Creating Clean Energy Through Redox Reactions

Subject Area(s) Chemistry Honors

Associated Unit Unit 15: Redox

Lesson Title Creating Clean Energy Through Redox Reactions

Header

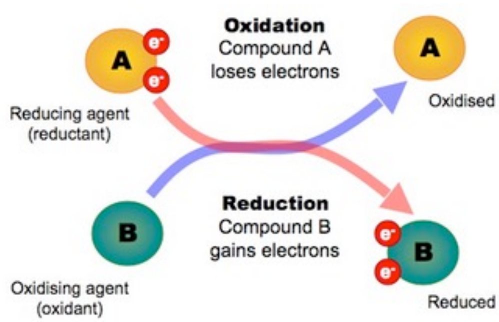

Image 1

Image file: Redox Reaction Mechanism

ADA Description: The above image shows the process of a reduction-oxidation reaction. An atom that gains electrons is said to be reduces. On the other hand, an atom that loses electrons is oxidized. The atom reduced is also called the oxidizing agent, while the atom oxidized is called the reducing agent.

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Caption: The mechanism of how electrons are transferred in a reduction-oxidation (redox) reaction.

Grade Level 10, 11, 12

Time Required 150 minutes (Three 50 minutes periods)

Summary
Over the course of this unit, students will learn about reduction-oxidation reactions and how they connect to everyday life. The lessons will include revisiting the idea of renewable energy, while learning about fuel cells and catalysts within them. Specifically, students will be able to make a connection between redox reactions and their use in engineering. The activities within these lessons will allow students to apply the knowledge obtained in the classroom by understanding how fuel cells work. Beyond this unit, the concepts learned will function as a building block for future energy technologies.

Engineering Connection
Researchers must find more clean and efficient ways to generate energy to supply the world. Engineers have discovered ways to create energy that reduces the carbon footprint, such as the use of fuel cells. Fuel cells operate via a redox reaction of oxygen and hydrogen to produce water. However, this technology cannot be used by everyone because of the expensive catalyst that allows it to work so efficiently. Students will see how important it is for engineers to come

up with different ways to produce clean energy so that the environment is not eventually depleted.

Engineering Category

Choose the category that best describes this lesson's amount/depth of engineering content: **Relating science and/or math concept(s) to engineering**

Keywords

Redox, reduction, oxidation, fuel cell, electrocatalyst, hydrogen energy, renewable resources, energy

Educational Standards (List 2-4)

State STEM Standard

CPALMS, 2008, SC.912.P.8.10, grades 9-12, Describe oxidation-reduction reactions in living and non-living systems.

CPALMS, 2008, SC.912.L.17.11, grades 9-12, Evaluate the costs and benefits of renewable and nonrenewable resources, such as water, energy, fossil fuels, wildlife, and forests.

ITEEA Standard

Standard 16 (Grades K-12): Students will develop an understanding of and be able to select and use energy and power technologies.

Learning Objectives

After this lesson, students should be able to:

- Understand how write out reduction-oxidation reactions.
- Identify the species that is oxidized and reduced, and identify which species is the oxidizing agent and reducing agent.
- Explain how engineers provide innovative ideas that increase the use of clean energy.
- Show their understanding of benefits of fuel cells over fossil fuels as an energy source.
- Describe how a fuel cell works and the chemical reactions that occur for energy to be created.
- Explain the importance of research of hydrogen evolution reaction and oxygen evolution reaction.

Introduction / Motivation (5E – Engage)

Day 2: Discuss importance of research on redox reactions for the future of renewable energy. Discussion should include information about catalysts as well.

- Introduce the use of fuel cells through a video on how fuel cells work and how they are made:
https://www.youtube.com/watch?v=imV_ufIzxPY

https://www.youtube.com/watch?v=LDwS31OE7ak

After the videos, students will be asked the following questions to generate a discussion:

- After seeing how a fuel cell works, what species is being oxidized? Reduced?
- Why do you think fuel cells should be used as opposed to fossil fuels?
- Do you think that solely using fuel cells as a renewable energy source would be a sustainable energy source?
- Fuel cells use hydrogen and oxygen gas. Where does the hydrogen come from to create energy production? The oxygen?
- Can you think of any problems that may occur with the use of fuel cells?

Lesson Background & Concepts for Teachers (5E – Explain)

The bulk of the energy used around the world is generated from fossil fuels. It has become evident that using fossil fuels has a negative impact on our environment and even our health, therefore it is imperative that other energy sources that have limited harmful outcomes be used instead. Renewable energy is a cleaner way to generate energy, and ultimately will be able to be restored over and over again.

One source of renewable energy are fuel cells. This technology uses an electrochemical reaction to create energy from hydrogen and oxygen. Hydrogen gas (H_2) flows through to the anode of the cell while oxygen (O_2) also flows in, but to the cathode. The protons on each hydrogen ion go through the electrolyte and are transferred to the cathode. At the same time the electrons from the hydrogen molecule go through the electrical circuit to get to the cathode because the electrolyte cannot carry electrons through. Hydrogen ions combine with the oxygen which goes through the cell at the cathode. This combination of hydrogen and oxygen makes water as a product. Since water is a product of this reaction, it makes the use of fuel cells a clean energy option.

Currently there is research being done that focuses on making hydrogen and oxygen from water electrolysis to provide fuel for fuel cells. Reactions such as hydrogen evolution (HER) and oxygen evolution (OER) have shown to produce hydrogen and oxygen respectively through redox reactions starting with water. In HER, a water molecule is split into hydrogen gas an hydroxide ions. However, in OER, four hydrogen ions and an oxygen molecule is produced from the two oxidized water molecules.

Before beginning this lesson, the teacher should teach oxidation numbers as the first lesson of the unit. Oxidation and reduction terms should also be taught prior to this lesson in terms of half reactions and balancing with atoms and electrons. It is also suggested that the teacher have a brief discussion with the students about non-renewable and renewable energy to review concepts from the previous thermochemistry unit. To execute the fuel cell car lab activity, a few fuel cell kits should be purchased and tested beforehand.

Image 2

Image file: Fuel Cell Diagram

ADA Description: This image shows a schematic of how a fuel cell works. First hydrogen gas flows onto the anode and the electrons go through the circuit while the protons go through the electrolyte. Oxygen gas also flows into the cell onto the cathode and combines with the protons to make water.

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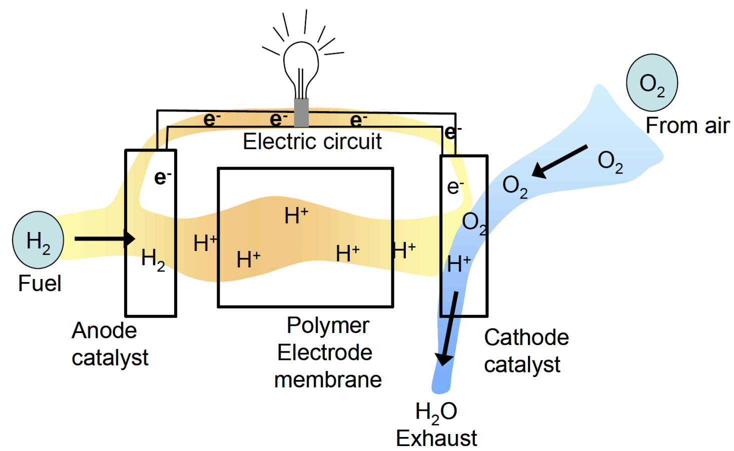
Caption: This shows the mechanism through which a fuel cell operates.



Day 1:

- Review oxidation/reduction written equations with worksheet (see attachment).
- Introduce HER and OER skeleton reactions. Have students write and balance half reactions of each reaction type and combine them to make a full equation.
  - HER: $H_2O \rightarrow H_2 + OH^-$
  - OER: $H_2O \rightarrow O_2 + H^+$
  - Overall equation: $2\ H_2O \rightarrow 2\ H_2 + O_2$
- Begin explaining the idea of HER and OER in research to lead into homework.
- Homework: give students excerpts of articles to read on HER and OER to supplement initial discussion. Have students write a paragraph summary of the information read (see attachment).

Day 2:

- Give redox quiz.
- Review and answer questions about HER and OER from yesterday's lesson. Ask what the main idea was so that lower level students can make sure they got the main idea too.
- Engage students with videos that introduce the use of fuel cells and how they work, then discuss afterwards.
- Discuss fuel cell activity in preparation for the next day.
- Homework: Find 3 redox reactions that take place in the real world. Write the reaction, tell what it is used for, balance the half reactions, and identify the species oxidized, reduced, reducing agent, and oxidizing agent.

Day 3:

- Put students into groups for fuel cell car lab (see attachment).

Vocabulary / Definitions

Word	Definition
Oxidation	The loss of electrons.
Renewable Energy	Energy that comes from natural resources and can be replenished.
Reduction	The gain of electrons.
Oxidizing Agent	Causes another atom to be reduced.
Reducing Agent	Causes another atom to be oxidized.
Catalyst	A substance that increases the rate of a chemical reaction.
Anode	The positively charged electrode.
Cathode	The negatively charged electrode.

Associated Activities (5E – Explore)
Day 3: Fuel Cell Car Lab (see attachment)

Assessment (5E – Evaluate)

Pre-Lesson Assessment
Initial Discussion: Teacher should discuss prior knowledge of non-renewable and renewable resources (pre-Day 1).

Post-Introduction Assessment
Redox Quiz: Assessment of understanding of writing and reading redox reactions (Day 2).

Lesson Summary Assessment
Use of Clean Energy Summary: Have students write a page on drawbacks of using current method of hydrogen energy and what are some future developments in the field of clean energy (after unit is done).

Homework
Article on HER and OER: Have students write a paragraph summary of what they read (Day 1).

Redox Reactions in the Real World: Students will find at least 3 redox reactions that take place in the real world. They should include each reaction, what the reaction is used for, balance the half reactions, and identify the species oxidized, reduced, reducing agent, and oxidizing agent (Day 2).

Lesson Extension Activities (5E – Extension)

- Have students analyze the mechanism of lithium-ion batteries and explain the difference between fuel cells and lithium-ion batteries. Also have them consider which energy source in their opinion is the best for cars for example.
- Have students relate the use of clean energy to other disciplines such as government, environmental science, etc.

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Attachments

1) Redox Reactions Practice
2) HER/OER Articles
3) Fuel Cell Car Lab

Contributors

This lesson plan was written by Omari Baines.

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Classroom Testing Information
N/A

ATTACHMENTS

Redox Reaction Practice (Day 1)

Unit 15: Redox Reactions Practice

Define the following words:

1. Oxidation – ____

2. Reduction – ____

Label the following as oxidized, reduced, oxidizing agent, and reducing agent:

3. $Zn + H_2SO_4 \rightarrow ZnSO_4 + H_2$

   Oxidized:_______ Reduced:_______

   Oxidizing Agent:_____ Reducing Agent:_____

4. $Al(s) + Fe^{2+}(aq) \rightarrow Fe(s) + Al^{3+}(aq)$

   Oxidized:_______ Reduced:_______

   Oxidizing Agent:_____ Reducing Agent:_____

Fill in the following chart.

	Balanced Reaction	Oxidation or Reduction
5. $F^- \rightarrow F_2^0$		
6. $Co^{6+} \rightarrow Co^{3+}$		
7. $Al^0 \rightarrow Al^{3+}$		
8. $Cl_2^0 \rightarrow Cl^-$		

Write and balance the half reactions for each of the following:

9. $Cr^{+} + Sn^{4+} \rightarrow Cr^{3+} + Sn^{2+}$

10. $3\ Hg^{2+} + 2\ Fe \rightarrow 3\ Hg_2 + 2\ Fe^{3+}$

11. $2\ As + 3\ Cl_2 \rightarrow 2\ AsCl_3$

12. $Hg_2^{2+} + 2\ MnO_4^{2--} \rightarrow 2\ Hg + 2\ MnO_4^{-}$

HER/OER Articles (Day 1)

Elucidating the Alkaline Oxygen Evolution Reaction Mechanism on Platinum

Introduction

With the world's energy utilization increasing, new solutions are required to satisfy the energy demand while minimizing the environmental impact. To meet this challenge, new technologies must be improved to achieve sustainable energy conversion and consumption.[1,2] Fuel cells and electrolyzers[3] constitute a promising candidate towards the clean conversion of chemical energy into electricity and electricity into chemical energy, respectively. However, their current use is still partially limited by several factors, such as the limited efficiency and stability of the low cost alternatives to platinum (Pt) for the electrocatalysis of oxygen reduction and evolution reactions (ORR and OER, respectively).[4,5] In order to enhance the catalytic performance of next generation fuel cells and electrolyzers, it is necessary to obtain a comprehensive understanding of the chemistry and electronic structure of the catalyst and the reaction intermediates/products under realistic operating conditions.[6,7] In particular, Pt has been used as a model system to provide surface chemical and structural transformation insights under various (electro)chemical reaction environments.[8–23] Ultimately, the scope of these studies is to expedite the development of novel and cost-effective catalysts with tailored physical/chemical properties, capable of achieving, if not surpassing, the Pt electrocatalytic performance.[8,24–27]

Previous studies have been conducted to indentify the role of Pt oxides in the oxygen evolution reaction pathway (also known as oxygen discharge).[8,24–26] Krasilshchikov[24,26,28] demonstrated that at high overpotentials the corresponding current density (Tafel slope 120 mV dec^{-1}) depends exponentially on the thickness of the Pt surface oxide. Other studies report much higher Tafel slopes (up to 160 mV dec^{-1})[13,24,26] in both acidic and alkaline environments. Such an increase is often attributed to an increase of the surface oxide layer thickness and Pt dissolution.[13,15–26,29] In alkaline media, the reversible binding of a hydroxide ion (OH^-) coupled to a one electron oxidation is thought to precede the removal of one proton and one electron to form surface oxide species.[30] This hypothesis has been mostly supported so far by surface structure and chemical characterizations far from *operando* conditions,[6,31,32] thereby limiting an unambiguous investigation of the role of Pt oxides in the oxygen evolution catalytic cycle. Moving towards realistic operating conditions, Arrigo *et al.* recently studied Pt nanoparticles deposited on an acidic-polymer membrane using ambient pressure X-ray photoelectron spectroscopy (APXPS) in a humidified (solid/gas interface) environment.[27] The authors found that the

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† Electronic supplementary information (ESI) available. See DOI: 10.1039/c7ta00409e

Investigation of the Catalytic Activity of $LaBO_3$ (B = Ni, Co, Fe or Mn) Prepared by the Microwave-assisted Method for Hydrogen Evolution in Acidic Medium

1. Introduction

The hydrogen evolution reaction (HER) is an attractive reaction that illustrates the importance of research in the field of renewable energy. There is a significant technological interest in this reaction due to its important role in electrodeposition and corrosion of metals in acids, in storage of energy via hydrogen production, and as the microscopic reverse of the hydrogen oxidation reaction in low-temperature fuel cells [1–3]. The electrocatalysis in the HER is one of the more important subjects in the field of electrochemistry. Three properties play an important role in selecting catalytically active materials for hydrogen evolution: (a) an actual intrinsic electrocatalytic effect of the material, (b) a large active surface area per unit volume ratio, both of which are directly related to the overpotential used to operate the electrolyzer at significant current densities, and (c) catalyst stability [4]. Thus, from an electrochemical point of view, the problem to be tackled in order to decrease the cost of electrolytic hydrogen is the reduction of overpotentials. The desired decrease in overpotential can be achieved by choosing highly catalytically active electrode materials, or by increasing the active surface area of the electrode.

Transition metals are the best candidate for HER. The electrocatalytic activity of transition metals for the HER can be enhanced by the modification of the electronic structure of the electrode metals by alloying or by the use of some suitable preparation method. Perovskite-type oxides, have the general formula ABO_3 (A: alkaline earth or lanthanide, responsible for the thermal resistance; B: transition element, responsible for catalytic activity) when subjected to redox processes, perovskite-type oxides produce very small particles, in the order of nanometers, with high metallic dispersion [5,6] thus, providing the best matrix for many transition metal catalysts. Many transitional metals, either in the state of element or oxide, possess catalytic activities for many oxidation and reduction reactions, which make perovskites containing the transition metal ions on the B-site to become strong candidates for studying as catalysts for such reactions.

The microwave irradiation process (MIP), which is one of the novel processes evolved from microwave sintering, was widely applied in inorganic/organic synthesis, food drying, microwave-induced catalysis and plasma chemistry. With its rapid development in recent decades, MIP has obtained a growing interest, especially in materials synthesis research. The advantages of MIP have been summarized as below: (i) rapid reaction velocity; (ii) uniform heating; and (iii) clean and energy efficient. During the past years, a lot of perovskites, such as $GaAlO_3$, $LaCrO_3$, etc., have been reported to be synthesized by MIP for their ferroelectricity, superconductivity, high-temperature ionic conductivity, or a variety of magnetic ordering, etc. [7–9]. It was reported that smaller grain size and more rapid lattice diffusion would be formed in microwave route than other wet chemical processes [10], which might enhance the lattice oxygen mobility in catalysis process. However, secondary phases were formed during the perovskite

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Advances in Electrocatalysts for Oxygen Evolution Reaction of Water Electrolysis-From Metal Oxides to Carbon Nanotubes

1. Introduction

Hydrogen plays an important role in the energy sector. It is not only one of the most important feedstocks for the production of hydrocarbon fuels and chemicals, but also considered to be an ideal energy carrier for the renewable energy storage due to its high energy density and environmental friendliness [1,2]. However, hydrogen does not exist in its pure state in nature, like oxygen, and has to be produced from hydrogen-containing resources such as natural gas, coal, biomass and water by reforming, gasification, thermal decomposition or electrolysis. Currently, about 96% hydrogen is produced from fossil fuels [3,4]. The industrial processes produce significant amounts of CO_2, which is a major greenhouse gas (GHG) to cause global warming.

Hydrogen production from water splitting or electrolysis derived from renewable energy, such as solar (photovoltaic) or wind energy, is sustainable and provides an environmentally-friendly pathway to contribute towards meeting the constantly growing demand for energy supply and storage. For example, conversion of intermittent or excess solar (photovoltaic, PV) electrical energy into chemical energy by water electrolysis into hydrogen fuels can be used to store surplus solar energy during peak generation periods. During low generation periods (e.g., the night), these H_2 fuels can then be used to efficiently re-generate electricity via fuel cells. Fuel cells are energy conversion devices that electrochemically convert fuels such as hydrogen into electricity with high power density, high efficiency, and low GHG emissions [5]. Using H_2 as a fuel, the only by-product of the fuel cell reaction is water, which can be fed back into the water electrolysis process. Fig. 1 shows a schematic of the role of water electrolysis (electrochemical or photoelectrochemical types) and fuel cells in such environmentally-friendly energy solutions.

Unfortunately, water electrolysis is greatly constrained by the kinetically sluggish oxygen evolution reaction (OER) because it is thermodynamically and kinetically unfavorable for removing of four electrons to form oxygen–oxygen double bond [6]. Consequently, huge amount of efforts have been devoted to develop catalysts for more effective water electrolysis. Metal oxides, including RuO_2 and IrO_2-based electrodes [7–9], base metal (Co, Fe, Ni, Mn) oxides [10,11] or hydroxides layers [12–14], spinels [15], and perovskites [16–18] have been intensively studied. One of the major disadvantages of metal oxides based catalysts is their relatively poor electrical conductivity. Carbon nanotubes (CNTs) possess high surface area, high conductivity and being corrosion resistant, providing an ideal platform to support the metal oxides for the development of efficient OER catalysts. CNTs based metal free catalysts also have been identified recently and showed the potential applications. In this review, we start with brief introduction to the basic principles in electrolysis, followed by the review of the key developments on metal oxides, metal oxide–CNTs hybrids and the CNTs based metal free OER catalysts.

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Peer review under responsibility of Chinese Materials Research Society.

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2. Water electrolysis reactions

Water electrolysis is the process of electrically splitting water into oxygen and hydrogen. The overall water electrolysis can be described by the following equation:

$$2H_2O \rightarrow 2H_2 + O_2 \quad (1)$$

The overall process is composed of hydrogen evolution reaction (HER) on the cathode and OER on the anode of the electrolyzer. Hence, in alkaline solutions (pH 14), the corresponding cathode and anode reactions are

$$4H_2O + 4e \rightarrow 2H_2 + 4OH^- \quad E^\circ_c = -0.826\ V \quad (2)$$

$$4OH^- \rightarrow O_2 + 2H_2O + 4e \quad E^\circ_a = 0.404\ V \quad (3)$$

where E°_c and E^o_a are the equilibrium half-cell potentials at standard conditions of 1 atm and 25 °C. In acid solutions (pH 0),

$$4H^+ + 4e \rightarrow 2H_2 \quad E^o_c = 0.0\ V \quad (4)$$

$$2H_2O \rightarrow O_2 + 4H^+ + 4e \quad E^o_a = 1.23\ V \quad (5)$$

In neutral conditions (pH 7), the reactions are

$$4H_2O + 4e \rightarrow 2H_2 + 4OH^- \quad E^o_c = -0.413\ V \quad (6)$$

$$2H_2O \rightarrow O_2 + 4H^+ + 4e \quad E^o_a = 0.817\ V \quad (7)$$

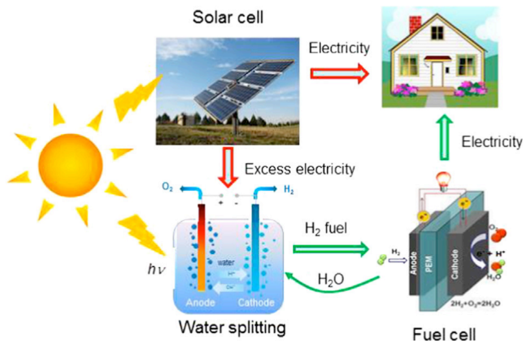


Fig. 1. Schematic representation of the energy cycle using water electrolysis to store excess solar electrical energy and fuel cells to provide the electricity during the low peak or night period.

Fuel Cell Car Lab (Day 3)

Fuel Cell Car Lab: Powering the car with hydrogen

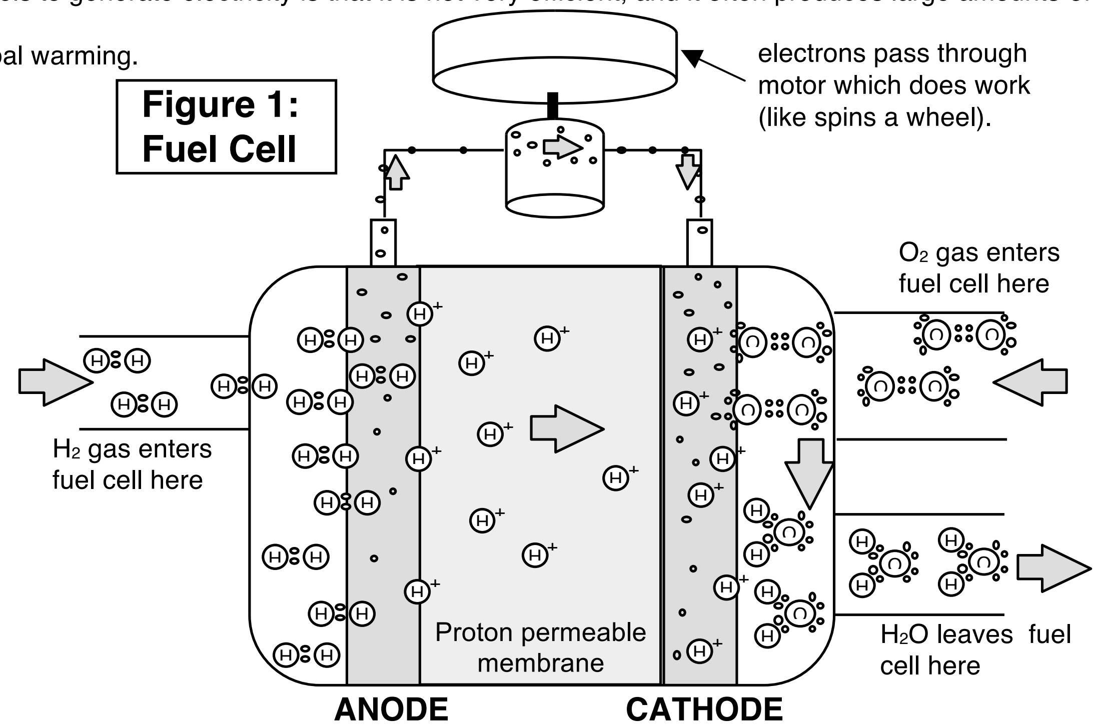
Objectives:

1. Students will produce hydrogen and oxygen with the solar panel connected to the fuel cell.
2. Students will use the hydrogen and oxygen to power the car

Background:

The most common way to obtain electricity from a combustible fuel is to burn the fuel and use the heat produced to boil water. The steam is used to turn a turbine (sort of like a windmill). This turbine turns a generator which generates electricity. This is how coal burning power plants work and that is where the US gets about 55% of its electricity from. The problem with burning fuels to generate electricity is that it is not very efficient, and it often produces large amounts of pollution and green-house gases that contribute to global warming.

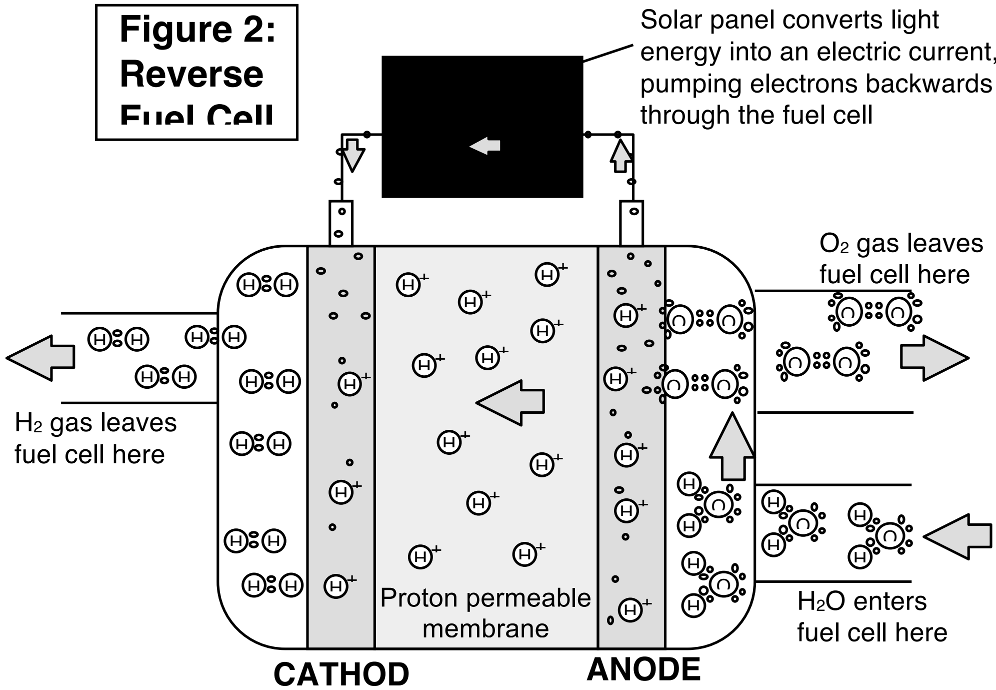
Figure 1: Fuel Cell



A fuel cell is a device that can use a constant supply of fuel and convert it directly to electricity without the need for combustion. We will be using a special type of fuel cell today called a Proton Exchange Membrane (PEM) fuel cell. This type of fuel cell uses hydrogen gas as the fuel, and it works to separate the electrons from the protons. The electrons travel one way through a circuit and power an electric motor. The protons (H+) travel a different path -- through the proton exchange membrane -- and rejoin the electrons on the other side of the fuel cell where they react with oxygen gas to form water as shown in Figure 1 above.

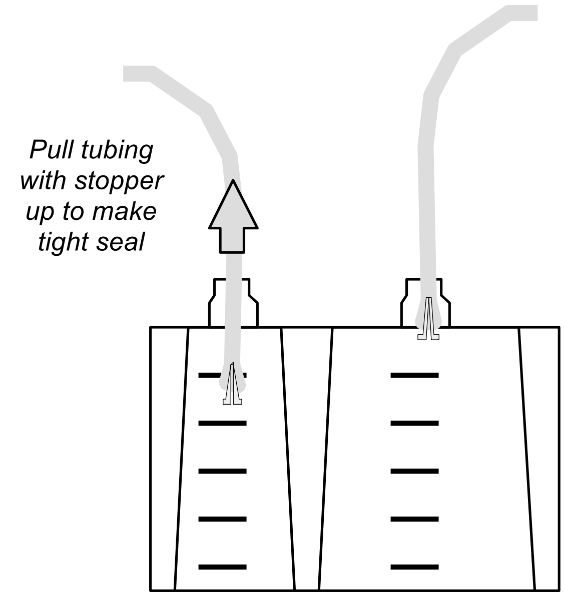
In this exercise, we will use the fuel cell **in reverse** to split water into hydrogen gas and oxygen gas (See Figure 2 at right.) This requires a power source such as a solar panel or a battery. Then we will use the fuel cell in its more commonly used manner to use hydrogen gas as a fuel to power the electric motor on the car.

Figure 2: Reverse Fuel Cell



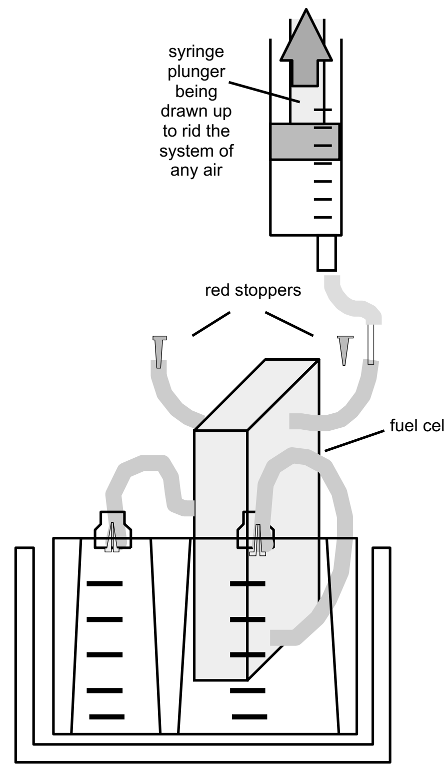
You will need the following materials:

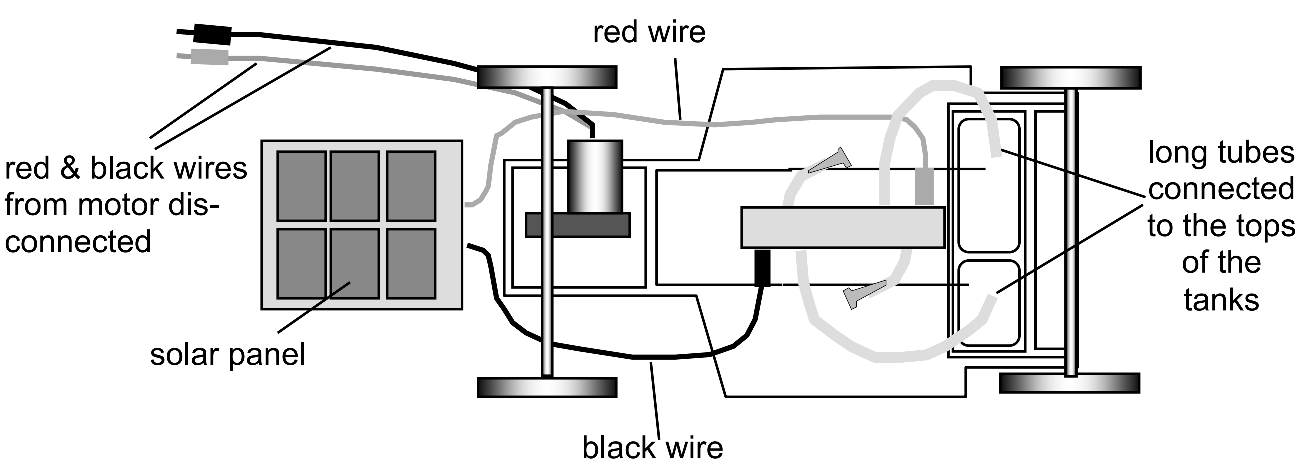
- Safety glasses
- Solar panel
- Electric Light (60-100 watt bulb)
- Car body with fuel cell
- Syringe with tubing nozzle
- Distilled water (Use only distilled water for experiments with the fuel cell. The water must be free of all ions and salts or it can destroy the fuel cell. NEVER USE WATER FROM THE TAP OR BOTTLED DRINKING WATER.)



Setting up:

1. Make sure the square fuel cell is in the center of the car with the side labeled “top” facing up. The fuel cell should fit securely in the center part of the car body.
2. The square fuel cell should have two pieces of tubing sticking out of it: two short pieces with red stoppers on the top, one from each side.
3. If the long tubes are connected to the fuel cell, disconnect them. Make sure that the ends with the clear plastic nozzles are securely seated in the tanks and the other end is sticking out the top as shown at right, above. Place the tanks into the reservoir in the rear of the car.
4. Fill the reservoir about two-thirds full with distilled water. Make sure that the insides of the tanks fill up.
5. Now attach the long tubing to the bottom connectors on the fuel cell, the one from the large tank to the red side of the cell, the one from the small tank to the bluish gray side.
6. Remove air from the system as follows:
   a. Remove the red stopper on one side of the short tubing.
   b. Start with the syringe completely empty. Insert the syringe nozzle into the short tubing.
   c. Gently pull on the end of the syringe to draw water from the reservoir up into the tank and through the fuel cell.
   d. When no more air can be seen in the fuel cell or in any of the tubing, remove the syringe and recap the short tubing on the fuel cell with the red stopper.
   e. Discard water from the syringe back into the reservoir.
   f. Repeat the procedure for the other side of the fuel cell.
7. You are now ready to start making gases to fill your hydrogen and oxygen tanks! Plug the solar panel wires into fuel cell with the red wire connected to the red side of the fuel cell and the black wire connected to the bluish gray side as shown below.





8. Turn on your light and position it to directly face the solar cell separated by approximately 10 cm.

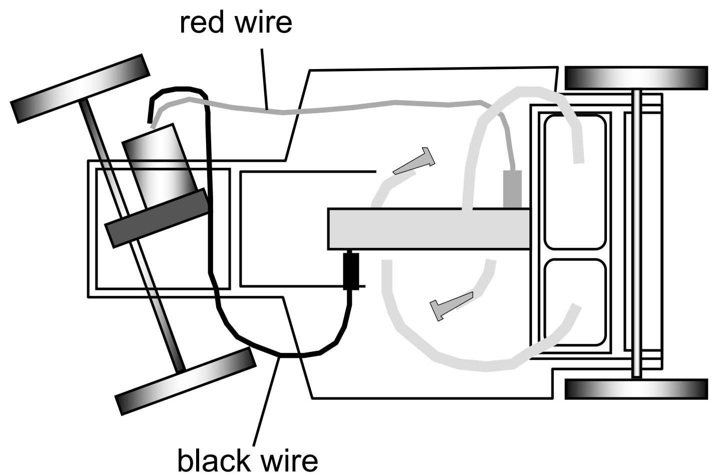
9. After a few seconds, gases should start passing through the long tubes and then begin to accumulate in the tanks. One of the gases is being produced at a significantly greater rate. (Why is that?)   Continue to fuel up your tanks for a few minutes. As you wait, try answering some of the questions below.

Operating the car on hydrogen fuel:

UP UNTIL THIS POINT, YOU HAVE NOT BEEN USING THE FUEL CELL AS A FUEL CELL! YOU HAVE BEEN ESSENTIALLY RUNNING THE CELL BACKWARDS (FIG 2 ON PAGE 1) TO BREAK WATER APART INTO ITS COMPONENT ELEMENTS: HYDROGEN AND OXYGEN. NOW YOU ABOUT TO SEE THE DEVICE FUNCTION AS A TRUE FUEL CELL (FIG 1 ON PAGE 1)-- WITH THE HYDROGEN AND OXYGEN REACTING TO PRODUCE AN ELECTRIC CURRENT!

1. Once the tanks have filled up most of the way, turn off your light source, and unplug the solar panel wires from the fuel cell.

2. Take your car to the designated test track. If the track is a circular one, then angle the front wheels to the left. **Careful not to pick up the car by the fuel cell, which might come loose**. Instead carry the car from the bottom. Now plug in the motor wires to the fuel cell -- again: red wire to the red side of the call, black wire to the bluish gray side, as shown at right. The car should begin to move when the second wire is attached. Be careful not to let the car drive off the table!!!



Investigating how a fuel cell works.

Take some time now to view the powerpoint tutorial that explains how a fuel cell works. It will help you answer some of the questions below.

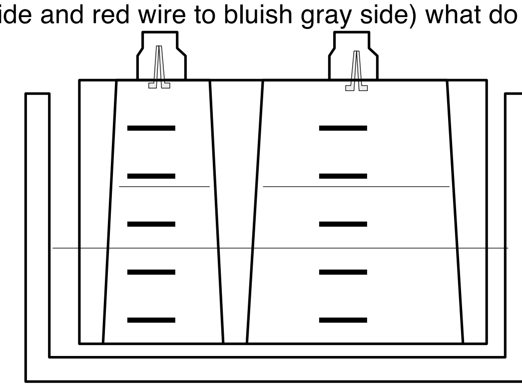
Questions:

1. Write a balanced chemical reaction for the splitting (decomposition) of water: ___________________________

2. Look back at the two diagrams on the first page. Which one of these (top or bottom) illustrates how the fuel cell was used in this lab? ______________

3. If the solar panel were connected the wrong way (black wire to red side and red wire to bluish gray side) what do you think would happen?

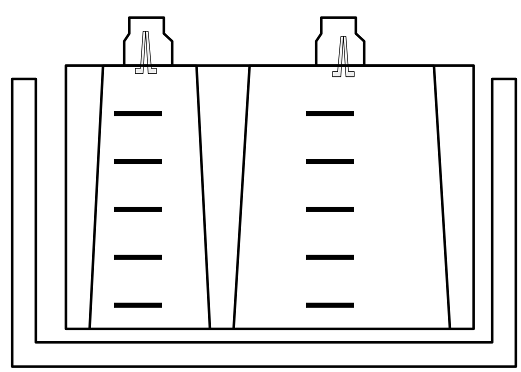
   ____
   ____



4. At top right is a sketch that shows the tanks as they looked after a few minutes of filling with the wires connected correctly. Below this, draw how you think the tanks might look after a few minutes with the wires connected incorrectly.

   What problem might this create if the tanks are allowed to fill for a longer time?

   ____



5. If instead the electric motor were connected the wrong way (black wire to red side and red wire to bluish gray side) what do you think would happen?

   ____

6. Do the electrons in the circuit move toward the hydrogen side of the fuel cell or the oxygen side? ____________
Why do they move in that direction?

____

7. What is another name for a hydrogen ion? _______________ Explain how these two things are the same.

____

8. For every O_2 molecule that gets used up in the fuel cell, how many H_2 molecules get used up? ____ And how many electrons are forced through the wire? ___

9. List five advantages that a “hydrogen economy” (one that runs on hydrogen power) has over the petroleum economy that the world has embraced for the past century.

   1. ____________________________________
   2. ____________________________________
   3. ____________________________________
   4. ____________________________________
   5. ____________________________________