FUEL CELLS:
ENERGY FROM GASES INSTEAD OF GASOLINE

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Introduction

Fuel cells transform chemical energy to electrical energy. They are used on space shuttles to generate electricity and water needed for the mission. Recently, fuel cells have been used to convert the air pollution generated during the treatment of wastewater into useful energy.

Green Chemistry Principle: Conserve Energy

Most of our current sources of energy are obtained from fossil fuels, such as coal, oil, and natural gas. Combustion of fossil fuels contributes to various forms of air pollution and produces carbon dioxide, a gas implicated in global warming. Furthermore, fossil fuels are not renewable resources. Recognition of both environmental and economic costs of energy production drives green chemistry research to find alternative, more sustainable sources of energy. Fuel cells are one type of alternative energy. Fuel cells offer several advantages over traditional energy sources, such as lower emissions of pollutants and greater efficiency.

(See 12 Principles for a complete list of green chemistry principles.)

Associated Chemistry Topics

- Energy
- Reduction-oxidation reaction
- Electrochemistry
- Atmospheric chemistry

Vocabulary

Aerobic – with oxygen present.

Anaerobic – without oxygen present.

Anaerobic Digester – a wastewater treatment process that uses microbes to reduce the amount of solid sludge waste; generates methane and carbon dioxide gases as byproducts.

Catalyst – a substance that helps chemical reactions to occur but is not changed in the reaction.

Electrodes – metal wires that provide electrical contact with an ionic solution and at which oxidation and reduction reactions occur.

Electrolysis – the use of electricity to cause a chemical reaction.

Electrolyte – a substance, often an ionic compound, which conducts electrical current through the movement of ions.

Fuel Cell – a device that uses hydrogen (or hydrogen-rich fuel) and oxygen to create electricity by an electrochemical process. If pure hydrogen is used as a fuel, fuel cells emit only heat and water as byproducts.[1] Also called a gas battery.

Green Chemistry – designing chemical products and processes to reduce or eliminate the use or generation of hazardous materials.

Oxidation – the loss of electrons, the gain of oxygen atoms, or the loss of hydrogen atoms.

Redox Reaction – the complete reaction that occurs when a reduction and oxidation occur together.

Reduction – the gain of electrons, the loss of oxygen atoms, or the gain of hydrogen atoms.

Voltage – electrical potential, or tendency of electrons to flow, measured in units of volts (joule per coulomb).

Wastewater Treatment – the process of removing solids and other contaminants from sewage.

Reactions: Oxidation and Reduction

1. Electrolysis of Water: $2 \mathbf{H_2O} \rightarrow 2 H_2 + O_2$
2. Reduction of Oxygen: $\mathbf{O_2} + 4 H^+ + 4 e^- \rightarrow 2 H_2O$
   $\mathbf{O_2} + 2 H_2O + 4 e^- \rightarrow 4 OH^-$
3. Oxidation of Hydrogen: $2 \mathbf{H_2} \rightarrow 4 H^+ + 4 e^-$
4. Oxidation of Iron: $\mathbf{Fe} \rightarrow Fe^{2+} + 2 e^-$
5. Oxidation of Methane: $\mathbf{CH_4} + 2 O_2 \rightarrow CO_2 + 2 H_2O$

Background

Energy consumption is a major issue in achieving a sustainable planet. Historically, humans have used wood, coal, oil and natural gas for energy. Before the industrial revolution, wood was the primary source of energy for human activities. As technology developed, coal, oil and natural gas were used in place of wood. These three fossil fuels reflect a trend toward cleaner and more efficient fuels, as evidenced by the increasing ratio of hydrogen to carbon. Since the industrial revolution, society has depleted fossil fuels faster than the fuels are generated. Coal, oil and natural gas provide a lot of energy when they are burned. Yet, the combustion of fossil fuels is slowly changing the composition of the atmosphere, with climate change a probable outcome. Furthermore, fossil fuel extraction, refinement, and transport create many hazards in the workplace and the environment. These are drawbacks to the use of fossil fuels as an energy source.

Developing alternative sources of safer, cleaner, renewable energy is a goal of green chemistry. Converting the energy of the sun, wind or plants into a form suitable for human consumption is a challenge. A promising alternative to fossil fuels is fuel cell technology. Power from fuel cells is cleaner, generating less than 1% of the amount of pollution produced by traditional power production. Furthermore, methane gas, a byproduct of the decomposition of human waste (sludge), has been used in fuel cells to efficiently produce electricity. So fuel cells are doubly good for the earth, first by converting a byproduct into useful energy and second, by reducing pollution involved in making that energy.

First built more than 150 years ago, the fuel cell has much lower emissions than traditional combustion sources and is cheaper than solar power. A fuel cell is similar to a battery, constructed of two electrodes connected by an electrolyte (see **Figure 1**). In a hydrogen fuel cell, air (oxygen) and hydrogen gas generate heat, electricity and water by means of an electrochemical reaction.[2]

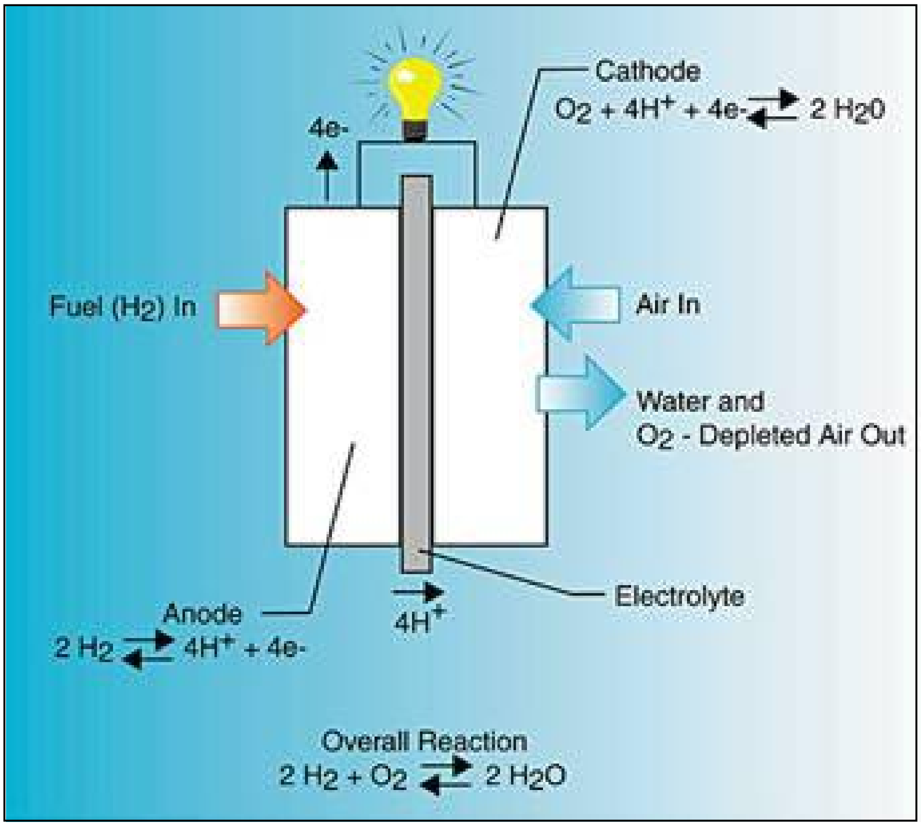

Figure 1: Diagram of a Fuel Cell
Source: Energy Types, "Fuel Cells and Hydrogen"
http://www.personal.psu.edu/users/m/e/mek183/energy_types.htm

The technology has the potential to increase energy efficiency, reduce greenhouse gas emissions and reduce air pollution compared with traditional combustion engines. Scientists expect fuel cells will be useful in a variety of personal devices ranging from automobiles and home furnaces to cellular phones. Fuel cells are still too expensive and experimental to be practical for widespread use. However, they are currently used to power city buses, NASA spacecraft and wastewater treatment plants.[3]

Fuel cell powered city buses are a technology on the ground, but with impacts on the quality of the earth's lower atmosphere. Several U.S. cities, including Chicago, IL; San Francisco, CA; and Washington, DC have fuel cell powered buses in operation in order to prevent air pollution associated with traditional combustion engines.

High-flying fuel cells are part of the National Aeronautics and Space Administration's (NASA) Environmental Research Aircraft and Sensor Technology (ERAST) program. The ERAST program aims to develop remote controlled flying vehicles to study the Earth's atmosphere.[4] NASA is currently developing fuel cell technology for uninhabited aerial vehicles (UAV). Fuel cells working together with solar cells offer electrical power during dark hours, less weight than battery systems and more reliability due to fewer moving parts. UAV are designed to provide atmospheric research, satellite relay, and news coverage of weather and natural disasters. The Helios Prototype UAV flew at a record-breaking altitude of nearly 100,000 feet. At this altitude, Earth's atmosphere is similar to the atmosphere of Mars. Fuel cell and UAV research will help NASA scientists design aircraft that can fly in the Martian atmosphere.

A more down to earth use of fuel cells has been developed at wastewater treatment facilities. These cells convert waste methane gas, or biogas, generated from sludge decomposition into useful electricity. The first successful use of biogas in fuel cells was in 1992 at a landfill demonstration test site in California. In 1997 the New York Power Authority installed the first commercial power plant to use this technology at a wastewater treatment facility in Yonkers, NY. Since then the Columbia Boulevard Wastewater Treatment Plant in Portland, Oregon, has instituted fuel cell technology. The King County Wastewater Treatment Division of Washington State has begun building a fuel cell demonstration project, and a similar facility is in progress in Fukuoka, Japan. Other sites in the U.S. and Asia are currently using or planning to build fuel cell systems operating on waste gases from a variety of methane sources (landfills, hog farms, breweries).[5] The technology offers the opportunity to reduce operating expenses by providing electricity in a more efficient manner than a combustion generator, and make use of a waste byproduct of the treatment process. The earth's atmosphere benefits from the reduction of methane gas emissions.

Materials (per group of four)

- 2 platinum wires (3-4 inches long)
- 6 steel paper clips
- 3 plastic cups (8 ounce size)
- 400 mL beaker
- 250 mL vinegar
- 250 mL water
- 0.250 g Epsom salt
- 1 multimeter
- 1 battery (9 or 12 volt)
- 4 sets of alligator clips
- stopwatch
- ruler

Safety: This activity is intended for use by students in the laboratory under the direct supervision of a qualified chemistry instructor. The chemicals may be harmful if misused or if the procedures described are not followed. Wear gloves and goggles offering indirect splash and impact protection. Follow responsible chemical safety guidelines. This experiment involves the use of electricity. Care must be taken to avoid electric shock.

Procedure

1. Prepare the Epsom salt solution in the 400 mL beaker by dissolving the 0.250 grams of salt in 250 mL of water.
2. Fill each of the three plastic cups with 250 mL of one of the following aqueous solutions (be sure to label them):
   (a) Water
   (b) Vinegar
   (c) Epsom salt solution
3. Measure the voltage of the water sample using the platinum wires for the electrodes. See **Figure 2** for assistance. The electrodes should be about 1 cm apart or closer, but not touching. Record the distance between the electrodes and make sure to use the same distance for all the samples.

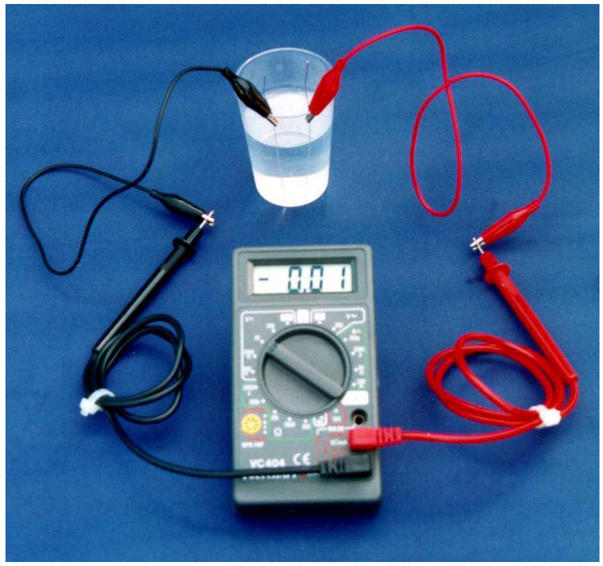

Figure 2: Photo showing how to measure the voltage of a solution
Source: Courtesy of Dr. Martin Schmidt, "Platinum Fuel Cell Kit Instructions"
http://www.geocities.com/fuelcellkit/pdf/FC1101e.pdf

4. Set up the multimeter, alligator clips, battery, platinum electrodes and sample water solution in a circuit as shown in **Figure 3**. Always attach the battery last, and never let the electrodes touch each other.

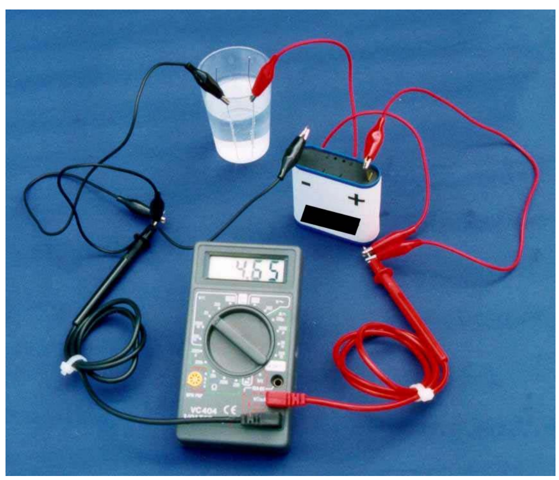

Figure 3: Photo of Electrolysis Experiment Set Up
Source: Courtesy of Dr. Martin Schmidt, "Platinum Fuel Cell Kit Instructions"
http://www.geocities.com/fuelcellkit/pdf/FC1101e.pdf

5. Record the voltage, and describe your observations.
6. Disconnect the battery, being careful not to disturb the solution or electrodes, record the voltage and start the stopwatch. Record the voltage and any other

observations every 15 seconds for three minutes. After three minutes, record the voltage (and observations) every 30 seconds for three more minutes.

7. Repeat steps 3-6 for the two other samples. Be sure to thoroughly rinse the electrodes with water between each sample. For accurate comparisons, be sure to maintain a constant distance between the electrodes for all the samples.
8. Repeat steps 3-7 using straightened paper clips instead of platinum wires for electrodes. Be sure to use a new paper clip for each sample.
9. Summarize your data and observations in a table for each of the samples and the two types of electrodes. Be sure you have all the data you need to answer the following questions.

Questions

1. Write the names and formulas for the chemicals present in each of the aqueous samples.
2. What are the concentrations of the vinegar and Epsom salt solutions? Report concentration both in units of % (w/w) and Molarity (mol/L).
3. Write the balanced redox reaction that occurs when the battery is disconnected from the platinum wires for either the vinegar or Epsom salt sample. Which chemical species undergoes oxidation and which undergoes reduction?
4. Write the balanced redox reaction that occurs when the battery is disconnected from the paper clips for either the vinegar or Epsom salt sample.
5. What product forms on the surface of the steel paper clip while the battery is connected? (Hint: steel contains iron)
6. Graph the voltage versus time you recorded in step 6 of the procedure for each of the samples.
7. List the solutions in order of increasing final voltage observed in step 6. Explain the physical and chemical significance of the order. [Hint: look up the dissociation constant and reduction potential for the electrolyte species.]
8. Using the final voltage you recorded for the Epsom salt solution in Step 6, and assuming a current of 0.01 milliamps, calculate how many of these fuel cells it would take to power a 100-Watt light bulb. (Hint: Watt = Volt * Amp)
9. Most fuel cells kits cost over $200, and fuel cells used in wastewater treatment plants, vehicles and space shuttles cost even more. What are some of the differences between this laboratory demonstration fuel cell and a fuel cell used to power an automobile?

Instructional Notes

Grade Level (Target Audience): high school

Estimated Time of Activity: 2 hours

Materials (per group of four)

- 2 platinum wires (3-4 inches long)*
- 6 steel paper clips
- 3 plastic cups (8 ounce size)
- 400 mL beaker
- 250 mL vinegar
- 250 mL water
- 0.250 g Epsom salt
- 1 multimeter
- 1 battery (9 or 12 volt)
- 4 sets of alligator clips
- stopwatch
- ruler

Safety: This activity is intended for use by students in the laboratory under the direct supervision of a qualified chemistry instructor. The chemicals may be harmful if misused or if the procedures described are not followed. Wear gloves and goggles offering indirect splash and impact protection. Follow responsible chemical safety guidelines. This experiment involves the use of electricity. Care must be taken to avoid electric shock.

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* Platinum wires are available from most chemical suppliers. In spring of 2003, prices ranged from $16 to $99, depending on the size of the order and wire specifications. Other sources include:
a) Hoffman electrolysis apparatus electrodes
b) Dr. Martin Schmidt (URL: http://www.geocities.com/fuelcellkit/offer.html). A set of electrodes is $29.90, or 10 sets for $149.90.

Considerations and Adaptations

*Considerations**:*** Students will need a copy of the original labels for Epsom salt and vinegar, or another source of the chemical names and formulas to answer Questions 1 and 2. Figure 2 may cause confusion due to the orientation of the alligator clips in the left-hand connection. The connection on the left is identical to the one on the right. Students may need help elucidating the reactions that are occurring at each electrode, especially the oxidation that occurs on the paper clip.

Less Advanced: The general principles of a fuel cell may be shown by a demonstration instead of the full laboratory activity. Alternatively, have students read articles (scientific journals, popular magazines, newspapers) about fuel cells and discuss the science, economics and policy. Some are of the opinion that fuel cells are the obvious energy source for our sustainable future. Others believe that ultimately fuel cells merely offer the same nonrenewable fossil fuel energy at a much higher cost. One issue at the heart of fuel cell technology is the source of hydrogen. Research is being done using methanol (CH_3OH), methane (CH_4) and hydrogen (H_2) as the hydrogen source. Compare and contrast each fuel source in terms of source of fuel (and whether it is renewable), production, handling safety, waste emissions (include the chemical reactions), cost, and compatibility with existing fuel distribution systems. Draft a recommendation for funding research focused on the use of one of the three fuels, explaining your reasons for choosing that particular fuel over the other two.
Suggested articles:

Chemical and Engineering News "New fuel cells run directly on methane" (August 16, 1999, page 7): http://pubs.acs.org/cgi-bin/bottomframe.cgi?7733notw7
The New Republic "Why Bush's H-car talk is just hot air" (February 24, 2003): http://www.tnr.com/doc.mhtml?i=20030224&s=easterbrook022403
Society of Automotive Engineering, International, "Fuel Cells Start to Look Real" http://www.sae.org/automag/features/fuelcells/index.htm

More Advanced: A high school AP chemistry laboratory, "Determination of the Fundamental Electronic Charge via the Electrolysis of Water" (*J. Chem. Educ.* **2000**, *77*, 95-96) offers a more challenging hands-on experience designed to reinforce the concepts of gas laws and stoichiometry.

Answers to Questions

1. Write the names and formulas for the chemicals present in each of the aqueous samples.
   (a) Water = H_2O
   (b) Vinegar = H_2O and CH_3COOH or $C_2H_4O_2$ (acetic acid, partially dissociates into CH_3COO^- and H^+)
   (c) Epsom salt solution = H_2O and $MgSO_4$ (magnesium sulfate, dissociates into Mg^{2+} and SO_4^{2-})
2. What are the concentrations of the vinegar and Epsom salt solutions?
   - Vinegar is 5% (w/w) acetic acid (30.06 g/mol) or 5.00 g in 100 mL of water. This is the equivalent of a 1.66 Molar solution (mol/L).
   - The Epsom salt ($MgSO_4 \cdot 7H_20$ = 246.52 g/mol) solution is 0.250 g in 250 mL of water or a 0.1% (w/w) solution. This is the equivalent of a 0.00406 Molar solution (mol/L) or 4.06 mM.
3. Write the balanced redox reaction that occurs when the battery is disconnected from the platinum wires for either the vinegar or Epsom salt sample. Which chemical species undergoes oxidation and which undergoes reduction?
   - $2\ H_2 + O_2 \rightarrow 2\ H_2O$
   - Hydrogen is oxidized.
   - Oxygen is reduced.
4. Write the balanced redox reaction that occurs when the battery is disconnected from the paper clips for either the vinegar or Epsom salt sample.
   - No reaction
5. What product forms on the surface of the steel paper clip while the battery is connected? (Hint: steel contains iron.)
   - The paper clip turns black as iron in the steel is oxidized, first to iron hydroxide, $Fe(OH)_2$, which then further reacts to form iron oxide, Fe_2O_3. Use the oxidation/reduction equations provided to guide students toward the reaction of Fe^{2+} and OH^- to form $Fe(OH)_2$.
     $4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4\ Fe(OH)_3 \rightarrow 2\ Fe_2O_3 \bullet H_2O$ (rust) + $4H_2O$

6. Graph the voltage versus time you recorded in step 6 of the procedure, for each of the samples.
    - Graphs will vary from student to student, but should show an immediate decrease, compared to the voltage observed while the battery was connected, followed by a gradual drop to relatively constant value by the end of six minutes.
7. List the solutions in order of increasing final voltage observed in step 6 of the procedure. Explain the chemical significance of the order.
    - The voltage for the Epsom salt solution should be higher than that for the vinegar solution because the salt is a strong electrolyte and dissociates completely, while the vinegar is a weaker electrolyte that dissociates to a much lesser extent. The plain water solution will have a very small, if any, voltage since there is no electrolyte present. The distance between the electrodes will also affect the observed voltage, and may disrupt the expected trend.
8. Using the voltage you recorded at three minutes for the Epsom salt solution in Step 6, and assuming a current of 0.01 milliamps, calculate how many of these fuel cells it would take to power a 100-Watt light bulb. (Hint: Watt = Volt * Amp)
    - Given: 1V * 0.01 mA * 1A/1000mA = 2×10^{-5} W
    - It would require five million (100W / 2×10^{-5} W = 5×10^{6}) of these simple fuel cells to provide 100W.
9. Most fuel cells kits cost over $200 and fuel cells used in wastewater treatment plants, vehicles and space shuttles cost even more. What are some of the differences between this laboratory demonstration fuel cell and a fuel cell used to power an automobile?
    - The main issue is the electrolyte and catalytic surface – these are much more advanced and larger in expensive fuel cells.

Web References:

12 Principles of Green Chemistry

- http://chemistry.org/greenchemistryinstitute/principles.html

Collecting the History of Fuel Cells: A Smithsonian Research Project

- http://americanhistory.si.edu/csr/fuelcells/

Discovering the principle of the fuel cell

- http://www.geocities.com/fuelcellkit/

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Environmental Protection Agency, Office of Research and Development, "The Fuel Cells in Our Future"

- http://www.epa.gov/ord/archives/2002/march/htm/article1.htm

Fuel Cells 2000

- http://www.fuelcells.org/

HowStuffWorks, "How Fuel Cells Work"

- http://www.howstuffworks.com/fuel-cell.htm

Merriam-Webster Online

- http://www.m-w.com/home.htm

National Fuel Cell Education Program: EcoSoul Fuel Cell Demonstration

- http://www.nfcep.org/html/fuelcell/fuelcell.htm

U.S. Department of Energy, Energy Efficiency and Renewable Energy, "Fuel Cells: Fuel Cell Basics"

- http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/basics.html

Endnotes:

[1] U.S. Department of Energy, "Fuel Cells: Fuel Cell Basics"
http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/basics.html

[2] The National Fuel Cell Education Program, EcoSoul's web site, "Fuel Cell Demonstration," offers a Macromedia Flash movie of a fuel cell in operation.
http://www.nfcep.org/html/fuelcell/fuelcell.htm

[3] (a) Spiegel, R.J. and J.L. Preston. "Test results for fuel cell operation on anaerobic digester gas" *Journal of Power Sources* **2000**, *86*: 283-288.
(b) EPA Office of Research and Development, "The Fuel Cells in Our Future"
http://www.epa.gov/ord/archives/2002/march/htm/article1.htm

[4] See NASA's web site for more information:
(a) http://www.dfrc.nasa.gov/Research/Erast/erast.html
(b) http://www.dfrc.nasa.gov/Newsroom/FactSheets/FS-020-DFRC.html
(c) http://www.dfrc.nasa.gov/Research/Erast/helios.html

[5] Fuel Cell 2000's Frequently Asked Questions Page
(a) http://www.fuelcells.org/fcfaqs.htm#landfill
Fuel Cell Energy Press Release
(b) http://www.fuelcellenergy.com/site/investor/press/releases/2001/01_25_01.html