Supplement A – Laboratory Exercises

Hydrogen from Water by Electrolysis

Adapted from Thomas, Nicholas, "A Fast Coulometric Estimation of Avogadro's Number " *J. Chem. Ed.* **2007**, *84*, 1667.

Objective To determine Avogadro's number; To determine the amount of electricity needed to generate a gram of hydrogen gas.

Review material: Gas Laws, reaction stoichiometry, charge on an electron, acid solution, definition of Amp, definition of watt, unit conversion.

Procedure

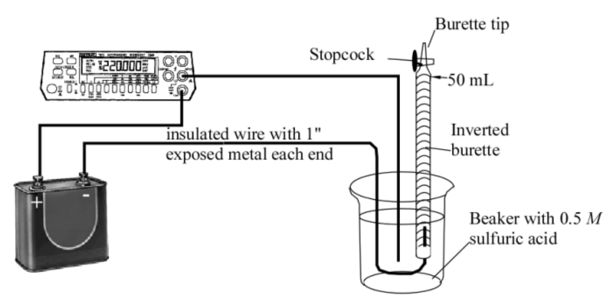


Figure 1: Sset up for generation of hydrogen from electrolysis.

Leak test a burette by filling it with water and suspending it upside down in a beaker filled with water. Make the sulfuric acid solution by obtaining approximately 500 mL water in a 600 mL beaker and approximately 14 mL of concentrated sulfuric acid in a 25 mL graduate cylinder. **Caution, concentrated (98%) sulfuric acid is a very strong acid. Wear gloves and exercise care as concentrated sulfuric acid can eat holes in clothing, skin, and other objects. Always add acid to the water** – *this is critical*. Dilution of acid literates a lot of heat, so if water is added to the acid, there is a significant risk of a spatter resulting in *hot* acid which may land on the skin. If acid is added to water, the large heat capacity and larger volume of water limits the temperature rise and, should there be a spatter, it will be dilute rather than concentrated acid. (Acid to Water: A&W). **After measuring the acid, rinse the graduated cylinder with lots of water.** (Acid concentration is not critical, so approximate volumes are adequate.) Elemental hydrogen is generated in this experiment: since it is potentially explosive, no sparks or flames should be present.

The battery produces a current that changes with time, but that change is nearly linear after about the first three minutes. Upon completion of the circuit, bubbles should be produced at the lead in the burette and the multimeter should read a current (about 0.25 amp). (If bubbles are coming from the other lead, check the circuit.) After about 3 minutes, simultaneously record both the time and the volume approximately every two or three minutes. Collect about 40 mL of gas. Other data that is needed: battery voltage, barometric pressure, and room temperature.

Typical results are 38 mL H_2 gas, 0.26 amp average current at 6 V for 18.8 minutes resulting in a value of 6.03×10^{23} for Avogadro's number. The battery costs $30, household electricity $0.17 per kW·h. Using this data, students calculate the cost per kg H_2 and per mile if a car goes 160 miles on 3.8 kg H_2. The result is $368/mi with the battery; $0.65/mi with household electricity.

Special Supplies:

- Lantern battery (Source McMaster-Carr part number 7690K33)

Hydrogen From Active Metals

Adapted from Bonatti, Carlos M.; Zurita, José L.; Sólimo, Horácio N., "An Alternative Methodology for General Chemistry Laboratories: Chemical Equivalent of a Metal " *J. Chem. Ed.* **1995**, *72*, 834-835.

Objective: To develop a procedure for determination of the atomic mass of a metal by determining its hydrogen equivalent; To gather data concerning the cost of generating hydrogen using active metals.

Review material: gas laws, stoichiometry, molecular equations, ionic equations, and net ionic equations, and nomenclature.

Procedure

Armed with experience collecting hydrogen gas from electrolysis, this is an active learning exercise tasking students with devising an apparatus to determine the atomic mass of the active metals Al, Mg, and Zn. They also determine the cost of generating hydrogen using these metals and hydrochloric acid.

Caution: The acid concentrations provided are concentrated HCl and 3 *M* HCl. **Concentrated acid is very strong (approximately 38% HCl by mass). Wear gloves and exercise care as concentrated HCl can eat holes in clothing, skin, and other objects. After measuring the acid, rinse the graduated cylinder with lots of water. If acid gets on the skin, flush with lots of water. Spills should be diluted immediately and wiped up – notify your teaching assistant.**

Result: 0.0287 g Al yields 40.8 mL gas

$$\text{atomic mass} = 0.0287\,\text{g} \times \frac{3\,\text{mol(H}_2)}{2\,\text{mol(Al)}} \times \frac{24900\,\text{mL}}{\text{mol(H}_2)} \times \frac{1}{40.8\text{mL(H}_2)} = 26.3\text{ g/mol}$$

Special Supplies needed

Samples of the following metals: Al – foil; Mg – ribbon; Zn – squares

Constructing Solar Cells

Adapted from Smestad, Greg; Huseth, Amy; Shanks, Kathleen; Bruecken, Peter; Goates, Wayne, *Nanocrystalline Solar Cell Kit* (Institute for Chemical Education, Madison, Wi, 1998) and Field, Simon Quellen, SciToys: A Flat Panel Solar Cell (scitoys.com; Accessed 3/2008).

Objective: To build an assembly consisting of a semiconductor, electrolyte, and circuit to gather energy from the Sun generating electrical power.

Review material: Bands in semiconductors, conductivity in oxides as well as molecular energy levels and molecular shape.

Procedure

A. The Grätzel cell

Follow Smestad, Greg; Huseth, Amy; Shanks, Kathleen; Bruecken, Peter; Goates, Wayne, *Nanocrystalline Solar Cell Kit* (Institute for Chemical Education, Madison, Wi, 1998).

B. The Cu_2O cell

Cut a copper U that is 4.5” high, 4” wide with ½-$^3/_4$” wide legs; cut one side of U to 4” high (Figure 2a). Cut a 4” by 4.5” copper rectangle; remove a strip from the 4.5” side that is 3.5” by 0.5” (Figure 2b).

Draw a bead of silicone glue along the outside of the U leaving the protruding ½” free of

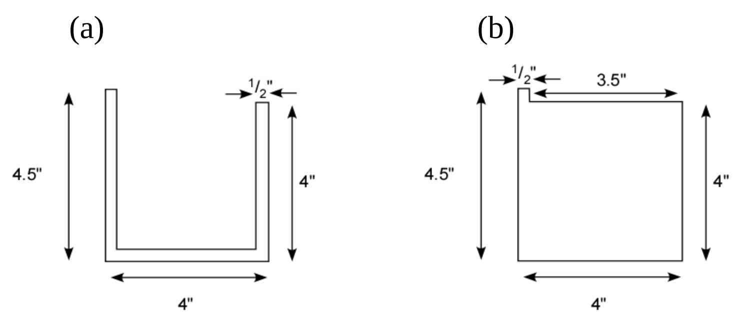


Figure 2: Cut a copper U with one leg ½” longer than the other (a) and a 4’ × 4’ square with a ½” tab on one corner (b).

glue. Clamp to the clear top from a jewel case using large binder clips. Set aside to cure. Wearing rubber gloves wash the copper square with laboratory soap, rinse well, and dry. Sand both sides.

To generate Cu_2O, place the copper square on an electric hot plate (1100 W) turned to the highest setting. When the plate is red-hot, let the copper square cook for 10 min; rotate the copper square ¼ turn. Repeat the heat-turn cycle until the copper square has heated for 40 min and been turned three times. Turn the hot plate off *but do not remove the copper square.* Let the square and burner cool slowly for 30 min. Much of the black copper oxide will have pealed or popped off, exposing red Cu_2O. Select the side of the plate that has the most pealed or popped CuO. Gently remove any lose black CuO, but do not scrub since the Cu_2O layer is a bit fragile. Sand the tab down to bare copper.

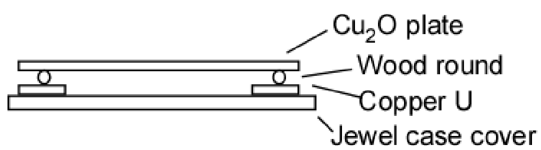
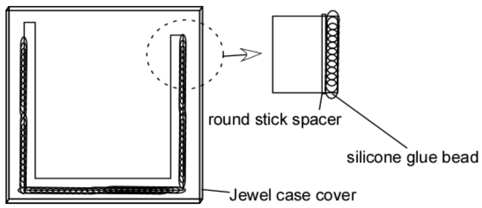


Figure 3: Side view of the layers of the Cu_2O solar cell. The wood rounds help electrically insulate the copper plate from the Cu_2O plate. Silicone glue seals the outside of the assemblage.

Assemble a water-tight container with the copper square and the jewel case cover with the U shaped copper sandwiched in between (Figure 3). To prevent contact between the copper and the Cu_2O, use round sticks as spacer-insulators (Figure 4). First, lay a bead of silicone glue on the three outside edges of the U, breaking the round sticks to fit, lay these inside the glue bead, then lay the Cu_2O square on top. Choose the best looking side of the Cu_2O plate to face the jewel case – this is the side that will collect the solar radiation. Clamp the assemblage with binder clips and let the glue cure for at least an hour. Longer is better.

(a)



(b)

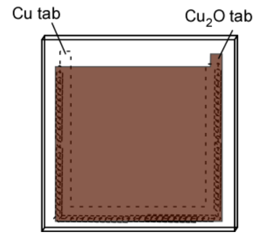


Figure 4: (A) Lay a bead of silicone glue along the outside edge of the U-shaped copper, then place round stick spacers just inside the bead. (B) With the best side of the Cu_2O plate facing the jewel case, lay the Cu_2O plate on top of the silicone bead with the tab protruding from the same side of the assemblage as that of the copper plate.

Remove the binder clips, trim excess glue using a razor blade. Draw the blade gently along the outside edge of the U, then lift the semicured bead away from the jewel case. When the edges have been trimmed, lay a generous bead of silicone glue along the three outside edges of the U, plus the top leaving about ½" unglued. (Hint, if the silicone bead has holes, the electrolyte to be added later will leak out. So - in the hood, using a gloved hand, dip your finger in some glacial acetic acid and draw it along the edge of the silicone bead. Use only gentle pressure: you are not trying to squeeze the glue out, just make sure air holes between the silicone glue and the copper or jewel case are all sealed.) Let this assemblage cure for at least 24 hours.

Inject a solution of 8.75 g NaCl in 250 mL water into the space between the Cu_2O plate and the jewel case. If the salt water leaks, the leak needs to be sealed. Seal the last ½" of the top with silicone glue. Set the solar cell upright and let the glue cure for at least ½ hour.

Fasten an alligator clip to each of the protruding tabs of the cell, place the solar cell under the lamp and record the open circuit voltage. Note which of the plates is positive and which is negative. Measure the short-circuit current noting which plate is positive, which is negative.

Verify that the solar cell is responding to the light by covering the cell with your lab notebook: the voltage and the current should drop. If not, check the circuit.

Typical results with the lamp provided: current on the order of 75 μA and voltages on the order of 75 mV for the dye sensitized solar cell and 30 μA and 30 mV for the Cu_2O cell.

Solar radiation is about 10 times the intensity of the laboratory lamp. It is instructive to have students calculate the size of a solar cell needed to produce 3.8 kg of hydrogen in one hour. Data: solar illumination delivers 800-1000 W/m^2, a typical solar cell is 12% efficient, so a 12% efficient panel produces 96-120 W/m^2, 3.8 kg of H_2 requires 120 kW·hr or a panel that is 960-1300 m^2 to produce the hydrogen in one hour.

Special Supplies needed

Silicone glue gun, silicone glue

Light – 150 W quartz-halogen lamp (Staples, item 227925)

1 *M* $CuSO_4$ in a crystallizing dish (to filter excessive red and infrared from the lamp)

5 in by 8 in copper flashing (Storm Copper Components, Co. item no. RC-SR-0216-80-10)

One-burner electric hot plate – 1100 Watt (BroilKing, Amazon item no. BR-5W)

~5” square polycarbonate – jewel case cover works well

3 round sticks about 2 mm diameter by 5-6” long

Single-edge razor blade

Multimeter (Silicon Solar, Inc. item no. 06-1014, $10.00)

Hydrogen Fuel Cells

Adapted from Bahnemann, Detlef; Pujiula, Francisco; Berge, Christopher, *Thames and Kosmos Fuel Cell Car and Experiment Kit* (Thames & Kosmos, LLC, Stuttgart, DE, 2000) and Field, Simon, Electrochemistry (sci-toys/scitoys/echem/fuel_cell/fuel_cell.html; Accessed 2, 29, 2008).

Objective: To explore hydrogen fuel cells; To build an assembly consisting of a solar and fuel cell both to generate hydrogen for the fuel cell and to use the fuel cell to power a small motor.

Review material: Bands in semiconductors, molecular shape; Gibbs Free energy, oxidation numbers, electrochemical potential, potential and thermodynamics.

Procedure

Battery-fuel cell

Assemble the fuel cell unit (Figure 5) by attaching a short tube with a septum cap plug to each of the top ports of the fuel cell (the water fill ports) and the longer tubes from the discharge ports to the appropriate H_2 or O_2 tank.

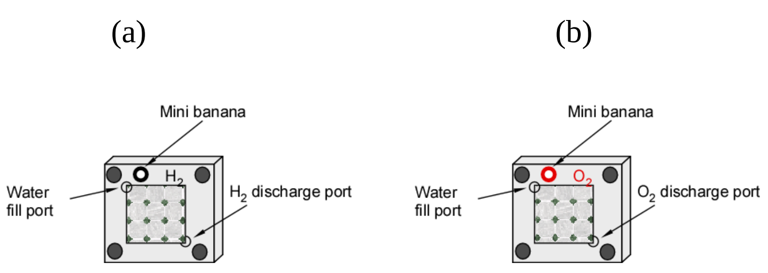


Figure 5: Schematic of the NO.Z 4959 fuel cell, (a) H_2 side, (b) O_2 side.

Fill the H_2 and O_2 tanks with 18 MΩ water. **Under no circumstances should you use tap water in this experiment.** Insert a syringe needle into the very center of the septum cap, draw the plunger back filling the fuel cell, the fuel tank and the fuel line with water. Repeat for the other side of the fuel cell.

Charge the tanks with hydrogen and oxygen by attaching the mini banana plugs to the fuel cell: red to red and black to black. Attach the black banana plug from the fuel cell lead to the negative pole of the battery, the red banana plug to the positive pole. Measure the time required to fill the gas tanks. Use the fuel cell and the collected hydrogen and oxygen to run a small fan.

C. Hybrid solar fuel cell

In this portion of the exercise, solar energy is used to generate the hydrogen and oxygen for the fuel cell. Connect the solar cell to a multimeter. Orient the solar panel in a horizontal configuration and put the sun-substitute lamp over the panel. On the more intense setting of the lamp, the solar cell delivers greater than 200 mV and more than 80 mA. If not, adjust the distance between the lamp and the solar cell. **Do not get the lamp too close as it will melt the solar cell housing, damaging or incapacitating it.**

Hydrogen side Oxygen side

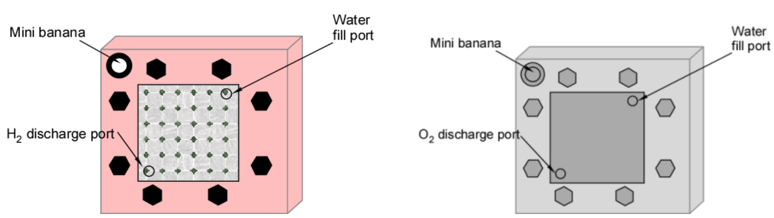


Figure 6: :Schematic of hydrogen fuel cell.

Connect the fuel cell unit as follows (Figure 6). The plastic tubing from the fuel tanks connects to the two lower ports on the fuel cell: the hydrogen side is the pink side; the oxygen side is the shinny metal side. Connect the two shorter lengths of tubing to the two top ports. Mount the fuel cell in the center of the model car chassis and the fuel storage tanks in the rear tank. Do not force the latter; they should slide in smoothly when properly aligned.

Obtain about 150 mL of 18 MΩ water. DO NOT USE TAP WATER IN THE FUEL CELL. Doing so will render the cell unusable for you and students to come later ☹. Fill the tank containing the fuel tanks with 18 MΩ water.

Insert the white tip of the syringe into one of the short tubes. Use the syringe to purge the system of air. This is done by first pulling on the plunger then using a combination of pulling and pushing plus tilting the fuel cell module until no visible air gap exists in the fuel cell. Pinch the tubing, remove the syringe and its white tip from the tubing and seal the tubing with the small red cone. Repeat this operation with the other side of the fuel cell.

The fuel cell is now loaded and ready for action. Using the double ended small banana patch lead, connect the fuel cell to the connector strip: the red lead connects to the pink or hydrogen side and the black lead to the oxygen side.

Illuminate the solar cell with the lamp on the more intense setting and observe the tubes connecting the fuel cell to the fuel tanks. Monitor the gas volume as a function of time. Note the relationship of the hydrogen volume to that of oxygen. When the tanks have reached some convenient level (about half full) turn the lamp to the lower illumination level and again record the volume as a function of time. When tanks are less than three-quarters full, stop illumination.

Unplug the mini banana connectors between the solar cell and the connector strip. Lift the front of the model car off the table and connect the motor leads to the connector strip. What do you observe? Place the model car on the floor – what happens?

Pick the car up and note the fuel tank level. Let the motor run and monitor the fuel level for a time interval approximately equal to the fill time.

Disconnect the motor, reinsert the test probes and measure the short-circuit current and the no-load voltage.

Clean up consists of returning the fuel cell and model car to its original state. Note that the tubes can be difficult to remove from the ports: use a flat blade screwdriver or other similar implement to *gently* pry under the end of the tube to encourage it to come off.

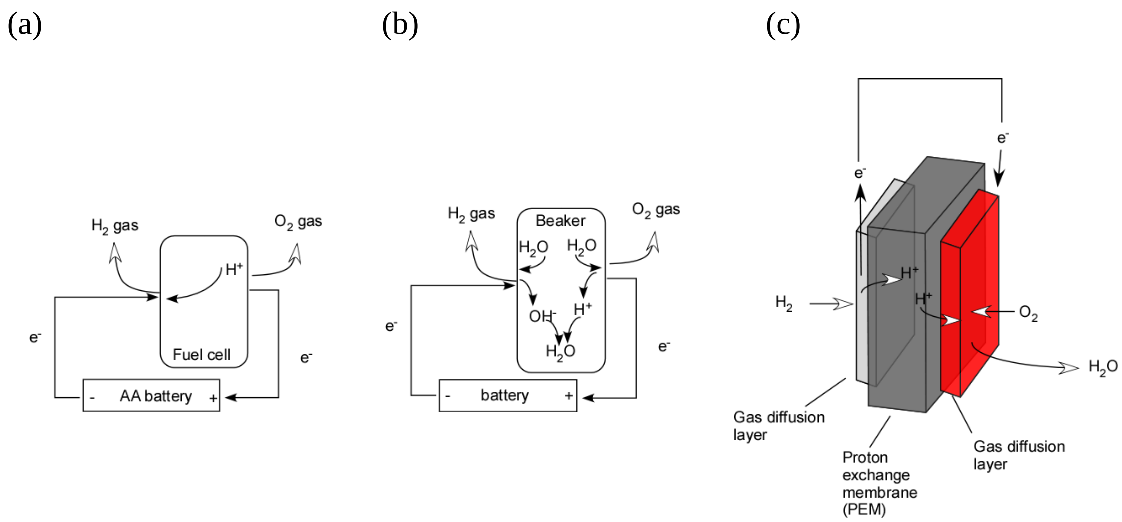


Figure 7: Diagram for (a) generation of hydrogen using a fuel cell contrasted to (b) the diagram for electrolyzing water. (c) Schematic diagram of a hydrogen fuel cell.

Special Supplies needed

18 MΩ water; 150 watt solar substitute lamp (Staples, item 227925)

Fan with motor (Hydro-Genius School Motor, FuelCellStore item No. 532908)

Fuel cell No. Z4959 (FuelCellStore, item no 632000)

Gas Storage Cylinders (FuelCellStore item no. 7110307)

Model Fuel Cell car including solar panel, leads to motor, test ports, solar cell, fuel cell, Hydrogen/oxygen storage tanks (Thames &Kosmos Fuel Cell Car, Amazon.com, $105.89)

Multimeter (Silicon Solar, Inc. item no. 06-1014, $10.00)

Methanol Fuel Cells

Adapted from Harper, Gavin D. J., How to build your own band aid fuel cell, archive/2006/06; how_to_build_your_own_band_aid.html, (Make Technology on Your Time http://blog.makezine.com; Accessed 1, 15, 2008).

Objective: To build a functional fuel cell using commonly available items with a prefabricated PEM membrane.

Review material: Gibbs Free energy, oxidation numbers, electrochemical potential, potential and thermodynamics.

Procedure

Two direct methanol fuel cells (DMFC) are constructed using different screen mesh sizes for the electrodes. Students determine the effect of screen size on energy generation.

Wires/in	Dia. (in)	wires/in	Dia. (in)	wires/in	Dia. (in)
70×70	0.0065	150×150	0.0026	325×325	0.0014
80×80	0.0055	200×200	0.0021	400×400	0.0011
100×100	0.0045	250×250	0.0016	500×500	0.0010

(a) (b) (c) (d) (e) (f)

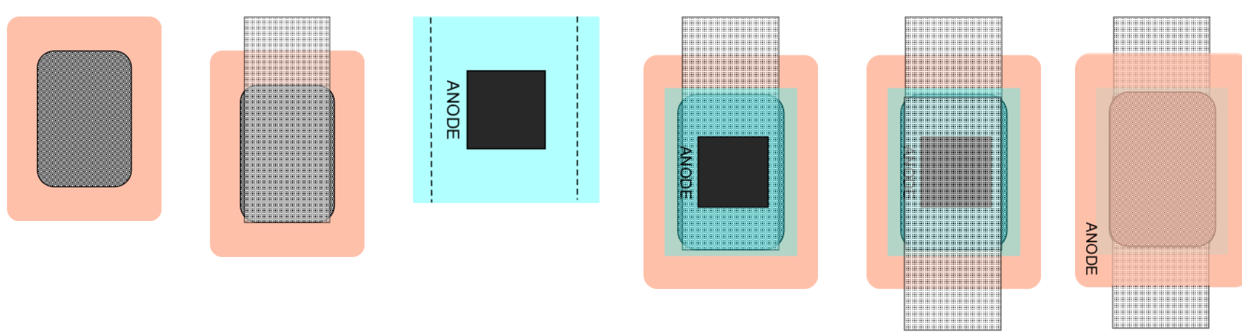


Figure 8 Assembly of methanol fuel cell. (a) Orientation of band aid, (b) placement of screen on band aid extending above the band aid, (c) (cotton gloves!) if necessary, trim the MEA edges so that they extend beyond the wound pad and screen leaving some surrounding adhesive exposed, (d) place the trimmed MEA on the screen-band aid with the word "ANODE" right side up, (e) place second screen strip on assembly extending below the band aid (f) label second band aid as "ANODE" and lay it over assembly.

WARNING *although the membrane electrode assembly, MEA, is relatively robust, oils from fingers can render it inactive. Handle the MEA ONLY with cotton gloves.*

Cut two 1.25 inches wide by 3 inches long strips from each chosen screen size. Assemble the methanol fuel cell as illustrated in Figure 8. Press the entire assembly together and bend the top screen toward the front of the assembly and the lower screen to the back. Use a single-edged razor blade to carefully cut an opening in the center of the band aid labeled “ANODE.” The size of the opening is not critical, but about 1-cm by 1-cm in the center is good. Connect a voltmeter (set to mV) to the two screen electrodes using alligator leads and measure the voltage noting the lead that is attached to the anode. Activate the fuel cell by applying several drops of 3% methanol solution to the opening. (A schematic diagram of the direct methanol fuel cell, DMFC, is shown in Figure 9.) Keep the uncut side dry. It takes a little time for the fuel cell to power up – it may be useful to apply a light pressure with a cotton-gloved hand. Record the voltage. Experiment by applying more methanol solution and different amounts of pressure.

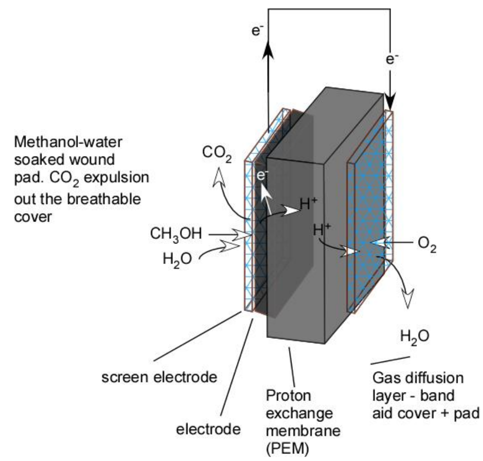


Figure 9: Schematic of a direct methanol fuel cell.

Take the fuel cell apart and repeat with a different screen size. One of the more effective methods to disassemble the cell is to use a very sharp scissors to cut one of the band aids in half in the long direction, then carefully *with gloved hand* and a flat tweezers, remove the membrane. Do not touch the black center where the catalyst is with the tweezers – clamp onto the edges of the membrane. Do the two screen sizes produce the same voltage?

Clean up by disassembling the fuel cell (remember: cotton gloves!), return the MEA to its protective plastic container, put the screens in the container labeled with the appropriate screen size, and discard the band aids in the trash.

Post laboratory

Calculation of the potential of the methanol fuel cell relies on the relationship between ΔG^o and $\mathcal{E}^o$. The half reactions are

oxidation: $CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$

reduction: $O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$

overall reaction: $2CH_3OH + 3O_2 \rightarrow 2CO_2 + 4H_2O$

Calculation of ΔG^o

$\Delta H^o = 4\times\Delta H_f^o(H_2O) + 2\times\Delta H_f^o(CO_2) - 2\times\Delta H_f^o(CH_3OH)$

$=[4\times(-285.8) + 2\times(-393.5) - 2\times(-239.2)]$kJ

$= -1451.8$ kJ

$\Delta S^o = 4\times S^o(H_2O) + 2\times S^o(CO_2) - 2\times S^o(CH_3OH) - 3\times S^o(O_2)$

$=[4\times(70) + 2\times(213.8) - 2\times(126.8) - 3\times(205.2)]$J/K

$= -161.6$ J/K

$\Delta G^o = \Delta H^o - T\Delta S^o = -1403.3$ kJ at room temperature.

The cell potential is determined using the Nernst equation: $\mathcal{E}^o = -\Delta G^o/nF$. $n = 6$ $F = 96{,}485$ C/mol. Cell potential is 2.42V.

The potential of the reduction reaction is +1.229 V, so the potential of the methanol oxidation reaction is

2.42 V – 1.229V = 1.20 V; the potential of the methanol reduction reaction is thus -1.20 V.

The volumetric energy density for the methanol fuel cell is

$$\frac{1451.8kJ}{2mol} \times \frac{1mol}{32g} \times \frac{0.7914g}{cm^3} \times 0.03 = 537 \text{ J/cm}^3$$

The gravimetric energy density (energy per unit mass: kJ/kg) assuming that the methanol solution has the same density as water, is 537 J/gm.

The volumetric energy density for hydrogen in a hydrogen fuel cell with a hydrogen pressure of 1 atm. is 12.8 J/cm^3. To produce a volumetric energy density comparable to that of the methanol solution, hydrogen would have to be compressed to 42 atm.

For comparison, the volumetric energy density for gasoline (assuming that gasoline is pure octane: C_8H_{18}. Density = 0.6986 g/cm^3) is 36.38 kJ/cm^3. This is about twice that of pure methanol and 67 times that of the methanol solution.

Special Supplies needed

Screen 6”×6” piece provides for 4 samples (McMaster-Carr screen assortment, part no. 92405T17)

2.25” by 3” band aids – the kind without any additive like aloe or antibacterial

Membrane electrode assembly (FuelCellStore, part no 590310)

Cotton gloves (Archival gloves)

Multimeter (Silicon Solar, Inc. item no. 06-1014, $10.00)

Supplement B – Student Paper

Hydrogen: Fuel of the Future

Instructions for Paper

The major purpose of your paper is to take a position on the question, "Is hydrogen the fuel of the future?" and to support your stand with data – your own and that from the literature.

An excellent paper will have

- Data from your labs. In several of the laboratory exercises, you have been asked to consider the costs associated with various methods of hydrogen generation, storage, or fuel cell assemblage. Incorporate this data into your arguments either in favor of or against hydrogen as the fuel of the future.
- Data from a review level paper.
- Data from an original research paper, e.g. one that is referenced in a review. Do not be discouraged if you do not understand the entire paper – the teaching staff is eager to discuss any paper with you.
- Synthesis of all the data cited into a coherent whole. For example, if your position is that hydrogen cannot be the fuel of the future because it is too expensive to generate, then cite papers on generation methods and costs associated with those. In addition address the question of whether future developments might significantly reduce that cost.

Start the paper with an abstract that sets out what your position is and a sentence or two about the evidence that supports your position.

1) The first section is an introduction: why is this issue important? What is the context?

2) The second section describes the experimental procedure used to get the cited data. This should be brief – only the essentials.

3) Results: give your own results as well as the data gleaned from other sources. Clearly indicate the source of the data: yours and that from another source citing the source. Also indicate further work needed to advance the hydrogen economy.

4) Discussion: This is where your position is supported and the synthesis presented.

5) Summary: Also brief, echoing the abstract. How has your position been supported? What further work is needed before a full implementation is supported?

6) References: These are the cited papers.

Length: Remember the teaching staff and I read these papers and we read slowly. Succinct papers are appreciated. An absolute upper limit is 15 pages, single space, 12 point font. I will stop reading at this point!

There is one excellent book that I can recommend for any of you interested in how scientific advances and engineering combine to solve real problems. The book is *Powering the Future: The Ballard Fuel Cell and the Race to Change the World* by Tom Koppel (Wiley, New York, 2001). Not heavy scientific writing, but it gives a reasonable overview of the issues in making fuel cells a potential part of our future.

Supplement C – Example Student Papers

Storage of Hydrogen

by Matthew Kelly

Abstract:

In order for hydrogen fuel cells to be truly viable for use in the transportation industry, it is necessary to develop an efficient and compact method of storing the hydrogen fuel. The two main technologies which are currently available for storing hydrogen are compression and liquefaction. These storage systems do not store the desired amount of hydrogen in a small enough space and take a great deal of energy to operate, thus reducing the overall efficiency of the system. There have been a variety of methods developed to combine new and existing technologies to improve these systems. Some of these improvements include, creating a better compression method, combining low temperature liquid storage and high pressure gas storage, and increasing the efficiency of the evaporation process in liquid storage systems.

Introduction:

The modern world is currently dependant on fossil fuels as our primary source of energy. At some point in the future, this will no longer be a viable means of energy production and the focus will shift to the renewable resources which are available. While fossil fuels store large amounts of chemical energy, they have two key problems. The first problem is that they are non-renewable, so we cannot make more once they are depleted. This means that the cost of fossil fuels will continue to increase until it is so high that they are no longer a viable energy source. The second major problem is that fossil fuels generate large amounts of pollution. One pollutant in particular, CO_2 (carbon dioxide), is of particular concern because of its contribution to global warming.

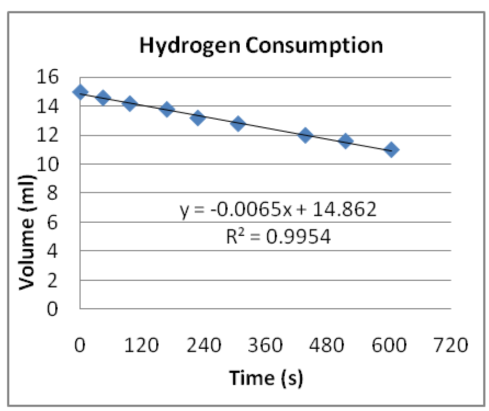
A variety of alternative energy sources are currently in use including solar, wind, hydro-electric, geothermal, and biomass. These energy sources will someday dominate the energy market because of their sustainability over fossil fuels, but they all have one big problem: they are not suited for compact mobile applications. This portion of the market, especially for transportation, is currently dominated by the internal combustion engine. As these engines are phased out, it is likely that they will be replaced with hydrogen fuel cells. Hydrogen fuel cells are particularly interesting to researchers because their only byproduct is water. Fuel cells have some technical problems which must be solved in order for their use to become widespread. First, less than 1% of hydrogen on earth is in the gaseous form[1], so it must be produced using electricity. To do this in an environmentally sound way, hydrogen is extracted from the water of an aqueous solution (currently hydrocarbons are used, but they produce carbon dioxide in the process). Extracting hydrogen through electrolysis is an energy intensive process, and should be powered with renewable resources to reduce carbon emissions. A second technical hurdle is that the fuel cells must be efficient, light, and compact, so that they are useful for mobile applications. The final and perhaps most challenging aspect of this system is the storage of enough hydrogen on the vehicle to give it sufficient range.

Hydrogen is very difficult to store in a compact fashion because it has a low volumetric energy density when compared to conventional fuels such as gasoline. Despite its large energy to mass ratio (nearly three times that of octane), an enormous volume is required to store enough hydrogen gas at STP to power a car for a reasonable distance. It has been determined that roughly 4 kg of hydrogen would be necessary to power a small hydrogen fuel cell car for 250 miles[1]. The actual mass of hydrogen required will depend on the application and desired range. It is also likely that the efficiency of cars will increase as technology develops, making this technology more and more feasible. The amount of volume set aside for fuel in conventional cars is usually about 15-20 gallons, and for hydrogen storage to become economical it should come close to this size of container. It is also possible to make storage tanks which could conform around components in the car, allowing more volume for hydrogen storage without using up as much of the valuable space within the car[8].

Fuel (STP)	Mass Density (g/L)	Volumetric Energy Density (MJ/L)	Gravimetric Energy Density (MJ/kg)
Hydrogen (g)	0.08988	0.013	142.9
Hydrogen (l), 20K	70.99	9.36	142.9
Octane (l)	737.22	34	48

This paper investigates the two more traditional ways of storing hydrogen: as a high pressure gas and as a liquid at 20 K. Some modern variations on these methods are also discussed. There are four other main directions that research is taking to solve this problem. Physisorption of hydrogen storing hydrogen on the surface of materials with extremely high surface area. This method works by taking advantage of the Van der Waals interactions between hydrogen atoms and the surfaces of materials such as nanostructure carbon and carbon nano-tubes. Metal Hydrides are binary hydrides of transition metals, which store hydrogen within the structure of the metal-like compound. These hydrides are capable of storing hydrogen safely at a high density. Complex hydrides are hydrides of the group 1, 2, and 3 metals. These hydrides are very light, and have very high hydrogen to metal ratio. They also exhibit an ionic or covalent bond structure in comparison to the metallic bonds in normal hydrides. These hydrides have reached hydrogen densities of up to 150 kg/m^3 (for Mg_2FeH_2 and $Al(BH_4)_3$. The last key topic of research is chemical reactions, which involve the reaction of a metal and a hydrogen-containing compound, to produce hydrogen gas and a byproduct. This method shows less promise due to high cost of the metal reactants, and reformation of the byproduct of reaction. Successful processes have been shown to work with Zn.[6]

While hydrogen fuel cells present numerous technical challenges, it is very likely that their use will become more widespread in the future. Most major car companies are developing hydrogen fuel cells currently, and some have working prototypes, including BMW[9], Honda[10], Ford[11], and Toyota[12] to name a few. If this is not telling, the sheer volume of research on topics related to hydrogen fuel cells is revealing. At some point the technology will improve enough to become economical, even if it requires the help of government subsidies. When this point is reached a slow transition to fuel cells and renewable resources over fossil fuels should begin. This is because fuel cells have many important advantages over the internal combustion engine. One that is becoming increasingly important is the low environmental footprint of fuel cells. If the hydrogen can be produced with electricity from renewable sources, then the only step in the process that isn't environmentally friendly is the actual construction of the fuel cell. Hydrogen is also good because it is essentially impossible to run out of it; as the hydrogen is used it is released back into the environment as water, which ideally is the source that it was derived from. This means that the cost of hydrogen should be fairly stable, and impossible for one group to monopolize, and making it a good long term resource.



Experimental / Calculations:

In the fuel cell lab[13], water was broken down into hydrogen and oxygen gas through electrolysis. This gas was then captured and stored in glass containers at atmospheric pressure and temperature. Using the power source available (batteries) it took 36 minutes to generate .015 L of hydrogen gas (this volume of gas stores about 195 Joules of energy). The cell produced .94V and 195 mA (equivalent to .189 W) which was used to power a small fan. At this rate the hydrogen would be used up in about 38 minutes (see chart). Hydrogen stored under these conditions would not be very efficient for powering a car. The 4 kg of hydrogen deemed necessary to make a hydrogen vehicle worthwhile takes up a volume of 44.48 cubic meters; roughly 4 times the size of an average car. To make hydrogen fuel cells a viable means of transportation the hydrogen must be stored in a far more compactly.

$n = (2\times1.00794 \text{ g/mol})^{-1}(4 \text{ kg}) = 1984 \text{ mol}$; $p = 1 \text{ atm}$; $T = 273.15 \text{ K}$; $V_{STP} = n\cdot\mathrm{R}\cdot T/p = 44.48 \text{ m}^3$

The amount of energy required to compress 4 Kg of hydrogen gas to 587atm (amount required to make 4 Kg of hydrogen fit in a volume of 20 gallons) is 29 MJ. This quantity represents the amount of work done to compress the gas isothermally at 100% efficiency. In reality, hydrogen is generally compressed with a mechanical compressor resulting in a large amount of energy loss due to friction, heat, and noise.

$n = (2\times1.00794 \text{ g/mol})^{-1}(4 \text{ kg}) = 1984 \text{ mol}$; $\mathrm{T} = 273.15 \text{ K}$; $P_{compressed} = n\mathrm{R}T/(20 \text{ gal}) = 587.45 \text{ atm}$

$$\int_{1atm}^{587atm} \frac{n\mathrm{R}T}{v} dv = 28.7 \text{ MJ}$$

The amount of energy required to cool hydrogen to its boiling point and liquefy it is given by the following for a 100% efficient (ideal) and slightly simplified process; this method ignores the fact that *c*, the heat capacity changes with temperature for hydrogen, as well as the fact that the gas changes pressure and volume during this process, both of which affect work. Most gasses, such as nitrogen have an inversion temperature of about room temperature, so they can be liquefied by being compressed and cooled, and then undergoing isenthalpic expansion (this is known as the Joule-Thompson or Linde cycle). One of the reasons that the real process for liquefying hydrogen consumes so much more energy is because hydrogen has an inversion temperature of 202 K. This means that when hydrogen expands at room temperature, it heats up. Thus, hydrogen must be cooled below this point by some other means, usually with liquid nitrogen, before it can be liquefied by the Joule-Thompson cycle.[6]

$Q_{\text{cooling}} = mc\Delta T$; $Q_{\text{condensing}} = Ln$

$Q_{\text{cooling}} = (4\text{ kg})(13.12\text{ kJ/kg}\cdot\text{K})(20.28\text{ K} - 295\text{ K}) = -14.43\text{ MJ}$

$Q_{\text{condensing}} = (-0.45\text{ kJ/mol})(2\times1.00794\text{ g/mol})^{-1}(4\text{kg}) = -892\text{ kJ}$

$Q_{\text{cooling+condensing}} = 15.3\text{ MJ}$

*Note: c is for hydrogen at 175K

The energy required to produce 4Kg of hydrogen gas as shown below is roughly 470 MJ. The actual amount of energy required is higher due to inefficiencies in the process.

$N_{\text{e}} = 2\times(\text{mole H}_2)(N) = 2.39\times10^{27}$

Charge = $N_{\text{e}}\times(1.6022\times10^{-19}\text{ C}) = 3.83\times10^{2}\text{ C}$

Energy = Charge × potential = 7.877×10^{2}J 788 MJ

The cost of electricity is roughly 17 cents per kW·hr[14]. The approximate cost of 4 Kg of hydrogen is $37. The energy equivalent of 4 kg H_2 in octane is about 6.1 gallons. At 3.62 $ per gallon[15], this costs $15.45; roughly 40% the ideal cost of hydrogen. While hydrogen is more expensive, it isn’t so expensive that this should be a limiting factor. In the future, the cost of gasoline will continue to increase, but the cost of hydrogen will only be dependant on the means used to generate it. As renewable energy becomes more efficient, the cost of producing hydrogen using this energy will be reduced.

Cost = Rate×energy = $37.21 for 4 kg of hydrogen at STP.

$\text{Mass}_{\text{octane}} = (4\text{ kg}\times142.9\text{ MJ/kg})/(48\text{ MJ/kg}) = 11.91\text{ kg}$;

V_{octane} = (0.358 gal/kg)×11.91 kg = 4.27 gal; $Cost_{octane}$ = (\$3.62/gal)(4.27 gal) = \$15.455

Summary of Information:

Chemical energy in 4 Kg of hydrogen:	568 MJ
Energy required to produce 4kg hydrogen by electrolysis (100% efficient):	788 MJ
Cost of 4kg of hydrogen by ideal process at .17$ per kW·Hr	$37.21
Cost of equivalent in octane (gasoline) at 3.62$ per gallon	$15.45
Energy required to compress 4 kg hydrogen to 587atm (100% efficient):	28.7 MJ
Energy Required to liquefy 4 kg hydrogen from room temperature (100% efficient):	15.3 MJ
Energy required to Liquefy 4 kg hydrogen (Ideal, using advanced methods)[6]:	46.5 MJ
Energy required to Liquefy 4 kg hydrogen (Real values)[6](2003):	219 MJ
Energy required to Liquefy 4 kg hydrogen (Real values)[5](2007):	144 MJ
Net energy for cycle using modified Brayton cycle (73% efficiency on evaporation)[5]:	38.9 MJ

Results and Discussion:

Compression is the simplest method of fitting a lot of hydrogen gas in a small space, but this method brings with it a large number of technical difficulties. During a complete fueling cycle, the internal pressure of the compressed gas tank will fluctuate from an internal pressure of 1 atm to extremely high pressure. Under these conditions, steel is very susceptible to hydrogen embrittlement[3], so it cannot be used for high-pressure tanks rated above about 200 atm[1]. Hydrogen embrittlement results from the diffusion of hydrogen into steel, which causes cracks to form along the grain boundaries making it brittle and weakening the tank. Higher pressure tanks

(450 atm) are made of composite materials and strengthened with carbon fiber which can hold roughly 4% hydrogen by mass[1]. This is roughly twice the mass of a conventional 20 gallon gas tank when full. Modern hydrogen storage tanks are now being built and certified for internal pressures of up to 5,000 (340atm) and 10,000 PSI (680atm). These tanks are currently in use on prototype vehicles and are built using a carbon-fiber epoxy resin composite shell, with a liner to contain the gas and protect the structure. These sections are encased in an outer shell to protect the tank[8]. The pressure regulator and value assemblies are contained within the tank to protect them from external damage, and to keep dangerous high-pressure lines out of the body of the vehicle.

Despite its challenges, compression of hydrogen to extreme pressures is making its way into prototypes[8] and in the near future may be featured in cars that are on the market. One of the key concerns holding back its development is safety. Compressed gas contains an enormous amount of potential energy. For example, at 22 ˚C, 4 kg of hydrogen gas pressurized to 10,000 PSI contains about 32 MJ (assuming rapid decompression and constant temperature) of mechanical energy (see below). If there were a leak or rupture in the tank the results could be catastrophic. The gas also contains a large amount of chemical energy (about 568 MJ), which could be released rapidly in the event of a fire.

$$n = \text{mol}_{H2}(4\text{kg}) = 1984 \text{ mol}; \int_{680atm}^{1atm} \frac{nRT}{v} dv = 31.73 \text{ MJ}$$

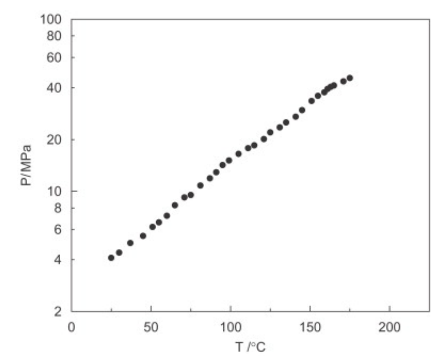
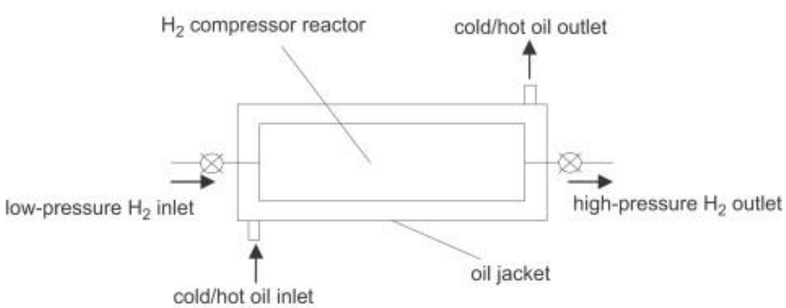


Fig. 4. Hydrogen pressure as a function of temperature during compression.

Schematic and Chart from source[4]

Traditionally, hydrogen gas is compressed mechanically, often with a piston compressor[6]. These compressors are simple but inefficient, with a large amount of energy lost to friction and noise. A new type of compressor has been created by a research team at Zhejiang University in China, which uses a metal hydride to compress the hydrogen gas. This has been done before, but only to pressures of about 150 atm; this compressor is able to reach pressures of about 450 atm. The compressor is made of a steel tube (38 mm outer diameter) which contains the metal hydride, and has inlet/outlet ports for hot and cold oil and hydrogen gas (see schematic below). The metal hydride is saturated with hydrogen at 4 MPa when cool oil is circulated through the reactor, and when hot oil is circulated hydrogen can be produced with an output pressure of 45 MPa. The rate of compression is 40 L/min and the metal hydride used was $Mm_{0.7}Ca_{0.2}La_{0.2}(Ni_{4.95}A;_{0.05})$. Mm is a Ce-rich mischmetal composed of La 23.8%, Ce 48.6%, Pr 8.1%, Nd 16.8%, and others 2.7%.[4] This hydride was found experimentally by starting with $MmNi_5$ and substituting varying amounts of La, Ca, and Al until the optimal proportions were determined. With a slightly altered metal hydride, a two stage compressor was also built which could use hot and cold water (this was deemed to be a safer alternative) to achieve the same input and output pressures, but at a rate of 20 L/min.[4]



At 45 MPa, the 4 kg of hydrogen gas would take up a volume of 26.5 gallons, which is slightly larger than desired, but still within the feasible range to be put inside a car. This compressor would then be able to condense the desired amount of hydrogen in about 5 minutes, which is comparable to the amount of time it currently takes to fill up a regular fuel tank at a gas station. The compressor is driven with the heat given off by the fluid being circulated, so it could be paired with a system that gives off heat, such as an air

conditioning system or solar panels to be environmentally-friendly. This type of compressor does not produce noise, giving it another advantage over conventional compressors.

One of the characteristics of a gas is that as its temperature decreases, so too does its pressure. One way to solve the high pressure issue is to store the gas at a lower temperature to reduce the required pressure. The density of hydrogen gas at 77 K is about 20% of its density at 289 K. If the hydrogen is stored on activated carbon, the density drops to about 10% of its value at 298 K. Activated carbon is carbon based material with extremely high surface area; in this case the activated carbon used was AX-22. This material is desirable because it can quickly and reversibly absorb hydrogen, effectively reducing the volume that the hydrogen takes up. Activated carbon is also available at a reasonable cost when produced on a large scale. The tank could be kept at 77 K by liquid nitrogen, which is fairly inexpensive. Liquid nitrogen would need to be

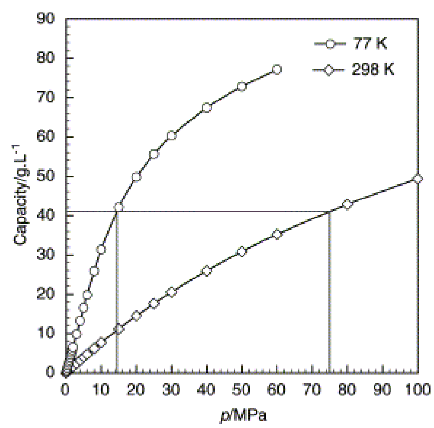


Chart from source[2]

C	compressor
COM	combustor
EVA	LH_2 evaporator
HEX	heat exchanger
MIX	mixer
P	pump
REP	recuperator
SEP	seperator
T	turbine

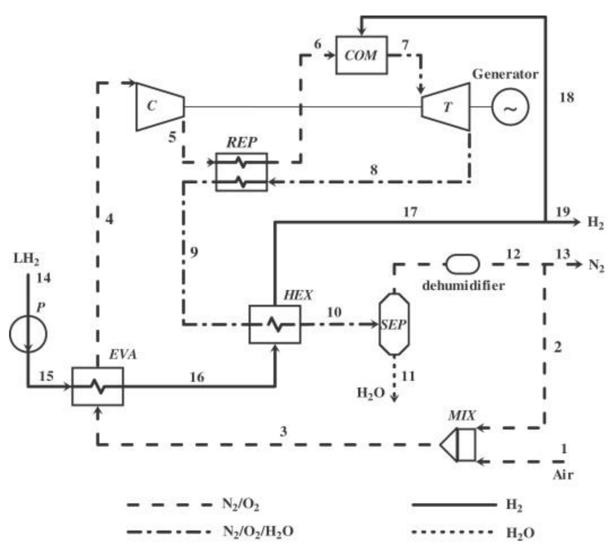
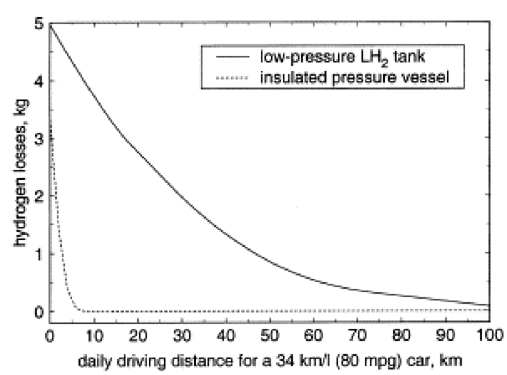


Chart from source[7] Schematic from source[5]

added to the tank about once a week to sustain the low temperatures.[2] This method has the advantages of lower energy costs than liquid hydrogen storage, and lower pressures than are required for ambient temperature compression of hydrogen.

Another method of storing hydrogen is as a liquid. Four kg of hydrogen in the liquid state takes up about 15 gallons, which is well within the target volume for this mass of hydrogen. Hydrogen is a liquid at 20 K, so one major technical problem is finding an efficient way to liquefy and store hydrogen at these cryogenic temperatures. The containers for liquid hydrogen are generally lighter and safer than their high-pressure counterparts, making this a desirable alternative[5]. In fact, liquid hydrogen is already being used for fuel in the space shuttle, as well as in some military aircraft. BMW has also been testing the possibilities of liquid hydrogen as a fuel[1],[9]. However, the liquefaction of hydrogen takes a very large amount of energy-currently about 36 MJ/kg (this could potentially drop to 18 MJ/kg). Liquid hydrogen must be stored in an open system, because standard containers are not designed to be pressurized. This means that a small percentage of the hydrogen is lost to evaporation during use. The hydrogen must be evaporated and heated back to ambient temperature in order to be used by a fuel cell. In this process a large amount of the energy that was put into liquefying the hydrogen is lost to the environment. If some of this energy could be used to power the vehicle, the process for liquefying hydrogen could be made much more energy efficient.

One way of doing this is through a variation on the Brayton cycle (a constant pressure gas cycle which is the basis for turbine-type engines), which is designed to optimize energy use during the evaporation of the liquid hydrogen. As the hydrogen evaporates, its energy is transferred to an air and N_2 mix. This mix then goes to a compressor, and is reheated by the exhaust gases before entering the combustion chamber with a small amount of the H_2 gas. The exhaust goes through a generator and a heat exchanger (this time with the hydrogen gas), before it is separated. The N_2 is re-circulated through the system, and the H_2O is separated by condensation and then released into the environment. The now ambient temperature H_2 is ready for use, and electricity has been generated in the process[5]. See figure above for a schematic of the process. This process can generate electricity from the evaporating gasses with an efficiency of 73%. This is due to a high temperature difference between the turbine inlet and compressor inlet, no heat loss due to exhaust gasses, and the use of the evaporation process to extract energy. In addition, this process releases no pollutants, does not need a coolant, and the nitrogen released is extremely pure and could be used for other applications.[5] It is likely that a process such as this will be used on future liquid systems where efficiency is more important than the added weight of the system.



It is possible to take the idea of compressing hydrogen at low temperatures and take it one step further. Liquefying hydrogen requires large amounts of energy and has losses of hydrogen due to evaporation. It is also difficult to store enough compressed hydrogen for longer-range vehicles. One way to solve these problems is to create a pressure vessel that can be operated at cryogenic temperatures. Since the tank can be pressurized, it isn't necessary to vent evaporated hydrogen, like conventional liquid hydrogen tanks, minimizing hydrogen losses (see above figure). The container could be filled with ambient temperature compressed hydrogen for shorter trips to save money and energy, or with liquid hydrogen for a higher storage capacity for longer trips. Since the tank can accept the most efficient fuel type for the trip, it saves an estimated 16% of energy over solely liquid systems.[7]

Summary:

Hydrogen fuel cells are likely to be one of the key technologies in the future of energy. They will be a key replacement for many applications of the internal combustion engine such as the transportation industry. Currently, the development of this technology is limited by three main factors: economic production of hydrogen (ideally using renewable resources and water), compact storage of adequate amounts of hydrogen, and the weight and efficiency of the fuel cells themselves. Storage is a key problem for mobile applications of fuel cells because large volumes of hydrogen must be made to fit into very small spaces. Currently, this is done through compression or liquefaction. While both of these technologies work, they have serious disadvantages and will likely be replaced by new technologies in the future. It is unlikely that there is a single ideal solution to the storage problem; there will be different techniques, which will be applied to fit a variety of applications. That being said, it is likely that the immediate future of hydrogen storage will rely on variations on the traditional methods of compression and liquefaction, combining them with new technologies to increase efficiency and safety. Fuel cells alone are not an energy source; they are merely a clever way of storing and transferring energy in an environmentally-friendly way. This means that in order for fuel cells to become commonplace, it will be necessary to develop an energy network based on renewable resources, not fossil fuels, to provide the hydrogen. These two technologies have to be developed in tandem, because fuel cells cannot generate energy, and most renewable energy sources are not suited for mobile applications. At some point in the future, the costs of fossil fuels, both environmentally and economically, will outweigh their benefits, leaving renewable energy and hydrogen fuel cells to take center stage.

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Hydrogen: Fuel of the Future?

by Leonid Paritsky

Abstract

Hydrogen has the potential to enhance our electric grids within the decade. It can shift the dependence of power plants from traditional fossil fuel-based production, to cleaner methods involving solar energy and electrolysis. But the technology required to store this potent source of energy is marred with difficulties. Weight, volume, and standards are all major concerns. The automotive industry will have to wait for its clean energy source. Hydrogen will not be applied to commercial cars on a large scale for decades to come.

Introduction

Energy is life. Whether extracted from nuclear bonds, ATP or geothermal vents, energy is so essential, so ingrained, that it has no real synonym. We transmit it as electricity to light up our houses, store it inside our bodies as complex phosphates, and pillage the Earth's own natural stores of it to run our planes, cars, and microwaves. Energy powers our minds and machines alike, making it the cornerstone of this modern technological society.

But while the first law of thermodynamics tells us that energy is conserved, the Earth's own usable supply of it is not. Since the onslaught of the industrial revolution, mankind's energy production has been inextricably tied to the *consumption* of one subset of natural resources – fossil fuels. These hydrocarbons found in the Earth's upper crust account for almost 86% of U.S. energy consumption.[1] The deadly carbon dioxide emissions that this economy is fostering are

[1] "U.S. Energy Consumption by Energy Source." Energy Information Administration. April 2008. U.S. Department of Energy. <http://www.eia.doe.gov/cneaf/solar.renewables/page/trends/table1.html>.

mounting. The Earth's ecosystem is suffering and the need for "greener" solutions is greater than ever.

The automobile industry is one of the many parts of world infrastructure in need of these new, alternative energy sources. Around 27% of total U.S. energy consumption went towards transportation in 2002.[2] The petroleum that fuels cars is now tied to inevitably rising prices, economic turmoil, and political unrest. But despite the 10% of global CO_2 emissions linked to consumer cars, the long established industry is reluctant to change, especially with no perfect alternative on the market.[3]

Along with solar, wind, and biofuels, hydrogen energy is quickly emerging as a possible solution to this global crisis. One of the simplest elements, hydrogen can be abundantly found as a part of water. But is this "hydrogen economy" feasible? How much energy must be put in to tap the potential of this element? If hydrogen can be efficiently produced from water, active metals – or even fossil fuels – and stored in a reasonable volume, then the means to meet the world's growing demands (a 14% increase by 2030) are near.[4]

Based on the state of modern technology, and supported by a survey of current research and statistics, as well as recently performed laboratory experiments, hydrogen *is not* the *immediate* new energy source the automobile industry has been waiting for. Although it may still hold potential to be used in power plants and industrial applications, hydrogen production is still too

[2] Hartsook, Christa. "United States Energy Industry Overview." Agricultural Marketing Resource Center. April 2004. <http://www.agmrc.org/NR/rdonlyres/A24B5841-2846-42E6-9C4C-D30C49D06B0E/0/energyoverview.pdf>.

[3] DeCicco, John and Freda Fung. "Global Warming on the Road: The Climate Impact of America's Automobiles." Environmental Defense. 2006. <http://www.edf.org/documents/5301_Globalwarmingontheroad.pdf>.

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energy inefficient, and hydrogen storage too primitively developed, in order to promote consumer usage in cars.

Experimental Procedure

Hydrogen From Water[5]

An acidic solution composed of H_2O and H_2SO_4 was connected in a series circuit along with a battery and ammeter. Electrolysis was performed, and hydrogen gas was collected in a burette positioned upside down in the solution.

Hydrogen From Active Metals[5]

Active metals were exposed to acids of varying concentration, and the amount of hydrogen gas released, as a result of the interactions, was noted. The three metals that were of particular interest were: magnesium, zinc and aluminum.

Constructing Solar Cells[5]

A TiO_2 and a Copper solar cell were constructed. A copper sheet was heated on a hot plate, yielding the necessary Cu_2O. The sheet was then combined with copper electrodes, and wedged into a cell made from a CD jewel case. The TiO_2 powder was filmed onto glass plates, one of which was annealed.

Results

Hydrogen From Water[5]

1) Kilowatt-hours required to produce 1kg of hydrogen: 166.84 kW*h
2) Cost of generating 3.8kg of hydrogen using batteries (52,000 mA*h): $60,960
3) Cost of generating 3.8kg of hydrogen using household electricity (17 cents/kW*h): $107.78

Hydrogen From Active Metals[6]

[5] Note: data taken from a laboratory exercise preformed by the author during the course of Chemistry 16.

1) Cost of generating 3.8kg of hydrogen using Mg (including cost of HCl): $305

2) Cost of generating 3.8kg of hydrogen using Zn: $109.45

3) Cost of generating 3.8kg of hydrogen using Al: $171

Constructing Solar Cells[7]

1) Coulombs required to generate 3.8kg of hydrogen: 3.67×10^8 C

2) At .5A/cell, hours required to generate 3.8kg of hydrogen: 2.04×10^5 hours

3) 84.6 kWh required to generate 3.8kg of H_2 at 830mV.

Methanol Fuel Cell[8]

	Volumetric Energy Density (kJ/cc)	Gravimetric Energy Density (kJ/kg)	Hydrogen Atom Storage Capacity (moles of H/cc)
H_2	0.011675	xxxxxxxxxxxxxxx	8.18E-05
Methanol	17.95	22684.4	0.0989
Octane	3.46	xxxxxxxxxxxxxxx	0.145

Hydrogen gas would have be compressed to 1537.5atm in order to achieve a volumetric energy density equal to Methanol. It would have to be compressed to 296.4atm to achieve a volumetric energy density equal to that of octane.

Hydrogen No Longer a High Cost Solution to Global Warming: New Ideas[9]

6 *Ibid.*
7 *Ibid.*
8 *Ibid.*
9 Bockris JO'M. "Hydrogen no longer a high cost solution to global warming: New ideas." *Int J Hydrogen Energy* **2008**.

1) Calculation for the cost of hydrogen produce via electrolysis:

Cost($) of 10^6 BTU of H_2 = 2.29Ec + 4

E = cell potential (V)

c = cost of electricity (cents/kWh)

$4 represents amortization costs, operation and maintenance costs, and insurance.

Note: 1MBTU = ~ 1GJ

2) Cost of utilizing solar energy to produce an amount of hydrogen equal to (in first law energy) to a gallon of gasoline.[10]: $2.50

Hydrogen Storage[11]

Material	H-atoms per cm^3 (x 10^{22})	% of weight that is hydrogen
H_2 gas, 200 bar (2850 psi)	0.99	100
H_2 liquid, 20 K (-253 C)	4.2	100
H_2 solid, 4.2 K (-269 C)	5.3	100
MgH_2	6.5	7.6
Mg_2NiH_4	5.9	3.6
FeTiH_2	6.0	1.89
$LaNi_5$ H_6	5.5	1.37

Discussion

10 *Ibid.*

11 Becker, Laura. "Hydrogen Storage." ProQuest/CSA. June 2001. <http://www.csa.com/discoveryguides/hydrogen/overview.php>.

Coming up with a meaningful benchmark for hydrogen generation is a difficult task. Methods of production range from using “green” energy sources such as solar or wind power, to conventional coal burning (with some CO_2 reclamation). And with no mainstream data regarding the usability of hydrogen with respect to cars and transportation, the task become even more complex.

To this end, a somewhat arbitrary goal has been set: to base our cost analysis on generating 3.8kg of hydrogen -- the amount required to fuel a concept car for 160 miles.[12] To put this figure in perspective, BMW’s recently announced Hydrogen 7, a hybrid car capable of running on conventional gasoline as well as H_2, has a storage capacity of roughly 8kg of hydrogen – enough to go at least 120 miles.[13] Considering the pace of current technological development and the need for cheaper energy, our 3.8kg benchmark is not as overly optimistic as it may seem.

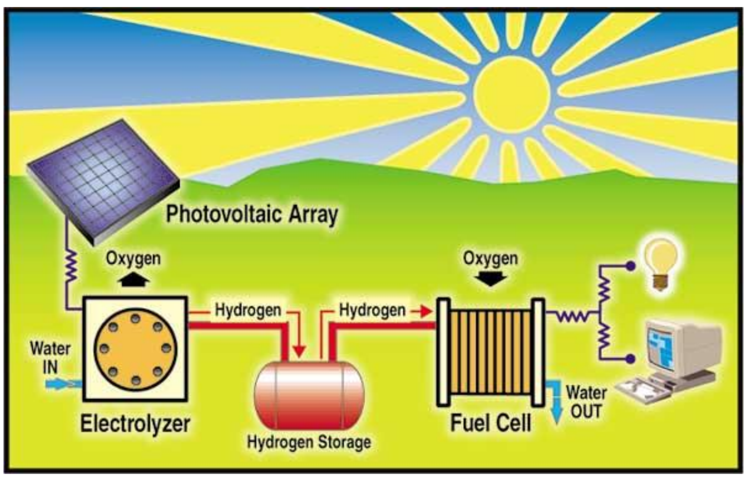
Before we start putting hydrogen in our cars, we need to find a way to reliably produce it. The H_2 generation process can often be complex and costly. There are many possible paths to be taken, and the juxtaposition between the traditional, more common methods and promising new technologies is presented below:

Generation

The costs of generating this critical 3.8kg from both electrolysis and active metals are summarized in the Results section. The cheapest option is to use household electricity, at $107.78 per 3.8kg, with generation from Zinc following as a close second. However, it is important to note that using metals will require more time and processing, and will also tie the price of energy to the price of that metal. A price that can only increase as the technology becomes more and more mainstream.

[12] Note: data taken from laboratory exercises performed by the author during the course of Chemistry 16.
[13] Vanzieleghem, Bruno. "BMW Officially Announces the BMW Hydrogen 7." Autoblog Green. 12 Sep 2006. <http://www.autobloggreen.com/2006/09/12/bmw-officially-announces-the-bmw-hydrogen-7/>.

Solar energy, on the other hand, is free, clean and a rapidly advancing field. With cell efficiencies on the rise, governments and the private sector are undertaking large solar projects and looking to tie this emerging energy source into the electrical network. The photovoltaic cells underlying this technology do not directly require hydrogen, but because the sun will not be radiating at a constant intensity at any given location (due to cloud formations, weather anomalies, and of course nighttime) some form of energy storage is required. Hydrogen can be the vessel for this storage, and provide for an efficient source of constant and continuous electricity, through electrolysis. The image below shows a simplified schematic of "The Solar Hydrogen Cycle"[14]:



http://www.schatzlab.org/solarh2cycle.html Copyright © Schatz Energy Research Center

An emerging company, Nanosolar, claims to have established a plant boasting electricity generation costs equal to that of coal-based systems (~2cents/kWh). Their technology is based on a revolutionary thin printing process that requires no pricey silicone and boasts $1/watt panel. A power plant in Europe is currently in development, expecting to produce 1.4MW and begin construction next year. No cell efficiencies are given, and the data is kept very secretive, but a

[14] "The Solar Hydrogen Cycle." Schatz Energy Research Center. <http://www.schatzlab.org/solarh2cycle.html>.

cost analysis done by researchers (see Results section) shows the promise of very reasonably priced energy. [15,16]

A more common method of generating hydrogen, currently used in most industrial applications, is to extract the gas from fossil fuels. Although this maintains the troublesome reliance on these controversial natural resources, a brief overview of the process is a necessary step in understanding the current state of the hydrogen economy.

Often, “a hydrocarbon gas,[such as methane], is mixed with steam at high temperatures and pressures in the presence of a catalyst producing hydrogen and CO_2.”[17] The reactions would look like the following:

$CH_4 + H_2O \rightarrow CO + 3H_2$ and then $CO + H_2O \rightarrow CO_2 + H_2$.[18]

Methanol is sometimes used as an alternative hydrocarbon. This process is known as steam reforming. Although the CO_2 can sometimes be collected and prevented from entering the atmosphere, no perfect system currently exists to make the reforming process pollutant-free.

Some research is currently being aimed at applying reforming on a compact scale, applicable to the automotive industry. The idea involves the use of compact fuel processors in conjunction with PEM (Proton Exchange Membrane) fuel cells.[19] Conceivably, hydrogen fuel cells could be used with the mini-reformers providing the necessary H_2 gas. These hydrogen cells operate due to the following chemical reactions:

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[15] Bockris JO’M. “Hydrogen no longer a high cost solution to global warming: New ideas.” *Int J Hydrogen Energy* **2008**.

[16] Moyer, Michael. "The New Dawn of Solar." Popular Science 12 Nov 2007 <http://www.popsci.com/popsci/flat/bown/2007/green/item_59.html>.

[17] "Generation of Hydrogen." Applied Alloy Chemistry Group. University of Birmingham. <http://www.aacg.bham.ac.uk/hydrogen/generation.htm>.

[18] *Ibid.*

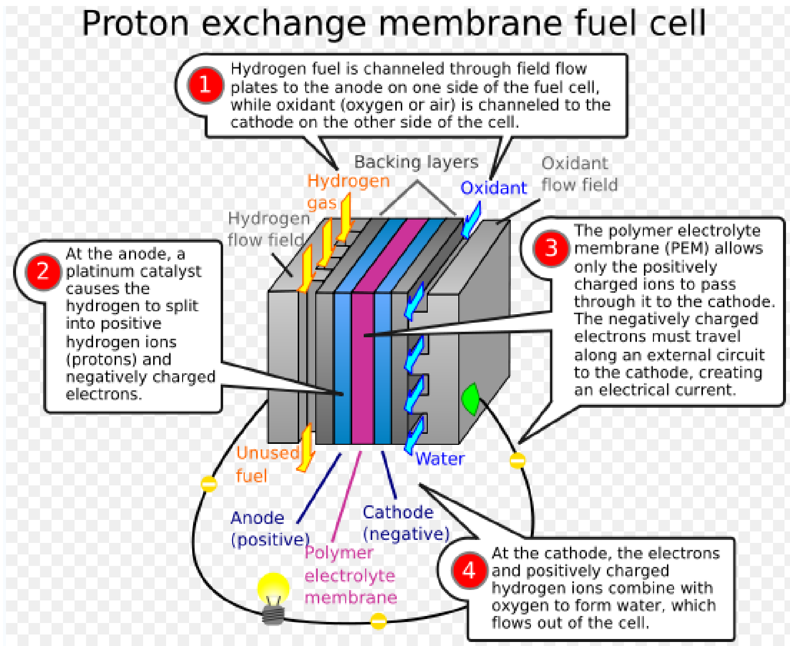
[19] "Compact Fuel Processors for Automotive Fuel Cells." Micro Chemical and Thermal Systems. 18 Dec 2002. Pacific Northwest National Laboratory. <http://www.pnl.gov/microcats/fullmenu/compfuelproc.html>.

At the anode: $2H_2 \rightarrow 4H^+ + 4e^-$

At the cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

The overall reaction is: $2H_2 + O_2 \rightarrow 2H_2O$

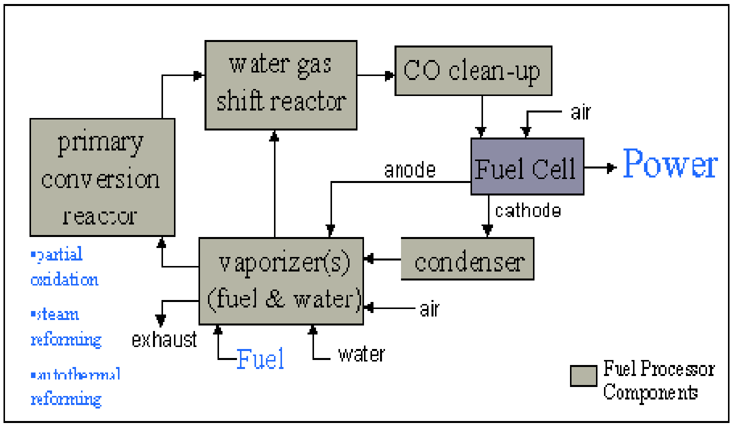
The electrons are channeled through the circuit, while the H^+ ions drift through the membrane, from anode to cathode. Below is a useful illustration of the overall cell[20]:



http://en.wikipedia.org/wiki/Image:PEM_fuelcell.svg

When this cell is combined with the reforming process described above, and the entire system is compacted to a usable size, an automotive fuel cell results:

[20] Nice, Karim, and Jonathan Strickland. "How Fuel Cells Work." 18 September 2000. HowStuffWorks.com. <http://auto.howstuffworks.com/fuel-cell.htm> 30 April 2008.



http://www.pnl.gov/microcats/fullmenu/compfuelproc.html

We have shown that hydrogen can be generated from a plethora of sources -- with byproducts ranging from harmful greenhouse gases to innocuous water. But the main question plaguing the minds behind the automotive industry is: can it be stored?

Storage

While easily exploitable, hydrogen gas is a very diffuse source of energy. Its volumetric energy density (See Results: Methanol Fuel Cell) is extremely low with respect to competing sources, including octane (representative of conventional gasoline). This shortcoming is echoed by H_2's tiny hydrogen atom storage capacity. In fact, it is octane that has the most hydrogen atoms per cubic centimeter, and thus the greatest capacity to yield energy. It is no coincidence that gasoline continues to be used as the primary fuel for cars.

In fact, hydrogen gas would have to be compressed to almost 300atm pressure in order to yield the same energy density as octane – an unreasonable amount for a commercial vehicle. Storage space may not be an issue for a solar-hydrogen power plant, but when we talk about vehicles, it is the primary concern.

Just one gram of H_2 gas occupies almost three gallons at atmospheric pressure. Storing hydrogen in liquid form is a possibility, but requires cryogenic temperatures that are not easily achieved for commercial use. Conventional methods use hydrides, alloys that bond with, and hold, hydrogen as container materials.[21] See Results: Hydrogen storage, for a table of commonly used alloys and their respective hydrogen densities. These alloys can absorb and release hydrogen numerous times, ideally without degrading. Chrysler is currently in the process of testing sodium borohydride (created from borax, a detergent ingredient).[22] The charging and discharging of hydrogen from these alloys can be modeled as a battery system:

$\text{Alloy} + H_2O + e^- \leftrightarrow \text{Alloy(H)} + OH^-$ [23]

Eventually, the “hydrogen cycling” will degrade and render the alloy useless.[24]

But while this hydride storage system looks promising – provided more research is done into preventing decay – the largest problem facing the hydrogen economy is standardization. Chrysler is researching their own alloy; no doubt BMW is doing the same. Refueling stations are a necessity, and they cannot operate while having to cater to multiple, inherently incompatible technologies. A successful network of stations would require one, possibly two, dominant storage systems or alloys to emerge. With isolated companies and governments currently conducting their own initial research, it does not appear that a certified “winner” will come onto the market in the near future.

Hydrides are just one of many options. Material developments have provided the technology behind carbon-reinforced, compressed hydrogen gas tanks. These tanks, currently being researched by Quantum Technologies, have already been certified by some governments for

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[21] Becker, Laura. "Hydrogen Storage." ProQuest/CSA. June 2001. <http://www.csa.com/discoveryguides/hydrogen/overview.php>.

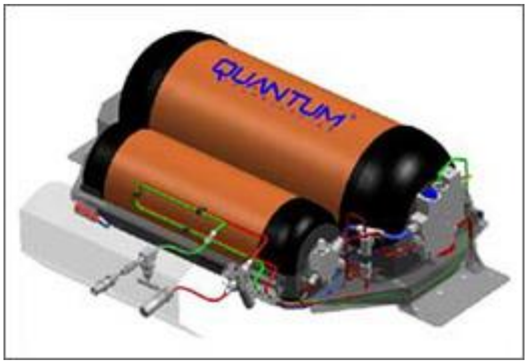
[22] Brain, Marshall. "How the Hydrogen Economy Works." 16 January 2002. HowStuffWorks.com. <http://auto.howstuffworks.com/hydrogen-economy.htm> 30 April 2008.

[23] Becker, Laura. "Hydrogen Storage." ProQuest/CSA. June 2001. <http://www.csa.com/discoveryguides/hydrogen/overview.php>.

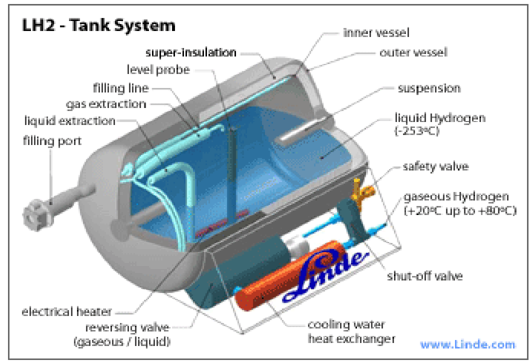
[24] *Ibid*.

commercial use. Even liquid hydrogen storage systems, previously discussed, are being experimented with by the DOE. [25]

Compressed Hydrogen Tanks



Liquid Hydrogen Tanks



http://www1.eere.energy.gov/hydrogenandfuelcells/storage/hydrogen_storage.html

Below is an image of the DOE's "Status of Hydrogen Storage Technologies". Note the relationship between volumetric and gravimetric capacity, as well as the government's targets for the upcoming years. Their cost estimates show that hydrides (the most tested method) are currently the cheapest option.

There are multiple possible paths towards hydrogen storage. Just looking at the chart above leaves no doubt that some solution to this road-block on the way to a cleaner energy economy will be found. But will it be found timely enough to stave the onset of global climate change? And will this profound development occur within our lifetime? Our children's lifetime? The state of research today is still too primitive, too exploratory, to ensure timely development. There is a lack of funding, facilities, and -- even with green energy becoming increasingly popular -- a lack of support for specific solutions. Researchers today are laying the foundation for a brighter future -- but do not expect to be driving your BMW Hydrogen 7 any time soon.

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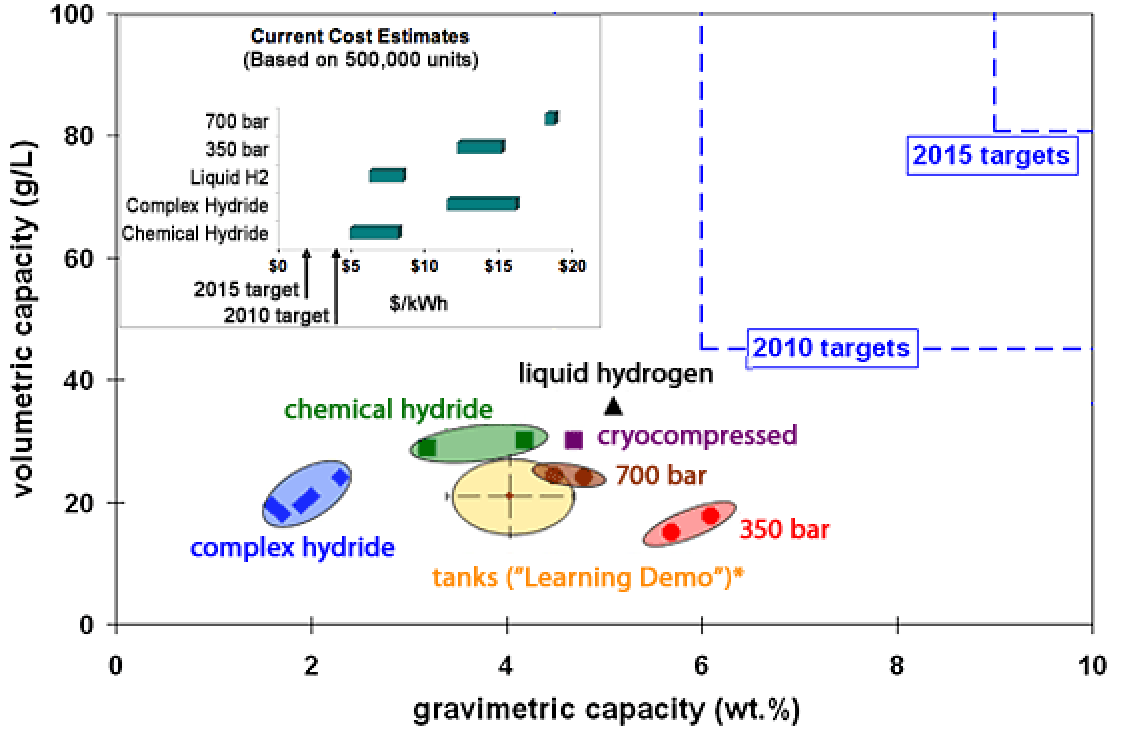
[25] "Gaseous and Liquid Hydrogen Storage." Energy Efficiency and Renewable Energy. 05 Mar 2008. U.S. Department of Energy. <http://www1.eere.energy.gov/hydrogenandfuelcells/storage/hydrogen_storage.html>.



http://www1.eere.energy.gov/hydrogenandfuelcells/storage/tech_status.html

Summary and Conclusion

Hydrogen can be extracted from a variety of sources. Solar energy coupled with electrolysis, metals reacted with acid, even conventional fossil fuels. The costs related to these processes have been discussed, and there is a promising future ahead. Solar energy is quickly becoming cheap, efficient and mainstream (not to mention clean) and makes for a perfect hydrogen generator.

Storing this newfound energy source presents more of a problem. The U.S. Department of Energy summarizes the challenges best:

1. "Weight and Volume" – needs to be minimized
2. "Efficiency" – lower the energy required to store/retrieve.
3. "Durability" – increase the amount of cycles that a tank can survive.
4. "Refueling Time" – should be in the order of minutes.
5. "Costs"

6. Standardization [26]

Hydrogen is a perfect means towards getting cleaner energy into our homes. Power plants that extract energy from the Sun and store it in the form of hydrogen are already cropping up in the U.S. and Europe. These plants can be massive (in fact have to be, in order to soak up enough rays) and building tanks large enough to store the hydrogen is increasingly less of an issue. Developments and updates to our mainstream electrical grid will be occurring within the decade.

The auto industry will have to wait longer. The six points made above, while being researched, are nowhere near to being answered. Much more research and development is needed, and a consensus that narrows down the options, to a handful of dominant technologies, is necessary. A network of refueling stations is decades away. And while individual car manufacturers (and enthusiasts) will continue to come up with concept cars running on hydrogen, it will take a large industry effort (think funding) and an increased level of public support to get any serious developments through. The researchers are there; the need is great; the technology is around the corner. All that's left to do is throw in money, some time -- and let global warming heat it all up.

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13. "The Solar Hydrogen Cycle." Schatz Energy Research Center. <http://www.schatzlab.org/solarh2cycle.html>.

14. "U.S. Energy Consumption by Energy Source." Energy Information Administration. April 2008. U.S. Department of Energy. <http://www.eia.doe.gov/cneaf/solar.renewables/page/trends/table1.html>.

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Current Solar Cell Technology and its Use in the Production of Hydrogen Fuel

by Julia Wagner

Abstract

Photovoltaic cells, with their clean-running modules and abundant, free power source, remain the best environmentally-responsible energy alternative both for consumer electricity and for the generation of hydrogen through electrolysis. Although the energy output from solar cells is still well below that of burning hydrocarbons, clean energy is a necessity now, and with the rate at which technology is progressing, PV efficiency can only increase. This paper provides some basic comparisons between different kinds of solar cells, and calculates the scale of solar energy needed to electrolyze water both in a fuel cell and from a sulfuric acid solution.

Introduction

Since the Industrial Revolution, humanity has based its technological advancement upon energy gained from burning fossil fuels. Engineers and businessmen of the past concerned themselves only with achieving the highest energy output possible from their fuel sources, disregarding the side effects. This incautious approach left modern engineers and businesspeople not only with acid rain and climate change, but also with the task of finding clean and renewable sources of energy for the modern world: sources that must be reliable, able to be widely produced, non-damaging to collect, capable of being stored, and low in harmful byproducts.

Solar energy, in conjunction with hydrogen as fuel, meets these requirements. In the southwestern US, sunlight is reliable and can be collected year-round. Unlike mining coal or oil, gathering sunlight does not cause irreparable damage to the surrounding environment. In addition, solar energy does not rely on a commodity that may run out, and the modules require little maintenance. The electricity from solar cells, or photovoltaic cells, can also be harnessed to create hydrogen gas by electrolysis. This hydrogen can be stored and used to produce electricity when combined with oxygen. Though this system is not perfect in efficiency, its important advantage over fossil fuels is that it produces only water in its reaction. The electrolysis of water provides a clean storage method for solar energy—a technology that has the potential to supplement solar power for, say, the night or cloudy days. The generation of energy by solar cells also produces no harmful byproducts except the panels themselves, which are now being recycled by some companies[1].

Since their development in the first half of the 20th century, solar cells have increased in efficiency and cost effectiveness. Though they are traditionally made from expensive materials such as refined silicon or other semi-conductors, as the cost of oil rises, solar cells are becoming more practical as the primary source of electricity for both industrial and developing countries. They can operate well in isolated areas, because they are reliable, and do not need to be attached to any electricity grid. They also work well in urban environments, unlike wind turbines, because multiple arrays on the roofs of houses and businesses can feed into one another so that a city can generate and use its own electricity communally. Furthermore, with oil near $120 per barrel, not to mention the political costs of continuing to use foreign oil, the costs associated with solar energy start to look less daunting. However, this paper's purpose is to compare the major categories of solar cells in development, with the understanding that a switch to renewable energy is inevitable, and so this paper does not deal with many economic specifics. Instead, this paper will explore and compare 5 types of solar cells: the two from Chemistry 16's Solar Cells lab and three from outside sources, which provide more information. Each of these will be analyzed for the area of solar panels needed to produce 3.8 kg of hydrogen gas in one hour, and rates of hydrogen generation will be compared for two methods.

Procedure

The three labs from Chemistry 16 that are relevant to the topic of solar energy and electrolysis are “Constructing Solar Cells,” “Hydrogen from Water,” and “Hydrogen Fuel Cells.” Described here are the procedures from these labs; all were performed during the spring semester of the 07-08 academic year.

Constructing Solar Cells

This lab required two different types of solar cells to be built. The first, the Gratzel cell, relies on a paste of TiO_2 and blackberry juice, a dye used to conduct electrons from the exited state in the TiO_2 into the external circuit. The second, the Cu_2O cell, relies on copper metal, a salt solution, and Cu_2O (a semiconductor). When excited from the Cu_2O, an electron transfers to the copper metal, then through the external circuit, then back into the cell through the salt solution.

The Gratzel cell was constructed by coating the sides of two, 1-in^2 indium tin oxide (ITO) conducting plates with a paste made of TiO_2 powder, an acetic acid solution, and the surfactant Titan X100. Once these had been baked dry, they were soaked in blackberry juice, placed coated-face-to-coated-face, clipped together, and tested under the sun lamp. Voltage and current were noted.

Building the Cu_2O cell began with heating a 4-in^2 copper plate over a hotplate. Then, a “U” shaped piece of copper metal was adhered to a plastic jewel case using silicone glue. The heated copper plate (now covered with Cu_2O), was then placed on top of two round, wooden “spacers” on top of the copper “U.” The whole apparatus was made water-tight with silicone glue, and was filled with NaCl solution via a syringe. Alligator clips were attached to a tab from the “U” and another tab protruding from the plate. This cell was also tested under the sun lamp. Voltage was noted.

Hydrogen from Water

In this lab, hydrogen gas was collected in an upturned burette over a beaker of a sulfuric acid solution. The negative lead from a 6-V battery was threaded into the mouth of the burette, so that the hydrogen released by electrolysis could only percolate up into the burette. Current, time, and volume of H_2 collected were noted.

Hydrogen Fuel Cells

Although one section of this lab dealt with using solar energy to electrolyze water in a hydrogen fuel cell, no group took satisfactory notes on the results, so it will be excluded from this paper. Instead, Section B will be described and analyzed.

An AA (1.5-V) battery was wired to a small hydrogen fuel cell. This apparatus was filled with 18 MΩ water; all air was removed. The circuit was completed and hydrogen and oxygen gases were produced. When about 15-mL of hydrogen gas had been generated, the battery was removed from the circuit and replaced with a small fan. The current, voltage, and rate of hydrogen consumption by the fan were noted.

Results

Constructing Solar Cells

Cell type	Voltage measured (mV)	Current measured (mA)
Gratzel	198	9.5 E -3
Cu_2O	10.5	---

Hydrogen from Water

Voltage provided by a 6-V battery.

Time (min)	Current (A)	Volume H_2O (mL)	Volume H_2 (mL)
3	.17	21.2	3.8
5	.1707	18.5	6.5
7	.1698	15.8	9.2
9	.1708	13.1	11.9
11	.1706	10.5	14.5
13	.169	7.9	17.1
15	.1687	5.2	19.8
17	.1693	2.7	22.3
19	.1666	.1	24.9

Run 1

Time (min)	Current (A)	Volume H_2O (mL)	Volume H_2 (mL)
3	.1873	20.4	4.6
5	.1866	17.8	7.2
7	.1856	14.9	10.1
9	.1845	12.0	13
11	.1828	9.1	15.9

13	.1818	6.4	18.6
15	.1826	3.5	21.5
17	.1780	.7	24.3

Run 2

The initial conditions for the experiments are given below:

Pressure (atm)	Temperature (K)
0.995	295.15

Hydrogen Fuel Cells

This data was collected by observing the rate at which the hydrogen fuel cell produced Hydrogen gas.[27]

Time (min:sec)	Volume generated (mL)
0:00	0
1:20	2

[27] Data from Matthew Kelly and Austin Lines, Chemistry 16, Tufts University

2:48	2.7
3:08	3
3:57	4
4:56	4.4
5:34	5
6:59	6
8:57	7
9:40	7.6
10:38	8
12:17	8.6

Time – con’t	Volume con’t
13:20	9
15:09	10
17:30	10.6
18:41	11
20:05	11.6
21:36	12
24:12	12.6
26:10	13
27:50	13.6
30:20	14
33:28	14.4
36:04	15

All outside research for this paper focused on three varieties of solar cell based on three different semiconductors: amorphous silicon, cadmium telluride, and copper indium gallium selenide (CIGS). Their raw data, collected from sources[3],[4], and[5], are given here; analysis and their qualitative properties are discussed in the next section.

Name	Amorphous Si	CdTe	CIGS
Voltage (mV)	550	849.9	665
Current (mA/cm^2)	30	25.5	31.5
Efficiency (%)	10.6	16.1	16.4

Analysis and Discussion

One constant for comparison throughout all of these analyses is the amount of charge needed to liberate 3.8 kg of H_2 from water. The calculation is given below.

$$3.8\,\mathrm{kg}\cdot\left(\frac{1\mathrm{mol}\cdot\mathrm{H2}}{2.016\mathrm{gm}\cdot\mathrm{H2}}\right)\cdot\left(\frac{4\cdot\mathrm{mol}}{2\cdot\mathrm{mol}\cdot\mathrm{H2}}\right)\cdot\left(\frac{6.02210^{23}\cdot\mathrm{elec}}{1\cdot\mathrm{mol}}\right)\cdot\left(\frac{1.60210^{-19}\cdot\mathrm{C}}{\mathrm{elec}}\right) = 3.637\times 10^{8}\,\mathrm{C}$$

If another constant is set, and it is assumed that the 3.8 kg are generated in 1 hour, then the following amount of current should be required from any given solar array:

$$\frac{3.637\times10^{8}\,C}{hr} = 1.01\times10^{5}\,A$$

This number was used to calculate the area needed for each type of solar cell to produce the required current in one hour. The above current was divided by each cell's current per unit area. Here is a table of the results:

	Amorphous Si	CdTe	CIGS	Grätzel	Cu_2O
Area (m^2)	336.667	396.078	320.635	6206	*Amps not measured

When hydrogen gas was generated from electrolysis of sulfuric acid solution or in a fuel cell, the voltages were fixed. Under these voltage conditions, the time needed to generate 3.8 kg are as follows:

Electrolysis:

Where the dependent variable (x) is time and the independent variable is current, the trend lines for Runs 1 and 2 as given above are:

Run 1: $-.0002x + .1715$ Run 2: $-.0005x + .1887$

When integrated, these give charge (C):

$$\int_0^{1.14\times10^3} -.0002x + .1715\,dx = 65.55$$

Run 1:

$$\int_0^{1.02\times10^3} -.0005x + .1887\,dx = 67.626$$

Run 2:

Then, time is calculated as follows:

$$3.637\times 10^8\ C\cdot\frac{(19\cdot min)}{65.66C} = 200.103yr \qquad 3.637\cdot 10^8\cdot C\cdot\left(\frac{17\cdot min}{67.626C}\right) = 173.834yr$$

Therefore, using the set-up from performed labs, the time required to generate 3.8 kg of hydrogen averages to be around 187 years.

Hydrogen Fuel Cell:

The fuel cell was powered by an AA battery, which lists a potential of 1.5-V.

The rate of hydrogen gas production is as follows:

$$\frac{15mL}{36\min + 4s} = 6.932\times10^{-3}\,mL/s$$

The density of hydrogen gas at room temperature was calculated:

$$\frac{1\cdot atm}{\left(\frac{0.082057L\cdot atm}{mol\cdot K}\right)\cdot(295.15K)}\cdot\left(\frac{2.016g\cdot H2}{mol\cdot H2}\right) = 8.324\times 10^{-5}\,\frac{g}{cm^3}$$

Thus, at this rate, to generate 3.8 kg would take:

$$3.8kg\cdot\left(\frac{1\cdot cm^3}{8.324\times 10^{-5}\cdot gm}\right)\cdot\left(\frac{1\cdot s}{6.932\times 10^{-3}\cdot mL}\right) = 208.688yr$$

The numbers for efficiency of electrolysis and fuel cells seem dishearteningly low, but if supplied with increased voltage, a fuel cell can run proportionally faster, so if it were supplied with 3 V instead of 1.5 V, it would run at twice the 1.5-V rate. A similar increase would be found with electrolysis. Furthermore, at an industrial level, electrolysis would be performed with much more conductive solutions—perhaps sea water, as in Japan—and would use much a much higher potential. Generation of hydrogen with fuel cells would use larger, layered fuel cells, so that more hydrogen could be generated from wall socket electricity. In fact, one idea for fuel cell cars is to pump extremely-low-conductivity water into them, plug them into a domestic wall socket, and let them generate their own hydrogen. With clean energy and a working storage system for the gases produced, this could be a viable transportation solution for the future.

Meanwhile, although solar cells are not yet as efficient as would be ideal, there are some new technologies that increase both their efficiency and their cost-effectiveness. First, researchers at the US Department of Energy's National Center for Photovoltaics have developed a “triple junction” solar cell that can capture a wide spectrum of the sun’s rays with groundbreaking efficiency. With the use of concentrating lenses, a 0.26686 cm^2 cell produced 2.6 W of electricity with a 40.7% efficiency rating. This extreme efficiency could drive the cost of solar electricity down to 10 or even 8 cents per kilowatt hour—a rate competitive with current consumer prices[2]. Another advance in solar technology is the development with “thin-film” solar panels. With efficiencies up to 19.9%, these varieties use about 100 times less semiconductor material than the standard-design photovoltaic. With silicon at $500 per kilogram, such savings will have a large impact on the practicality of solar power as the energy source for the future[1]. These thin-film cells are being tested with the three semiconductors listed from outside references: silicon, CdTe, and CIGS. According to Scientific American, thin-film solar cells made with CIGS can theoretically operate at up to 25% efficiency. CdTe cells have different, but still notable environmental benefits. Despite being made from heavy metals, they require the least amount of energy to manufacture, and their primary producer, First Solar, has begun a recycling program for used PV cells[1].

Analysis of the collected and calculated data shows that solar cells made with CIGS are the most efficient readily available technology for investment and large-scale use. However, developments in the triple junction model should be watched closely, because research in this area could provide the economic breakthrough solar needs to be taken seriously by consumers and the US government.

The main inhibitor for solar and fuel cell technologies is economic scale. The fossil fuel industry is long established, government-subsidized, and familiar to consumers.

For a solar energy economy to work, thousands of acres of desert would need to be converted into PV energy farms, with possible extensions of the solar grid onto urban roofs. With regard to hydrogen fuel, many electrolysis plants would have to be financed, built, and run, or each car (or, perhaps, home) would have to be able to electrolyze its own hydrogen from water. Such changes would require either heavy government subsidy or serious venture capitalism. Furthermore, additional problems lie outside the realms of economics and policy. New technologies, requiring different kind of cars, fuels, and consumer behavior take effort to launch, requiring the skills of marketing professionals and media campaigns.

Despite the initial difficulties associated with solar power and the use of fuel cells, these technologies are reliable and perhaps the cleanest methods available for energy production, conversion to fuel, and transportation. It is important to note, however, that hydrogen can only reasonably be used as an alternative fuel if it is generated from a clean source. Thus, the use of hydrogen fuel cells as fuel cannot go forward without further development of solar or other clean technology. In the same way, engineers are designing and testing methods of storing solar energy (in compressed gas or in "hot salt," for example)[6], and fuel cells could provide that service for solar cells by storing the energy as hydrogen gas. The two technologies have many possibilities for being linked.

Summary

Photovoltaic cells are the best solution for both the energy and environmental crises. They can provide clean energy for the needs of everyday life and for the industrial-scale generation of hydrogen gas for transportation uses. Solar technologies are improving at rapid rates, and the technology exists even today for solar to meet the energy demand of the United States[6]. What remains is to establish the necessary infrastructure to begin the transition to a sustainable energy future.

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"Hydrogen Fuel Cells," Shultz, M.

Supplement D – Diagnostic Quiz

1. Math with scientific notation

(a) Complete $\frac{1.49\times10^{11}}{91\times10^{-12}} =$

(b) Complete $\frac{3.6\times10^{-29}}{1.6\times10^{-49}} =$

(c) An isotope of a newly synthesized element #114 survives for 4.2×10^{-6} sec. An isotope of element #109 survives for 7.6×10^{-9} sec. Which isotope survives for the longer time? (Circle your choice.)

(d) A liter of saturated $PbCrO_4$ solution contains 1.3×10^{-7} moles of Pb^{2+} ions and 1.3×10^{-7} moles of CrO_4^{2-} ions. A liter of saturated CdS solution contains 6.0×10^{-15} Cd^{2+} ions and 6.0×10^{-15} moles of S^{2-} ions. Which solution contains more ions? (Circle your choice.)

2. Balancing equations

Circle the following reactions that are not balanced. Insert coefficients to balance them.

(i) $C + Cl_2 \rightarrow CCl_4$

(ii) $KClO_3 \rightarrow KCl + O_2$

(iii) $SO_2 + H_2O \rightarrow H_2SO_3$

(iv) $Au^{3+} + Ag \rightarrow Ag^{+} + Au$

(v) $CO + O_2 \rightarrow CO_2$

(vi) $FeO + H_2O \rightarrow Fe(OH)_2$

3. The periodic table

(a) Period three begins with ____ and contains _____ elements. Si is in group ____ and is a (metal) (semimetal) (a gas). (Circle the correct choice.)

(b) _______ is a transition metal. ______ is in period 4 and _____ is in group IV. In periods containing transition elements, there are ____ transition elements. (Only one of the several possible answers is required.)

3. Gas laws

(a) Party balloons are filled with helium and placed in a car for a surprise party. The car is parked in the sun. Do the balloons expand, contract or stay the same size. (Circle your choice.)

(b) Does the volume of a gas increase, decrease, or stay the same when the pressure decreases from 760 to 350 Torr and the temperature decreases from 250 °C to – 50 °C?

(increase) (decrease) (stay the same) (Circle the correct choice.)

(c) A 1-foot diameter cylinder is closed on one end and fitted with a moveable piston on the other. With 1.0 atm applied pressure, the piston is located 20 ft from the closed end. Where is the piston located if the pressure is reduced to 0.15 atm?

4. Avogadro's hypothesis

(a) Ozone (O_3) consists of three atoms of oxygen. At 20 °C and one atmosphere pressure, the density of ozone is 2.14 g/L. How many molecules of ozone are in one liter at 20 °C and one atmosphere?

(b) How many atoms of oxygen are in one liter of ozone at 20 °C and one atmosphere?

(c) An atmospheric reaction responsible for the brown haze over many cities is the conversion of N_2O_4 to NO_2. Both may be considered to be ideal gases. Which is more dense? (Circle your choice.)

5. Stoichiometry and mass

(a) How many atoms of S in one molecule of $Pb_2(SO_4)_3$?

(b) What is the molar mass of $Ca_3(PO_4)_2$? How many grams of P in 1 kg $Ca_3(PO_4)_2$?

(c) What is the molar mass of H_3PO_4? How many grams of O in 1 kg H_3PO_4?

6. Density and reasoning

(a) The density of Cu is 8.96 g/cm^3. How many Cu atoms in a cube 1 cm on a side?

(b) The density of Al is 2.6989 g/cm^3. How many Al atoms in a cube 1 cm on a side?

(c) Which is larger, an atom of Cu or an atom of Al? (Circle your choice.)