Washington Fuel Cell Education Project

Teachers Guide to Eight Fuel Cell Car Activities

2003/2004

Funded by a US DOE grant

Teachers Guide to Eight Fuel Cell Car Activities—2003/2004

Funded by a US DOE grant

Second edition, January 2004, using the Heliocentris Hydrogen Fuel Cell Model Car kit

Equipment supplied by Sargent-Welch

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Preface

Perhaps one of the greatest challenges humanity faces is how to avoid poisoning our planet as a result of our changes to our global habitat. Our present technologies, although valuable and perhaps necessary, produce pollution that can turn our air and water toxic, remove our protective layer of ozone, increasing the danger of UV radiation.

This manual is being written to introduce the concept and understanding that underlie a hydrogen based economy. With a hydrogen based economy we might be able to reduce emissions into the atmosphere, which could allow our damaged atmosphere to begin to heal itself. This economy, as presented in this manual, would begin and end with water so there would be no toxic byproduct and the emissions would be consist of only water vapor or liquid water.

The hydrogen-based economy would take water as the raw material and use renewable sources of electrical energy plus the action of a catalyst, to break it up into hydrogen and oxygen. It would then, by use of hydrogen fuel cells and the action of a catalyst recombine these two gases to form water and release electrical energy. The electricity in turn would drive other devices, providing heat, light, motion, magnetism and other types of energy.

The United States Department of Energy has written the following* to explain the advantages of fuel cells.

> Greenhouse gases are thought to be responsible for changes in global climate. They trap excess heat from the sun's infrared radiation that would otherwise escape into space, much like a greenhouse is used to trap heat. When we drive our cars, and light, heat, and cool our homes, we generate greenhouse gases. However, if we used hydrogen in very high efficiency fuel cells for our transportation and to generate power, we could significantly reduce the GHG emissions - especially if the hydrogen is produced using renewable resources, nuclear power, or clean fossil technologies.
>
> The combustion of fossil fuels by electric power plants, vehicles, and other sources is responsible for most of the smog and harmful particulates in the air. Fuel cells powered by pure hydrogen emit no harmful pollutants. Fuel cells that use a reformer to convert fuels such as natural gas, methanol, or gasoline to hydrogen do emit small amounts of air pollutants such as carbon monoxide (CO), although it is much less than the amount produced by the combustion of fossil fuels.
>
> Fuel cells are significantly more energy efficient than combustion-based power generation technologies. A conventional combustion-based power plant typically generates electricity at efficiencies of 33 to 35 percent, while fuel cell plants can generate electricity at efficiencies of up to 60 percent.
>
> When fuel cells are used to generate electricity and heat (co-generation), they can reach efficiencies of up to 85 percent. Internal-combustion engines in today's automobiles convert less than 30 percent of the energy in gasoline into power that moves the vehicle. Vehicles using electric motors powered by hydrogen fuel cells are much more energy efficient, utilizing 40-60 percent of the fuel's energy. Even Fuel Cell Vehicles (FCVs) that reform hydrogen from gasoline can use about 40 percent of the energy in the fuel.

Hydrogen powered fuel cells offer our planet a chance to reverse some of the destructive changes that are taking place in our environment right now. It is hoped that by allowing the students who will become the citizens, scientists and engineers of tomorrow to experience first hand the advantages of the hydrogen fuel cell, they will become strong positive voices for continued exploration that will let us right some environmental wrongs and live in a cleaner and more sustainable manner.

* http://www.eere.energy.gov/hydrogenandfuelcells/hydrogen/why.html

Correlation of the Investigations with Washington State Standards,

Essential Academic Learning Requirements (science TM draft 3b, 2003 09 24)

Essential Academic Learning Requirements—Science

GRADE 10

Investigation 1 – Observing, Predicting and Questioning
Investigation 2 – Solar Panel Orientation
Investigation 3 – Simple Electrolysis
Investigation 4 – Understanding Electrolysis
Investigation 5 – Hydrogen Power
Investigation 6 – Hydrogen Power in Motion
Investigation 7 – Energy Efficiency
Investigation 8 – Extending our Knowledge

Investigation ➔ correlates with standards	1	2	3	4	5	6	7	8
1. SYSTEMS: The student understands and uses scientific concepts and principles to understand systems. To meet this standard, the student will:								
1.1. Properties of Systems: Use properties to identify, describe, and categorize substances, materials, and objects and use characteristics to categorize living things.								
PHYSICAL SCIENCE								
Properties of Substances								
1. Recognize the atomic nature of matter, how it relates to physical and chemical properties, and serves as the basis for the structure and use of the periodic table.			●	●				
Motion of Objects								
2. Describe the average speed, direction of motion, and average acceleration of objects, for example, increasing, decreasing, or constant acceleration.								
Wave Behavior								
3. Describe waves, relating the ideas of frequency, wavelength, and speed, and by relating energy to amplitude.								
Energy Sources and Kinds								

Investigation → **correlates with standards**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
4. Understand many forms of energy as they are found in common situations on earth and in the universe.		●			●	●		
EARTH/SPACE SCIENCE								
Nature and Properties of Earth Materials								
5. Correlate the chemical composition of earth materials such as rocks, soils, water, gases of the atmosphere, with properties.			●	●				
1.2. Structure of Systems: Recognize the components, structure, and organization of systems and the interconnections within and among them.								
Systems Approach								
1. Analyze systems, including the inputs and outputs of a system and its subsystems.	●	●	●	●	●			
PHYSICAL SCIENCE								
Energy Transfer and Transformation								
2. Understand that total energy is conserved; analyze decreases and increases in energy during transfers and transformations in terms of total energy conservation.					●		●	
Structure of Matter								
3. Relate the structural characteristics of atoms to the principles of atomic bonding.			●	●				
1.3. Changes in Systems: Understand how interactions within and among systems cause changes in matter and energy.								
PHYSICAL SCIENCE								
Nature of Forces								
1. Identify various forces, and their relative magnitudes, and explain everyday situations in terms of force.								
Forces to Explain Motion								
2. Explain the effects of unbalanced forces in changing the direction of motion of objects.								
Physical/Chemical Changes								
3. Analyze and explain the factors that affect physical, chemical, and nuclear changes and how matter and energy are conserved in a closed system.	●	●	●	●	●	●	●	

Investigation ➔ correlates with standards	1	2	3	4	5	6	7	8
2. *INQUIRY:* The student knows and applies the skills, processes, and nature of scientific inquiry. To meet this standard, the student will:								
2.1. Investigating Systems: Develop the knowledge and skills necessary to do scientific inquiry.								
Questioning								
1. Study and analyze questions and related concepts that guide scientific investigations.	●	●	●	●	●	●	●	●
Planning and Conducting Investigations								
2. Plan, conduct, and evaluate systematic and complex scientific investigations, using appropriate technology, multiple measures, and safe approaches.	●	●	●	●	●	●	●	●
Explaining								
3. Formulate and revise scientific explanations and models using logic and evidence; recognize and analyze alternative explanations and predictions.	●	●	●	●	●	●	●	●
Modeling								
4. Use mathematics, computers and/or related technology to model the behavior of objects, events, or processes; analyze advantages and limitations of models.					●		●	●
Communicating								
5. Research, interpret, and defend scientific investigations, conclusions, or arguments; use data, logic, and analytical thinking as investigative tools; express ideas through visual, oral, written, and mathematical expression.	●	●	●	●	●	●	●	●
2.2 Nature of Science: Understand the nature of scientific inquiry.								
Intellectual Honesty								
1. Analyze and explain why curiosity, honesty, openness, and skepticism are integral to scientific inquiry.								
Limitations of Science and Technology								
2. Identify and analyze factors that limit the extent of scientific investigation.								●

Investigation ➔ **correlates with standards**	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Evaluating Inconsistent Results								
3. Compare, contrast, and critique divergent results from scientific investigations based on scientific arguments and explanations.		●						●
Evaluating Methods of Investigation								
4. Analyze and evaluate the quality and standards of investigative processes and procedures.								●
Evolution of Scientific Ideas								
5. Know that science involves testing, revising, and occasionally discarding theories; understand that scientific inquiry and investigation lead to a better understanding of the natural world and not to absolute truth.	●	●	●	●	●	●	●	●
3. DESIGN: The student knows and applies the design process to develop solutions to human problems in societal contexts. To meet this standard, the student will:								
3.1. Designing Solutions: Apply design processes to develop solutions to human problems or meet challenges using the knowledge and skills of science and technology.								
Identifying Problems								
1. Study and analyze challenges or problems from local, regional, national, or global contexts in which science/technology can be or has been used to design a solution.	●	●	●	●	●	●	●	●
Designing and Testing Solutions								
2. Research, model, simulate, and test alternative solutions to a problem.		●	●					●
Evaluating Potential Solutions								
3. Propose, revise, and evaluate the possible constraints, applications, and consequences of solutions to a problem or challenge.			●				●	●
3.2. Science, Technology, & Society: Know that science and technology are human endeavors, interrelated to each other, to society, and to the workplace								
All Peoples Contribute to Science and Technology								

Investigation ➔ correlates with standards	1	2	3	4	5	6	7	8
1. Analyze how scientific knowledge and technological advances discovered and developed by individuals and communities in all cultures of the world contribute to changes in societies.	●							●
Relationship of Science and Technology								
2. Analyze how the scientific enterprise and technological advances influence and are influenced by human activity, for example, societal, environmental, economical, political, or ethical considerations.								●
Careers and Occupations Using Science, Mathematics, and Technology								
3. Investigate the scientific, mathematical, and technological knowledge, training, and experience needed for occupational/career areas of interest.								
Environmental and Resource Issues								
4. Analyze the effects of natural events and human activities on the earth's capacity to sustain biological diversity.								

Correlation of the Investigations with Washington State Standards,

Essential Academic Learning Requirements (science TM draft 3b, 2003 09 24)

Essential Academic Learning Requirements—Science

GRADE 8

Investigation 1 – Observing, Predicting and Questioning
Investigation 2 – Solar Panel Orientation
Investigation 3 – Simple Electrolysis
Investigation 4 – Understanding Electrolysis
Investigation 5 – Hydrogen Power
Investigation 6 – Hydrogen Power in Motion
Investigation 7 – Energy Efficiency
Investigation 8 – Extending our Knowledge

Investigation ➔ correlates with standards	1	2	3	4	5	6	7	8
1. SYSTEMS: The student understands and uses scientific concepts and principles to understand systems. To meet this standard, the student will:								
1.1. Properties of Systems: Use properties to identify, describe, and categorize substances, materials, and objects and use characteristics to categorize living things.								
PHYSICAL SCIENCE								
Properties of Substances								
1. Use physical and chemical properties to sort and identify substances, for example, density, boiling point, and solubility.								
Motion of Objects								
2. Describe the positions, relative speeds, and changes in speed of objects.								
Wave Behavior								
3. Describe sound, water waves, and light, using wave properties such as wavelength, reflection, refraction, transmission, absorption, scattering, and interference.								
Energy Sources and Kinds								

Investigation → correlates with standards	1	2	3	4	5	6	7	8
4. Understand that energy is a property of matter, objects, and systems and comes in many forms, including stored energy, energy of motion, and heat energy such as heat, light, electrical, mechanical, sound, nuclear, and chemical.		●		●		●		
1.2. Structure of Systems: Recognize the components, structure, and organization of systems and the interconnections within and among them.								
Systems Approach								
1. Describe how the parts of a system interact and influence each other.		●	●	●	●			
PHYSICAL SCIENCE								
Energy Transfer and Transformation								
2. Determine factors that affect rate and amount of energy transfer; associate a decrease in one form of energy with an increase in another.		●	●		●	●		
Structure of Matter								
3. Understand that all matter is made up of atoms, which may be combined in various kinds, ways, and numbers to make molecules of different substances.			●	●				
1.3. Changes in Systems: Understand how interactions within and among systems cause changes in matter and energy.								
PHYSICAL SCIENCE								
Nature of Forces								
1. Know the factors that determine the strength and interactions of various forces.								
Forces to Explain Motion								
2. Understand the effects of balanced and unbalanced forces on the motion of objects along a straight line.								
Physical/Chemical Changes								
3. Understand physical and chemical changes at the particle level, and know that matter is conserved.				●		●		

Investigation → **correlates with standards**	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
2. INQUIRY: The student knows and applies the skills, processes, and nature of scientific inquiry. To meet this standard, the student will:								
2.1. Investigating Systems: Develop the knowledge and skills necessary to do scientific inquiry.								
Questioning								
1. Generate questions that can be answered through scientific investigations.	●							●
Planning and Conducting Investigations								
2. Plan, conduct, and evaluate scientific investigations, using appropriate equipment, mathematics, and safety procedures.		●	●	●	●	●	●	●
Explaining								
3. Use evidence from scientific investigations to think critically and logically to develop descriptions, explanations, and predictions.		●	●	●	●	●	●	●
Modeling								
4. Correlate models of the behavior of objects, events, or processes to the behavior of the actual things; test models by predicting and observing actual behaviors or processes.								
Communicating								
5. Communicate scientific procedures, investigations, and explanations visually, orally, in writing, with computer-based technology, and in the language of mathematics.		●		●		●	●	●
2.2 Nature of Science: Understand the nature of scientific inquiry.								
Intellectual Honesty								
1. Understand the operational and ethical traditions of science and technology such as skepticism, cooperation, intellectual honesty, and proprietary discovery.								
Limitations of Science and Technology								
2. Understand that scientific investigation is limited to the natural world.								
Evaluating Inconsistent Results								

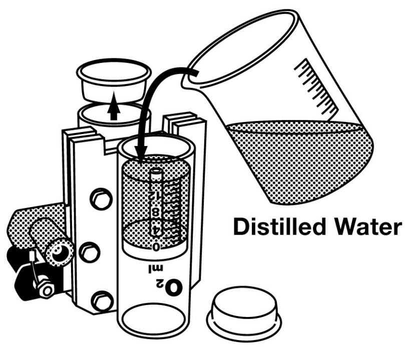
Investigation → correlates with standards	1	2	3	4	5	6	7	8
3. Provide more than one explanation for events or phenomena; defend or refute the explanations using evidence.								●
Evaluating Methods of Investigation								
4. Describe how methods of investigation relate to the validity of scientific, experiments, observations, theoretical models, and explanation.								
Evolution of Scientific Ideas								
5. Explain how scientific theory, prediction or hypothesis generation, experimentation, and observation are interrelated and may lead to changing ideas.								
3. DESIGN: The student knows and applies the design process to develop solutions to human problems in societal contexts. To meet this standard, the student will:								
3.1. Designing Solutions: Apply design processes to develop solutions to human problems or meet challenges using the knowledge and skills of science and technology.								
Identifying Problems								
1. Identify and examine common, everyday challenges or problems in which science/technology can be or has been used to design solutions.	●		●	●	●	●		●
Designing and Testing Solutions								
2. Identify, design, and test alternative solutions to a challenge or problem.		●						●
Evaluating Potential Solutions								
3. Compare and contrast multiple solutions to a problem or challenge.								
3.2. Science, Technology, & Society: Know that science and technology are human endeavors, interrelated to each other, to society, and to the workplace								
All Peoples Contribute to Science and Technology								

Investigation ➔ correlates with standards	1	2	3	4	5	6	7	8
1. Know that science and technology have been developed, used, and affected by many diverse individuals, cultures, and societies throughout human history.	●							
Relationship of Science and Technology								
2. Compare and contrast scientific inquiry and technological design in terms of activities, results, and influence on individuals and society; know that science enables technology and vice versa.								
Careers and Occupations Using Science, Mathematics, and Technology								
3. Investigate the use of science, mathematics, and technology within occupational/career areas of interest.								
Environmental and Resource Issues								
4. Explain how human societies' use of natural resources affects quality of life and the health of ecosystems.								

Using the Fuel Cell Model Car Kit

Filling the electrolyzer

Before starting the electrolyzer, the bottom of the fuel cell storage cylinders should be completely filled with distilled water with no air space or other gas in the cylinders. If you need to add distilled water to the fuel cell, do so in this way:



Place the fuel cell on a flat surface and turn it upside down, so that the removable stoppers are facing up. Remove the stopper from the hydrogen storage cylinder. Add distilled water to the storage cylinder until the water reaches the top of small tube in the center of the cylinder. Tap the fuel cell lightly on the table to help water flow into the area surrounding the membrane and metal current-collecting plates. Add more water until it starts to overflow through the small tube in the center of the cylinder. Replace the stopper, making sure it fits tightly with no air trapped inside the cylinder. A small air bubble will not cause problems, and can be ignored. However any significant amount of air remaining in the cylinder will affect fuel cell performance; if this occurs you should try the filling procedure again.

Fill the oxygen storage cylinder in the same way.

Turn the fuel cell right side up. The open ends of the cylinders are now facing up. The lower portion of both cylinders should be completely filled with water.

Use only distilled water

It is absolutely required that only distilled (de-ionized) water be used in the reversible fuel cell. Damage to the membrane and reduced performance will result if tap water is allowed to enter the device. If students are using the fuel cell without close supervision, it might help to put tape or a sign on the water taps to prevent mistakes. There is no need for any tap water when using the fuel cell. For the same reason, students should rinse their hands before putting a finger into water that may be used in the electrolyzer or fuel cell. Student snacks may provide a source of ions that poison the membrane. Rinsing will probably prevent this.

Illuminating the Solar panel

The solar panel can be permanently damaged by overheating, usually the result of being too close to the light source.

A 75 watt PAR30 incandescent lamp is recommended for use with the *Fuel Cell Model Car Kits* and should be kept a minimum of 20 cm (8 inches) away from the solar panel. Other lamps can also provide good results, for example an 85 watt reflector (R) spot lamp. If you are using a different light source, you could occasionally touch the surface of the solar panel to ensure it is not overheating. The solar panel can be safely operated in bright sunlight. Do not use homemade reflectors made of foil or paper as they may cause overheating.

The surface of the solar panel should be evenly illuminated. The nature of solar panels makes the current output dependent on the darkest spot on the panel. As a result, although the bright spots from your PAR lamp may be shining strongly on the solar panel, if a corner of the panel is in relative darkness, that dark area will limit the output current regardless of how brightly the light shines on other areas.

Because the electrolyzer membrane is hidden inside the device, you cannot see the hydrogen and oxygen bubbles forming, and it may be difficult to get a sense of which lamp placement works best. Temporarily connecting the solar panel to the load box ammeter (set LOAD to SHORT CIRCUIT) will allow you to experiment with the best lamp placement. The solar panel properly illuminated by a 75 watt PAR lamp at 20 cm will typically produce 200 mA short circuit current. When you generate hydrogen using this level of illumination, you will need about 10 minutes to fill the storage cylinder.

Keeping the membrane hydrated

If the fuel cell is new, or the membrane has dried out since its last use, the cell will not work at full capacity on the first filling. Gas production will be slow, and power from the fuel cell will be limited. To obtain reproducible behavior after a prolonged period of non-use, it is necessary to re-hydrate the membrane. To a limited extent, you can hydrate the membrane by filling the electrolyzer with distilled water and letting it sit at least 20 minutes before use. For even better hydration, put the device through a complete cycle: generating 10 ml of hydrogen and then using it.

If you expect to use the fuel cell within the next few days, to avoid the fuel cell drying out, simply leave water in the storage cylinders. If you want the students to start with an empty device, you could discard the water just before the class.

If you plan to store the fuel cell for a longer time, it's recommended that you drain the fuel cell and store it in a zippered plastic bag to keep it hydrated.

Fuel cell stops working before it runs out of hydrogen?

On occasion, you may notice that the fuel cell slows or stops working even though visible quantities of hydrogen and oxygen are present in the storage cylinders. There are two possible causes:

Air was left in the cylinders when you filled the electrolyzer. If a significant amount of air is mixed with the hydrogen, eventually as the hydrogen is consumed in the fuel cell, the remaining gas mixture will contain proportionally less and less hydrogen, until the fuel cell stops working. Don't allow any air bubbles to remain when you fill the cylinders, as described in *Filling the electrolyzer*.

Hydrogen has diffused through the membrane. The hydrogen molecule is very small and readily diffuses through the membrane, contaminating the oxygen side. This effect is more evident when the membrane is dry, and of course increases the longer that hydrogen remains in contact with the membrane. You can minimize this effect in several ways:

- Ensure the device is properly hydrated, which is also recommended for other reasons (see *Keeping the membrane hydrated*)
- Do not allow hydrogen to sit in the fuel cell for a long time. Instead, generate and use the gases in the same laboratory session.
- Often when you generate gases in the electrolyzer, in order to observe the classic "2-to-1" hydrogen-to-oxygen ratio, you will stop generating before hydrogen starts to escape through the upper reservoir. However, if you do continue generating gases past the point at which hydrogen escapes, you will have surplus oxygen to combine with the accumulated hydrogen. Then later when the fuel cell is consuming hydrogen and has used up almost all of it, the effect of some hydrogen having diffused into the relatively larger amount of oxygen will not be significant.

Water leaking from the fuel cell?

With time and exposure the plastic stoppers on the bottom of the storage cylinders may shrink slightly resulting in a water leakage. Should this occur, the problem can easily be corrected. Turn the cell upside down and remove the plastic stopper from the leaking cylinder. Place the stopper on a firm surface, and with the palm of your hand, press the stopper flat, expanding it to its original size. Refill the storage cylinder with distilled water, then press the stopper back into place.

Car won't move on a smooth surface?

If it appears that the motor is not strong enough to drive the car, make sure that you filled the electrolyzer properly (see *Filling the electrolyzer*), and that you have generated enough (5-6 ml) hydrogen. In addition, it may be necessary to lubricate the gears in the car's drive mechanism.

Using the Load Box

It is advisable to keep the load box OFF unless it's needed. The battery will last indefinitely if the load box is turned off after use. If changing the battery becomes necessary, use a small Phillips driver to remove the front panel.

You may notice that if you connect the load box voltmeter to the fuel cell immediately after using it as an electrolyzer, you will see a voltage displayed that is apparently greater than the ideal fuel cell voltage—more than 1.23 V. The problem is not in the load box. Because of a transient surface layer on the catalyst, the initial output voltage of the device really is higher than the voltage of a normal fuel cell. This layer disappears in a few seconds of use.

If you attempt to use the load box ammeter or voltmeter to measure current or voltage at the model car motor, electrical noise from the motor will produce false meter readings. The meters are designed for use with the lamp, motor, and resistive loads supplied in the load box.

Goggles

Although goggles may not seem necessary, it is good practice to wear them throughout your science experiences with chemicals. No experimenters have had their vision damaged by wearing appropriate eye protection but many have suffered eye damage because they did not put their eye protection in place! Students should wear goggles even for demonstrations.

Student questions

It is strongly suggested that students answer the questions using full sentences that restate the question. The answers provided in the Teaching Supplement use this style. It is much easier for students to study from their lab notes and the skill of writing in sentences will be needed as students write up their future investigations in the manner of a scientific report.

Investigation 1:
Observing, Predicting and Questioning using the Apparatus as a Focus

Scientists look at their world and what happens in it carefully. Their observations usually begin with unusual or peculiar events—things that arouse their curiosity. One scientist said, "The cure for boredom is curiosity. There is no cure for curiosity!" In this class you will be introduced to some apparatus that is quite new. Even many scientists have never seen such a device. Your task today is to observe, question and predict based upon what goes on in this class time.

As a scientist, you will make and write careful observations about what you see. These observations may be as simple as the color of the wires of the apparatus or as complicated as a guess at the chemical formula of the plastic used in the apparatus. There are no right or wrong observations. What you see is important.

As soon as your teacher has the apparatus ready for operation, look over the components carefully. You might consider:

- Do they have any signs on them that give some clue to what this apparatus does?
- Are any measuring devices in use?
- Are all of the materials familiar to you?
- Are any special precautions being taken during the setup?
- Is there any relationship between the colors of each component or connection?
- Can you see all of the apparatus or are some parts hidden?
- Can you name any parts of the apparatus or from their structure or position figure out what they are used for?

Remember that no one is evaluating these observations. They are simply the base from which we begin to predict and question what happens.

Imagine how Luigi Galvani (1737-1798) might have felt when during a thunderstorm he noticed how a frog's leg muscle, which he had suspended from a brass hook as part of an experiment he was working on, jumped for no apparent reason. For more information about Galvani and his famous observation, go to http://www.corrosion-doctors.org/Biographies/GalvaniBio.htm

When your teacher begins to work the apparatus you will be given a chance to make more observations.

- What do you notice happening that was not happening before?
- Are there any moving parts?
- Is anything moving or changing position?
- What do you think is happening?
- What do you observe has happened?

Now you can begin to form some predictions beginning with the words, "I think that…." But you need to experiment with the apparatus to be sure of what is happening. It is from such predictions we can design experiments that will prove or disprove our ideas. Some of your predictions may be easily tested, and others may be more complex, needing special equipment or equipment that has not been developed.

You are now experiencing something of the true nature of science where an idea must be tested, retested and shown to be repeatable. If you cannot see the same (or at least similar) results when you do your test again, then something else may be actually causing the phenomenon. Galvani originally suspected the electrical storm was causing the frog's leg to jump, but his subsequent testing showed that the combination of metals—copper in the brass hook and iron in the scalpel—was causing it.

Always remember that the nature of science is to look for events that may not quite fit into our understanding of the world and then test them to see if we can refine our understandings or create new ones. For every answer to an experiment or investigation there are countless new questions that may prove to be far more valuable than the small piece of information we obtained from the investigation.

This testing, the basis for scientific *truths*, can be a lengthy and exacting process. As Michael Jordan says, "Step by Step. I can't see any other way to accomplish anything." Scientists' steps are the many observations, predictions and questions that lead to more experimentation and testing that lead to more questions and so on. Your task today is to **observe** carefully, make some **predictions** about what you think may be happening and then design some **questions** that may allow you to confirm or negate your predictions.

Observe, Predict and Question. O – P – Q: part of the scientist's alphabet.

Teaching supplement for Investigation 1: *Observing, Predicting and Questioning using the Apparatus as a Focus*

The major goal of this investigation is to allow the students to begin to ask questions about the apparatus and what it is doing. The learning objectives may be written:

- Students will observe, predict and formulate questions while watching the apparatus being set up and operated.

Teacher Notes

OPQ stands for Observation, Prediction, and Question. These are the driving forces for the beginning of any scientific investigation. It is important for students to be allowed to practice these skills intentionally and with guidance from a teacher. This fits in well at the beginning of a unit as an Elicit activity (7E) and should be repeated intermittently throughout a school year to gauge student progress towards growth and mastery of these skills.

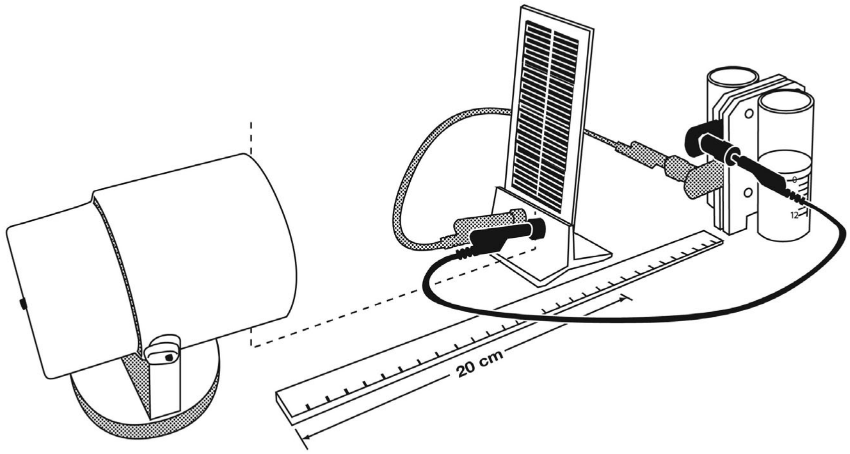
We use this Discovery Activity on the first day of the fuel cells unit. Discovery Activities are open-ended explorations for students to whet their appetites to explore and learn more. As you probably have only one Fuel Cell Model Car Kit, the Discovery Activity needs to be with the whole class.

OPQ is a format that allows students as a class to observe and consider an event in a non-threatening manner, with all students having the chance to participate. It is good to let students explore in any direction they choose, even if the ideas presented are incorrect. Students may end up arguing with each other about misguided concepts, but it is best you don't intervene, other than to encourage extended thinking about the concepts and to encourage students who have differing views to try to support them in a logical manner. This is quite important, as one vocal student with an incorrect idea may mislead less-sure students. This activity is designed for open exploration. You should emphasize that today's "I think" ideas are nothing more than possible predictions until we have established them conclusively through a scientific investigation.

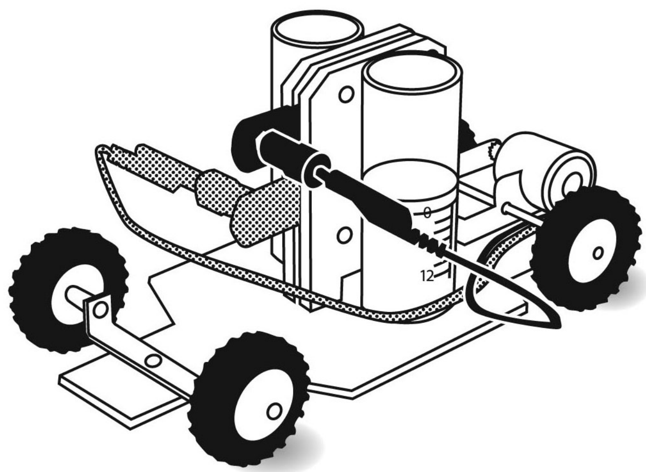
To begin the class, show the students the set up procedure. Let them see you pour the water, plug in the cords, and turn on the light as the event unfolds. Follow the directions at the front of this booklet regarding the use of distilled water, placement of the light, etc.

Demonstrating the Model Car Kit

1. Put on goggles. Remember that they will protect only if worn properly.
2. The bottom of the fuel cell storage cylinders should be filled with distilled water, with no air space or other gas in the cylinders. If you need to add distilled water to the fuel cell, refer to *Filling the Electrolyzer* at the front of this book.
3. With the patch cords, connect the solar module to the reversible fuel cell, which we are using here as an electrolyzer. Red to red and black to black. Position the solar panel so it faces the light source at a distance of at least 20 cm.



4. When the hydrogen storage cylinder has filled to at least 5 ml, remove the solar panel from the system by disconnecting the patch cords from the reversible fuel cell.
5. On the top side of the car base directly in front of the gears, there is a felt-covered upright piece of plastic. Turn the fuel cell so that the red and black contacts are towards the front of the car. Carefully slide the fuel cell over the black felt and push down gently until the fuel cell is fully seated on the car base. You may need to hold the connecting cables out of the way as you do this.
6. Connect the black and red wires from the motor to the fuel cell. The car should start to move.



If you have time, you might try the following. Set up the solar panel and the electrolyzer again as in step 3. This time let the hydrogen fill the entire storage cylinder until hydrogen gas bubbles rise through the small tube, the upper reservoir and escape. Hold a lighted match above the escaping bubbles to see and hear the effects of burning hydrogen.

When you have completed the set up, explain the OPQ activity to the students. Ask them to write ten observations of the entire apparatus. Everything—no matter how mundane it may seem—is important. You should affirm each student's observations as valid. Many students may try to scoff at others' responses, but some of the most basic observations may offer critical insights into the apparatus. We can use this opportunity to train students to not overlook things that they may feel are unimportant. For example, the wires are red and black. Background knowledge may suggest some kind of direct current circuit is involved.

As the electrolyzer begins to bubble, encourage students to offer any observations. Don't evaluate any response; just allow students to engage. At this point many students will begin to think about what is going on and may offer explanations. You can use one of their first explanations as a jumping-off point to say that while their explanation may be true, we don't have enough evidence at this time. Indeed, by saying, "I think that…" they are really making a *prediction*.

Some of these predictions are easily tested, some will take more time later on, but you should encourage students to write or state several "I think that…" predictions. Here is also an opportunity to talk about the nature of science as a process whereby events must be tested, retested, and found to be repeatable. It is not merely something that we dictate as things already learned. You want your students to realize that the nature of science is to look for events that may or may not quite fit into our understanding of the world and then test those events to perhaps refine our understandings or create new ones.

By the end of the period, students will have started to ask questions. Take the lead from the students to use some quiet time to write in their journals and come up with some questions. The purpose of this time is to allow the students to engage in the unit and start the exploration of the fuel cell. Some of the questions that students ask can be tested immediately. Some other questions are challenging the fuel cell industry at this time. Either way, just as scientists need a question to guide their scientific investigations, students need the opportunity to develop the skill of forming those questions.

There are no right or wrong questions. Do not evaluate the questions as good questions or not-so-good questions. Instead, model for students a way to frame their thoughts into a scientific investigation. You might suggest a similar question that can be answered through investigation.

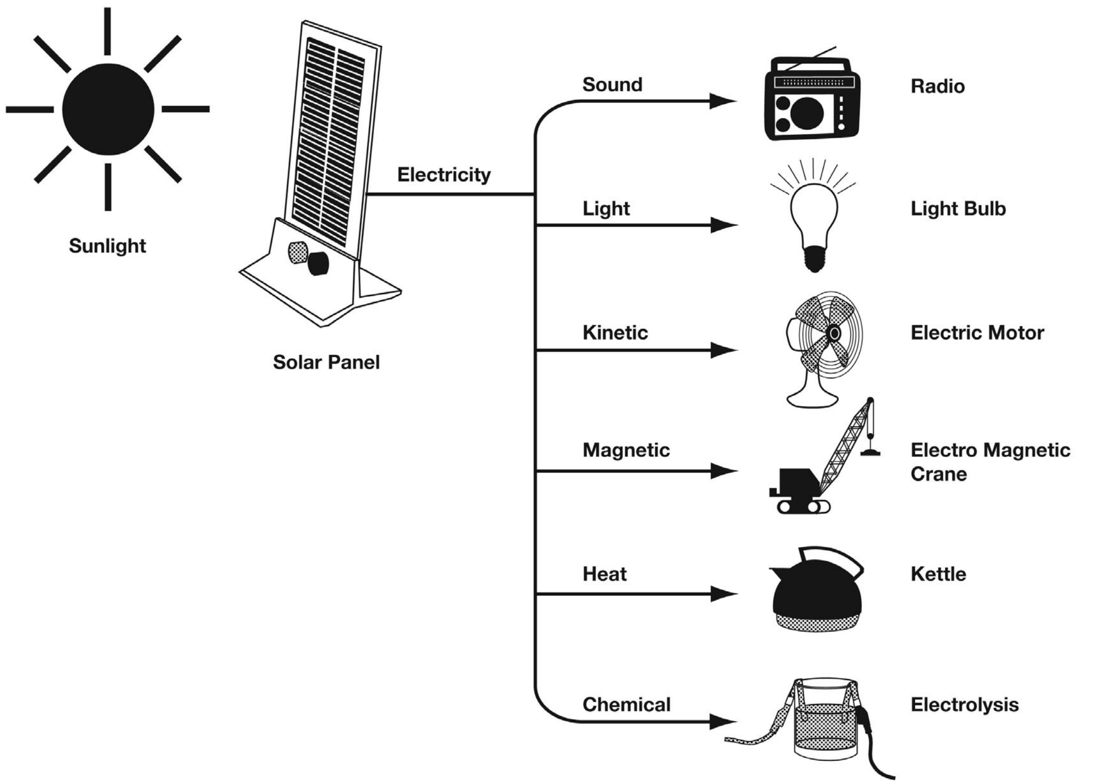
This may not turn out to be the most scientifically intense day with the most content learning. However, the Discovery Activity is vital to the success of this unit. Students may later remember the time that a teacher took to get them hooked. It's like fishing. You have to allow time for the fish to swallow the bait so you can eventually reel it in. Today is a day for your patience and guidance, and allowing the students to direct the pace and path of the class.

If this is the first time your class has experienced the OPQ format, you may need to take time to discuss the timing of the activity. If students get going with ideas and arguments, it may be difficult to finish OPQ in a single period. Trust in the process, avoid judgments or pronouncements and within a few OPQ sessions you will find that the students are able to commit to some ideas and possible investigations that will maintain intense interest for the remainder of the unit. As discussion leader you are needed as a focusing agent, but do allow the students to choose the aiming point.

The work of Luigi Galvani is fascinating and may be further explored with Internet searches. Several sites have original drawings and translations from Galvani's original documents.

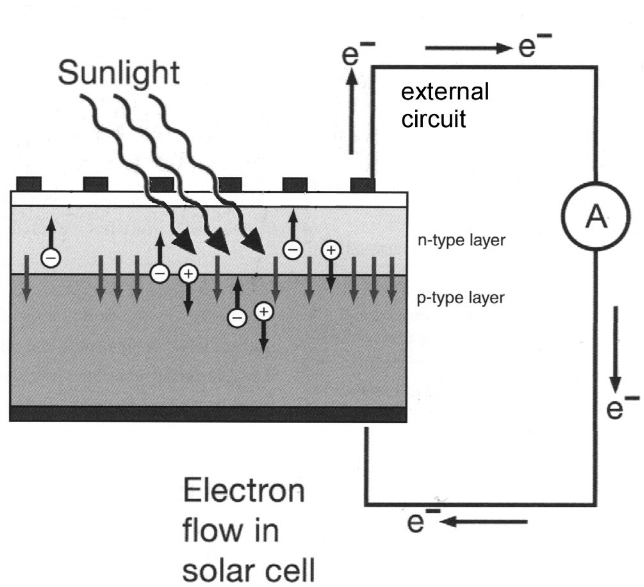
Investigation 2:
Solar Panel Orientation

Individual solar cells convert the radiant energy of sunlight into electricity. The solar panel that we are using consists of several solar cells connected in series. The panel can generate enough electricity to power an electrolyzer in some of the following investigations. The principle of a solar cell is that it converts a stream of **photons** (the radiant energy of sunlight) into a stream of **electrons** (electricity). The conversion, or transfer of energy from one form to electricity is the principle behind any **electrical generator**. Electrical generators include solar panels, diesel or gas engine generators, hydroelectric turbines and fuel cells. Perhaps you can think of more examples.



Solar cells are examples of very useful electrical technology as they can transform the renewable energy of sunlight into electricity. The light source we are using in our investigations is an incandescent lamp but in practical applications sunlight is used. Throughout the world we have sunlight at various times throughout the day. However we often need electrical power when sunlight is not available, for example at nighttime. If a solar cell is connected to an electrolyzer, the radiant energy of the sunlight can be stored as hydrogen and oxygen gas. A fuel cell can use these gases to make electricity when it is needed.

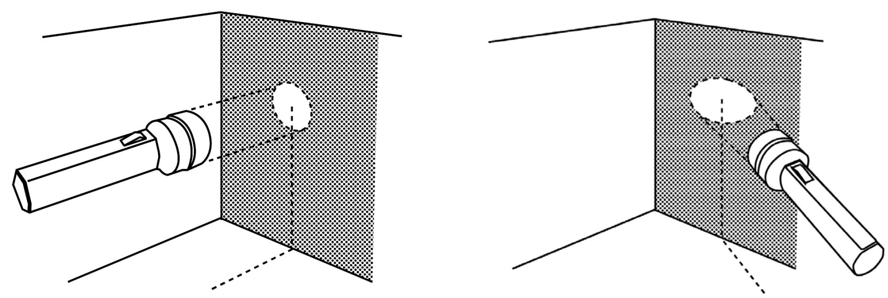
A solar cell contains layers of two types of silicon. Photons striking its surface knock electrons loose from one layer. The electrons are drawn to the other layer. If the two layers are connected through an external circuit, electrons will flow though that circuit. The flow of electrons is observed as an electric current. As more light is supplied to the solar cell, more photons are available to knock the electrons loose, and more current is generated.



This flow of electrons may be thought of as similar to a waterfall and has two values that are easily measured. One measurement is like the height of the waterfall, which is a fixed value. In electrical units, this is the **electric potential**, measured in **volts**. The other measurement is like the amount of water that falls down the waterfall, and allows us to actually do work with the water. In electrical units, this is called the **current,** measured in **amperes** (or simply **amps**). Thousandths of an ampere are called milliamperes, or mA. One interesting property of solar cells is that as the intensity of supplied light increases, the current increases but the voltage remains almost the same.

The sun is earth's nearest star and the sun seems to move across our sky each day. But in fact, earth travels in an orbit around the sun, spinning (once a day) as it goes. This means that if we want to collect the most sunlight we can with a solar cell array that cannot move, we have to place it in the best position to receive the maximum amount of energy available. In this investigation we will explore how to find the best position for the solar cell placement and whether this difference is worth considering.

Imagine a flashlight beam aimed directly at a chalkboard from a distance of 1 meter. The illumination in the beam is distributed over a certain area. As the angle of this ***incident*** *light is increased from 0 degrees (straight-on) to a greater angle, say 45 degrees, the beam becomes spread out over a larger area. The number of photons from that light source on a particular area of the blackboard is reduced. Thus if a light is tilted at an angle to the solar cell, the solar cell will not receive as many photons, or as much energy, as if the lamp was placed perpendicular to the plane of the solar cell. As a result the solar cell will generate less current.*



Your teacher will shine a flashlight directly at a chalkboard so that it is exactly 1 meter away from the board and the angle at which the light strikes the blackboard is 0 degrees (perpendicular, straight-on). We can say the **angle of incidence** is 0 degrees at a distance of 1 meter. The outline of this circular spot of light will be marked in chalk. If we now change the angle of incidence to 45 degrees the spot of light will be an ellipse, which will be marked in chalk as before. In both cases, the flashlight is 1 meter away from the center of the spot of light it makes on the board. But is the area inside each chalk figure the same?

If the flashlight is emitting the same number of photons in each case we should be able to compare the areas of the circle and the ellipse to see if there is a difference. If there is a difference then the smaller area is receiving a larger number of photons per unit of area and a solar cell placed flat on the chalkboard in this area would generate more current.

Now, let's see if the orientation of a solar panel really makes much (or any) difference in the current produced.

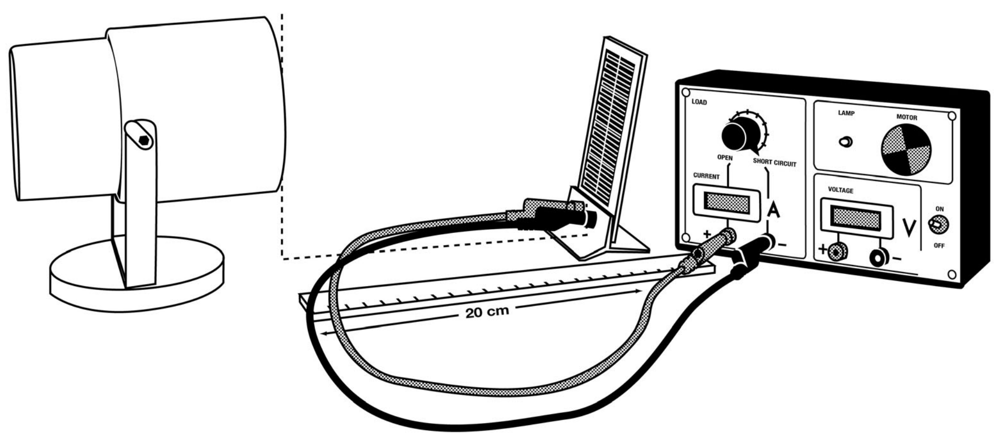
How can we maximize the electrical power coming from the solar panel?

You will need:

- solar panel from the *Fuel Cell Model Car Kit*
- load box from the *Fuel Cell Model Car Kit*
- two patch cords, red and black
- 75 watt PAR30 incandescent lamp, or equivalent light source
- protractor to measure angles (or make your own paper protractor from the template on page 2-8)

Procedure

1. Ensure the load box switch is in the **OFF** position. Use the patch cords to connect the solar panel to the load box **CURRENT** terminals—red to red and black to black. Turn the Load selector knob to **SHORT CIRCUIT**. Move the load box switch to **ON** and see if a number appears in the “Ampere” meter. If nothing appears, then check your connections. If a negative number appears, you have the connections reversed.



2. Adjust your solar panel and light source so the angle of incidence is exactly at 0 degrees. (The panel directly facing the light source.) Ensure the solar panel is placed exactly 20cm from the light source, or at whatever distance your teacher recommends. Measure this distance, and write it here. Then turn on the light.

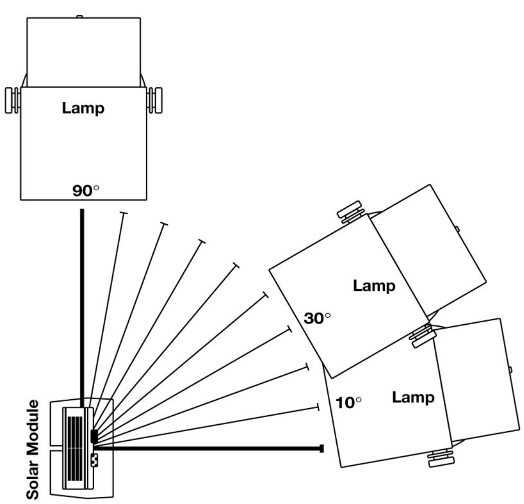
____

3. Look at the current as displayed in the ammeter window. Write this number in the table below.

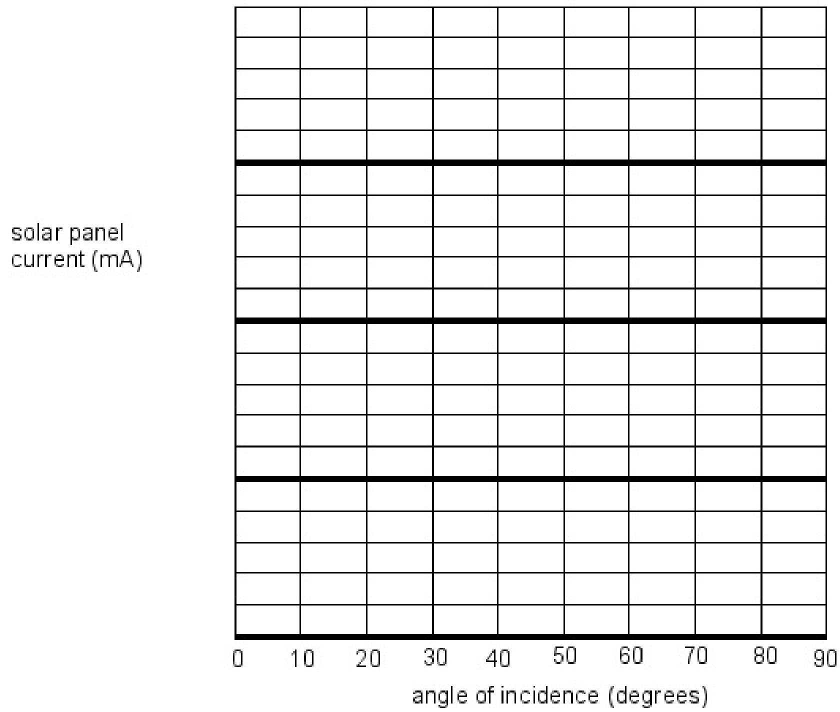
*Notice that the displayed number has a leading decimal point. For example the number **.105A** represents a little more than a tenth of an ampere, or 105 milliamperes.*

Angle of incidence (degrees)	**Predicted Current (mA)**	**Actual Current (mA)**
0º		
10º		
20º		
30º		
40º		
50º		
60º		
70º		
80º		
90º		

4. Now place your solar panel so the angle of incidence is exactly 90 degrees from the light source, taking care to keep the center of the solar panel exactly the same as before. In your table, write the current as displayed in the ammeter window.
5. What do you think the reading will be at a 10-degree angle of incidence. Write your prediction in the table.
6. Using your protractor template, adjust the angle of incidence of the solar panel to 10 degrees still keeping the center of the solar panel exactly the same as before. Record the actual milliamp reading in your table.
7. Continue predicting and measuring in this way at 10 degree intervals until you reach 80 degrees. Make sure you check the distance to the center of your solar panel for each measurement.



8. When you have made and recorded your measurements then use your data from your measurements to draw a graph indicating your findings in the space below.



9. Disassemble the equipment carefully and return it.

Questions

1. What is an ampere? What is a milliamp?

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2. Are milliamps a useful measure to see at which angle our solar cells work best?

____

____

3. What did you find out about the orientation of your solar cell to the light source?

____

____

4. Why is it important to keep the center of the solar panel the exact same distance away from the light source for each different angle? Is this important when using sunlight as a source?

____

____

5. How did your prediction for the 10-degree angle compare with your actual result? How did you adjust your predictions for the other angles? Did they become more accurate as a result of your actual measurements?

____

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6. With your graph could you make a fairly accurate prediction of the milliamp reading for 25 or 75 degrees? Is there any way to check your predictions for 25º and 75º?

____

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7. In this investigation we have placed the light source and the solar panel in the same plane. In real life the sun appears to move both horizontally and vertically. What would you need to know before you permanently position a solar panel on top of your school?

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8. Will the rate of electrical energy production be the same for every day of the year? Why or why not? How could you plan for this? Would your solution necessarily be a practical one?

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9. What is the answer to the question at the beginning of this investigation: *How can we maximize the electrical power coming from the solar panel?*

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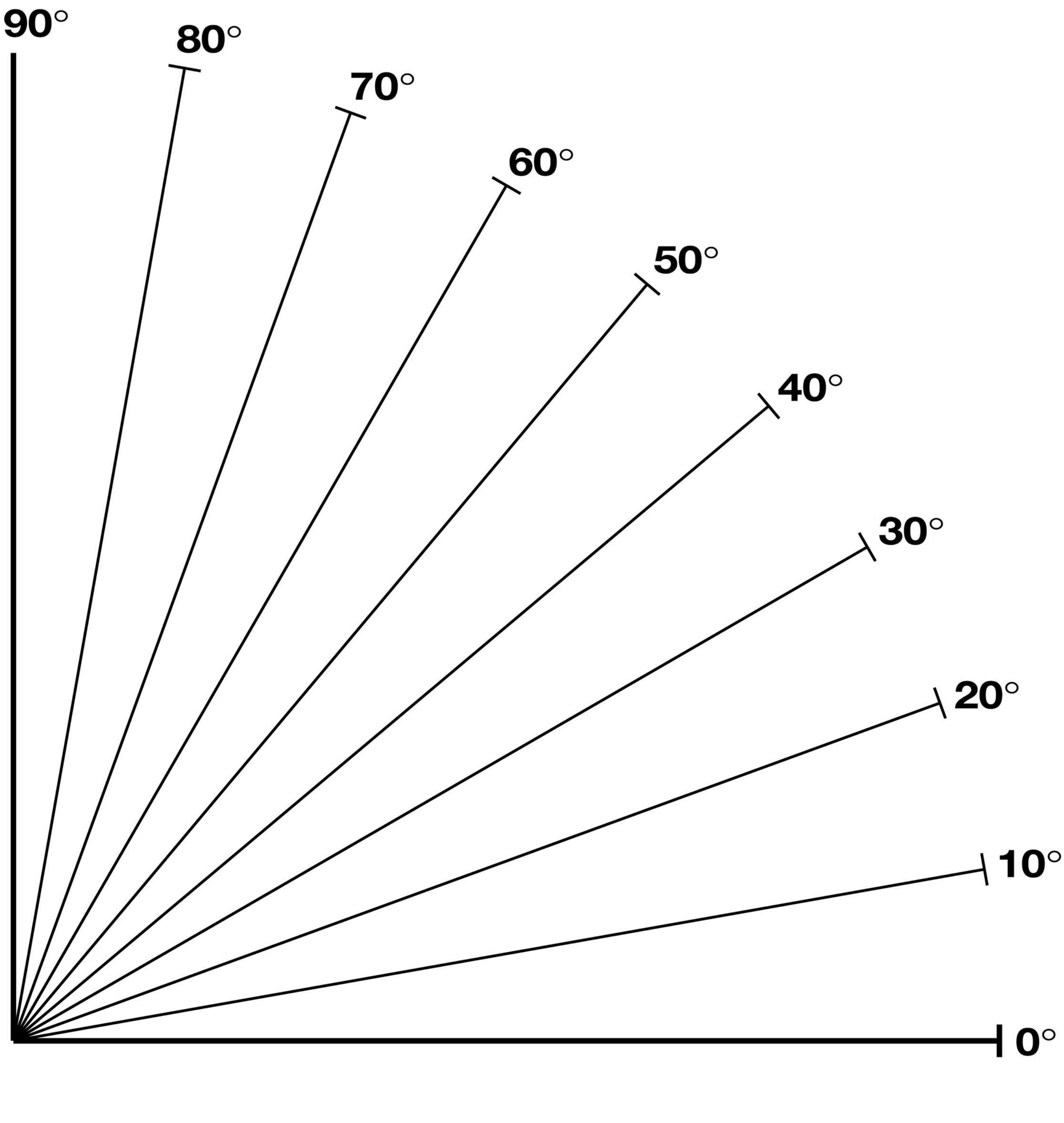

90°
80°
70°
60°
50°
40°
30°
20°
10°
0°

Teaching supplement for Investigation 2: *Solar Panel Orientation*

The objective of this investigation is to allow students to explore how the orientation of solar cells can result in the maximizing of the electrical power produced by the solar cell.

The objectives may be written:

- Students will record the current produced by different orientations of their solar cell to the incident light after predicting from previous results.
- Students will use this data to produce a table and a graph that will allow them to predict the amount of electrical power produced by their solar cell at different orientations.

Teacher notes

It may be helpful to produce a simple template that can be placed on the table to allow for rapid orientation of the solar cell. An example of such a template is provided.

Try out the system beforehand to ensure that the light source is positioned so it will provide maximum light on the panel without overheating it.

Remind your students to measure the distance to the center of the panel each time so distance from the light source does not become another variable.

1. *What is an ampere? What is a milliamp?*

   An ampere is a measurement of electrical current. A milliamp is one one-thousandth of an ampere.

2. *Are milliamps a useful measure to see at which angle our solar cells work best?*

   Milliamps are a useful measure of the angle at which our solar cells work best as it is a small measure suited to our solar cell array and it is sensitive enough to allow us to see how the angle of incidence of the light source affects the current flowing from the solar cell.

3. *What did you find out about the orientation of your solar cell to the light source?*

   I found out that as the light source changed from a low angle of incidence to a higher angle of incidence the current decreased.

4. *Why is it important to keep the center of the solar panel the exact same distance away from the light source for each different angle? Is this important when using sunlight as a source?*

   It is important to keep the center of the solar panel the exact same distance away from the light source for each different angle if we want to compare the results with each other. When we use sunlight as the light source it is so far away from the solar panel that the distance on our tabletop is insignificant.

5. *How did your prediction for the 10-degree angle compare with your actual result? How did you adjust your predictions for the other angles? Did they become more accurate as a result of your actual measurements?*

   My prediction for the 10-degree angle was different from my actual result. I thought there would be a greater difference. The differences between each measurement grew larger as the angle of incidence increased so I increased the differences each time.

6. *With your graph could you make a fairly accurate prediction of the milliamp reading for 25 or 75 degrees? Is there any way to check your predictions for 25º and 75º?*

   We could check my predictions for 25 degrees and 75 degrees by actually doing it and getting the results from the ammeter.

7. *In this investigation we have placed the light source and the solar panel in the same plane. In real life the sun appears to move both horizontally and vertically. What would you need to know before you permanently position a solar panel on top of your school?*

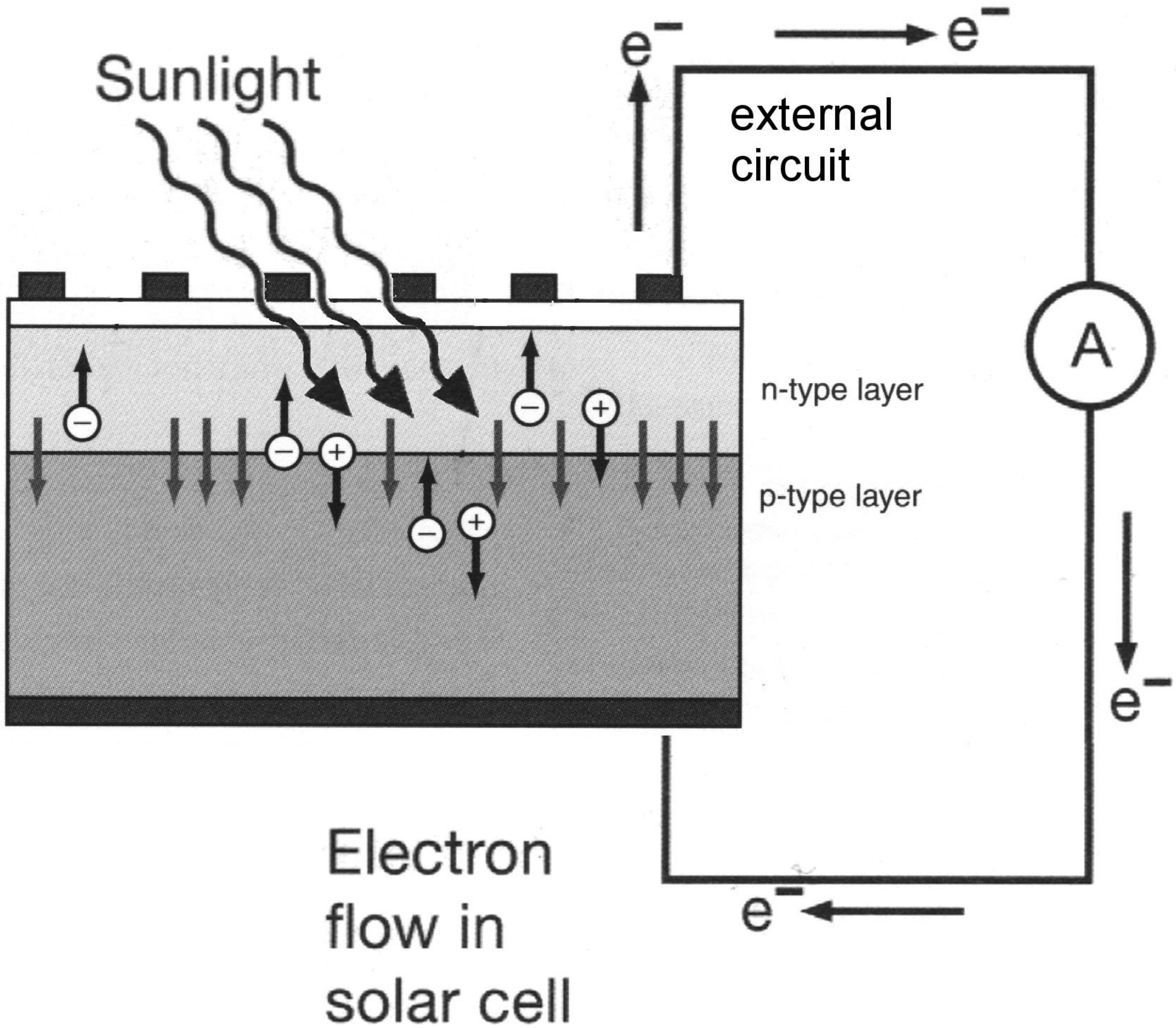
   I would need to determine my latitude and where geographic south is before I permanently position a solar panel on top of my school. It would be similar to positioning a sundial correctly.

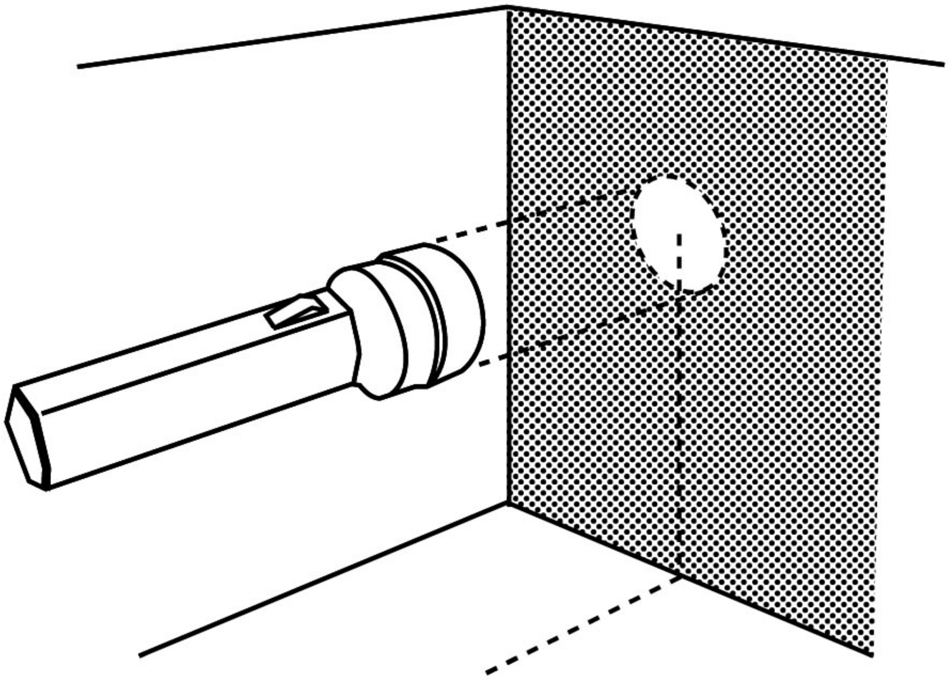
8. *Will the rate of electrical energy production be the same for every day of the year? Why or why not? How could you plan for this? Would your solution necessarily be a practical one?*

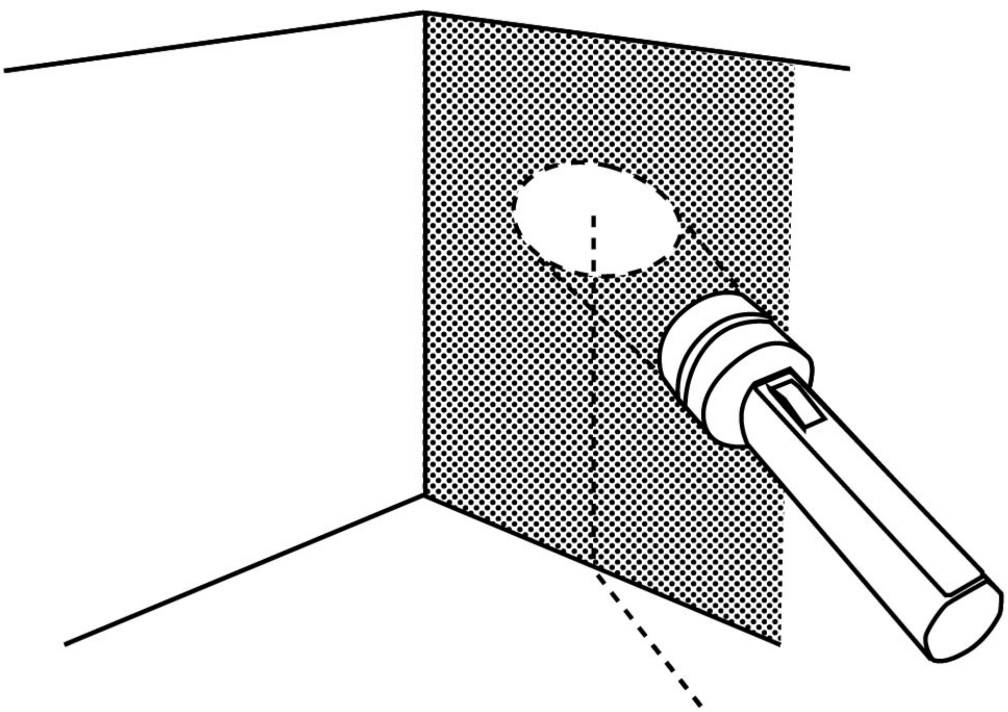
   The rate of electrical energy production will not be the same for every day of the year because of the weather or time of the year. I might be able to make a motorized mount for a solar panel that would automatically track the sun wherever it is or find the brightest spot in an overcast sky. It might be too expensive to set it up this way and might present more problems or things that could go wrong.

9. *What is the answer to the question at the beginning of this investigation:* How can we maximize the electrical power coming from the solar panel?

   We can maximize the electrical energy coming from the solar cell if we position it correctly.


Sunlight
external
circuit
e−
e−
e−
e−
A
n-type layer
p-type layer
Electron
flow in
solar cell





Investigation 3:
Simple Electrolysis

Matter is made up of small particles that scientists call **atoms**. Atoms are often combined to form **molecules**. **Ionic compounds**, like sodium chloride, are composed of particles that form when atoms loose or gain electrons. An **element** is a substance consisting of atoms of one type.

Oxygen is an element and each molecule of oxygen is made up of two oxygen atoms joined chemically. In scientific shorthand oxygen is O and a molecule of oxygen is written as O_2.

In the same way, hydrogen is another element and each molecule of hydrogen is made up of two atoms of hydrogen joined chemically. A molecule of hydrogen is written as H_2.

A compound is described by its **formula**. For example, table salt is made up of one atom of the element sodium chemically joined with one atom of the element chlorine. This ionic compound is called sodium chloride. The shorthand for sodium is Na and the shorthand for chlorine is Cl. Therefore the formula for sodium chloride is written NaCl. Water is a compound containing two atoms of the element hydrogen and one atom of the element oxygen. The formula for water is H_2O.

Often, applying energy to a molecule can break it apart. The energy needed is usually heat, light, or electricity. The pulling apart is a type of change, called a chemical **reaction**. As the molecule breaks apart, its atoms may re-join to form different substances.

Later, these new substances might be used to make other compounds, or even make the original molecule again, and may give back some of the energy that was used in breaking apart the original molecule.

In this investigation we are going to look at the process of breaking up a compound. We will investigate what will happen if we let electricity flow through water.

Can you guess what might happen if we add enough energy to water to break it into its two elements, and then later let the elements re-join?

This kind of thinking about the background of an investigation can often help you with your observations and allow you to understand what you are seeing.

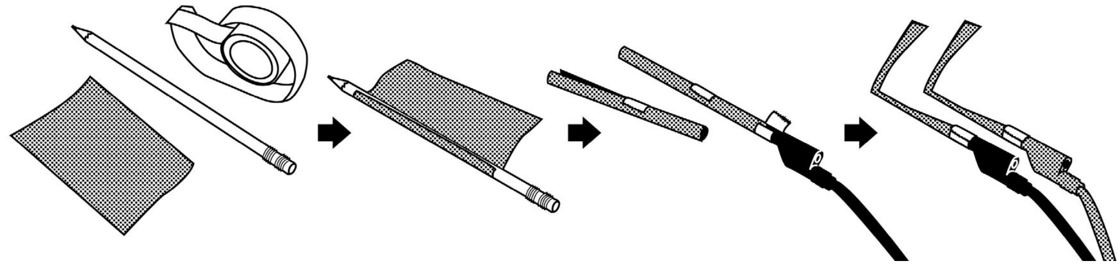
What evidence do we have that water can be taken apart using electricity?

You will need:

- goggles or eye protection
- solar panel from the *Fuel Cell Model Car Kit*
- two patch cords
- two 10cm x 5cm pieces of aluminum foil
- clear 200ml plastic cup or 250ml beaker
- 150 ml distilled water
- 15ml table salt
- 75 watt PAR30 incandescent lamp, or bright sunlight, or equivalent light source.
- utility tape to fasten aluminum foil
- magnifying glass (optional)

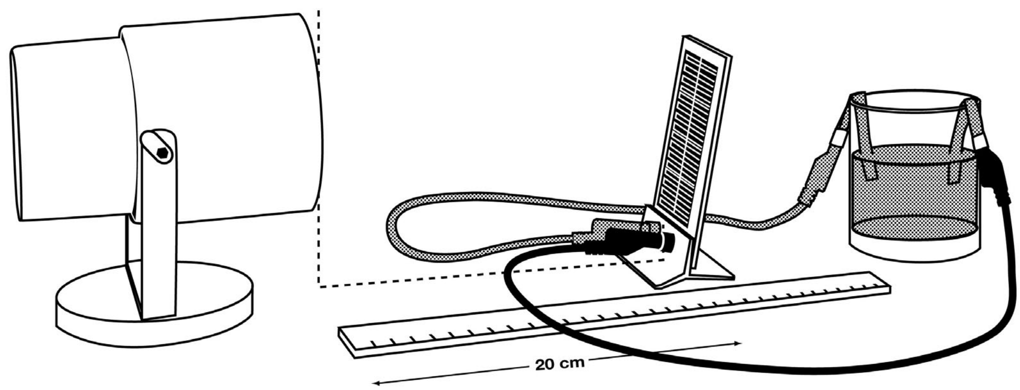
Procedure

1. Put on your goggles. Remember that they will only protect you if you wear them properly.
2. Roll a piece of aluminum foil around a pencil. Use a small piece of tape to hold the foil in a cylinder and slide it off the pencil. Place one end of the cylinder over the metal tip of a patch cord, squeeze the foil and wrap that end tightly with tape so it is secure. Flatten the other end of the foil cylinder, forming an **electrode**. Repeat this step with another piece of foil and the other patch cord.



3. Pour 150ml of distilled water into a small beaker or clear plastic cup.
4. Bend the aluminum electrodes and hang them on the edge of the beaker or plastic cup with the electrodes immersed in the water. The metal ends of the patch cords should not touch the water directly.
5. Place the solar panel directly facing the light source, but not closer than 20cm. Turn on the light, but do not connect the patch cords yet.
6. What do you think is going to happen when you connect the patch cords to the solar panel and why? Make an entry on your lab sheet before you continue.

7. Connect the patch cords to the solar panel - red to red and black to black. The connectors on the solar cell are colored in the usual way: red is positive, black is negative.



8. Observe what is happening under the water on the surface of each electrode

9. Lift the electrodes out of the water and set them aside. Add 15ml (1 tablespoon) of ordinary table salt to the water and stir until the salt is completely dissolved.
10. Replace the electrodes in the water, now a **salt solution**.
11. Observe what is happening under the salt solution on the surface of each electrode. You may wish to use a magnifying glass.

12. After recording your observations remove the electrodes from the salt solution and pull them off the patch cords. Dispose of the aluminum foil responsibly. Empty the salt-water solution and wash the cup or beaker so it is ready for use again. Disconnect the patch cords and return all equipment as directed by your teacher.
13. Take off your goggles and return them carefully.

Questions

1. What is the reason for ensuring the solar panel is perpendicular to the light source and no closer than 20 cm?

2. Why is salt added to the water and how does it change what happens when the electrodes are under the water and connected to the solar panel?

3. During electrolysis, the electrode attached to the black patch cord is called the CATHODE. Is the cathode positive or negative with respect to the other electrode?

4. During electrolysis, the electrode attached to the red patch cord is called the ANODE. Is the anode positive or negative with respect to the other electrode?

5. When the patch cords were connected to the solar panel what did you notice happening at the cathode when you observed carefully?

6. Was the same thing happening at the anode? What do you think is the reason for any differences in your observations?

7. What is the answer to the question at the start of the investigation: *What evidence do we have that water can be taken apart using electricity?*

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____

8. Looking at the scientific formula for water, H_2O, what do you think happened in this investigation? How can you be sure?

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9. What questions do you now have about this process?

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10. What is the scientific name for this process?

____

____

Teaching supplement for Investigation 3: *Simple Electrolysis*

The major goal of this investigation is to allow the students to begin to ask questions surrounding energy and water. It is not a quantitative investigation that needs to be fully articulated into formulae and reactions as this will be developed in the next two investigations.

The learning objectives may be written:

- Students will set up apparatus according to instructions and will observe, make notes and answer questions after observing the electrolysis of water.
- Students will observe that when electrical energy is supplied to a dilute solution of water and salt, gases are produced at each electrode.
- Students will use the terms anode and cathode correctly to identify the positive and negative electrodes.
- Students will demonstrate correct safety procedures for this investigation.

Teacher Notes

In general, the term *anode* refers to the electrode where the oxidation reaction takes place; that is, a reaction where there is a loss of electrons. Similarly, *cathode* refers to the electrode where the reduction reaction takes place; that is, a reaction where there is a gain of electrons. In this investigation, the electrode attached to the positive (red) side of the solar panel releases oxygen, and is the *anode*. The other electrode, attached to the negative (black) side of the solar panel releases smaller hydrogen bubbles and is the *cathode*.

If you don't have beakers and are using plastic cups, try to use plastic cups wide at the base as they are more stable. They may be sold as *highball* glasses.

A dissecting microscope will make it easier to see the difference between anode and cathode bubbles at the electrodes. Putting the electrolyte and electrodes in a shallow dish such as a Petri dish allows observation with the microscope. With care, you can even place a shallow dish of electrolyte on the glass of an overhead projector.

If a very strong salt solution is used, the electrolysis will produce chlorine and oxygen. Telltale signs of this happening would be gases produced in equal amounts and a greenish hue to the gas produced at the cathode. However, at the salt concentration suggested in this procedure—15ml salt to 150 ml water—chlorine will not be produced.

Answers to the student questions

1. *What is the reason for ensuring the solar panel is perpendicular to the light source and no closer than 20 cm?*

   The solar panel is placed perpendicular to the light so the greatest amount of energy can be had from the light source. The light source must be at least 20cm away from the solar panel to avoid overheating.

2. *Why is salt added to the water and how does it change what happens when the electrodes are under the water and connected to the solar panel?*

   Salt is added to the water to allow electricity to flow through it. When it is added the electricity begins to flow and bubbles begin to appear on the surface of the tinfoil electrodes.

3. *During electrolysis, the electrode attached to the black patch cord is called the CATHODE. Is the cathode positive or negative with respect to the other electrode?*

The cathode is more negative than the other electrode.

4. *During electrolysis, the electrode attached to the red patch cord is called the ANODE. Is the anode positive or negative with respect to the other electrode?*

The anode is more positive than the other electrode.

5. *When the patch cords were connected to the solar panel what did you notice happening at the cathode when you observed carefully?*

When I connected the patch cords to the solar panel I noticed that the cathode was giving off lots of very small bubbles.

6. *Was the same thing happening at the anode? What do you think is the reason for any differences in your observations?*

When I looked at the anode after connecting the patch cords to the solar panel I noticed that larger bubbles were forming on it but they didn't come to the surface as often. I think that there were different gases being produced at each electrode.

7. *What is the answer to the question at the start of the investigation:* What evidence do we have that water can be taken apart using electricity?

We have seen that when electricity flows through water, different gases are produced at the two points where the current enters the water. Probably these gases are the elements that water is composed of.

8. *Looking at the scientific formula for water, H_2O, what do you think happened in this investigation? How can you be sure?*

Water is made up of two elements, hydrogen and oxygen. Both are gases and when water is taken apart by electricity the gases bubble up from the electrodes and escape into the air. I think we could collect the gases and test them to be sure of what they are.

9. *What questions do you now have about this process?*

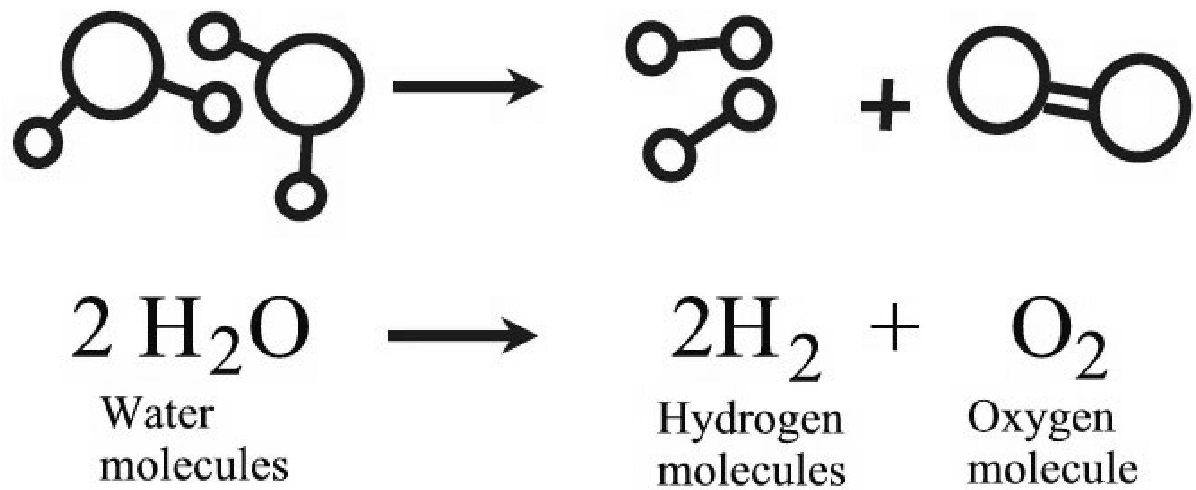
Accept any questions the students suggest. The students may want to know what would happen if we used stronger light or more solar panels or added something else to the water such as sugar or more salt in the water or whatever they suggest. Some may notice that the gases seem to be coming off in a different manner with more rapid bubbling, smaller bubbles, and such.

The process here is to encourage questions beyond the immediate experience so as to allow the natural curiosity of the student to suggest further investigation that may be part of these experiences or extras that may add greatly to the unit. It may be helpful to ask questions during the investigation that would promote such questions.

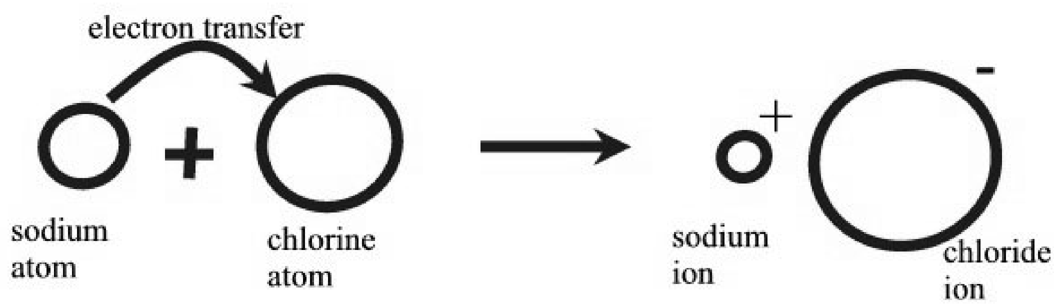
10. *What is the scientific name for this process?*

The scientific name for taking water apart by using electricity is electrolysis.

The Latin suffix -lysis means to dissolve or take apart thus electrolysis is the taking apart of something by using a flow of electrons.



$2\,H_2O \longrightarrow 2H_2 + O_2$
Water molecules
Hydrogen molecules
Oxygen molecule



electron transfer
sodium atom
chlorine atom
sodium ion
chloride ion

Investigation 4:
Understanding Electrolysis

In a previous investigation you saw that electricity flowing through water with a little salt added produced gases at each electrode. Electricity is a flow of electrons and this flow needed to have the salt dissolved in the water in order to have these electrons complete their journey through the wires from the anode to the cathode. An interesting extra effect was that along the way the electron flow broke up water molecules to produce the bubbles of gas. When you look at the formula for water (H_20) you probably have some idea of what these two gases might be. This investigation will introduce you to another way to break up water with electricity by having it flow through a special piece of equipment called an electrolyzer. The electricity to break up water will come from the solar panel as before.

The electrolyzer is quite different from your electrolysis tank in Investigation 3. We must not contaminate its special membrane by letting it contact damaging chemicals such as table salt. If the membrane becomes contaminated it will not work as well and the electrolyzer will not be able to break up water. Even tap water is not pure enough. You must use pure distilled water when you fill the electrolyzer or you could permanently damage the membrane.

In the previous investigation dissolving salt in water created charged particles called ions. Electricity was able to flow through the water using these ions. The electrolyzer can break up water because it contains a special membrane containing a substance that allows hydrogen ions to jump between molecules and flow in one direction through the membrane. This substance is held inside two very thin layers of carbon that have had tiny amounts of the element platinum added to them on one side and tiny amounts of platinum plus another element, iridium on the other side. These microscopic amounts of platinum and iridium allow the water molecules to break apart when the membrane is being used as an electrolyzer.

The platinum and iridium do not change in the electrolysis reaction but remain in place to continue helping with the reaction. Substances that change reaction rates but do not change themselves are called catalysts and are a very important part of fuel cells. You must always use pure distilled water to avoid destroying their properties.

The concept of a catalyst is an important one. A baseball bat is used to propel the ball a long distance but hitting the ball does not materially change the bat. Swim fins allow a swimmer to go faster but do not change while they are being worn. These examples are not usually considered catalysts but perhaps you can see how platinum and iridium allow a reaction to happen much faster than if they weren't there. Pure water is very difficult to break apart so the platinum catalyst is essential.

Now, put on your goggles and take a look at this electrolyzer.

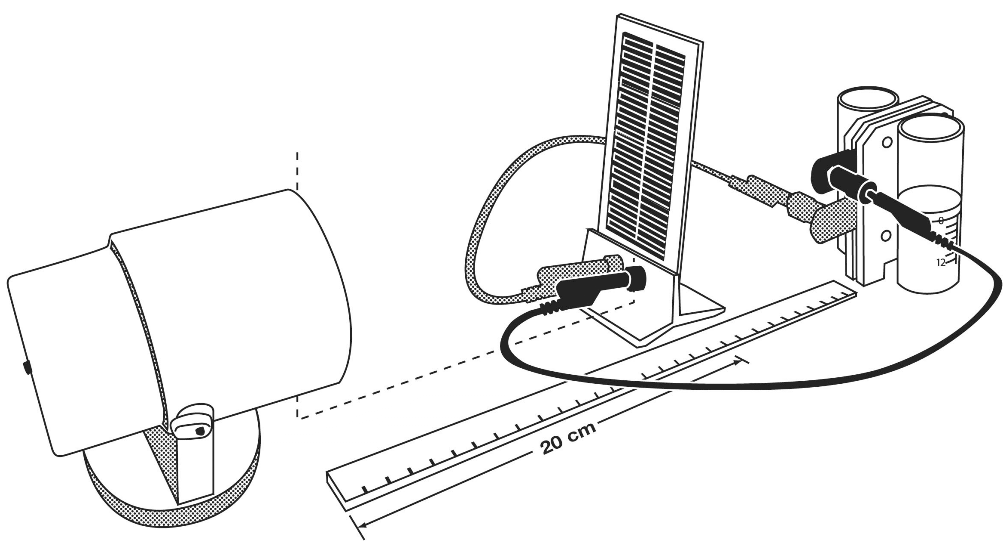
What is an electrolyzer and what does it do?

You will need:

- goggles or eye protection
- solar panel from the *Fuel Cell Model Car Kit*
- two patch cords
- reversible fuel cell from the *Fuel Cell Model Car Kit,* used here as an electrolyzer
- distilled water
- 75 watt PAR30 incandescent lamp, or equivalent light source.
- two small test tubes, 1 cm by 10 cm
- matches
- wooden splints
- tray to place under fuel cell, or paper towels

Procedure

1. Put on your goggles. Remember that they will only protect you if you wear them properly.
2. The bottom of the fuel cell storage cylinders should be completely filled with distilled water, with no air space or other gas in the cylinders. If you need to add distilled water to the fuel cell, refer to *Filling the electrolyzer* in the section *Using the Fuel Cell Model Car Kit* at the start of this handbook.



3. Place the fuel cell on a tray or folded paper towels to catch the water that will overflow in the later steps of this investigation. Watch the top of the small tubes for 30 seconds to see if some water comes out.

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4. With the patch cords, connect the solar module to the reversible fuel cell, which we are using here as an electrolyzer. Red goes to red and black goes to black. Position the solar panel so it directly faces the light source at the distance your teacher recommends and turn on the light.
5. Watch the top of the small tubes again. What is pushing the water out?

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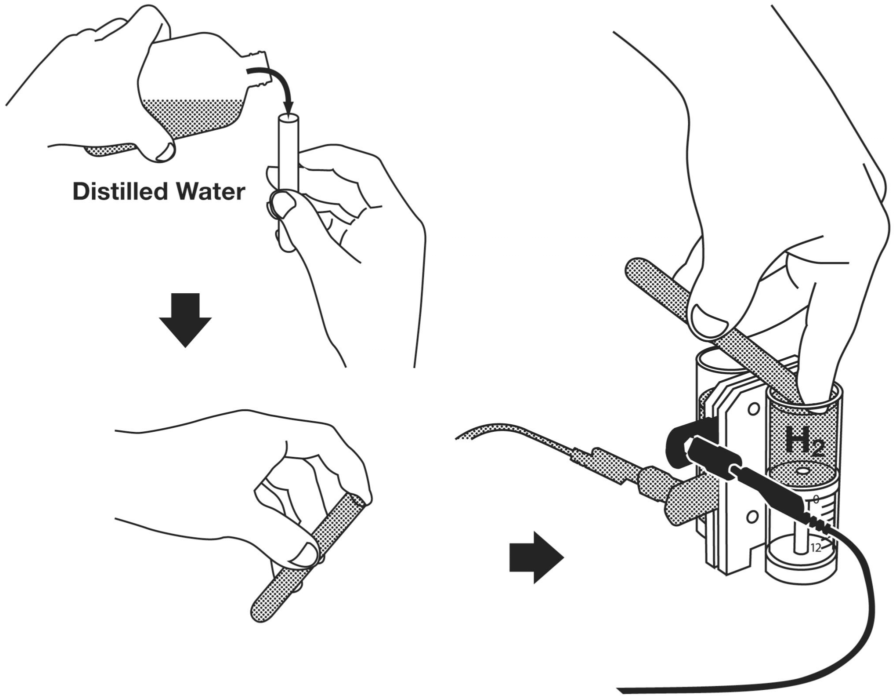
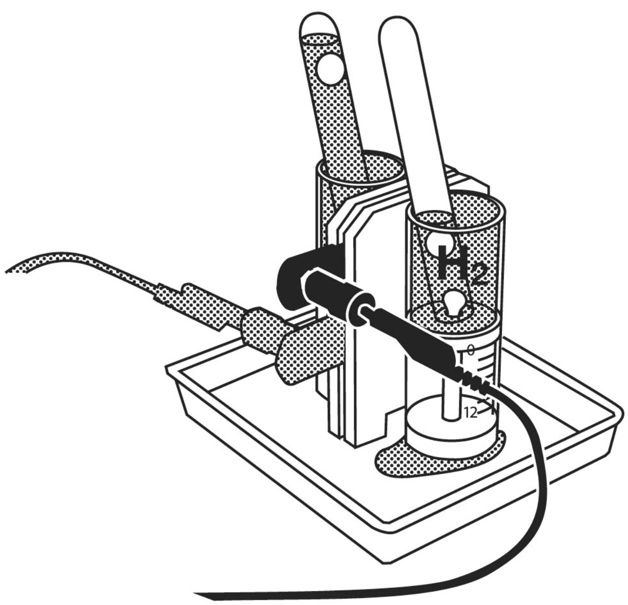
6. Continue observing and every two minutes record the amount of gas collected in each storage chamber in this table.

Time From Start	Cathode Gas Volume (black)	Anode Gas Volume (red)
0 minutes	0 ml	0 ml
2 minutes		
4 minutes		
6 minutes		

7. When 10ml of gas is collected in one cylinder, record the time, and record the amount of gas in the other cylinder. This completes your table.
8. Let the electrolyzer continue working until all the water has moved into the upper portion of one of the cylinders. (With optimum lighting, it will take about 10 minutes to displace all the water into the upper hydrogen cylinder.)
9. As the production of gas continues, you will see bubbles moving up through the water as the gas escapes through the small tube in the center of the cylinder.
10. If necessary, add more distilled water to the upper part of the cylinder so it is overflowing.
11. Wash and rinse your hands carefully to ensure no other chemicals or dirt contaminate the electrolyzer. Avoid using soap that could contaminate the distilled water. Completely fill one of the small test tubes with distilled water. Cover the end of the tube with your finger, turn the tube upside down and keeping it covered

place it under the surface of the water as quickly as you can, trying to prevent any air getting into the tube. (A small amount of air, less than 1 ml in the test tube will not matter. But if there is more you should repeat the procedure, perhaps asking someone with smaller fingers to help!) Then uncover the tube and position it so the bubbles of gas will be collected in the inverted test tube.

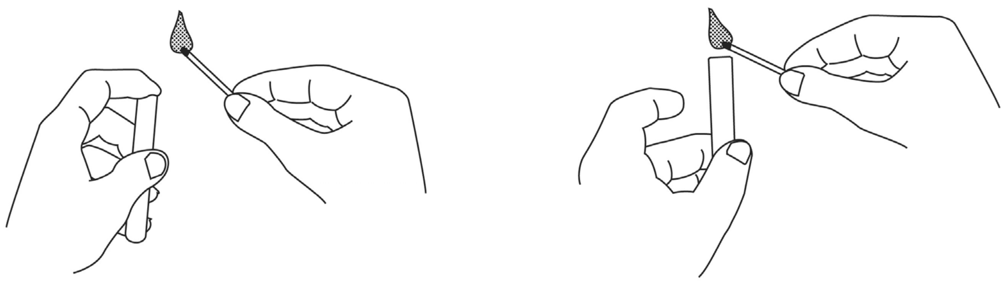




12. When bubbles of gas start to escape in the other cylinder, repeat steps 10 and 11 for that cylinder.

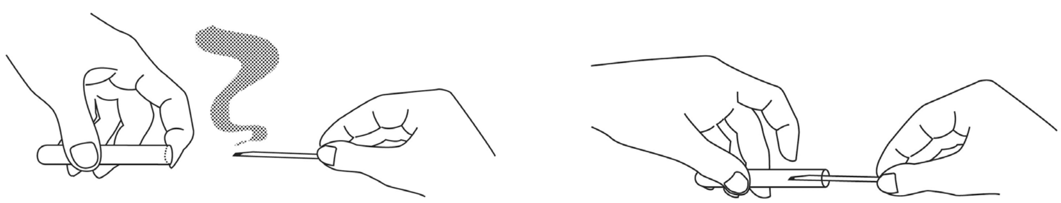
Your instructor may wish to supervise the following gas tests.

13. When the test tube above the cathode is filled with gas, again cover the end with your finger before you remove the tube from the water, trapping the collected gas.



14. Still keeping the tube closed, hold it right side up. Bring the flame of a lighted splint to the top of the tube and release your finger. There will be a visible and audible reaction. Also look carefully at the inside of the mouth of the tube immediately after. Use all your senses for observations. Write your observations here.

15. When the test tube above the anode is filled with gas, cover the end with your finger before you remove the tube from the water, trapping the collected gas.



16. Still keeping the tube closed, hold it horizontally. Light a wooden splint and then blow it out to leave a glowing ember on the end of the splint. Release you finger and insert the glowing splint half way into the tube. Write your observations here.

17. Take apart the equipment, put it away and then take off your goggles and return them carefully.

Questions

1. Why is it important to ensure there are no large bubbles of air remaining when we fill the gas storage cylinders with water?

2. Using the information provided by the labels on the gas storage cylinders, which electrode is attached to which cylinder?

3. Is gas produced at similar rates at each electrode? What evidence do you have of this?

4. What simple ratio can you use for this gas production?

5. Why do we test the gas from the cathode first?

6. Do you have any evidence that the labels on the cylinders are placed on the correct cylinder?

7. Looking at the scientific formula for water, H_2O, what do you think happened in this investigation?

8. Looking back at investigation 3 can you make any inferences about the gases you saw being produced at each electrode? Did you observe any differences when you watched the gases being produced by simple electrolysis and by the electrolyzer?

9. Use the data from your table to create a simple graph. How much gas would be produced if you ran your electrolyzer for one hour? How long would it take you to collect a litre of Cathode gas? Of Anode gas?

10. From your careful reading of the introduction and the results you obtained from this investigation, what is the answer to the question at the start of the investigation: *What is an electrolyzer and what does it do?*

11. Is hydrogen a good name for the gas collected over the cathode?

Teaching supplement for Investigation 4: *Understanding Electrolysis*

The objective of this investigation is to introduce students to the reversible fuel cell as it is used as an *electrolyzer* to break water into hydrogen gas and oxygen gas through electrolysis. The students will move from qualitative observations as done in Investigation 3 through quantitative observations of the 2:1 ratio when water is broken down into hydrogen and oxygen. The learning objectives may be written:

- Students will set up the *electrolyzer* according to instructions and will observe, make quantitative observations and answer questions on the construction and function of a reversible fuel cell used as an *electrolyzer*.
- Students will observe that in electrolysis twice as much gas is produced at the cathode than is produced at the anode.
- Students will make inferences as to the identity of the two gases.
- Students will demonstrate correct safety procedures for this investigation.
- Students will observe that the gas collected above the cathode can be ignited in air to produce a mild explosion complete with heat, light, sound and the production of water and that this is a test for the presence of hydrogen gas.
- Students will observe that the gas collected above the anode will support rapid combustion when a glowing splint is thrust into it and that this is a test for the presence of oxygen.

Teacher Notes

Although the device that produces the gases in this investigation is more complex than the simple aluminum electrodes of investigation 3, the polarity is exactly the same. Specifically, the positive (red) side of the electrolyzer releases oxygen, and is the *anode*. The negative (black) side releases hydrogen and is the *cathode*.

You should consider whether you want students to do this investigation, or you will do it as a demonstration. The last part of the procedure, steps 14 to 17 involve open flames, and a small explosion as the hydrogen ignites. There may also be a popping sound as the lighted splint is placed within the oxygen tube. If students do perform the investigation they may be startled and drop the test tube so close supervision may be advisable. In any case, use small test tubes.

Try out the procedure steps yourself to ensure you have allowed enough time to collect gas and perform the demonstrations. The entire gas storage cylinder needs to fill before any bubbles of hydrogen collect in the test tube. Even with bright light, it will take at least 10 minutes to fill the storage cylinder with hydrogen and then another 5 minutes to collect the first tube of hydrogen. Additional tubes could be obtained at 5-minute intervals. For oxygen, all the times are doubled. For this reason, you may want to start the electrolyzer before class begins.

Practice placing the water filled test tubes over the gas bubbles before you have students arrive as this is a little tricky and requires you use your index finger to cap the tube as you reach inside the reservoir. A small student hand may help here if you have the student practice before attempting it.

Your students should understand the importance of using only distilled water for this investigation. It might be a good idea to put tape or a sign on the water taps to prevent mistakes. There is no need for any tap water when using the fuel cell. Wash and rinse your hands carefully to ensure no other chemicals enter the system. Avoid using soap that could contaminate the distilled water.

With the students, examine the markings used on the gas collection cylinders so that all students can read them correctly. Some students will not be familiar with scales that have “missing” numbers.

Place the *electrolyzer* on a tray or absorbent towels to catch the considerable overflow. Water in the test tube is displaced and runs over the edge of the reservoir.

You should stop measuring the gas levels when the H_2 gas cylinder is reading 10 ml. When the hydrogen begins to escape into the upper reservoir, the ratio of stored hydrogen to stored oxygen becomes meaningless.

If you are doing this as a demonstration, when you remove the tube filled with hydrogen from the reservoir, hold it as close to the bottom as you can so that your index finger is extended and when pulled away will allow the students to see the reaction easily. As the reaction is instantaneous you will need to prepare the students to watch carefully. With the hydrogen it may help to darken the room so the light blue explosion from the combustion may be seen. Do not point the tube at yourself or a student. As soon as the hydrogen burns take the tube to the students to allow them to observe the water droplets that have been produced just inside the top edge of the tube. They will be small but they will be there.

When performing the oxygen test considerable heat may be produced. Hold the tube in such a way that you will not be burned. As soon as the splint ignites and burns brightly remove it from the tube to show the students that it has reignited. After the splint reignites, do not insert it a second time into the tube of oxygen. Gases produced by the volatilization of the wood resins, with a lesser concentration of oxygen could result in a large 'pop'. Although not dangerous, it may cause you to drop the tube.

Answers to the student questions

1. *Why is it important to ensure there are no large bubbles of air remaining when we fill the gas storage cylinders with water?*

   It is important to ensure there are no large bubbles of air remaining when we fill the gas storage cylinders so we can get an accurate measure of the gas collected.

2. *Using the information provided by the labels on the gas storage cylinders, which electrode is attached to which cylinder?*

   The H_2 gas-collecting cylinder is attached to the cathode (black, negative) and the O_2 gas collecting cylinder is attached to the anode (red, positive).

3. *Is gas produced at similar rates at each electrode? What evidence do you have of this?*

   The gases are not produced at similar rates at each electrode. Our table shows that in four minutes we collected x ml at the anode and 2x ml of gas at the cathode.

4. *What simple ratio can you use for this gas production?*

   Our table shows us that for every two millilitres of gas collected at the cathode there is one millilitre collected at the anode. The ratio is 2:1.

5. *Why do we test the gas from the cathode first?*

   We test the gas collected at the cathode first because it is the gas that is produced more quickly and the test tube will be filled first.

6. *Do you have any evidence that the labels on the cylinders are placed on the correct cylinder?*

I think the labels are placed correctly because there is twice as much gas in the hydrogen storage cylinder. The formula for water, H_2O shows that there is twice as much hydrogen as oxygen.

7. *Looking at the scientific formula for water, H_2O, what do you think happened in this investigation?*

When I look at the formula for water, H_2O, I think that water is being broken up into hydrogen and oxygen with twice as much hydrogen being produced as oxygen.

8. *Looking back at investigation 3 can you make any inferences about the gases you saw being produced at each electrode? Did you observe any differences when you watched the gases being produced by simple electrolysis and by the* electrolyzer*?*

I think that in the other electrolysis investigation that hydrogen gas was being produced at the cathode and oxygen gas was being produced at the anode. The bubbles of hydrogen gas appeared smaller in size.

9. *Use the data from your table to create a simple graph. How much gas would be produced if you ran your* electrolyzer *for one hour? How long would it take you to collect a litre of Cathode gas? Of Anode gas?*

The graphs will be straightforward and the amount of gas produced in one hour should be easily extrapolated from the amount collected in ten or twenty minutes (i.e. 6 times or 3 times). The time needed to collect a litre of Cathode gas would be 100 x the time for 10ml and the time for the collection of Anode gas should be double that of the Cathode gas.

10. *From your careful reading of the introduction and the results you obtained from this investigation, what is the answer to the question at the start of the investigation:* What is an electrolyzer and what does it do?

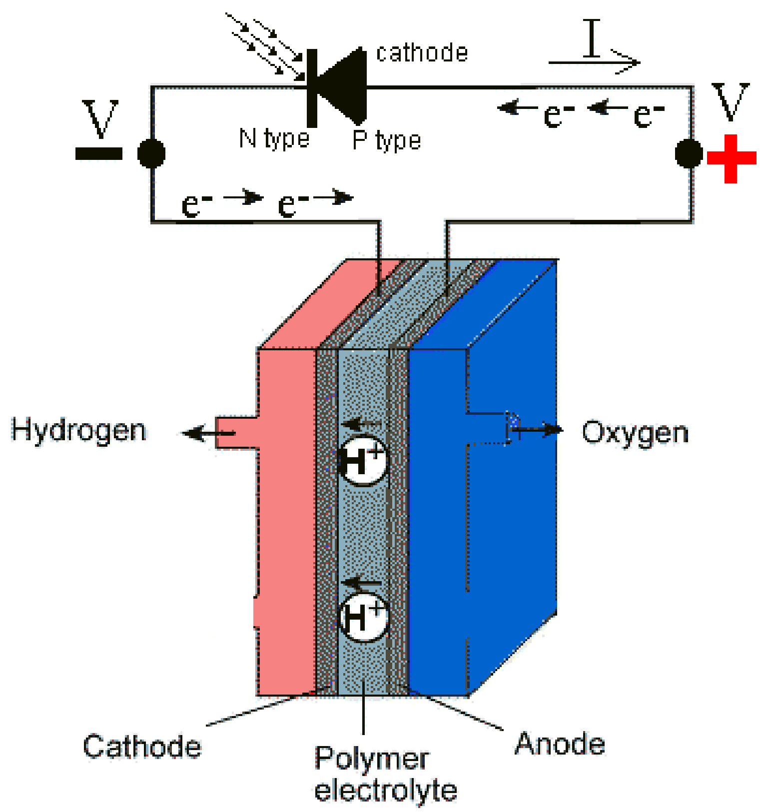
An electrolyzer is a device that allows us to break water into hydrogen and oxygen using electricity. Its solid electrolyte in the membrane between the electrodes makes it work like the simple electrolysis process that used a dissolved-salt electrolyte.

11. *Is hydrogen a good name for the gas collected over the cathode?*

As hydrogen means *water former* it is a good name for this gas which produces water when burned with oxygen.

Electrolysis

Negative Pole	Positive Pole
Hydrogen evolution	Oxygen evolution
Reduction	Oxidation
Cathode	Anode



The current produced by the P-N junction of a solar cell is in the opposite direction to the forward-bias current of an ordinary diode. Therefore the “P” side of the solar cell is its cathode. (The “N” side of an ordinary diode is its cathode.)

Investigation 5:
Hydrogen Power!

We now have almost all the components for actually powering a car. In the electrolyzer we have a source of hydrogen, and a way of storing it in the gas cylinder. We also have a source of oxygen, although we could simply use air, as it contains 20% oxygen. Now we need a way to change the hydrogen and oxygen back into electricity that will power an electric motor to move the car.

In the *Fuel Cell Model Car kit* you have the device to do this. In Investigation 4 we used the main component in this kit—the reversible fuel cell—as an electrolyzer. But if you supply hydrogen on one side of the fuel cell and oxygen on the other, the fuel cell produces an electric current. The hydrogen unites with the oxygen to produce water again, which is the raw material we started with. You could diagram this as follows:

Electricity + Water → Hydrogen + Oxygen

Hydrogen + Oxygen → Water + Electricity

This could be a wonderful solution to the air pollution problem as hydrogen fuel cell power would add only water vapor or liquid water to our atmosphere while using pure water and electricity as the source of the hydrogen needed to power the fuel cell.

Astronauts living in space stations already use this technology. With solar cells, electrolyzers, fuel cells, and an initial supply of water, the astronauts have a source of electricity and oxygen as well as an abundant supply of hydrogen. As the hydrogen is used as fuel to produce electricity, it also produces water.

With the *Fuel Cell Model Car* we can use stored hydrogen to produce electricity to power the motor. Because the electric motor spins very quickly it has a gearbox to reduce the speed of the motor shaft and carry power the rear wheels of the car. In this investigation we don't put the car on the floor. Instead we support the car so its wheels can turn without touching anything. This makes it easier to collect some data.

When describing electrical events, the power (in watts) going into or out of a device can be determined by multiplying the current (in amperes) passing through the device by the voltage (in volts) that exists across that device. Power describes the strength of a process. We can write:

I * V = P (amperes * volts = watts)

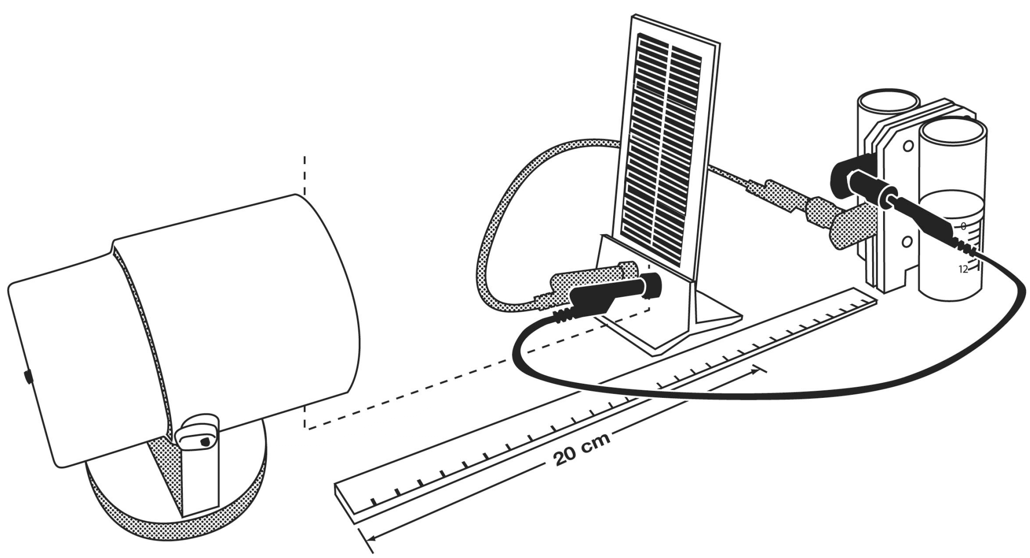
Can we use stored hydrogen to produce electricity?

You will need:

- goggles or eye protection
- solar panel from the *Fuel Cell Model Car Kit*
- three patch cords
- reversible fuel cell and car base from the *Fuel Cell Model Car Kit*
- load box from the *Fuel Cell Model Car Kit*
- distilled water
- 75 watt PAR30 incandescent lamp, or equivalent light source.
- block of wood or other support for the car
- watch with second hand or stopwatch function

Procedure

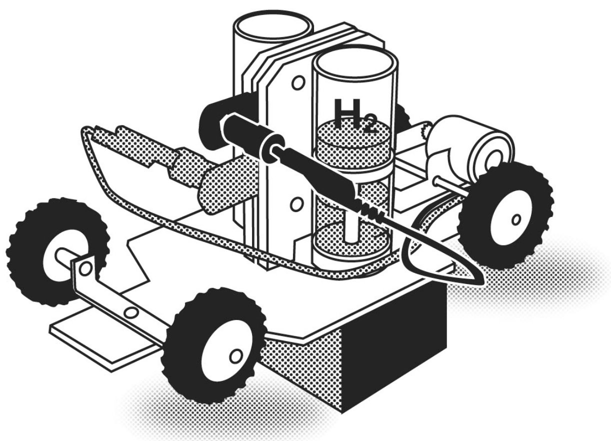
1. Put on your goggles. Remember that they will only protect you if you wear them properly.
2. The bottom of the fuel cell storage cylinders should be completely filled with distilled water, with no air space or other gas in the cylinders. If you need to add distilled water to the fuel cell, refer to *Filling the electrolyzer* in the section *Using the Fuel Cell Model Car Kit* at the start of this handbook.



3. With the patch cords, connect the solar module to the reversible fuel cell, which we are using here as an electrolyzer. Red goes to red and black goes to black.

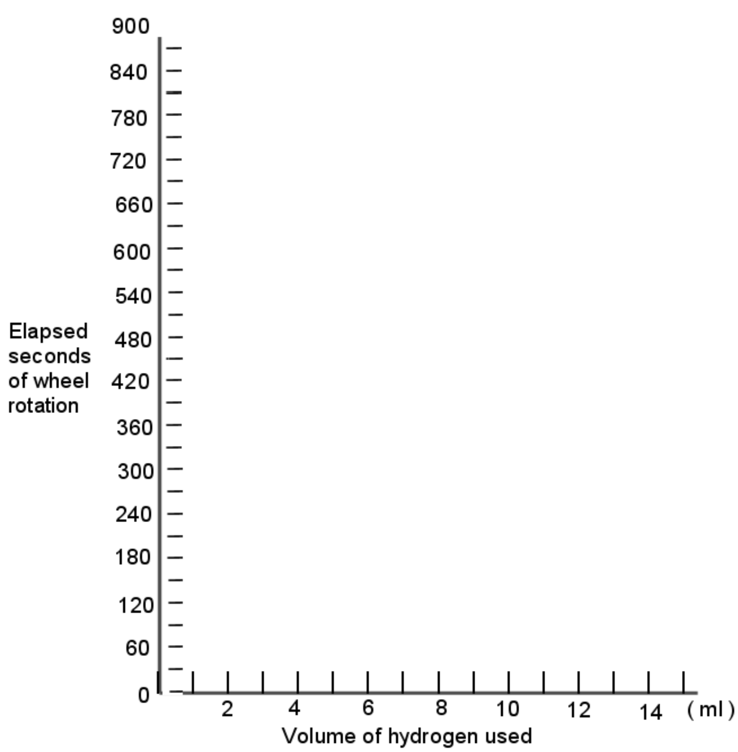
Position the solar panel so it directly faces the light source at the distance your teacher recommends and turn on the light.

4. When the hydrogen storage cylinder is filled to a little more than 12ml carefully remove the solar panel from the system by disconnecting the patch cords from the reversible fuel cell.
5. On the top side of the car base directly in front of the gears, you will notice a felt-covered upright piece of plastic. Also notice that the bottom of the fuel cell has a slot between the two cylinders. Turn the fuel cell so that the red and black contacts are towards the front of the car. Carefully slide the fuel cell over the black felt and push down gently until the fuel cell is fully seated on the car base. You may need to hold the connecting cables out of the way as you do this. Place the block of wood under the car base, so that the wheels on your car are free to turn. Connect the car motor to the fuel cell as shown.



6. Watch the level of gas in the hydrogen storage cylinder, and when the gas level reaches exactly 12ml, start a stopwatch (or record the time to the nearest second). Again record the time on the stop watch (or the current time) when the gas level has been reduced to 11ml and again at 10ml, and so on. Use the table to continue recording the time at each ml until the hydrogen is gone. Record any extra time the wheels turn after the cylinder seems to have no more hydrogen. If you were not using a stopwatch, you will need to do some arithmetic to fill in the “elapsed seconds” column.
7. Set up the light source again, and repeat the steps 3 to 6 as many times as your teacher suggests. Always begin your timing when the gas level is at exactly 12ml. On the axes supplied, plot a graph of your results showing time of wheel rotation against the volume of hydrogen used.
8. Disassemble the equipment, put it away and then take off your goggles and return them carefully.

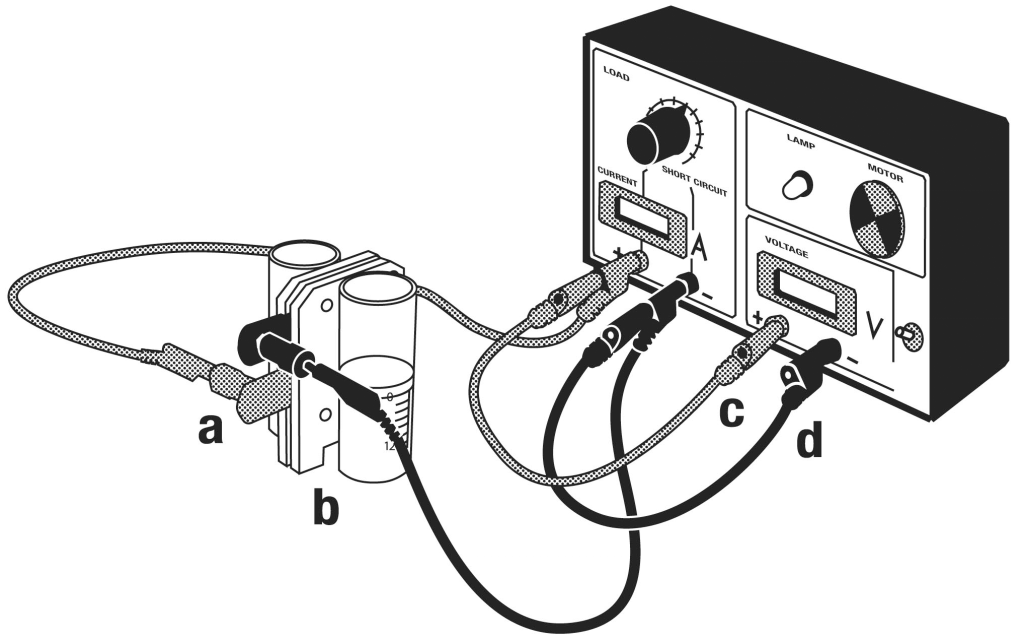
	Trial 1		Trial 2		Trial 3			
	time	elapsed seconds since 12 ml level	time	elapsed seconds since 12 ml level	time	elapsed seconds since 12 ml level	Elapsed seconds of wheel rotation (average of trials)	volume of hydrogen used
Time when 12 ml H_2 left								0 ml
Time when 11 ml H_2 left								1 ml
Time when 10 ml H_2 left								2 ml
Time when 9 ml H_2 left								3 ml
Time when 8 ml H_2 left								4 ml
Time when 7 ml H_2 left								5 ml
Time when 6 ml H_2 left								6 ml
Time when 5 ml H_2 left								7 ml
Time when 4 ml H_2 left								8 ml
Time when 3 ml H_2 left								9 ml
Time when 2 ml H_2 left								10 ml
Time when 1 ml H_2 left								11 ml
Time when no H_2 left								12 ml
Time when wheels stop								

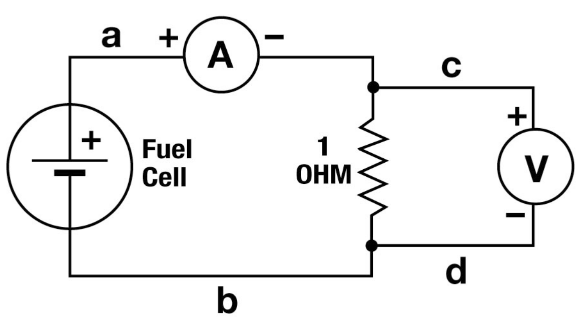


Duration of rotation per given volume of hydrogen

E1. **Extension:** In this investigation you have seen that with the stored hydrogen it is possible to produce electricity in the fuel cell to power the car wheels. If you have time left you can also try the following extension activity to find out how much power the small fuel cell can deliver.

E2. Repeat steps 3 and 4 to load the storage cylinders with gas. Turn the load box ON. Set LOAD to OPEN and connect the patch cords as shown. Then set LOAD to 10Ω.





This schematic diagram is another way of describing the circuit you have made. Notice how the ammeter (A) on the load box measures the current flowing through the load, at the same time the voltmeter (V) measures the voltage across the fuel cell output connectors.

E3. Briefly observe the current, and the voltage and write them in the following table. Also calculate the power output of the fuel cell. Change the load setting to 5Ω, 3Ω and then to 1Ω and again observe and record the current and voltage and calculate the power. Then disconnect the load box from the fuel cell and turn it OFF.

E4. Disassemble the equipment, put it away and then take off your goggles and return them carefully.

Load	Current	Voltage	Power
10 Ω	_____ Amperes	_________Volts	________Watts
5 Ω	_____ Amperes	_________Volts	________Watts
3 Ω	_____ Amperes	_________Volts	________Watts
1 Ω	______Amperes	_________Volts	________Watts

Questions

1. Why is it important to have the hydrogen gas cylinder filled with exactly 12ml each time we start to measure the length of time the wheels turn for each ml of gas?

____

____

2. What happens to the level of gas in the hydrogen storage cylinder as the wheels turn? Why does this occur?

____

____

3. Could you power the electric motor with electricity produced by the solar panel? What is the advantage of powering a car with hydrogen fuel rather than a solar panel connected directly to the electric motor?

____

____

4. What did you notice as you compared the time the wheels turned as you repeated the experiment?

____

____

5. What is the advantage of having hydrogen combine with oxygen in this way rather than having it burn and explode as it did in Investigation 4?

____

____

6. Predict how long the wheels would rotate for 24ml of hydrogen gas. Refer to your graph and extrapolate an answer.

____

____

7. Why do you think the motor continued to turn after the volume of hydrogen reached 0ml in the storage cylinder?

____

____

8. What is the answer to the question at the start of the investigation: *Can we use stored hydrogen to produce electricity? Explain*

____

____

9. (Extension activity) When you decreased the resistance from 10 Ω to 1Ω, what happened to the current? What happened to the voltage? What is the maximum power output from the fuel cell you have determined?

____

____

10. (Extension activity) The dependence of current and voltage you have determined is typical for batteries too. Can we say the fuel cell is a battery? Please discuss this.

____

____

Teaching supplement for Investigation 5: *Hydrogen Power!*

The expected learning outcome of this investigation is to have students experience that hydrogen fuel can produce an electrical current when used in a fuel cell. The objectives may be written:

- Students will record that electrical energy is produced when hydrogen is used to power a fuel cell.
- Students will note that repeating an experiment will produce similar results.
- Students will use this data to produce a graph that will allow them to predict the duration of rotation for a given volume of hydrogen gas.
- Students will demonstrate correct safety procedures for this investigation.

Teacher Notes

When we used the reversible fuel cell as an electrolyzer, we observed the polarity: negative (black)=hydrogen=cathode, and positive (red)=oxygen=anode. Now that we are using the reversible fuel cell as a fuel cell, it is convenient that the polarity is almost the same. The hydrogen side (black) produces a negative voltage; the oxygen side (red) produces a positive voltage. However in keeping with the definition of anode/cathode (electrons are lost at the anode), the hydrogen side is now called the *anode* and the oxygen side is called the *cathode*.

This investigation requires that the electrolyzers are hydrated and able to produce bubbles of hydrogen quite soon after the class begins. To ensure that the hydrogen is pure and not mixed with air, the electrolyzer cylinders must be filled with distilled water before gas is produced and accumulated. To save class time, you could generate some hydrogen before the class, and leave it in the storage cylinder. If several groups are doing this investigation in a succession of classes, there is no need to empty the electrolyzer each time.

Teachers should specify the minimum distance from the solar panel to the light source to avoid damaging the solar panel through overheating by the light source.

Try out the system beforehand to see how many times students may repeat this experiment within your block of time. Generally, the more data the more accurate the results will be.

Remind your students to measure the volumes carefully to ensure reproducible results.

If you wish to demonstrate powering the car by the solar panel alone you should be aware that the amount of power needed to turn the wheels is considerably more the power needed to run the electrolyzer. To make the wheels turn, the light source must be placed very close to the solar panel. Take care if you demonstrate this, as you will overheat and damage the solar panel if you keep it this close to the light for any length of time.

Answers to the student questions

1. *Why is it important to have the hydrogen gas cylinder filled with exactly 12ml each time we start to measure the length of time the wheels turn for each ml of gas?*

   If we want to compare the duration of the wheels turning for each ml of hydrogen gas used it is important to begin our timing exactly at the 12ml mark each time

2. *What happens to the level of gas in the hydrogen storage cylinder as the wheels turn? Why does this occur?*

   The volume of gas in the hydrogen storage cylinder decreases because as the wheels turn they use electricity to power the electric motor and this electricity comes from the hydrogen gas combining with the oxygen gas to form water and produce electricity.

3. *Could you power the electric motor with electricity produced by the solar panel? What is the advantage of powering a car with hydrogen fuel rather than a solar panel connected directly to the electric motor?*

Yes, I think you could power the electric motor with electricity produced by the solar panel. Powering a car with hydrogen fuel rather than a solar panel would mean that you could drive the car in the dark when there is not enough light to allow a solar panel to work.

4. *What did you notice as you compared the time the wheels turned as you repeated the experiment?*

As we repeated the experiment the duration of the wheels turning for each 4ml of hydrogen gas used became more regular. At first there was a shorter duration.

5 *What is the advantage of having hydrogen combine with oxygen in this way rather than having it burn and explode as it did in Investigation 4?*

The advantage of having the hydrogen combine with oxygen in this way rather than having it burn and explode is that it produces a much more controlled energy flow in the form of electricity. This electricity can be turned on and off so you can use it a little at a time. With an explosion a lot of the energy is released in the form of heat and cannot be used to power the car.

6. *Predict how long the wheels would rotate for 24ml of hydrogen gas. Refer to your graph and extrapolate an answer.*

Answers may vary depending upon the individual car and the graph results.

7. *Why do you think the motor continued to turn after the volume of hydrogen reached 0ml in the storage cylinder?*

I think the wheels keep on turning after the volume of gas in the hydrogen gas storage cylinder reaches 0ml because of the extra hydrogen gas that is in the cell itself and surrounds the membrane.

8. *What is the answer to the question at the start of the investigation:* Can we use stored hydrogen to produce electricity? *Explain*

Yes, we can use stored hydrogen to produce electricity. We have seen the fuel cell use hydrogen while making electrical energy.

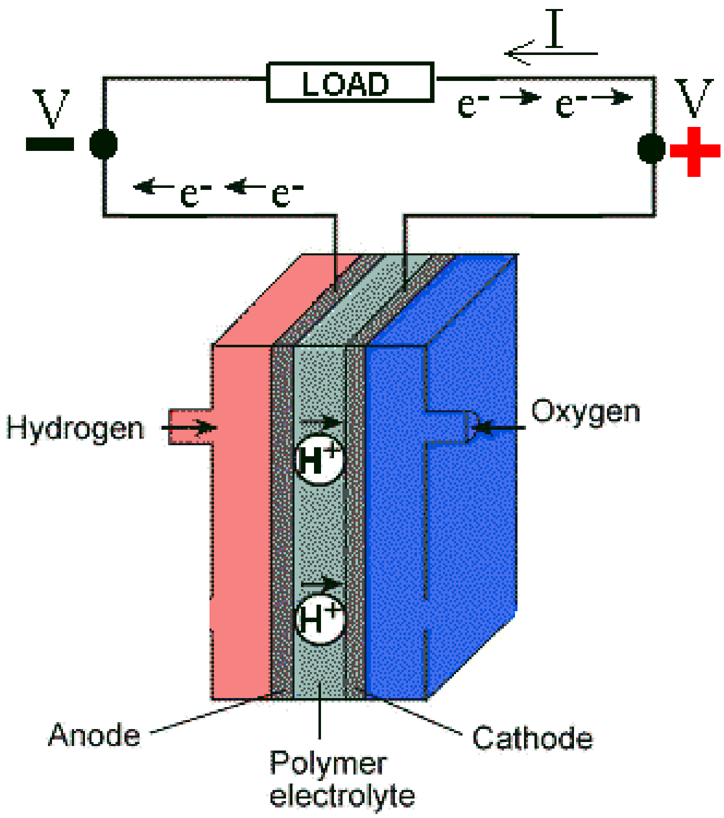
9. *(Extension activity) When you decreased the resistance from 10 Ω to 1Ω, what happened to the current? What happened to the voltage? What is the maximum power output from the fuel cell you have determined?*

When I decreased the resistance, the current increased but the voltage decreases with increasing current. The maximum power I have measured was for the 1 Ω resistor and is ______ watts.

10. *(Extension activity) The dependence of current and voltage you have determined is typical for batteries too. Can we say the fuel cell is a battery? Please discuss this.*

Batteries show a similar behaviour. They have a no-load voltage which is for example 1.2 volts for a NiCd battery and the voltage decreases with increasing current. Yes we can say that a fuel cell is a battery because it makes electricity out of a chemical reaction which is separated in two half-cells having a minus pole anode and a plus pole cathode.

Fuel Cell

Negative Pole Hydrogen consumed Oxidation Anode		Positive Pole Oxygen consumed Reduction Cathode

Investigation 6:
Hydrogen Power in Motion

In Investigation 5 you saw Hydrogen powering the car's wheels as they turned free in air. In this investigation you will see if there is a difference between how long the wheels will turn when suspended in air and when the car is actually running on a surface. What do you think will happen? Will the wheels turn for a longer time, shorter time, or much the same?

You may already have some idea of what you will see in this investigation. You may have ideas about what would cause any change in the time the wheels turn, but think some more and come up with some reasons to support your thinking. This thinking about an investigation is called a hypothesis by scientists and is usually a written description of what you expect to happen and why. By writing down a hypothesis and then asking the appropriate questions in experiments, scientists get answers, adding to the information they already have. They might then revise the previous information, or form a new hypothesis and ask more questions.

It is important to run the car on a flat, smooth and clean surface such as your classroom, hall or gymnasium floor. You will usually need to turn the front wheels of the car so the radius of the circle traveled is small. If you have the opportunity to run the car on a swept gymnasium floor, you may be able to send it in a straight line from one corner of the room to the other.

Remember that your model car is actually running on Hydrogen Power that comes from a fuel cell using hydrogen produced by electrolysis of water. This is a completely pollution-free energy source. With an appropriate number of fuel cells connected to produce more power, experimental hydrogen powered cars and buses are now on the road, producing only water vapor in their exhaust.

When you have written your hypothesis, put on your goggles and let's find out what happens!

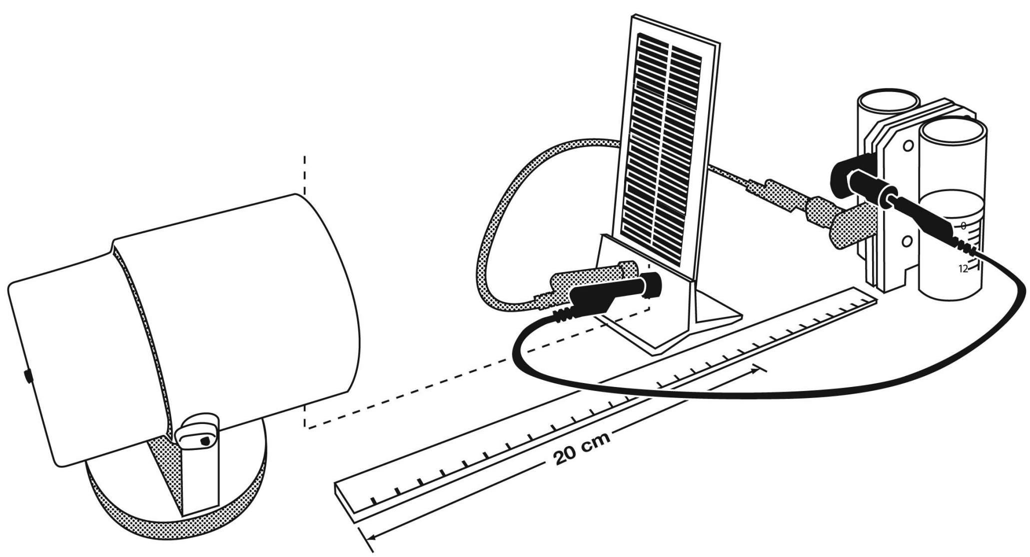
Will the wheels turn for the same period of time when used to power the car on a flat surface?

You will need:

- goggles or eye protection
- solar panel from the *Fuel Cell Model Car Kit*
- two patch cords
- reversible fuel cell and car base from the *Fuel Cell Model Car Kit*
- distilled water
- 75 watt PAR30 incandescent lamp, or equivalent light source.
- block of wood or other support for the car
- watch with second hand or stopwatch function

Procedure

1. Put on your goggles. Remember that they will only protect you if you wear them properly.
2. The bottom of the fuel cell storage cylinders should be completely filled with distilled water, with no air space or other gas in the cylinders. If you need to add distilled water to the fuel cell, refer to *Filling the electrolyzer* in the section *Using the Fuel Cell Model Car Kit* at the start of this handbook.



3. With the patch cords, connect the solar module to the reversible fuel cell, which we are using here as an electrolyzer. Red goes to red and black goes to black.

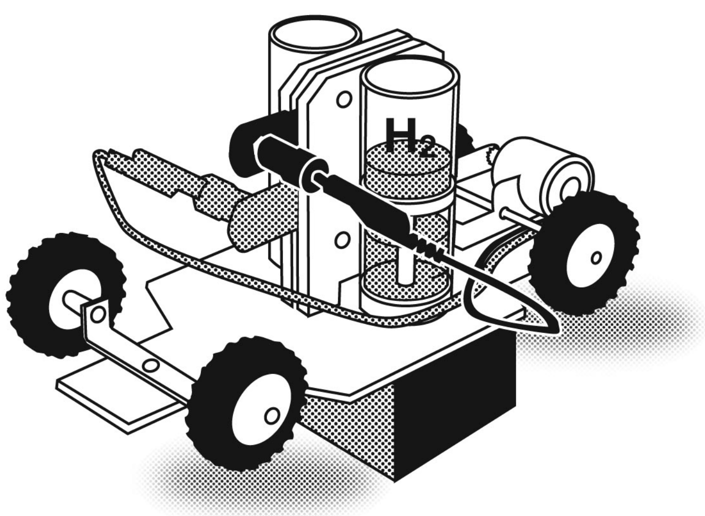
Position the solar panel so it directly faces the light source at the distance your teacher recommends and turn on the light.

4. When the hydrogen storage cylinder is filled to around 6 ml carefully remove the solar panel from the system by disconnecting the patch cords from the reversible fuel cell.

5. On the top side of the car base directly in front of the gears, you will notice a felt-covered upright piece of plastic. Also notice that the bottom of the fuel cell has a slot between the two cylinders. Turn the fuel cell so that the red and black contacts are towards the front of the car. Carefully slide the fuel cell over the black felt and push down gently until the fuel cell is fully seated on the car base. You may need to hold the connecting cables out of the way as you do this.

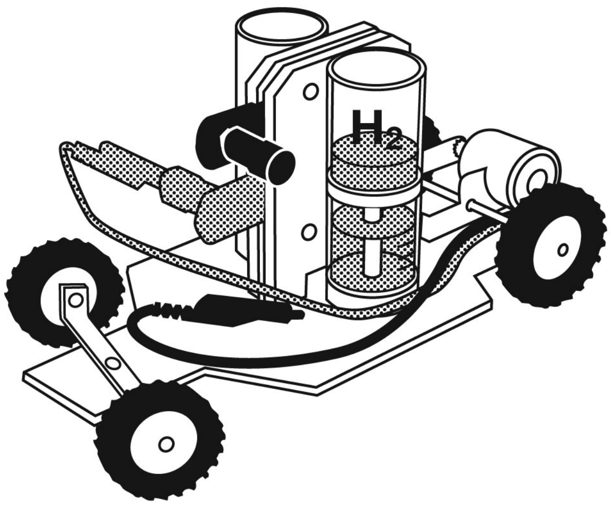
6a. **If you are running the car in a circle**

- Position the car on the floor and turn the front wheels so that the car will run in a fairly small circle without hitting anything. (Don't turn the wheels so much they catch on the frame of the car.)
- Connect the black and red wires from the motor to the fuel cell and let the car run in a circle. If necessary, adjust the front wheels and the car position until you are satisfied with the circle the car is making.
- Use chalk or a piece of tape to mark a point on the circle and another point exactly opposite. Mark where the centre of the car travels, not the outside or inside wheels. Measure this distance and make note of it as the diameter of your driving circle. You will need this measurement to calculate how far your car travels for each ml of hydrogen.
- Place the car on the block of wood so that the wheels are free to turn, and let the motor continue to run until the level of hydrogen is exactly 4ml. At this point disconnect the black wire so the motor stops (If already below 4ml reconnect the solar panel to produce more hydrogen)



6b. **If you are running the car in a straight line**

- place the block of wood under the car base, so that the wheels on your car are free to turn. Connect the black and red wires from the motor to the fuel cell and let the motor run until the level of hydrogen in the hydrogen storage cylinder is exactly 4ml. At this point disconnect the black wire so the motor stops.



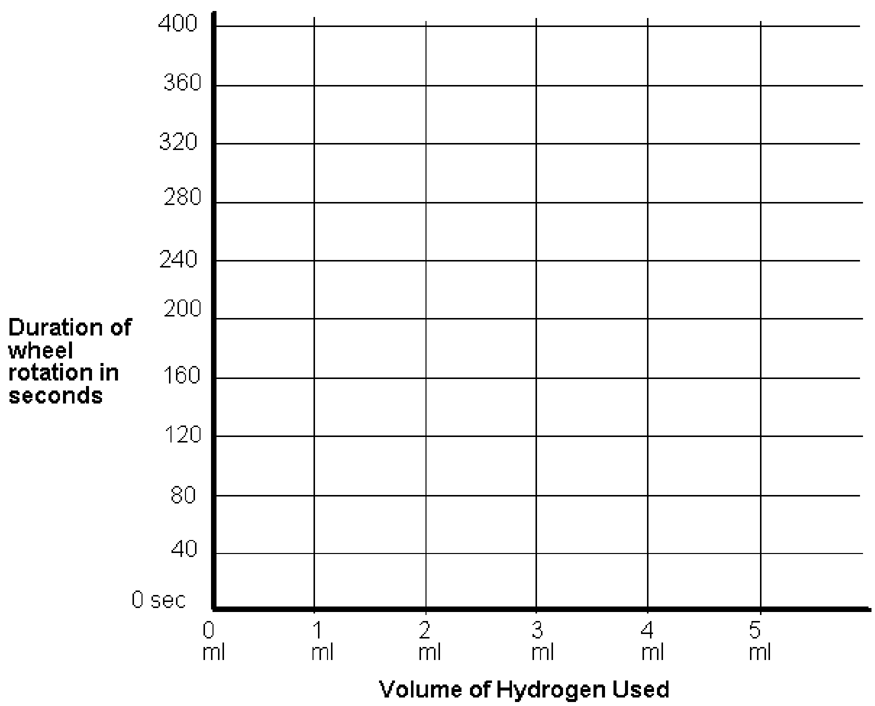
7. Be ready with a stopwatch or some means to record the time to the nearest second. Position the car on the floor and connect the black cable. If your car does not move immediately give it a slight push to overcome the starting friction in the gears. Start the stopwatch or note the time.
8. As the car travels, count the number of circles it makes, or keep track of the straight-line distance travelled, If the car runs into a wall quickly turn it around sending it back and repeat until the car finally stops. When the car finally stops, note the time on the stop watch (or the current time) and write it in the table. If you were not using a stopwatch, you will need to do some arithmetic to fill in the "elapsed seconds" column. Write the number of circles or the straight-line distance the car travelled.

Check the level of hydrogen gas in the storage cylinder; there should be no hydrogen gas left in the storage cylinder. If there is, see your teacher for further instructions.

	Trial 1		Trial 2		Trial 3		
	time	elapsed seconds	time	elapsed seconds	time	elapsed seconds	Elapsed seconds of car travel (average of trials)
Starting time							
Time when car stops, 4 ml H_2 used							

9. If there is enough time, repeat the procedure as many times as your teacher suggests, noting the duration your car was able to run for each filling.

10. Put your “elapsed seconds” data on the following graph, at the “4 ml” point. If you have data from Investigation 5—time of wheel rotation when the car was not moving—then add this data to your graph, and notice any difference.



Duration of Rotation per given volume of Hydrogen

11. If your teacher wants you to disassemble the equipment, do so, put it away, then take off your goggles and return them carefully.

Questions

1. Why must we start the car with the hydrogen at a known level?

2. What is a hypothesis and why do we write one before an investigation?

3. What did you find when you compared the times of rotation between this investigation and investigation 5?

4. If you found a difference, what do you think caused this?

5. Can you think of any other examples of this from your personal experience?

6. How do you think this would affect cars in the future if they drove on flat or hilly roads? Is this effect similar to what happens to the cars we drive now?

7. Using your data on the distance your car travelled, how far did your car travel on 4ml of hydrogen? How much hydrogen would you need to have your car travel exactly one kilometer? Show all your calculations. Circumference = $\pi \bullet$ diameter of circle

Teaching supplement for Investigation 6: *Hydrogen Power in Motion*

The major objective of this investigation is to have the students realize that putting a car in motion on the road will involve a greater load on the electric motor due to increased friction as the work done in having the entire car move is greater. The learning objectives may be written:

- Students will record that hydrogen is used up at a faster rate when the electrical motor does more work.
- Students will note that repeating an experiment will produce similar results.
- Students will use this data to produce a graph that will allow them to compare the duration of rotation for a given volume of hydrogen gas when the electric motor is doing more work.
- Students will demonstrate correct safety procedures for this investigation.
- Students will answer questions designed to elicit understandings and allow teachers to assess the efficacy of the investigation.

Teacher Notes

As in Investigation 5, this investigation requires that the electrolyzer is hydrated and able to produce bubbles of hydrogen fairly soon after the lesson begins. If several classes are to do this investigation in succession the electrolyzer should not be emptied between sessions and may be left filled overnight for use on the subsequent day.

Try out the system beforehand to see if there is enough time to have your students repeat this experiment to get more data. Two repetitions may take about forty minutes.

It is important that the floor surface be as smooth as possible. The car will not run on carpeting. Having a broom or dry mop available to sweep the area before the car begins its travel will help. Because of the car's turning radius, you will need an area at least 2.5m wide.

If it appears that the motor is not strong enough to drive the car, make sure that you filled the electrolyzer properly (see *Filling the electrolyzer* in the section *Using the Fuel Cell Model Car Kit* at the start of this handbook), and that you have made enough (5-6 ml) of hydrogen. In addition, it may be necessary to lubricate the gears in the car's drive mechanism.

Remind your students to measure the volumes very carefully to ensure reproducible results. Students must get at eye level with the electrolyzer to read the graduations on the hydrogen storage cylinder accurately when the car is placed on the support block and the motor connected to get the hydrogen storage cylinder level to exactly 4ml.

If the car stops before you think it should, refer to *Fuel cell stops working before it runs out of hydrogen?* in the section *Using the Fuel Cell Model Car Kit* at the start of this handbook.

Answers to the student questions

1. *Why must we start the car with the hydrogen at a known level?*

> We must start the car with the hydrogen at a known level if we are to compare our results with the results we obtained in Investigation 5.

2. *What is a hypothesis and why do we write one before an investigation?*

A hypothesis is a statement made to try to explain something before we actually test it. We write one before we do an investigation because it helps us to think about what we might find and whether the investigation is asking the question we want to answer.

3. *What did you find when you compared the times of rotation between this investigation and investigation 5?*

We found out that when the car was placed on a flat surface it did not run nearly as long as it did when the car was placed on a support with the wheels turning in the air.

4. *If you found a difference, what do you think caused this?*

We did find a change and we think it was caused because the electric motor had not only to turn the wheels but it had to get the wheels to drive the car over the ground. This would need more work from the motor and it would use up the hydrogen faster.

5. *Can you think of any other examples of this from your personal experience?*

There may be many answers here. Assess them all for reasonableness. For example; When I ride my bicycle on flat ground it is a lot easier than when I go up a hill. When I turn it upside down and just run the wheels in the air I can turn the pedals really easily with my hand and the wheel can go around really fast.

6. *How do you think this would affect cars in the future if they drove on flat or hilly roads? Is this effect similar to what happens to the cars we drive now?*

I think that cars used on hilly roads would use up the hydrogen faster than cars running on flat surfaces. I think cars on hilly roads use up the gasoline faster than cars running on flat roads. The principle is the same - more work requires more fuel.

7. *Using your data on the distance your car travelled, how far did your car travel on 4ml of hydrogen? How much hydrogen would you need to have your car travel exactly one kilometer? Show all your calculations.*

Answers will vary depending upon the experimental results. The students will need to know how to determine the circumference of a circle given the diameter.

($C = \pi D$ where C = circumference, D = diameter, $\pi = 3.14$)

Investigation 7:
Energy Efficiency

We have seen that electricity can make hydrogen, and in turn hydrogen can be converted back to electricity. This offers a way to "store" electricity. But not all the electricity used to make the hydrogen may be recovered when the hydrogen is consumed in the fuel cell. Just how much is recovered and how much is lost is the subject of this investigation.

In non-scientific writing, the two words Power and Energy are often used interchangeably. In fact, they describe quite different concepts.

When describing electrical events, the power (in watts) going into or out of a device can be determined by multiplying the current (in amperes) passing through the device by the voltage (in volts) that exists across that device. We can write:

$$I * V = P \qquad \text{(amperes * volts = watts)}$$

Many examples will be familiar: a 1000-watt heater, a 200 watt amplifier, a 15 watt fluorescent lamp.

Power describes the strength of a process; it says nothing about the amount of work done. Energy (or work) is a measure of power that continues over a certain time. A familiar example will be the use of kilowatt-hours in your household's electric utility bill. The energy used by various devices is not determined by their power only. A 15-watt fluorescent left on over a weekend will have consumed more energy than a 1000-watt heater used for a half-hour.

A common measure of energy is the joule*, the equivalent of a watt-second (one watt of power produced or consumed for one second). The amount of energy being used or supplied by a device can be determined by multiplying the power (in watts) by the time (in seconds) that power is used. We can write:

$$P * t = E \qquad \text{(watts * seconds = joules)}$$

As a measurement, the joule is used for more than electrical power. For example, the exact composition of the gas that gas utilities deliver to their customers varies from month to month. Therefore gas utility companies often calculate customer bills according to the "joules" or heating value of the gas consumed. The utility charges for the amount of energy that was in the gas you consumed that month. Whether or not you actually obtained that much energy (heat) from it depends on your heating system and how you used the gas.

**named after James Prescot Joule, an English scientist born in 1818.*

Continuing with the heating gas example, If all the energy in the gas is recovered, we would say the furnace is 100% efficient. In reality, this does not happen. The types of furnaces being installed in houses typically have efficiency between 80% and 96%. That is, between 20% and 4% of the energy in the gas is wasted. In some older furnaces or furnaces that are poorly maintained the efficiency can drop below 50%.

In this investigation, when we make a known amount of hydrogen we can measure the voltage and current that was applied to the electrolyzer and the duration of time it was applied. From this we can calculate the energy used to make that hydrogen.

Then in a fuel cell we can use that same amount of hydrogen to send current through a simulated electrical load, again noting the energy that was applied to the load.

You might guess that not all the energy used to make the hydrogen will be recovered. Indeed, the question is important: what proportion is recovered?

We can calculate the fraction:

$$\frac{\textbf{electrical energy produced from hydrogen in the fuel cell}}{\textbf{electrical energy consumed to make hydrogen in the electrolyzer}}$$

We can then write this fraction as a percentage. This is the overall efficiency of the electrolyzer-fuel cell system.

Overall efficiency calculates the ratio **energy out / energy in.** You could also investigate the efficiency of each stage of this process to see where the most energy is lost. It is helpful to know the amount of chemical energy that hydrogen gas contains. This is commonly called the *energy density*, or *heating value*. That is, the theoretically maximum amount of energy that could be obtained from a given amount of hydrogen in a perfect converter. The concept is similar to the gas utility billing its customers for the amount of heat that might be obtained in a perfect furnace.

The electrical efficiency of the electrolyzer, (energy out) / (energy in), can be written as:

$$\frac{\text{energy content of the hydrogen}}{\text{electrical energy consumed in electrolyzer}}$$

The electrical efficiency of the fuel cell, energy out / energy in, can be written as:

$$\frac{\text{electrical energy produced in fuel cell}}{\text{energy content of the hydrogen}}$$

You obtain the overall efficiency of the two stages by simply multiplying the two efficiencies above. The two “energy content of the hydrogen” values cancel out, leaving as before:

$$\frac{\text{electrical energy produced in fuel cell}}{\text{electrical energy consumed in electrolyzer}}$$

The questions at the end of this investigation will explore this further.

In the preceding discussion we noted that the fuel cell does not convert all the hydrogen’s energy to electricity. **So what becomes of the remaining energy?** As you might expect, a significant part is lost as heat. But what if we could put that heat to some practical use?

The customary way to produce electricity today is by first burning fuel to produce heat in a combustion engine or turbine, and then driving a generator to produce electricity.

However a fuel cell uses hydrogen fuel to produce electrical energy through a direct process. We saw how its electrical efficiency, typically between 40% and 60%, could be measured. If the secondary heat in a fuel cell can be utilized, we can include it in a “total efficiency” calculation:

Total efficiency = Electrical efficiency + Thermal efficiency

$$= \frac{\text{electrical energy produced in fuel cell + heat produced in fuel cell}}{\text{energy content of the hydrogen}}$$

Electrical generating systems that use the waste heat, whether they are fuel cells or conventional steam- or gas-turbines, are called Combined Heat and Power (CHP) systems. Most electrical generators convert only a third of the fuel's energy into electricity. Where heat is needed as well as electricity, a CHP system is 30 to 35 percent more efficient than separate heat and power systems, converting as much as 85 percent of the fuel into usable energy. CHP systems save energy, pollute less and are very reliable.

Fuel cell CHP systems can provide space heat, hot water, steam, process heating and cooling, depending on what kind of heat is generated and needed. Some fuel cell systems produce low temperature heat, and only warm air or water can be recovered. Other systems produce high temperature heat, so steam can be generated. High temperature heat is needed to produce a cooling effect, using absorption chillers and other specialized equipment.

Fuel cell CHP systems can reach overall efficiencies of 85% with about 45% electrical and 40% thermal efficiency.

Where did the energy go?

You will need:

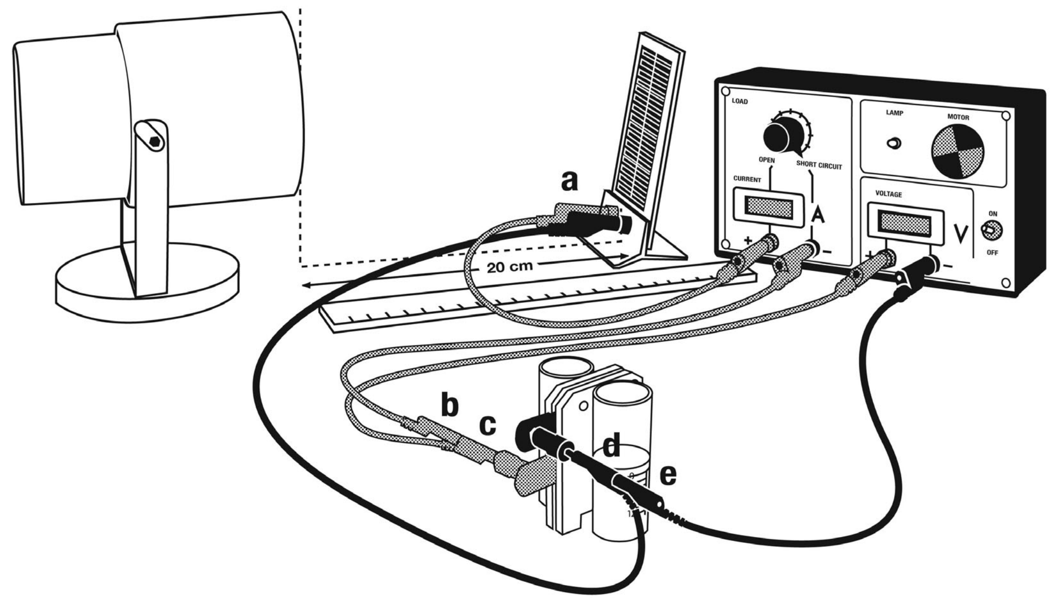
- goggles or eye protection
- solar panel from the *Fuel Cell Model Car Kit*
- reversible fuel cell from the *Fuel Cell Model Car Kit*
- load box from the *Fuel Cell Model Car Kit*
- five patch cords
- distilled water
- 75 watt PAR30 incandescent lamp, or equivalent light source.
- watch with second hand or stopwatch function

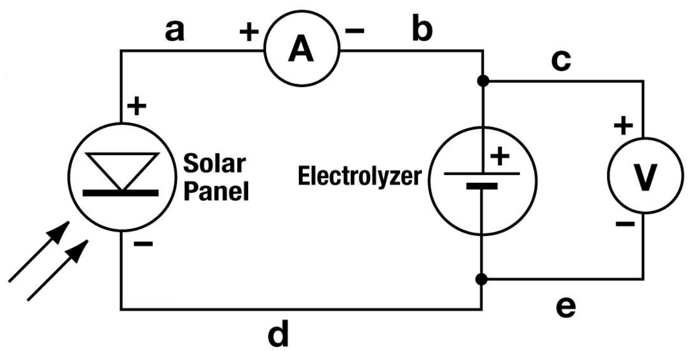
Procedure

1. Put on your goggles. Remember that they will only protect you if you wear them properly.
2. The bottom of the fuel cell storage cylinders should be completely filled with distilled water, with no air space or other gas in the cylinders. If you need to add distilled water to the fuel cell, refer to *Filling the electrolyzer* in the section *Using the Fuel Cell Model Car Kit* at the start of this handbook.

PART 1: Determination of the energy used in production of hydrogen

3. In this step we will use the reversible fuel cell as an electrolyzer. With the patch cords connect the solar module, the load box, and the electrolyzer as shown below. Set the load to SHORT CIRCUIT and turn the load box ON. Position the solar panel so it directly faces the light source at the distance your teacher recommends, and turn on the light.





This schematic diagram is another way of describing the circuit you have made. Notice how the ammeter (A) on the load box measures the current flowing into the electrolyzer, at the same time the voltmeter (V) measures the voltage across the electrolyzer input connectors.

Look at the current displayed in the ammeter window. Notice that it has a leading decimal point. For example the number **.105A** represents a little more than a tenth of an ampere, or 105 milliamperes.

4. Let the electrolyzer run, collecting hydrogen and oxygen. When the level of gas in the hydrogen storage cylinder reaches exactly 4 ml, start a stopwatch (or record the time to the nearest second).

   Time when hydrogen level at 4 ml: ________________________________

5. Observe the current, and the voltage and write them here. Make sure that the position of the lamp does not change for the next few minutes, so that the current remains the same. Multiply the current and voltage to obtain the power (in watts) going into the electrolyzer.

Current	•	Voltage	=	Power
_________ Amperes	•	__________Volts	=	____________Watts

6. When the hydrogen gas level has increased to 10ml, record again the time on the stop watch (or the current time).

   Time when hydrogen level at 10 ml: ______________________________

7. Calculate the difference in times and write it here.

   Elapsed Time to make 6 ml hydrogen: ____________________ seconds ___

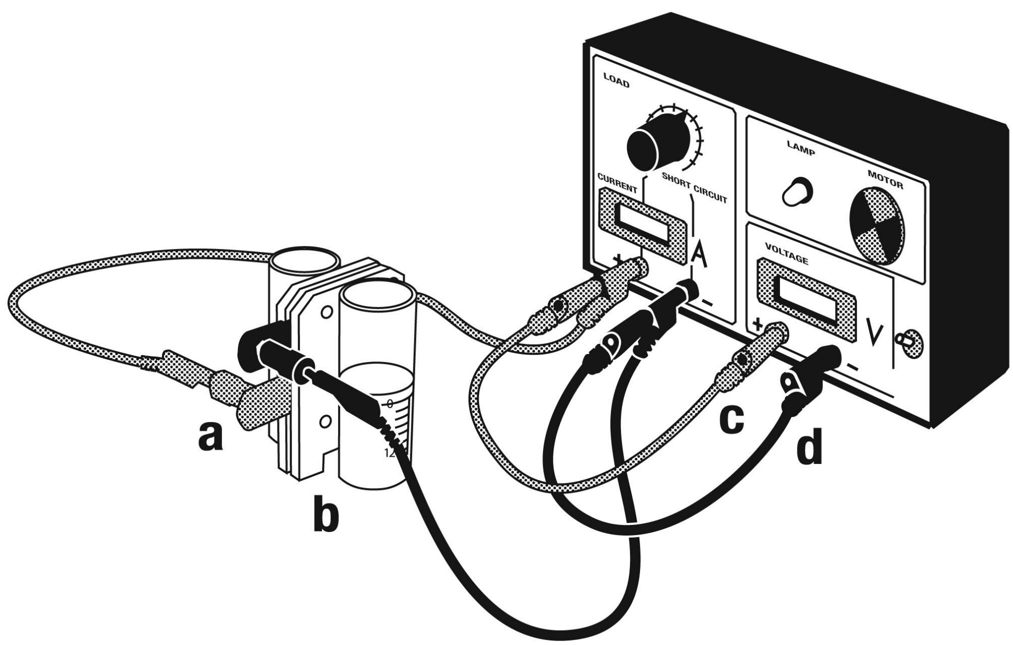
8. Taking care not to disturb the electrolyzer, turn off the light and the load box, and disconnect all the patch cords.

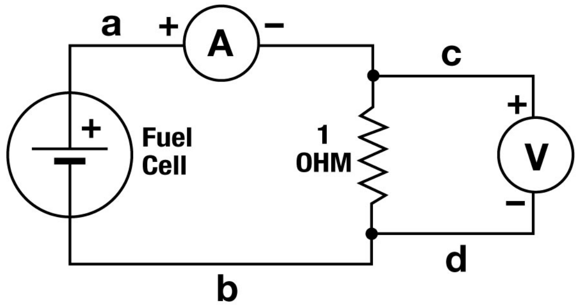
9. Multiply the Power and Elapsed Time to obtain the Energy used to make 6 ml hydrogen.

Power	•	Time	=	Energy
___________ Watts	•	___________sec	=	_______Watt-sec

PART 2: Determination of the energy produced while consuming hydrogen as a fuel

10. Now we will use the reversible fuel cell as a fuel cell. Turn the load box ON and set LOAD to OPEN. With the patch cords connect the load box and the fuel cell as shown below. Then set the load to 1Ω.





This schematic diagram is another way of describing the circuit you have made. Notice how the ammeter (A) on the load box measures the current flowing through the one-ohm load, at the same time the voltmeter (V) measures the voltage across the fuel cell output connectors.

11. Let the fuel cell run, using hydrogen and oxygen. When the level of gas in the hydrogen storage cylinder reaches exactly 8 ml, start a stopwatch (or record the time to the nearest second).

    Time when hydrogen level at 8 ml: ______________________________

12. Observe the current, and the voltage and write them here. They should be steady. Multiply the current and voltage to obtain the power (in watts) the fuel cell is generating.

    Current • Voltage = Power

    _________ Amperes • __________Volts = ____________Watts

13. When the hydrogen gas level has decreased to 2ml, record again the time on the stop watch (or the current time).

    Time when hydrogen level at 2 ml: ___________________________

14. Calculate the difference in times and write it here.

    Elapsed Time to consume 6 ml hydrogen: _______________ seconds

15. Multiply the Power and Elapsed Time to obtain the Energy produced while consuming 6 ml hydrogen.

    Power • Time = Energy

    ___________ Watts • ___________sec = _______Watt-sec

16. Use the information in the introduction to calculate the overall efficiency:

    Overall efficiency of the electrolyzer-fuel cell system: _____________ %

17. Disassemble the equipment, put it away and then take off your goggles and return them carefully.

Questions

1. In this investigation we used a resistor as a simulated load. Why did we use this and not the car motor?

2. When making hydrogen, we measured the current through the electrolyzer, but isn't some of that current flowing through the voltmeter too? Should we consider this current?

3. Our calculations of energy-in and energy-out were described in terms of making and using hydrogen. What about the oxygen? Does it matter?

4. Do you suppose the fuel cell might be more or less efficient if we run it at a different current? Increasing the resistance of the simulated load will result in a lower current, and therefore the fuel cell will take longer to consume the same amount of hydrogen. But will the total energy obtained from the hydrogen be about the same? If you have time, repeat the investigation using a load of 3 ohms. In order to get through the steps quickly, you might make and use a smaller volume of hydrogen, less than 6 ml.

5. What is the answer to the question at the start of the investigation: *Where did the energy go?*

6. Are the individual efficiencies of the electrolyzer and the fuel cell about the same? A table of physical constants will tell us that the *energy density* of hydrogen is 33.3 kW-hr/kg. Can you determine the efficiency of each stage of the electrolyzer – fuel cell process?

   Here's a start. Knowing that the density of hydrogen gas at room temperature is 12 m^3/kg, we can use unit-cancellation to convert "kW-hr/kg" to a more convenient term for our investigation:

$$\frac{33.3\text{ kW-hr}}{\text{kg}} \quad \frac{1\text{kg}}{12\text{ m}^3} \quad \frac{1000\text{ W}}{\text{kW}} \quad \frac{\text{m}^3}{(100\text{cm})^3} \quad \frac{1\text{ cm}^3}{\text{ml}} \quad \frac{3600\text{ sec}}{\text{hr}} = 10\ \frac{\text{watt-sec}}{\text{ml}}$$

   Now you can use the information in the box at the start of this investigation, with the energy calculations you already made in the procedure steps.

7. One way to calculate the amount of "lost" power in a fuel cell is to consider the Theoretical Cell Voltage of a Hydrogen-Oxygen cell. This value, 1.23 volts, represents the ideal voltage of a perfect (but unrealizable) fuel cell. The difference between this ideal voltage and the actual working voltage, which you measured in step 12, gives us a way to calculate the lost power. Recall that current * voltage = power. Using the Theoretical Cell Voltage, and the voltage and current measurements from step 12, calculate the power loss inside the fuel cell. What happens to this power?

   With practical technology, some but not all the lost power can be recovered as heat. Perhaps 70% can be recovered and used. In your fuel cell, this is a small amount of power, and it may be hard to get a sense of its magnitude. Again using your observations from step 12, calculate the ratio of "recoverable heat" to electrical power produced.

   In a larger fuel cell power unit, say 50KW (typical for a fuel cell car) how much secondary heat could be utilized? Assume this power unit has the same efficiency characteristics as the fuel cell in your investigation.

Teaching supplement for Investigation 7: *Energy Efficiency*

The expected learning outcome of this investigation is to have students understand that total energy is conserved; analyze decreases and increases in energy during transfers and transformations in terms of total energy conservation.

The objectives may be written:

- Students will compare the difference between energy into the electrolyzer with energy out of the fuel cell to determine the overall efficiency of the system.
- Students will learn that the efficiency of a process is the product of the respective single efficiencies.
- Students will use the terms energy, power, current and voltage to calculate efficiencies.

Teacher Notes

With the students, examine the markings used on the gas collection cylinders so that all students can read them correctly. Some students will not be familiar with scales that have “missing” numbers.

Teachers should specify the minimum distance from the solar panel to the light source to avoid damaging the solar panel through overheating by the light source.

This investigation requires that the electrolyzer is hydrated and able to produce bubbles of hydrogen fairly soon after the lesson begins. If several classes are to do this investigation in succession the electrolyzer should not be emptied between sessions and may be left filled overnight for use on the subsequent day.

Answers to the student questions

1. *In this investigation we used a resistor as a simulated load. Why did we use this and not the car motor?*

   Using a resistor in the load box as a simulated load gives us more flexibility to choose different resistances and currents.

2. *When making hydrogen, we measured the current through the electrolyzer, but isn't some of that current flowing through the voltmeter too? Should we consider this current?*

   The current we measured while making hydrogen was the sum of current flowing through the electrolyzer and current through the voltmeter. But the voltmeter has such a high resistance that the current flow is so small it can be ignored.

3. *Our calculations of energy-in and energy-out were described in terms of making and using hydrogen. What about the oxygen? Does it matter?*

   Both hydrogen and oxygen are produced and both are used. Because we compared the total energy input and total energy output, any contribution from the oxygen was included in the final comparison.

4. *Do you suppose the fuel cell might be more or less efficient if we run it at a different current? Increasing the resistance of the simulated load will result in a lower current, and therefore the fuel cell will take longer to consume the same amount of hydrogen. But will the total energy obtained from the hydrogen be about the same? If you have time, repeat the investigation using a load of 3 ohms. In order to get through the steps quickly, you might make and use a smaller volume of hydrogen, less than 6 ml.*

   The volume of hydrogen produced and consumed will not change the efficiency, although a smaller volume increases the effect of experimental errors from reading the gas levels.

   Operating at a lower current, the efficiency of the fuel cell will be higher.

5. *What is the answer to the question at the start of the investigation:* Where did the energy go?

   More electricity was used to make hydrogen than was recovered with the fuel cell. Probably some of that missing energy was lost as heat.

6. *Are the individual efficiencies of the electrolyzer and the fuel cell about the same? A table of physical constants will tell us that the* energy density *of hydrogen is 33.3 kW-hr/kg. Can you determine the efficiency of each stage of the electrolyzer – fuel cell process?*
   Here's a start. Knowing that the density of hydrogen gas at room temperature is 12 m^3/kg, we can convert "kW-hr/kg" to a more convenient term for our investigation:

$$\frac{33.3\ \text{kW-hr}}{\text{kg}}\ \frac{1\text{kg}}{12\ m^3}\ \frac{1000\ W}{kW}\ \frac{m^3}{(100cm)^3}\ \frac{1\ cm^3}{ml}\ \frac{3600\ sec}{hr} = 10\ \text{watt-sec/ml}$$

   Now you can use the information in the box at the start of this investigation, with the energy calculations you already made in the procedure steps.

   The power to produce 6 ml hydrogen was already measured. Electrolyzer efficiency is therefore:

$$\frac{\text{energy content of the hydrogen}}{\text{energy consumed in electrolyzer}}$$

$$6\ \text{ml}\ \ \frac{10\ \text{watt-sec}}{\text{ml}}\ \ \frac{1}{\text{(energy in step 9) watt-sec}}\ \ \underline{100\ \%}$$

   Fuel cell efficiency is:

$$\frac{\text{energy produced in fuel cell}}{\text{energy content of the hydrogen}}$$

$$\underline{\text{(energy in step 15) watt-sec}}\ \ \frac{1}{6\ \text{ml}}\ \ \frac{\text{ml}}{10.0\ \text{watt-sec}}\ \ \underline{100\ \%}$$

7. *One way to calculate the amount of "lost" power in a fuel cell is to consider the Theoretical Cell Voltage of a Hydrogen-Oxygen cell. This value, 1.23 volts, represents the ideal voltage of a perfect (but unrealizable) fuel cell. The difference between this ideal voltage and the actual working voltage, which you measured in step 12, gives us a way to calculate the lost power. Recall that current * voltage = power. Using the Theoretical Cell Voltage, and the voltage and current measurements from step 12, calculate the power loss inside the fuel cell. What happens to this power?*

From my observed values of 0.40A and 0.53 V

current * voltage loss = power loss

0.40 A * (1.23 – 0.53) V = 0.28 W = power loss inside the fuel cell

This power loss is related to energy in the fuel cell that I cannot use to produce electricity. Some of the lost power appears as heat.

With practical technology, some but not all the lost power can be recovered as heat. Perhaps 70% can be recovered and used. In your fuel cell, this is a small amount of power, and it may be hard to get a sense of its magnitude. Again using your observations from step 12, calculate the ratio of "recoverable heat" to electrical power produced.

We can't recover 0.28 W, but we might recover 70% of that, 0.19 W

Electrical power that the fuel cell is generating:

current * voltage = power

0.40 A * 0.53 V = 0.21 W

ratio of "recoverable heat" to electrical power produced. = 0.19 W / 0.21 W = 0.90

In a larger fuel cell power unit, say 50KW (typical for a fuel cell car) how much secondary heat could be utilized? Assume this power unit has the same efficiency characteristics as the fuel cell in your investigation.

At the calculated ratio, a 50 KW fuel cell automobile power unit might at peak output provide an additional 50 KW * 0.90 = 45 KW in heat.

Investigation 8:
Extending our Knowledge

Finally we have come to a point where we can look at hydrogen fuel cell technology and automobile development now and in the future. In this investigation you will look back at your questions from the beginning, your notes and investigation reports, and use your findings with Internet research. This will enable you to develop some understanding of what to expect as hydrogen fuel cell technology and practical applications come together and are made available for the general market. Imagine an unmanned plane that can fly for years or an isolated beacon that needs almost no maintenance.

In this investigation you will be acting as a research scientist and you will design a supplemental inquiry that could be ongoing. It may be possible to do your inquiry in the classroom with the knowledge and equipment you already have. Or you may find that your inquiry needs some specialized equipment that you, your fellow students and your teacher could try to obtain. Perhaps your inquiry will be into the unknown where very specialized equipment may be needed or developed. Your question may turn out to be one that researchers are presently wrestling with or may have to wrestle with in the future.

In short, you are invited to develop a question about hydrogen fuel cells that could be investigated scientifically. Science and technology often go hand in hand and are definitely influenced by human activity. If there is a perceived need for an unmanned airplane that can fly indefinitely and be directed from the surface of the earth then the need for that technology may drive scientists to find some answers. These answers might involve lightweight storage of hydrogen, very efficient electrolyzers, light electric motors or high efficiency lifting surfaces—perhaps even hydrogen filled!

You should begin by developing a question about fuel cells that can be scientifically investigated and then list several possibilities for inquiries that would help to answer your question or that may allow you to get closer to answering your question. From those possibilities you will need to decide which one has the highest interest level for you and your group. When that has been determined you are ready to develop a method of investigation and possibly obtain results. The statement of Louis Pasteur, a famous French research scientist, "Fortune favors the prepared mind' has been a touchstone for countless discoveries by alert observers.

The most important piece to develop is the question. Just as with computers, garbage-in yields garbage-out. If you ask 'nature' a good question you may get a good answer but if you ask a poor question you will most likely not get a useful answer. Your teacher and the nature of your inquiry will decide the way you present your results. Good luck with your research!

Internet Research hints

If you do not search effectively Internet research often yields material that is not particularly valuable for your purpose. Using accurate search terms can narrow down the number of sources you find and emphasize useful sources. Some appropriate search terms may be:

"Fuel cell"	Hydrogen	"Electric motor"	Range
Power	Transmission	Storage	Safety
Technology	Speed	Acceleration	Weight
Power	Capacity	Emission	Waste
Pollution	Solar	Generation	Urban
Environment	Vehicle	Passenger	Repair
Disadvantages	Advantages	Expense	Efficiency
Co-generation	CHP	"Heat Recovery"	Renewable

You can combine these terms to get to the particular sources that may be helpful. If you were searching for typical speeds reached by vehicles powered by hydrogen technology you would use the most important words first, for example: Hydrogen Vehicles Speed in that order as your search words. Your search would yield a selection of websites that mentioned all of these words and after looking at five or six sites you would have an idea of the speeds current hydrogen powered vehicles could travel at. You would be surprised!

You may also find information that could help other research teams who are working on different questions. This information could be shared and add to the collective information base of your laboratory. Such teamwork is common in industry where everyone stands to benefit greatly if answers can be found quickly. Research should not be a competition but a team effort. We need to find solutions to many problems or we may find humanity in difficulties we cannot overcome.

Teaching supplement for Investigation 8: *Extending our Knowledge*

The major objective of this investigation is to allow students to review and summarize their learning about hydrogen fuel cells from these investigations and pose a question that they can investigate scientifically. The learning objectives for this investigation may be written:

- Students will develop a question that could be investigated scientifically.
- Students will refine their question and design an investigation that will allow them to get closer to the answer of their question.
- Students will present the results of their research to their classmates.

Teacher Notes

This investigation is designed to summarize and extend the learning from this unit in a manner that will realize the synergy between fixed laboratory investigations and freeform scientific thinking about what has been learned. The students will brainstorm, reflect, develop, research and refine their questions until they come up with one inquiry that they are most interested in. How this is brought about is your personal preference as the teacher. It could be another activity that has not been done in this unit, a research project that could be part of a science fair, or even something that the students recognize could not be completed within the scope of their experience and current skills. You will have to decide whether students will work in groups or allow individual projects. Flexibility in grouping is recommended and will maximize learning opportunities for all students.

The summation of this activity will be group presentations of the answers to the students' questions. These answers will provide a strong summation of the entire unit of hydrogen fuel cells as well as some departure points for further study and analysis as the students continue to follow the progress of hydrogen technology, as it unfolds in the next few years.

Other bonus presentations could be undertaken, in the form of a final report, a PowerPoint presentation, the beginning of a science fair board, a journal or newspaper article, a role play, phone call or television documentary or some other method that you would like them to undertake. The scientific piece of the presentation is paramount but the delivery method should allow variation to ensure exciting learning opportunities for all. As a comprehensive experience for this unit it could provide the beginnings of a lifelong interest in the hydrogen technology that is certain to affect us all in the coming years.

Glossary

ammeter	A device that measures current flowing in a circuit.
ampere (amp)	The unit of electric current, having the symbol A.
angle of incidence	That number of degrees by which a line deviates from the perpendicular to a designated plane.
anode	The electrode where the oxidation reaction takes place; that is, a reaction where there is a loss of electrons.
catalyst	Any substance that reduces the activation energy of a reaction but does not take part in the net reaction and so remains unchanged.
cathode	The electrode where the reduction reaction takes place; that is, a reaction where there is a gain of electrons.
circuit, electrical	Any closed path followed or capable of being followed by an electrical current.
circumference	The distance around a path or object. The circumference of a circle is determined by multiplying the diameter (or twice the radius) of the circle by π.
compound, chemical	A substance composed of two or more different types of atoms.
current, electrical	A flow of electrons usually measured in amperes and designated by the symbol I.
distilled water	Water which has been made into vapor and then condensed back into pure water so that any dissolved or suspended substances are left behind.
efficiency	A measure of the energy-effectiveness of a system with unity or 1 being a perfect result. Efficiencies are usually expressed as percentages where the output is divided by the input.
electrical generator	A device that produces a flow of electrons.
electrolysis	Chemical change, especially decomposition, produced in an electrolyte by an electric current.
electrolyte	A substance that when dissolved breaks into ions, allowing the resulting solution to conduct electricity.

electrolyzer	A device that uses a flow of electrons to break a compound into its constituent elements. The electrolyzer in this kit breaks water into hydrogen gas and oxygen gas.
electron	A subatomic negatively charged particle.
energy, electrical	The energy (in joules) generated or used by a device can be calculated as the product of its power (in watts) and the time over which that power occurs (in seconds). Often designated by the symbol E.
formula (chemical)	A symbolic expression that describes the number and kind of atoms within one molecule of a substance or ionic compound.
hypothesis	A possible explanation, subject to verification or proof, used as a basis for investigation or further investigation.
input	The amount of whatever is being measured entering a system.
joule	The unit of electric energy, having the symbol J. One joule is equivalent to one watt-second. (The joule is also used as the unit of work and of heat.)
milliampere	One thousandth of an ampere, having the symbol mA.
observation	The use of any and all senses to notice something. Observations could include smells, heat changes, light emissions, movements or sounds.
output	The amount of whatever is being measured leaving a system.
PAR lamp	Parabolic Aluminized Reflector lamp.
patch cord	An electrical conductor made of a flexible insulated cable with plugs or clamps at each end designed to temporarily connect components.
photon	A quantum of electromagnetic energy usually associated with light. Photons exhibit qualities of both waves and particles.
power, electrical	The power (in watts) generated or used by a device can be calculated by multiplying its current (in amperes) times the voltage across its terminals (in volts). Often designated by the symbol P.
prediction	The act of making known in advance what is liable to occur.
questioning	An inquiry that invites or calls for a reply or response.

reaction (chemical)	A chemical change or transformation in which a substance decomposes, combines with other substances or interchanges constituents with other substances.
short circuit	A situation in which a circuit is complete but has little or no resistance or load.
solar cell	A device that changes light into an electric current. Solar cells are usually mounted together to produce a solar panel.
volt	The unit of electric potential difference, having the symbol V.
voltage	A measure of the electrical potential between two points, usually measured in volts and designated by the symbol V.
voltmeter	A device that measures voltage difference between two points in a circuit.
watt	The unit of electric power, having the symbol W.