11.7

Electricity from a Fuel Cell

A damp sheet of paper is sandwiched between two pieces of wire gauze. This sandwich is mounted between two transparent plastic squares having two tubes connected to each. A tank of hydrogen gas is connected to a tube on one of the plastic squares and a tank of oxygen is connected to the other square. When the terminals of an electric motor are connected to the two pieces of wire gauze, the motor runs.†

MATERIALS

ca. 50 mL 3M hydrochloric acid, HCl (To prepare 1 liter of solution, slowly pour 250 mL of concentrated [12M] HCl into 600 mL of distilled water and dilute the resulting, cooled solution to 1.0 liter.)

ca. 500 mL distilled water

0.5 g hydrogen hexachloroplatinate(IV) hydrate (chloroplatinic acid), $H_2PtCl_6 \cdot xH_2O$

or

30 mL concentrated (12M) hydrochloric acid, HCl

10 mL concentrated (16M) nitric acid, HNO_3

0.2 g platinum metal (e.g., wire)

50 mL distilled water

100-mL beaker

30-mL porcelain evaporating dish

watch glass to cover evaporating dish

hot plate

cylinder of hydrogen gas, with pressure regulator

cylinder of oxygen gas, with pressure regulator

ca. 50 mL 1M sodium hydroxide, NaOH (To prepare 1 liter of stock solution, dissolve 40 g of NaOH in 600 mL of distilled water, and dilute the resulting, cooled solution to 1.0 liter.)

2 sheets of ¼-inch acrylic, 12 cm square

drill, with ⅜-inch and ¼-inch bits

4 5-cm lengths of acrylic tubing, with outside diameter of ⅜ inch

acrylic cement

† We wish to thank Ronald R. Esman of Abilene High School, Abilene, Texas, for providing us with a description of this demonstration, which he developed.

sheet of rubber, 8 cm × 16 cm × ca. 2 mm thick (e.g., piece of inner tube)
2 pieces of nickel screen, 8 cm × 12 cm, 50–100 mesh
scissors or tin snips to cut nickel screen
2 10-cm petri dishes
2 gas washing bottles
4 0.5-m lengths of plastic or rubber tubing, with outside diameter of ⅜ inch
index card, 4 inches × 6 inches
tape or glue
dc motor that operates on 1 volt, with clip leads (Suitable motors are available from hobby shops and electronic parts stores.)
stand, with clamp for motor
2 pieces of 8-cm round filter paper
4 ³⁄₁₆-inch × 1-inch bolts, with wing nuts
dropper
stand, with clamp for fuel cell
voltmeter, with clip leads

PROCEDURE

Preparation

Drill matching holes through the two 12-cm-square sheets of ¼-inch acrylic: Align the squares on top of each other and drill two ⅜-inch holes about 3 cm apart near the centers of both sheets (Figure 1). Drill four ¼-inch holes through both sheets, one hole near each corner.

Using acrylic cement, glue one end of the four 5-cm pieces of ⅜-inch acrylic tubing to each of the center holes in the squares (Figure 2). These form the entry and exit ports for the fuel gases.

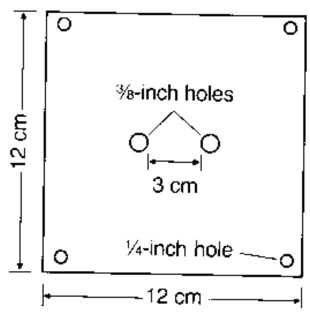

Figure 1. Location of holes in acrylic square.

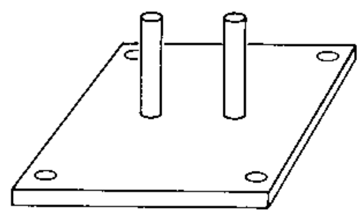
Figure 2. Gas ports attached to acrylic square.

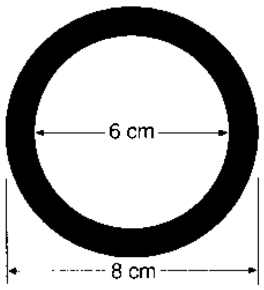

Figure 3. Gasket cut from rubber sheet.

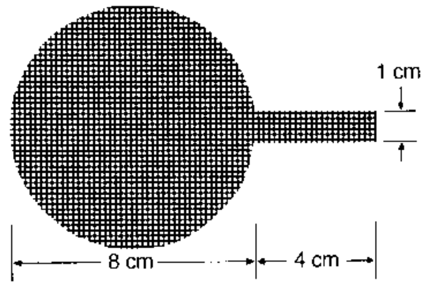

Figure 4. Electrode cut from nickel screen.

From the rubber sheet cut two disks 8 cm in diameter. Cut a 6-cm disk from the center of each of these, leaving a circular ring (Figure 3). These will be used as gaskets.

From the nickel screen, cut two circular electrodes with a diameter of 8 cm and having a 4-cm × 1-cm tab at the circumference (Figure 4). These electrodes must be cleaned and platinized (coated with a spongy black form of metallic platinum) before use. Clean the electrodes by soaking them in 3M HCl for several minutes and then rinsing them with distilled water. The electrodes are platinized by soaking them in a solution containing hexachloroplatinate(IV) ions. This solution is prepared by dissolving 0.5 g hydrogen hexachloroplatinate(IV) hydrate in 50 mL of distilled water. If $H_2PtCl_6 \cdot xH_2O$ is unavailable, the solution may be prepared from platinum metal as described in the following paragraph.

In a fume hood, prepare the hexachloroplatinate(IV) solution from platinum metal as follows. Combine 30 mL of concentrated (12M) HCl and 10 mL of concentrated (16M) HNO_3 in a 100-mL beaker. Place 0.2 g of platinum metal in the evaporating dish, and pour enough acid mixture from the beaker into the disk to cover the wire. Cover the dish with the watch glass, and set the evaporating dish on the hot plate. Set the hot plate to a low setting to warm the dish. Continue to warm the dish until all the platinum has dissolved. (This can take several hours.) It may be necessary to add more acid mixture as it evaporates. Once the platinum has dissolved, uncover the dish and continue heating it until all the liquid has evaporated. Cool the dish. Dissolve the orange residue in the cooled dish in 50 mL of distilled water.

Place each of the screen electrodes in a petri dish and pour enough of the hexachloroplatinate(IV) solution into each dish to cover the circular portion of the electrodes. Soak the electrodes for several hours. While the electrodes are soaking, nickel in the electrode will reduce platinum from the solution, forming a spongy black coating of platinum on the screen. Swirl the dishes and turn the electrodes periodically while soaking them to promote formation of a uniform coating of platinum black. Rinse the coated electrodes gently with distilled water and store them immersed in distilled water. They may be stored indefinitely in this condition. The hexachloroplatinate(IV) solution can be stored in a sealed container for future use.

Fill each of the gas washing bottles half full with water and close them. Use a piece of the 0.5-m plastic or rubber tubing to attach the outlet of the hydrogen cylinder to the inlet (the opening connected to the central tube) of one of the gas washing bottles. Attach another piece of tubing to the outlet of the bottle. In a similar fashion, attach the oxygen cylinder to the other gas washing bottle.

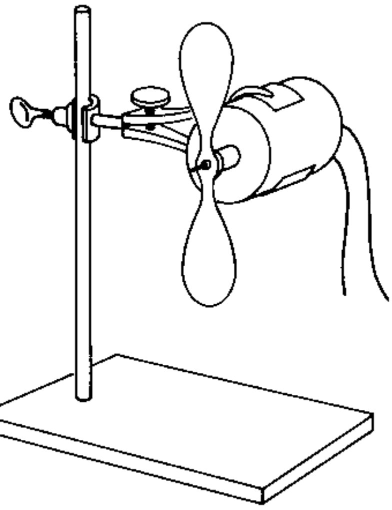

Figure 5. Direct-current motor mounted on stand.

Cut a propeller about 15 cm in diameter from the index card, insert the motor shaft through its center, and secure it in place with tape or glue. Clamp the motor to the stand so the propeller can turn freely when the motor's shaft rotates (Figure 5).

Presentation

Assemble the fuel cell. (Figure 6 shows the assembled cell, Figure 7 shows it in cross section.) Holding one of the acrylic squares with its tubes pointing down, center a rubber gasket ring on the square. Align one of the platinized electrodes atop the gasket. Be sure the tab protrudes beyond the edge of the acrylic square. Align both pieces of filter paper on the electrode. Cover the filter paper with the remaining electrode. Situate the tab on the second electrode so it, too, protrudes beyond the edge of the acrylic square, and so it does not touch the first electrode. Place the remaining gasket on top of the second electrode. Set the remaining acrylic square on top of the gasket and align the holes in the top square with those in the bottom square. Insert the four 1-inch bolts through the four corner holes in the acrylic squares. Attach the wing nuts to the bolts and tighten them to hold the assembly together. Be sure the two electrodes do not touch each other or the bolts holding the cell together.

Thoroughly moisten the filter paper with 1M NaOH solution by dropping it through the fuel ports. Clamp the cell assembly vertically to the stand. Attach the tube from the hydrogen gas washing bottle to the upper fuel port on one side of the cell. Attach the tube from the oxygen gas washing bottle to the lower gas port on the opposite side of the cell.

The cell is now ready to operate. Attach one of the wire leads from the voltmeter to each of the electrodes and note the voltage reading. Open the needle valve on the hydrogen regulator to produce a slow bubbling in the washing bottle. Note the change in the potential of the cell as detected by the voltmeter. Now, slowly open the valve on the oxygen regulator to produce a gentle bubbling in its washing bottle. Again, note the effect on the potential of the cell. A few minutes are required for the potential to become stable. After the potential has stabilized, turn off the hydrogen flow and note what

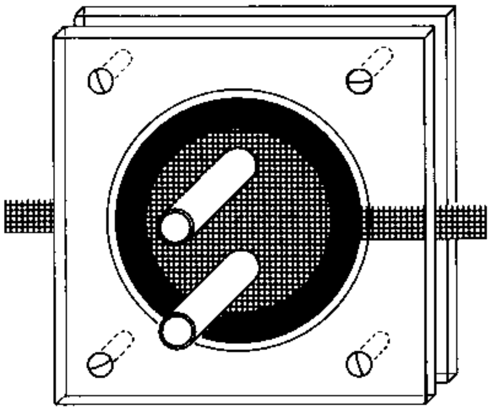

Figure 6. Assembled fuel cell.

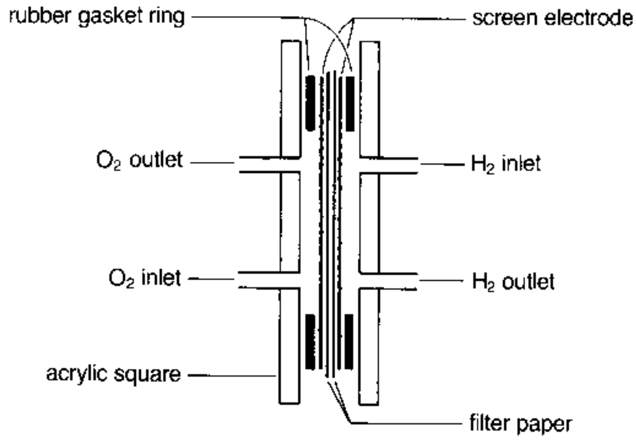

Figure 7. Cross-section of assembled fuel cell.

happens to the cell potential. Increase the hydrogen flow again to about what it was before.

Attach the wires from the electric propeller motor to the electrodes. The propeller will turn. While the motor is running, vary the flow rate of the hydrogen and note the effect on the speed of the motor. The cell can be operated continuously for several hours. However, if the filter paper should dry, the cell will cease to function.

HAZARDS

Hydrogen is extremely flammable. Therefore, this demonstration should be presented away from open flames and sparks.

Concentrated nitric acid is both a strong acid and a powerful oxidizing agent. Contact with combustible materials can cause fires. Contact with the skin can result in severe burns. The vapor irritates the respiratory system, eyes, and other mucous membranes, and therefore concentrated nitric acid should be handled only in a well-ventilated area.

Concentrated hydrochloric acid can irritate the skin. Its vapors are extremely irritating to the eyes and respiratory system. It should be handled only in a well-ventilated area.

Mixtures of concentrated nitric acid and concentrated hydrochloric acid (aqua regia) release chlorine gas (Cl_2) and other reactive and toxic gases (NO_2, NOCl, NO_2Cl, etc.). Therefore, these mixtures should be used only in well-ventilated areas.

Complex platinum salts may irritate the skin.

DISPOSAL

The excess mixture of concentrated nitric and hydrochloric acids should be diluted by pouring it into 500 mL of water. This diluted acid should be neutralized by adding sodium bicarbonate ($NaHCO_3$) until fizzing stops. The resulting mixture should be flushed down the drain with water.

The remaining 1M sodium hydroxide solution should be flushed down the drain with water.

The cell should be disassembled and the filter paper rinsed with water and discarded in a solid-waste receptacle.

The platinized screens should be rinsed with distilled water and stored in water for repeated use. Eventually, the platinum black coating will become ineffective and will need to be regenerated as described in the procedure.

DISCUSSION

A fuel cell is a voltaic cell which converts the chemical energy of a fuel and its oxidizing agent directly into electrical energy. In other words, the fuel and its oxidizer could be combined under other circumstances to generate heat, which could be converted mechanically into electrical energy. Certainly, the hydrogen used in this demonstration would react with oxygen in a highly exothermic reaction. The fuel cell produces electrical energy directly, without the production of heat and the energy loss associated with mechanical conversions. Mechanical electric generators have efficiencies between 40% and 50%, whereas the efficiency of a fuel cell can be close to 100%.

Electrochemical reactions are heterogeneous. They involve electron exchange reactions which occur at the interface between two or three phases, such as the interface between a metal electrode and a solution. In the hydrogen-oxygen fuel cell used in this demonstration, three phases are involved: the solid platinum surface, the liquid solution of sodium hydroxide, and a gas (hydrogen at one electrode and oxygen at the other).

At the hydrogen electrode, hydrogen gas flows over the platinum surface. Hydrogen gas is chemisorbed onto the platinum surface; that is, it forms chemical bonds with atoms of platinum at the electrode's surface [*1*]. When the hydrogen is chemisorbed, it dissociates into hydrogen atoms. Some hydrogen atoms lose an electron to the metal and combine with hydroxide ions from the electrolyte, forming water [*2*]. Hydrogen gas is oxidized to water; therefore this electrode is the anode. Having gained electrons in this way, the metal electrode becomes negatively charged. Thus, the reactions at the anode are

$$H_2(g) + Pt(s) \rightleftharpoons 2\ H{\cdot}Pt(\text{chemisorbed})$$

$$2\ H{\cdot}Pt + 2\ OH^-(aq) \rightleftharpoons 2\ H_2O(l) + Pt(s) + 2\ e^-$$

Oxygen gas is reduced at the cathode. Oxygen molecules strike the platinum surface and are weakly bound. The adsorbed oxygen molecules dissociate into oxygen atoms. These oxygen atoms capture electrons from the metal, producing chemisorbed oxide ions. These react with water molecules from the solution at the interface and produce hydroxide ions in the solution. The electrode, having lost some electronic charge to the electrolyte phase, becomes positively charged. The reactions occurring at the cathode are

$$O_2(g) + Pt(s) \rightleftarrows 2\ O{\cdot}Pt(\text{chemisorbed})$$

$$2\ O{\cdot}Pt + 4\ e^- \rightleftarrows 2\ O^{2-}{\cdot}Pt$$

$$O^{2-}{\cdot}Pt + H_2O(l) \rightleftarrows 2\ OH^-(aq) + Pt(s)$$

When the two electrodes are connected by a conductor of electrons, such as the leads from the motor, electrons flow from the negative electrode (H_2) through the circuit of the electrical device to the positive electrode (O_2). In order for electron current to flow continuously the hydroxide ions produced at the cathode must migrate toward the anode. The cell reactions are

cathode:	$O_2(g) + 2\ H_2O(l) + 4\ e^- \rightleftarrows 4\ OH^-(aq)$
anode:	$2\ H_2(g) + 4\ OH^-(aq) \rightleftarrows 4\ H_2O(l) + 4\ e^-$
overall:	$2\ H_2(g) + O_2(g) \rightleftarrows 2\ H_2O(l)$

Water is the product of the reaction of hydrogen with oxygen. The intermediate hydroxide ions travel through the sodium hydroxide solution from the cathode to the anode, and the intermediate electrons travel from the anode to the cathode through the external circuit.

The standard cell potential (E°) of a hydrogen-oxygen fuel cell is 1.23 volts. This value is the sum of the standard reduction potentials in basic solution [3]:

$$2\ H_2O(l) + 2\ e^- \rightleftarrows 2\ OH^-(aq) + H_2(g) \qquad E^\circ = -0.83\ \text{volt}$$

$$O_2(g) + 2\ H_2O(l) + 4\ e^- \rightleftarrows 4\ OH^-(aq) \qquad E^\circ = 0.40\ \text{volt}$$

The fuel cell in this demonstration develops a maximum potential of about 1 volt.

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