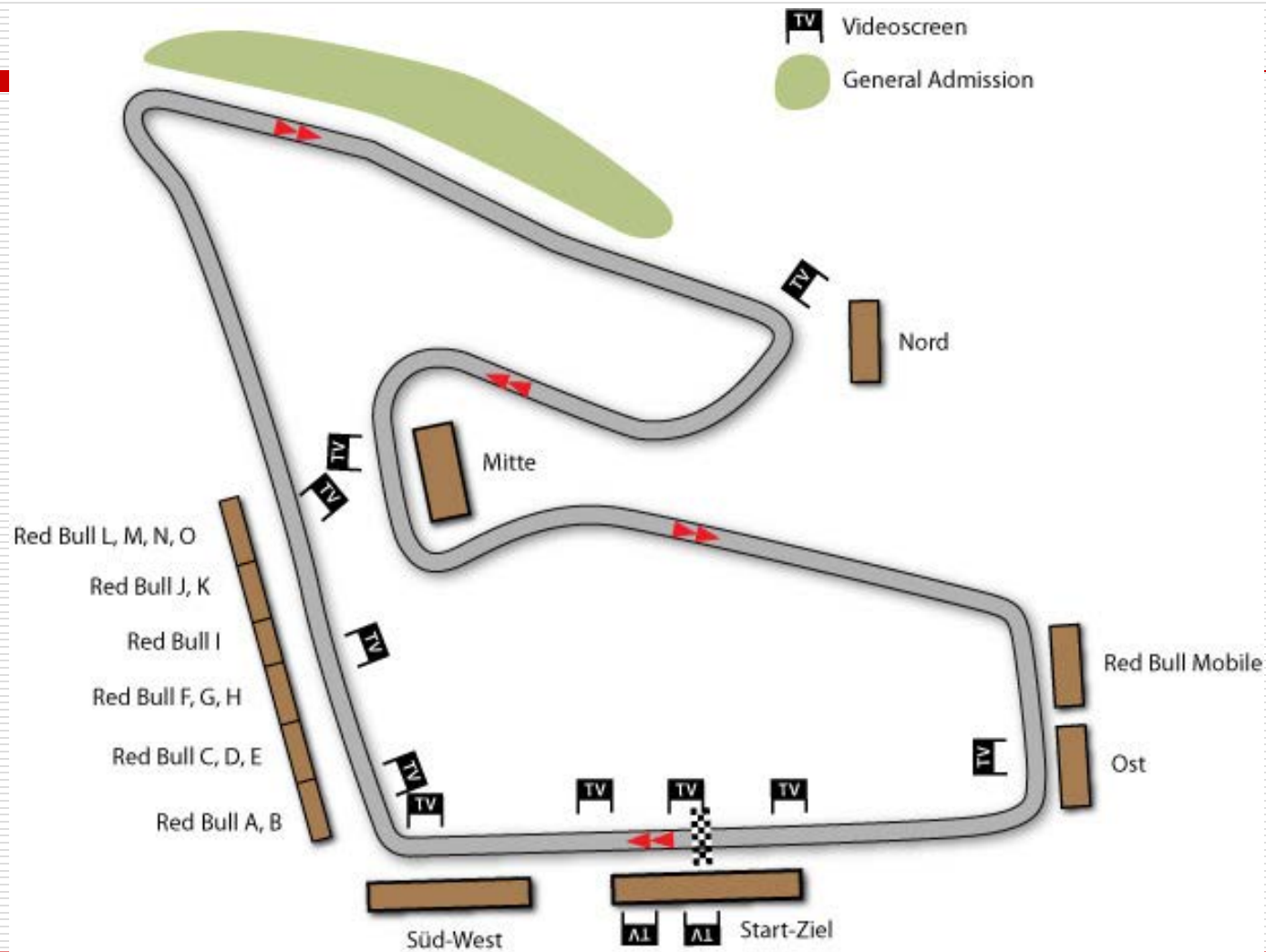
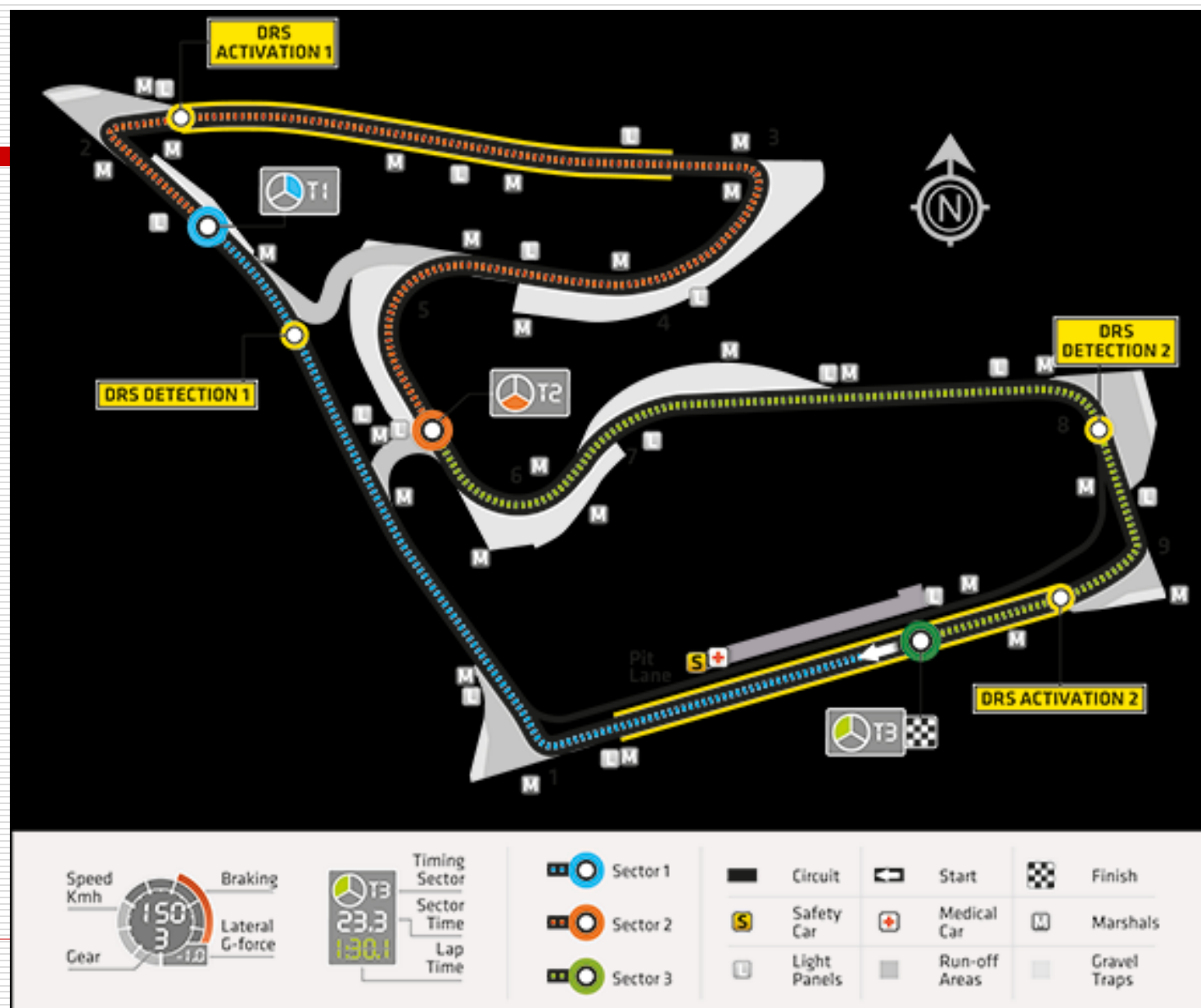


School of Engineering

Introduction to Fuel Cell Technology

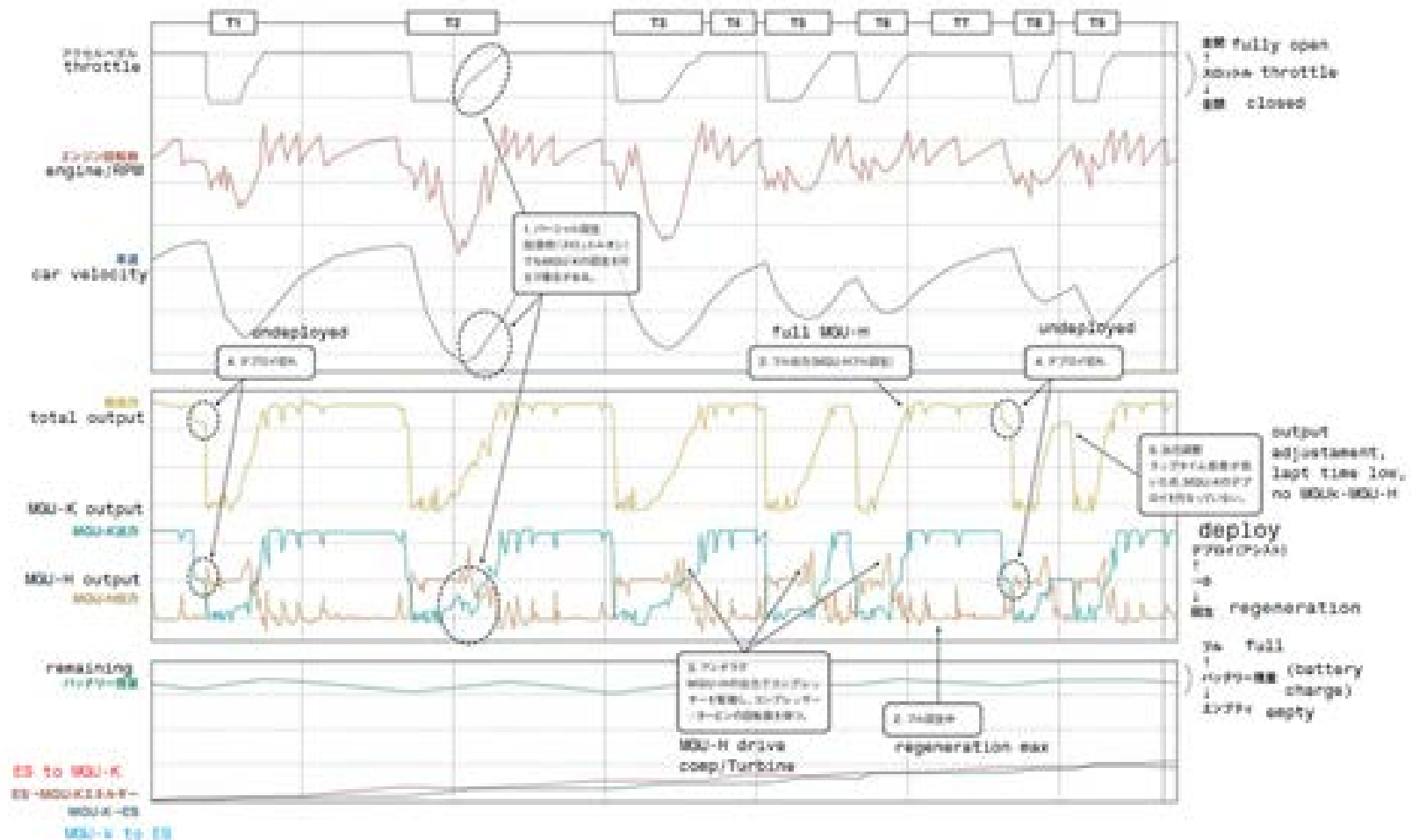
Mark Sandford





2016年第9戦オーストリアGP 決勝レース

1周あたりにMGU-Kで発生できるエネルギー量は3MJ、 outputsできるエネルギー量は4MJと規制で定められている。バッテリー残量のマネジメントが重要で、1周した際に収支がとれている状態にすることが重要。そうでないとエネルギーをたくさん消費した周は良くても、その後の周がきつくなるから、予選は収支に気を遣う必要がない。



What is a fuel cell?

- A fuel cell is a device that generates electricity by a chemical reaction. Every fuel cell has two electrodes, one positive and one negative, called, respectively, the anode and cathode. The reactions that produce electricity take place at the electrodes
-

What is a fuel cell 2

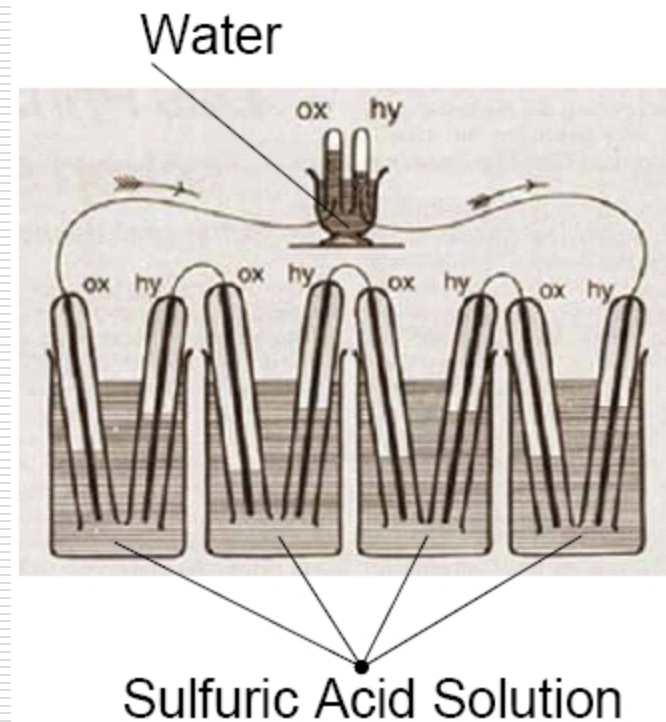
- Every fuel cell also has an electrolyte, which carries electrically charged particles from one electrode to the other, and a catalyst, which speeds the reactions at the electrodes.
 - What is a battery?
-

What is a fuel cell 3

- Hydrogen is the basic fuel, but fuel cells also require oxygen. One great appeal of fuel cells is that they generate electricity with very little pollution—much of the hydrogen and oxygen used in generating electricity ultimately combine to form a harmless byproduct, namely water.
-

William Grove

Swansea born 1811



William Grove

William Robert Grove (1811 -1896), a Welsh 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.

The Grove Cell

In 1800, British scientists William Nicholson and Anthony Carlisle had described the process of using electricity to decompose water into hydrogen and oxygen. But combining the gases to produce electricity and water was, according to Grove, "a step further than any hitherto recorded." Grove realized that by combining several sets of these electrodes in a series circuit he might "effect the decomposition of water by means of its composition." He soon accomplished this feat with the device he named a "gas battery"— the first fuel cell.

Christian Friedrich Schönbein et al



Francis Bacon



To a certain extent, fuel cells remained a solution in search of a problem. As Europe plunged toward the Second World War, a problem suggested itself to a researcher in Britain. **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 the war he thought they might provide a good source of power for Royal Navy submarines in place of dangerous storage batteries then in use and set to work at King's College. But after a short time he was assigned to work on underwater sound-detection and his fuel cell research was put on hold.

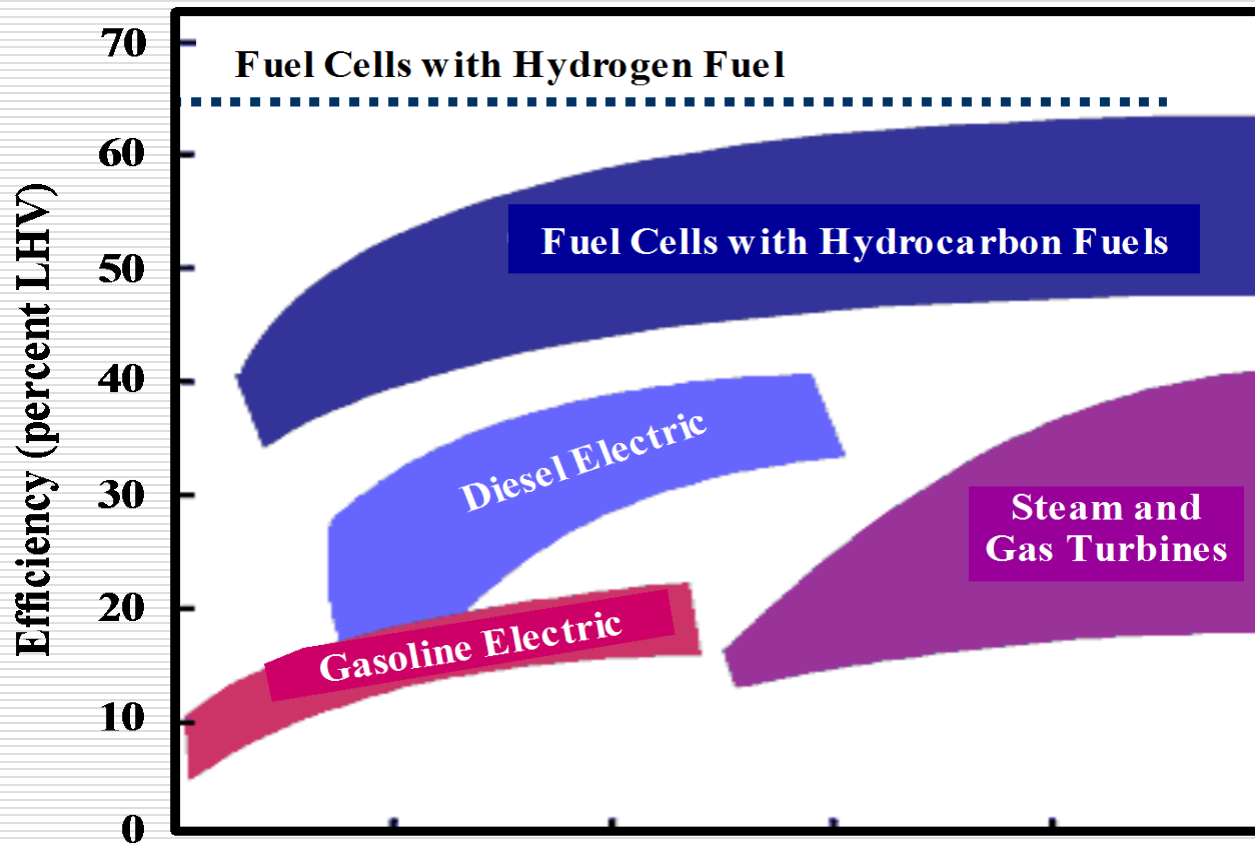
Francis Bacon

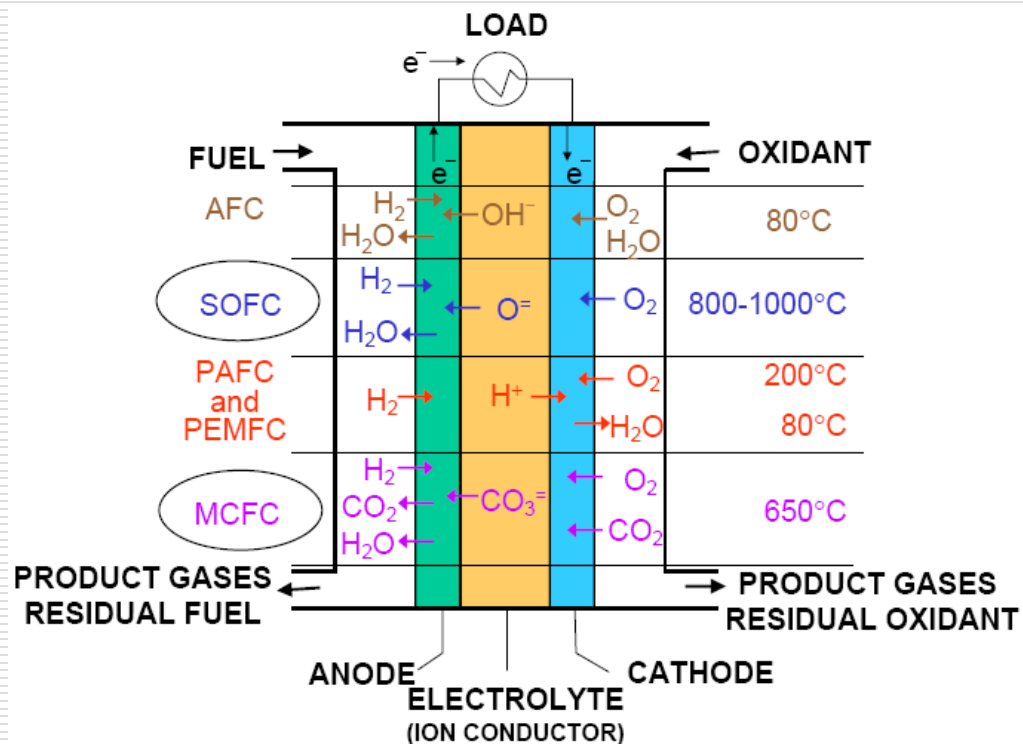
After the war, Bacon went to Cambridge and over the course of the following twenty years, his progress with alkali cells resulted in large scale demonstrations. In 1958 he demonstrated an alkali cell using a stack of 10-inch diameter electrodes for Britain's National Research Development Corporation. Bacon experimented with alkali electrolytes, settling on potassium hydroxide (KOH) instead of using the acid electrolytes known since Grove's time. KOH performed as well as acid and was not as corrosive to the electrodes. 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.

How does a fuel cell work?

- hydrogen atoms enter a fuel cell at the anode where a chemical reaction strips them of their electrons. The hydrogen atoms are now “ionized,” and carry a positive electrical charge. The negatively charged electrons provide the current through wires to do work.
-

Fuel Cell Efficiency

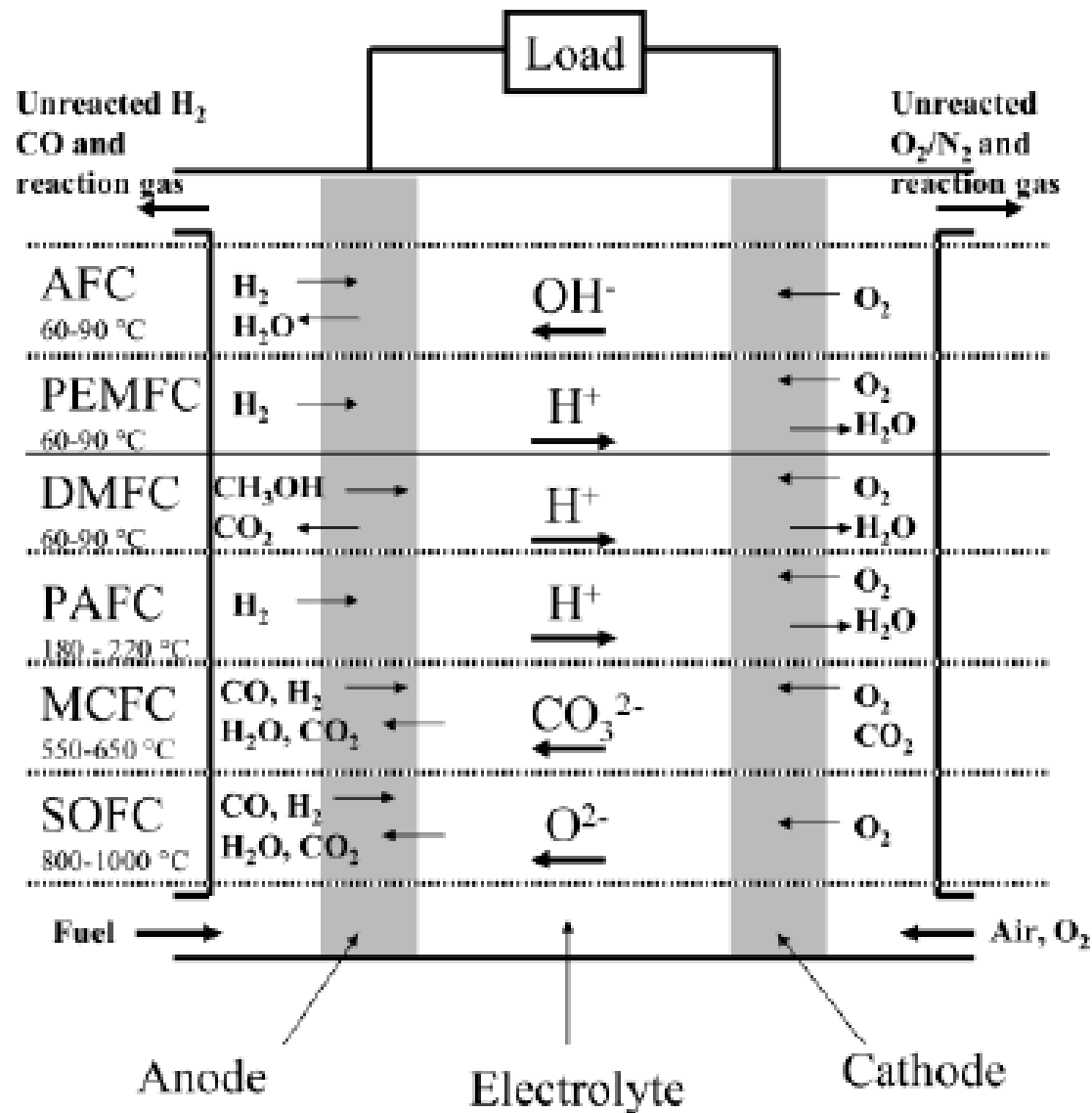




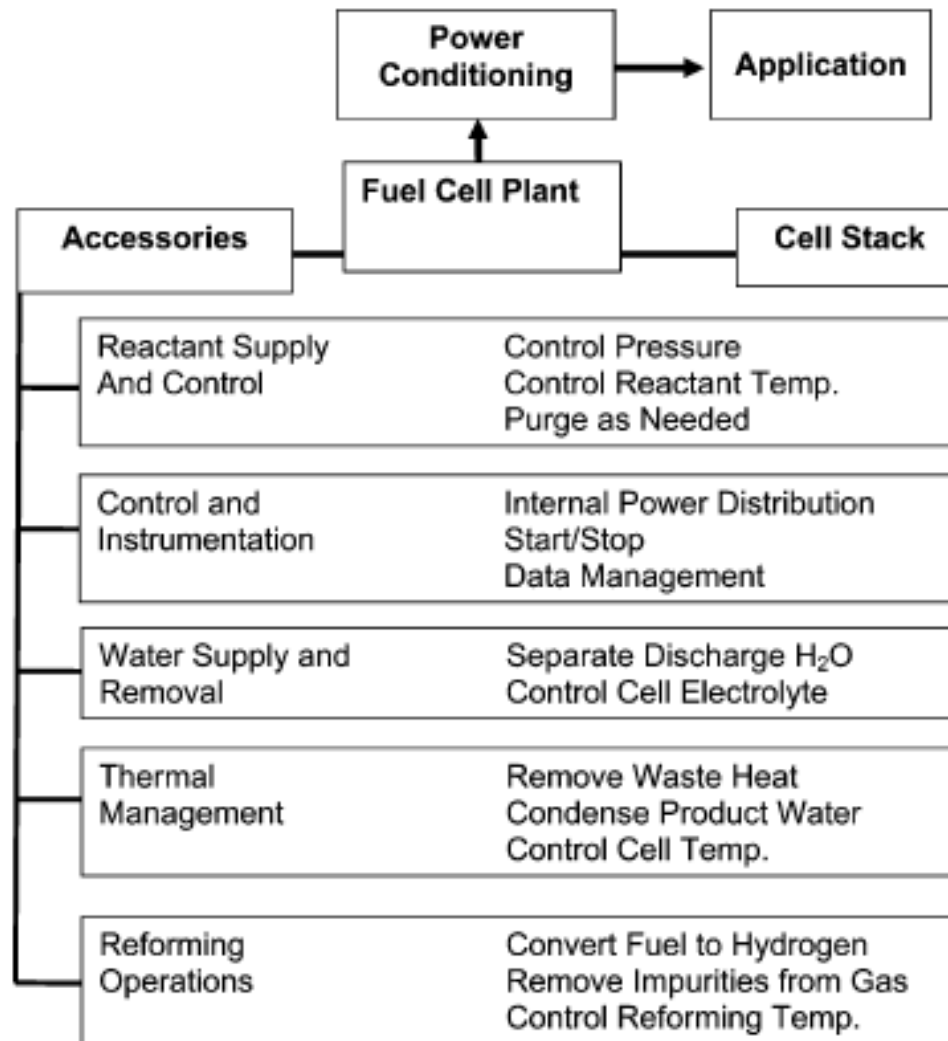
Types of Fuel Cells

Fuel Cell	Operating Conditions
Alkaline FC (AFC)	Operates at room temp. to 80 °C Apollo fuel cell
Proton Exchange Membrane FC (PEMFC)	Operates best at 60-90 °C Hydrogen fuel Originally developed by GE for space
Phosphoric Acid FC (PAFC)	Operates best at ~200 °C Hydrogen fuel Stationary energy storage device
Molten Carbonate FC (MCFC)	Operates best at 550 °C Nickel catalysts, ceramic separator membrane Hydrocarbon fuels reformed in situ
Solid Oxide FC (SOFC)	Operates at 900 °C Conducting ceramic oxide electrodes Hydrocarbon fuels reformed in situ
Direct Methanol Fuel Cell (DMFC)	Operates best at 60-90 °C Methanol Fuel For portable electronic devices

Summary of Reactions and Processes in Various Fuel Cells

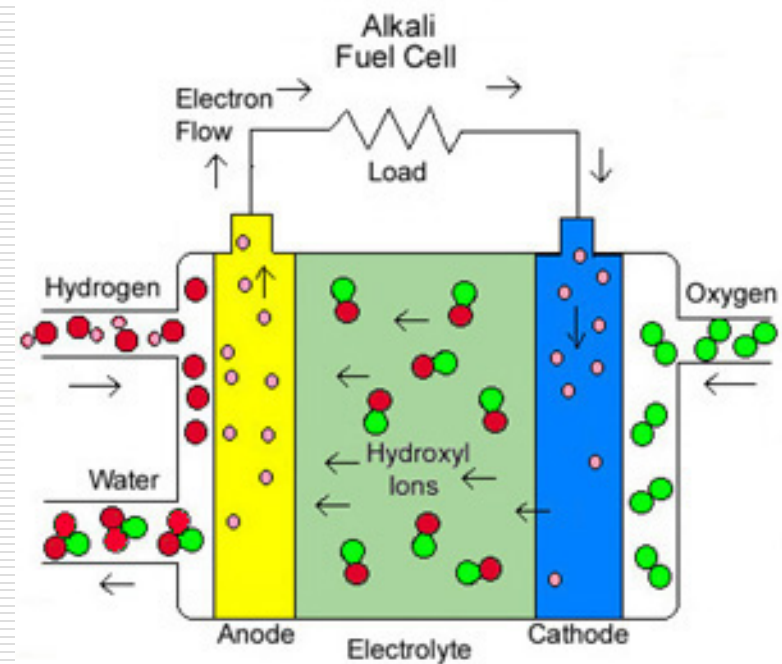


Block Diagram of the Component Parts of a Fuel Cell



Alkali Fuel Cells

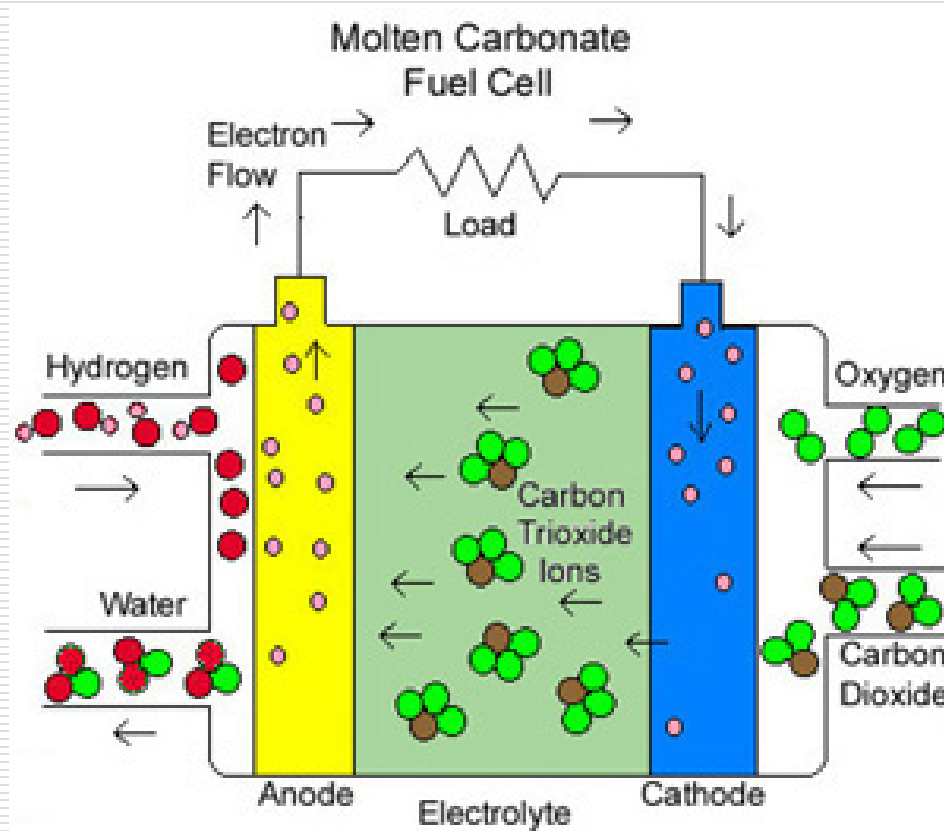
Alkali fuel cells operate on compressed hydrogen and oxygen. They generally use a solution of potassium hydroxide (chemically, KOH) in water as their electrolyte. Efficiency is about 70 percent, and operating temperature is 150 to 200 degrees C, (about 300 to 400 degrees F). Cell output ranges from 300 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.



Moulton Carbonate

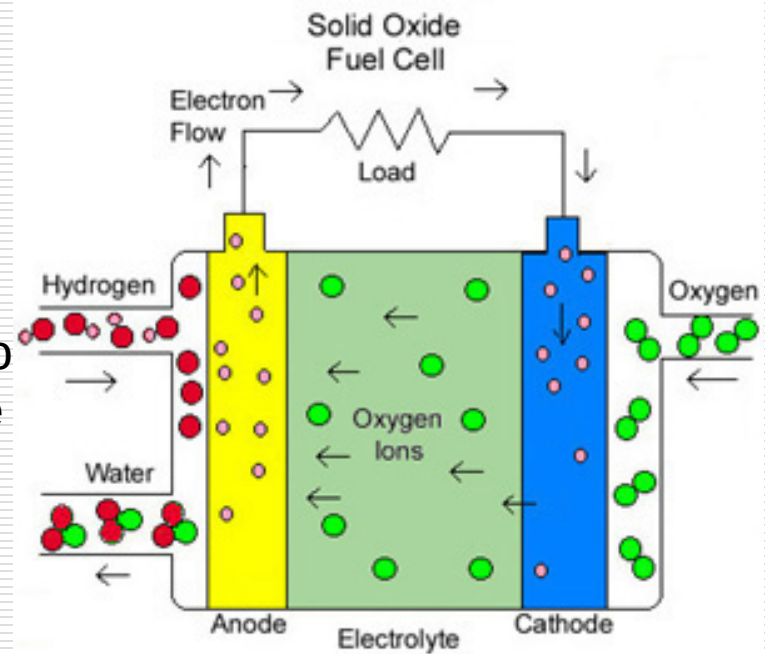
Molten Carbonate fuel cells (MCFC) use high-temperature compounds of salt (like sodium or magnesium) carbonates (chemically, CO_3) as the electrolyte. Efficiency ranges from 60 to 80 percent, and operating temperature is about 650 degrees C (1,200 degrees F). Units with output up to 2 megawatts (MW) have been constructed, and designs exist for units up to 100 MW. The high temperature limits damage from carbon monoxide "poisoning" of the cell and waste heat can be recycled to make additional electricity. Their nickel electrode-catalysts are inexpensive compared to the platinum used in other cells. But 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.

Moulton Carbonate



Solid Oxide

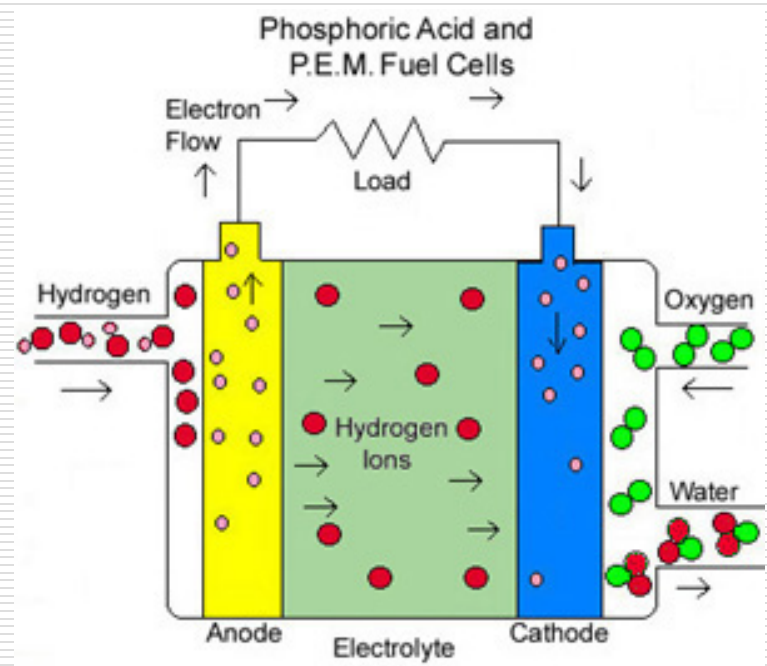
Solid Oxide fuel cells (SOFC) use a hard, ceramic compound of metal (like calcium or zirconium) oxides (chemically, O_2) as electrolyte. Efficiency is about 60 percent, and operating temperatures are about 1,000 degrees C (about 1,800 degrees F). Cells output is up to 100 kW. At such high temperatures a reformer is not required to extract hydrogen from the fuel, and waste heat can be recycled to make additional electricity. However, the high temperature limits applications of SOFC units and they tend to be rather large. While solid electrolytes cannot leak, they can crack.



PEM

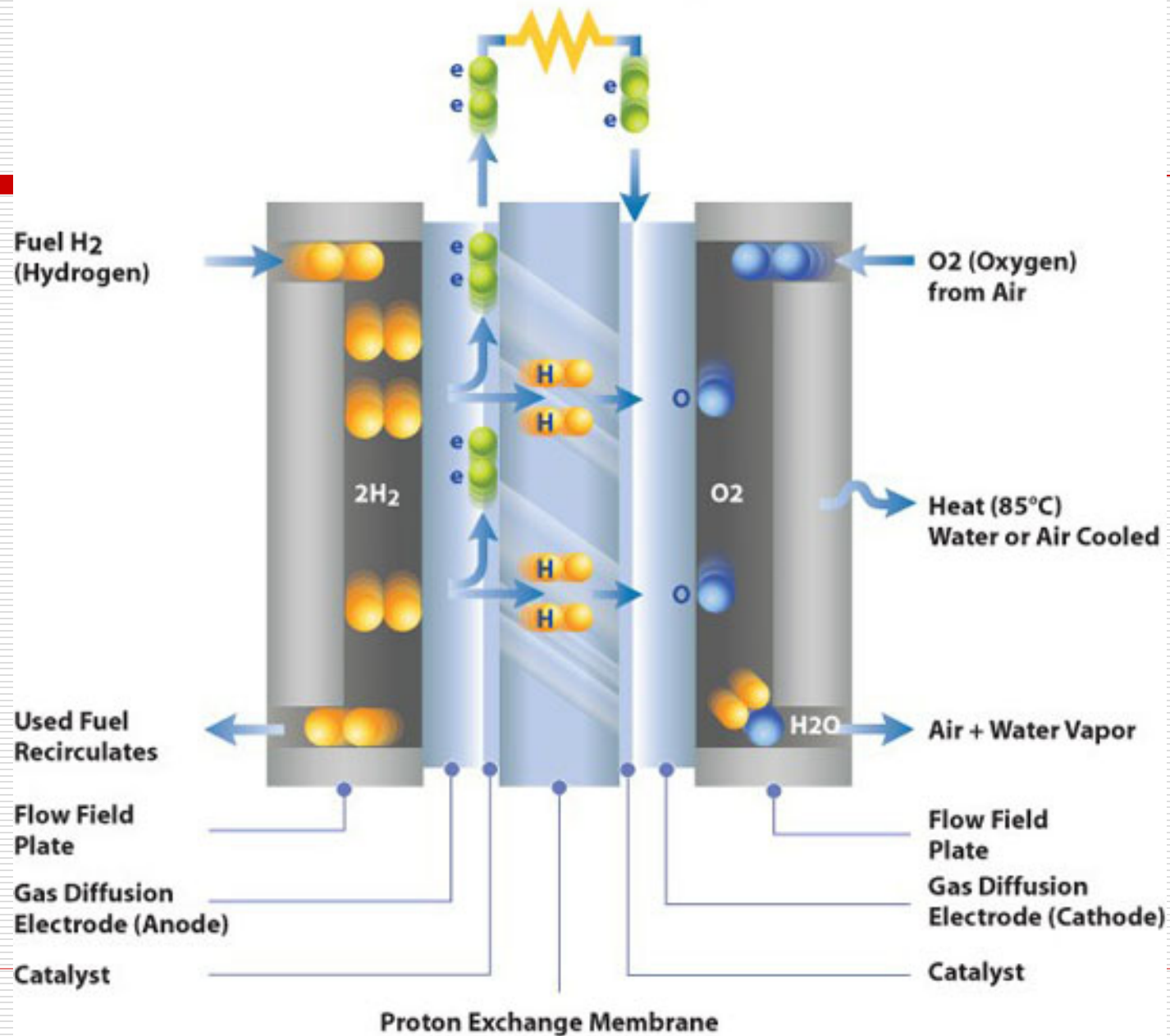
Proton Exchange Membrane

Proton Exchange Membrane (PEM) fuel cells work with a polymer electrolyte in the form of a thin, permeable sheet. Efficiency is about 40 to 50 percent, and operating temperature is about 80 degrees C (about 175 degrees F). Cell outputs generally range from 50 to 250 kW. 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. But their fuels must be purified, and a platinum catalyst is used on both sides of the membrane, raising costs.



ELECTRIC CIRCUIT

(40% - 60% Efficiency)



The core of the Ballard® fuel cell consists of a membrane electrode assembly, which is placed between two flow-field plates. The MEA consists of two electrodes, the anode and the cathode, which are each coated on one side with a thin catalyst layer and separated by a proton exchange membrane (PEM). The flow-field plates direct hydrogen to the anode and oxygen (from air) to the cathode.

When hydrogen reaches the catalyst layer, it separates into protons (hydrogen ions) and electrons.

The free electrons, produced at the anode, are conducted in the form of a usable electric current through the external circuit. At the cathode, oxygen from the air, electrons from the external circuit and protons combine to form water and heat.

Parts of a Ballard® fuel cell Expanded Single Fuel Cell

A single fuel cell consists of the membrane electrode assembly and two flow-field plates.

Hydrogen

Hydrogen flows through channels in flow field plates to the anode where the platinum catalyst promotes its separation into protons and electrons. Hydrogen can be supplied to a fuel cell directly or may be obtained from natural gas, methanol or petroleum using a fuel processor, which converts the hydrocarbons into hydrogen and carbon dioxide through a catalytic chemical reaction.

Membrane Electrode Assembly

Each membrane electrode assembly consists of two electrodes (the anode and the cathode) with a very thin layer of catalyst, bonded to either side of a proton exchange membrane.

Air

Air flows through the channels in flow field plates to the cathode. The hydrogen protons that migrate through the proton exchange membrane combine with oxygen in air and electrons returning from the external circuit to form pure water and heat. The air stream also removes the water created as a by-product of the electrochemical process.

Flow Field Plates

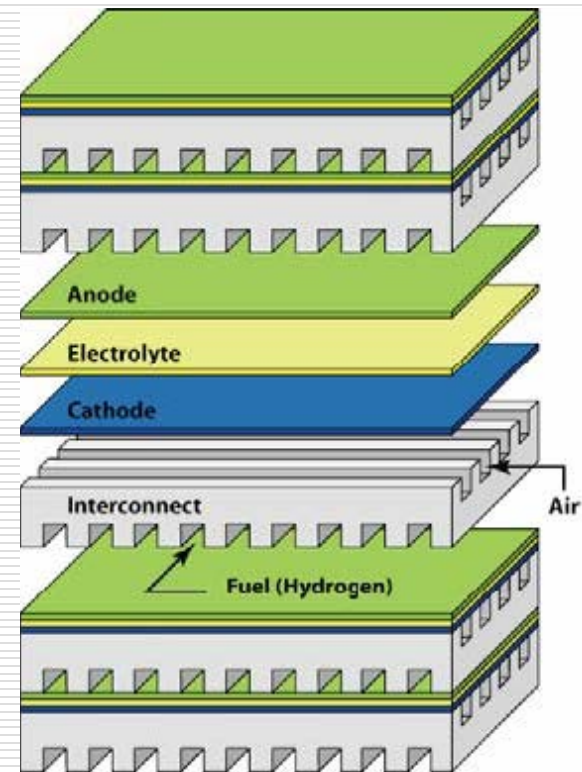
Gases (hydrogen and air) are supplied to the electrodes of the membrane electrode assembly through channels formed in flow field plates.

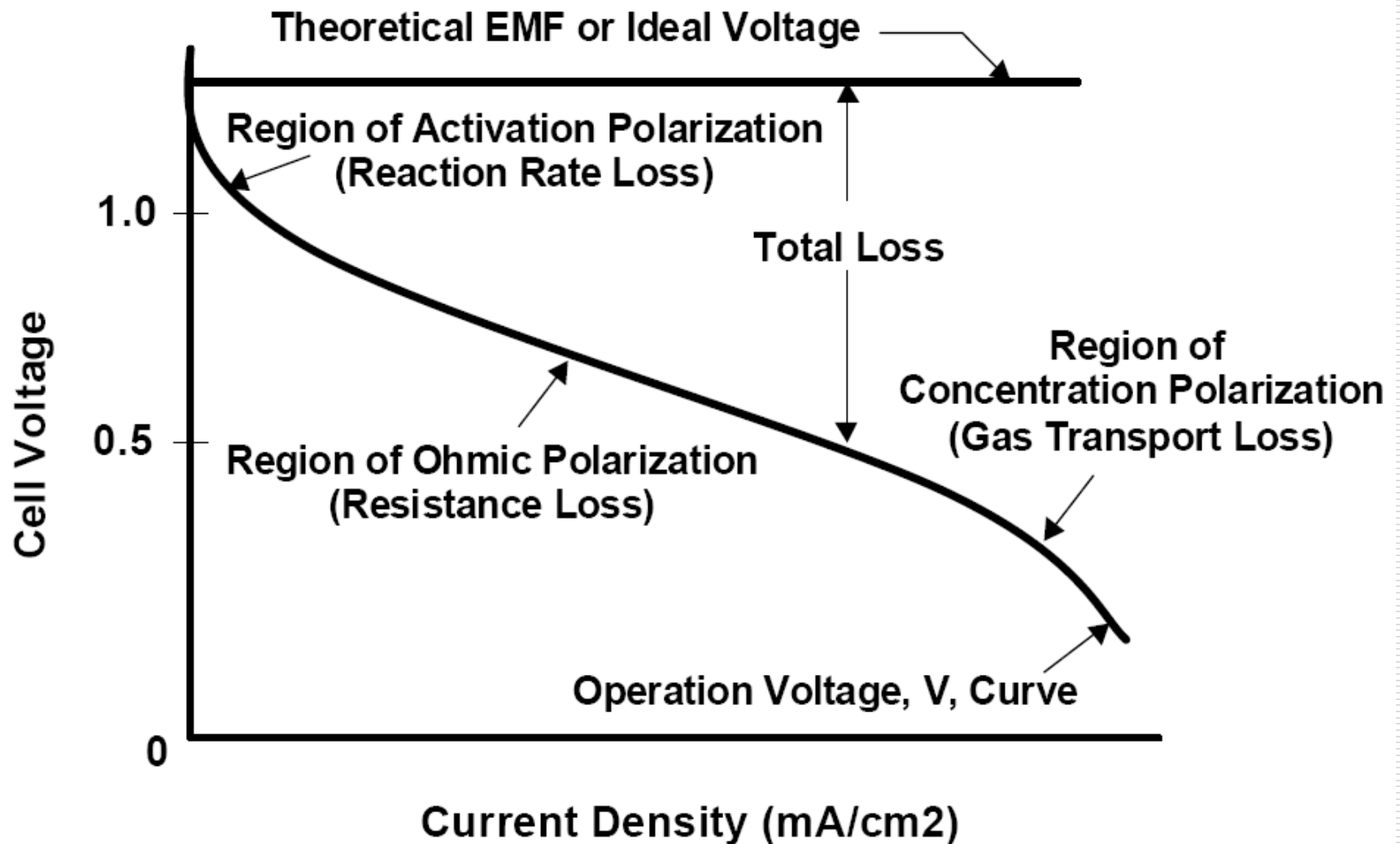
Fuel Cell Stack

To obtain the desired amount of electrical power, individual fuel cells are combined to form a fuel cell stack. Increasing the number of cells in a stack increases the voltage, while increasing the surface area of the cells increases the current.

Stacks

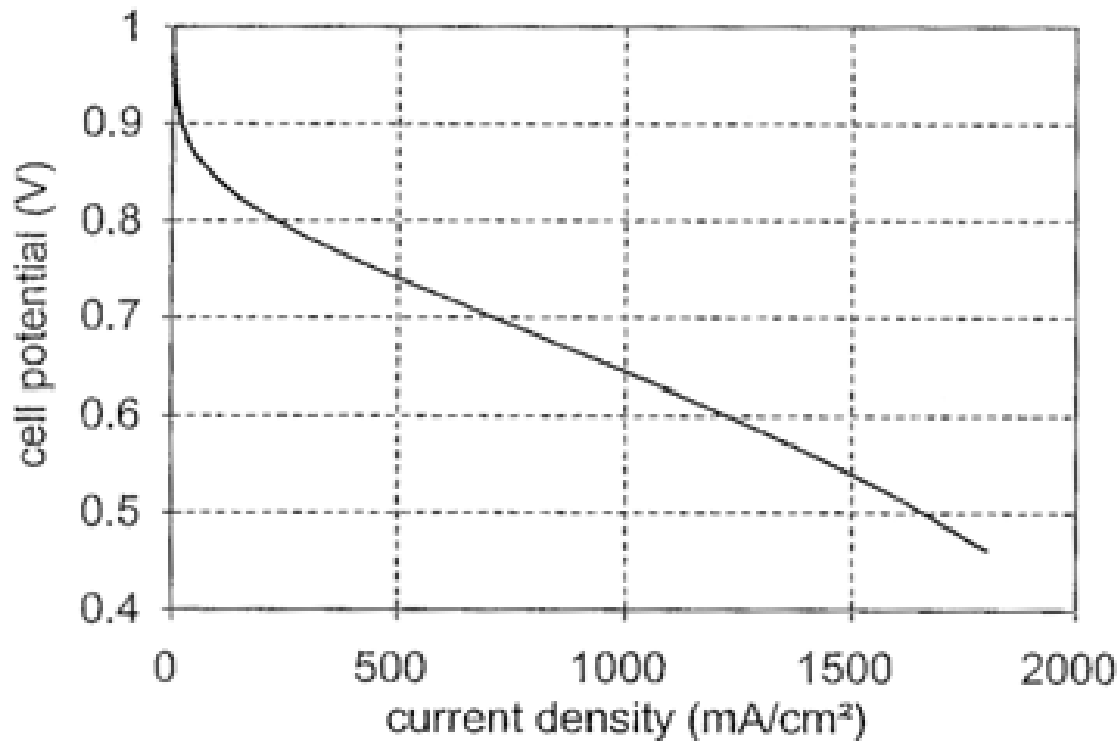
- Each fuel cell layer operates at 0.3-0.9V
- Power is increased two ways
 - Increase voltage by stacking (like batteries)
 - Increase current by increasing active area



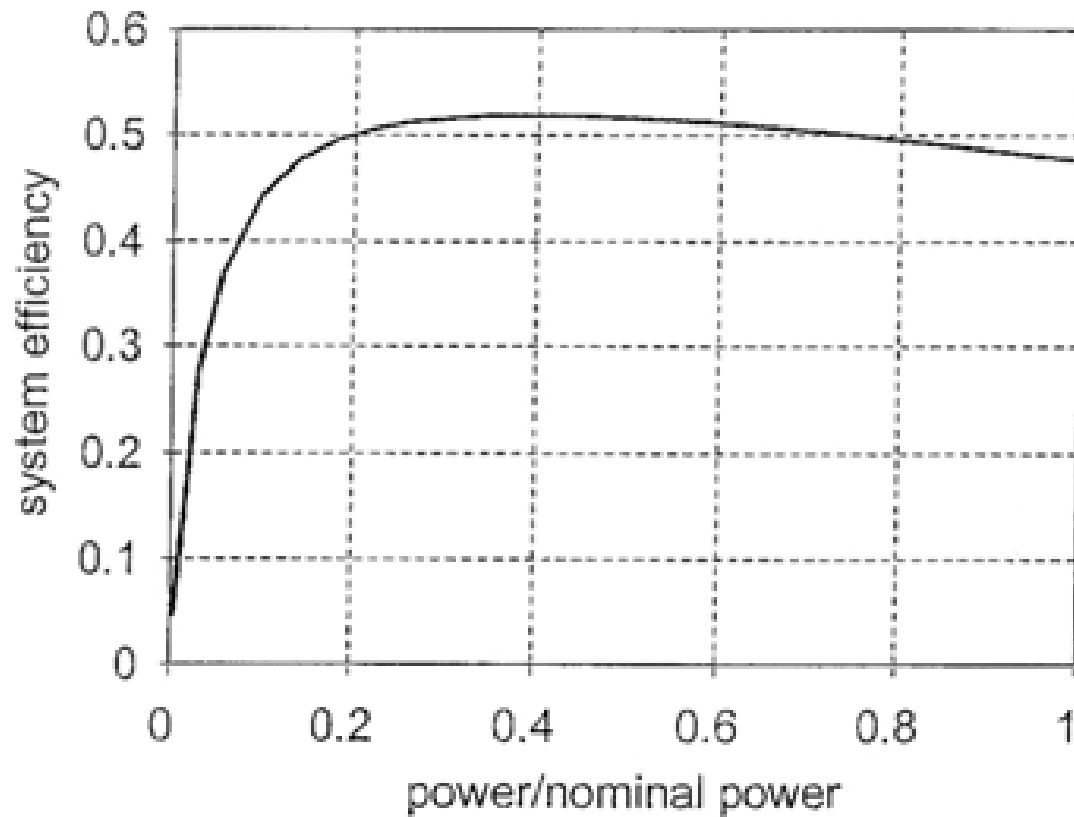


This is the fundamental fuel cell performance measurement

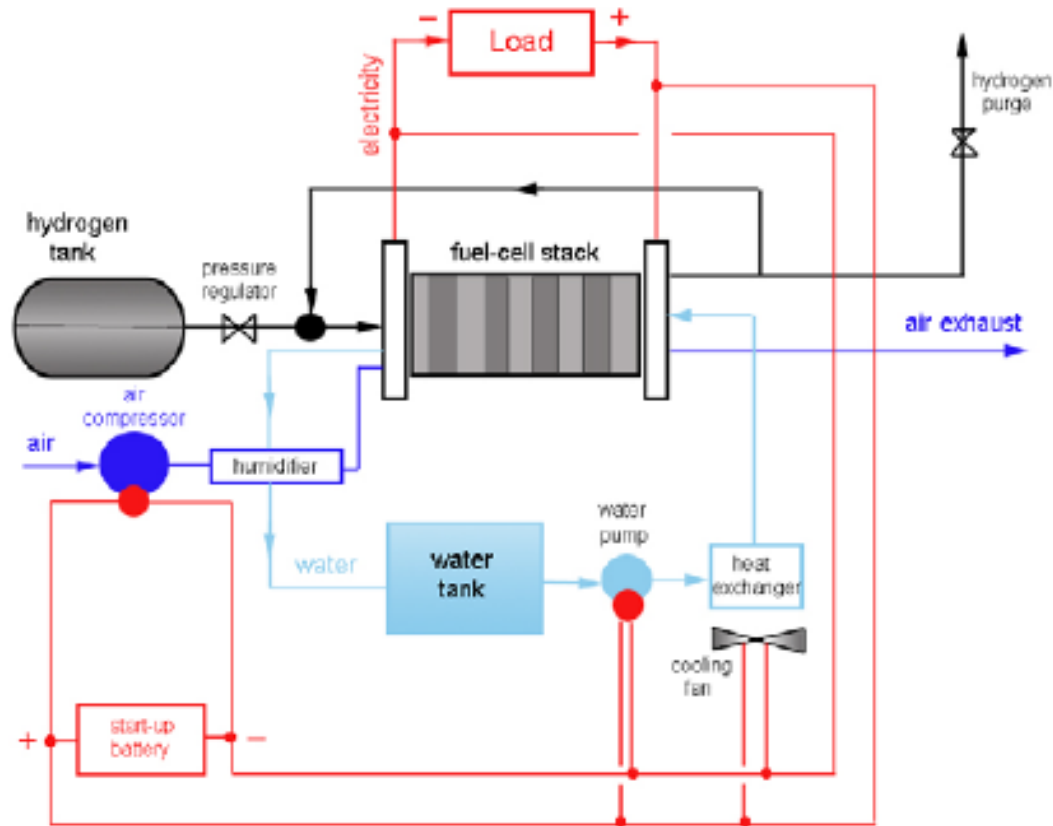
Volt and current density



Efficiency



The fuel cell system

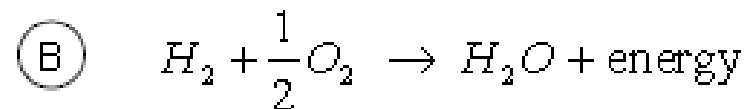
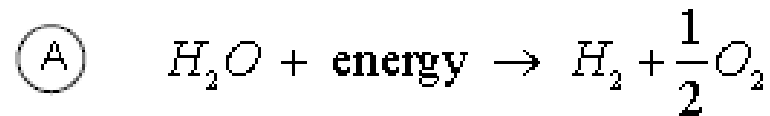


Hydrogen Production

Where does Hydrogen come from?

- ❑ Hydrogen is not a source of energy, but rather a carrier of energy.
 - ❑ In other words, it takes energy to produce hydrogen fuel.
 - ❑ To understand how much energy is needed, we need to look at a little
 - ❑ chemical thermodynamics.
-

Thermodynamics of hydrolysis and water formation



The splitting of water (Reaction A) is an endergenic (endothermic) reaction, meaning that it requires a net input of energy because the products are inherently more energetic than the original molecule.

Conversely, Reaction B is exergenic (exothermic), meaning that it creates a net release of energy to the environment.

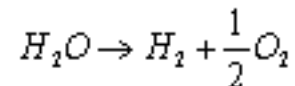
However, the "energy" terms in Reactions A and B are not equal due to the Second Law of Thermodynamics.

2nd Law of Thermodynamics

The Second Law of Thermodynamics has been expressed in many different ways over the years.

Perhaps the most well known form is the following:
"The entropy of the universe is always increasing."

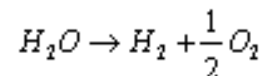
This means that the universe is becoming more disordered with every chemical reaction. The splitting and recombination of H₂O is no exception.



Water, being a single compound, is more ordered than the two components, H₂ and O₂, taken separately. Thus, it takes some energy to cleave water to create the more disordered H₂ and O₂.

The energy associated with creating the disorder, or entropy, ultimately dissipates and cannot be recovered to do useful work.

Water



For the above reaction, we have:

$$\Delta H = 286 \text{ kJ/mol } H_2O$$

$$\Delta G = 237 \text{ kJ/mol } H_2O \quad @ 298 \text{ K} = 25^\circ\text{C}$$

Now, if it takes ΔH to cleave water into hydrogen and oxygen, and we can only get ΔG back through using hydrogen as fuel, then the maximum efficiency we can possibly attain for the entire process, from hydrogen production to automobile propulsion, is:

$$\eta_{thermal} = \frac{237 \text{ kJ/mol}}{286 \text{ kJ/mol}} = 0.83 = 83\%$$

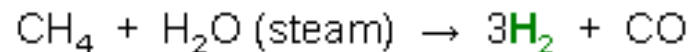
Typically, however, actual efficiencies are much smaller, on the order of 40%.

Hydrogen Production

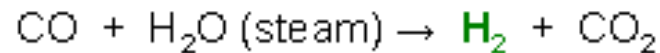
- Hydrogen can be produced in two ways
 - Electrolysis – splitting of water
 - Through a series of high temperature reactions (
-

Possible Chemical Reactions

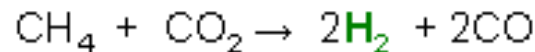
Steam reforming (750 – 800°C)



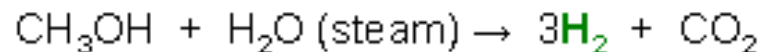
Water gas shift (200 or 350°C)



Dry reforming (600 – 700°C)



Partial oxidation of methanol (250°C)



EFOY fuel cell

<https://www.youtube.com/watch?v=1vWvPwiQazI>

Electrolysis

A typical value for the amount of energy needed to produce hydrogen by electrolysis is 367 kJ/mol.

(Note that this is appreciably higher than the ΔH value, 286 kJ/mol).

This means that 1 kW of electricity can produce $1/367 = 0.00272$ mole/s or 0.00545 g/s of H₂.

Equivalently, 1 MW can produce 0.00545 kg/s.

Fuel Cell Vehicles

Honda FCX Clarity



Fuel Cell Vehicles

BMW 1 series



The relatively small fuel cell APU supplies sufficient power for a zero-emission range of several hundred kilometers in urban traffic and can be recharged with hydrogen in a few minutes. The gasoline engine is only used for high-speed travel with the super capacitors supplying peak power when needed, such as during acceleration and taking off at traffic lights.

Toyota FCHVs



More than 100 Toyota Fuel Cell Hybrid Vehicles (FCHVs) are participating in a US nationwide demonstration program with universities, private companies, and government agencies in California and New York over the next three years. The aim is to demonstrate the reliability and performance of fuel cell technologies and vehicles leading up to the Toyota FCHV's 2015 market introduction, plus spur the expansion of a hydrogen infrastructure.

Toyota FCHVs



First introduced in 2002, the Toyota FCHV has evolved over the years to offer better efficiency, durability, and 150 percent better range, driven primarily by improvements in the vehicle's fuel cell stack and high-pressure hydrogen storage system. Manufacturing and materials cost reductions have also been achieved along the way. Notably, an evaluation by the National Renewable Energy Laboratory in 2009 saw the latest FCHV fuel cell variant averaging the equivalent of 68 mpg with an estimated single-fill hydrogen range of 431 miles.

Hydrogen Storage

- How can we store hydrogen ?
 - In volume
 - In a vehicle
-

In Vehicle Hydrogen Storage

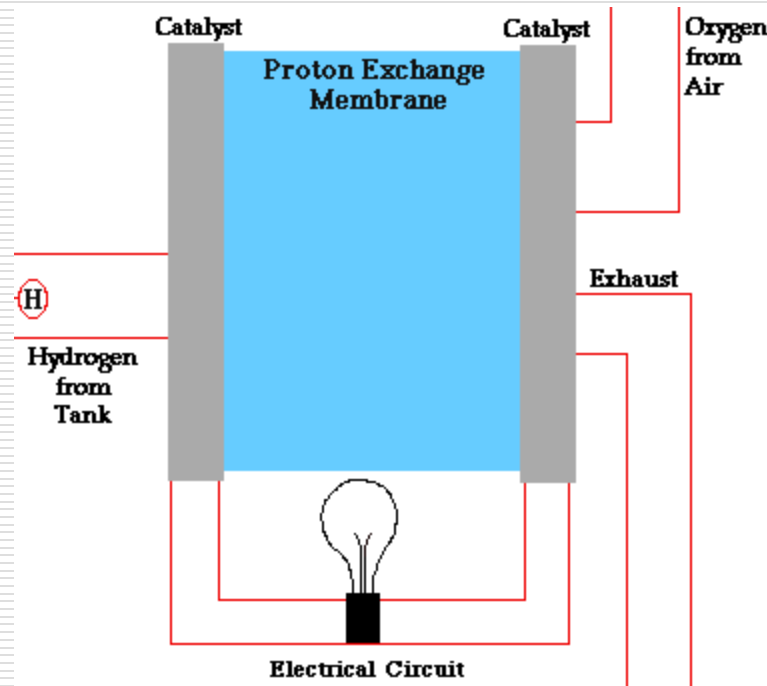
- ☐ Hydrogen is small and light
 - ☐ Under pressure
 - ☐ Really cold
 - ☐ In a metal matrix
-
- Being small, hydrogen is tricky to contain.
-

School of Automotive Engineering

Introduction to Fuel Cell Technology

Mark Sandford

How does a fuel cell work?



Proton exchange membrane fuel cell

