Solar Kit Lesson #15
Solar-Powered Electrolysis of Water and the Hydrogen Economy

TEACHER INFORMATION

LEARNING OUTCOME
After producing hydrogen and oxygen gases through the electrolysis of water and studying the process, students realize that hydrogen can act as an energy carrier and that as an energy carrier it has many properties that are useful to humankind.

LESSON OVERVIEW
Students complete a short reading on hydrogen as an energy carrier, and use solar electric panels to produce hydrogen and oxygen gases from the electrolysis of water. They then test for the presence of flammable gases and propose and balance the chemical reaction for the process of the electrolysis of water.

GRADE-LEVEL APPROPRIATENESS
This Level III Physical Setting lesson is intended for use in chemistry and technology education classrooms in grades 10–12.

MATERIALS
Per work group
- beaker (250 ml)
- two aluminum electrodes (electrical tape and 8 cm long, small-diameter aluminum rods)
- metric ruler
- two small test tubes (13 x 100 mm to 18 x 150 mm) or (10 mL to 20 mL).
- five 1 V, 400 mA mini–solar panels* mounted on a board
- two pieces of wire (30–40 cm)
- stirring rod
- candle
- wooden splint
- matches
- ring stand
- two clamps
- graduated cylinder (10–20 mL)
- teaspoon
- two teaspoons of sodium carbonate (washing soda) or sodium bicarbonate (baking soda)
- safety goggles
- clear plastic tape (optional)
- grease pencil
- water and paper towels

* Available in the provided Solar Education Kit; other materials are to be supplied by the teacher

SAFETY

As with all lab work, try this lab yourself before having the students perform it. Hydrogen gas is explosive and oxygen gas can promote rapid burning of flammable materials. The amount of hydrogen and oxygen gases produced in this lab, however, is small enough that there should be no safety hazard. To be on the safe side, instruct students not to displace so much water that bubbles begin to escape from the test tubes. This will reduce opportunities for the mixing of the two gases. Have students wear safety goggles during the lab work.

The amount of hydrogen gas produced when ignited will explode, making a “pop” or “whoosh” sound. If large test tubes are used (this will produce a larger explosion of hydrogen gas), wrap the tubes first in clear plastic tape.

TEACHING THE LESSON

Preparation: For each lab setup, use double-sided tape to attach five mini–solar panels to a piece of wood or cardboard roughly 125 cm by 15 cm.

Prepare two aluminum electrodes for each lab setup. For each electrode, bend an aluminum rod into a j-shape with the turned end bent up far enough to form the bottom of the j at the end of the rod. Wrap tightly with electrical tape all except 5 mm of the two ends of the aluminum rod.

Suggested Approach: The Solar Kit contains sufficient mini–solar panels to run three lab setups at a time. Because of this, you should run this lab each time with six to nine students divided into three teams that investigate while the remainder of the class is occupied with other projects such as completing the required reading.

Alternatively, the electrolysis lab can be conducted as a class demonstration with limited student participation. If that approach is used, the rate of electrolysis can be increased by using all 16 solar panels at once. Connect pairs of panels (eight pairs in all) in parallel. Then connect the eight pairs in series to produce an 8-volt, 800 mA digital power source.

Before beginning the lab work, conduct a discussion to find out what your students already know about the topics hydrogen power, “hydrogen economy,” and fuel cells. Then have students bring in and share news articles and other information from books, newspapers, magazines, TV, and the Internet that pertain to these topics. Distribute the student reading, “Hydrogen: An Energy Carrier,” or assign that reading for homework. When students have completed the reading, discuss as a class what they have learned about hydrogen from the assigned reading and the other sources they obtained.

Distribute the lab instructions, “Solar-Powered Electrolysis of Water,” to the first three student teams and have students follow the instructions. Supervise and assist students as needed during the investigation. Repeat as needed when the remaining students perform their lab work.

Follow-up Discussion: Go over with students the overall and simplified chemical equations for electrolysis of water. Elicit from them why this process produced H_2 at twice the rate it produced O_2.

Discuss the tests for the two gases, one resulting in an explosive sound and the other in increased flammability. See that students can not only identify test results for each gas, but also why each produces its particular outcome.

Find out whether any students can cite from their pre-lab research other methods for producing hydrogen. If they can't do so, relate for them how hydrogen is produced commercially today.

Describe why hydrogen might someday become the ideal and predominant energy carrier.

ACCEPTABLE RESPONSES FOR DEVELOP YOUR UNDERSTANDING SECTION
Students should be encouraged to accurately follow directions for all steps of the procedure.

Step 8: **Observation:** Bubbles form on both electrodes. The negative electrode appears to be more reactive yet produces smaller bubbles than the positive electrode.
Analysis: Students may correctly infer that in order to give off hydrogen, water must be reduced and the negative electrode is supplying the electrons necessary for that process to take place.

Step 13: **Observation:** Students hear a "pop" or "whoosh" sound and see a flash of flame inside the test tube.
Analysis: Since hydrogen is the only explosive gas that could be produced, this test confirms that hydrogen is produced at the negative electrode.

Step 17: **Observation:** Students see the splint glow brighter for a moment. The splint may even burst briefly back into flame.
Analysis: The presence of high concentrations of oxygen promotes more rapid oxidation (burning) of the splint material. The gas collected should be inferred to be oxygen.

Step 18: **Observation:** By volume, twice as much hydrogen as oxygen is produced.
Analysis: Students can surmise that in this electrolysis procedure, all of the hydrogen and oxygen atoms in a water molecule are released as hydrogen gas and oxygen gas. Since there are twice as many hydrogen atoms as oxygen atoms per molecule of water, twice the volume of hydrogen gas was produced, as expected.

Step 19: $2\ H_2O \rightarrow 2\ H_2 + O_2$

Step 20: Radiant energy → [solar cell] → electrical energy → [water] → chemical energy

Through the photovoltaic effect, the energy of solar radiation is converted into electrical energy. Through electrolysis, electrical energy is converted into chemical energy stored in hydrogen gas.

ADDITIONAL SUPPORT FOR TEACHERS

SOURCE FOR THIS ADAPTED ACTIVITY

The electrolysis of water lab is adapted from *Hydrogen: An Energy Carrier*, Chris Mason, Northeast Sustainable Energy Association, 2004, and from the following lesson plans from the World Wide Web:

- *Electrolysis of Water* at the Siraze Chemistry Club website, www.chemistry.lmt.md
- *Electrolysis of Water and Salts* at the Collaborative Pre-University Science Projects website, www.science-projects.com
- *Electrolysis of Water* at the Resources For Chemistry Teachers and Students website, http://129.93.84.115/#NSF.

BACKGROUND INFORMATION

Hydrogen: The U.S. government lists hydrogen as an alternative fuel for transportation even though very little hydrogen gas (H_2) exists naturally on Earth. Hydrogen (H), however, is the most abundant *element* in the universe. It is

- a major component of biomass, making up about 14% by weight of such carbon-based organic materials;
- one of two primary components of water (H_2O); and
- the 10^{th} most abundant element in Earth's crust, where it is mainly present in water (H_2O), but also is present in such hydrocarbons as coal, petroleum, and natural gas.

For information on the abundance of hydrogen, see John Emsley, *Nature's Building Blocks*, Oxford University Press. 2001.

Electrolysis: Electrolysis is a process by which a chemical reaction is carried out by means of the passage of an electric current. For the electrolysis of water, water is oxidized at the anode (positive) and reduced at the cathode (negative).

In the electrolysis of water, the reaction at the cathode is:
$4H_2O + 4e- \rightarrow 2H_2 + 4OH^-$
The reaction at the anode is:
$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$
The net reaction is:
$6H_2O \rightarrow 4OH^- + 4H^+ + 2H_2 + O_2$
The simplified balanced chemical reaction is:
$2\ H_2O \rightarrow 2\ H_2 + O_2$

This last equation reveals why the rate of hydrogen gas production is twice that of oxygen during the electrolysis of water. Be aware that hydrogen is much less dense than air. This becomes important when students cover the test tubes to prevent gas from escaping. Accordingly, the tubes should be held up-side-down rather than upright. Oxygen is slightly more dense than air, but, for simplicity sake, both test tubes can be held up-side down.

Given the contents of the water molecule, the only possible explosive gas that can form is hydrogen.

Production of Hydrogen: The United States produces approximately three billion cubic feet of hydrogen gas annually. The most common source for hydrogen production is natural gas. Natural gas is heated in the presence of steam to around 1,000°C ($CH_4 + H_2O \rightarrow 3\ H_2 + CO$). In a second reaction using steam, the carbon monoxide and water are converted into carbon dioxide and hydrogen, ($H_2O + CO \rightarrow CO_2 + H_2$).

Passing steam over red-hot coals produces a mixture of equal parts hydrogen and carbon monoxide. This mixture is known as synthesis gas, a useful fuel that can be converted into methanol. Ethanol reacts with water in the presence of a rhodium catalyst, producing hydrogen and some heat. The electrolysis of water is not yet an economical process, although it has been suggested as a feasible way to store the energy from excess electricity derived from nuclear power plants or hydroelectric dams.

Hydrogen also can be obtained from some kinds of bacteria and algae—the ones that give off hydrogen as they ferment the sugar glucose producing acetic acid.

Using Solar Energy to Produce Hydrogen: When steam is “superheated” to about 1,400°C, the water molecule literally begins to break apart into hydrogen and oxygen. This can be accomplished by mirrors focusing sunlight on a single location wherein steam is present. This method currently is considered impractical because of the amounts of energy needed to initiate the process and the expense of producing special containers that can withstand such high temperatures.

When water is heated to 300°C–1,000°C in the presence of powdered iron oxide, the iron rusts, tying up the oxygen and leaving behind hydrogen gas. This process also can be brought about by the focusing of sunlight by mirrors. The focused light reaches a location containing water and, in this case, powdered iron oxide. This method is considered practical because the production temperature for it is relatively low.

Electrolysis of water can be accomplished by passing DC current from a solar electric panel through an alkaline solution. Although this is not yet an economical process, improvements achieved include such methods as

- the electrolysis of steam inside porous electrodes of zirconium oxide
- the use of fuel cells for achieving electrolysis

The latter method is a newly rediscovered technology having potential efficiencies of 80%–90% and corrosive alkaline solutions are not necessary for this process to occur.

For additional information on producing hydrogen from solar energy sources, refer to Francisco Fantes, *Solar Hydrogen Energy: Mining the Oceans for the Holy Grail*, Winter 2003 issue of Harvard Science Review, *Climate and the Environment*, Vol. 16, No. 1. September 2002–January 2003. http:/hcs.harvard.edu/~hsr/winter2003.html

REFERENCES FOR BACKGROUND INFORMATION

John Emsley, *Nature's Building Blocks*, Oxford University Press. 2001.

Francisco Fantes, *Solar Hydrogen Energy: Mining the Oceans for the Holy Grail*, Winter 2003 issue of Harvard Science Review, *Climate and the Environment*, Vol. 16, No. 1. September 2002–January 2003. http:/hcs.harvard.edu/~hsr/winter2003.html

LINKS TO MST LEARNING STANDARDS AND CORE CURRICULA

Standard 1—Analysis, Inquiry, and Design: Students will use mathematical analysis, scientific inquiry, and engineering design, as appropriate, to pose questions, seek answers, and develop solutions.

Scientific Inquiry Key Idea 1: The central purpose of scientific inquiry is to develop explanations of natural phenomena in a continuing, creative process.

Standard 4—Physical Setting: Students will understand and apply scientific concepts, principles, and theories pertaining to the physical setting and living environment and recognize the historical development of ideas in science.

Key Idea 3: Matter is made up of particles whose properties determine the observable characteristics of matter and its reactivity.

Key Idea 4: Energy exists in many forms, and when these forms change energy is conserved.

Standard 5—Technology Education: Students will apply technological knowledge and skills to design, construct, use, and evaluate products and systems to satisfy human and environmental needs.

Key Idea 6: Technology can have positive and negative impacts on individuals, society, and the environment and humans have the capability and responsibility to constrain or promote technological development.

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www.nyserda.org

Should you have questions about this activity or suggestions for improvement, please contact Chris Mason at cmason@nesea.org.

(STUDENT HANDOUT SECTION FOLLOWS)

A Reading

Hydrogen: An Energy Carrier

The U.S. government lists hydrogen as an alternative fuel for transportation even though very little hydrogen gas (H_2) exists naturally on Earth. Hydrogen (H), however, is the most abundant *element* in the universe. It is

- a major component of biomass, making up about 14% by weight of such carbon-based organic materials;
- one of two primary components of water (H_2O); and
- the 10th most abundant element in Earth's crust, where it is mainly present in water (H_2O), but also is present in such hydrocarbons as coal, petroleum, and natural gas.

Energy is required to isolate hydrogen, in the form of hydrogen gas (H_2), from the elements present on Earth that combine chemically with H. Once separated, hydrogen gas has the potential to release energy in a controlled and useful manner. Because of this, it is said that hydrogen acts as an energy carrier; much of the energy used to produce hydrogen gas can later be extracted in a separate location for a useful purpose.

Many scientists/technologists believe hydrogen gas is likely to be the clean fuel of the future. When burned, it produces only heat and water resulting in almost no pollution. When fed into a fuel cell along with oxygen, the fuel cell produces electricity, water, and heat—no dangerous emissions. The U.S. space program has made use of this technology for decades to supply both electric power for spaceships and drinking water for crews.

Hydrogen gas and the useful energy it contains, when used as an energy source, are potentially

- storable
- transportable
- pollution-free
- useful in transportation systems, homes, and industry.

Also, hydrogen gas can be produced from a wide selection of abundant resources including biomass, water, and hydrocarbons. Yet, scientific and technological advances in storage, transportation, and fuel cell technologies will be needed before hydrogen gas can be economically used on a widespread basis.

How environmentally friendly hydrogen power ultimately will be is heavily dependent on where the hydrogen gas is obtained and what energy source is used to obtain it. For example, when hydrogen is obtained from a fossil fuel, a powerful greenhouse gas (carbon dioxide) is released. On the other hand, when hydrogen is obtained from water, it is the gas oxygen that is released

When fossil fuels are used as an energy source to isolate hydrogen gas, the process produces the same harmful emissions that we are familiar with today. The amount of emission, however, may be reduced if the production, transportation, and use of hydrogen gas turns out to be more efficient than the production, transportation, and use of a petroleum product such as gasoline or heating oil. Alternatively, when a renewable energy source such as solar electric, hydro, or wind power is used to isolate hydrogen gas, there are almost no emissions, although there are other environmental impacts that certainly should be considered.

Name ___________________________________

Date ____________________________________

Solar-Powered Electrolysis of Water

In this investigation you experience a way to use solar electric power to isolate hydrogen (and oxygen) from water. You make use of the process known as electrolysis.

Vocabulary terms:

Electrolysis (e·lec·trol·y·sis) n. The decomposition of an electrolyte by an electrical current.

Electrolyte (e·lec·tro·lyte) n. Any substance which in solution or in a liquid form ionizes to produce an electrically conductive medium.

In electrolysis, electricity is applied to a liquid electrolyte by means of metals called electrodes that are immersed in the liquid. In this investigation the electrolyte used is water.

Most tap water conducts electricity poorly because tap water contains very few positive and negative ions; it is a very weak electrolyte. To increase conductivity, you add a small amount of sodium carbonate (Na_2CO_3) to the tap water. Sodium carbonate molecules dissolve in water into charged particles called ions. An ion having a negative charge, such as CO_3^{-2}, is called an anion because it moves through its solution to the positive charge on the anode. A particle having a positive charge, such as Na^+, is called a cation. It moves through the same solution to the cathode.

PROCEDURE

1. Fill the beaker half full of water.

2. Add a teaspoon of sodium carbonate to the water and help dissolve it by stirring the resulting solution.

3. Completely fill the test tubes with water from the beaker. Close the mouth of the first test tube, using a finger to prevent air from entering the test tube, and invert the tube into the remaining water in the beaker. Leave the tube inverted in the water. Repeat the procedure for the second test tube.

4. Hook the bottom of the j-shaped electrodes into the mouths of the test tubes.

5. Using the clamps, secure each test tube and electrode in place. See that the mouths of the test tubes are located below the surface of the water in the beaker and the electrodes are hooked in the mouths of the test tubes.

6. Connect five 1 V, 400 mA mini–solar panels in series and place them facing the sun in direct sunlight.

7. Use the alligator clips and extra wire to connect the positive lead (red) of the string of solar panels to one electrode and the negative lead (black) to the other.

8. Observe and record the changes that take place on the surface of the electrodes. What do you infer has been forming at

    - the cathode or negative electrode (black wire)?

    - the anode or positive electrode (red wire)?

9. Continue until you notice that one of the test tubes is 2/3 full of gas, and then disconnect the solar panels from the electrodes.

Throughout the next step, make sure the mouths of the test tubes remain below the surface of the water within the beaker.

10. Loosen the clamp holding one of the test tubes and electrodes. Position the tube up or down so the meniscus inside the tube is even with the level of the liquid in the beaker. Using a grease pencil, mark the position of the meniscus. Reposition the test tube and electrode, retightening the clamp. Repeat the procedure for the second test tube.

11. Reconnect the solar panels and continue electrolysis. Make sure to connect the negative and positive wires to the same electrodes as originally. Continue to collect gas until one of the test tubes is just about full of gas, and then disconnect the solar panels from the electrodes.

12. Position a lighted candle next to your setup. Slip your finger under water and cover the opening of the full-of-gas tube to stopper it. Release the clamp holding that tube and lift the tube out of the water. Towel off most of the water on the outside of the tube and on your hand.

The next step is best completed in a somewhat darkened room.

13. Keeping the test tube positioned mouth down, remove your finger as a stopper and slowly move the mouth of the test tube over the candle flame. Observe what happens. Record what you see and hear. Was the gas in the tube explosive? What caused you to reach this conclusion? If you observed that the gas was explosive, use a grease pencil to mark the test tube with the letter *E* for explosive.

14. Fill the test tube with water and add a pinch of sodium carbonate. Close the mouth of the test tube with your finger and invert it into the water in the beaker. Secure the test tube and electrode as before.

15. Reconnect the solar panels to continue the electrolysis. Make sure to connect the negative and positive wires to the same electrodes as before. Continue the gas collection until the second test tube is more than 2/3 full of gas, and then disconnect the solar panels from the electrodes.

16. As before, slip your finger under water and cover the opening of the second tube to stopper it. Release the clamp holding the second tube and lift the tube out of the water. Let the last of the water in the tube slip out by loosening your finger slightly. Towel off most of the water on the outside of the tube and on your hand. Label the tube.

17. Light the wooden splint and then blow out the flame present on the splint. Immediately insert the glowing splint into the test tube and observe what happens. Record what you see and hear. What gas do you infer caused this reaction? What caused you to come to this conclusion?

18. Remove and empty both test tubes. Fill each test tube with water up to the grease pencil mark. Using the graduated cylinder, measure the volume of water in each test tube. By volume, what ratio (larger volume to smaller volume) do the two gases form? What conclusions do you draw on the basis of this ratio?

At the negative electrode, there were two elements that might be reduced, H^+ to H_2 and/or Na^+ to Na°. If the gas H_2 is produced it bubbles away, and if Na° is produced, it reacts with water to form H_2 and soluble NaOH. So at the negative electrode, it always has to be the gas H_2 that is seen bubbling up.

At the positive electrode, the carbon in carbonate cannot be oxidized any more than it already has been oxidized. So, the only oxidation product possible is from O^{-2} becoming the gas O_2. The oxygen gas essentially bubbles away because of its low solubility in water (8ppm).

19. Write the balanced simplified chemical reaction for the electrolysis of water.

20. Draw a diagram, and provide written explanations, of the energy conversions carried out in this investigation.