



Electrochemistry

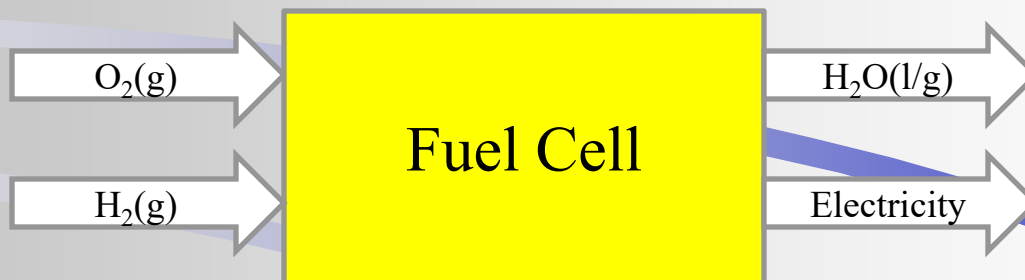
CHEM 5390

Fuel Cells

What is a fuel cell?

An electro-chemical energy conversion device

A “factory” that takes fuel as input and produces electricity as output.



Converts chemical energy → electricity without intermediate heat step.

Similar to a battery except – a fuel cell is not consumed – will continue to produce electricity as long as fuel is supplied.

Fuel Cells

Basics

Every fuel cell has two electrodes, one positive and one negative, the anode and cathode. The reactions that produce electricity take place at the electrodes.

Every fuel cell also has an electrolyte, which carries electrically charged particles from one electrode to the other, and a catalyst, which speeds the reactions at the electrodes.

Hydrogen is the basic fuel, but fuel cells also require oxygen.

Fuel Cells

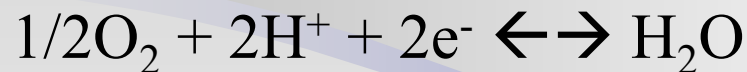
Basics

The basic reactions are:

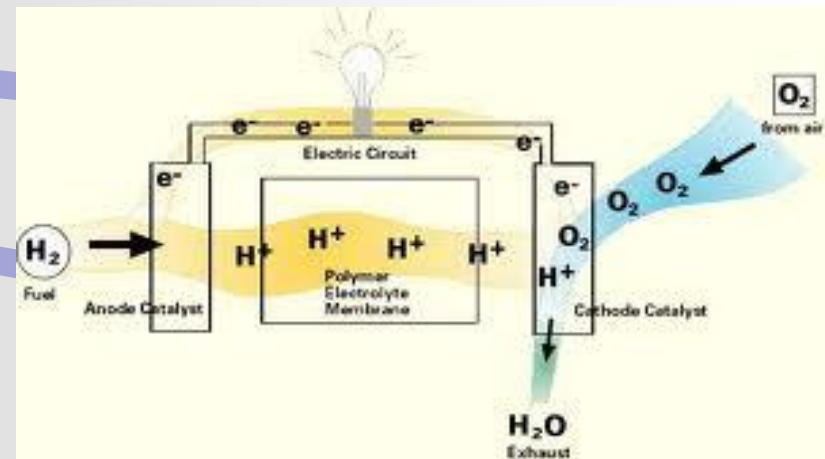
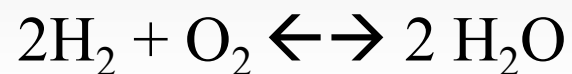
Anode:



Cathode:



Overall reaction:



Fuel Cells

Advantages

Fuel cells have several advantages over conventional combustion-based technologies currently used in many power plants and passenger vehicles

- more efficient
- no moving parts
- reliable
- long-lasting
- quiet
- less emissions (smaller quantities of greenhouse gases and none of the air pollutants that create smog and cause health problems)

Fuel Cells

Disadvantages

Fuel cells have several technological barriers to overcome

- cost
- power density (power per unit volume)
- fuel availability and storage (hydrogen gas)
- alternative fuels require reforming (gas, methanol, formic acid, ethanol)
- operating temperature

Fuel Cells

Fuel Cell Technology Challenges

Durability and Reliability.

The durability of fuel cell systems has not been established.

For transportation applications, fuel cell power systems will be required to achieve the same level of durability and reliability of current automotive engines [i.e., 5,000-hour lifespan (150,000 miles)] and the ability to function over the full range of vehicle operating conditions (40°C to 80°C).

For stationary applications, more than 40,000 hours of reliable operation in a temperature at -35°C to 40°C will be required for market acceptance.

Fuel Cells

Fuel Cell Technology Challenges

System Size

The size and weight of current fuel cell systems must be further reduced to meet the packaging requirements for automobiles. This applies not only to the fuel cell stack, but also to the ancillary components and major subsystems (i.e., fuel processor, compressor/expander, and sensors) making up the balance of power system.

Fuel Cells

Fuel Cell Technology Challenges

Air, Thermal, and Water Management

Air management for fuel cell systems is a challenge because today's compressor technologies are not suitable for automotive fuel cell applications.

Thermal and water management for fuel cells are issues because the difference between the operating and ambient temperatures necessitates large heat exchangers.

Fuel Cells

Types of fuel cells

Fuel cells are classified primarily by the kind of electrolyte they employ.

Phosphoric Acid Fuel Cells

*Polymer Electrolyte Membrane (PEM) Fuel Cells

Alkaline Fuel Cells

Molten Carbonate Fuel Cells

*Solid Oxide Fuel Cells (SOFCs)

Direct Methanol Fuel Cells

Regenerative Fuel Cells

All operate at different temperatures and differ in fuel tolerance and performance.

Fuel Cells

Types of fuel cells

Phosphoric Acid Fuel Cells

The phosphoric acid fuel cell (PAFC) is considered the "first generation" of modern fuel cells, the first to be used commercially.

Efficiency ranges from 40 to 80 percent, and operating temperature is between 150 to 200 °C (about 300 to 400 °F).

They are 85% efficient when used for the co-generation of electricity and heat but less efficient at generating electricity alone (37%–42%). This is only slightly more efficient than combustion-based power plants, which typically operate at 33%–35% efficiency.

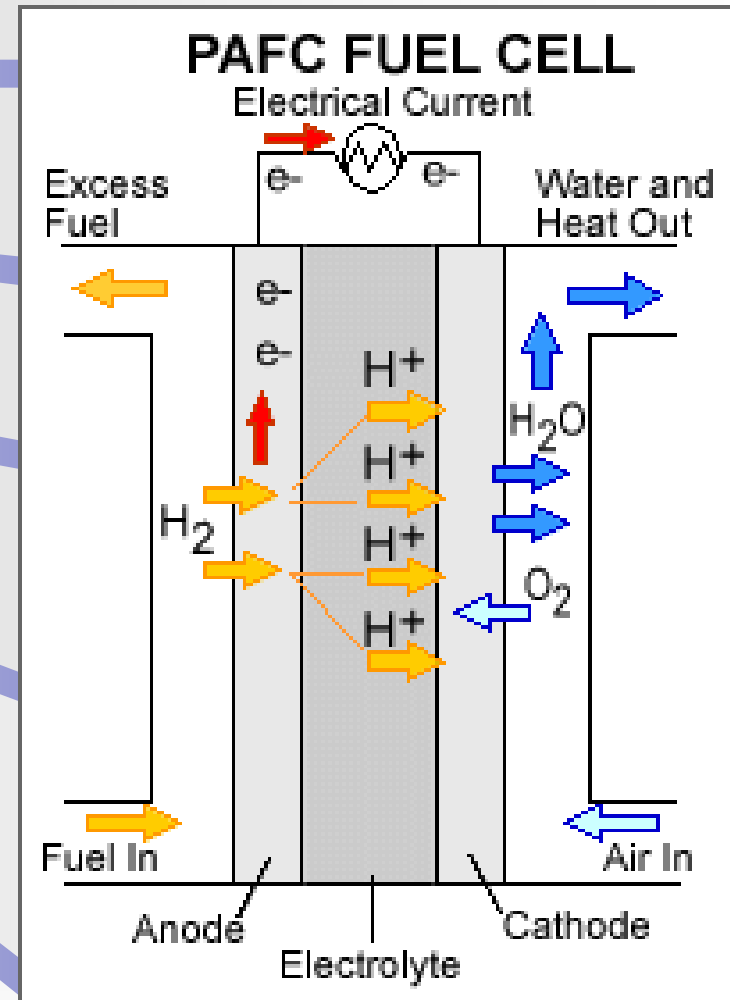
This type of fuel cell is typically used for stationary power generation, but some PAFCs have been used to power large vehicles such as city buses.

Fuel Cells

Types of fuel cells

Phosphoric Acid Fuel Cell

Phosphoric acid fuel cells use liquid phosphoric acid as an electrolyte—the acid is contained in a Teflon-bonded silicon carbide matrix—and porous carbon electrodes containing a platinum catalyst.



Fuel Cells

Types of fuel cells

Phosphoric Acid fuel cells (PAFC)

Advantages:

Tolerate a carbon monoxide concentration of about 1.5 percent, which broadens the choice of fuels they can use. (If gasoline is used, the sulfur must be removed.)

Disadvantages:

Internal parts must be able to withstand the corrosive acid.

Less powerful than other fuel cells, given the same weight and volume.

Typically large and heavy.

PAFCs are also expensive (require an expensive platinum catalyst).

Fuel Cells

Types of fuel cells

Alkaline Fuel Cells

Alkaline fuel cells (AFCs) were one of the first fuel cell technologies developed, and they were the first type widely used in the U.S. space program to produce electrical energy and water on-board spacecrafts.

Efficiency is about 70 percent, and operating temperature is 150 to 200°C, (about 300 to 400°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.

Fuel Cells

Types of fuel cells

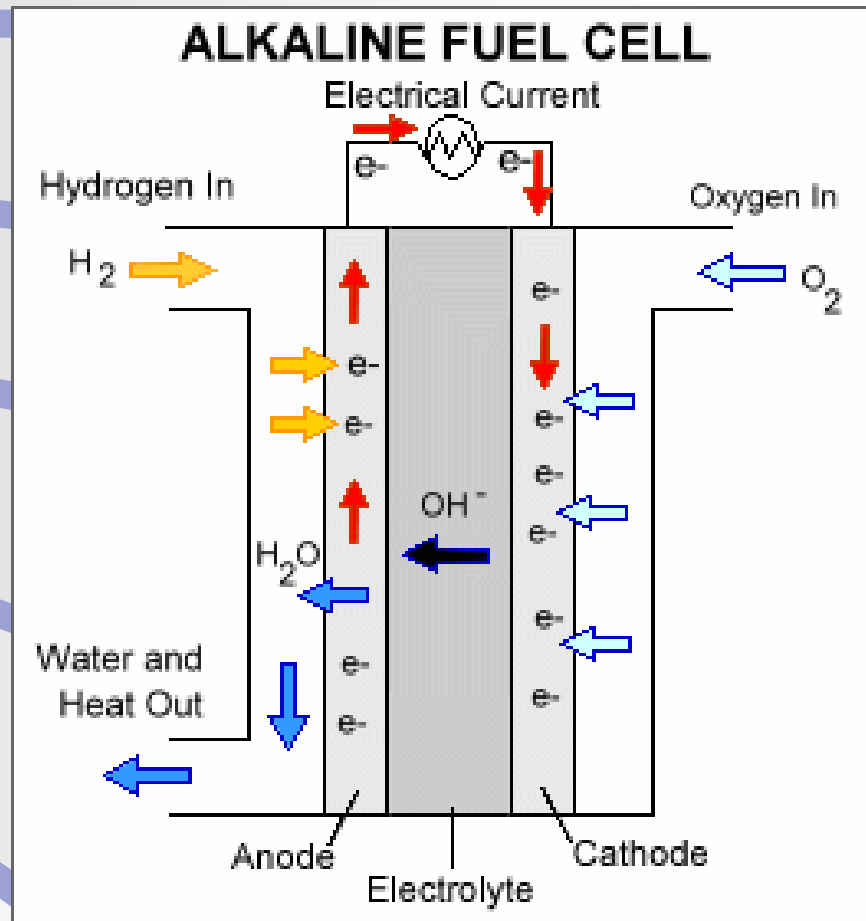
Alkaline fuel cell

Operate on compressed hydrogen and oxygen.

These fuel cells use a solution of potassium hydroxide in water as the electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode.

High-temperature AFCs operate at temperatures between 100°C and 250°C (212°F and 482°F).

However, newer AFC designs operate at lower temperatures of roughly 23°C to 70°C (74°F to 158°F).



Fuel Cells

Types of fuel cells

Alkaline Fuel Cells

Disadvantages:

- Easily poisoned by carbon dioxide (CO_2), making it necessary to purify both the hydrogen and oxygen used in the cell.
- Purification process is costly.
- Susceptibility to poisoning also affects the cell's lifetime adding to cost.
- Platinum electrode catalysts are expensive.
- Like any container filled with liquid, they can leak.

AFC stacks have been shown to maintain sufficiently stable operation for more than 8,000 operating hours. To be economically viable in large-scale utility applications, these fuel cells need to reach operating times exceeding 40,000 hours.

Fuel Cells

Types of fuel cells

Molten Carbonate Fuel Cells

Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications.

Molten carbonate fuel cells can reach efficiencies approaching 60%, considerably higher than the 37%–42% efficiencies of a phosphoric acid fuel cell plant. When the waste heat is captured and used, overall fuel efficiencies can be as high as 85%.

Operating temperature is about 650°C (1,200°F).

Units with output up to 2 megawatts (MW) have been constructed, and designs exist for units up to 100 MW.

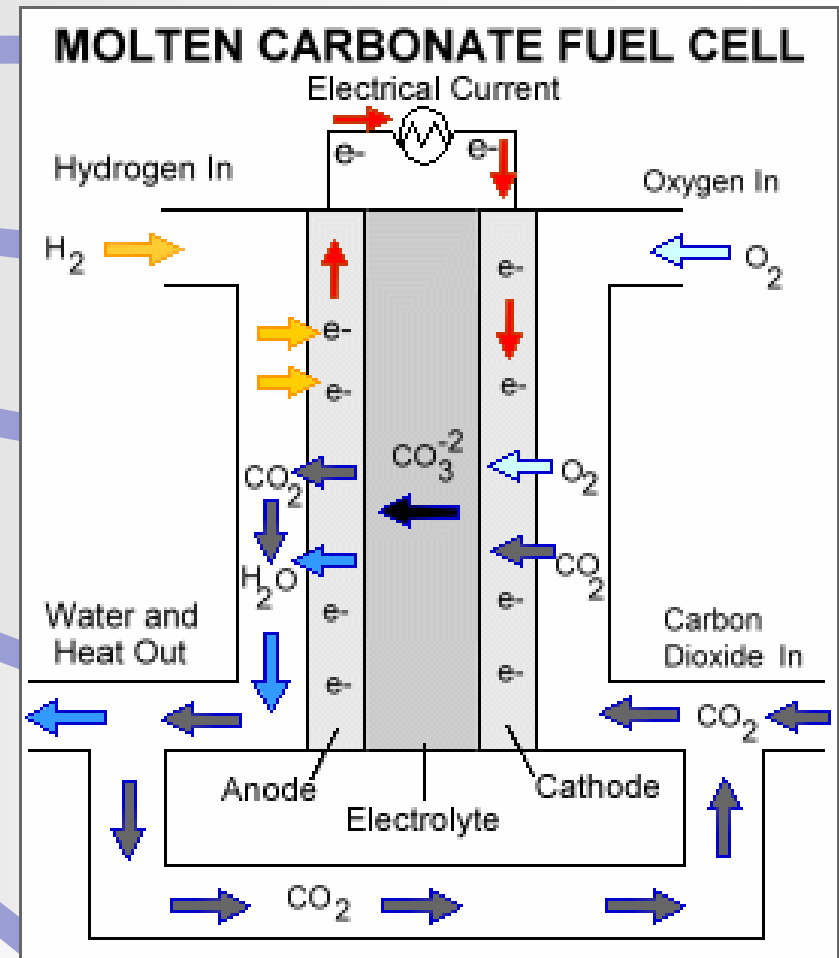
Because they are more resistant to impurities than other fuel cell types, scientists believe that they may be capable of internal reforming of coal, assuming they can be made resistant to impurities such as sulfur and particulates that result from converting coal, into hydrogen.

Fuel Cells

Types of fuel cells

Molten Carbonate Fuel Cell

MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture (like sodium or magnesium carbonates) suspended in a porous, chemically inert ceramic lithium aluminum oxide (LiAlO_2) matrix.



Fuel Cells

Types of fuel cells

Molten Carbonate Fuel Cells

Advantages:

Unlike other fuel cells, MCFCs do not require an external reformer to convert more energy-dense fuels to hydrogen.

Because they operate at extremely high temperatures of 650°C and above, non-precious metals can be used as catalysts at the anode and cathode, reducing costs.

Improved efficiency is another reason MCFCs offer significant cost reductions over phosphoric acid fuel cells (PAFCs).

The high temperature limits damage from carbon monoxide "poisoning" of the cell and waste heat can be recycled to make additional electricity.

Fuel Cells

Types of fuel cells

Molten Carbonate Fuel Cells

Disadvantages:

The primary disadvantage of current MCFC technology is durability. The high temperatures at which these cells operate and the corrosive electrolyte used accelerate component breakdown and corrosion, decreasing cell life.

The high temperature also limits the materials and safe uses of MCFCs—they would probably be too hot for home use.

Also, carbonate ions from the electrolyte are used up in the reactions, making it necessary to inject carbon dioxide to compensate.

Fuel Cells

Types of fuel cells

Direct Methanol Fuel Cells

Most fuel cells are powered by hydrogen, which can be fed to the fuel cell system directly or can be generated within the fuel cell system by reforming hydrogen-rich fuels such as methanol, ethanol, and hydrocarbon fuels.

Direct methanol fuel cells (DMFCs), however, are powered by pure methanol, which is mixed with steam and fed directly to the fuel cell anode.

Fuel Cells

Types of fuel cells

Direct Methanol Fuel Cells

Direct methanol fuel cells do not have many of the fuel storage problems typical of some fuel cells because methanol has a higher energy density than hydrogen—though less than gasoline or diesel fuel. Methanol is also easier to transport and supply to the public using our current infrastructure because it is a liquid, like gasoline.

Direct methanol fuel cell technology is relatively new compared with that of fuel cells powered by pure hydrogen, and DMFC research and development is years behind that for other fuel cell types.

Fuel Cells

Types of fuel cells

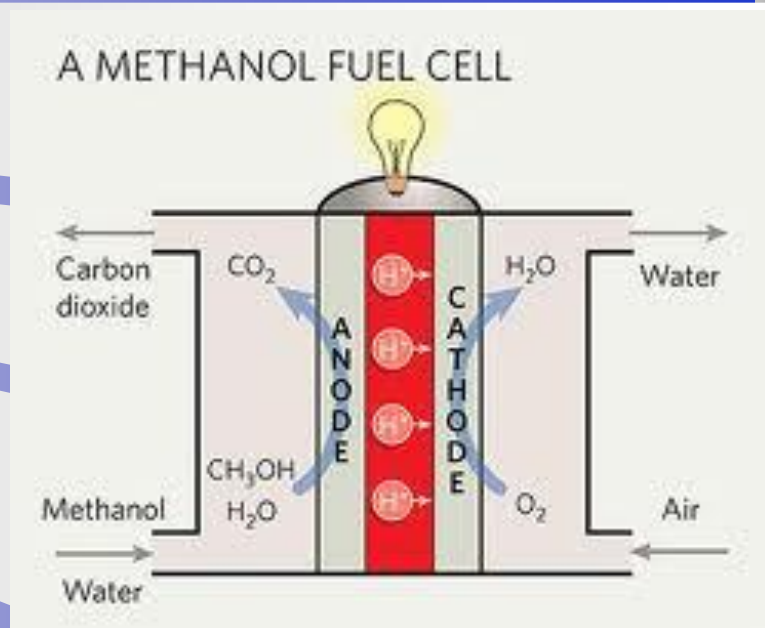
Direct Methanol Fuel Cells

DMFC is similar to the PEMFC in that the electrolyte is a polymer and the charge carrier is the hydrogen ion (proton). However, the liquid methanol (CH_3OH) is oxidized in the presence of water at the anode generating CO_2 .

Anode Reaction: $\text{CH}_3\text{OH} + \text{H}_2\text{O} \Rightarrow \text{CO}_2 + 6\text{H}^+ + 6\text{e}^-$

Cathode Reaction: $3/2 \text{O}_2 + 6 \text{H}^+ + 6\text{e}^- \Rightarrow 3 \text{H}_2\text{O}$

Overall Cell Reaction: $\text{CH}_3\text{OH} + 3/2 \text{O}_2 \Rightarrow \text{CO}_2 + 2 \text{H}_2\text{O}$



Fuel Cells

Types of fuel cells

Polymer Electrolyte Membrane (PEM) Fuel Cells

Polymer electrolyte membrane (PEM) fuel cells are also called proton exchange membrane fuel cells.

PEM fuel cells are used primarily for transportation applications and some stationary applications.

Polymer electrolyte membrane fuel cells operate at relatively low temperatures, around 80°C (176°F).

Efficiency is about 40 to 50 percent, and operating temperature is about 80°C (about 175°F). Cell outputs generally range from 50 to 250 kW.

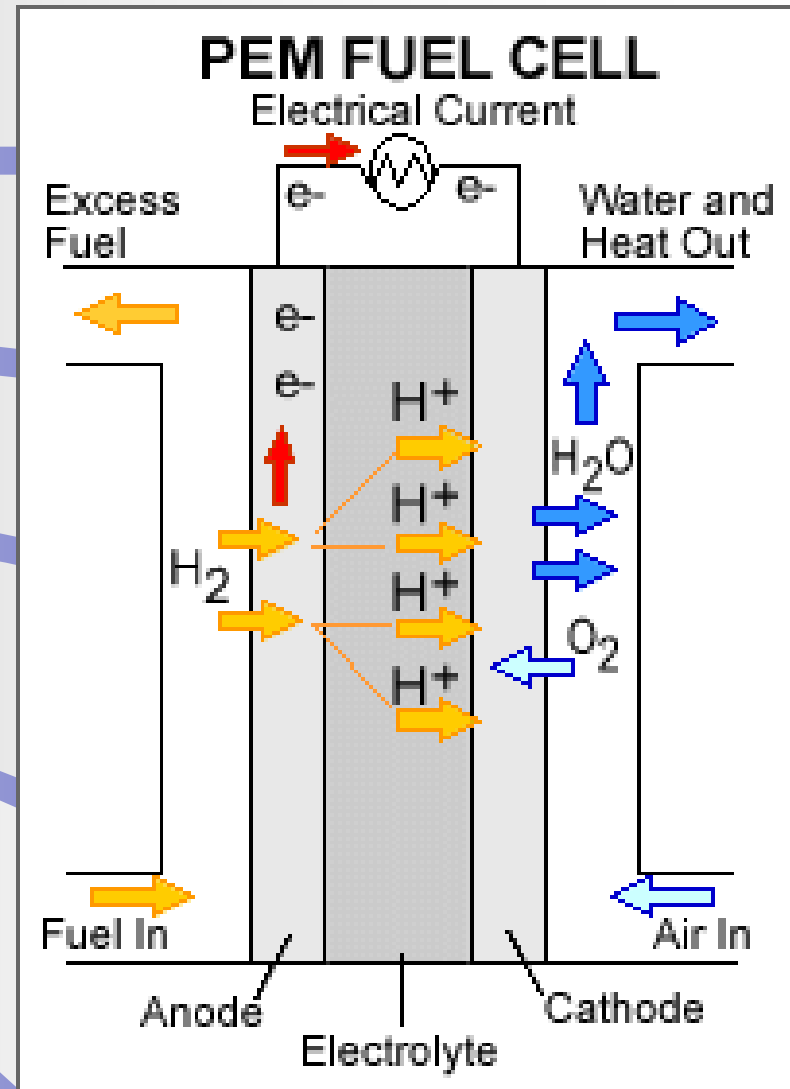
Fuel Cells

Types of fuel cells

PEM fuel cell

PEM fuel cells use a solid polymer in the form of a thin, permeable sheet as an electrolyte and porous carbon electrodes containing a platinum catalyst.

They need only hydrogen, oxygen from the air, and water to operate.



Fuel Cells

Types of fuel cells

Polymer (Proton) Electrolyte Membrane (PEM) Fuel Cells

Advantages:

Deliver high-power density and offer the advantages of low weight and volume, compared with other fuel cells.

Low-temperature operation allows them to start quickly (less warm-up time) and results in less wear on system components, resulting in better durability.

Due to their fast startup time, low sensitivity to orientation, and favorable power-to-weight ratio, PEM fuel cells are particularly suitable for use in passenger vehicles, such as cars and buses.

The solid, flexible electrolyte will not leak or crack, and these cells operate at a low enough temperature to make them suitable for homes and cars.

Fuel Cells

Types of fuel cells

Polymer Electrolyte Membrane (PEM) Fuel Cells

Disadvantages:

Fuels must be purified, and a platinum catalyst is used on both sides of the membrane, raising costs.

The platinum catalyst is also extremely sensitive to CO poisoning, making it necessary to employ an additional reactor to reduce CO in the fuel gas if the hydrogen is derived from an alcohol or hydrocarbon fuel. This also adds cost. Developers are currently exploring platinum/ruthenium catalysts that are more resistant to CO.

Fuel Cells

Types of fuel cells

Polymer Electrolyte Membrane (PEM) Fuel Cells

Disadvantages:

A significant barrier to using these fuel cells in vehicles is hydrogen storage. Most fuel cell vehicles (FCVs) powered by pure hydrogen must store the hydrogen on-board as a compressed gas in pressurized tanks. Due to the low-energy density of hydrogen, it is difficult to store enough hydrogen on-board to allow vehicles to travel the same distance as gasoline-powered vehicles before refueling, typically 300–400 miles.

Higher-density liquid fuels, such as methanol, ethanol, natural gas, liquefied petroleum gas, and gasoline, can be used for fuel, but the vehicles must have an on-board fuel processor to reform the methanol to hydrogen. This requirement increases costs and maintenance. The reformer also releases carbon dioxide (a greenhouse gas), though less than that emitted from current gasoline-powered engines.

Fuel Cells

Types of fuel cells

Solid Oxide Fuel Cells

Efficiency is about 60 percent however in applications designed to capture and utilize the system's waste heat (co-generation), overall fuel use efficiencies could top 80%–85%.

Cells output is up to 100 kW.

SOFCs operate at very high temperatures—around 1,000°C (1,830°F).

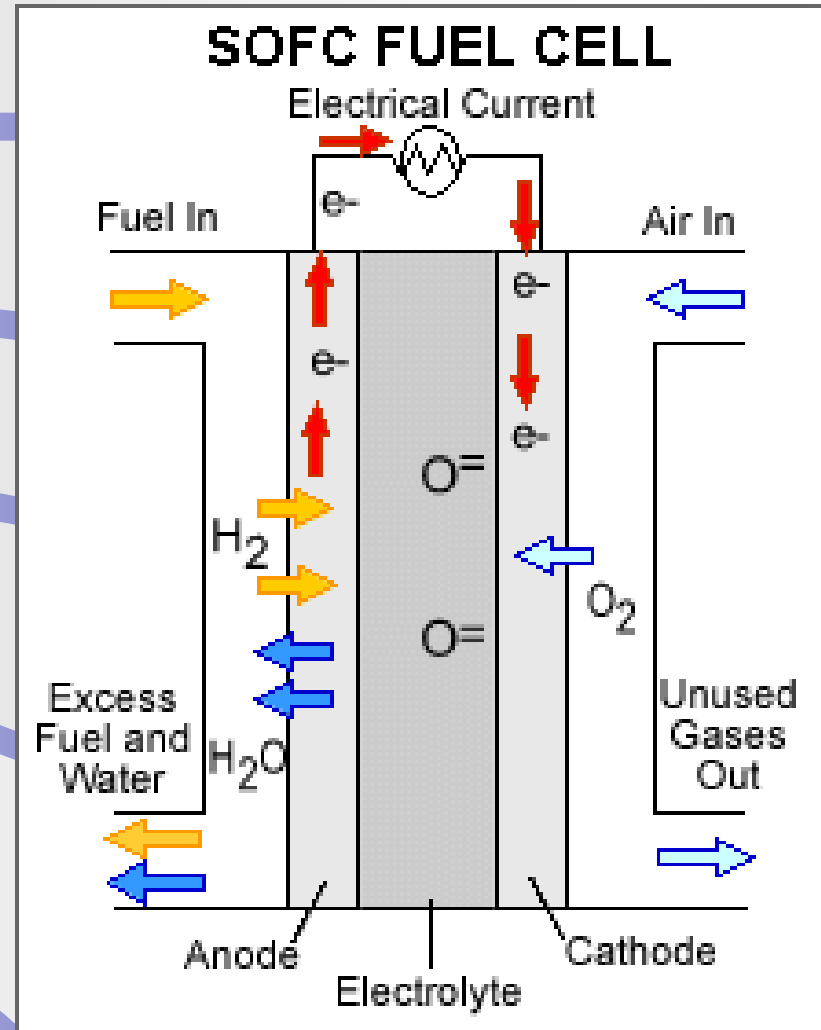
Scientists are currently exploring the potential for developing lower-temperature SOFCs operating at or below 800°C that have fewer durability problems and cost less.

Fuel Cells

Types of fuel cells

Solid Oxide Fuel Cells

Use a hard, ceramic compound of metal (like calcium or zirconium) oxides (chemically, O_2) as electrolyte. Because the electrolyte is a solid, the cells do not have to be constructed in the plate-like configuration typical of other fuel cell types.



Fuel Cells

Types of fuel cells

Solid Oxide fuel cells (SOFC)

Advantages:

High-temperature operation removes the need for precious-metal catalyst, thereby reducing cost.

At such high temperatures a reformer is not required to extract hydrogen from the fuel, and waste heat can be recycled to make additional electricity.

SOFCs are also the most sulfur-resistant fuel cell type; they can tolerate several orders of magnitude more of sulfur than other cell types. In addition, they are not poisoned by carbon monoxide (CO), which can even be used as fuel. This property allows SOFCs to use gases made from coal.

Fuel Cells

Types of fuel cells

Solid Oxide fuel cells (SOFC)

Disadvantages:

High-temperature operation has disadvantages.

It results in a slow startup and requires significant thermal shielding to retain heat and protect personnel, which may be acceptable for utility applications but not for transportation and small portable applications.

The high operating temperatures also place stringent durability requirements on materials. The development of low-cost materials with high durability at cell operating temperatures is the key technical challenge facing this technology.

While solid electrolytes cannot leak, they can crack.

Fuel Cells

Basic Operation

The current produced by a fuel cell is proportional to the fuel cell's area (where the reactants, electrode, and electrolyte meet).

Larger surface areas translate into larger currents.

Electrochemical reactions are heterogenous reactions (must occur at an interface or reaction surface).

To provide large reaction surfaces, fuel cells are usually made into thin, planar structures, highly porous electrodes.

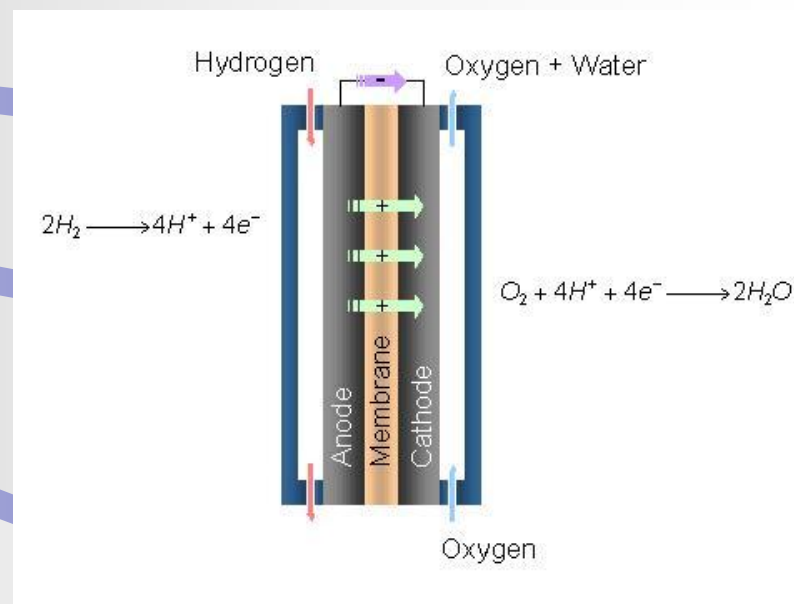
Fuel Cells

Basic Operation

Step 1:

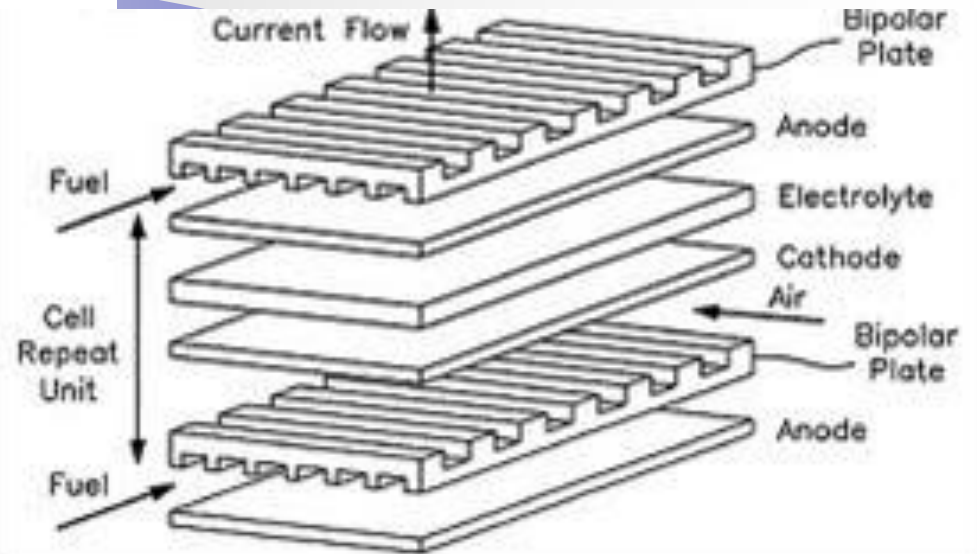
Reactant delivered into the fuel cell. Fuel and oxidant must be continually supplied to produce electricity.

This seems simple, but if fuel is not supplied quickly enough, the device will “starve”.



Flow field plates in combination with porous electrode structures help distribute the gas over the surface of the fuel cell.

Fuel Cells



Fuel Cells

Basic Operation

Flow field plates in combination with porous electrode structures help distribute the gas over the surface of the fuel cell.

The shape, size, and pattern of the flow channels significantly affect the performance of the fuel cell.

Mass transport, diffusion, and fluid mechanics are important in understanding the flow.

Fuel Cells

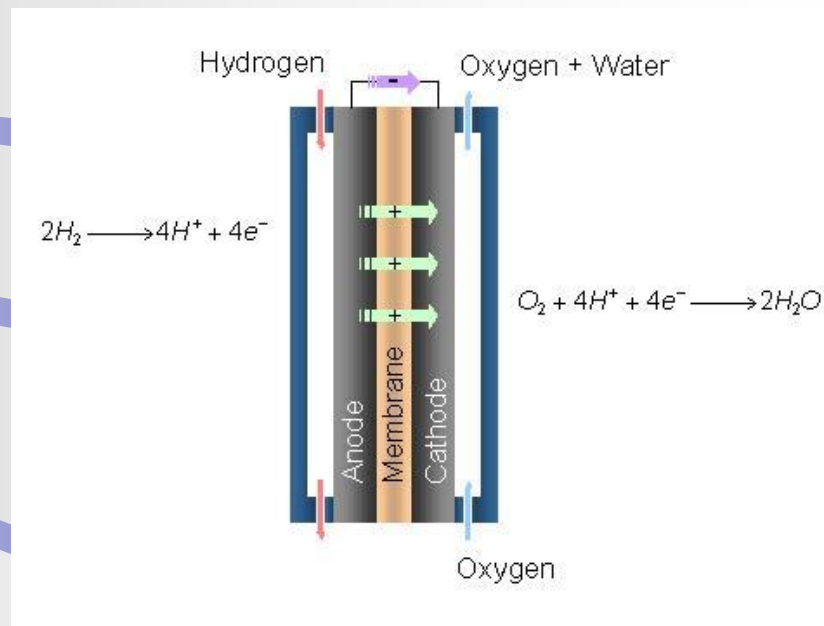
Basic Operation

Step 2:

Electrochemical reaction.

The reactants undergo electrochemical reactions at the electrodes producing current.

The speed of these reactions are a measure of the kinetics of the reactions.



Catalyst are used to increase the speed and efficiency of the reactions.

Fuel Cells

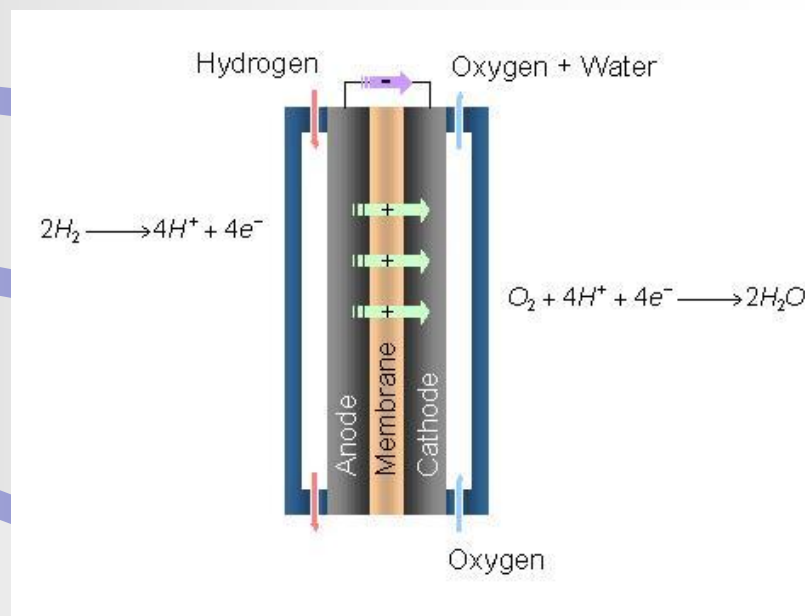
Basic Operation

Step 3:

Ionic conduction through the electrolyte and electron conduction through the external circuit.

Ions and electrons produced at one electrode must be consumed at the other electrode.

Transportation of ions and electrons must be fast for the fuel cell to be efficient.



Fuel Cells

Basic Operation

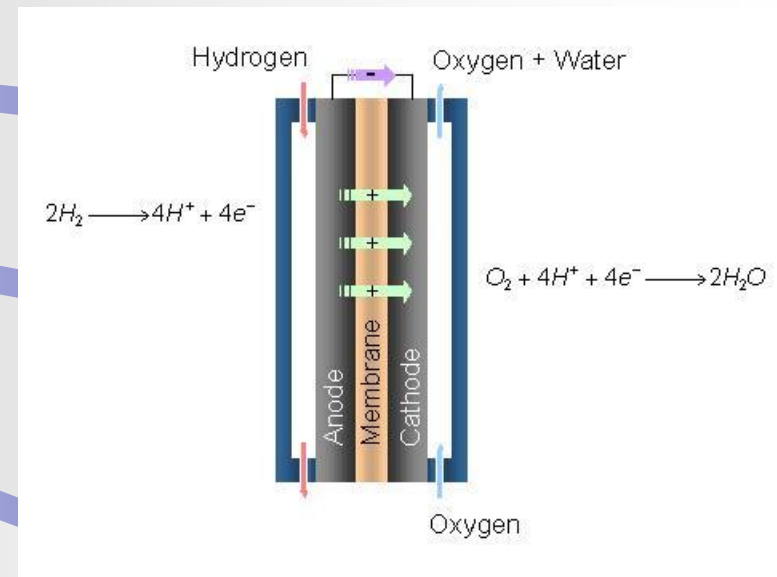
Step 4:

Product removal from the fuel cell.

Fuel cells can produce water and carbon dioxide.

Removal of these products must be fast or the build up will “strangle” the fuel cell.

Mass transport, diffusion, and fluid mechanics are important for reactant flow as well as product removal.



Fuel Cells

Fuel Cell Performance

The performance of fuel cell device are typically represented by current-voltage (i-V) curves and power density curves.

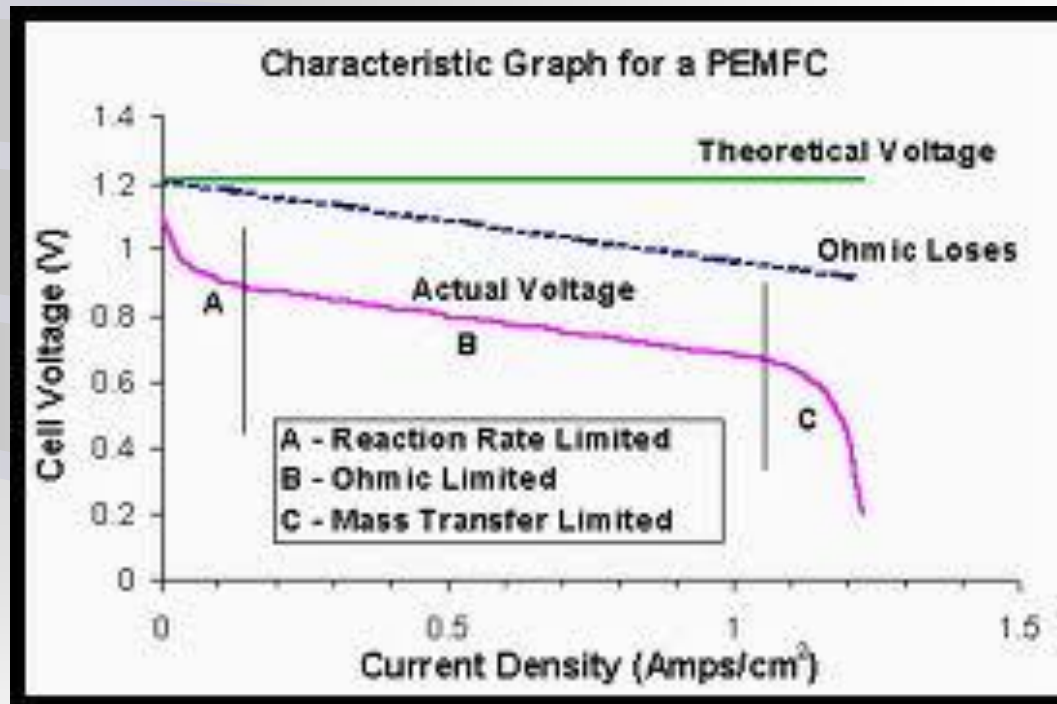
An ideal fuel cell would supply varying amounts of current while maintaining a constant voltage.

Power $P = i V$

Fuel Cells

Fuel Cell Performance

i-V curve



Fuel Cells

Fuel Cell Performance

The performance of fuel cell device are typically represented by current-voltage (i-V) curves and power density curves.

Power density curve is produced by multiplying the voltage at each point on the i-V curve by the corresponding current density.

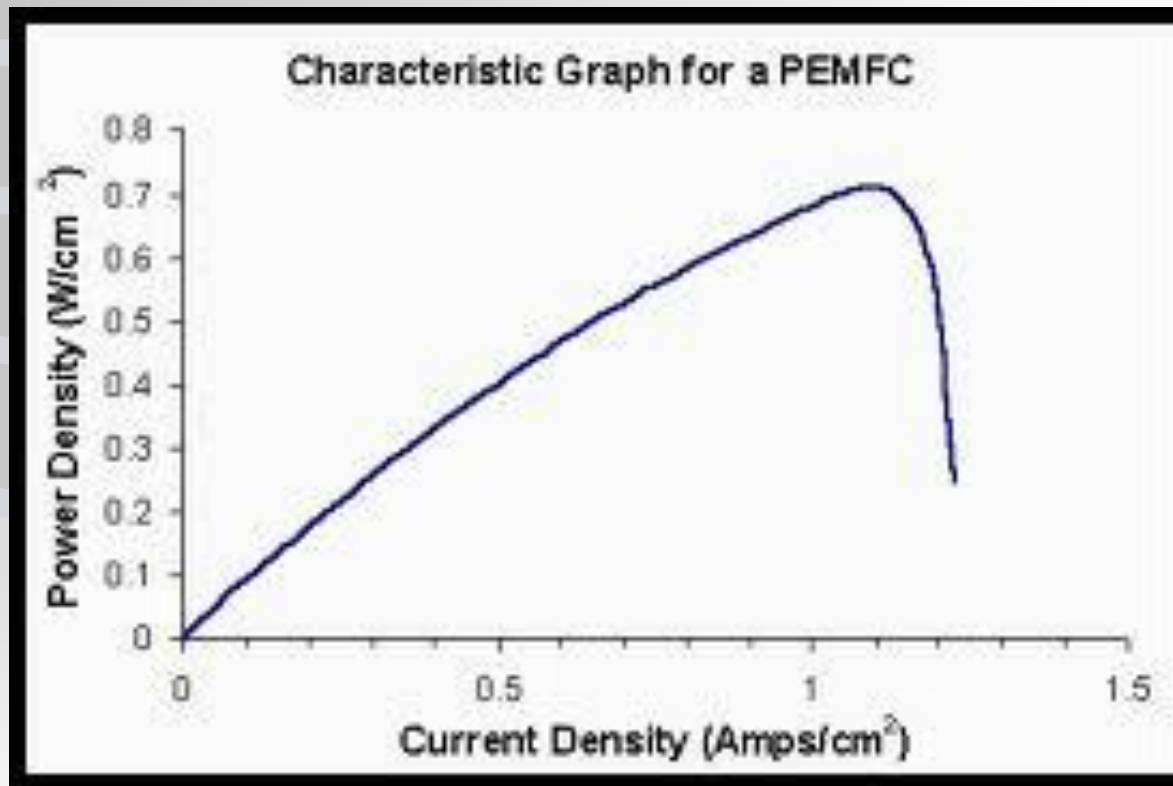
As fuel cell voltage decreases, the electric power produced per unit of fuel also decreases.

Fuel cell voltage is a measure of fuel cell efficiency.

Fuel Cells

Fuel Cell Performance

Power density curve



Fuel Cells

Fuel Cell Performance

Three major types of fuel cell losses:

- Activation losses (losses due to the electrochemical reaction)
- Ohmic losses (losses due to ionic and electronic conduction)
- Concentration losses (losses due to mass transport)

$$V = E_{\text{thermo}} - \eta_{\text{act}} - \eta_{\text{ohmic}} - \eta_{\text{conc}}$$

V – real output voltage of fuel cell

E_{thermo} – thermodynamic predicted fuel cell voltage

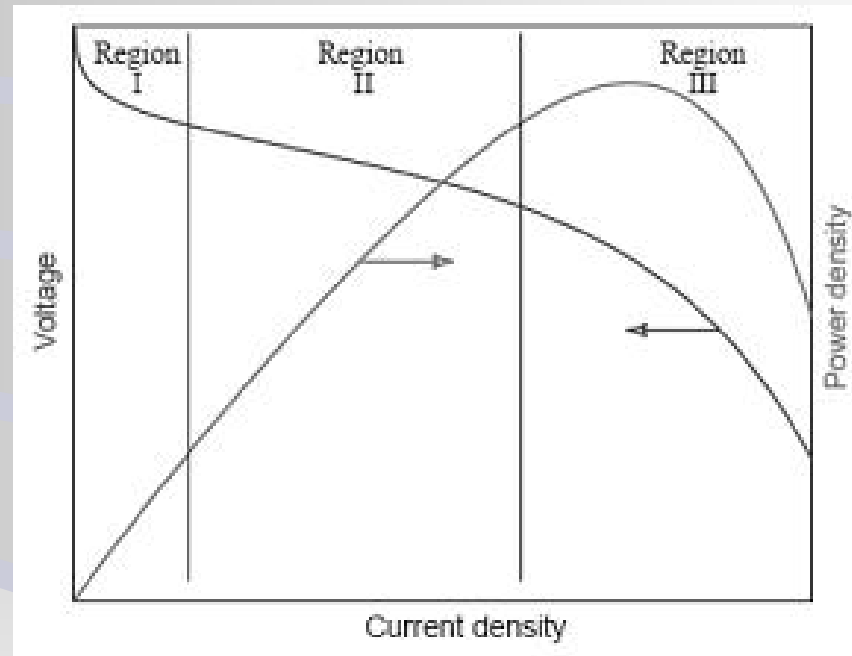
η_{act} – activation losses due to reaction kinetics (affect initial part of the curve)

η_{ohmic} – ohmic losses from ionic and electronic conduction (most apparent in middle)

η_{conc} – concentration losses due to mass transport (most significant at end of i-V curve)

Fuel Cells

Fuel Cell Performance



Fuel Cells

Fuel Cell Systems

The design of fuel cell systems is complex and can vary significantly depending upon fuel cell type and application. However, most fuel cell systems consist of four basic components:

- Fuel cell stack
- Fuel processor
- Current inverters and conditioners
- Heat recovery system

Most fuel cell systems also include other components and subsystems to control fuel cell humidity, temperature, gas pressure, and wastewater.

Fuel Cells

Fuel Cell Systems

Fuel Cell Stack

The fuel cell stack is the heart of a fuel cell power system.

It generates electricity in the form of direct current (DC) from chemical reactions that take place in the fuel cell.

A single fuel cell produces enough electricity for only the smallest applications.

Therefore, individual fuel cells are typically combined in series into a fuel cell stack.

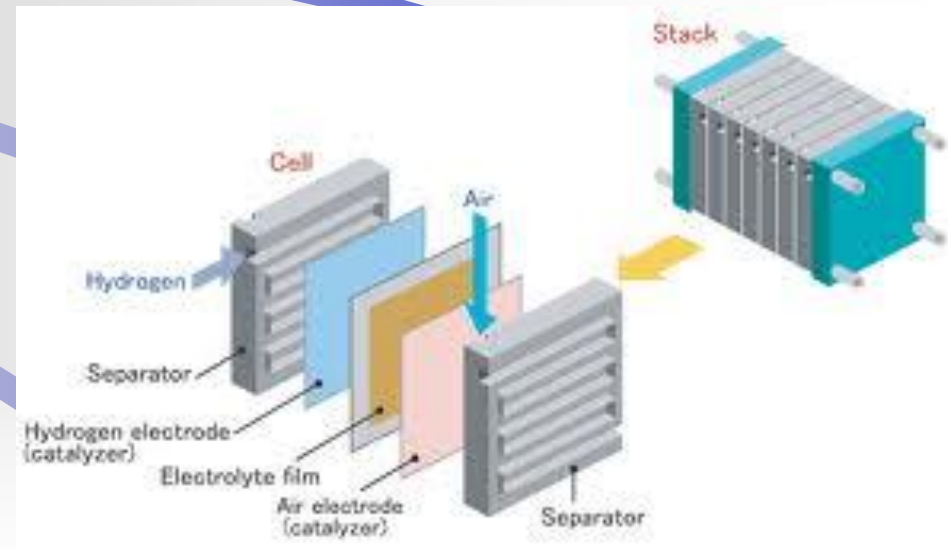
A typical fuel cell stack may consist of hundreds of fuel cells.

Fuel Cells

Fuel Cell Systems

Fuel Cell Stack

A typical fuel cell stack may consist of hundreds of fuel cells.



Fuel Cells

Fuel Cell Systems

Fuel Processor

The fuel processor converts fuel into a form useable by the fuel cell. If hydrogen is fed to the system, a processor may not be required, or it may be needed only to filter impurities out of the hydrogen gas.

If the system is powered by a hydrogen-rich, conventional fuel, such as methanol, gasoline, diesel, or gasified coal, a reformer is typically used to convert hydrocarbons into a gas mixture of hydrogen and carbon compounds called "reformat."

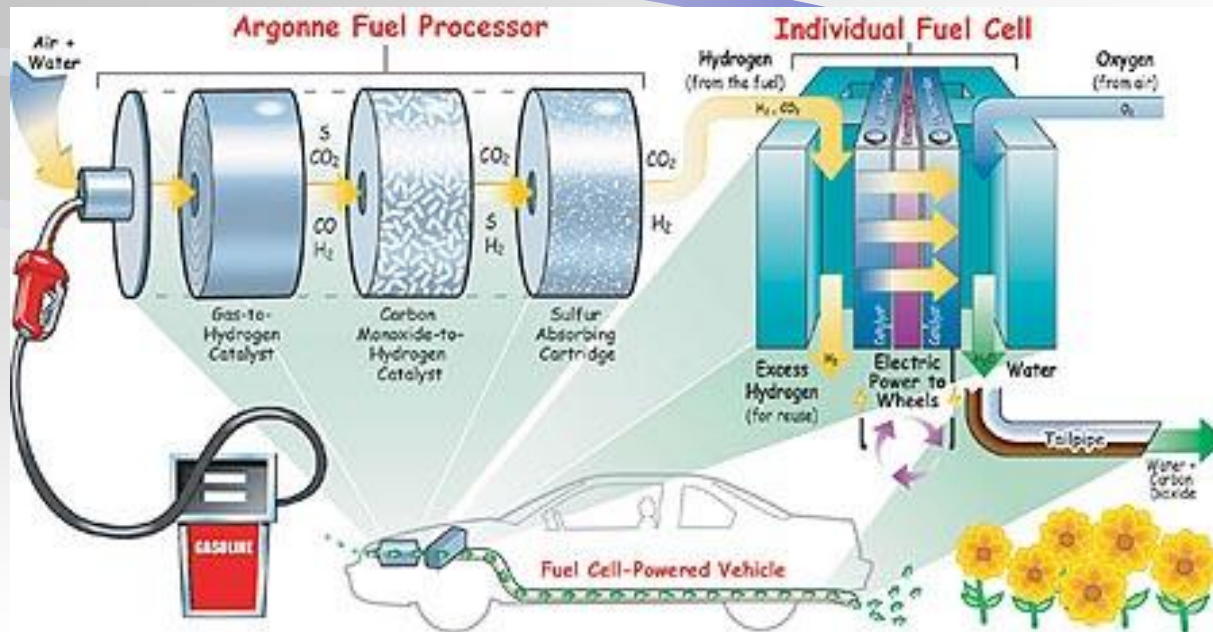
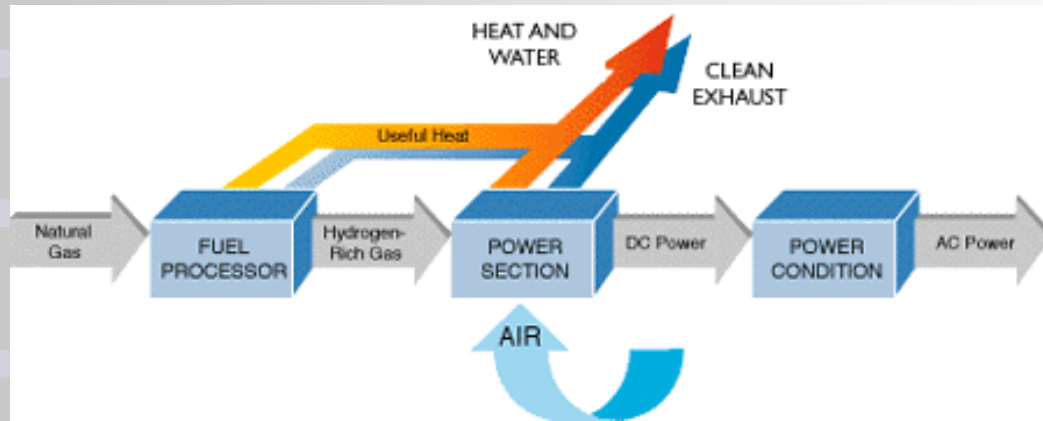
In many cases, the reformat is then sent to another reactor to remove impurities, such as carbon oxides or sulfur, before it is sent to the fuel cell stack.

This process prevents impurities in the gas from binding with the fuel cell catalysts. This binding process is also called "poisoning" because it reduces the efficiency and life expectancy of the fuel cell.

Fuel Cells

Fuel Cell Systems

Fuel Processor



Fuel Cells

Fuel Cell Systems

Current Inverters and Conditioners

Current inverters and conditioners adapt the electrical current from the fuel cell to suit the electrical needs of the application, whether it is a simple electrical motor or a complex utility power grid.

Fuel cells produce electricity in the form of direct current (DC). If the fuel cell is used to power equipment using AC, the direct current will have to be converted to alternating current.

Both AC and DC power must be conditioned. Power conditioning includes controlling current flow (amperes), voltage, frequency, and other characteristics of the electrical current to meet the needs of the application. Conversion and conditioning reduce system efficiency only slightly, around 2%–6%.

Fuel Cells

Fuel Cell Systems

Current Inverters and Conditioners

Direct current (DC) to alternating current (AC) converter.



Fuel Cells

Fuel Cell Systems

Heat Recovery System

Fuel cell systems are not primarily used to generate heat.

However, because significant amounts of heat are generated by some fuel cell systems—especially those that operate at high temperatures, such as solid oxide and molten carbonate systems—this excess energy can be used to produce steam or hot water or to be converted to electricity via other technology.

These methods increase the overall energy efficiency of the systems.

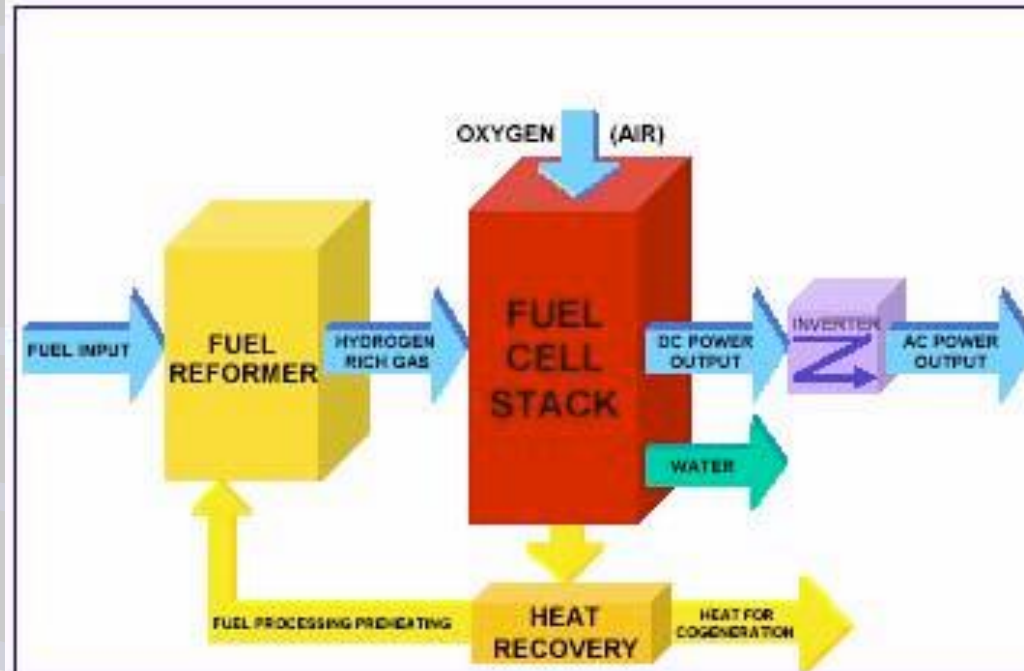
Fuel Cells

Fuel Cell Systems

Heat Recovery System



Fuel Cells



Class Assignment

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