Fuel Cells – Futuristic Battery

Student Objectives
The student:
- will be able to explain the chemical reaction in the electrolysis procedure
- will be able to explain the chemical reaction occurring in the fuel cell
- will be able to calculate the efficiency of the fuel cell system
- will understand how conservation of energy relates to the electrolysis/fuel cell procedure
- will be able to explain the benefits and disadvantages of using fuel cells to generate electricity and power vehicles.

Key Words:
anode
catalyst
cathode
nafion
PEM
platinum

Time:
1-2 class periods

Materials
For each lab group
- PEM reversible fuel cell with gas storage tanks
- rechargeable battery paired to input amps and volts of fuel cell (or a transformer of the correct output)
- wires with alligator clips (2)
- multimeter
- small motor and propeller
- distilled or de-ionized water
- stopwatch

Background

A fuel cell produces electricity by a chemical reaction, and can continue to do so as long as it is supplied with hydrogen and oxygen. Inside a fuel cell, hydrogen and oxygen combine to produce electricity and water. As a simple electrochemical device, a fuel cell does not actually 'burn' fuel, so it operates pollution-free. This also makes it quiet, dependable and fuel-efficient.

Inside most fuel cells, a selectively permeable membrane is sandwiched between two electrodes. Hydrogen gas feeds into the negative chamber (the anode), and oxygen enters the other side in the positive chamber (the cathode). As the hydrogen atoms flow through the anode, a platinum-based catalyst separates the hydrogen proton from its electron. The charged protons

are attracted to the oxygen's negative ions on the other side and pass through the electrolyte membrane. The electrons cannot pass through this membrane, and instead must get to the cathode via an electrical wire–creating electricity! When the electrons arrive at the cathode they recombine with the hydrogen protons and the oxygen molecules to make water. This process also generates some heat which can be used for other purposes.

Fuel cells directly change chemical energy into electric energy. An individual fuel cell produces low voltage DC electricity. To meet other power needs, fuel cells are put together in a 'stack', to create any voltage needed. Large stacks may contain hundreds of fuel cells to get the desired voltage. Spacecraft have been using fuel cells as a support power source for decades.

This investigation demonstrates the decomposition of water in an oxidation-reduction (redox) reaction producing a ratio of 2 volumes of hydrogen gas to 1 volume of oxygen during the electrolysis phase. Electric energy is used to produce a chemical reaction.

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

More specifically:

Anode: $6\ H_2O\ (l) \longrightarrow 4\ e^- + O_2\ (g) + 4\ H_3O^+\ (aq)$; oxidation

Cathode: $4\ H_2O\ (l) + 4e^- \longrightarrow 2\ H_2\ (g) + 4\ OH^-\ (aq)$; reduction

In the fuel cell, the reverse of electrolysis takes place; the gases stored during electrolysis are reconverted into water.

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

More specifically:

Anode: $2H_2\ (g) + 4\ OH^-\ (aq) \longrightarrow 4\ e^- + 4\ H_2O\ (l)$; oxidation

Cathode: $O_2\ (g) + 2\ H_2O + 4\ e^- \longrightarrow 4\ OH^-\ (aq)$; reduction

This proves that this electrochemical reaction is reversible. The first reaction (electrolysis) requires electrical energy, whereas the second reaction releases electrical energy. In any such energy cycle the conversion of one form of energy to another is never 100% efficient. The fuel cell, however, is about twice as efficient as the internal combustion engine.

Procedure

1. **Engage:** Show the video *Energy 101: Fuel Cell Technology* (link is in the Internet Sites section)
2. Show the class the reversible Proton Exchange Membrane (PEM) fuel cell. Tell them that it is a fuel cell and that they will be using one in their lab today. Explain that it is a 'reversible' fuel cell, meaning that it can be used in electrolysis mode to break water down into hydrogen and oxygen, as well as in fuel cell mode when it becomes a galvanic cell to change chemical energy into electrical energy.
3. Divide the students into lab groups of 3 - 5 students per team.
4. Demonstrate how to set up the fuel cell for their lab.
   - hydrate the fuel cell with de-ionized or distilled water
   - put bells into tanks with gas displacement notches open
   - fill tanks to '0' mark
   - attach tubing from fuel cells to top of bells matching the hydrogen side to the hydrogen tank and the oxygen side to the oxygen tank
4. Demonstrate how to attach the fuel cell to the battery (or transformer):

- Attach the red wire to the red terminal on the fuel cell and the positive post on the battery. Repeat with the black wire to the black terminal and the negative post on the battery.
- Tell the students not to reverse the wires (polarity) as this will short the fuel cell.

5. If the students are unfamiliar with a multi-meter or it has been awhile since they have worked with one, demonstrate its use with your particular multi-meter:
   - Put the black lead in the common plug.
   - Show the students where to plug the red lead in for readings of voltage and current (amperage) readings.
   - Show students which setting to use for amperage and voltage (the voltage in this experiment will be in the range of .5 to 2.0V range and the current will be in the .3 to 1A range)
6. **Explore:** Distribute the equipment and have the students complete the exploratory experiment in their lab manuals.
7. Assist students as necessary.
8 **Explain and Elaborate:** After the students finish the lab, show them the Department of Energy animation of a fuel cell (listed in Internet Sites below). Pause the video at each step and make sure the students can explain to you what is happening.
9 Discuss the lab and the fuel cell information to help evaluate what students learned. Questions you may wish to pose to your class:
   - How are fuel cells and conventional 'batteries' alike? *(batteries and fuel cells both produce electricity, they both have anodes and cathodes, and they requre an electrolyte material)*
   - How are fuel cells and conventional 'batteries' different? *(batteries are less efficient and need to be recharged or replaced while fuel cells are more efficient and will continue as long as they have a supply of gases)*
   - How could we use fuel cells in the future? *Student generated answers.*
   - What are the advantages of using fuel cells to produce electricity? *(non-polluting, no moving parts, quiet, uses a renewable energy source, water)*
   - What are the disadvantages of using fuel cells? *(no hydrogen infrastructure at the present time, cost, needs de-ionized or distilled water)*

Answer Key

1. Answers will vary slightly, however the answers should be consistent with the rated output voltage and amperage of the battery.
2. Students should have recorded their data neatly and thoroughly.
3. Answers will vary between lab groups, however students should have recorded their answers in Watts (volts x amps).
4. The amount of hydrogen produced is twice the volume of oxygen.
5. O_2
6. $2H_2O \rightarrow 2H_2 + O_2$
7. Students should have recorded their data neatly and thoroughly.
8. Answers will vary between lab groups, however students should have recorded their answers in power units of Watts (volts x amps). Power is work or energy per unit of

time.

9. $2H_2 + O_2 \rightarrow 2H_2O$
10. Students should notice that the fuel cell essentially reverses the reaction of the electrolysis. Depending on your battery output and the load of your motor, in most cases the fuel cell will run longer in fuel cell mode than it did in electrolysis mode.
11. Answers will vary, but the method of calculation should follow the same procedure. The watt units should be changed to watt hours by dividing the watts that were recorded in minutes by 60. Then efficiency should be calculated by dividing the energy output by the energy put into the system and the quotient is multiplied by 100. This number should then be written as a percentage.

$$\% \text{ Efficiency} = \frac{\text{Output}}{\text{Input}} \times 100$$

12. Evidence that a chemical reaction is taking place includes the transformation of energy, and a gas being produced. (Students may also list the change in temperature since they know there is one, although this was not directly measured or observed.)
13. The Law of Conservation of Energy states that energy can not be created or destroyed. Energy provided by the power source was transformed to chemical energy to produce a chemical reaction which in turn transformed into electric energy. Water was changed chemically into its components, hydrogen and oxygen gas; same elements, same proportions and the fuel cell combined the components back into water molecules to increase the efficiency of the fuel cell as a power source. Laws describe a natural event without providing explanations.
14. Advantages of using fuel cell: non-polluting, no moving parts, quiet, uses water not petroleum as an energy source. Disadvantages: no hydrogen infrastructure at the present time, cost, some types of fuel cells use scarce elements (platinum)

Key Words & Definitions

- **anode** - the negative terminal or chamber, as in a fuel cell
- **cathode** - the positive terminal or chamber, as in a fuel cell
- **catalyst** - a substance that modifies and increases the rate of a reaction without being consumed in the process
- **Nafion** - Nafion® is DuPont's trademark of a sulfonated tetrafluorethylene polymer modified from Teflon®. Nafion is used as an ion-exchange membrane for applications such as PEM fuel cells
- **PEM** - Proton Exchange Membrane, refers to the most common type of fuel cell
- **platinum** - a valuable, heavy, precious metal, grayish white colored, noncorroding malleable and ductile element. It is generally unreactive and has stable electrical properties. It is used as an alloy in electrodes, electrical contacts, dental and medical equipment, chemical lab ware and equipment; used as a catalyst in chemical reactions including the catalytic converter, and in making jewelry

Further Research

1. Research NASA's use of fuel cells on the space shuttle and the space station.

2. Providing a reliable supply of hydrogen and an infrastructure for mobile uses such as cars, poses a host of transportation and storage problems. Have students pick a fuel cell application (a car, train, home, apartment complex or factory), and work up a plan to make this application a reality.
3. Research the different types of fuel cells such as the PEM fuel cell, alkaline fuel cell, phosphoric acid fuel cell, solid oxide fuel cell and molten carbonate fuel cell. Include their function, efficiency, and information on their current and future use.
4. Research Sir William Robert Grove who is given credit for building the first fuel cell in 1839. Reproduce his early fuel cell.

Related Reading

- ***Hydrogen: Hot Stuff Cool Science–Jouney to a World of Hydrogen Energy and Fuel Cells at the Wasserstoff Farm*** by Rex Ewing (Pixyjack Press, 2004)
  This book is a clever, innovative meld of "Harry Potter makes contact with the Hydrogen Wizard and together they travel Back to the Future", which is entertaining even for reluctant readers. Following each chapter are technical notes and references.

Internet Sites

https://energy.gov/eere/education/videos/energy-101-fuel-cell-technology
U.S. Department of Energy video, *Energy 101: Fuel Cell Technology*

https://energy.gov/eere/fuelcells/fuel-cells
US Department of Energy, Energy Efficiency and Renewable Energy. The basics of hydrogen fuel cells, includes a fuel cell animation

http://americanhistory.si.edu/fuelcells/basics.htm
Smithsonian Institute, Fuel Cell Basics, site includes basic animation as well as illustrations of different types of fuel cells.

https://www.youtube.com/watch?v=Z5zxpiDORQ0
Design World video *Who Needs Batteries When You've Got a Hydrogen Fuel Cell*, conference footage showing Teledyne Technologies' 6kW fuel cell. The video discusses the difference between fuel cells and traditional batteries.

Fuel Cells – Futuristic Battery

Florida NGSS Standards & Related Subject Common Core

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Nature of Science																					
Standard 1	**SC.912.N.1.**	X																			
Physical Science																					
Standard 8	**SC.912.P.8.**	X	X		X			X	X		X										
Standard 10	**SC.912.P.10.**	X	X	X												X					

Standard 1: The Practice of Science

- SC.912.N.1.1- Define a problem based on a specific body of knowledge, and do the following: 2) conduct systematic observations; 6) use tools to gather, analyze, and interpret data; 7) pose answers, explanations, or descriptions of events; 8) generate explanations that explicate or describe natural phenomena; 9) use appropriate evidence and reasoning to justify these explanations to others; and 10) communicate results of scientific investigations.

Standard 3: The Role of Theories, Laws, Hypothesis, and Models

- SC.912.N.3.3 **-** Explain that scientific laws are descriptions of specific relationships under given conditions in nature, but do not offer explanations for those relationships.

Standard 8: Matter

- SC.912.P.8.1 - Differentiate among the four states of matter.
- SC.912.P.8.2 - Differentiate between physical and chemical properties and physical and chemical changes in matter.
- SC.912.P.8.4 - Explore the scientific theory of atoms (also known as the atomic theory) by describing the structure of atoms in terms of protons, neutrons, and electrons, and differentiate among these particles in terms of the mass, electrical charges and locations within the atom.
- SC.912.P.8.7 - Interpret formula representations of molecules and compounds in terms of composition and structure..
- SC.912.P.8.8 - Characterize types of chemical reactions, for example: redox, acid-base-synthesis, and single and double replacements.
- SC.912.P.8.10 - Describe oxidation-reduction reactions in living and non-living systems.

Standard 10: Energy

- SC.912.P.10.1 - Differentiate among the various forms of energy and recognize that they

can be transformed from one form to others.

- SC.912.P.10.2 - Explore the Conservation of Energy by differentiating among open, closed, and isolated systems and explain that the total energy in an isolated system is a conserved quantity.
- SC.912.P.10.3 - Compare and contrast work and power qualitatively and quantitatively.
- SC.912.P.10.15 - Investigate and explain the relationship among current, voltage, resistance and power.

National Next Generation Science Standards

Matter and Its Interactions

- HS-PS1-2 - Construct and revise an explanation for the outcome of a simple chemical reaction based on the outermost electron states of atoms, trends in the periodic table, and knowledge of the patterns of chemical properties.

Motion and Stability: Forces and Interactions

- HS-PS2-6 - Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.

Energy

- HS-PS3-2 - Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motions of particles and energy associated with the relative position of particles.

Earth and Human Activity

- HS-ESS3-4 - Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.

Fuel Cells – Futuristic Battery

1. To find how much voltage and amperage you will be putting into the electrolysis procedure, connect the multimeter in a parallel circuit with the battery. Read and record the voltage and amperage below.

   Voltage of the battery _____ Amperage from the battery _____

Fill the water tanks of the fuel cell. Remember:

- hydrate the fuel cell with de-ionized or distilled water
- put bells into tanks with gas displacement notches open
- fill tanks to '0' mark
- attach tubing from fuel cells to top of bells matching the hydrogen side to the hydrogen tank and the oxygen side to the oxygen tank

Attach the battery using wires with alligator clips:

- Attach the red wire to the red terminal on the fuel cell and the positive post on the battery. Repeat with the black wire to the black terminal and the negative post on the battery.
- Remember, do not reverse the wires (polarity) as this will short out the fuel cell and ruin it.

2. Using a stopwatch, begin timing as soon as you make the second connection. Read and record in the table below the level of gases, in one minute intervals by observing the markings on the tanks, until both gas tanks are completely filled and both are bubbling.

Time (minutes)	H_2 level	O_2 level
0		
1		
2		
3		
4		
5		

When both tanks are completely filled, record the time and disconnect the fuel cell from the battery.

3. Energy or work done within the system per unit of time is Power and the unit of measurement is watts. *(Remember watts = volts x amps!)*

_____ time to fill the H_2 chamber with _____ Watts of electrical energy

4. Reducing the water molecule into its components is a decomposition or redox type of chemical reaction. What did you notice about the ratio of hydrogen and oxygen produced during the electrolysis procedure?

5. What gas was collected at the positive or cathode terminal?

6. Write a balanced chemical equation for the electrolysis procedure.

7. Attach the fuel cell to a motor and propeller. (This time it doesn't matter which wire goes to which terminal on the motor since reversing the wires will only reverse the spin of the motor.)
   - Begin timing with a stopwatch as soon as you make the second connection, and record the level of gases at one minute intervals.
   - During the first few minutes take a voltage reading with your multi-meter by placing the probes on the connections from the fuel cell to the motor (these can be held in place on top of the existing connections without disconnecting the motor). Record the voltage in the table below.
   - Next, take an amperage reading by breaking the circuit briefly to add in the multi-meter. After you take the reading, you may leave the multi-meter in the circuit.

Time (minutes)	H_2 level	O_2 level
0		
1		
2		
3		
4		
5		

8. When the motor stops or the hydrogen tank is almost empty (only a small bubble of hydrogen left in the gas collection chamber), remove the wires and record the time.

_____ time it took to use the H_2 in the chamber with _____ Watts of electricity.

9. Write a balanced chemical equation for the fuel cell procedure.

10. What did you observe about the electrolysis reaction and the fuel cell reaction? Compare and contrast the two.

11. Calculate how much energy is lost to heat in the sum of these reactions. (Hint: Convert both measurements to standard units–watts per hour--and calculate efficiency by dividing the energy out by the energy in and multiply the quotient by 100. Express the efficiency as a percentage.)

$$\% \text{ Efficiency} = \frac{\text{Output}}{\text{Input}} \times 100$$

12. How do you know a chemical reaction was taking place?

13. Briefly defend the Law of Conservation of Energy during the fuel cell process.

14. Based on your observations, what are the benefits and disadvantages of using fuel cells to generate electricity?