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 (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 (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

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

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:

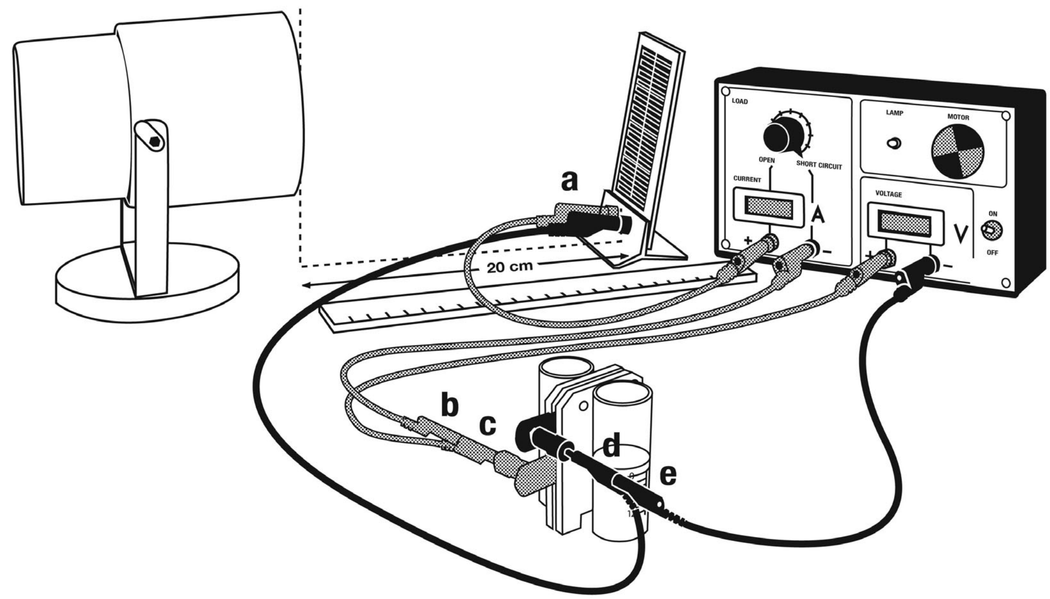
- goggles or eye protection
- solar panel from the *Fuel Cell Model Car Kit*
- reversible fuel cell from the *Fuel Cell Model Car Kit*
- load box from the *Fuel Cell Model Car Kit*
- five patch cords
- distilled water
- 75 watt PAR30 incandescent lamp, or equivalent light source.
- watch with second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

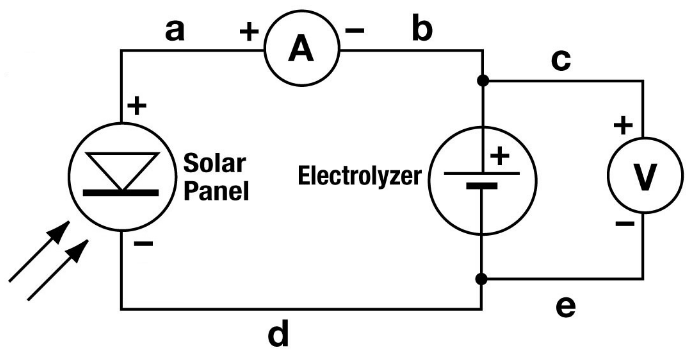
Procedure

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 ____

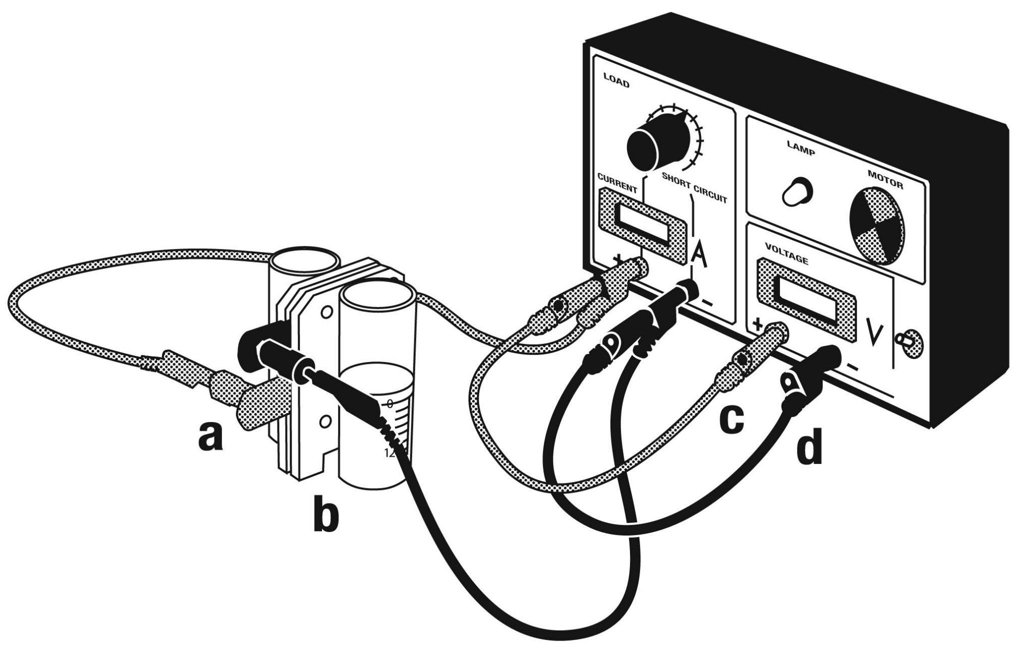
8. Taking care not to disturb the electrolyzer, turn off the light and the load box, and disconnect all the patch cords.

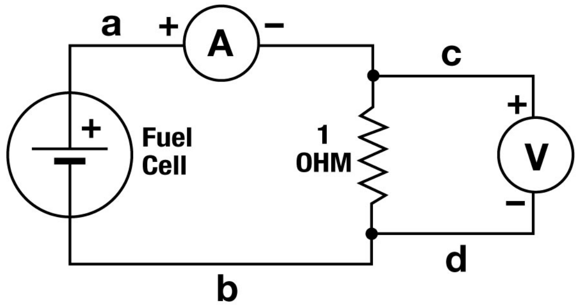
9. Multiply the Power and Elapsed Time to obtain the Energy used to make 6 ml hydrogen.

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:

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

   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:

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

   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:

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

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

   Fuel cell efficiency is:

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

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

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.