Fuel Cells for Electric Vehicles
Knowledge Gaps and Development Priorities[1]

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ABSTRACT

Long range zero emission vehicles will require the development of low cost hydrogen/air fuel cells power systems. These vehicle systems will consist of an on-board hydrogen storage, a fuel cell stack, auxiliary system, and probably acceleration batteries or ultra capacitors. A fuel cell power system is now technically possible however there are many developments needed before such a system would be commercially viable. The following paper reviews the use of fuel cells for electric vehicles and discusses knowledge gaps that exist and where development should be emphasized.

INTRODUCTION

Electric vehicles will play a significant role in solving energy and environmental problems. The new clean air laws in California mandate the sale of zero emission vehicles by 1998, (2% of total vehicle sales increasing to 10% by the year 2005). The only vehicle power systems that can meet the zero emission requirement are battery or fuel cell power systems with on-board hydrogen. Initial sales requirements will be met by battery powered vehicles for use in an urban setting (range of less than 200 km/day). Long range general purpose vehicles will require fuel cell power systems.

The following table compares the energy density and relative refueling rates of batteries, hydrogen and gasoline. The energy density is expressed in terms of mass (Watt Hours/kg) and volume (Watt Hours/liter). The refueling rate is the rate at which energy can be loaded on to the vehicle. High and low cases are presented for both batteries and hydrogen storage. The energy density of the two battery cases represent what is available today and the long term goal for the US Advanced Battery Consortium. The energy density of the hydrogen cases is presented as function of weight fraction. Weight fraction is defined as the percentage of stored hydrogen weight to the total storage system weigh. The 2% case can be easily accomplished using compressed natural gas storage tank technology. The 10% case can be easily accomplished using liquid hydrogen tank technology.

Technology	On-Board Energy Density Wh/kg	On-Board Energy Density Wh/l	Vehicle Refueling Rate (kW)
Batteries			
Present EV Batteries	25 to 50	50 to 75	5 to 15
Advanced EV Battery Technology	200	300	100
Hydrogen Storage			
2% System Weight Fraction	660	400 to 1000	90 to 8,000
10% System Weight Fraction	3,300	1000 to 1500	90 to 8,000
Gasoline and Tank	8700	7900	10,000 to 20,000

Table 1.
Comparison of ZEV On-Board Energy Storage Systems

Notes; Gasoline refueling rate is based on vehicle loading rate of 4.4 to 8.8 gallons/minute. Battery energy density is based on US Advanced Battery Consortium long term goal. Hydrogen refueling rate is based on author estimates from Mercedes Benz and BMW systems. Weight Fraction is the percentage of hydrogen weight to total on-board storage system weight.

The comparison indicates that the energy density of hydrogen is much greater then batteries and the refuel rate approaches that of gasoline. The wide range for hydrogen refuel rate is dependent on the on-board storage technology used. The energy density of the 10% weight fraction hydrogen case is approximately 1/3 by weight and 1/5 by volume of gasoline. This difficulty is overcome by the higher energy conversion efficiency of the fuel cell compared to the internal combustion engine (2 to 3 times).

FUEL CELLS

In comparison to a battery, the fuel cell is different in several ways. A battery is an energy storage device, the amount of electrical energy that is available is dependent on the mass of chemical reactant stored in the battery. When the reactants are fully consumed (discharged), the battery must be recharged before it is useful again. The fuel cell is an energy conversion device, no component is consumed with the reaction. As a result, the fuel cell is able to produce electricity as long as reactants are provided. Because the fuel cell transforms the fuel directly to electricity without combustion (no Carnot cycle limitation), there is little waste heat and a very high chemical to electrical energy conversion (40% to 60% based on lower heating value). The construction of a fuel cell is similar to a battery, except that it does not undergo a material change and consequently operates as long as hydrogen fuel and air are available.

Specifically the fuel cell is made up of an electrolyte sandwiched between two electrodes. In a typical fuel cell, reactant gases are fed continuously to the negative electrode (anode) and the positive electrode (cathode).

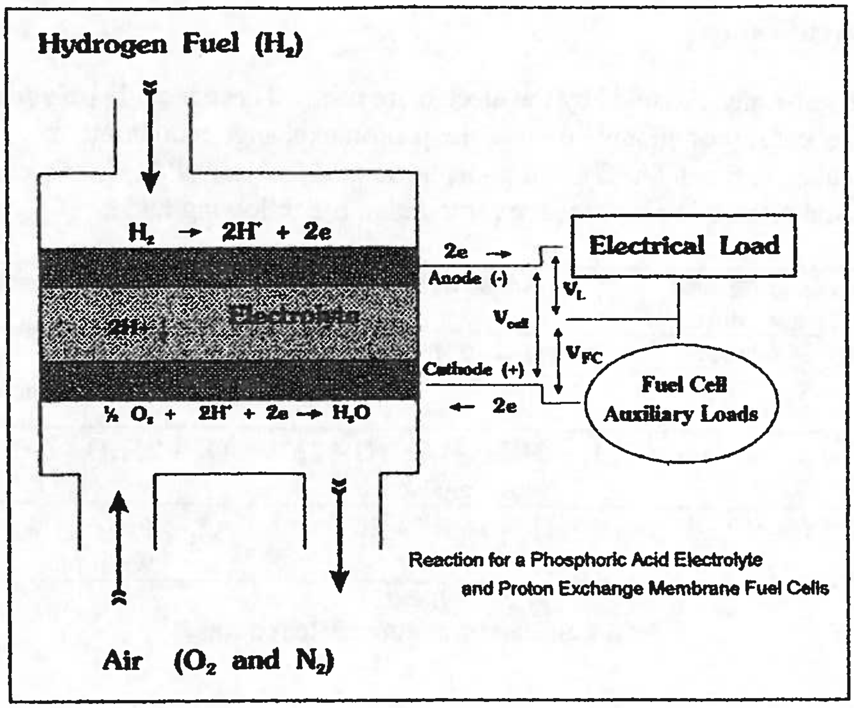


Figure 1 Single Cell Schematic

Fuel Cell Operating Principle

All energy-producing oxidation reactions are fundamentally the same and involve the release of chemical energy through the transfer of electrons. During combustion, of hydrogen and oxygen there is an immediate transfer of electrons, heat is released and water is formed. In a fuel cell the hydrogen and oxygen do not immediately come together but are separated by an electrolyte. First the electrons are separated from the hydrogen molecule by a catalyst (reduction) creating a hydrogen ion (no electrons). The ion then passes through the electrolyte to the oxygen side. The electrons cannot pass through the electrolyte and are forced to take an external electrical circuit which leads to the oxygen side. The electrons can provide useful work as they pass through the external circuit. When the electrons reach the oxygen side they combine with the hydrogen ion and oxygen creating water. By forcing the electrons to take an external path, a low temperature direct energy conversion is achieved.

The theoretical efficiency for the conversion of heat energy into electrical energy in a hydrogen-oxygen fuel cell is 83% [2]. Efficiencies of practical fuel cells using pure hydrogen and oxygen range from 50% to 65% based on lower heating value. The theoretical voltage of the hydrogen-oxygen cell operating reversibly at 1 atmosphere and 25°C is 1.23 volts. Under electrical load the fuel cell voltage falls to 0.6 to 0.8 due to polarization effects. To make a useful voltage, multiple cells are connected in electrical series and are referred to as a stack. Manifolds provide reactant gases to the individual cells and water is removed by a variety of means. The fuel cell stack and all necessary auxiliaries are referred to as a fuel cell system. The efficiency associated with a fuel cell can be described as follows:

Fuel Cell Classifications

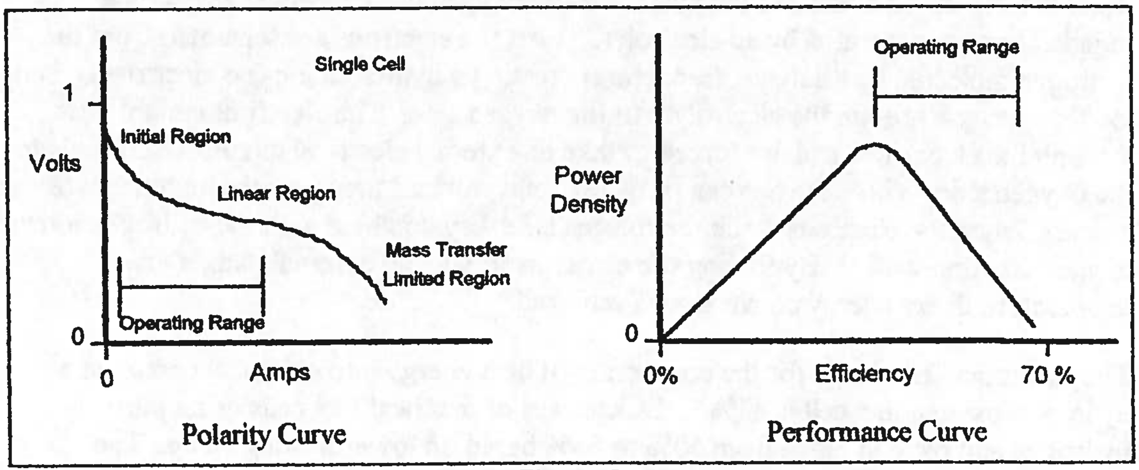
Fuel cells are generally classified by the electrolyte used. These include polymer electrolyte fuel cells, (commonly know as the proton exchange membrane fuel cell PEMFC), alkaline fuel cell (AFC), and phosphoric acid fuel cell (PAFC). Operating temperature and electrode reactions are provided in the following table;

Fuel Cell Type and Normal Operating Temperature	Anode Reaction	Cathode Reaction
Proton Exchange Membrane (PEMFC) 50 to 110 °C	$H_2 \rightarrow 2H^+ + 2e^-$	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ water production
Alkaline (AFC) 80 to 120 °C	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$ water production	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
Phosphoric Acid (PAFC) 160 to 210 °C	$H_2 \rightarrow 2H^+ + 2e^-$	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ Water production

Table 2
Fuel Cell Electrochemical Reactions

Fuel Cell Performance Characteristics

The performance characteristics of a fuel cell can be shown in graphical form in terms of polarity and power/efficiency curves. The polarization curve of a fuel cell shows the relationship between voltage and current. It is typically characterized by three regions; an initial region followed by a linear region, and finally a mass transfer limited region. Consider the following Figure;



Polarity Curve

Performance Curve

Figure 2
Fuel Cell Performance Curves

1. The initial region (0 to 100 mA/cm²) shows an initial steep drop in the cell potential due to slow cathode kinetics. With sufficient voltage drop (0.1 to 0.15 volts) the kinetics improve and are no longer limiting.

2. The linear region (100 to 500 mA/cm^2) is characterized by a linear voltage drop primarily due to ionic resistance in the electrolyte.
3. As the current density further increases, the polarization curve enters the mass transfer limited region (500+ mA/cm^2). Cell potential drops off rapidly primarily due to the inability of oxygen to reach reaction sites fast enough. This inability may be caused by a combination of an oxygen gradient through the electrode, process water blockage and/or nitrogen blanketing.

The power efficiency curve presents the relationship between electrode power density and efficiency. The ordinate is in W/cm^2 and is an indication of how much electrode material is necessary to construct a fuel cell. A higher electrode power density means less surface electrode area will be needed to achieve a given power level. The abscissa is electrode efficiency based on the higher heating of hydrogen. Higher efficiency translates to greater fuel economy and thus a smaller on-board hydrogen storage system and or a longer vehicle range. It should be noted that lower efficiency translates also to greater heat generation within the fuel cell.

The power efficiency curve indicates that there is a trade off between electrode power density and efficiency. A higher power density is achieved at a lower efficiency and a peak is reached where the power density and efficiency declines. At no time would it be advantageous to operate the fuel cell beyond the peak power density. An advantage of the fuel cell compared to the internal combustion engine is that under part load conditions efficiency increases. This is particularly important for a city driving cycle.

KNOWLEDGE GAPS

It is technically possible to use a fuel cell to power an electric vehicle. However the present cost per kW is very high and the available system power density (kW/kg and kW/liter) is very low. This makes fuel cells today impractical for transportation. The knowledge gap is how to make fuel cell technology cost effective and practical for the consumer market.

Of the fuel cell types suitable for transportation, the proton exchange membrane (PEMFC) system is presently the strongest candidate. The PEMFC is a favored technology due to its use of a solid electrolyte, cold start capability, relatively high power density, and efficiency characteristics. The PEMFC uses a solid polymer electrolyte that is manufactured in thin sheets (the solid electrolyte resembles an overhead transparency sheet and is referred to as a membrane). The electrolyte membrane consists of a perfluoro linear polymeric backbone with immobilized side chains of sulphonic acid radicals. The PEMFC electrodes have a thin film of platinum catalyst supported on carbon and are bonded to the faces of the solid polymer electrolyte. The PEMFC was designed and first fabricated by the General Electric Company for the Gemini space flights as an auxiliary power source. Automotive applications of PEMFC technology are being developed by Ballard Power Systems, Vancouver Canada, General Motors and Energy Partners of Florida.

Consider that the fundamental parts of a fuel cell are: the electrolyte, the electrodes (anode and cathode) and the electrode catalyst. These components when assembled are referred to as the electrode membrane assembly (EMA). They constitute a fuel cell as the pistons and cylinder block do an internal combustion engine. In order to operate, the reactant gases at the appropriate pressure and humidity must be provided to each side of the EMA. The resulting electrons, product water and heat from the reaction at the EMA must be removed. This is generally accomplished by a bipolar plate that encompasses reactant gas distribution and a stacking arrangement to achieve a high overall voltage. The total power available from a fuel cell is simply a function of the EMA power density and the total EMA area. The following table summarizes the cost of the fundamental parts as a function of EMA area. Considering an EMA power density of 0.5 W/cm² the cost and mass per kW is calculated.

Basic Fuel Cell Components	Cost per m² of EMA	Density (Kg/m²)	At 0.5 W/cm² $/kW	At 0.5 W/cm² kg/kW
Membrane (Nafion)	$600	0.125	$120	0.025
Electrodes (C. cloth)	$77	0.204	$15	0.041
Electrode Catalyst Platinum 4 mg/cm²	$5200	0.08	$1040	0.016
Bipolar Plate	$5000	20.0	$1000	4.0
Total	**$10,877**	**20.4**	**$2175**	**4.1**

Table 3
Today's PEMFC Component Cost and Mass

Notes All values are approximate and author estimates, Membrane Material - Dupont Nafion 0.125 mm thickness, Electrode material - Textron Carbon Cloth (102 g/m2, $380/kg), prepared Platinum Black $65/g.

The table indicates that major cost components are the electrode catalyst and the bipolar plate. The major weight component (and volume) is the bipolar plate. The typical automotive propulsion system is between $50 and $100/kW. Thus the basic materials cost alone for a PEMFC is far beyond what is possible for consumer transportation.

The fuel cell density of 4.1 kg/kW is good but rapidly increases when all the required auxiliary system components are considered. Typically the fuel cell stack has cooling plates, a humidification section, end plates, circulation pumps and an air compressor. Including these supporting components the density may increase to 15 to 25 kg/kW. A typical automotive propulsion system has a density of 2.5 to 5 kg/kW.

Present day fuel cells have evolved from space and military programs that generally operate at high pressure and only consider oxygen on the cathode. The air breathing systems today strongly resemble in design the military and space fuel cells. The fuel cell knowledge gap is how to make this technology cost effective and practical for the consumer market. With good design and a large production run, the fuel cell cost may approach the cost of materials. Thus to over come the two problems of cost and density there must be a concentrated engineering effort to reduce materials required and their costs.

DEVELOPMENT PRIORITIES

Electrochemically there are still many questions to be answered, however the development priority must now emphasize the engineering of a specific fuel cell for transportation applications. To solve the two problems of cost and fuel cell density there must be a concentrated engineering effort to simplify the materials required and to create a suitable design for transportation. Synergism's must be exploited for a total systems approach. For example the trade off between electrode power density and efficiency. For a given power requirement a higher average operating efficiency results in a larger electrode area but a smaller on-board hydrogen storage system. The following text briefly explores 4 development priority areas; electrodes, electrode catalyst loading, air compression and bipolar plate design.

Electrodes

The electrodes of a PEMFC can be made from carbon cloth or carbon paper. Carbon cloth has been used to achieve high performance under very low platinum loading and is the preferred material at this time. Typically the carbon cloth used in fuel cell electrodes is of a military quality and has been designed for tensile strength. It typically has a density of 102 grams per m^2 thus 204 grams are needed for each m^2 of EMA. The cost of the cloth is \$380/kg in small quantities resulting in cost given in Table 3. Graphite powder is typically \$15/kg.

A high strength cloth is not necessary, the cloth should be designed for electrical conductivity and an ideal weave and pore size for the fuel cell reaction. It is conceivable that a different cloth should be used on the anode and cathode sides of the fuel cell.

Electrode Catalyst Loading

Current electrode catalyst loading require substantially more platinum than is used in the internal combustion engine 3-way catalytic converter. The platinum catalyst must be replaced or its utilization must be significantly increased. Platinum utilization is defined as the number of peak kilowatts produced per gram of platinum (kW/gram). As a result, utilization is affected by the amount of platinum used in the electrode preparation (mg/cm^2) and the specific performance of the electrode membrane assembly (W/cm^2). The specific performance of the electrode in turn depends on the platinum loading, gas pressure, temperature, and humidity. Commercially available PEMFCs use high platinum loading (about 4 mg/cm^2) in each electrode (8 mg per cm^2 of membrane area). Experimental low platinum loading electrodes can use as little as 0.1 mg/cm^2 (0.2 mg per cm^2 of EMA area).

Recent experiments at the CESHR have found that high electrode platinum loading increases performance (W/cm^2) but reduce platinum utilization (kW/gram)[3]. The trend is to lower electrode platinum loading (g/cm^2) while maintaining electrode performance. The following Table 3 indicates At some point the reduction in platinum will probably reduce utilization however, that limit has not yet been experimentally reached.

Electrode Platinum Loading	Utilization kW/gram	Experiment
10.0 mg/cm^2	0.021 to 0.04	CESHR Single Cell
4.0 mg/cm^2	0.08	Ballard Multi Cell Stack
0.45 mg/cm^2	0.35 to 0.71	CESHR Single Cell
0.10 mg/cm^2.	3.25	CESHR Single Cell*

Table 4
Electrode Platinum Utilization

Notes; CESHR data was taken using a single test cell with 5 cm^2 electrodes. The electrode membrane assemblies were fabricated using porous gas diffusion electrodes and Dow Chemical membrane material. The fabrication method and a schematic of the test cell is provided in reference[4]. * unpublished results - January 1992.

Auxiliary Systems - Air Compression

Auxiliary systems in a fuel cell include controls, cooling fans, recirculation pumps and often process air compression. The difference between gross fuel cell power and net power are the requirements of the auxiliaries. Of the auxiliary power requirement, process air compression dominates. In the following Figure 3 polarization curves are presented for process air operating pressures of 1 and 5 atmospheres utilizing low platinum loading electrodes.

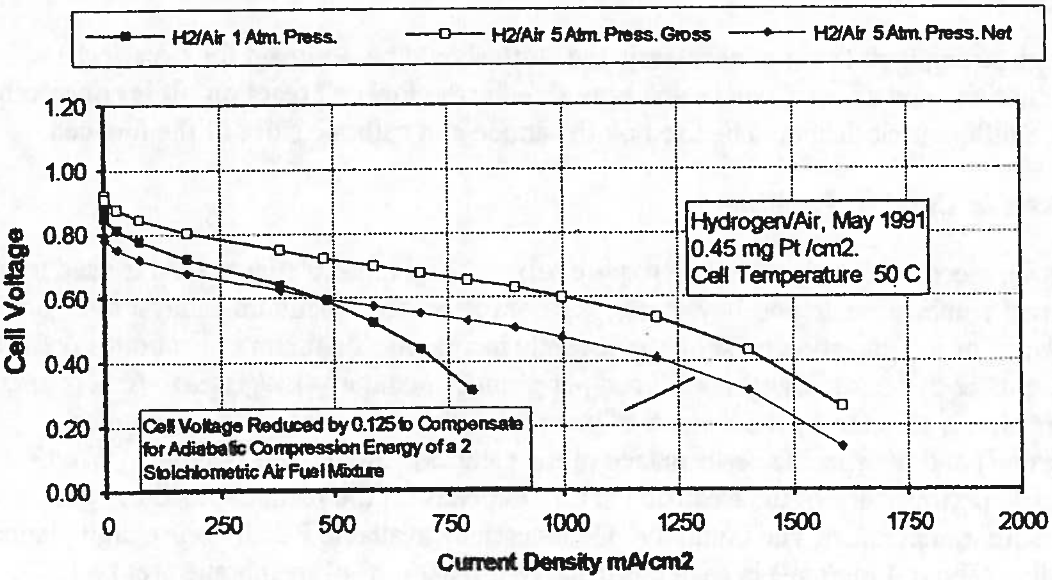


Figure 3. Polarity - Air Compression Comparison

Notes; Fuel cell data was taken at CESHR using a single test cell with 5 cm^2 electrodes. The electrode membrane assemblies were fabricated using porous gas diffusion electrodes and Dow Chemical membrane material.

Pressurization significantly increases the electrode performance. The 5 atmosphere air case achieves 0.6 volts at 1000 ma/cm^2 while the 1 atmosphere curve can only produce 475 mA/cm^2, greater than a factor of 2 decline in current density. It would seem logical that to achieve a high platinum utilization the reactant gases should always be compressed. For oxygen breathing fuel cells this is usually not a problem as the oxygen will be generally available in a compressed state. However, for an ambient air breathing electric vehicle fuel cell the pressurization will require energy to operate the air compressor.

The energy for compression must be supplied by the fuel cell system, and the net fuel cell performance is therefore less than the gross stack performance. The air compression process can be adiabatic or isothermal and part of the compression energy may be recovered by an expander such as a turbine. To simplify the analysis, it is assumed that the compression is performed by an ideal adiabatic compressor with no energy recovery upon expansion.

In summary, if a constant number of stoichiometric mixtures is used throughout the operating region, the energy of compression can be treated as an equivalent cell voltage loss that is not available to the electrical load (see Figure 1). The voltage loss is a function of the number of stoichiometric mixtures, the initial air temperature T_1 and the pressure ratio P_2/P_1. Thus the effect of air compression can be simply presented on a polarization diagram as a constant reduction in voltage. The reduced voltage curve then may be used to determine the impact air compression has on power density and efficiency. The following equation was first derived in reference[5] and is plotted in Figure 4.

$$v_C = \frac{1.287}{3600} \times \text{\# of Stoich. Mixtures} \times C_p\, T_1 \left(\frac{P_2}{P_1}^{\frac{k-1}{k}} - 1 \right) \quad \text{Volts}$$

Where	v_c	Effective Compressor voltage
	C_p	Specific Heat (Air 1.004 J/(g K))
	T_1	Inlet Air Temperature
	P_1	Inlet Air Pressure
	P_2	Fuel Cell Air Pressure
	k	Specific Heat Ratio (Air 1.4)

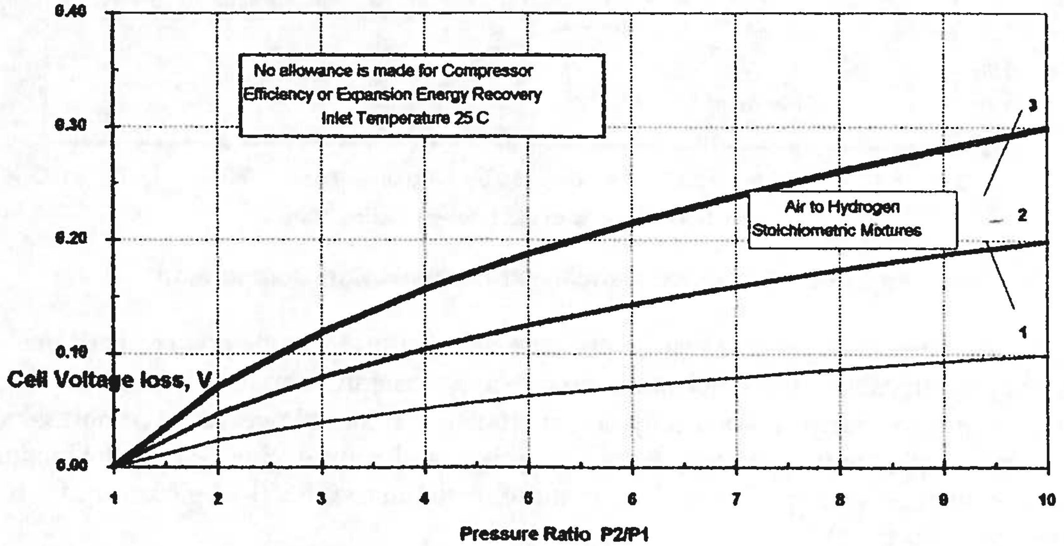


Figure 4. Effective Voltage Loss Due to Adiabatic Air Compression

Figure 4 indicates that increasing the number of stoichiometric mixtures proportionately increases the effective voltage needed for compression. The effect pressure ratio has on compression energy is a power function that is less then 1. As a result the effective voltage loss is most pronounced at small pressure ratios. As the pressure ratio continues to increases the incremental impact on effective voltage loss is less.

The effect of energy of air compression on the 5 atmosphere case presented in Figure 3 is determined by reducing the polarity curve by 0.125 volts (see Figure 3). This reduction corresponds to an adiabatic compression of 2 stoichiometric air mixtures. Considering compression energy, the figure shows that the 1 atmosphere condition actually out performs the 5 atmosphere condition down to 0.6 volts where the two curves cross.

The following Figure 5 presents the Figure 3 data as performance curves. The three curves represent the 1 atmosphere case and the 5 atmosphere gross and net power density cases. The curves show that when compressor energy is not considered, pressurization significantly increases efficiency at any given power density. For example at a power density of 0.2 W/cm^2 the 1 atmosphere case has an efficiency of 54%. Pressurized to 5 atmospheres the gross efficiency is 62%, however when the energy of air compression effect is considered the efficiency reduces to 52% (less than the 1 atmosphere case).

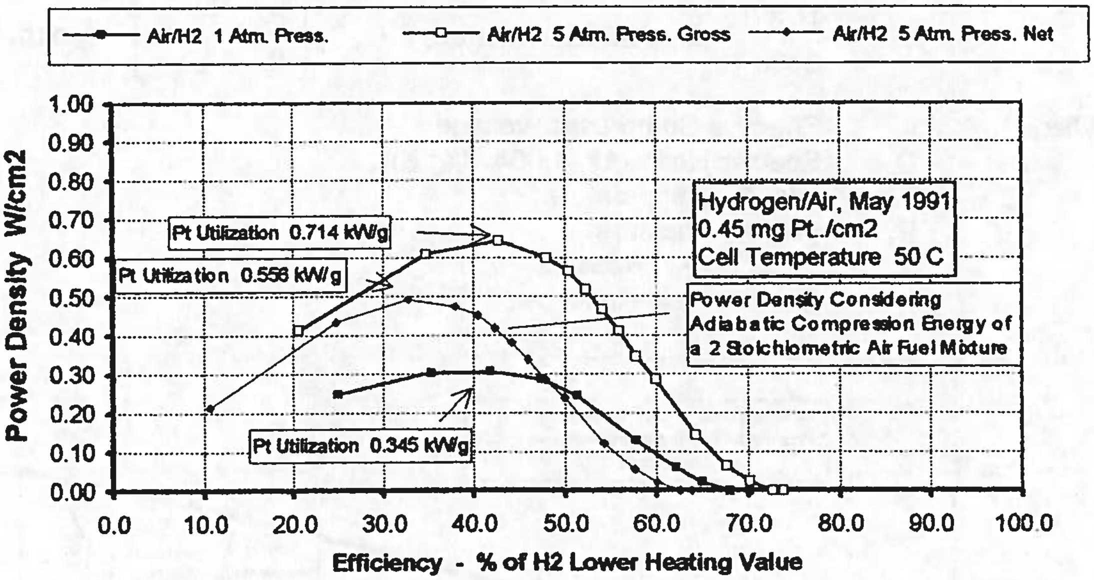


Figure 5. **Performance - Air Compression Comparison**

The curves in Figure 5 indicate that air pressure affects the electrode power density/cell efficiency relationship. The efficiency drop due to air compression may be most significant as it translates to a larger on-board hydrogen storage system. However air compression does improve platinum utilization, Comparing the 1 and 5 atmosphere cases, the platinum utilization increases from 0.345 kW per gram of platinum to 0.556 kW/g (factor of 1.6 increase in utilization).

SUMMARY

Mandates for zero emission vehicle are stimulating the development of fuel cells as a power systems for electric vehicles. It is technically possible to operate an electric vehicle on a fuel cell, however high cost and low power density make it impractical at this time. The major knowledge gaps to overcome before the fuel cell will be commercially viable for transportation are not electrochemical but are materials and engineering related. A systems approach must be made to simplify the design so that a minimum of low cost materials are used. The PEMFC is a favored technology due to its use of a solid electrolyte, cold start capability, high power density, and efficiency characteristics.

Specific development priorities for a transportation fuel cell are as follows:

- Engineering parameters for the design of an air breathing fuel cell - There is little understanding of the fuel cell performance operating on air as a function of reactant gas humidity, temperature, pressure and stoichiometry, an engineering design envelope needs to be developed.
- Fuel cell stack design - A compact design that maximizes electrode area and minimizes the bipolar plate material and resistance losses.
- Air Compressor - Air compression increases the electrode power density and thus the platinum utilization is improved. However the energy for compression must be supplied by the fuel cell system, and the net fuel cell performance is therefore less than the gross performance. The trade off between platinum utilization, electrode power density, and efficiency is very complex. The optimum combination will depend on the vehicles performance requirement, the cost of hydrogen the on-board storage system, and finally the market cost and availability of platinum. From a systems point of view a variable capacity, high efficiency air compression system may be necessary to balance the conflicting goals of platinum utilization, fuel cell power density and overall system efficiency.
- Hybridization with batteries or ultra capacitors
- Materials specific to fuel cell - electrode material, bipolar plate material.
- Low platinum loading electrode membrane assembly - All low platinum results have been obtained using < 50 cm^2 single cells. Fuel cell stacks using these electrodes need to be constructed and life testing under cyclic operation
- In vehicle demonstration/field testing - At this time there is little laboratory and almost no field test data available of fuel cell power systems under driving cycle type loads.

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