorg/education/resources/highschool/chemmatters/gc-beyond-hydrogen.pdf (attached)

- Context 3 (page 57-77) Nelson 3AB Textbook

Students will be expected to complete the assessment WITHOUT bringing in any notes.



BEYOND HYDROGEN: The New Chemistry of Fuel Cells

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.

GETTY IMAGES

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.

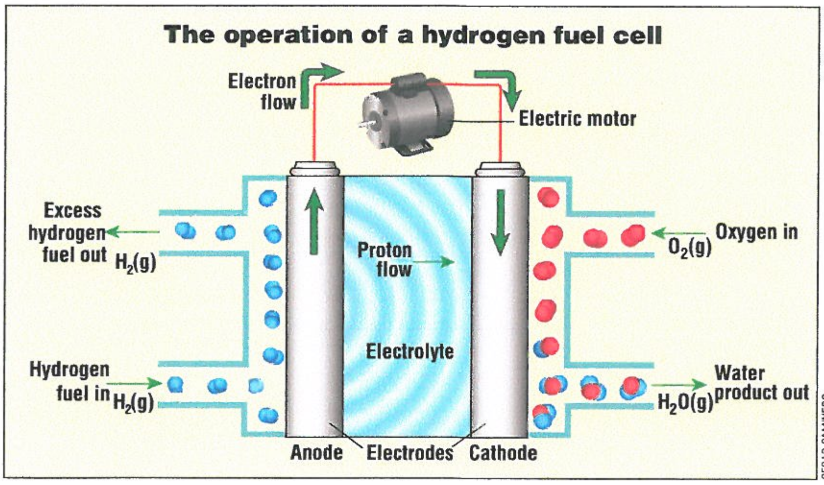
What fuel cells do

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-



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.

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 DaimlerChrysler 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.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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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