Chapter 1

Calculation/Short Answer Problems:

1.1 Go online and try to find 10 reliable fuel cell information websites. There are good general sites as well as industrial sites with reliable information available. There are also dozens in not hundreds of sites with questionable accuracy.

Soln:

Obviously, the Internet is a fluid environment. The following have been decent sources:

1) www.**fuelcells**.org *Regularly updated fuel cell information site*
2) www.usfcc.com *The USA Fuel Cell Council site*
3) http://dodfuelcell.cecer.army.mil/ *USA Department of Defense fuel cell site.*
4) http://www.cafcp.org/ *California fuel cell vehicle partnership site*
5) http://www.sae.org/fuelcells/fuelcells.htm *American Society of Automotive Engineers Fuel Cell site*
6) http://www.hfcletter.com/ *Hydrogen and fuel cell letter*
7) http://www.fuelcelltoday.com/ *Regularly updated fuel cell information site*
8) http://www.fuelcellsworks.com/ *Regularly updated fuel cell information site*
9) http://www.fuelcelleurope.org/ *European fuel cell information site*
10) http://www1.eere.energy.gov/hydrogenandfuelcells/ *U.S. Department of Energy, Energy Efficiency and Renewables program information site*
11) http://www.fossil.energy.gov/programs/powersystems/fuelcells/ *U.S. Department of Energy, fuel cells program information site*
12) http://www.hydrogenassociation.org/general/fuelingSearch.asp *National Hydrogen association site*

1.2 Go online and identify companies that currently are developing each fuel cell technology listed in Table 1.1. Which technologies have the most/least current developers?

Soln:

There are numerous companies in development, the list is too numerous to provide a comprehensive and updated list. The main ones are most major automotive companies (transportation), many portable electronics manufacturers (portable devices) and several companies developing stand-along back up or stationary power. The website: http://www.fuelcells.org/ has maintained a list of fuel cell developers for several years.

1.3 Go online to the U.S. Patent and Trade Office and determine how many fuel-cell-related patents were granted for the latest year available. How does it compare to Figure 1.1?

Soln:

Depending on the year this question is answered and the particular search terms used, many more patents related to fuel cells can be found in comparison to Figure 1-1, which was obtained strictly for the search term "fuel cell". The number grows each year in a highly non-linear fashion.

1.4 Describe the differences between a battery and a fuel cell.

Soln:

A battery has stored reactants, where a fuel cell has flowing fuel and oxidizer. Therefore, a fuel cell can achieve a true steady state operation, whereas a battery is always discharging under galvanic operation. The fuels and oxidizers are generally different as well. There are several other differences that students can note, although these are the main ones stated in the text.

1.5 List the relative advantages and disadvantages of the PAFC, SOFC, MCFC, AFC, H_2 PEFC, and DMFC. List one potential power application well suited for each type of fuel cell.

Soln:

See Table 1.1.

1.6 List some potential niche applications for fuel cells.

Soln:

There are many, each with a different range of practicality. A partial list includes power for wheelchairs, implanted pacemakers and other medical applications, remote sensors, isolated off-grid power sources, golf carts, neighborhood vehicles, fork lifts, and many others.

1.7 Why do you think AFCs have been successfully implemented in space applications?

Soln:

In many space applications, some of the propulsion units have been powered by liquid hydrogen and oxygen. Since pure oxygen was available, the advantages of the AFC such as high cathode reaction efficiency can be realized without the limitations of electrolyte poisoning by carbon dioxide if operating on ambient air.

1.8 Why don't fuel cell manufacturers simply use one large fuel cell plate to obtain the required power output instead of stacking many fuel cell plates?

Soln:

I suppose this could be done, but it would not make sense for a variety of reasons. First, a single plate provides less than 1 V of potential, so that a step-up transformer and associated losses would be needed to condition the voltage to levels appropriate for most applications. Most fuel cell applications need some power conditioning, but the stack is generally designed to provide something close to the required voltage levels. A second practical limitation is that of the shape of the fuel cell. A single plate would require a large footprint, and be difficult to fit into the overall system of most applications. A third concern is that of reactant delivery. A stack with chimney manifold system to feed to all plates requires less pressure drop and lower local flow rates than a single large plate responsible for all of the required flow.

1.9 Why would a stack be aligned in series or parallel and what specific advantages can you think of where a combination of series and parallel would be useful?

Soln:

The use of a series or parallel configuration depends on the footprint, voltage, current, and reliability requirements of the system. A high-voltage requirement is best managed with multiple plates in series. A high-current requirement is best managed with multiple plates in parallel. A parallel arrangement has advantages in reliability, since a single fuel cell becoming non-operational does not shut down the entire stack. In many systems, a combination is used. For example, in many SOFCs, a bundle arrangement of SOFCs in a parallel and series configuration is used. In this situation, the overall fuel cell stack reliability is improved while the voltage output is also boosted to appropriate levels. In some transportation applications, the engine is split into two, four, or more individual series-arranged stacks tied in parallel for the same reasons.

1.10 Find a market price for hydrogen gas and normalize the energy content compared to the current local price of gasoline. Using octane as an approximation for gasoline energy content, compare the cost per kilojoule of energy of hydrogen to gasoline. What cost per liter of gasoline do you think must be reached before the hydrogen fuel source is economically competitive?

Soln:

Online, I found http://www.eere.energy.gov/afdc/altfuel/fuel_properties.html The LHV of gasoline is 44 MJ/kg. The LHV of H_2 is 120 MJ/kg. You could look this up or derive this from the balanced chemical reaction and the heats of formation.
Depending on the storage pressure, the volume of hydrogen will vary.

The density of gasoline, approximated as octane, is:691 kg/m^3
A gallon of gasoline is 0.003785411784 m^3

$$691\frac{kg}{m^3}\cdot 0.003785411784\frac{m^3}{gal} = 2.615\frac{kg}{gal}\cdot 44\frac{MJ}{kg} = 115\frac{MJ}{gal}$$

So one gallon of gasoline is roughly equivalent to 1 kg of hydrogen. The price of hydrogen will vary to a great extent depending on the production and delivery method, but the lowest cost estimate I have seen is around $2.50/kg, and the highest is around $10/kg. I typically see a hydrogen cost of $4.00 per gallon equivalent as the equivalent cost, with variation up or down depending on the production method and assumptions used.

So it looks like if the cost of gasoline becomes permanently ~ $3-$4 per gallon, hydrogen could become a viable alternative. The problems though are numerous: The cost of a new infrastructure for H_2, the safety concerns, and the fact higher prices inspire more drilling and more petroleum.

Ref: "About the real economics of massive hydrogen production at 2010 AD" by J. O'M Bockris and J.C. Weiss. in Hydrogen Energy VII, edited by T.N. Veziroglu and A. N. Protsenko, pp. 101-151. New York. Pergamon Press.

http://www.eere.energy.gov/afdc/resources/pricereport/price_report.html

1.11 Estimate the current approximate cost per kilowatt of power from a standard automotive combustion engine. (*Hint*: You can find this information if you do an internet search of "crate engines.") This is the cost target for fuel cell systems.

Soln:

From a google search of GM Crate engines, the following website was found (there are many more of a similar nature): http://www.crateenginedepot.com/
From this, I selected the "most popular engine", the ZZ4, at $3,779 and 350 hp. This works out to be 260 kW, or $14.50 per kilowatt. That is very inexpensive, for an engine not even designed to be particularly inexpensive (note that one would have to buy some other accessories to make it go). Some other engines listed are $12,000, which would be ~ $45 per kW, which is the US Department of Energy stated cost goal for 2010. The PEFC needs significant improvement in cost to be competitive. The answers students will get will vary around this target depending on the source used.

1.12 Estimate the current approximate cost per kilowatt of power from a standard laptop computer and cell phone battery. This is the cost target for portable cell systems.

Soln:

A comparison between batteries and fuel cells here is a little bit more difficult, as the batteries used in these applications are generally rechargeable and hold a total charge, or energy. You can come up with the same numbers for a fuel cell if you consider the energy in the fuel as part of the system. If you consider the fuel cell as fuel + fuel cell, and consider roughly half the volume of the battery to be replaced as fuel, then some proper comparisons can be drawn. The US Department of Energy stated cost goal for portable systems in 2010 is $3/kW electric. Numbers close to this are reasonable. The answers people get depend on the technology to be replaced and the sources used.

1.13 Estimate the current approximate cost per kilowatt of power from a standard stationary power generator system. This is the cost target for stationary cell systems.

Soln:

Online I searched and found a 7 kW electric stationary power generator powered by diesel for roughly $18,000, or $2,500 per kW electric. A 2 kW auxiliary unit cost $500, or roughly $250/kW. The US Department of Energy stated cost goal for auxiliary (3-5kWe) systems in 2010 is $400/kW electric, for larger, 250 kW electric systems the longer term goal is $750/kW electric. The answers people get will depend on the technology to be replaced and source chosen.

1.14 Estimate the power density of a combustion engine on a volume basis, that is, kilowatts per liter. Compare this to a power density for PEFCs of 1.3 kW/L.

Soln:

The crate engine in Problem 1.11 was a 350 litre/355 hp. So we get about 260 kW/350 liter = 0.74 kW/liter. The PEFC is comparable in terms of power density (note: this is an order of magnitude estimate, not including other system components for the IC Engine). However, the result is correct, we can indeed fit a comparably powered PEFC into an automotive chassis. The fuel cell stack itself is comparable in size to a combustion engine.

1.15 Make a plot of the volume of gas-phase hydrogen required to contain the equivalent energy in a gallon of gasoline as a function of pressure of 0–10,000 psig. (*Hint:* Assume the ideal gas law is valid.)

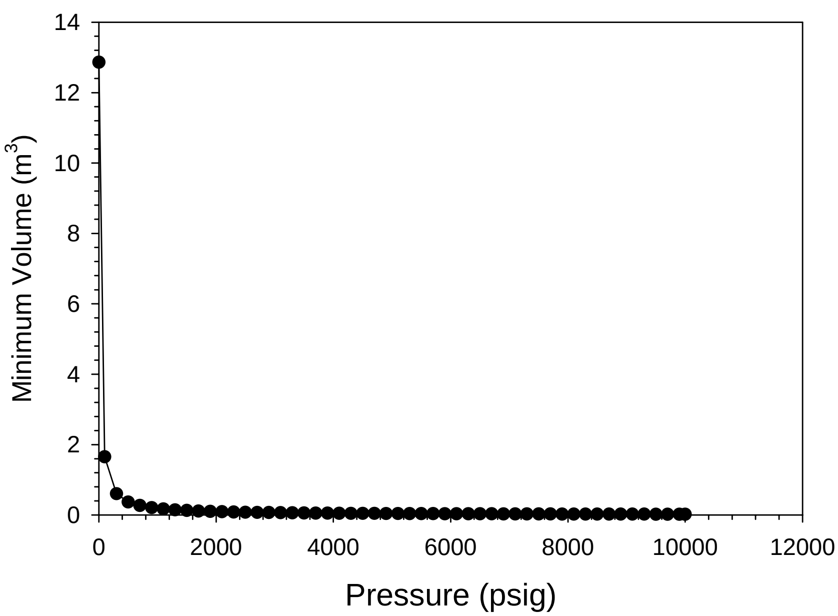
Soln:

Instructors Note: Problem 1.15. You need to assume room temperature of 293 K for this problem. I used this value in the solution here, and modified the question to include this information, which should be corrected in the second printing.

A gallon of gas contains about $1.3\text{x}10^8$ Joules of chemical energy, which you can look up online or in various texts. The low heating value of hydrogen is 242 kJ/mole. Thus a the equivalent amount of hydrogen for a gallon of gas is 537 moles of H_2, or roughly 1 kg of hydrogen. (This is a nice rule of thumb- one kg per gallon equivalent)
Now, using the ideal gas law (we shall see in Chapter 2 this is not always appropriate for hydrogen storage but we will use it here)

$$V = \frac{mR_uT}{MW \cdot P} = \frac{1.07kg \cdot 8.314\frac{kJ}{kmol \cdot K}293K}{2\frac{kg}{kmol}\left[\frac{P(psig)+14.7}{14.7}\right] \cdot 101.325\frac{kPa}{atm}}$$

This can be plotted in terms of minimum required gas volume (not including container volume, which increases substantially with increasing pressure):



1.16 List the three products of reaction from an operating fuel cell and discuss how each can be utilized in a fuel cell system.

Soln:

1) Electricity – this is obvious- to power the application.
2) Waste heat – this is less obvious. The waste heat can go toward *external* processes needing heat, such as a water heater in a house, or providing space heat, a process termed co-generation. Many high-temperature fuel cell systems use co-generation to increase the overall effective system efficiency. The waste heat can also be recycled for *internal* purposes to increase efficiency. For example, the waste heat can be used to preheat incoming gas, or to vaporize humidification water used for low temperature fuel cells.
3) Water - since the fuel cell produces water, in some cases it can be utilized. In low temperature fuel cells requiring humidification, the waste water can be partially recycled into the incoming stream to avoid the need for periodic refilling of a humidification water tank. Waste water can be used by fuel cells operating on reformed gas for the reformation process that breaks the gas down into carbon dioxide, hydrogen, and other species through a water-gas shift reaction (see Chapter 8). In some limited space applications, the waste water has been used to drink for the astronauts.

1.17 Consider an automotive application where nominally 300 V is required to operate the electric motors powering the wheels. If the fuel cells operate at an average cell voltage of 0.6 V, 1.1 A/cm^2, how many cells in series will the stack have? If the cells are 300 cm^2 active area each, what is the total current out of the stack? If the stack is now arranged with the individual cells in parallel, rather than in series, what is the current and voltage output of the stack? Is there a difference in power output ($P_e = IV$) of the two designs (parallel vs. series)? Why would we choose one design over the other in a practical application?

Soln:

If the fuel cell operates at an average cell voltage of 0.6 V, 1.1 A/cm^2, how many cells in series will the stack have?

A total of 300 *V* is needed. Assuming this all comes from the stack (there will be power management, with transformers and inverters, but we do want the initial voltage to be close to the motor requirements for high efficiency), then we need:

300/0.6 = 500 plates in series.

The total current would be 1.1 A/cm^2 * 300 cm^2 = 330 A.

If the stack is now arranged with the individual cells in parallel, rather than in series, what is the current and voltage output of the stack?

In parallel, the voltage is 0.6 V. The current becomes 330 A/per plate*500 plates = 165,000 A.

Is there a difference in power output ($P_e = IV$) of the two designs (parallel vs. series)?

Total power case 1 = 330A*300V = 99kW
Total power case 2 = 165,000A*0.6V = 99 kW There is *no* difference in power output.

Why would we choose one design over the other in a practical application?
It depends on the needs of current, voltage, footprint, and reliability. A high-voltage requirement is best managed with multiple plates in series. A high-current requirement is best managed with multiple plates in parallel. A parallel arrangement has advantages in reliability, since a single fuel cell that fails and becomes non-operational does not shut down the entire stack, as a series arrangement does. In many systems, a combination is used. For example, in many SOFCs, a bundle arrangement of SOFCs in a parallel and series configuration is used. In this situation, the overall system reliability is improved while the voltage output is also boosted to appropriate levels. In PEFCs as well, often several individual series-based fuel cell stacks are tied to each other in parallel, achieving the same purpose.

Open-ended Problems:

1.18 Consider that, at present, about 0.8 mg/cm^2 total of platinum is used to make a hydrogen fuel cell that can operate at around 0.65 W/cm^2. Calculate how much platinum would be needed to replace 50% of the cars on the road in the United States alone with fuel cells. Do you think this would affect world platinum markets? *Note*: You will have to go outside the textbook to answer this question as well as make some reasonable estimates to enable calculation. Although it is clear that a great reduction in the precious metal loading of a hydrogen fuel cell would be desirable to achieve ubiquitous implementation, there are differing views about the effect that such a conversion would have. Do you think platinum recycling would be neccessary?

Soln:

Total platinum per fuel cell car:

$$0.8\frac{mg}{cm^2}\cdot\frac{cm^2}{0.65W}=1.23\frac{g}{kW}$$

Assuming we have about 100 kW per car (134 hP), we will need 123 g per car. The estimate can be from 20-150 g per car depending on the assumptions made. According to one 2006 study, there were roughly 250 million registered passenger vehicles in the United States, for a total requirement of 15,375,000 kg or 15,375 metric tons for 50% of the total cars. Considering the world proven reserves estimated (US Geological Survey, 2001 US Geological Survey, 2001. Platinum Group Metals: Mineral Commodity Summaries, US Geological Survey, Washington DC.) at around 76,000 tons, with a vast majority (~70-80%) of it located in South Africa. There are also a high number of other industrial applications that require platinum, it is almost certain this would cause a major economic and/or political disruption.

The result depends on who you ask (I have seen both viewpoints defended from several different reliable sources) and the basic assumptions made, but the general agreed upon facts include that platinum is indeed rare, needed for other applications as well as fuel cells, and immediate conversion to a 'platinum-based' economy would be difficult. An alternative to greatly reduce the platinum loading by at least an order of magnitude is required to make automotive applications a large-scale reality. Note that some savings from the Pt use in the catalytic converter in our cars that would no longer be needed (only about 2-5 g per vehicle), and Pt recycling from old fuel cells would help save resources.

Two opposing viewpoints can scenarios are discussed in the following references:

1) R.H. Borgwardt (2001), Platinum, fuel cells, and future US road transport, *Transportation Research Part D* **6**, pp. 199–207.
2) R.J. Spiegel (2004), Platinum and fuel cells, *Transportation Research Part D: Transport and Environment*, Volume 9, Issue 5, pp. 357-371.

1.19 List some potential power source applications where a fuel cell could potentially replace a battery and discuss the relative advantages and disadvantages of this. Use Table 1.1 to help you decide which fuel cell would be most appropriate for each application.

Soln:

This is open ended, and there is no correct answer. Essentially all applications requiring battery power could use a fuel cell, with different levels of practicality depending on the existing solution and the type of fuel cell.

1.20 List some potential power source applications where a fuel cell could potentially replace a combustion-based power source and discuss the relative advantages and disadvantages of this. Use Table 1.1 to help you decide which fuel cell would be most appropriate for each application.

Soln:

This is open ended, and there is no correct answer. Essentially all applications now using combustion based power could also use a fuel cell, with different levels of practicality depending on the existing solution and the type of fuel cell.

1.21 For a hydrogen-based economy, a large supply of hydrogen will be needed. There are many ways in which hydrogen generation can be achieved. Do some research and discuss the various potential sources of hydrogen and comment on the advantages and drawbacks of each source. You can start in Chapter 8 of this text, but there are many more resources you can find.

Soln:

Again, this is open-ended and can be answered in a variety of different ways. The main methods of hydrogen generation are listed below with primary advantages and disadvantages. Depending on the level of detail asked, the answers can be much more in depth.

Method of generation	Advantages	Disadvantages
Electrolysis	Proven technology, pure hydrogen and oxygen generated	Relatively expensive. Need to use the pure oxygen
Fuel reformation	Can use existing natural gas or fuel infrastructure.	Impure hydrogen gas is generated, CO_2, CO generated.
Biomass hydrogen production	Potential for environmentally benign hydrogen production	Present technology has very low hydrogen yield rate.

1.22 Consider development of a fuel cell for weight loss. That is, a fuel cell would be attached to the human body and be fueled from the glucose in the bloodstream, effectively burning calories from the user's blood effortlessly. Consider a current biological glucose-burning fuel cell current density of 5 mA/cm^2 at 0.4 V and a fuel cell stack mounted next to the person with 100 cm^2 per plate and 3 mm total per plate. Calculate the approximate volume of a weight loss fuel cell stack to burn 500 *food* calories (e.g., 500,000 thermodynamic calories) in an hour of use. Is this practicals? What current density would make this approach feasible?

Soln:

This seems like an awesome concept. Simply eat all the food you want, then plug yourself in to power the television while you burn it off. First, consider the total calories burned, and convert into Joules:

$$500{,}000(cal)\cdot 4.1868\left(\frac{Joule}{cal}\right) = 2{,}093{,}400(Joule)$$

The fuel cell is operating at the following power rating and approximate volume:

$$P = iAV = 0.005\frac{A}{cm^2}\cdot 0.4V\cdot 100cm^2\cdot n_{cells} = n\cdot 0.2\frac{W}{cell}$$
$$Volume = n_{cells}\cdot 0.3cm\cdot 100cm^2 = n_{cells}\cdot 30cm^3$$

Considering you need to burn off 2,093,400 *J* in an hour, this translates to:

$$2{,}093{,}400\frac{J}{3600s} = 581W$$

Which means you need 2,907 plates, for a total volume of 87,210 cm^3. A three thousand plate fuel cell stack is excessive, and the volume of over 8 cubic meters is large. It did not include manifold volumes, etc. A current density of 20 times higher would require a stack of 145 plates, which is a reasonable arrangement. Another consideration is the volume of blood needed to fill the stack, which would likely be more than in your body!