Electrolysis: Obtaining hydrogen from water: The Basis for a Solar-Hydrogen Economy

Curriculum: Hydrogen Power (fuel cells, atomic structure, chemical reactions, electricity, circuitry, energy resources, electrolysis, electrolytes, thermodynamics, efficiency, oxidation, catalysts, & energy resources/transformations)

Grade Level: Middle or high school

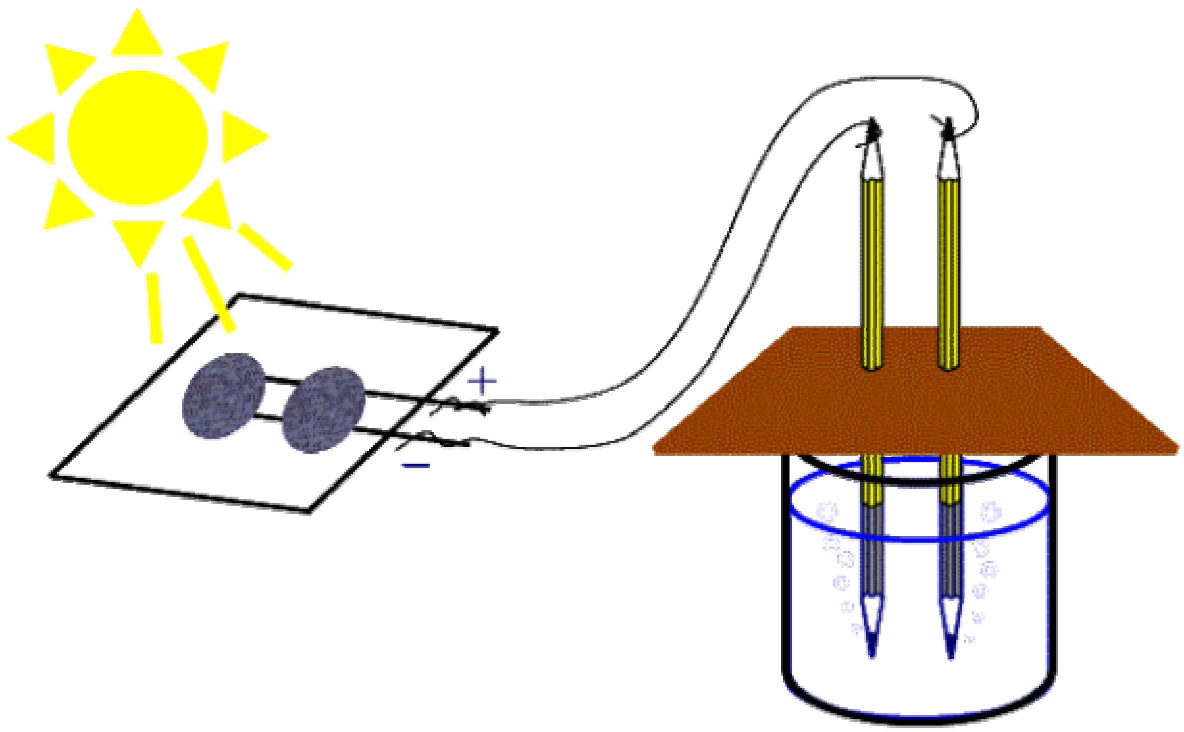
Size: Group or individual laboratory activity

Time: One-two hours

Summary: This project involves a fascinating experiment in electrochemistry that illustrates several important energy related processes, and provides an ideal context for discussion of several issues related to hydrogen, fuel cells, and electricity generation.

By the New Mexico Solar Energy Association

Provided by the Department of Energy's
National Renewable Energy Laboratory
and BP America Inc.



Introduction to Electrolysis: Hydrogen from Water

As covered in the discussion section below, it is possible to use hydrogen as a fuel, that is, a way to store energy, for days when the Sun doesn't shine, or at night time, or for powered mobile devices such as cars.

The process by which we generate hydrogen (and oxygen) from water is called **electrolysis.** The word "lysis" means to dissolve or break apart, so the word "electrolysis" literally means to break something apart (in this case water) using electricity.

Electrolysis is very simple - all you have to do is arrange for electricity to pass through some water between to electrodes placed in the water, as shown in the diagram above. It’s as simple as that! Michael Faraday first formulated the principle of electrolysis in 1820.

If the electricity used for electrolysis is generated from fossil fuels, then carbon dioxide would be emitted in support of our electrolysis process, and the advantage of using hydrogen as a fuel would be lost. But if the electricity is produced by *solar cells*, as we suggest in the diagram above, then there will be no pollutants released by our process.

Materials you will need

- A battery or solar panel with a voltage greater than 1.5 volts - 9-volt batteries work well.
- Two pieces of electrical wire about a foot long. It's convenient, but not necessary, if the wires have alligator clips at each end.
- Two number 2 pencils
- A jar full of tap water
- Small piece of cardboard
- Electrical or masking tape.

Tools you will need

- Pencil sharpener (an exacto knife will do if a sharpener is unavailable)
- Wire strippers or scissors, if the wires are insulated.

Procedure

1. Remove the erasers and their metal sleeves from both pencils, and sharpen *both* ends of both pencils.
2. Fill the glass with warm water.
3. Attach wires to the electrodes on the solar cell or battery, and the other ends to the tips of the pencils, as shown in the diagram above. It is important to make good contact with the graphite in the pencils. Secure the wires with tape.
4. Punch small holes in the cardboard, and push the pencils through the holes, as shown in the diagram above.
5. Place the exposed tips of the pencils in the water, such that the tips are fully submerged but are not touching the bottom, and adjust the cardboard to hold the pencils.
6. Wait for a minute or so: Small bubbles should soon form on the tips of the pencils. Hydrogen bubbles will form on one tip (associated with the negative battery terminal - the cathode) and oxygen from the other.

Specific things you can point out:

- It is very important to note that electrolysis does not depend intrinsically on the generation of heat (although some may be produced, for example, from the turbulence created by the bubbles of gas in the liquid). Therefore, it is not subject to a *fundamental* thermodynamic limitation on efficiency, which would be the case if a fixed fraction of the energy used was converted into heat (since creating heat creates entropy). Therefore, electrolysis can be (and is) performed at very high efficiencies close to 100%.

- If you use a battery, then chances are that the battery was charged with electricity produced by burning fossil fuels, so that the hydrogen you produce isn't produced cleanly. If you use a solar cell, however, then the hydrogen will be produced cleanly, except for any pollutants that were emitted when the cell was made (we say that the solar cell has no "point-of-use" emissions).
- If you use a battery or solar panel that generates less than 1.5 volts, then it will be necessary to add an *electrolyte*, such as a salt, acid, or base, that will disassociate into charged ions and increase the flow of electrical current.
- We use pencils as electrodes because the carbon (in the form of graphite) that they consist of will not dissolve into the water under the influence of the electron current - the carbon is electrically neutral.
- If the electrodes are made of metal, and if there is another metal dissolved into the water, then the metal electrode will become plated with the dissolved metal. This process is called *electroplating*, and is used in industry to produce aluminum and also to plate things with gold or silver.

Advanced Experimentation

Advanced students may want to study the efficiency of the electrolysis project. This can be done, under careful supervision (since you will be collecting hydrogen), in the following way:

1. First make the following measurements carefully and *simultaneously*:
    - **Collect the hydrogen produced with a test tube:** The test tube should be initially filled with water (by submerging it) and positioned over the negative electrode, with the open end submerged and the closed end pointing upwards (such that the tube is completely filled with water at the start of the experiment). Run the experiment until the water level inside the test tube matches the water surface level. At this point the pressure of the hydrogen will equal ambient pressure. Stop the experiment when this level is reached.
    - **Measure the current I in amps:** Do this by placing an ammeter in the electrolysis circuit - have someone read the meter during the experiment to get a good idea of the average current. Make sure you express the result in amps, which may require conversion from milliamps.
    - **Time the entire experiment with a stopwatch in seconds.** (This may be a large number).
    - **Measure the ambient (room) temperature in Celsius degrees.**
2. **Calculate the volume of hydrogen produced at ambient pressure in cubic meters:** Measure the dimensions of the test tube, and the length of the tube above water. Make sure you answer is expressed in cubic meters. For example, if you initially calculate the volume in cubic centimeters, divide your answer by 1 million.

3. Now calculate the theoretical (maximum) volume of the hydrogen produced, also in cubic meters, from the other data for the current and the time, using "Faraday's First Law":

   $$V_{theoretical} = (R \cdot I \cdot T \cdot t) / (F \cdot p \cdot z)$$

   Where R=8.314 Joule/(mol Kelvin), I = current in amps, T is the temperature in Kelvins (273 + Celsius temperature), t = time in seconds, F = Faraday's constant = 96485 Coulombs per mol, p = ambient pressure = about 1×10^5 pascals (one pascal = 1 Joule/meter^3), z = number of "excess" electrons = 2 (for hydrogen, H_2), 4 (if you're measuring oxygen production instead).

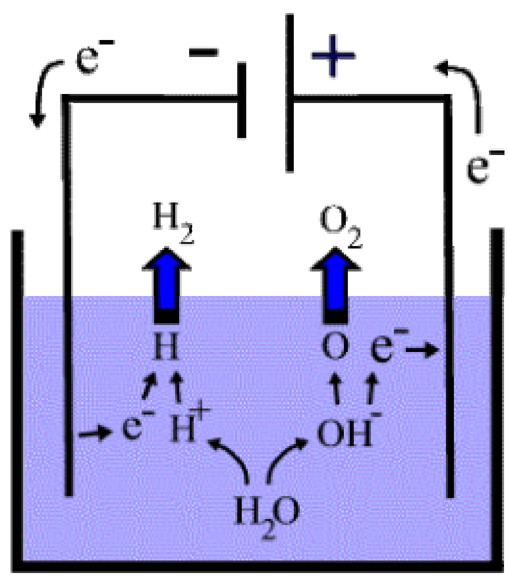
4. Finally, calculate the efficiency by comparing the volume produced to the theoretical maximum volume:

   Efficiency (in %) = $100 \times V_{produced} / V_{theoretical}$

5. Discuss the possible sources of inefficiencies/errors, such as
   - Failure to capture all the hydrogen
   - Energy lost to heat
   - Various measurement errors

How Does it Work?

Electrolysis: Splitting water with electricity to produce hydrogen and oxygen:



The chemical equation for electrolysis is: **energy (electricity) + 2 H_2O → O_2 + 2 H_2**

At the cathode (the negative electrode), there is a negative charge created by the battery. This means that there is an electrical pressure to push electrons into the water at this end. At the anode (the positive electrode), there is a positive charge, so that electrode would like to absorb electrons. But the water isn't a very good conductor. Instead, in order for there to be a flow of charge all the way around the circuit, water molecules near the cathode are split up into a positively charged hydrogen ion, which is symbolized as H^+ in the diagram above (this is just the hydrogen atom without its electron, i.e. the nucleus of the hydrogen atom, which is just a single proton), and a negatively charged "hydroxide" ion, symbolized OH^-:

$$H_2O \rightarrow H^+ + OH^-$$

You might have expected that H_2O would break up into an H and an OH (the same atoms but with neutral charges) instead, but this doesn't happen because the oxygen atom more strongly attracts the electron from the H - it *steals* it (we say the oxygen atom is more "electronegative" than hydrogen). This theft allows the resulting hydroxide ion to have a completely filled outer shell, making it more stable.

But the H^+, which is just a naked proton, is now free to pick up an electron (symbolized e^-) from the cathode, which is trying hard to donate electrons, and become a regular, neutral hydrogen atom:

$$H^+ + e^- \rightarrow H$$

This hydrogen atom meets another hydrogen atom and from a hydrogen gas molecule:

$$H + H \rightarrow H_2$$

And this molecule bubbles to the surface, and wa-la! We have hydrogen gas!

Meanwhile, the positive anode has caused the negatively charged hydroxide ion (OH^-) to travel across the container to the anode. When it gets to the anode, the anode removes the extra electron that the hydroxide stole from the hydrogen atom earlier, and the hydroxide ion then recombines with three other hydroxide molecules to form 1 molecule of oxygen and 2 molecules of water:

$$4\ OH^- \rightarrow O_2 + 2\ H_2O + 4e^-$$

The oxygen molecule is very stable, and bubbles to the surface.

In this way, a closed circuit is created, involving negatively charged particles - electrons in the wire, hydroxide ions in the water. The energy delivered by the battery is stored by the production of hydrogen.

Discussion: Hydrogen as a fuel for heat or electricity

Water is perhaps the most important substance to life on Earth. It is a simple compound made from the two elements hydrogen (H) and oxygen (O), and each molecule of water consists of two hydrogen atoms and one oxygen atom. Thus we write the chemical formula for water as "H_2O".

Hydrogen itself is also a very important element in the universe. For example, it is the fuel for the Sun, which generates power by fusing (combining) hydrogen atoms into a helium atom in a process call nuclear fusion. Because it can be obtained from water, as this project demonstrates, the German's call hydrogen "wasserstoff", which literally means "water stuff".

Suppose that you just happen to have some pure hydrogen gas on hand, stored in a container. The hydrogen gas consists of H_2 molecules zipping around in a container (hydrogen atoms like to bond together into H_2 molecules). If there also happens to be oxygen gas around (O_2), and there is always plenty oxygen in the air (air consists of about 20% oxygen), then the oxygen can react violently with the hydrogen gas, such that the hydrogen *burns*, or *combusts*, with the oxygen to form water and heat, according to the chemical reaction

$2H_2 + O_2 \rightarrow 2\ H_2O$ + energy (heat).

Therefore, if you have some hydrogen, you can burn it for fuel to generate heat!

Generating heat, however, is not always the best thing to do, because ***entropy*,** which may be thought of as molecular *disorder*, is created when heat is generated, and that can limit the efficiency of devices that use that heat energy to do useful work. Fortunately, there exists a device called a ***fuel cell***, which can chemically combine hydrogen with oxygen to make electricity.

Fuel cells can also accomplish what this project demonstrates - electrolysis - which generates hydrogen from water.

Carbon-based Fuels

Notice from the equation above that, unlike burning a fossil (carbon-based) fuel such as coal, burning hydrogen doesn't produce any byproducts except water, which is environmentally benign. **Hydrogen burns clean!**

Burning fossil fuels on the other hand, always results in carbon monoxide (CO) and/or carbon dioxide (CO_2), which are produced when the carbon atoms combine with oxygen. These compounds are now considered pollutants because they are greenhouse gases - that is, they help trap heat near the Earth's surface, causing the Earth's surface temperature to rise, i.e. global warming.

Burning fossil fuels such as coal also usually releases other pollutants, including sulfur dioxide, mercury, and uranium to the atmosphere, because these substances are usually present to varying extent in fossil fuels. But if we can obtain hydrogen without producing greenhouse gases or these other pollutants, then hydrogen is a better fuel to use than fossil fuels. Many people are now hopeful that a "**hydrogen-economy**" will soon replace our fossil fuel economy.

Obstacles to a hydrogen-economy

There are two obstacles to a hydrogen-economy.

- **It takes a lot of volume (or energy) to store hydrogen** - usually five times or so the volume, at reasonable pressures, needed to store an equivalent amount of energy with gasoline. One company that has made headway on solving this problem, however, is Dynetek (www.dyneteck.com).
- **There is no hydrogen infrastructure:** Making the transition to a hydrogen economy might mean having to scrap the fossil fuel infrastructure that we have already developed. One company that has made progress on refueling equipment is Stuart Energy (www.stuartenergy.com).

Using synthetic fuels might surmount both of these problems. For example, it is possible, using a catalyst, to combine water, carbon dioxide (extracted from the air), and renewable electricity to make fuels such as methanol, a carbon-based fuel. When this fuel is burned, water and carbon dioxide are produced. But because the carbon dioxide used initially to make the fuel was extracted from the air, the cycle is closed with respect to both water and carbon dioxide, and so won't contribute excess carbon dioxide to the atmosphere. Fuel cells can already use such fuels (either by extracting the hydrogen from the fuel prior to the fuel cell, or even directly in certain types of fuel cells).

Is Hydrogen Dangerous?

Some people are worried that hydrogen might be too dangerous. It is true that hydrogen is a very explosive fuel, but so is natural gas and gasoline. For example, movies commonly depict automobiles burning up after crashing, and explosions involving natural gas are reported in the press from time to time. Two famous disasters involving hydrogen are the explosion of a zeppelin (an airship) called the Hindenburg (in 1937), and the explosion of the Space Shuttle Challenger (in 1986). You may want to study these disasters as a class project. The Hindenburg explosion, although often cited as an example of the danger of hydrogen, is thought by many to have been caused by flammable paint that caught fire from an electrical spark, and so might have caught fire even if the zeppelin had been filled with helium (an inert, nonflammable gas). Moreover, most of the people that died may have done so from coming into contact with burning diesel fuel (which powered the Hindenburg's airplane-type prop-engines) or from jumping of the Zeppelin before it landed.