Lesson 3 – Battery and Fuel Cell Technologies

Concepts

1. There is a need for alternative fuels to supplement or replace fossil fuels, which are a limited resource and cause pollution.

2. Battery electric and fuel cell cars both rely on an electric motor to convert electricity to mechanical energy to propel the car. Electrochemical reactions are the basis for both types of automobiles.

3. Hydrogen gas has been proposed as a potential alternative fuel. Hydrogen is an energy carrier, it is not a primary energy source the way we consider gasoline.

4. Fuel cells require hydrogen and oxygen as “fuel” to produce electricity and water.

5. Hydrogen does not exist free in nature, and must be isolated in order to use it for energy production.

6. Electricity can be used to produce H₂ from water in an electrochemical reaction. This is an inefficient process that requires energy.

7. Although the use of hydrogen in fuel cells is clean and efficient, the creation of hydrogen from electricity or fossil fuels is less so.

8. Fuel cell design affects efficiency.

9. Fuel cell stacks for transportation or electricity generation often contain hundreds or thousands of individual cells to get more power out of fuel cells. Cells connected in series add up their voltages, while cells connected in parallel keep the same potential (voltage) but can transfer more electrons at a time.

10. Voltage is a measure of electric potential.

11. Power, measured in watts or kilowatts (kW), is equal to the product of voltage and current (amps).

12. Energy is measured in watt-hours or kilowatt-hours (kW-h), and is a measure of how much power is produced over a certain period of time (power x time). Our electric bills are calculated in terms of kW-h.

13. Efficiency is a measure of the amount of power delivered by a system relative to the amount of power provided to the system ((power out/power in) x 100%).

Relationship to Guiding Question

Students need to develop an understanding of how a fuel cell operates in order to evaluate if the technology is a worthwhile component of our transportation energy future. The activities in this section are designed to give students hands-on experience with the technical aspects of fuel cell operation.
Key Questions

1. What happens in a fuel cell?
2. What happens during electrolysis?
3. What advantage does a fuel cell have over a traditional battery?
4. What are the environmental benefits of a hydrogen fuel cell car, relative to a fossil fuel combustion engine?
5. How can we determine the efficiency of our fuel cell?
6. How can we improve the performance of our fuel cell?

Student Learning Objectives

<table>
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<tr>
<th>Objectives</th>
<th>Standards</th>
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<tr>
<td>Students will be able identify the basic components of a fuel cell.</td>
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<td>Students will be able to describe how a fuel cell operates and the chemical reactions that take place during operation.</td>
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<td>Students will demonstrate an understanding of the environmental benefits of hydrogen fuel cells over fossil fuel combustion systems for transportation energy.</td>
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<td>Students will be able to describe 3 applications of hydrogen fuel cells.</td>
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<td>Students will be able to describe some challenges to the wide-spread application of fuel cells for meeting our nation's energy needs.</td>
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<td>Students will be able to analyze their original fuel cell design and make improvements based on performance.</td>
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<td>Students will be able to measure the amount of power supplied by their model fuel cell.</td>
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<td>Students will be able to calculate the efficiency of their model fuel cell.</td>
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<td>Students will be able to describe the chemical reactions that take place during the electrolysis of water, identifying which reaction occurs at the cathode and which at the anode.</td>
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<td>Students will be able to state whether electrolysis produces or consumes energy.</td>
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Students will be able to state the reasons why one would consider using electrolysis to produce hydrogen.

Students will be able to describe the relationship between what happens during electrolysis and what takes place during the operation of a fuel cell.

Background

The main purpose of this lesson is to help students gain a conceptual understanding of the technical aspects of electric motor cars (batteries or fuel cell to generate electricity) (components, structure, chemical reactions that take place) and hydrogen production.

A fuel cell is a device that converts chemical energy into electrical energy. It works like a battery, but is continually fed with a fuel – usually hydrogen. The output voltage of a fuel cell can be increased by adding cells in series, called “stacking.”

Fuel cells have many benefits such as higher energy efficiency, less emission of pollutants and greenhouse gases, and have combined heat and power capabilities. Some applications of fuel cells include transportation, space missions, stationary power generation to buildings and remote areas, portable applications such as back batteries for laptops etc. However, currently the cost, fuel storage, and fuel delivery have been the main challenges that face fuel cells and are preventing their wide-scale use.

Electrochemistry Basics

There are a few useful tricks to try to remember the complexities of electrochemical reactions:

- **LEO the GERM**
  - Loss of electrons – oxidation
  - Gain of electrons – reduction
- Oxidation – the atom goes from a lower oxidation state to a higher oxidation state. For example, hydrogen gas has a zero oxidation state, H\(^{+}\) has a +1 oxidation state: \(2H_2 \rightarrow 4H^+ + 4e^-\)
- Reduction – the atom goes to a lower oxidation state. For example, O\(_2\) has a zero oxidation state and the oxygen atom in water has a -2 oxidation state.
  \(O_2 + 4H^+ + 4e^- \rightarrow 2H_2O\)
- Cathode = a negatively charged electrode that is the source of electrons entering an electrical device. For the electrolysis of water, the hydrogen gas is produced at the cathode.
  \(4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-\)
How does it work?

In a typical fuel cell, gas (hydrogen) is fed continuously to the anode (negative electrode) compartment and an oxidant (e.g. oxygen from the air) is fed continuously to the cathode (positive electrode) compartment. Electrochemical reactions take place at the electrodes to produce electric current.

- Two key components –
  - Electrodes – that catalyze the electrochemical reactions
  - Electrolyte – that facilitates the transfer of hydrogen ions from the anode to the cathode. In this case – the electrolyte is a PEM – polymer electrode membrane. It allows the passage of protons, but not electrons.

Hydrogen enters the fuel cell at the anode (negative electrode) where it is oxidized into two H^+ ions (protons) and 2 electrons for every hydrogen molecule. This is called an **electrochemical reaction**. That just means it requires the transfer of electrons.

\[ 2H_2 \rightarrow 4H^+ + 4e^- \]

The protons pass through the PEM (electrolyte) to the cathode side of the fuel cell. The electrons can’t pass through the PEM, so instead they pass through the electrical circuit and through the electric load (e.g., the electric motor on an automobile) before reaching the cathode (positive electrode). Oxygen enters the fuel cell at the cathode and combines with the hydrogen ions and the electrons in a **reduction reaction** to produce water:

\[ O_2 + 4H^+ + 4e^- \rightarrow 2 \text{H}_2\text{O} \]

Oxygen is the **oxidant** in this reaction, it is **reduced**.

Overall – hydrogen and oxygen molecules are the reactants and H\text{2}O is the product:
Fuel cell: Hydrogen and oxygen gases flow into the cell producing water and electricity.

Electrolysis cell: Hydrogen and oxygen gases produced when electricity flows through an electrolyte containing water.

The fuel cell is the physical structure that makes these electrochemical reactions happen and captures and utilizes the current generated by electrons as well. This rapid combination of elements also creates heat (e.g., the process is not 100% efficient). A PEM fuel cell has an average operating temperature of about 80°C (176°F).

A fuel cell differs from a traditional battery because it continues to operate as long as the fuel and oxidant are supplied to the electrodes. The transfer of ions is the fundamental chemical process that creates the electrical energy within the fuel cell.

The PEM fuel cell uses hydrogen fuel and oxygen from the air and gives off water as a waste product. The theoretically maximum voltage that can be produced from the fuel cell is 1.23 volts. This voltage is the theoretical electrochemical potential of the reduction half-cell reaction which occurs at the cathode. However, this is impossible to achieve because of internal resistance, diffusion losses, and voltage losses manifested as heat.

To define the efficiency of a fuel cell, the 2nd law efficiency is used that relates the power produced in a fuel cell to the maximum theoretical power produced by oxidizing the same amount of hydrogen:

\[
\text{\% efficiency} = 100\% \times \frac{\text{power out}}{\text{max. power}}
\]

Assuming that the current is constant, we can use \( P=IV \), to simplify this formula to:

\[
\text{\% efficiency} = 100\% \times \frac{\text{voltage out}}{\text{max. voltage}}
\]
The maximum voltage is 1.23 volts and the actual voltage can be measured with a multimeter. A typical fuel cell can generate 0.6 – 0.7v. Thus, the efficiency is approximately 50-55%.

But driving an automobile requires hundreds of volts, and a single fuel cell can only produce ~1v. An engineering design question arises - How can fuel cells be designed to provide the voltage, and therefore power, required to drive a vehicle? A collection of fuel cells connected together is known as a “stack”. In order to increase the voltage available, cells are connected in series. Several hundred fuel cells can be connected in a stack to provide over two hundred volts in a typical automobile fuel cell. The newest Honda fuel cell design provides 100kW of power (about 134 hp) to drive their FCX Clarity, the latest H2 car design.

Another possibility for connecting several fuel cells together is a parallel connection. This type of connection is essentially the same as creating one large cell, so the voltage would remain at the 0.6-0.7v range, but there would be more surface area available for the chemical reactions and so there would be the potential for more electrons to flow, which would provide more current at that voltage. There are limitations to the size of a single fuel cell. For example, if there is not enough pressure or volume of H2 flow, the entire area of the fuel cell may not act effectively. The cell size factor must be considered in design of fuel cell stacks to optimize efficiency.

**Hydrogen Production**

Hydrogen is the most abundant element in the universe. It’s a component in a wide variety of compounds (CH4, H2O etc.), but is rarely found in our natural world as H2 – the form we need for a FC. Thus, we need to make hydrogen to supply the H2 fuel required for a FC vehicle. How hydrogen is produced is very important to overall efficiency and environmental impact of the hydrogen based energy system.

**Electrolysis**

Electrolysis is one method for producing hydrogen. This is basically the reverse of what happens in a fuel cell– electrolysis uses an electric current passed through an electrolyte to split H2O into hydrogen and oxygen. (remember – a fuel cell combines hydrogen and oxygen ions to produce an electric current). In our electrolysis experiment, the electrolyte is a solution of water and salt (sodium chloride or sodium acetate). When we apply an electrical current to the electrolyte solution we supply electrons to the system. This electrical energy causes the water (H2O) to decompose. Hydrogen forms at the anode (negative electrode) and oxygen forms at the cathode (the positive electrode).

The overall chemical equation for electrolysis is:

\[ \text{energy (electricity)} + 2 \text{H}_2\text{O} \rightarrow \text{O}_2 + 2 \text{H}_2 \]

At the anode, the water molecules split up into positively charged hydrogen ions (H+) and oxygen. The electrons are produced at the anode by this oxidation reaction help to create the external circuit:
At the cathode, there is an electrical pressure to push electrons from the external circuit into the water where the water is reduced into hydrogen gas:

$$4\text{H}_2\text{O} + 4\text{e}^- \rightarrow 2\text{H}_2 + 4\text{OH}^-$$

In the solution, the extra hydrogen ions from the anode and hydroxide ions from the cathode react to form water. Overall, for the transfer of 4 electrons through the circuit, 2 molecules of hydrogen gas are created and one molecule of oxygen gas is created. When doing an electrolysis experiment, it is easy to tell which electrode is the cathode because twice as much gas (hydrogen) is produced there.

$$2\text{H}_2\text{O} \rightarrow \text{O}_2 + 2\text{H}_2$$

Electrolysis was the main method for hydrogen production in the U.S. until the 1950’s, but currently is not a very widely used method for producing hydrogen because it is relatively inefficient and can be expensive, depending on the cost of electricity (only about 4% of all H₂ is produced by electrolysis). However, developing this technology in combination with a renewable energy source (solar, wind, hydro) offers the chance for a “green” (environmentally friendly) hydrogen economy and a true Zero Emission Vehicle (ZEV).

It is important to realize that the process that happens in a fuel cell is similar to but the reverse of what happens during electrolysis. Hydrogen and oxygen are supplied to the fuel cell. The elements combine within the fuel cell and produce free electrons, which leave the anode side and travel through an electric circuit to power an electrical device before returning to the fuel cell at the cathode side. Thus, while the electrolysis process uses electrical energy to separate water molecules into hydrogen and oxygen gases, the fuel cell creates electrical energy by combining hydrogen and oxygen to form water molecules.

**Reforming of Hydrocarbons**

Hydrogen can also be produced from hydrocarbons such as methane or gasoline through a process called reforming. This process has approximately an 80% efficiency. Worldwide, 48% of hydrogen is produced from natural gas, 30% from oil (mostly consumed in refineries), 18% from coal, and the remaining (4%) via water electrolysis.

Commercial bulk hydrogen is usually produced by the steam reforming of natural gas. High temperature steam (H₂O) reacts with methane (CH₄) to yield syngas:

$$\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2$$

Additional hydrogen can be recovered through a lower-temperature reaction with the carbon monoxide:

$$\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$$

Essentially, the oxygen atom is stripped from the water (steam) to oxidize the carbon, liberating the hydrogen formerly bound to the carbon and oxygen. Overall, one molecule of carbon dioxide is formed for every molecule of methane consumed.
in this series of reactions. Thus, the same amount of fossil carbon is produced in this
development as is produced by directly combusting the methane.

Hydrogen production can be centralized, distributed or a mixture of both. While
generating hydrogen at centralized energy plants promises higher hydrogen
production efficiency, difficulties in high-volume, long-range hydrogen transportation
(due to factors such as hydrogen damage and the ease of hydrogen diffusion
through solid materials) makes electrical energy distribution attractive within a
hydrogen economy. In such a scenario, small regional plants or even local filling
stations could generate hydrogen using energy provided through the electrical
distribution grid or on-site wind or solar power. While hydrogen generation efficiency
is likely to be lower than for centralized hydrogen generation, losses in hydrogen
transport can make such a scheme more efficient in terms of the primary energy
used per kilogram of hydrogen delivered to the end user. The proper balance
between hydrogen distribution and long-distance electrical distribution is one of the
primary questions that arises in the hydrogen economy.

**Historical Context:**

The fuel cell technology is not as new as you might think! It was initially observed in
1839 by Sir William Grove while he was experimenting with the electrolysis of water.
He reversed the electrolysis process, reacting oxygen with hydrogen to produce
electricity. Ludwig Mond and Charles Langer tried to build the first practical device
in 1889 using air and industrial coal gas. Francis Bacon made improvements to that
model and invented the first successful fuel cell device in 1932. It was a 20-
horsepower fuel cell-powered tractor. In the late 1950’s, NASA explored the use of
fuel cell technology to develop a power source for space travel and, ultimately, in the
space shuttle program and space stations.

**Key Terms**

- **Anode:** a positively charged electrode by which electrons leave an electrical
device; the electrode at which oxidation occurs.

- **Catalyst:** substance that speeds up the chemical process by lowering the
amount of energy needed to cause the reaction.

- **Cathode:** a negatively charged electrode that is the source of electrons entering
an electrical device; the electrode at which reduction occurs.

- **Efficiency:** a measure of how energy is delivered per unit of energy input to a
system (efficiency = energy out/energy in x 100% OR
energy out/max. theoretical energy produced).

- **Electricity:** the flow of electrons in a circuit.

- **Electrochemical reaction:** a reaction that involves the transfer of electrons
among ions and molecules to convert chemical energy to electrical energy (or
vice versa).
**Electrodes**: typically metal rods that catalyze the electrochemical reactions. (Al, Pd, Pt, Cu etc.)

**Electrolyte**: solution that allows the flow of ions required in the electrochemical reactions. In a fuel cell, the electrolyte is a PEM – polymer electrode membrane that facilitates the diffusion of the hydrogen ions from the anode to the cathode.

**Fuel Cell**: the physical structure that facilitates electrochemical reactions to create electrical energy from chemical energy.

**Hydrogen**: chemical fuel of a fuel cell flowing through the anode.

**Membrane**: substance that allows hydrogen and oxygen to pass through while preventing the diffusion of other molecules or electrons.

**Operating temperature**: temperature needed for the chemical reactions to occur (this will depend on the fuel cell type).

**Oxidation**: change in chemical composition to a higher oxidation state.

**Oxygen**: chemical fuel of a fuel cell flowing through the cathode.

**PEM**: proton exchange membrane.

**Prototype**: small scale model of a real system.

**Reduction**: an electrochemical reaction that causes a molecule or ion to change to a lower oxidation state.

**Stacking**: method of adding fuel cells in series to increase voltage.

**Voltage**: measure of electric potential of an electrical circuit or device.

**ZEV**: zero emissions vehicle. A vehicle fueled by an energy source that does not produce any tailpipe emissions.

**Activities:**

This series of classes is comprised of 4 basic activities designed to help students understand 1) how batteries work; 2) how a fuel cell works (two activities); and, 3) how hydrogen is produced. Students will build and test a battery and two different fuel cell prototypes. They will calculate the efficiency of their model and then change their design to try to make improvements and increase the power production. Students will also perform a short electrolysis experiment to observe what happens as electricity is used to split water into hydrogen and oxygen gases – which is one method of hydrogen production. The total time for these activities will be about one week.
Introduction general concepts (1 – 1.5 days)

- Briefly recap from previous activities – ask students, based on what they’ve learned so far, do they think electric vehicle (EV) or fuel cell cars are a good idea? Why or why not? (We’ve talked a lot about the need for a change – the problems associated with fossil fuel combustion – but what about the batteries or fuel cells? How reliable are they? How do they work?) Do we need to know something about how an EV fuel cell operates, in order to decide if it’s better than an internal combustion engine? (yes). Over the next week we’re going to spend some time now learning about how EVs and fuel cells work.

- Provide demonstrations to give basic idea – Battery connected to Lego car (built by instructor), H-Tec fuel cell model car. Key concepts:
  - Both have an electric motor that converts electrical energy to mechanical energy that provides power to the drive train.
  - The electricity sent to the electric motor is generated in the battery of fuel cell through electrochemical reactions:
    - Battery – from chemical energy stored in chemicals within the battery (often lead and sulphuric acid). The chemical energy stored in the battery can be depleted, reducing the power output of the battery over time. Batteries are recharged by plugging the batteries into an electric power source.
    - Fuel cell – hydrogen fuel continuously supplied. The fuel cell can provide power as long as fuel supplied. Hydrogen has to be provided as fuel at regular intervals (like refilling the vehicle with gasoline)
  - Neither vehicle has any tailpipe emissions of concern.

- Introduce basic electrical and electrochemical concepts
  - An electrical current is caused by moving free electrons. Free electrons can move through a conductor but not through an insulator. Ask the class if they can name some conductors and insulators. (ex. Conductors: silver, gold, iron, copper. Insulators: glass, plastic, rubber, wood)
Certain materials are less conductive than others. For example, the human body conducts electricity but copper conducts electricity better. The human body has more **resistance** to electrical current than copper does. Resistance is the opposite of conductance. To prove that the human body conducts electricity, bring in the “touch circuit”.

- Have the students pretend that their hand is an electron. Have them open their hand and move it up and down. Tell them that since their hand is now a moving electron, they are modeling an electrical current. Now tell them to put a book on their hand and move it at the same speed. By putting the book on their hand, they are adding resistance. In which case did they use more force, with our without the added “resistance”? Lead them to the conclusion that if you add more resistance, you use more force. Electrical force is called **voltage**.

- Define that most appliances are rated in terms of power, with units of **Watts**. How are all of these things related? Give them the following equations for future reference:
  - \[ \text{voltage} = \text{resistance} \times \text{current} \quad (V = I \times R) \]
  - \[ \text{power} = \text{voltage} \times \text{current} \quad (P = I \times V = V^2/R) \quad (R=\text{resistance}) \]

- A common way of generating electricity is by turning a magnet in a coil (A Lego generator with a Lego LED are a good way to illustrate this (need a axle on the generator to spin rapidly by hand to spin the magnets within the generator)). This is how hydro-electric plants, steam turbines in a coal-fired power plant and wind turbines work.

- Demo (or brief activities to do in smaller groups) to show electric circuit using a battery to supply electric energy
  - materials: battery, LED bulb, glass of water (distilled best), copper wire, and some salt.
    - Connect anode of the LED to the negative side of the battery and the cathode to the positive to show that the bulb lights up. The circuit is completed.
    - Change the wire to the cathode - submerge the cathode wire of the LED in the glass of water (you may need to attach longer wire leads. Run an additional wire from the positive side of the battery into the water. Observe that the circuit is not completed; the bulb is not lit. Turn on the lights and have a volunteer start the shake some salt into the water. The class will see the LED bulb start to light up and become brighter as more salt is added. Now explain what is happening.
    - Distilled (and most tap) water doesn’t conduct electricity. When you dissolve table salt in water, the salt dissolves into positive sodium ions and negative chloride ions. The more salt you add,
the more the water conducts. This salt-water is acting as an electrolyte.

- If you put two dissimilar (differently charged) metals into the electrolyte, the positive ions will migrate towards one metal and the negative ions will migrate towards the other metal. If the metals are connected by a good conductor, a current will flow through the conductor. Show the potato clock. This is a wet-cell battery because the electrolyte is a liquid. Another example of a wet-cell battery is a normal car battery. 9 volt, AA, AAA, D, and C batteries are all dry-cell batteries because the electrolyte is a paste.

- Write on the board these general definitions:
  - A battery stores electrical energy and is made up of an electrolyte, a conductor, and two oppositely charged metals. A battery can be recharged but degrades with each charge. A used battery is hard to dispose of.
  - A fuel cell is made up of an electrolyte, a conductor, and two oppositely charged fluids (liquids or gases). A fuel cell does not store energy because the fluids need to be constantly fed into the electrolyte in order to produce electricity. Fuel cells produce no harmful waste products and indefinitely reparable.

**Batteries for EVs (0.5 - 1 day)**

- Complete the Saltwater Battery Activity
  - Split the class into their groups and hand out the materials
  - Let them just start to build their batteries, but walk around and make sure that they aren’t shorting out the battery by filling the ice-trays too high. Also make sure the paper clips are making connections to the dimes and foil.
  - At the end of class, go over discussion questions and, if there’s time, try stacking all the batteries and see how much voltage they produce.
  - Be sure to have them try running the motor off the battery. It probably won’t work. This will just add some perspective when motor does end up working off the fuel cell.

**Fuel Cell Basics (1 day)**

- VERY BRIEFLY Show fuel cell model car again and refresh major components of car. (use a transparency or powerpoint for this figure)
Our goal is to understand how the fuel cell works and how we can generate hydrogen to use as a fuel. Let’s look at the fuel cell:

- There is an electric motor in this car – so the fuel cell must make electricity.
- What do we need to move to create the current necessary for electricity? (We need to move electrons).
- So – a Fuel cell must separate electrons from our fuel to create electricity.
- What is our fuel? Hydrogen.

Use board work and/or “fuel cell powerpoint.ppt” to explain operation and electrochemical reactions in a fuel cell at a class-specific level.

Show students an example of the fuel cell that they will be building from their kits – show the parts and also the finished fuel cell.

- Pass out activity sheets and fuel cell kits. Have students carefully explore the kit contents as you go over what the materials are - define the materials used in the FC and what role each of these materials play (show each material as you describe what it is):
  - Membrane electrode assembly (MEA) – a combination of a Proton Exchange Membrane (PEM) and a catalyst (usually platinum). These are the small black squares in the center of our cell.
  - Proton Exchange Membrane (PEM) – electrolyte material (such as DuPont Nafion) that promotes the passage of protons but blocks electrons from passing through.
  - Catalyst – A material (such as platinum) that promotes the splitting of Hydrogen into its component electron and proton.
• Graphite Plates – Serve to direct the flow of Hydrogen gas, air, and exhaust, as well as conduct electricity from the surface of the MEA to the copper-clad plates.

• Copper-clad plates – Sturdy, conducting casing for the cell. It protects the delicate graphite inside while efficiently conducting charge from the interior of the cell to the terminals (where wires would be hooked).

• Silicon gasket (part of MEA assembly) – Serves to electrically insulate the anode from the cathode and prevent leakage of Hydrogen gas from the grooves in the graphite plate.

• Anode – electrode where the $H_2$ is oxidized to $H^+$ ions and electrons

• Cathode – electrode where electrons consumed to reduce oxygen to create water

• Demonstrate the layers (order) that the students need to assemble the FC. Show students the diagram at the back of their activity packet.

• Finish assembling the graphite plate fuel cells and test with hydrogen generated with electrolyzer (Activity – PEM Fuel Cells). Total time will depend greatly on the extent of preparation and preassembly completed by the instructor before class. Based on experience with students not following instructions closely, it is best to have the components preassembles – layered and one bolt holding layers together.

• Discuss low voltage output (would be 0.6-0.7v in commercial FC). Calculate the actual efficiency of the fuel cell from measured voltage and theoretical maximum.

### Fuel cell testing (1 day)

• Review fuel cell components

• Discuss results of graphite plate fuel cells. Define specific issues:
  
  o Which side is anode/cathode

  o Low power output from fuel cell

  o Not a lot of surface area where grooves for gas flow, contributes to low efficiency of a homemade fuel cell

• Discuss - How can a car be powered by fuel cells?

  o Single fuel cell – no more than 1.23V (1.16 from fueleconomy.gov), typically 0.6-0.7

  o Honda FCX powered by a fuel cell “stack”
    
    ▪ >200V

    ▪ Several hundred cells together in a stack

    ▪ Newest design has vertical orientation – water drainage.
- 80-100 kW (1kW = 1.34 horsepower)
- Introduce today’s lab – test better fuel cells and determine how to best maximize power from a set of fuel cells rather than just one.
  - Show fuel cells and observe to define important component parts and how they work.
  - Introduce concept of maximum voltage per fuel cell, but the need of much higher voltages for car motors.
  - Therefore – need to stack fuel cells
- Review Ohms law as required and basic series vs. parallel circuits
  - \( P=IV \)
  - Need higher current or voltage or both to increase power
  - Circuits in series – voltage added, current same through all
  - Circuits in parallel – current added, voltage drop across each fuel cell the same

![Series circuit vs. Parallel circuit diagram]

- Do activity. Encourage students to explore as much as possible different combinations of series and parallel configurations to try to maximize power.
  - Debrief – how well did students do? What was best combination to maximize power? (draw pictures and review Ohm’s law).
  - Calculate the fuel cell efficiency with the class. How does it compare to the efficiency of the graphite plate FC? What is the efficiency of the whole system from Hydrogen production to Fuel Cell output?
    - In this case, efficiency will be defined as actual energy output / theoretical maximum (the approximation as a ratio of voltages does to account for variable current expected in stacked FCs).
    - Actual energy = Power x time (time of hydrogen injection); where \( P = V^2/R \) (\( V \) and \( R \) measured with the multimeter)
• Theoretical energy - The energy content of hydrogen being oxidized is 10.92 J/ml [1]. Multiple this energy content by the volume of H₂ injected.

• Debrief – key concepts
  o Hydrogen fuel into FC
  o Power output of the FC can be calculated from measured voltage and resistance.
  o Voltage or current, and therefore power, can be increased with stacked fuel cells (series circuit – voltage added; parallel circuit – current additive)
  o Efficiency is determined as a ratio of voltage (in simple systems) or energy output divided by theoretical maximum.

Where does Hydrogen come from? (1 day)

• Discussion - Let’s look at the bigger picture – look again at the car (show slide): we are putting hydrogen and oxygen into this system. Where do we get these? Oxygen, obviously, comes from the air. Where does the hydrogen come from?
  o Hydrogen is the most abundant element in the universe. It's a component in a wide variety of compounds (CH₄, H₂O etc.), but is rarely found in our natural world as H₂ – the form we need for a FC. Thus, we need to make hydrogen to supply the H₂ fuel required for a FC vehicle. How hydrogen is produced is very important to overall efficiency and environmental impact of the hydrogen based energy system.
  o Show FC model car again – ask students to recall how H₂ is provided for the FC car (show schematic transparency if required; the model car uses a solar panel to generate hydrogen by electrolysis).

• Explain basics and importance of electrolysis (save specific equations until after the activity).
  o Electrolysis is one method for producing hydrogen (definition). Explain to the students that electrolysis is basically the reverse of what happens in a fuel cell – electrolysis uses an electric current to split H₂O into hydrogen and oxygen. (remember – a fuel cell combines hydrogen and oxygen ions to produce an electric current).
  o Interesting tidbits
    • In fact, the fuel cell was discovered accidentally in 1839 by Sir William Grove, when he was experimenting with electrolysis (see background).
    • Electrolysis was the main method for hydrogen production in the U.S. until the 1950’s
Currently, it is not a very widely used method for producing hydrogen because it is relatively inefficient and can be expensive, depending on the cost of electricity (only about 4% of all H₂ is produced by electrolysis).

- Electrolysis demonstration
  - Have a working electrolysis setup as a demonstration in the front of the room, running off of a solar cell (could be the model car). Ask:
    - where is the electricity coming from to generate hydrogen in this system? (answer: solar cell).
    - So, what is the net effect on the environment? (no emissions produced). In reality, though, we are getting power from the grid to fuel this system (because we are using a light in the classroom) – and that power is generated from --- what?
    - Does anyone know the primary energy source for most of our electricity? (Coal! (U.S.) Actually in NY state we also have a lot of hydro and nuclear power plants). So, if we look at the whole fuel cell system and include the production of hydrogen, are we producing any emissions? YES (through combustion of coal).
    - This demonstrates that the method for producing the hydrogen makes a big difference in our overall environmental impact.

- Do electrolysis activity.
  - Show students the electrolyzer they will construct. Explain the goals of this part of the activity – to actually generate hydrogen from an external electricity source – in this case a battery. NOTE – once they get started, this activity is done on their own in an inquiry mode – explain to the students that you want them to figure out what is happening.
  - Probing Questions to ask as students perform activity:
    - What’s happening at the wires in the water? What do you call the wires? What do you call the salt solution? What are the bubbles composed of?
    - What do you notice about the volumes of the gases produced at each electrode? Which gas is which?
    - What is happening to the electrodes? (corrosion) (Note: if it seems that very little oxygen gas is generated – then it is being consumed at the electrode to oxidize the metal (corrosion). Depending on the electrode used, you can get rust (Fe(OH)₃), Al(OH)₃, or CuO.

- Show “electrolysis.ppt” or use board to better explain the specifics of electrochemical reaction.
- Go through discussion questions on activity sheet.
- Revisit project statement
OPTIONAL – see “hydrogen infrastructure” lesson and activity for additional 1-2 day discussion of what is required to enable the wide spread use of hydrogen fuel cell vehicles.

Resources
For more information on the different types of fuel cells and operating temperatures visit the following websites:

http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/
http://www.fuelcells.org
http://www.epa.gov/fuelcell/basicinfo.htm

For more information about fuel cell and fuel cell activities for the classroom, visit:
http://www.eere.energy.gov/hydrogenandfuelcells/education/classroom.html

Supply list
Graphite Fuel Cells
(see materials list)

Fuel cells
(h-tec Fuel Cell Mini Kit:


Multimeter


Fresh batteries

Small electronic device such as fan, clock *with voltage low enough so it can be powered by the homemade fuel cell (need to test beforehand)

Supply of hydrogen with fixtures and flow meter

Resource Files
Activity – Saltwater Battery
Activity – Electrolytes and Chemical Power (optional)
Activity – Building a Fuel Cell.doc
Activity – Testing a Fuel Cell.doc
Activity – Electrolysis.doc
Powerpoint slides for this lesson: Fuel Cell Powerpoint.ppt; Electrolysis.ppt
FC materials list
Activity – Saltwater Battery

Purpose
In this experiment you will build a multi-cell battery that will be able to power a calculator. You will plot the battery voltage as a function of battery cells.

Background
Electrical power is (current) x (voltage). Battery cells and fuels can either be stacked (connected in series) or bundled (connected in parallel). Below is a diagram of both configurations.

Series: As you stack cells, the voltage increases and the current remains the same.

Parallel: As you bundle cells, the voltage stays the same and the current increases.

Many appliances need a minimum voltage to run. In this activity we will only be measuring voltage. The batteries shown above are dry-cell batteries with a paste for an electrolyte. We will be building a wet-cell battery, with a liquid for an electrolyte (saltwater). Remember, a battery needs 2 dissimilar metals, an electrolyte, and a conductor to operate.
Equipment (per group)

- Ice tray
- 2 cups of tap water
- 2 tablespoons of salt
- 15 U.S. dimes
- 1 foot of Aluminum foil
- An inexpensive solar LCD calculator, with the solar panel removed.
- 15 paper clips
- DMM (Digital Multi-Meter) w/ leads
- Scotch tape (or any tape that’s available)
- An empty container

Procedure

1. Fill the empty container with 2 cups of tap water and mix with 2 tablespoons of salt. Bring this back to your group.

2. Tape the dimes to the inside of each ice tray compartment as shown in the picture below. Use tape loops so that the tape is only between the dimes and the ice tray. The dimes are the anodes because they contain 92% copper which acts as the negative metal. (10 yen pieces work even better)

3. Fold up small squares of tin foil and tape them (with tape loops) to the opposite sides of the dividers as the dimes. The foil pieces are the cathodes because they contain aluminum which acts as the positive metal.
4. You now need to connect your two dissimilar metals (the dime and the foil) with a conductor. We will use paper clips. You want to make sure that the paper clip touches both metals. *Suggestion: Deform the paper clip in the steps shown below. Squeeze the deformed paper clip onto the ice-tray divider, making a tight connection between the dime and the foil.*

![Paper clips deformed and squeezed onto ice tray divider](image)

5. Pour the saltwater slowly into each cell of the ice-tray. You want the water to touch the dime and/or foil in each cell, but you don't want to fill it to the top. You don't want water from one cell flowing into another cell.

6. You now have your battery! One cell is saltwater-dime-paperclip-foil-saltwater (electrolyte-metal#1-conductor-metal#2-electrolyte). How many cells are in your battery?

________________ cells

7. Draw a schematic below of how the cells in your battery are connected?
8. Let’s test the battery. Set the multi-meter to “DC volts” and measure the voltage of the battery. Put the black lead into the saltwater on the negative side of the battery (anode) and the red lead into the saltwater on the positive side of the battery (cathode) as shown below.

9. How much voltage does the battery produce? __________V

10. Is it enough to power the calculator? (try it out)
Data sheet:

Measure the voltage for just one cell, then two cells, and so on.

Plot the voltage vs. # of cells. Be sure to label each axis.
Observations

1. What is the minimum voltage needed to power the calculator?

3. Based on the graph, are the cells connected in series or parallel?

4. Bonus: Try connecting your ice-tray battery to another group’s ice-tray battery and see how much voltage you get.

Discussion Questions

5. What are some problems you can see associated with this battery? What are some problems with batteries in general?

6. What do you think the battery might look like in a few days? What might it look like in a few weeks?

7. Why is it called an ice-tray battery and not an ice-tray fuel cell?
Activity – Assemble and Test a Fuel Cell

Purpose
Fuel cells are highly efficient and they produce no harmful emissions, making them a cleaner fuel alternative than the combustion of fossil fuels. When electric energy is needed to supply power, hydrogen and oxygen are fed to the fuel cell producing electricity. In order to make good choices about fuel cells, we need to understand the basics of how they operate by assembling and testing a simple fuel cell.

Equipment
• Partially assembled graphite plate fuel cell
• Screw fasteners and wing nuts with shrink tube coating
• Electrolyzer or H₂ gas cylinder for H₂ supply

Procedure
1. To save time, the fuel cell has already been assembled for you and we have discussed how we made these fuel cells. Three screws have been removed so that you can slide the pieces around and examine the structure of the cell. Please do so and make observations about the structure of the fuel cell in the space below.

2. Align the pieces by sliding them together to form a cube and attach your binding posts, screws, washers, and wing nuts. Tighten the screws until they are snug but don’t overdo it. Make sure washers are on the OUTSIDE of the plates, not the interior. Identify the oxygen and hydrogen entry points.

3. Does it work? Connect it to a hydrogen supply and observe the reading on your voltmeter. If you’re not getting a reading, you may have to adjust the screws a bit. They should be tight enough to prevent any gas leaks but loose enough to allow air flow.
Discussion Questions

1. What are the basic parts of a fuel cell?

2. How does a fuel cell work?

3. What gases did we use to feed the fuel cell to produce electricity?
4. Can you name any by-products that may have been produced?

5. Discuss some ways in which hydrogen fuel cells are more environmentally sound than typical fossil fuel engines. Does this mean that utilizing power derived from hydrogen fuel cells is harmless to the environment?
Fuel Cell Activity Materials List

- Double or single-sided copper clad circuit board  
  **Radio Shack** part 276-1499. double-sided board 4 ½”x 6 3/8”, One piece is sufficient for making the two endplates (1 per fuel cell)

- Graphite sheets  
  **McMaster-Carr** part 95715K63.  12”x12” graphite sheet (~4 fuel cells) Website: [http://www.mcmaster.com](http://www.mcmaster.com)

- Silicone rubber sheet  
  **McMaster-Carr** part 86435K35. 12”x12” and 0.020” thick, with 35A durometer rating (~4 fuel cells)

- Insulated binding posts with banana jacks  
  **Radio Shack** part 274-661. (2 per fuel cell)

- MEA (Membrane electrode assembly)  
  **Element 1 Power Systems** 1.25”x1.25” 1 watt raw PEMembrane (1 per fuel cell)  
  Website: [http://e1ps.tripod.com/E1PSwebsite/](http://e1ps.tripod.com/E1PSwebsite/)

- Screw fasteners, wing-nuts, fiber washers  
  **Local hardware store** 10-24 x 1” socket head cap screws, 10-24 wing nuts, fitting insulating fiber washers (4 of each needed per fuel cell)

- Shrink Tubing  
  Radio Shack or hardware store (~5 in. per fuel cell)

- Hose connectors (1/8” diameter)  
  **Small Parts, Inc.** Item number SVD-02-01. In-line shutoff valve 1/8” (2 per fuel cell) Website: [http://www.smallparts.com](http://www.smallparts.com)

- Silicone rubber adhesive  
  **Local hardware store** (~1 tube per class)

- Scraping instrument  
  Small knitting needles
Activity – Testing Fuel Cells

Purpose

In this experiment you will build a mini PEM (Proton Exchange Membrane) fuel cell and calculate the 2\textsuperscript{nd} law efficiency of the cell. You will connect the fuel cells as a class in series (and perhaps also in parallel) and test the voltage to understand the effect of connecting more than one fuel cell. We may also power a small motor or light with the cells and observe the reaction to one or more fuel cell(s).

Background

The PEM fuel cell uses Hydrogen and Oxygen (from the air) as fuel and gives off water as a waste product. The maximum voltage that can be produced from the fuel cell is 1.23 volts. However, this is almost impossible to achieve because of internal resistance, diffusion losses, and voltage losses manifested as heat.

Because the hydrogen (if combusted) usually has a much higher power than the fuel cell needs, we will not compare power in to power out. Instead, we will use 2\textsuperscript{nd} law efficiency:

\[
\text{% efficiency} = \frac{\text{Power out}}{\text{max. Power}} \times 100\%
\]

We can use \(P=IV\), and assume the current, \(I\), stays the same. This simplifies our formula to:

\[
\text{% efficiency} = \frac{\text{Voltage out}}{\text{max. Voltage}} \times 100\%
\]

and we know the Max. Voltage is 1.23 volts.

Equipment

- h-tec Fuel Cell Mini Kit
- multi-meter
- syringe
- hydrogen (supplied by instructor)
- small motor
- jumper wire
- breadboard (shared as a class for connecting the fuel cells)
Procedure

1. Build the Fuel Cell, following the instructions (in English or German, whichever you prefer). These are sensitive and expensive, so treat delicately!

2. Fill your syringe with Hydrogen from the electrolyzer.

3. Set your multi-meter to measure volts and hold the meter leads to the fuel cell terminals. Someone else should hold the meter itself, another person should record the highest voltage, and another person should slowly feed the hydrogen into one of the small holes on the fuel cell.

4. Try this three times and record your voltages. Do you notice any condensation on the fuel cell? Where do you think the condensation could come from?

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<thead>
<tr>
<th>Trial</th>
<th>Voltage</th>
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<tbody>
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<td>1</td>
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<td>2</td>
<td></td>
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<tr>
<td>3</td>
<td></td>
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<tr>
<td>Average</td>
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</table>

5. Now try connecting your small motor to the fuel cell. Make observations and record them below.

Fuel Cell Stacking

Now we will try “Stacking” our fuel cells - The Triple Fuel Cell Stack

Record data and observations in the table provided on the back of this page.

1. Work with two other groups to stack (connect) the fuel cells in series using the connectors and the solderless breadboard provided. Try two cells first. The teacher will have prepared syringes with hydrogen. Use the syringes and coordinate to inject hydrogen into the connected fuel cells at the same time and at the same slow rate. Make sure to have the multimeter ready to measure the voltage of your fuel cell stack.

2. Now try connecting three fuel cells in series. Inject hydrogen simultaneously at the same slow rate. Record the voltage measured in each of three trials.

3. Now connect two fuel cells in parallel. Again, inject hydrogen into the fuel cells simultaneously using the syringes and record the voltage obtained in three trials.


5. Connect the stacks a load (such as a motor or light) in order to measure the current. To measure current, we must connect the load between the multimeter and the stack, forming one circuit and set the meter to measure milliamps (mA). Measure the current from both series-connected stack and parallel-connected...
stack. Record the readings from three trials below. Also, make observations about how the load functions (e.g. if the load is a light, is it brighter or dimmer with the different types of connections).

6. Connect ALL of the groups fuel cells in series. Have them predict how much total voltage will be produced. When they are ready, someone needs to count-down so that each group is injecting the hydrogen at the same time and at the same (slow) speed into each fuel cell. Make sure also that everyone starts with the same volume of hydrogen.

Discussion Questions for Lab Report

1. What is the second-law efficiency of your fuel cell? Use the average value from the three trials.

2. Discuss the difference between fuel cells connected in series and fuel cells connected in parallel. Be sure to talk about how the voltage changed with different circuit configurations, and, if the cells were connected to a load, what observations you made.

3. Is one type of circuit better than the other? Why or why not?

4. Would it be possible to just make one big fuel cell, instead of stacking many little ones? What would be the advantage or disadvantage of this approach?

5. Why do we use the theoretical maximum voltage of 1.23V? How do you think this is determined? What are some reasons why our little PEM fuel cells cannot achieve this voltage? Hint: think about the type of chemical reactions are occurring within the fuel cell.
For this activity, you are required to write and hand in a lab report. The report should look professional and be acceptable as a college (freshman) level report. The format can be of your own design, but should include the following sections (some are mandatory).

**Introduction** (must be included) – Briefly describe what the activity is about.

**Hypothesis** (optional) – This is where you would describe your expected outcome.

**Procedure** (must be included) – Describe the steps you took in your investigation

**Results** (must be included) – What you found during your investigation.

**Discussion** (must be included) – Address the discussion questions on the previous page. The discussion should be written in an essay-like form, not just answers to the questions. Talk about what you learned, using the questions as a guide. If you have questions of your own, feel free to include them.

**Conclusion** (optional, but easy) – Summarize the activity, similar to introduction, but include important points from results and discussion also. Make suggestions for future investigation.

You are not expected to stress-out about lab reports, which helps no one. You are expected to **spend some time on** and **invest effort in** the assignment. A little additional research on your own may help in providing a full discussion. If you can’t answer all the questions, it’s OK, but at least give them all a try.
<table>
<thead>
<tr>
<th>Voltage “V”</th>
<th>Trial</th>
<th>Series</th>
<th>Parallel</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>2 cells</td>
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<td>2 cells</td>
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<td>Average</td>
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<table>
<thead>
<tr>
<th>Current “I” (with load)</th>
<th>Series Stack</th>
<th>Parallel Stack (“bundle”)</th>
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<tbody>
<tr>
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<td>Average</td>
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Activity – Hydrogen Production by Electrolysis

Purpose
With the increased interest in fuel cells as a power source, there has been a related interest in various methods to produce $\text{H}_2$. The production of $\text{H}_2$ is a critical component of the overall fuel cell system. It may impact our ability to develop fuel cell systems for energy needs.

Electrolysis is one way to generate the hydrogen fuel required for fuel cells. In this electrochemical reaction, $\text{H}_2\text{O}$ water molecules are split into hydrogen gas ($\text{H}_2$) and oxygen gas ($\text{O}_2$) molecules. This activity shows how we can produce hydrogen gas from water using electricity.

Equipment
- 1 600 milliliter (mL) beaker
- warm water
- salt (pinch; adjust as needed)
- Direct current (DC) power supply (6 or 9 volt battery)
- Solar Cell
- 2 insulated copper wires with alligator clips (insulation stripped from ends)
- 2 small plastic graduated cylinders or narrow test tubes
- Safety Glasses

Procedure
1) Mix warm water and salt. Make sure salt is mixed in completely
2) Fill beaker with warm salt water.
3) Fill each graduated cylinder (or test tube) with warm water salt to the brim.
4) Place a finger over each graduated cylinder, flip over and insert the ends underwater in the beaker.
5) Remove fingers from cylinder ends. The cylinders should have no air in them. If air gets into them, simply repeat this procedure until there is no air in them.
6) Connect one alligator clip to each terminal of the power source.
7) Bend the exposed ends of the wire into a U shape and insert the ends into the graduated cylinders (one wire end to each cylinder). MAKE SURE METAL ENDS DO NOT TOUCH.
8) Observe what happens at the ends of the wires and note the gas collected in the cylinders
9) Explore variables that affect the rate of hydrogen production. Try changing your system to make use of the following (remember to formulate a hypothesis about the change you expect in the $\text{H}_2$ production rate).
a. Use a different electricity source (higher voltage battery, batteries in series, solar cell)

b. Add more salt to the water

10) Answer the concluding questions.

**Discussion Questions**

- Sketch a diagram of your set-up. Label each wire end as the anode or the cathode.

- Describe what you see happening at each wire end when it is submerged in the salt water. Is there a difference in what is happening, or are they both the same (look carefully!).

- What was the ratio of volumes of the gases you observed the graduated cylinders? Which gas do you think is which and why?

- Write the chemical equations for what is happening at the two different wire ends:
  - The anode:
  - The cathode:
• If 20 molecules of water are split, how many molecules of hydrogen and how many molecules of oxygen will be produced?

• Why did you put the salt in the water? What happens when we add more salt?

• What if we used a stronger or weaker (higher or lower voltage) battery? Would you see more or less bubbles being produced compared to the unit powered by this power source? Explain why they were different.
Lesson Plan – Hydrogen Infrastructure

Background

So far in our systems analysis we have considered the methods used to produce the hydrogen fuel, as well as the technology of the hydrogen fuel cell car itself. Students will now look at other issues surrounding the feasibility of the fuel cell car, including those associated with hydrogen delivery and refueling options, safety issues, consumer convenience, and so on.

One thing that must be considered is the number and location of hydrogen filling stations. The current hydrogen fuel cell car can carry enough hydrogen to travel about 300 miles. Thus, the consumer must be constantly aware of his fuel level and the location of the nearest filling station. In rural areas, fuel must be available within reasonable distances so that people will not have to drive excessive distances – out of their way – just to refuel.

Another issue is how much hydrogen needs to be available. This clearly depends on how many hydrogen fuel cell cars are in operation. There are currently studies being done that are based on certain percentages of the U.S. vehicle fleet being converted to hydrogen fuel cells. One estimate is that even in the early stages of implementation, nearly 300 hydrogen stations will be required along the U.S. interstate highway system (http://www1.eere.energy.gov/hydrogenandfuelcells/). Ultimately, hydrogen stations must be located throughout cities and rural areas, similar to today’s gasoline stations.

Decisions about hydrogen infrastructure – including: hydrogen production technology, the use of large, centralized production facilities vs. small, on-site production, and if centralized production, the method for delivering the hydrogen from the production facility to the filling station – include many tradeoffs. In terms of lower production costs and higher efficiency (hence lower energy requirements), large scale, centralized hydrogen production facilities may offer a better choice than smaller, on-site production. However, once it is produced, the hydrogen gas must be delivered to the refueling station. Hydrogen is a bulky gas, and it is not nearly as easy to work with as gasoline. Compressing the gas requires huge amounts of energy, and compressed hydrogen contains far less energy than the same volume of gasoline. (This presents problems not only with getting the fuel to the filling station, but also with carrying the fuel in the vehicle.) Once compressed, either to a compressed gas stage or to liquid hydrogen, the hydrogen must be delivered to the consumer, either by pipeline or by tanker truck. These processes also require energy and expense.

The following information on hydrogen delivery systems is taken from http://www.fe.doe.gov/programs/fuels/hydrogen/Hydrogen_Delivery_R%26D.html:

Currently, hydrogen delivery systems exist only for the small merchant hydrogen market in the chemical and refining industries. This limited system lacks the scope or scale to deliver hydrogen outside geographically limited areas. It is insufficient by orders of
magnitude from being capable of supplying the hydrogen fuel needs of the Hydrogen Initiative announced in 2003 by President Bush.

Hydrogen has physical properties that may cause embrittlement of some high-strength steel piping materials and components such as compressors and valves that are commonly used today to transport natural gas. Even if these problems could be overcome, today’s natural gas pipelines may not be available or capable of handling the additional volumes of hydrogen projected. Therefore, it is likely that significant capital investments in a dedicated hydrogen delivery infrastructure will be required before a hydrogen economy is practicable.

To begin studying possible hydrogen delivery alternatives, DOE will use computational techniques and analyses to determine the most attractive "carriers" of hydrogen. These studies could include investigations of new chemical process routes and reaction catalysts. Trade-offs will be studied between the massive capital investments in new delivery systems associated with central location hydrogen plants and the use of today’s liquid and natural gas transportation systems to deliver fuels from which hydrogen can be extracted at end-use locations. Concepts for small-scale, on-site reforming will be evaluated against the large capital costs of a dedicated hydrogen infrastructure.

For a very thorough, easy to understand background on things to consider with respect to hydrogen fuel cell infrastructure, see the fact sheet: How Much Will Hydrogen Infrastructure Cost?


the DOE website:
http://www.eere.energy.gov/hydrogenandfuelcells/delivery/current_technology.html

Concepts
1. Choices we make as consumers have environmental, economic, and societal impacts.
2. Developers need to consider trade-offs of different alternatives, and be able to defend their choices when they propose development plans.
3. A support system, or infrastructure, needs to be in place for hydrogen delivery before consumers will be willing to purchase hydrogen fuel cell vehicles.
4. An appropriate system for hydrogen delivery will be based on a thorough analysis of how the hydrogen is produced, where it is produced, and how it gets from the production facility to the point of consumption.

Relationship to Guiding Question

Students continue to gather information about the “whole system” of the fuel cell car, now considering issues that relate to actually using the car in today’s world – how to refuel the car, how much will the fuel cost,… how do we create the “infrastructure” of the hydrogen fuel cell economy.

Key Questions
1. What is “infrastructure”?
2. How many hydrogen filling stations would we need in our area?
3. What can we expect to pay for the hydrogen fuel?
4. What are some benefits of small, on-site hydrogen production?
5. What are some benefits of large, centralized hydrogen production?
6. What methods are available to transport hydrogen from the production facility to the filling station?
7. How is hydrogen provided to the hydrogen fuel cell cars and buses now in operation?
8. How safe is hydrogen to the consumer?
9. With current and emerging technologies, how can we positively impact our consumption of renewable energy sources?

### Student Learning Objectives

<table>
<thead>
<tr>
<th>Student Learning Objectives</th>
<th>Standards</th>
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<tbody>
<tr>
<td>Students will be able to identify the complexity of factors involved in developing a workable appropriate hydrogen infrastructure.</td>
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<tr>
<td>Students will be able to analyze several alternatives with respect to hydrogen delivery systems and propose a best alternative.</td>
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<tr>
<td>Students will be able to defend their decision with facts.</td>
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<tr>
<td>Students will be able to describe how hydrogen is now provided to the few hydrogen fuel cell cars and buses currently in operation.</td>
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### Key Terms

- **Pipeline**: a network of pipes used to deliver a commodity, such as natural gas or hydrogen.
- **Delivery system**: combination of methods used to bring hydrogen from the site of production to the location where it is available to the consumer (pipelines, trucks, tankers, etc.)
- **Infrastructure**: The basic facilities, services, and installations needed for the functioning of a society or a component of that society. With respect to hydrogen, infrastructure includes production and delivery systems.

### Activities:

*The Hydrogen Infrastructure Activity is a relatively unstructured research activity where students independently research the topic of developing a hydrogen infrastructure in St. Lawrence County. Students are given a time period to conduct their research, and ultimately are required to propose a plan for their system.*

**Activity: Hydrogen Infrastructure (2 days)**

- Introduction – remind students of overall goal – to evaluate the potential for future reliance on hydrogen use with a fuel cell car. We’ve been gathering all this information and learning a lot about fuel cell technologies and hydrogen production, but one big question remains:
Once somebody buys their fuel cell car, how will they “fill up?”

- Relate this to the situation that happened at the turn of the century, when the gasoline engines were first developed – same thing. Many people doubted the success of the gasoline powered vehicle because there was no method in place for delivering fuel, and investors were hesitant to put money into the infrastructure because of the risk that nobody would buy the cars and use the infrastructure.

- This is a classic “chicken and egg” problem. (see information below about the introduction of gasoline and internal combustion engine)

- Review options for Hydrogen production. This will help to illustrate the need to consider transporting hydrogen long distances (e.g., if made in a centralized steam reforming facility) versus the possibility of making hydrogen locally via electrolysis and a distributed (solar, wind, hydro) electricity generation system.
  - Natural Gas (Steam) Reforming
    - Typically used to produce large quantities of fuel so as to make use of economies of scale.
    - Use of fossil fuels as feedstock as well as energy source
    - Product requires further refining, hydrogen not 100% pure
    - Show chemistry of \( \text{CH}_4 + 2\text{H}_2\text{O} + \text{ENERGY} \rightarrow 4\text{H}_2 + \text{CO}_2 \)
  - Electrolysis
    - A lot less energy efficient per unit of hydrogen produced than natural gas reforming
    - Easy to do at a smaller scale
    - Only feedstock required is water
    - Very pure product
    - Requires a source of electricity (coal, nuclear, renewable)
    - Show chemistry of \( 2\text{H}_2\text{O} + \text{ELECTRIC ENERGY} \rightarrow 2\text{H}_2 + \text{O}_2 \)

- What is infrastructure?
  - Infrastructure is the basic facilities, services, and installations needed for the functioning of a society or a component of that society. With respect to hydrogen, infrastructure includes production and delivery systems.

  - Who’s going to build hydrogen fueling stations if there are no hydrogen cars? Who wants a hydrogen car if there are no fueling stations?

- What would be needed to create a hydrogen infrastructure? – Here ask leading questions to get the students to be aware of the necessity of the following pieces of infrastructure, which will lead into the activity.
  - Fueling stations
  - \( \text{H}_2 \) production
  - \( \text{H}_2 \) transport
• Provide a limited amount of background – just to let students know that scientists (mostly DOE) are working on developing plans for hydrogen delivery systems. Discuss what currently happens in California (see background information for description). Describe some of the trade-offs with respect to large, centralized production and delivery vs. small, on-site production.

• Tell them that to enable someone here to buy a fuel cell car, they need to have a plan in place for how people will fill up their tanks. For the next few days they will be putting together that plan – they will have access to computer documents and can also search the web (search “hydrogen fuel cell infrastructure” for example).

• Show a large map of St. Lawrence (or whatever is local) County. Tell them that their task will be to identify their proposed locations for hydrogen filling stations with color-coded pins on this map, and describe their proposed method of hydrogen production and delivery. They will need to defend their choices to the rest of the class.

• Pass out activity sheets. Emphasize that the critical questions are basically their task – all relate to their proposal. The other questions on the sheet are meant to help them search particular types of information that might help them make their decisions – they do not need to answer each question!

• Spend the remaining class period and the next day on this activity. Allow each group 5 minutes to present their proposal.

• Wrap up. Revisit problem solving and how this relates to overall issue of recommending a vehicle. Discuss issues related to other vehicle types (Is there enough power and electric grid infrastructure to support battery electric vehicles? How much land mass would be required for ethanol production?)

Resources

http://www1.eere.energy.gov/hydrogenandfuelcells/
From the American Congressional Record of 1875:

"A new source of power, which burns a distillate of kerosene called gasoline, has been produced by a Boston engineer. Instead of burning the fuel under a boiler, it is exploded inside the cylinder of an engine. This so-called internal combustion engine may be used under certain conditions to supplement steam engines. Experiments are under way to use an engine to propel a vehicle.

This discovery begins a new era in the history of civilization. It may some day prove to be more revolutionary in the development of human society than the invention of the wheel, the use of metals, or the steam engine. Never in history has society been confronted with a power so full of potential danger and at the same time so full of promise for the future of man and for the peace of the world.

The dangers are obvious. Stores of gasoline in the hands of the people interested primarily in profit would constitute a fire and explosive hazard of the first rank. Horseless carriages propelled by gasoline engines might attain speeds of 14 or even 20 miles per hour. The menace to our people of vehicles of this type hurtling through our streets and along our roads and poisoning the atmosphere would call for prompt legislative action even if the military and economic implications were not so overwhelming. The Secretary of War has testified before us and has pointed out the destructive effects of the use of such vehicles in battle. Furthermore, the cost of producing it is far beyond the financial capacity of private industry, yet the safety of the nation demands than an adequate supply should be produced. In addition, the development of this new power may displace the use of horses, which would wreck our agriculture. The discovery with which we are dealing involves forces of a nature too dangerous to fit into any of our usual concepts.”