Fuel Cells

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Mechanical Engineering 496ALT

Alternative Energy

April 14, 2009

California State University Northridge

Reminder – optional campus energy facilities tour scheduled next Saturday, April 18, 9 am to noon. Details on next chart.

Readings:

Today – Section 7.3.4 on fuel cells

Thursday and next Tuesday – Chapters 19 and 20 on energy conservation

Homework problems on biofuels due on Thursday (April 16). Download problem assignment from web site.

Saturday

- Meet in PPM conference room at 9:00 am
- Can park in adjoining lot on Halstead St.
- Cannot drive there from campus

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This Saturday we will have the campus tour of energy facilities.

We will start at 9 am in the Physical Plant Management (PPM) conference room off Halstead Street as shown in the map.

Note that you cannot drive there from campus via Etiwanda Street; it is closed at Halstead.

We will start with a presentation of the campus facilities for energy conservation and alternative energy use followed by a tour to visit the coolers that provide air conditioning to campus by using off-peak energy storage, the solar collectors in lot E6, and the fuel cell south of the Student Union.

You will see the actual installation of the faciltiies that we have been discussing in class. In particular, you will see the so called balance of plant (BOP) facilities that are required to make the individual operations, such as a fuel cell, practicable.

Because this tour is scheduled outside of normal class hours, it is optional and any material discussed during the day will not be covered on any examinations. However, your attendance is strongly encouraged because it will provide you with a first-hand view of actual equipment and the ability to ask questions of a facilities manager responsible for the actual operation of this equipment.

Outline

- Electrochemistry fundamentals
- Fuel cell basics and different types
- Current and proposed applications
  - Distributed electrical generation
  - Transportation
  - Substitutes for batteries
- Getting the fuel for fuel cells

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Reference: Fuel Cell Handbook (Seventh edition) November 2004 (Accessed April 17, 2007.)

By EG&G Services, Parsons, Inc., and Science Applications International Corporation, prepared under contract DE-AM26-99FT40575 for U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, P. O. Box 880, Morgantown, WV 26507-0880.

Available on line as http://www.cleanfuelcellenergy.com/FCHandbook7.pdf

Seventh edition available at cost from various online sources.

Supramaniam Srinivasan, Renaut Mosdale, Philippe Stevens, and Christopher Yang, "Fuel Cells: Reaching the Era of Clean and Efficient Power Generation in the Twenty-First Century," in *Annual Reviews of Energy and the Environment*, Annual Reviews, Inc., **24**:281-238 (1999).

Electrochemistry Basics

- Oxidation and reduction
  - Electrons are transferred from the reducing agent to the oxidizing agent
  - Oxidation is a loss of electrons
  - Reduction is a gain of electrons
- Electrochemical cells
  - Oxidation (electron loss) at the anode
  - Reduction at the cathode

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Reference: http://electrochem.cwru.edu/ed/dict.htm (Accessed April 17, 2007.)

An electrochemical cell device that converts chemical energy into electrical energy or vice versa when a chemical reaction is occurring in the cell. Typically, it consists of two metal electrodes immersed into an aqueous solution (electrolyte) with electrode reactions occurring at the electrode-solution surfaces.

It consists of two electronically conducting phases (e.g., solid or liquid metals, semiconductors, etc) connected by an ionically conducting phase (e.g aqueous or non-aqueous solution, molten salt, ionically conducting solid). As an electrical current passes, it must change from electronic current to ionic current and back to electronic current. These changes of conduction mode are always accompanied by oxidation and reduction reactions. An essential feature of the electrochemical cell is that the simultaneously occurring oxidation-reduction reactions are spatially separated. E.g., in a spontaneous "chemical reaction" during the oxidation of hydrogen by oxygen to water, electrons are passed directly from the hydrogen to the oxygen. In contrast, in the spontaneous electrochemical reaction in a galvanic cell the hydrogen is oxidized at the anode by transferring electrons to the anode and the oxygen is reduced at the cathode by accepting electrons from the cathode. The ions produced in the electrode reactions, in this case positive hydrogen ions and the negative hydroxyl (OH^-) ions, will recombine in the solution to form the final product of the reaction: water. During this process the electrons are conducted from the anode to the cathode through an outside electrical circuit where the electrical current can drive a motor, light a light bulb, etc. The reaction can also be reversed, water can be decomposed into hydrogen and oxygen by the application of electrical power in an electrolytic cell.

Electrolytic Cell

- Converts electrical energy into chemical energy
- The anode is the positive electrode and the cathode is the negative electrode
- Current flows from the anode to the cathode
- Electrolysis and battery ***recharging*** are examples of electrolytic cells

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Reference: http://electrochem.cwru.edu/ed/dict.htm (Accessed April 17, 2007.)

An electrochemical reaction is an oxidation/reduction reaction that occurs in an electrochemical cell. The essential feature is that the simultaneously occurring oxidation-reduction reactions are spatially separated.

An electrolytic cell is an electrochemical cell that converts electrical energy into chemical energy. The chemical reactions do not occur "spontaneously" at the electrodes when they are connected through an external circuit. The reaction must be forced by applying an external electrical current. It is used to store electrical energy in chemical form. It is also used to decompose or produce (synthesize) new chemicals by application of electrical power.   This process is called electrolysis, e.g., water can be decomposed into hydrogen gas and oxygen gas. The free energy change of the overall cell reaction is positive.

The cathode is the electrode where reduction occurs in an electrochemical cell. It is the negative electrode in an electrolytic cell, while it is the positive electrode in a galvanic cell. The current on the cathode is considered a negative current according to international convention.

The anode is the electrode where oxidation occurs in an electrochemical cell. It is the positive electrode in an electrolytic cell, while it is the negative electrode in a galvanic cell. The current on the anode is considered a positive current according to international convention.

Galvanic Cell

- Converts chemical energy into electrical energy
- The anode is the positive electrode and the cathode is the negative electrode
- Current flows from the cathode to the anode
- Fuel cells and battery ***discharging*** are examples of galvanic cells

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Reference: http://electrochem.cwru.edu/ed/dict.htm (Accessed April 17, 2007.)

A galvanic cell is an electrochemical cell that converts chemical energy into electrical energy. A cell in which chemical reactions occur spontaneously at the electrodes when they are connected through an external circuit, producing an electrical current. E.g., in a fuel cell hydrogen is oxidized at the anode by transferring electrons to the anode and the oxygen is reduced at the cathode by accepting electrons from the cathode. During this process the electrons are carried from the anode to the cathode through an outside electrical circuit where the electrical current can drive a motor, light a light bulb, etc.

Also called "voltaic" cell. The Gibbs function (Gibbs free energy) change of the overall cell reaction is negative.

Current is the movement of electrical charges in a conductor carried by electrons in an electronic conductor and by ions in an ionic conductor. "By definition" the electrical current always flows from the positive potential end of the conductor toward the negative potential end, independent of the actual direction of motion of the differently charged current carrier (or "charge carrier") particles.

The "defined" current flows from the positive terminal of the current source, trough the load, to the negative terminal of the source. Consequently, inside the "source" (whether it is electromechanical or electrochemical) the current must flow from the negative terminal to the positive terminal since there must be a complete circuit. This concept is especially important in electrochemistry because an electrochemical cell can be either a current "source" (galvanic cell) or a "load" (electrolytic cell). Furthermore, a rechargeable battery operates as a "source" during discharge and as a "load" during charge.

Fuel Cell History

- First proposed and demonstrated by Grove in 1839
- Small developments over next 100 years including basic theory
- Bacon (~1938 to 1958) developed modern fuel cell
- NASA used fuel cells on Apollo

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Reference: http://fuelcells.si.edu/origins/origins.htm (Accessed April 17, 2007.)

William Robert Grove (1811 -1896), an English lawyer turned scientist, won renown for his development of an improved wet-cell battery in 1838. The "Grove cell," as it came to be called, used a platinum electrode immersed in nitric acid and a zinc electrode in zinc sulfate to generate about 12 amps of current at about 1.8 volts.

Grove discovered that by arranging two platinum electrodes with one end of each immersed in a container of sulfuric acid and the other ends separately sealed in containers of oxygen and hydrogen, a constant current would flow between the electrodes. The sealed containers held water as well as the gases, and he noted that the water level rose in both tubes as the current flowed.

Ludwig Mond (1839 -1909). In 1889, he and his assistant, **Langer**, described their experiments with a hydrogen-oxygen fuel cell that attained 6 amps per square foot (measuring the surface area of the electrode) at .73 volts

Friedrich Wilhelm Ostwald (1853 -1932), a founder of the field of physical chemistry, provided much of the theoretical understanding of how fuel cells operate. In 1893, he experimentally determined the interconnected roles of the various components of the fuel cell: electrodes, electrolyte, oxidizing and reducing agents, anions, and cations.

Emil Baur (1873 -1944) of Switzerland (along with several students at Braunschweig and Zurich) conducted wide-ranging research into different types of fuel cells during the first half of the twentieth century. Baur's work included high temperature devices (using molten silver as an electrolyte) and a unit that used a solid electrolyte of clay and metal oxides.

Francis Thomas Bacon (1904 -1992) began researching alkali electrolyte fuel cells in the late 1930s. In 1939, he built a cell that used nickel gauze electrodes and operated under pressure as high as 3000 psi. During World War II, Bacon worked on developing a fuel cell that could be used in Royal Navy submarines, and in 1958 demonstrated an alkali cell using a stack of 10-inch diameter electrodes for Britain's National Research Development Corporation. Though expensive, Bacon's fuel cells proved reliable enough to attract the attention of Pratt & Whitney. The company licensed Bacon's work for the Apollo spacecraft fuel cells.

Fuel Cell

- 1 – O_2 and H_2 In
- 2 – Ions move in electrolyte
- 3 – Electrons in external circuit send current to load
- 4 – Product water leaves cell

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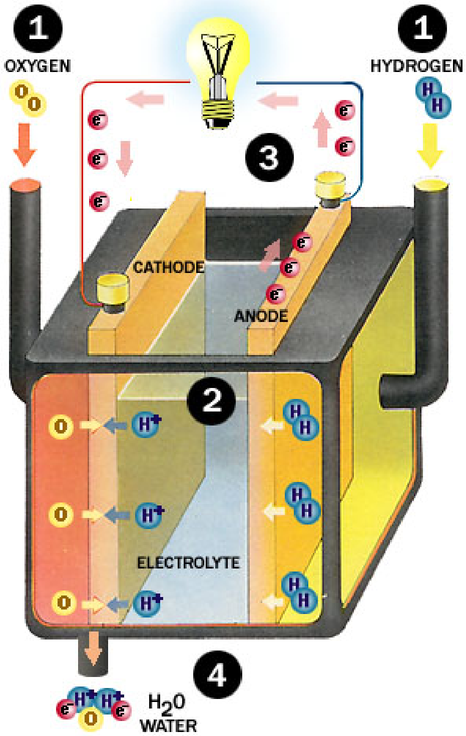

Reference: http://www.fe.doe.gov/coal_power/fuelcells/fuelcells_howitworks.shtml

A fuel cell produces electricity by means of an electrochemical reaction much like a battery. But there is an important difference. Rather than extracting the chemical reactants from the plates inside the cells, a fuel cell uses hydrogen fuel and oxygen extracted from the air to produce electricity. As long as these substances are fed into the fuel cell, it will continue to generate electric power.

Different types of fuel cells work with different electrochemical reactions. The following is a basic description of how a phosphoric acid fuel cell generates electric power.

Hydrogen gas is extracted from natural gas or other hydrocarbon fuels and permeates the anode. Oxygen from the air permeates the cathode.

Aided by a catalyst in the anode, electrons are stripped from the hydrogen. Hydrogen ions pass into the electrolyte.

Electrons cannot enter the electrolyte. They travel through an external circuit, producing electricity.

Electrons travel back to the cathode where they combine with hydrogen ions and oxygen to form water.

A fuel cell provides DC (direct current) voltage that can be used to power motors, lights or other electrical appliances. To supply grid power (or locally generated electric power), the direct current an inverter is required to convert the DC power into AC.

Fuel Cell Reactions

- Anode: $2H_2 \rightarrow 4H^+ + 4e^-$
- Electrons released at anode flow to cathode through an external circuit
- H^+ ions produced at anode flow through electrolyte to cathode
- Cathode: $4H^+ + O_2 + 4e^- \rightarrow 2H_2O$
- Net reaction: $2H_2 + O_2 + \rightarrow 2H_2O$

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This chart shows the chemical reactions that take place in the fuel cell that uses hydrogen as the fuel and oxygen as the oxidizer. We see that the net reaction is the same as for combustion of hydrogen. However, as discussed during the lecture on basic thermodynamics, because the reaction does not involve the conversion of chemical energy to heat (as is done in combustion) we do not have the usual efficiency limit of the second law.

Instead, the idealized second-law approach to the analysis of a fuel cell considers a reversible process at constant temperature and pressure. Later this lecture we will see that the maximum work that can be done by the fuel cell is given by the change in the Gibbs function between the products and the reactants. (The Gibbs function, G, is defined in terms of other thermodynamic functions: $G = U + PV - TS = H - TS$.)

Fuel Cell Stacks

- The previous diagrams showed individual cells
- Typical voltage of these cells is about one volt
- Individual cells are joined together in an assembly called a "stack"
- Separator (bipolar) plates are used to link individual cells in the stack

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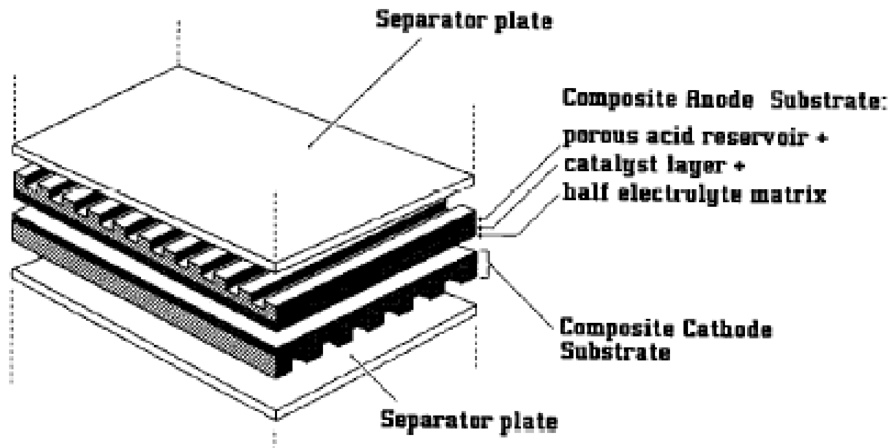
The following quote is adapted from the *Fuel Cell Handbook:* As with batteries, individual fuel cells must be combined to produce appreciable voltage levels and so are joined by interconnects, which are sometimes called bipolar plates. Because of the configuration of a flat plate cell, the interconnect becomes a separator plate with two functions: 1) to provide an electrical series connection between adjacent cells, specifically for flat plate cells, and 2) to provide a gas barrier that separates the fuel and oxidant of adjacent cells. (The interconnect of a tubular solid oxide fuel cell is a special case.)

All interconnects must be an electrical conductor and impermeable to gases. Other parts of the cell of importance are (1) the structure for distributing the reactant gases across the electrode surface and which serves as mechanical support, (2) electrolyte reservoirs for liquid electrolyte cells to replenish electrolyte lost over life, and (3) current collectors (not shown) that provide a path for the current between the electrodes and the separator of flat plate cells. Other arrangements of gas flow and current flow are used in fuel cell stack designs, and are mentioned in Sections 3 through 6 of the Fuel Cell Handbook for the various type cells.

Assembling a Stack



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Reference: Figure 1-4 in the *Fuel Cell handbook*. This shows a phosphoric acid fuel cell. Several individual cells are placed together to form an complete stack.

Membrane Electrode Assembly

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Reference: http://www.fuelcellstore.com/products/solarEn/mea.html

The membrane electrode assembly or MEA is the basic component of the fuel cell stack. This is placed between separator plates to complete the stack. This particular assembly, available from the Fuel Cell Store, has the following specifications.

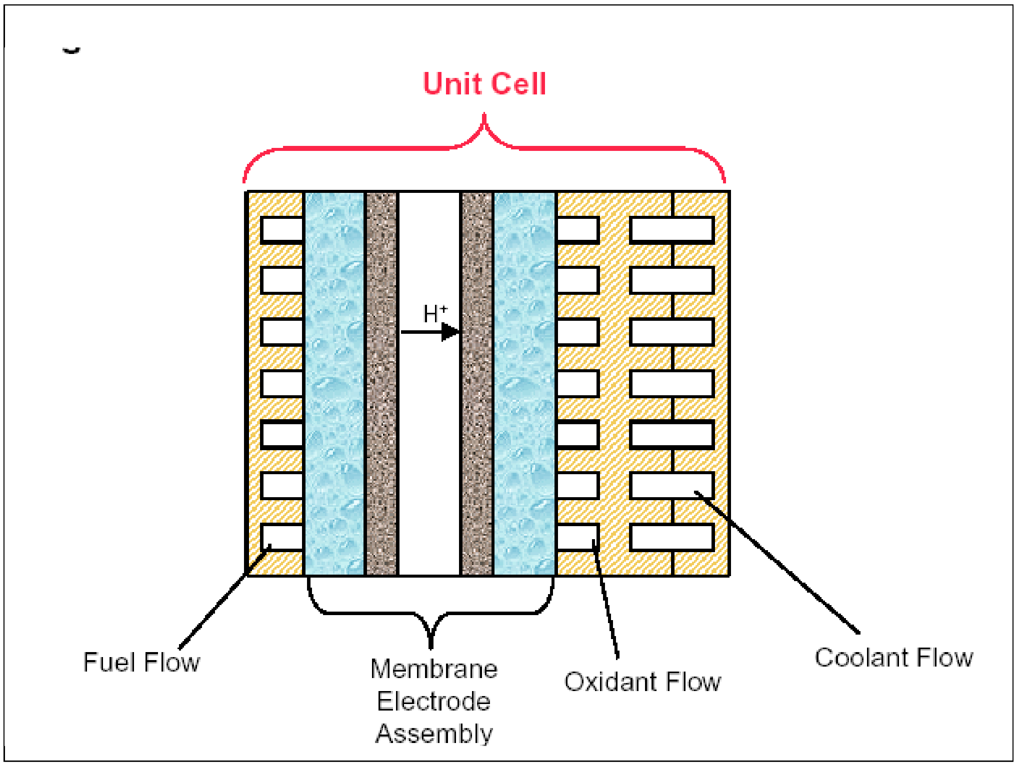
Membrane PEM, 100-120 or 170 micron thick
Acid capacity 0.8-0.9 m.eq./g

Electrode (gas diffusion layer with catalyst) With catalyst loading 30% Pt on Vulcan XC-72 at 0.5 mg/cm^2 Pt

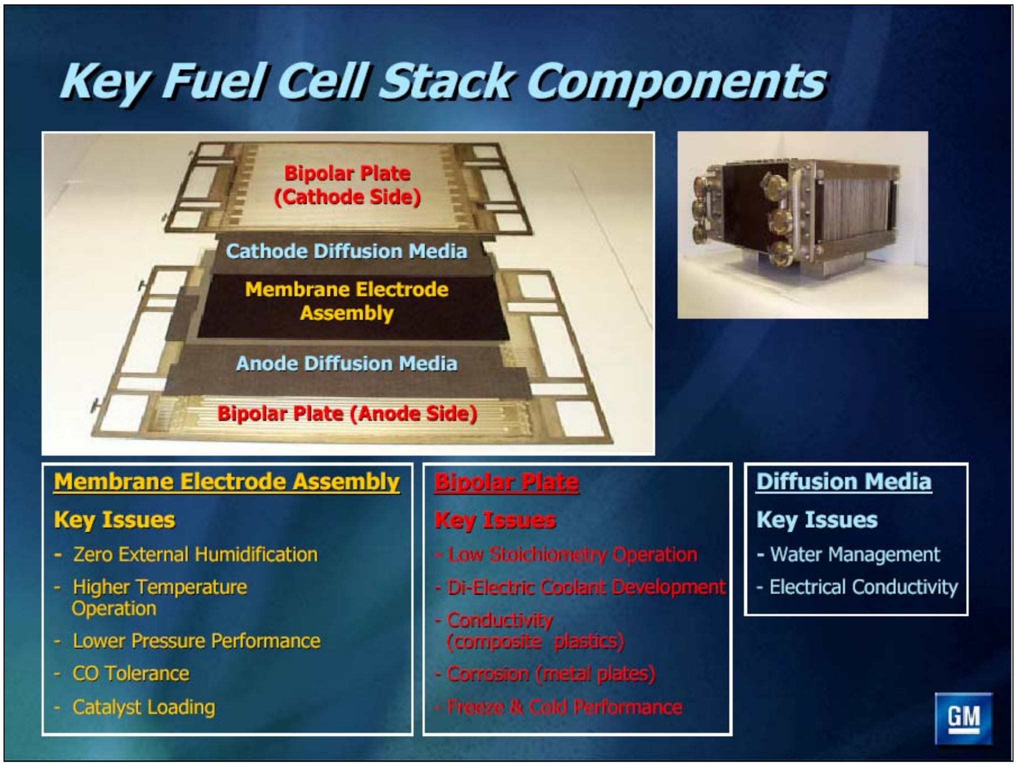
Membrane Size up to 225 cm^2

Electrode Size up to 144 cm^2

Power density @ 0.6V (PH2=PO2=1bar, T=50°, no humidification of gases) 350 mA / cm^2 (average)



Reference: http://216.51.18.233/library/ADLCostModel.pdf

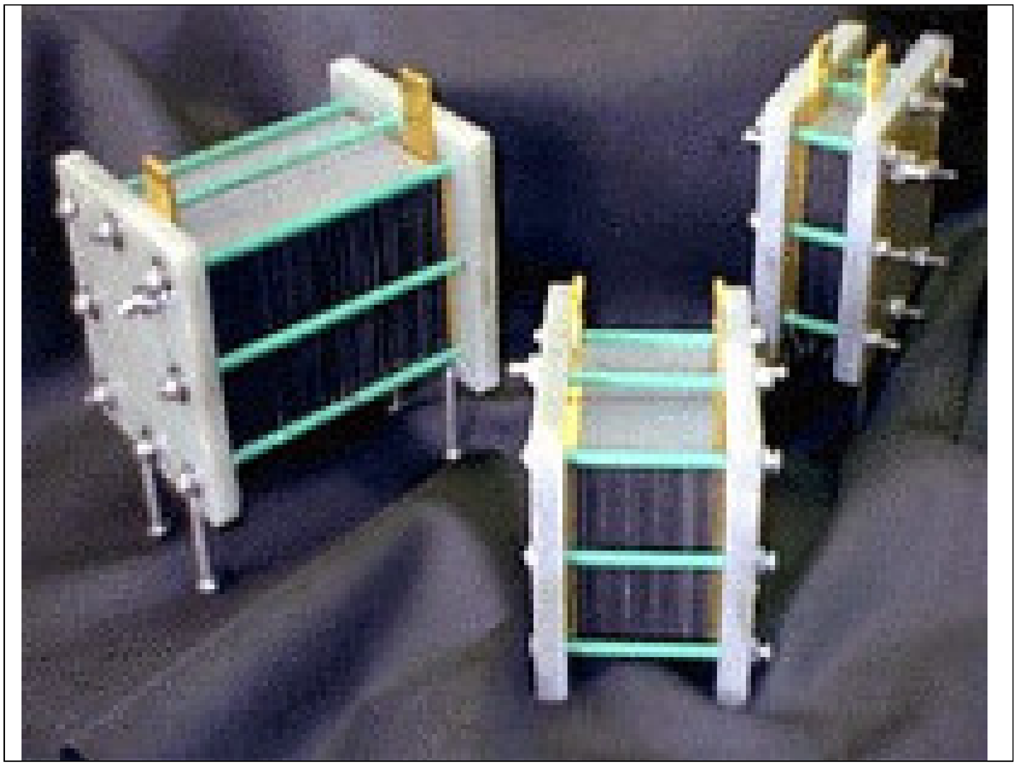


http://www.gmfuelcell.com/w_shoop/pdf/Andrew%20Bosco%20FC(E).pdf

Latest Fuel Cell Stack Developments

Andrew Bosco, Manager - Architecture, Design & Modeling

Global Alternative Propulsion Center (GAPC)



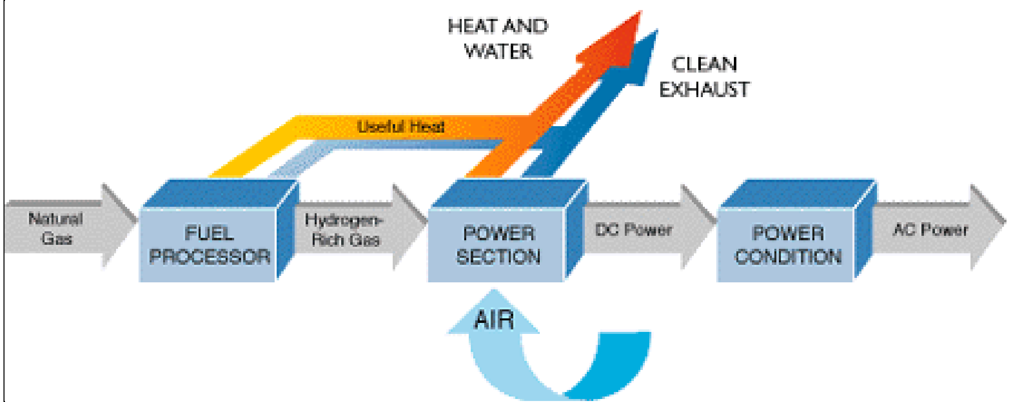
Reference: http://www.fuelcellstore.com/products/fuelcell/forced_flow_stacks.html

Forced Flow Fuel Cell Stack Features:

Stacks operate with hydrogen/air and reformate (with 10-15 ppm CO)/air.
Self-Humidified Membrane and Electrode Assemblies.
Hydrogen can be kept dead-ended.
Water is removed continuously from the stack.
The maximum operating temperature can be from 70-75°C.
There is no cell failures at higher temperatures.
The stacks can operate at ambient temperature.
No special startup procedure is required.

Power (W)	Stack Size	Area cm2	Current (A)	Voltage (V)
150	10-cell	64	25	6
300	20-cell	64	25	12
500	32-cell	64	25	20
1,000	24-cell	245	75	14
1,500	36-cell	245	75	22
1,600	34-cell	155		24
2,000	48-cell	245	75	28
2,800	34-cell	155		15
3,000	72-cell	245	75	42

Fuel Cell Systems



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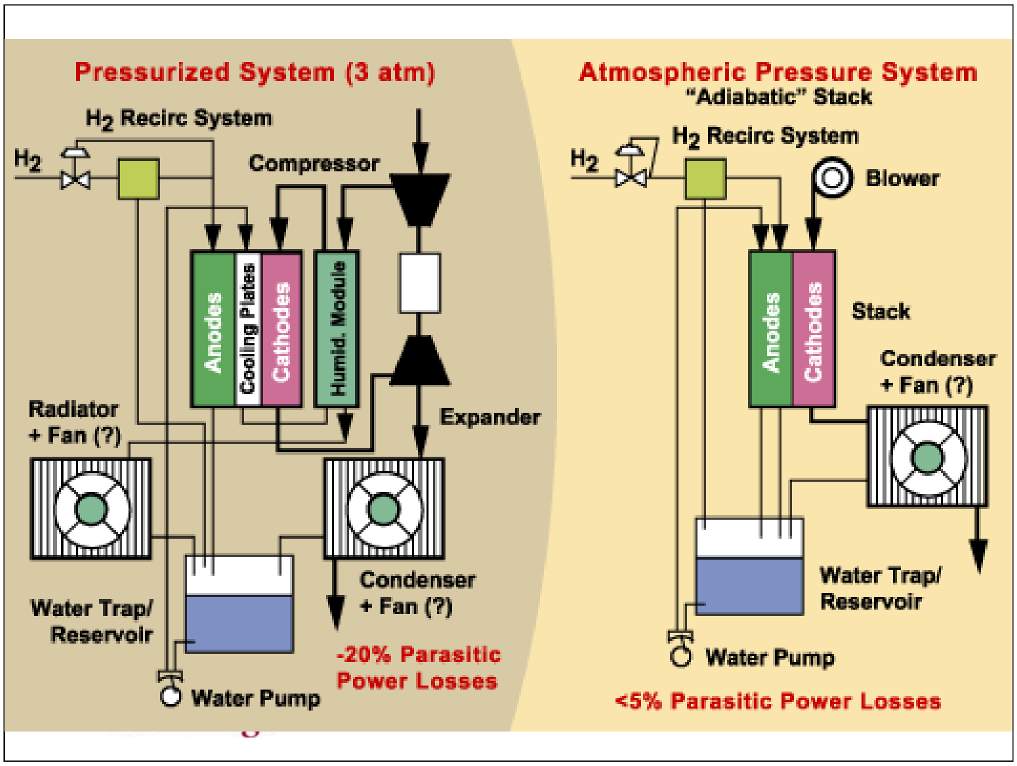
Reference: http://www.dodfuelcell.com/fcdescriptions.html

Fuel cells are typically grouped into three sections: (1) the fuel processor, (2) the power section (fuel cell stack), and (3) the power conditioning.

In the fuel processor, a fuel such as natural gas is reformed to boost the concentration of hydrogen. The hydrogen rich fuel and oxygen (air) then feeds into the power section to produce DC electricity and reusable heat. The power section includes a fuel cell stack which is a series of electrode plates interconnected to produce a set quantity of electrical power. The output DC electricity is then converted to AC electricity in the power conditioning section where it also reduces voltage spikes and harmonic distortions.

The notion of a fuel processor is an important one because fuel cells generally work best on hydrogen. We will see that some types of fuel cells can reform the fuel internally.



Reference: http://www.lanl.gov/mst/fuelcells/adiabatic.shtml

Adiabatic fuel cell stacks have been developed and patented by Los Alamos National Laboratory.

The simplicity of adiabatic stacks is their most attractive feature and is accomplished primarily through two technological elements. First is the direct humidification of the fuel cell membrane electrode assemblies (MEAs) with liquid water, and the second is operation of the fuel cell stack at very-near-ambient pressure. Direct MEA humidification is made possible through the introduction of an anode-wicking backing that conveys liquid water from the anode flow-field plenum through the nominally hydrophobic gas diffusion layer directly to the membrane throughout the active area.

Because even modest pressure can result in high compression power requirements, near-ambient pressure operation is critical to the stack's efficiency. In conventional systems humidification modules, internal manifolding, and two-phase flows in the cathode channels create high-pressure drops that necessitate air inlet pressurization, but the direct humidification system avoids these pressure drops and allows the inlet pressure to be kept to about six inches of water. During the normal operation of this well-humidified fuel cell stack with a dry, ambient temperature cathode air inlet, the ai rstream becomes heated and saturated with water vapor as it passes through the cells. This effect provides in situ evaporative cooling of the stack, eliminating the need for separate cooling systems or in-stack cooling plates. The non-isothermal stack operation and evaporative cooling result in an "adiabatic" stack.

The simplicity of the adiabatic system is easy to appreciate when compared to the conventional system, with its extensive flow and control elements. A simple plastic condenser is used to recover surplus water and works effectively even in Los Alamos' high desert climate. The single-step heat exchange process allows higher temperature differentials in the condenser than could be attained in a radiator, and may prove to be a general improvement over more conventional approaches using radiators and coolants.

Fuel Cell Types

- Phosphoric acid fuel cell (PAFC)
- Molten carbonate fuel cell (MCFC)
- Alkaline fuel cell (AFC)
- Solid oxide fuel cell (SOFC)
- Direct methanol fuel cell (DMFC)
- Proton exchange membrane (PEMFC)
- Reversible fuel cells

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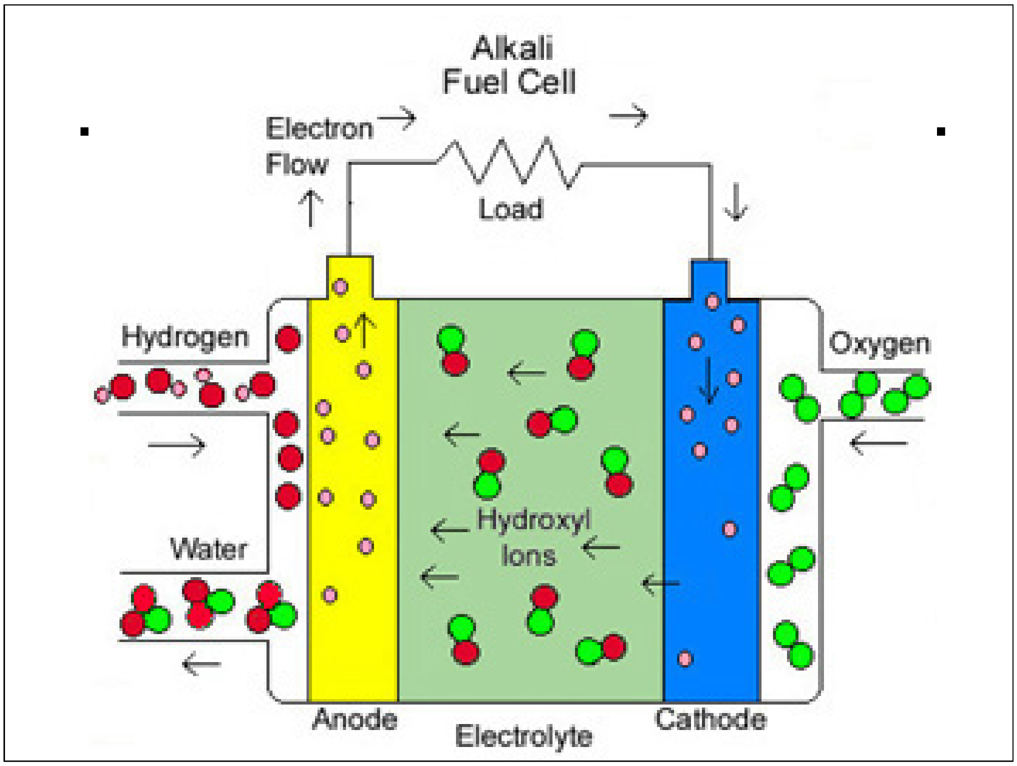
This is a list of common fuel cells that we will be discussing further in later charts. The proton exchange membrane fuel cell has a variety of abbreviations including PEMFC, PEFC, and PEM.

Reversible fuel cells are ones that can be run in reverse to generate hydrogen and oxygen from an electrical input. We will not be discussing these further. Similarly, the alkaline fuel cells are a specialized product that continues to be used for space applications, but are not considered for ground transportation or distributed electrical generation.



Reference: http://fuelcells.si.edu/basics.htm

Alkali or Alkaline fuel cells operate on compressed hydrogen and oxygen. They generally use a solution of potassium hydroxide (chemically, KOH) in water as their electrolyte. Efficiency is about 70 percent, and operating temperature is 150 to 200 degrees C, (about 300 to 400 degrees F). Cell output ranges from 300 watts (W) to 5 kilowatts (kW). Alkali cells were used in Apollo spacecraft to provide both electricity and drinking water. They require pure hydrogen fuel, however, and their platinum electrode catalysts are expensive. And like any container filled with liquid, they can leak.

At the cathode, the oxygen reacts with the electrolyte, typically potassium hydroxide to form two hydroxyl ions, OH^-. These hydroxyl ions then migrate to the anode where they react with hydrogen to produce water. The reaction with hydrogen liberates electrons that then go through the external circuit.

Although these cells are quite effective in space applications, operating on H_2 and pure O_2, the deteriorate rapidly when used with air as the oxidizer due to the CO_2 in the air. The CO_2 goes into solution forming carbonate ions that reduce the performance of the cell much more rapidly than the normal deterioration when operating with pure oxygen. Further research on alkaline cells for terrestrial applications is essentially zero.

Fuel Cell Types

	PAFC	MCFC	SOFC	PEMFC
Electrolyte	Phosphoric Acid	Molten car-bonate salt	Ceramic	Polymer
Temperature	375 F	1200 F	1830 F	175 F
Fuels	H_2	H_2/CO	H_2/CH_4	H_2
Reforming	External	Internal	Internal	External
Oxidant	O_2/Air	O_2/Air	O_2/Air	O_2/Air
Efficiency	40 – 50%	50 – 60%	45 – 55%	40 – 50%

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Reference: http://www.dodfuelcell.com/fcdescriptions.html

These four fuel cell types are the ones under most intensive investigation by the DOE for distributed power generation. Note that the MCFC and the SOFC fuel cells are high temperature cells. The use of these fuel cells is typically done in conjunction with some application for the heat rejected by them.

Specific details about each of these four are presented on the next set of charts.

Phosphoric Acid Fuel Cells

- Phosphoric acid in porous matrix
- Porous carbon electrodes with platinum
- Electrical efficiencies from 36% to 42% (HHV)
- Pressurized reactants for high efficiency
- Can supply usable thermal energy – some at ~ 250°F to ~ 300°F -- majority at ~150°F.
- Power density of 160 to 175 watts/ft^2 of active cell area

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Reference: http://www.dodfuelcell.com/phosphoric.html

The Phosphoric Acid Fuel Cell (PAFC) is the most mature fuel cell technology in terms of system development and commercialization activities with more than 20 years of development. The total worldwide investment in development and demonstration exceeds of $500. One reason for selecting the PAFC for substantial development was its believed tolerance for reformed hydrocarbon fuels.

The PAFC uses liquid phosphoric acid as the electrolyte. The phosphoric acid is contained in a Teflon bonded silicone carbide matrix. The small pore structure of this matrix preferentially keeps the acid in place through capillary action. Some acid may be entrained in the fuel or oxidant streams and addition of acid may be required after many hours of operation. Platinum catalyzed, porous carbon electrodes are used on both the fuel (anode) and oxidant (cathode) sides of the electrolyte.

Fuel and oxidant gases are supplied to the backs of the porous electrodes by parallel grooves formed into carbon or carbon-composite plates. These plates are electrically conductive and conduct electrons from an anode to the cathode of the adjacent cell. In most designs, the plates are "bi-polar" in that they have grooves on both sides - one side supplies fuel to the anode of one cell, while the other side supplies air or oxygen to the cathode of the adjacent cell.

The byproduct water is removed as steam on the cathode (air or oxygen) side of each cell by flowing excess oxidant past the backs of the electrodes. This water removal procedure requires that the system be operated at temperatures around 375°F (190°C). At lower temperatures, the product water will dissolve in the electrolyte and not be removed as steam. At approximately 410°F (210°C), the phosphoric acid begins to decompose. Excess heat is removed from the fuel cell stack by providing carbon plates containing cooling channels every few cells. Either air or a liquid coolant, such as water, can be passed through these channels to remove excess heat.

Molten Carbonate Fuel Cell

- Operating temperature 1200 F (650 C)
- Electrolyte is molten carbonate salt mixture, typically Li_2CO_3 and K_2CO_3
- CO in fuel stream CO_2 in oxidant stream
- Cathode: $O_2 + 2CO_2 + 4e^- \rightarrow 2(CO_3)^=$
- Anode reactions
  - $H_2 + (CO_3)^= \rightarrow CO_2 + H2O + 2e^-$
  - $CO + (CO_3)^= \rightarrow 2CO_2 + 2e^-$

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Reference: http://www.dodfuelcell.com/molten.html

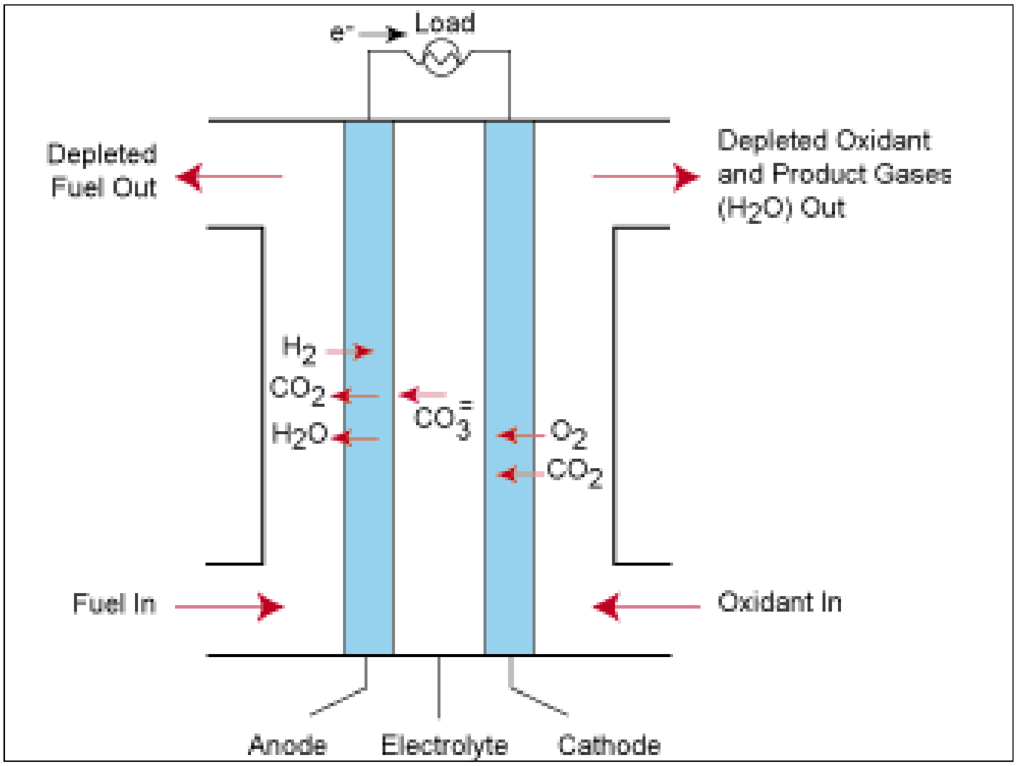
The Molten Carbonate Fuel Cell (MCFC) evolved from work in the 1960's aimed at producing a fuel cell which would operate directly on coal. While direct operation on coal seems less likely today, operation on coal-derived fuel gases or natural gas is viable.

The MCFC uses a molten carbonate salt mixture as its electrolyte. The composition of the electrolyte varies, but usually consists of lithium carbonate and potassium carbonate. At the operating temperature of about 1200°F (650°C), the salt mixture is liquid and a good ionic conductor. The electrolyte is suspended in a porous, insulating and chemically inert ceramic (LiA102) matrix.

The anode process involves a reaction between hydrogen and carbonate ions (CO3=) from the electrolyte which produces water and carbon dioxide (CO2) while releasing electrons to the anode. The cathode process combines oxygen and CO2 from the oxidant stream with electrons from the cathode to produce carbonate ions which enter the electrolyte. The need for CO2 in the oxidant stream requires a system for collecting CO2 from the anode exhaust and mixing it with the cathode feed stream.

As the operating temperature increases, the theoretical operating voltage for a fuel cell decreases and with it the maximum theoretical fuel efficiency. On the other hand, increasing the operating temperature increases the rate of the electrochemical reaction and thus the current which can be obtained at a given voltage. The net effect for the MCFC is that the real operating voltage is higher than the operating voltage for the PAFC at the same current density.

The higher operating voltage of the MCFC means that more power is available at a higher fuel efficiency from a MCFC than from a PAFC of the same electrode area. As size and cost scale roughly with electrode area, this suggests that a MCFC should be smaller and less expensive than a "comparable" PAFC.



Reference: http://www.dodfuelcell.com/molten.html

The MCFC also produces excess heat at a temperature which is high enough to yield high pressure steam which may be fed to a turbine to generate additional electricity. In combined cycle operation, electrical efficiencies in excess of 60% (HHV) have been suggested for mature MCFC systems.

The MCFC operates at between 1110°F (600°C) and 1200°F (650°C) which is necessary to achieve sufficient conductivity of the electrolyte. To maintain this operating temperature, a higher volume of air is passed through the cathode for cooling purposes. The high operating temperature of the MCFC offers the possibility that it could operate directly on gaseous hydrocarbon fuels such as natural gas. The natural gas would be reformed to produce hydrogen within the fuel cell itself.

The need for CO_2 in the oxidant stream requires that CO_2 from the spent anode gas be collected and mixed with the incoming air stream. Before this can be done, any residual hydrogen in the spent fuel stream must be burned. Future systems may incorporate membrane separators to remove the hydrogen for recirculation back to the fuel stream.

At cell operating temperatures of 1200°F (650°C) noble metal catalysts are not required. The anode is a highly porous sintered nickel powder, alloyed with chromium to prevent agglomeration and creep at operating temperatures. The cathode is a porous nickel oxide material doped with lithium. Significant technology has been developed to provide electrode structures which position the electrolyte with respect to the electrodes and maintain that position while allowing for some electrolyte boil-off during operation. The electrolyte boil-off has an insignificant impact on cell stack life. A more significant factor of life expectancy has to do with corrosion of the cathode. The cell performance is sensitive to operating temperature. A change in cell temperature from 1200°F (650°C) to 1110°F (600°C) results in a drop in cell voltage of almost 15%. The reduction in cell voltage is due to increased ionic and electrical resistance and a reduction in electrode kinetics.

Solid Oxide Fuel Cell

- Solid ceramic electrolyte, typically dense yttria-stabilized zirconia
- Operating temperature 1830 F (1000 C)
- Cathode: $O_2 + 4e^- \rightarrow 2O^=$
- Anode reactions depend on fuel
  - $2H_2 + 2O^= \rightarrow 2H_2O + 4e^-$
  - $2CO + 2O^= \rightarrow 2CO_2 + 4e^-$
  - $(1/2)CH_4 + 2O^= \rightarrow (1/2)CO_2 + H_2O + 4e^-$

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reference: http://www.dodfuelcell.com/solidoxide.html

The Solid Oxide Fuel Cell (SOFC) uses a ceramic, solid-phase electrolyte which reduces corrosion considerations and eliminates the electrolyte management problems associated with the liquid electrolyte fuel cells. To achieve adequate ionic conductivity in such a ceramic, however, the system must operate at about 1830°F (1000°C). At that temperature, internal reforming of carbonaceous fuels should be possible, and the waste heat from such a device would be easily utilized by conventional thermal electricity generating plants to yield excellent fuel efficiency.

The SOFC is based upon the use of a solid ceramic as the electrolyte. The preferred material, dense yttria-stabilized zirconia, is an excellent conductor of negatively charged oxygen (oxide) ions at high temperatures. The SOFC is a solid state device and shares certain properties and fabrication techniques with semi-conductor devices. The anode is a porous nickel/zirconia cermet while the cathode is magnesium-doped lanthanum manganate. The Westinghouse cell design constructs the fuel cell around a porous zirconia support tube through which air is supplied to the cathode which is deposited on the outside of the tube. A layer of electrolyte is then deposited on the outside of the cathode and finally a layer of anode is deposited over the electrolyte. A number of cells are connected together by high temperature semiconductor contacts.

In operation, hydrogen or carbon monoxide (CO) in the fuel stream reacts with oxide ions (O=) from the electrolyte to produce water or CO_2 and to deposit electrons into the anode. The electrons pass outside the fuel cell, through the load, and back to the cathode where oxygen from air receives the electrons and is converted into oxide ions which are injected into the electrolyte. It is significant that the SOFC can use CO as well as hydrogen as its direct fuel.

Solid Oxide Fuel Cell (cont'd)

- Development cells and small stacks have 0.6 V/cell at about 232 A/ft^2
- Lifetimes 30,000+ hours for single cells
- Unpressurized cell efficiency~45% (HHV).
- Pressurized cells could be ~60% efficient
- Provide high temperature waste heat
- Internal fuel reforming possible
- CO can be used directly as a fuel
- Most tolerant of any fuel cell type to sulfur

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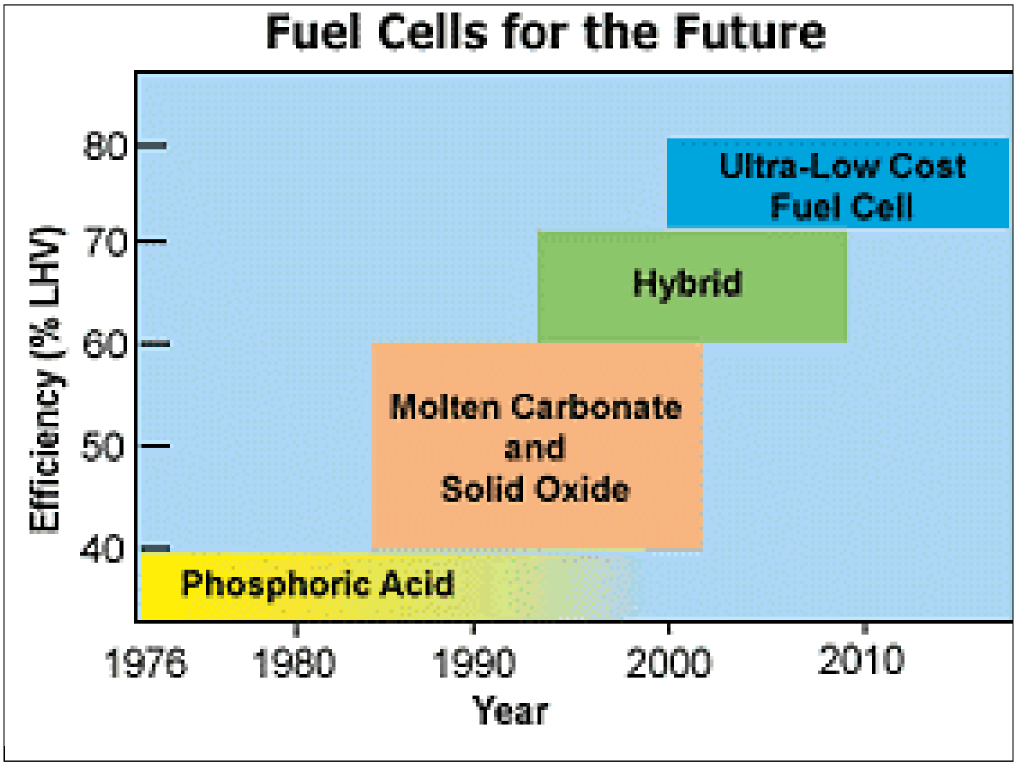
reference: http://www.dodfuelcell.com/solidoxide.html

In development cells and small stacks, the SOFC has demonstrated 0.6V/cell at about 232 A/ft^2. Lifetimes in excess of 30,000 hours for single cells have been demonstrated as have a number of heat/cool cycles. Presently available, unpressurized SOFCs deliver fuel to electric efficiencies in the range of 45% (HHV). Argonne National Laboratories suggests that pressurized systems could yield fuel efficiencies of 60% (HHV). Bottoming cycles, using the high temperature waste heat from the fuel cell, could add another few percent to the fuel efficiency of the SOFC system.

The SOFC operates at approximately 1830°F (1000°C). Temperature management is achieved through maintenance of proper volume of the air stream into the cell. The high operating temperature of the SOFC offers the possibility of internal reforming. As in the MCFC, CO does not act as a poison and can be used directly as a fuel. The SOFC is also the most tolerant of any fuel cell type to sulfur. The anode consists of metallic Ni and Y_2O_3-stabilized ZrO_2 skeleton, which serves to inhibit sintering of the metal particles and to provide a thermal expansion coefficient comparable to those of the other cell materials. The anode structure is fabricated with a porosity of 20 to 40% to facilitate mass transport of reactant and product gases. The Sr-doped lanthanum manganite (La1-xSrxMnO3, x = 0.10-0.15) that is most commonly used for the cathode material is a p-type conductor. Similar to the anode, the cathode is a porous structure that must permit rapid mass transport of reactant and product gases.

The 1830°F (1000°C) operating temperature of the SOFC requires a significant start-up time. The cell performance is very sensitive to operating temperature. A 10% drop in temperature results in ~12% drop in cell performance due to the increase in internal resistance to the flow of oxygen ions. The high temperature also demands that the system include significant thermal shielding to protect personnel and to retain heat. While such requirements are acceptable in a utility application, they are not consistent with the demands of most transportation applications nor do they lend themselves to small, portable or transportable applications.



Reference: http://www.fe.doe.gov/coal_power/fuelcells/

The U.S. Department of Energy's Office of Fossil Energy is partnering with several fuel cell developers to develop the technology for the stationary power generation sector - that is, for power units that can be connected into the electricity grid primarily as distributed generation units. Industry participation is extensive, with more than 40 percent of the program funded by the private sector.

For most of the 1970s and early 1980s, the federal program included development of the phosphoric acid fuel cell system, considered the "first generation" of modern-day fuel cell technologies. These are now considered a commercial product.

In the late 1980s, the department shifted its emphasis to advanced generations of fuel cell technologies, specifically the molten carbonate and solid oxide fuel cell systems. The goal is to ready these technologies for initial commercial entry by 2003.

Fuel cells are one of the cleanest and most efficient technologies for generating electricity. Since there is no combustion, there are none of the pollutants commonly produced by boilers and furnaces. For systems designed to consume hydrogen directly, the only products are electricity, water and heat.

When natural gas or other hydrocarbons are used, fuel cells produce some carbon dioxide, though much less than would be created if the fuel was burned. Advanced fuel cells using natural gas, for example, could potentially reduce carbon dioxide emissions by 60% compared to a conventional coal plant and by 25% compared to today's natural gas plants. Moreover, the carbon dioxide is emitted in concentrated form which makes its capture and sequestration much easier.

Fuel cells are also inherently flexible. Like batteries in a flashlight, the cells in fuel cells can be stacked to produce voltage levels that match specific power needs, from a few watts for certain appliances to multiple megawatt power stations that can light a community.

Fuel Cell Thermodynamics

- First law (steady-flow, negligible KE and PE, F = Fuel, O = oxidizer, P = product)

$$\dot{Q} = \dot{W} + \dot{m}_P h_P - \dot{m}_F h_F - \dot{m}_O h_O$$

- Second law and mass balance

$$\dot{Q}/T + \dot{S}_{irr} = \dot{m}_P s_P - \dot{m}_F s_F - \dot{m}_O s_O$$

$$\dot{m}_P = \dot{m}_F + \dot{m}_O$$

- Combine first and second law

$$\dot{W} + \dot{m}_P h_P - \dot{m}_F h_F - \dot{m}_O h_O = \dot{m}_P T s_P - \dot{m}_F T s_F - \dot{m}_O T s_O - T\dot{S}_{irr}$$

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The first law of thermodynamics for an open system is

$$\frac{dE_{system}}{dt} = \dot{Q} - \dot{W} + \sum_{inlet} \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + g z_i \right) - \sum_{outlet} \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + g z_i \right)$$

For a steady system the time derivative is zero and for many engineering systems, including fuel cells, the kinetic and potential energy terms are negligible. For the fuel cell we will have three flowing streams. The fuel, F, and oxidizer, O, are inlet streams and the products stream, P, is the outoet. For this case our first law becomes the equation shown on the slide. Note that the work term is the useful work delivered by the thermodynamic system. For a fuel cell, this would be the electric power delivered.

The second law for an open system gives an entropy balance. The transient increase in the entropy of the system is due to three sources: (1) the difference between the entropy supplied by the entropy of the inlet and outlet flows, (2) the reversible entropy change equal to Q/T, and (3) entropy generated by irreversible processes, S_{irr}. This balance is written as follows.

$$\frac{dS_{system}}{dt} = \frac{\dot{Q}}{T} + \dot{S}_{irr} + \sum_{inlet} \dot{m}_i s_i - \sum_{outlet} \dot{m}_i s_i$$

(continued on next notes page)

Fuel Cell Thermodynamics II

- Rearrange to give work

$$\dot{W} = -\dot{m}_P(h_P - Ts_P) + \dot{m}_F(h_F - Ts_F) + \dot{m}_O(h_O - Ts_O) - T\dot{S}_{irr}$$

- Introduce Gibbs Function, g ≡ h – Ts

$$\Delta\dot{G} = \dot{m}_P(h_P - Ts_P) - \dot{m}_F(h_F - Ts_F) - \dot{m}_O(h_O - Ts_O)$$

$$\Delta\dot{G} = \dot{m}_P g_P - \dot{m}_F g_F - \dot{m}_O g_O$$

- No irreversibilities gives maximum work

$$\dot{W} = -\Delta\dot{G} - T\dot{S}_{irr} \qquad \dot{W}_{max} = -\Delta\dot{G}$$

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(continued from previous notes page)

For a steady system the time derivative is zero in the entropy balance, just as it was in the first law and we still have the same three streams: inlet fuel and oxidizer and outlet products. In this case the second law has the form shown on the previous chart.

When we combine the first and second laws to eliminate the heat transfer term we get the final equation on the previous chart, which gives an equation for the work in terms of the flowing stream properties and the entropy generated by irreversible processes. We can rearrange this equation to the form shown in the first equation on this chart. This equation has been written to introduce the term h – Ts, which is known in thermodynamics as the Gibbs function. (Named after Joshia Willard Gibbs who is famous for his contributions to basic thermodynamics; he received the first PhD in Mechanical Engineering in the US.)

The definition of the ΔG term leads to the simple equation for the power produced by the fuel cell. The generation of entropy by irreversible processes will always be positive. The maximum work output occurs in the (impossible) limit where this term is zero.

Fuel Cell Thermodynamics III

- Per-unit-mass quantity and electric power

$$w = \frac{\dot{W}}{\dot{m}_F} = \frac{EI}{\dot{m}_F} = -\frac{\Delta\dot{G}}{\dot{m}_F} - \frac{T\dot{S}_{irr}}{\dot{m}_F} = \frac{\dot{m}_P}{\dot{m}_F} g_P - g_F - \frac{\dot{m}_O}{\dot{m}_F} g_O$$

$$w = -\Delta g - Ts_{irr}$$

- Power $\dot{W}$ = EI, E = voltage, I = current from from electrons released by fuel
  - F = Faraday constant = 96485.3383 coulomb/gmmol; n = electrons released

$$E = \frac{M_F\left(-\Delta g - Ts_{irr}\right)}{nF} \qquad E^o = -\frac{M_F \Delta g}{nF} = -\frac{\Delta\bar{g}}{nF}$$

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We can relate the reversible work to the voltage from the fuel cell. If a fuel molecule releases n electrons when it react, it will release a charge of ne per fuel atom reacted where e is the charge on the electron (1.0621×10^{-19} coulomb).

The fuel mass, m, has m/M_F moles where M_F is the molecular mass of the fuel. One mole of fuel has Avagadro's number (6.023×10^{23}/gmmol) of atoms, so the total charge released per unit mass of fuel reacted is neN_{av}/M_F. The produce of Avagadro's number and the charge on the electron, eN_{av} is known as the Faraday constant, F (= 96485.3383 coulomb/gmmol). Making the substitution $F = eN_{av}$ and noting that the current is proportional to the mass flow rate of fuel gives the following result for the current

$$I = \frac{\dot{m}_F neN_{av}}{M_F} = \frac{\dot{m}_F nF}{M_F} \qquad w = \frac{-\Delta\dot{G} - T\dot{S}_{irr}}{\dot{m}_F} = \frac{\dot{W}}{\dot{m}_F} = \frac{EI}{\dot{m}_F} = \frac{E\dfrac{\dot{m}_F nF}{M_F}}{\dot{m}_F}$$

The maximum voltage. E^o, called the reversible cell potential or open circuit voltage, occurs when the entropy generation is zero. This gives

$$\frac{EnF}{M_F} = -\Delta g - Ts_{irr} \qquad E = \frac{M_F\left(-\Delta g - Ts_{irr}\right)}{nF} \qquad E^o = -\frac{M_F \Delta g}{nF} = -\frac{\Delta\bar{g}}{nF}$$

Voltages and Potentials

- Equilibrium electrochemical potential
  - open circuit voltage (ocv)
  - electromotive force (emf)
  - value when no current is flowing
- Cell voltage – potential difference when current is flowing
- Overpotential – difference between cell voltage and emf

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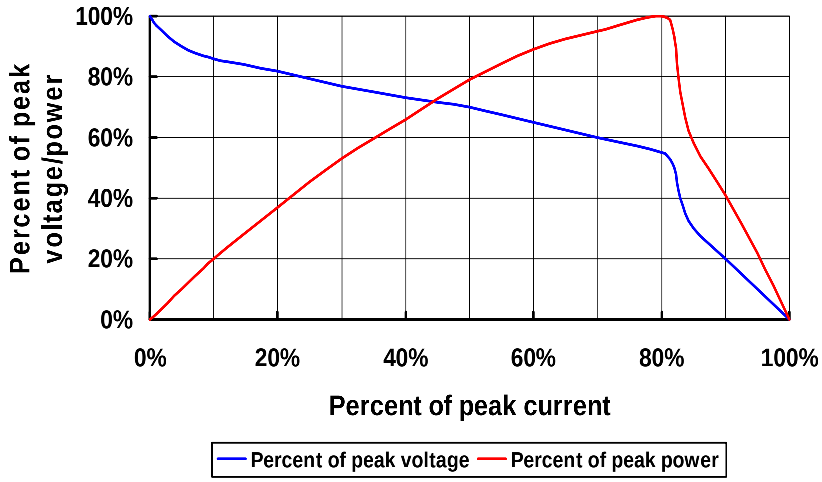
Reference: http://electrochem.cwru.edu/ed/dict.htm (Accessed April 17, 2007.)

Cell voltage, which is the electrical potential difference between two electrodes of an electrochemical cell, usually refers to nonequilibrium conditions. This occurs when when current is flowing through the cell (although this convention is not always followed). The "cell voltage" differs from the electromotive force of open-circuit voltage by the amount of the overvoltage. The term "voltage" is usually reserved for the case when an electrochemical cell is under consideration, while the term "potential" is usually reserved for the case when an electrode is considered. The terms "voltage" and "potential" are sometimes used interchangeably.

The electromotive force or equilibrium electrical potential is the potential measured when there is no current flow. This is also called the open circuit voltage. At "equilibrium" the chemical driving force and the opposing electrical force are equal. The potential difference between the metal and the solution phases under these conditions is the "equilibrium potential difference." This potential difference cannot be measured because there is no way to make an electrical connection to the solution phase without setting up another electrode potential. Consequently, electrode potentials are always measured against a reference electrode whose potential is known on an arbitrary scale.

The overvoltage is the difference between the cell voltage (with a current flowing) and the open circuit voltage. The overvoltage represents the extra energy needed (an energy loss that appears as heat) to force the cell reaction to proceed at a required rate. Consequently, the cell voltage of a galvanic cell (e.g., a rechargeable battery during discharge) is always less than its open circuit voltage, while the cell voltage of an electrolytic cell (e.g., a rechargeable battery during charging) is always more than its open circuit voltage. Occasionally also referred to as "polarization" of the cell.

Fuel Cell Characteristics



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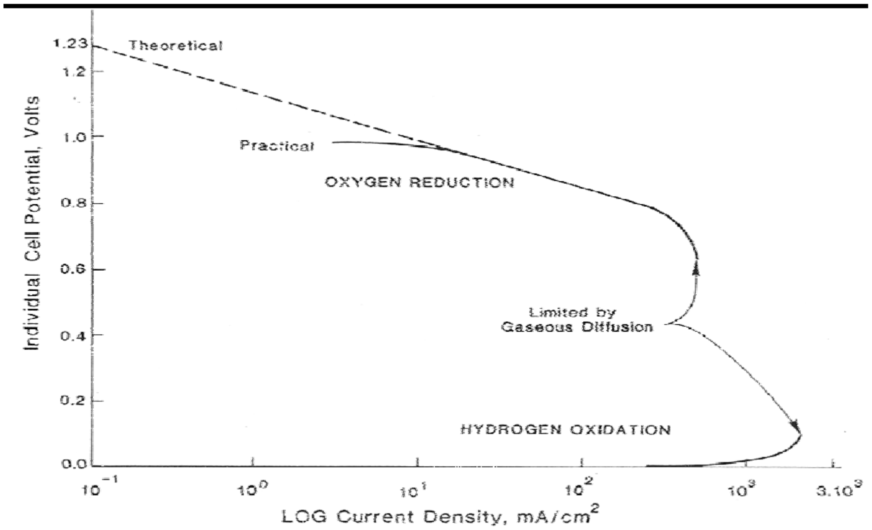
The left hand side of this chart is the thermodynamic equilibrium side, showing the open circuit voltage. As we try to take current to the external load, irreversibility set in and the cell voltage becomes lower than the open circuit voltage. However, as we do this the power increases because we have an actual current. At a certain point, the power peaks and then drops off to zero at the short circuit (or peak) current.

H2 – O2 Fuel Cell
(Typical Polarization Characteristics of a PAFC)



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Reference: Web site at the University of California, Davis

Future Applications

- Distributed electric power
- Transportation applications
  - Cars
  - Buses
- Substitutes for batteries
- Fuel productions, conversion and storage an issue

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Reference: http://fuelcells.si.edu/future/furmain.htm

Fuel cells may be a substitute for batteries, for example in powering laptop computers.
Over the next decade, one kind of equipment common to many experiments with fuel cells will probably by passenger vehicles. Major automotive makers are conducting research into fuel cell power plants, even as they begin introducing hybrid vehicles that use a combination of fossil fuel and electric motors.

The 28 February 2000 cover story of *Aviation Week & Space Technology* disucssed AeroVironment's development of a long-duration remotely piloted vehicle named "Helios." The company hopes to integrate photovoltaics with fuel cells to power their small aircraft for months at a time. Solar cells mounted on the aircraft's wing run electric motors during the day–and also electrolyze water into hydrogen and oxygen. At night a fuel cell recombines the gases to run the motors and replenishes the supply of water for the next day. Designed to operate around 90,000 feet the aircraft could be used for military reconnaissance, scientific research, or as a communications relay.

Distributed Electrical Generation

Type	Size	Efficiency, %
Reciprocating Engines	50 kW – 6 MW	33 – 37
Micro turbines	10 kW – 300 kW	20 – 30
Phosphoric Acid Fuel Cell (PAFC)	50 kW – 1 MW	40
Solid Oxide Fuel Cell (SOFC)	5 kW – 3 MW	45 – 65
Proton Exchange Membrane Fuel Cell (PEM)	<1 kW – 1 MW	34 – 36
Photovoltaics (PV)	1 kW – 1 MW	NA
Wind Turbines	150 kW – 500 kW	NA
Hybrid Renewable	<1 kW – 1 MW	40 – 50

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Reference: *Fuel Cell Handbook*

Power Generation Economics

System	Efficiency(%)	P (MW)	Life (yr)	Cost ($/kW)
PAFC	40-45	0.2-10	5	1500
MCFC	50-55	1-100	5	1000
SOFC	50-60	1-100	5	1000
Steam	25-35	~1000	>20	1500
Gas T	25-60	100-1000	>20	250-700

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Reference: Supramaniam Srinivasan, Renaut Mosdale, Philippe Stevens, and Christopher Yang, "Fuel Cells: Reaching the Era of Clean and Efficient Power Generation in the Twenty-First Century," in *Annual Reviews of Energy and the Environment*, Annual Reviews, Inc., **24**:281-238 (1999).

Power Generation Economics 2

System	Efficiency(%)	P (MW)	Life (yr)	Cost ($/kW)
Hydro	65	0.1-1000	>20	1,500
Nuclear	35	~1000	>20	2,000
PhotoV	10	0.1-1	>10	5,000
Wind	75	0.1-1	>10	1,500
MHD	40	0.1-100	>10	2,000

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Reference: Supramaniam Srinivasan, Renaut Mosdale, Philippe Stevens, and Christopher Yang, "Fuel Cells: Reaching the Era of Clean and Efficient Power Generation in the Twenty-First Century," in *Annual Reviews of Energy and the Environment*, Annual Reviews, Inc., **24**:281-238 (1999).

Daimler Chrysler FCV

Name	Type	Year	Power (kW)	Fuel	Fuel Storage	Range (km)
NECAR2	Van	1996	50	Com-pressed H_2	5 kg 250 bars	250
NECAR3	Car	1997	50	CH_3OH	38 L	400
NECAR4	Car	1999	70	Liquid H_2	5 kg 123 K	400

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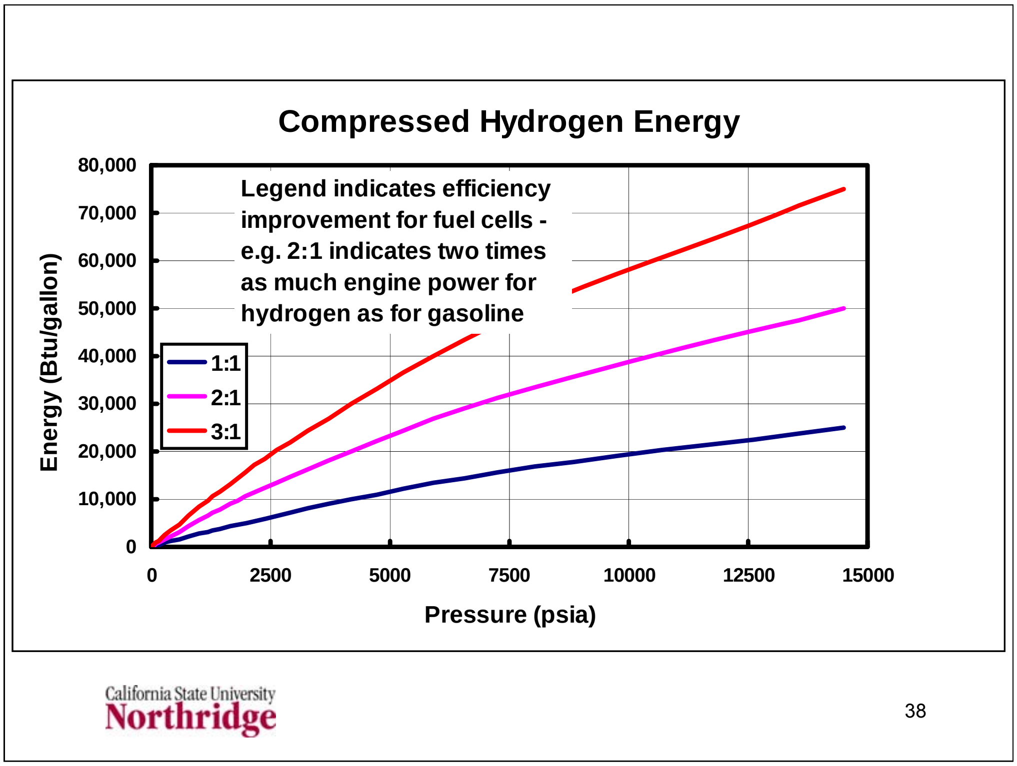
Reference: Supramaniam Srinivasan, Renaut Mosdale, Philippe Stevens, and Christopher Yang, "Fuel Cells: Reaching the Era of Clean and Efficient Power Generation in the Twenty-First Century," in *Annual Reviews of Energy and the Environment*, Annual Reviews, Inc., **24**:281-238 (1999).

These data show the performance characteristics of Daimler Chrysler demonstration vehicles using different fuel cells. The "cars" listed above are compact cars. The notation CH_2 and LH_2 are sometimes used to denote compressed and liquid hydrogen, respectively.

The methanol fuel economy in the 1997 compact car is 10.5 km/L or 24.8 mpg. Since methanol has about half the heating value of gasoline, this is about 50 miles per gallon of gasoline equivalent.

Five kilograms of hydrogen, with a higher heating value (HHV) of 141,800 kJ/kg, has a total thermal energy of 709,000 kJ or 672,000 Btu. This is about the same thermal energy as 5.6 gallons of gasoline. Because the fuel cell power plant is expected to have a higher efficiency than the combustion engine, the range for the 5 kg of hydrogen should be larger than the range for 5.6 gallons of gasoline.

The rule of thumb that 1 kg of hydrogen is about equal to 1 gallon of gasoline is often used, but it typically understates the effective energy of hydrogen.



This chart shows the energy available from compressed gaseous hydrogen as a function of the storage pressure.

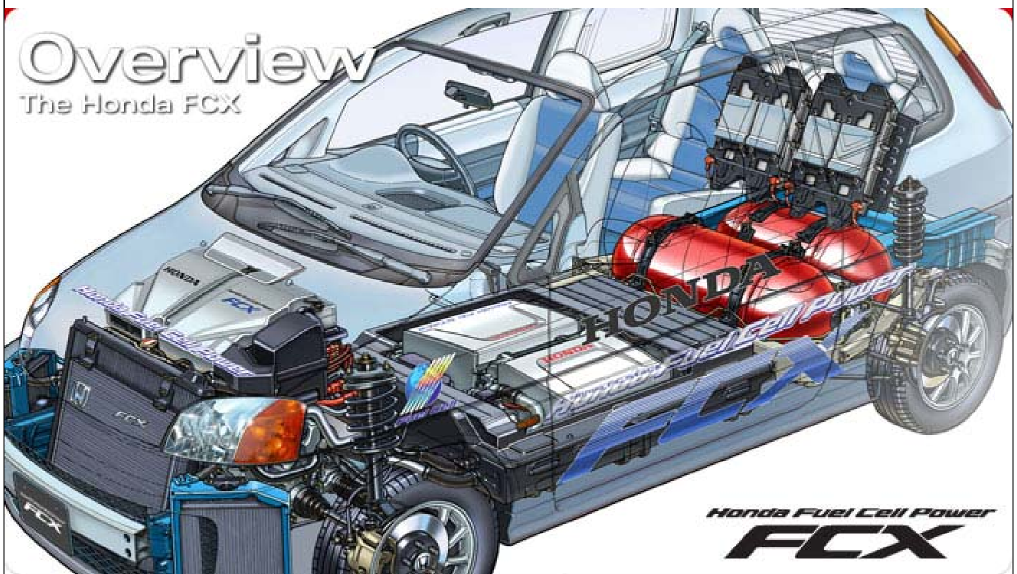
Because the efficiency of a fuel-cell power plant is expected to be greater than that of a gasoline-fueled combustion engine, the plot shows three curves.

In the first curve, labeled 1:1, the efficiency of the power plant is assumed to be the same for gasoline and hydrogen. This is appropriate for a combsution engine using hydrogen.

The curves labeled 2:1 and 3:1 assume that the there is fuel cell power plant that can produce, respectively, two or three times the engine power for a given unit of fuel energy.

Even at an optimistic efficiency gain of 3:1 and a high pressure of 14,000 psia (greater than the current practice of 10,000 psia), the volumetric energy density for compressed hydrogen is still less than the 120,000 Btu/gallon for gasoline.

2005 Honda Fuel Cell Vehicle



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Reference: http://world.honda.com/FuelCell/FCX/overview/ (accessed April 17, 2007)

Additional data and description on next notes page.

Red tanks are hydrogen storage.

Two fuel cell stacks are silver colored elements located under where the passenger seat location.

Electric motor in front of vehicle provides front wheel drive

Energy storage in ultra-capacitor (rather than batteries) is intended to provide quick response for absorbing and releasing power to the motor.

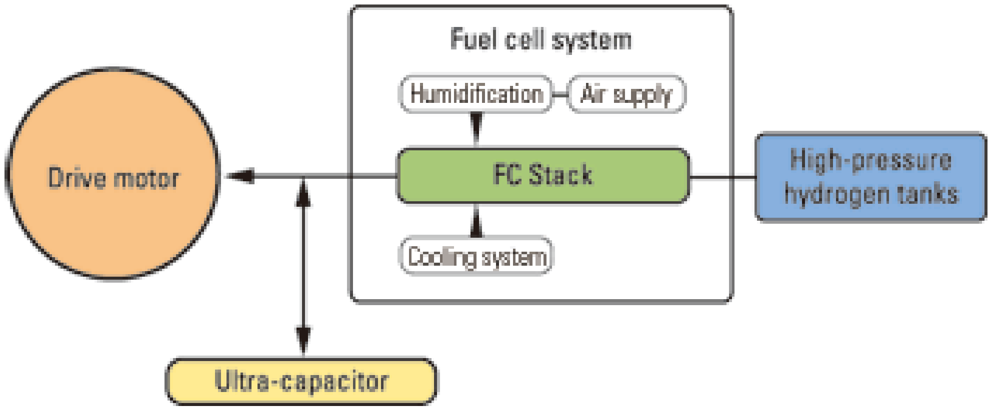
Maximum speed is 150 km/h

Available for lease to “certain” government agencies for gaining in-use experience.

See http://world.honda.com/FuelCell/FCX/specifications/ for full vehicle specifications

Honda has announced a new car to be leased to Southern California customers in 2008, but details of that car have not been so widely distributed as those for the 2005 version.

Honda Fuel Cell Car Diagram



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http://world.honda.com/FuelCell/FCX/overview/components/ (4/17/07)

Honda FC Stack PEMFC (Proton Exchange Membrane Fuel Cell) two stacks with a total maximum output of 86 kW.

Humidification system The recycled water recovery/humidification system recycles water generated in the stack .

PCU (Power Control Unit) Controls electrical systems, including FC Stack output, capacitor output, drive motor output, air pump, and cooling pump.

Fuel cell cooling system Equipped with one fuel cell system radiator (large) and two drive train radiators (small).

·**Drive train** drive motor, transmission, and drive shaft (maximum torque: 272N·m).

Honda ultra-capacitor Instantaneous high-output assist during startup and acceleration, with efficient regenerative braking.

High-pressure hydrogen supply system Two tanks can be filled with up to 156.6L of hydrogen at approximately 350 atmospheres. Can be filled in 3 minutes. Range up to 430 km ≈ 270 mi

Air supply system An air pump with a high-voltage electric drive motor supplies the stack with air..

Honda FCX Clarity

- Announced in November 2007
- Available for limited lease in Southern California starting summer 2008
- Improvements over previous FCX cars
  - Increased range to about 270 miles
  - Improved fuel cell stack
  - Changed energy storage system from ultra–capacitor to lithium-ion battery pack
  - Starts at –30^{o}C (–22^{o}F)

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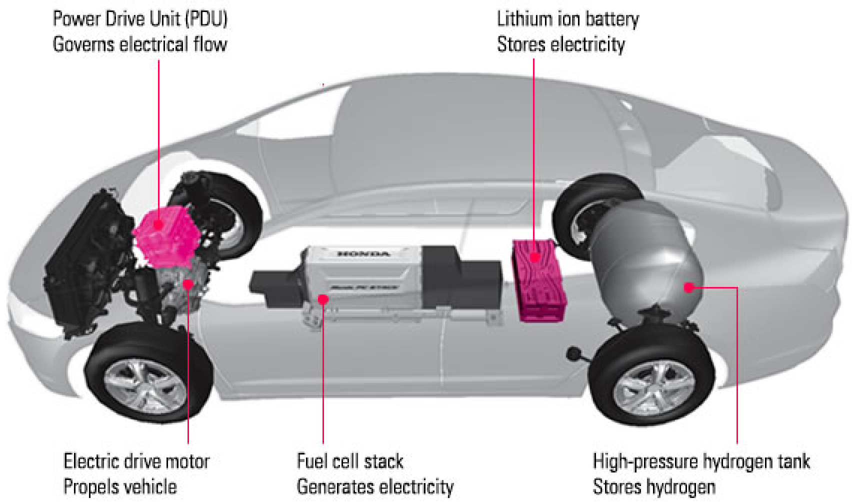
Reference: http://automobiles.honda.com/fcx-clarity/ (accessed February 13, 2008)

The leasing of the new FCX will be limited to Torrance, Santa Monica and Irvine. Leases are expected to cost $600 per month.

Fuel economy is equivalent to 68 miles per gallon of gasoline.

Honda FCX Clarity



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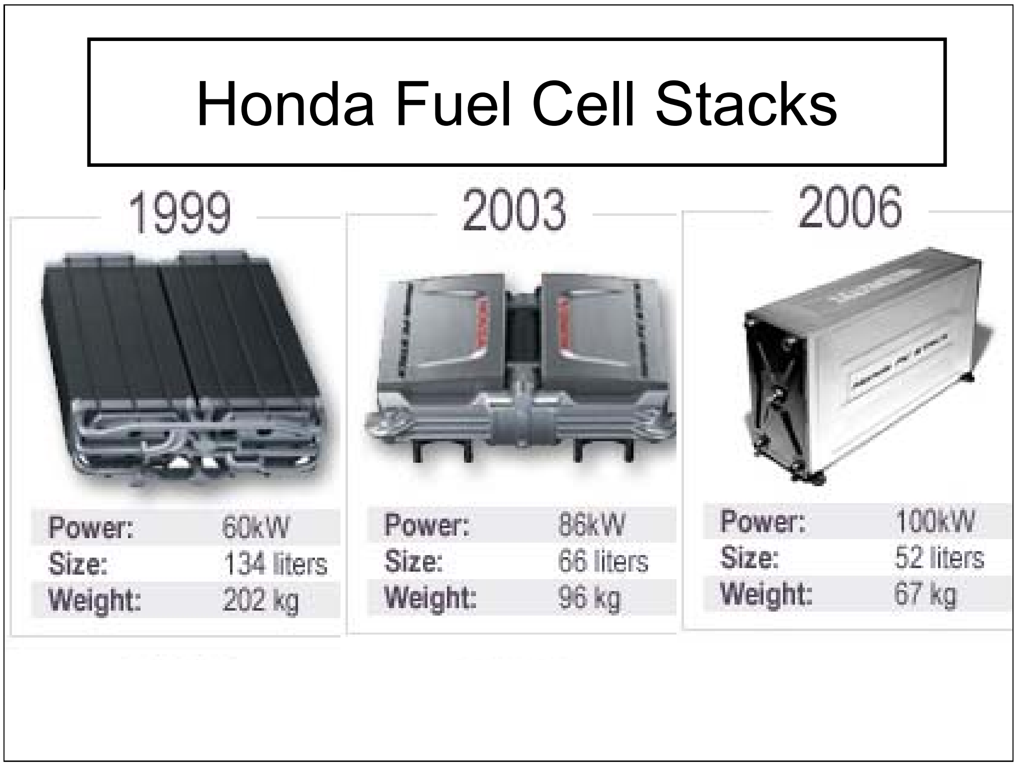
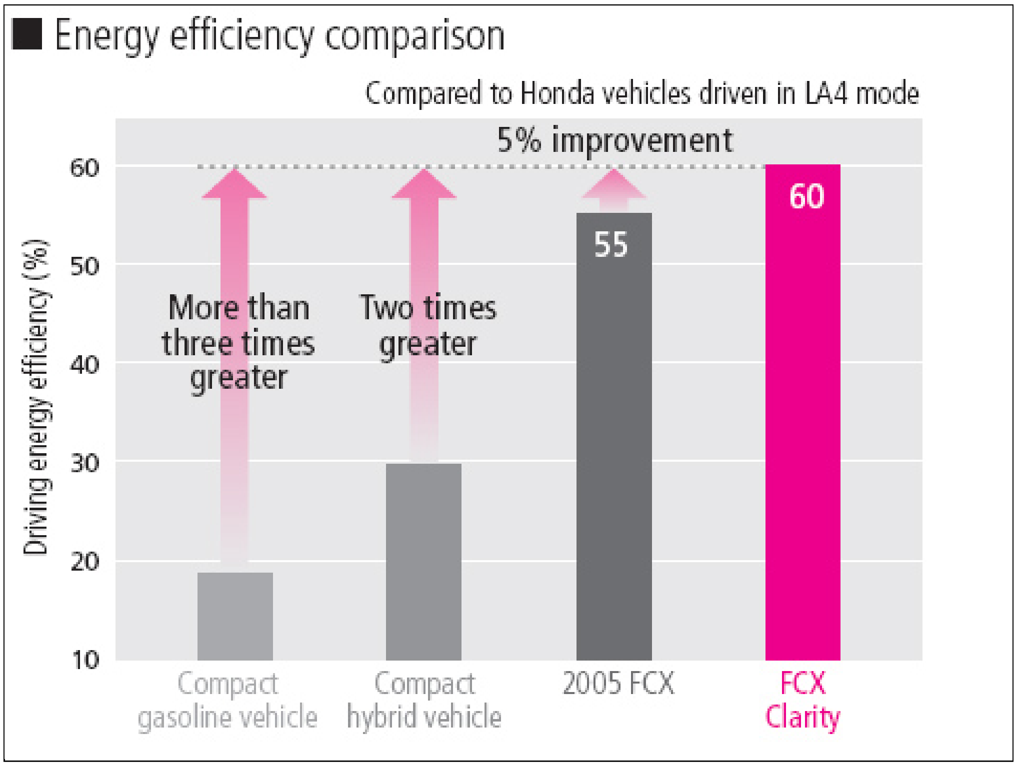
http://automobiles.honda.com/fcx-clarity/how-fcx-works/v-flow/ (accessed April 13, 2008)



http://automobiles.honda.com/fcx-clarity/fuel-cell/evolution/ (accessed April 13, 2008)

The power to mass ratio for the fuel cell (not the entire drivetrain) has increased by a factor of five from 0.3 kW/kg to 1.5 kW/kg. The power to volume ratio has increased by a factor of over four from 0.45 kW/L to 1.92 kW/L. The reduction in weight provides the designer to add more weight while maintaining the fuel economy or to improve fuel economy due to reduced weight. The reduced volume allows the designer to add more usable volume to the vehicle or to reduce the vehicle size and hence the aerodynamic drag.



http://automobiles.honda.com/fcx-clarity/fuel-cell/comparison/ (accessed April 13, 2008)

The web page on which I found this chart does not contain any explanation of how the numbers on the chart were generated. Based on the information on the chart I assume that the individuals who prepared the chart have computed the energy required to drive the conventional driving cycle (the LA4) that has been used to measure vehicle emissions since the early 1970s. This could be done by actual measurements or a computerized vehicle simulation.

Next the fuel energy required to drive the cycle would be determined. This would have to be an energy calculation rather than a miles per gallon calculation since different fuels are used. Finally the efficiency would be computed by dividing the driving energy required by the fuel energy input.

There are two factors working here. One is the greater efficiency of the fuel cell as compared to the combustion engine. The other is the ability of all vehicles except the compact gasoline vehicle to use regenerative braking. In theory energy used for acceleration and upgrades should be recoverable. In practice, drivers have to apply brakes to avoid crashes which does not allow full energy recovery.

Presumably all the vehicles shown here are comparable in size.

Automotive Fuel Cell Costs

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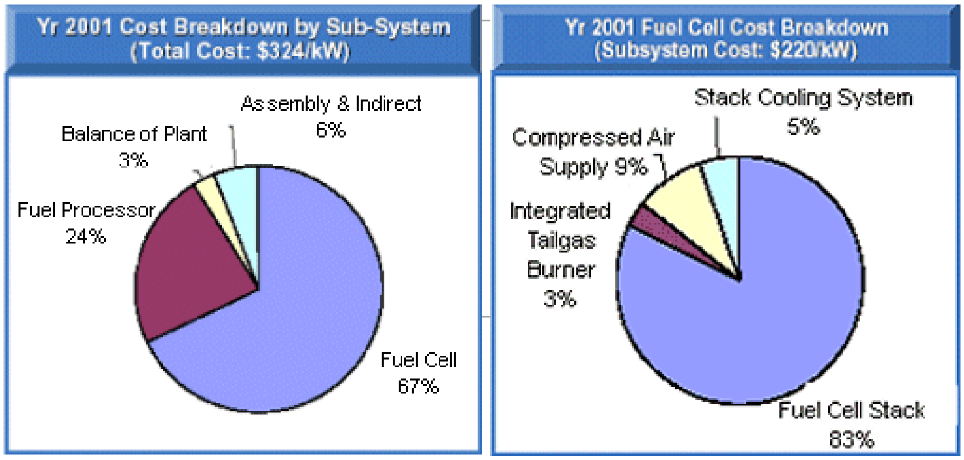

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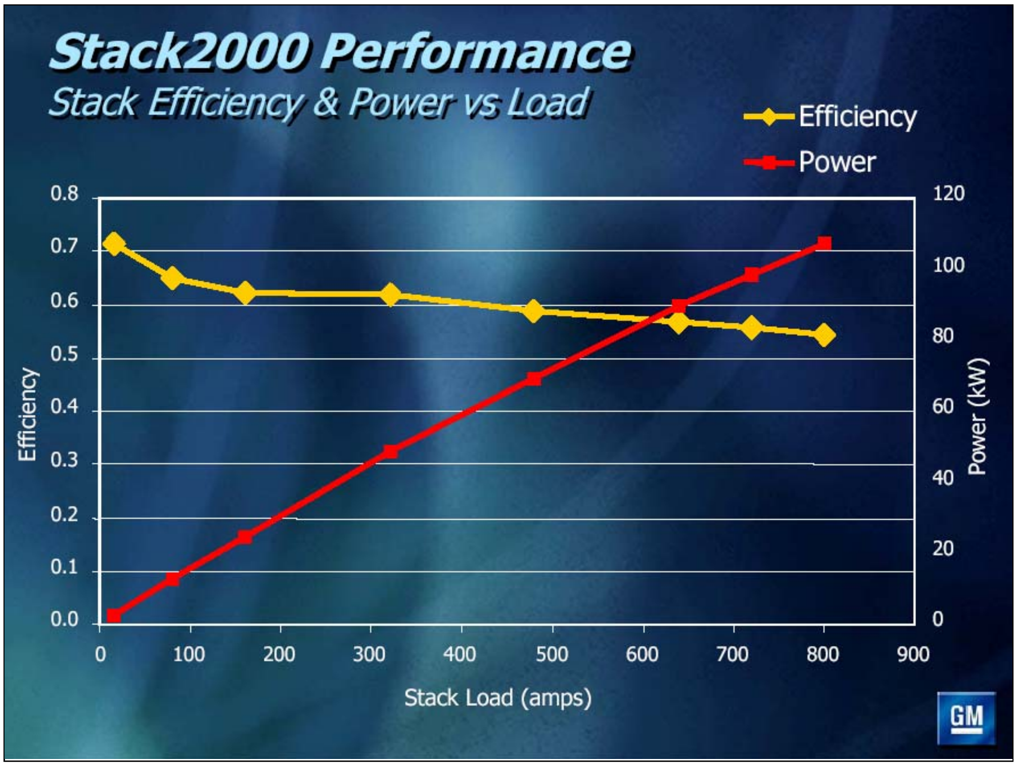
Reference: http://www.cartech.doe.gov/research/fuelcells/cost-model.html

Under a contract with DOE, Arthur D. Little is assessing the fuel cell cost issue during a multiyear project to: (1) Develop a baseline PEM fuel cell system configuration and cost model to assess current and future technology and manufacturing practices at production volumes of 500,000 units per year; and (2) Update the system "scenario" and cost model annually through 2004 to reflect new technology development, alternative system scenarios, manufacturing process improvements, and industry feedback. The results of the project are being used to help guide development of DOE programs.

The baseline configuration system and cost model for a 50-kW system (sufficient for powering a family sedan) has been completed. By linking the system configuration and cost models, Arthur D. Little has made available a sophisticated tool for evaluating the impact of various performance assumptions on overall costs.

Not surprisingly, the analysis indicates that total fuel cell system costs are dominated by subsystem costs. The latter costs are related to the size of the stack (power density), platinum loading, and the material costs of the membrane electrode assembly. Among key findings are that operating the fuel cell stack near the maximum power point, on balance, was not an attractive option because of the reduced efficiency and negligible weight benefit. The gain from lowering stack cost is offset by declines in system efficiency and increases in fuel-processor and heat exchanger weight to compensate for lower fuel cell efficiency.

A range of system assumptions has been evaluated using the cost model. So far, no changes to current technology have been identified that would significantly lower the cost of a complete PEM fuel cell system. However, development of new membrane systems and use of hydrogen as a fuel could lead to lower costs through system simplification and higher stack performance. Even with these advances, the fuel cell system cost target will remain a challenge to technology developers.

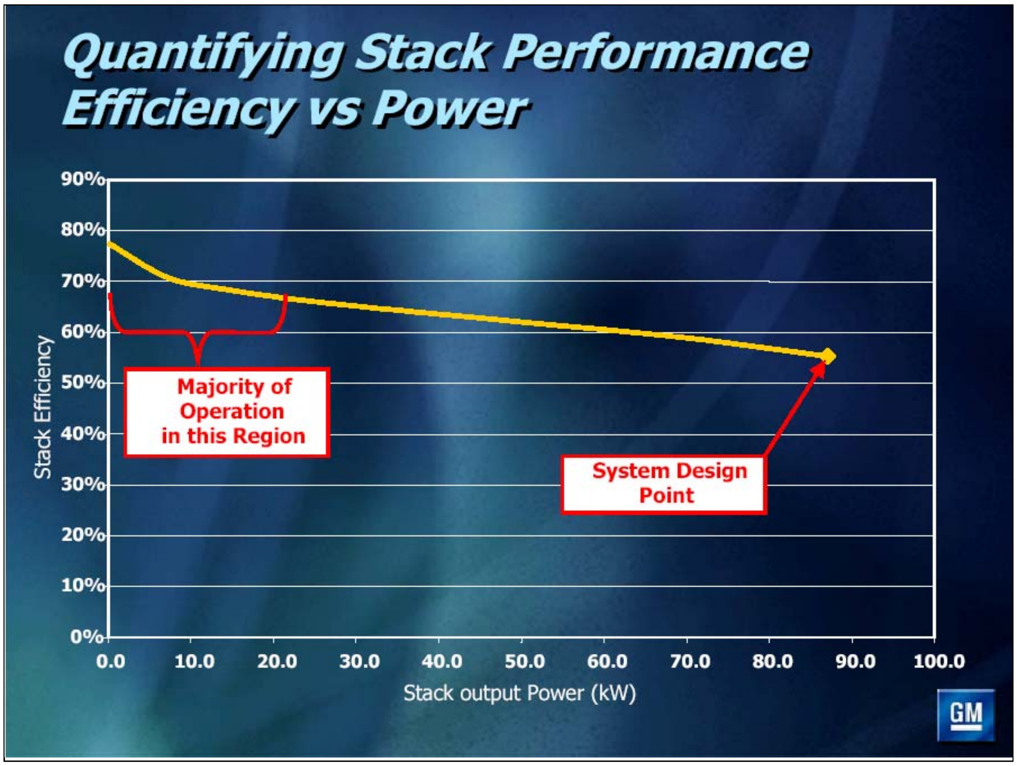


http://www.gmfuelcell.com/w_shoop/pdf/Andrew%20Bosco%20FC(E).pdf

Latest Fuel Cell Stack Developments

Andrew Bosco, Manager - Architecture, Design & Modeling

Global Alternative Propulsion Center (GAPC)



http://www.gmfuelcell.com/w_shoop/pdf/Andrew%20Bosco%20FC(E).pdf

Latest Fuel Cell Stack Developments

Andrew Bosco, Manager - Architecture, Design & Modeling

Global Alternative Propulsion Center (GAPC)

Government Initiatives

- Freedom Car Project
  - http://www1.eere.energy.gov/vehiclesandfuels/
  - http://www.ornl.gov/sci/eere/transportation/freedomcar.htm
- California Fuel Cell Partnership and hydrogen highway
  - http://www.fuelcellpartnership.org/
  - http://www.hydrogenhighway.ca.gov/

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The National Research Council Peer Review recommended restructuring the **Partnership for a New Generation of Vehicles (PNGV)** program because of developments and advancements in related fields: (1) Automobile fuel economy is declining as sport utility vehicle (SUV) market share increases. (2)Significant R&D progress has been achieved. (3) Industry partners have announced they will introduce hybrid technology in production vehicles within the next few years. (4) Other PNGV technologies (e.g., lightweight materials) are being introduced in conventional vehicles. (5)Substantial programs similar to PNGV are underway around the world. (6) Full fuel efficiencies associated with PNGV technologies will not be realized in large numbers until breakthroughs render them more cost-competitive. (7) Reevaluation is appropriate as PNGV approaches the end of a ten-year project.

In evaluating the former PNGV program, DOE and auto industry partners agree that public/private partnerships are the preferred approach to R&D, as highlighted in the President's National Energy Plan, but the cooperative effort must be refocused to (1) Aim at longer range goals with greater emphasis highway vehicle contributions to energy and environmental concerns (2) Move to more fundamental R&D at the component and subsystem level (3) Assure coverage of all light vehicle platforms (4) Maintain some effort on nearer term technologies that offer early opportunities to save petroleum (5) Strengthen efforts on technologies applicable to both fuel cell and hybrid approaches (e.g., batteries, electronics, and motors)

The **California Fuel Cell Partnership** aims to achieve four main goals: (1) Demonstrate vehicle technology by operating and testing the vehicles under real-world conditions in California; (2) Demonstrate the viability of alternative fuel infrastructure technology, including hydrogen and methanol stations; (3) Explore the path to commercialization, from identifying potential problems to developing solutions; and (4) Increase public awareness and enhance opinion about fuel cell electric vehicles, preparing the market for commercialization.

ADL Cost Study Forecasts

Characteristic	Units	Calendar Year		
		1997	2000	2004
Energy Efficiency @ 25% peak power	%	35	40	48
Power Density	W/L	200	250	300
Specific Power	W/kg	200	250	300
Cost	$/kW	300	150	50
Startup to full power	min	2	1	0.5
Transient Response (time from 10 to 90% power)	sec	30	20	10
Emissions		<Tier 2	< Tier 2	< Tier 2
Durability	hour	1000	2000	5000

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http://216.51.18.233/library/ADLCostModel.pdf

PNGV Goals Integrated System Targets

The listed goals pertain to a gasoline fueled flexible fuel system which includes fuel processor, fuel cell stack, and auxiliaries but excludes the gasoline tank and DC-DC converter.

ADL Analysis Forecasts

Honda 2008: 2000 W/L and 1500 W/kg

Characteristic	Units	Calendar Year		
		1997	2000	2004
Stack system power density (net power)	W/L	300	350	500
Stack system specific power	W/kg	300	350	500
Stack system efficiency @ 25% peak power	%	50	55	60
Stack system efficiency @ peak power	%	40	44	48
Precious metal loading	g/peak kW	2.0	0.9	0.2
Cost (500,000 units per year)	$/kW	200	100	35
Durability (< 5% power degradation)	hour	>1000	>2000	>5000
Cold Startup to max. power 20oC	min	2	1	0.5
CO tolerance (steady state)	ppm	10	100	1000
CO tolerance (transient)	ppm	100	500	5000

http://216.51.18.233/library/ADLCostModel.pdf

Cost Analysis of Fuel Cell System for Transportation Baseline System Cost Estimate

Arthur D. Little, Inc., Acorn Park, Cambridge, Massachusetts

02140-2390

Ref 49739

SFAA No. DE-SCO2-98EE50526

Topic 1 Subtopic 1C

Task 1 and 2 Final Report to:

Department of Energy:

March 2000

Fuel Cell Challenges

- Current cost is > $2000/kW compared to $35/kW for combustion engine
- Fuel cell lifetime is about 1000 hours compared with 5000 hours for combustion engine
- How to produce hydrogen production with small energy input, environmental problem, and cost
- Hydrogen storage

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Reference:
http://news.uns.purdue.edu/html4ever/2005/050510.Agrawal.fuelcells.html (Accessed April 13, 2008)

The site summarizes an article written by Rakesh Agrawal, a chemical engineering professor at Purdue. The quantitative data in the slide are taken from the web site.

According to the web site, the online information, dated May 10, 2005, was a summary of an article that was to be published in the June 2005 issue of the Journal of the American Institute of Chemical Engineers.

The author concluded that fuel cell vehicles will not be in widespread use before 2020.

Fuel Processing

- Raw Fuel Cleaning
  - removal of sulfur, halides, and ammonia
  - prevent cell catalyst poisoning.
- Raw Fuel Conversion – converting a hydro-carbon fuel to a hydrogen-rich gas reformate.
- Reformate Gas Alteration
  - Converting CO and H2O in the fuel gas reformate to H2 and CO_2
- Selective oxidation to reduce CO or removal of water to increase the H_2 concentration.

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Reference: *Fuel Cell Handbook*

A fuel processor is defined in this Handbook as an integrated unit consisting of one or more of the above processes, as needed according to the fuel cell requirements and the raw fuel, that function together to be cost effective for the application. Figure 9-2 is a depiction of the component path needed. Cost effectiveness may include high thermal efficiency, high hydrogen yield (for some fuel cells hydrogen plus carbon monoxide yield), multi-cycling, compact, lightweight, and quick starting, depending on application. Most fuel processors make use of the chemical and heat energy left in the fuel cell effluents to provide heat energy for fuel processing that enhances system efficiency. The system section addresses using fuel cell anode effluent (residual fuel), and rejected heat from the fuel cell and other components.

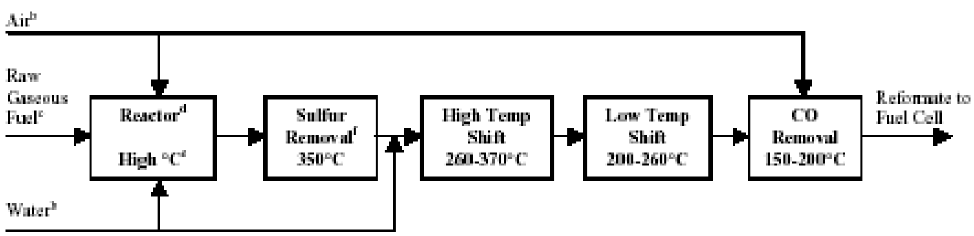
Fuel conversion and alteration catalysts are normally susceptible to poisoning; thus the raw fuel cleaning process takes place upstream or within the fuel conversion process. The fuel conversion and reformate gas alteration processes can take place either external to the fuel cell or within the fuel cell anode compartment. The former is referred to as an external reforming fuel cell system and the latter is referred to as an internal reforming fuel cell system. Cells are being developed to directly react commercially available gas and liquid fuels but the chemically preferred reaction of present fuel cells is via a hydrogen-rich gas. These notes address external reforming fuel processors only.

Fuel processors are being developed to allow a wide range of commercial fuels suitable for stationary, vehicle, and military applications to be used in a fuel cell system. Technology from large chemical installations has been successfully transferred to small compact fuel cell units to convert pipeline natural gas, the fuel of choice for small stationary power generators. Cost is an issue as it is with the entire fuel cell unit for widespread application. Several hundred multi- kW(e) commercial fuel cell units are operating. Scaling of the fuel processing technology to larger power plants using pipeline gas will lower the specific cost of the fuel processor.

Recent fuel processor research and development has become focused on consumer vehicles and military applications. The issue with consumer vehicles is how to match a plausible commercial fuel infrastructure with the requirements of the fuel cell unit to be competitive.

Fuel Processing Diagram

Representative Fuel Processor Major Components[a] & Temperatures



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Reference: *Fuel Cell Handbook*

Footnotes for diagram: a) - For MCFC & SOFC, no high temperature shift, low temperature shift, nor CO removal required; for PAFC, no CO removal required; for PEFC, all components required. b) Possible to use residual air, water, and heat of fuel effluent from fuel cell and other downstream components. c) Vaporizer required for liquid fuels. d) Non-catalytic POX does not require water. e) Temperature dependent on fuel and type of reactor.

What fuel to use is open to question at this time. Infrastructure economics drive the fuel of choice toward a gasoline type fuel. Environmental concerns drive the fuel of choice toward pure hydrogen. Methanol fuel processors (regarded by some as a step towards the eventual fuel) are easier to develop, hence further along in development than processors capable of converting gasoline that has high sulfur content and requires high conversion temperatures. Processors for both methanol and gasoline have been tested up to the 50 kW(e) level for vehicle application.

The US military has a significant fuel supply infrastructure in place. The two predominant fuel types in this infrastructure are diesel and jet fuel, a kerosene. It is highly improbable that the US military would change these fuels to accommodate fuel cells. Use of a fuel more suitable to the fuel cell would limit the technology's military use (there is R&D activity for fuel cell power packs to provide man-portable soldier power using hydrogen cartridges or other forms as well as methanol). Diesel and jet fuel are two of the most difficult conventional fuels to convert to a hydrogen-rich gas. They contain a large amount of sulfur, a catalyst poison, that requires high conversion temperature. Fuel processors that convert diesel and jet fuel to a hydrogen-rich gas are in the early stages of development. The technology has been demonstrated at a 500 W size; 50 kW(e) units are being developed.

Transportation Fuel Cell Fuels

- Possible options
  - Reform fuel (gasoline, methanol or natural gas directly on vehicle)
  - Use direct methanol fuel cells
  - Reform fuel and store H_2 on vehicle
    - Compressed gas, cryogenic liquid, hydride
    - Local hydrogen manufacture
    - Large manufacturing facility with H_2 pipelines
  - Hydrogen storage an issue
    - Gas, liquid, solid hydrides

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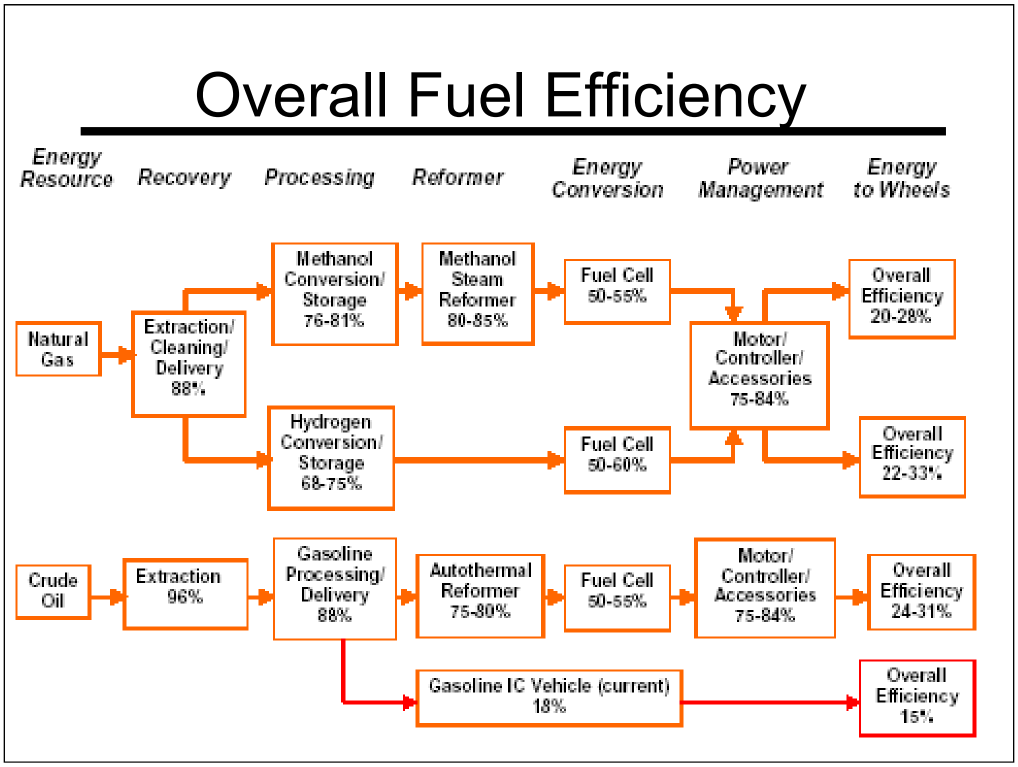

Reference: *Fuel Cell Handbook*

Reforming Fuels

- Steam reforming (SR)
  - High fuel conversion efficiency
  - Highest H_2 concentrations
  - steam to carbon molar ratio about 2.5 to 1
- Partial oxidation (POX)
  - Fast, good for starting
  - Requires only small reactor size
- Auto thermal reforming (ATR)
  - Combination of POX and ATR

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Reference: *Fuel Cell Handbook*

Non-catalytic POX operates at temperatures of approximately 1,400 C, but adding a catalyst (catalytic POX or CPOX) can reduce this temperature as low as 870 C. Combining steam reforming closely with CPOX is termed autothermal reforming (ATR).

Steam Reforming Description Historically, steam reforming has been the most popular method of converting light hydrocarbons to hydrogen. In the steam reforming process, the fuel is heated and vaporized, then injected with superheated steam into the reaction vessel. The steam-to-carbon molar ratio used is usually in the neighborhood of 2.5:1 but developers strive for lower ratios to improve cycle efficiency. Excess steam is used to help force the reaction to completion as well as to inhibit soot formation. Like most light hydrocarbons, heavier fuels can be reformed through high temperature reaction with steam. Steam reforming is usually carried out using nickel-based catalysts. Cobalt and noble metals are also active but more expensive. The catalytic activity depends on metal surface area. For nickel, the crystals will sinter quickly above the so-called Tamman temperature (590 C) approaching a maximum size related to the pore diameter of the support. The crystal growth results in loss of surface area and activity. The steam reformer can operate with (always in conjunction with fuel cells) or without a catalyst. Most commercial applications of steam reforming use a catalyst to enhance reaction rates at decreased temperatures. Lower temperatures favor high CO and hydrogen equilibrium. The reforming catalyst also promotes the competitive water-gas shift reaction. Steam reforming is endothermic thus favored by high temperatures. But it is a slow process and requires a large reactor. As a result, rapid start and transients cannot be achieved by steam reforming due to it inherently slower indirect heating. The steam reforming process suits pipeline gas and light distillate stationary fuel cell power generation well.

An intrinsic, exothermic water-gas shift reaction occurs in the steam reformer reactor. The combined reaction, steam reforming and water gas shift, is endothermic. As such, an indirect high temperature heat source is needed to operate the reactor. This heat source usually takes the shape of an immediately adjacent high temperature furnace that combusts a small portion of the raw fuel or the fuel effluent from the fuel cell. Efficiency improves by using rejected heat from other parts of the system. Note that the intrinsic water-gas shift in the reactor may not lower the CO content to the fuel cell requirement and additional shifting and alteration will be needed for lower temperature fuel cells.

Reference: http://www.amazon.com/Fuel-Cell-Car-Experiment-Kit/dp/B00006YYOG (Accessed April 17, 2007)

Available from Amazon.com for $131.97

Recommended for children 12 years old and older

Produces hydrogen and oxygen from water by electrolysis using solar energy