Introduction to Fuel Cell Systems

Overview

- Why Fuel Cells?
- Fuel Cell Fundamentals
- FC Modeling
- FC Applications
- Challenges with FC Utilization
- Various Types of Fuel Cells
- H2 Production

Why Fuel Cells?

- Clean (CO_2 and emissions), Flexible, Distributed Energy Carrier…
- Electricity!
  - Generate with Nuclear, PV, Wind!
- Storage Problem in Vehicles
  - **This is changing…**

Why Fuel Cells?

- The Pros:

- High Energy Density compared to Batteries
- Continuous energy available as long as hydrogen is supplied
- Portable system able to provide power for a wide range of applications
- Fuel Cells produce the cleanest by-product which is water and heat

Why Fuel Cells?

- Applications:

- Note: Fuel Cells have a voltage output dependent on the load current demand. Thus a converter is usually used to stabilize the output voltage to a desired value.

- Distributed Generation
- Hybrid Electric Vehicles (HEVs): Fuel Cell in parallel with batteries
- Portable Power Supplies
- Charging Stations
- Single Home Residential Power
- Electricity and Water Generation in Space Shuttle

Why Fuel Cells?

- Conventional Motor
  - Fuel → Heat → Mechanical (vehicle)
  - Mechanical Power → Electricity (coal plant)
  - 20% - 30% Fuel → Electricity efficiency

- Fuel Cell: Electrochemical Device
  - Fuel (hydrogen) → Electricity (power plant)
  - Electricity → Mechanical Power (vehicle)
  - “Steady Flow Battery”

Why Fuel Cells?

1. For vehicles, over 50% reduction in fuel consumption compared to a conventional vehicle with a gasoline internal combustion engine
2. Increased reliability of the electric power transmission grid by reducing system loads and bottle necks
3. Increased co-generation of energy in combined heat and power applications for buildings
4. Zero to near-zero levels of harmful emissions from vehicles and power plants
5. High energy density in a compact package for portable power applications

Why Fuel Cells?

- Fossil Fuel Dependant → CO_2
  - Hydrocarbon Reforming for Hydrogen
  - Electrolysis? (only if you have clean e^-)

- Well to Wheel studies by Stodolsky et al., Mizey et al., and Rousseau et al. (15% → 40%, so CO_2 reduction)

- Single Point Emissions

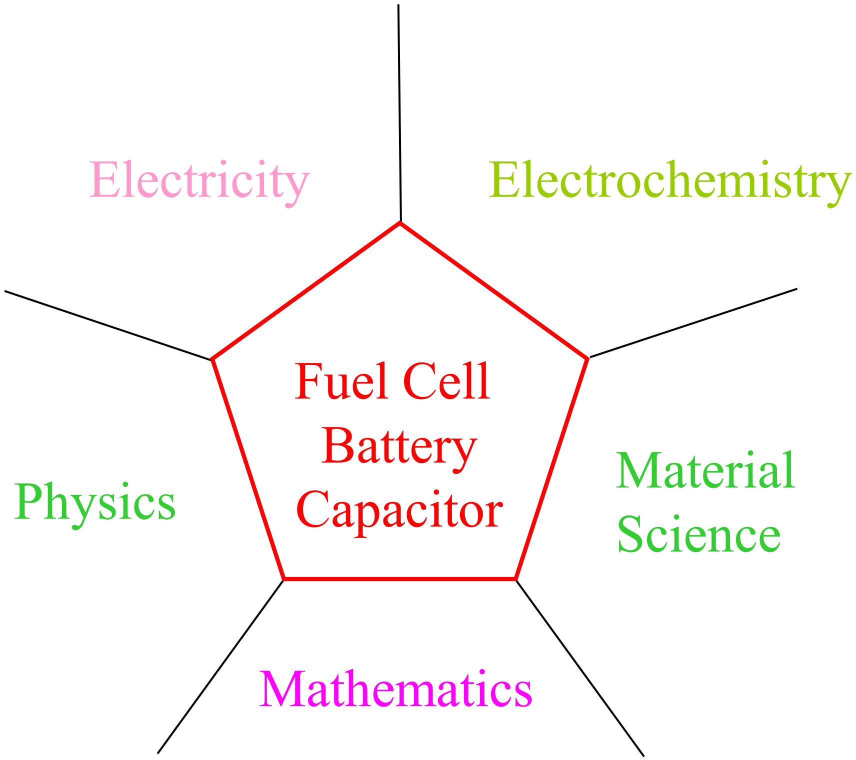
Why Fuel Cells?

- Without clean e^-, fuel cells DO NOT solve the CO_2 problem, but they can help alleviate it through higher efficiencies
- Fuel cells DO shift non-CO_2 emissions to single point sources
- Fuel cell easily converts H_2 to e^- (REVERSE OF WATER ELECTROLYSIS)
- Fuel cells, through H_2 energy carrier, get around the on-board e^- storage issue.

Why Fuel Cells?

- Major players: Ballard, zTEK, UTC, Siemens, Plug Power

Multidisciplinary



Electricity

Electrochemistry

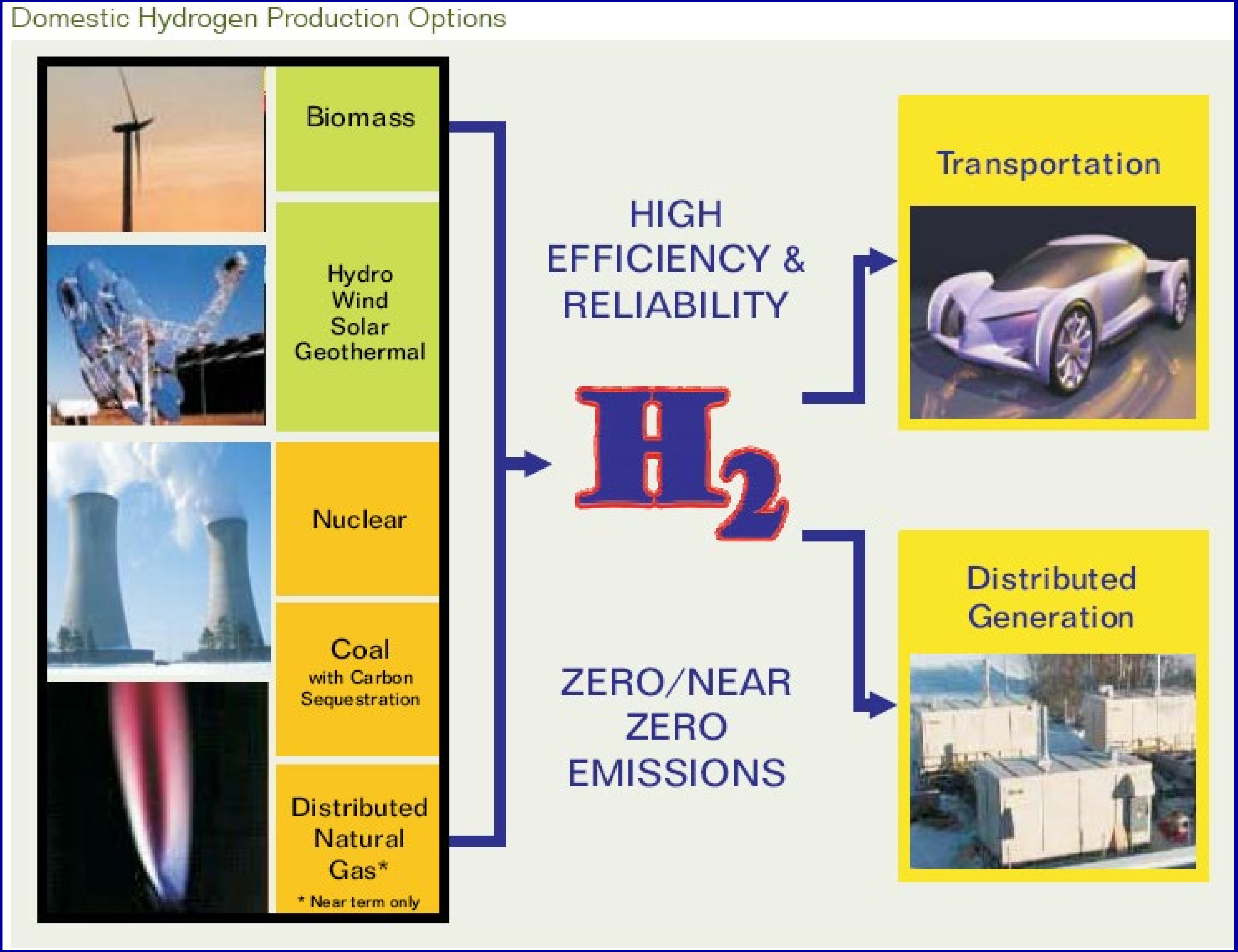
Fuel Cell
Battery
Capacitor

Physics

Material
Science

Mathematics

Hydrogen Energy (Economy)



Domestic Hydrogen Production Options

Biomass

Hydro
Wind
Solar
Geothermal

Nuclear

Coal
with Carbon Sequestration

Distributed Natural Gas*
* Near term only

HIGH EFFICIENCY & RELIABILITY

H_2

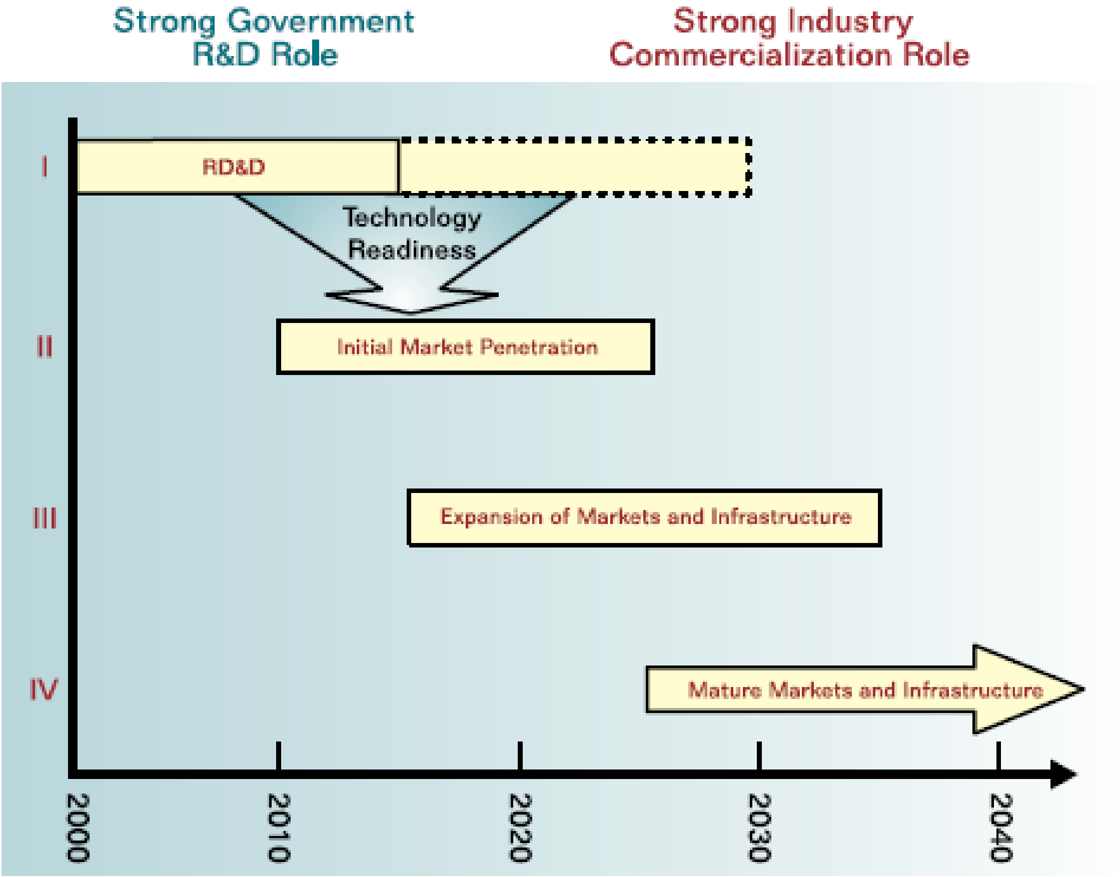
ZERO/NEAR ZERO EMISSIONS

Transportation

Distributed Generation

Road map of Hydrogen R&D

Figure ES-1. Possible Scenarios for Hydrogen Technology Development and Market Transformation



I. Technology Development
Research to meet technology performance and cost targets and establish technology readiness

II. Initial Market Penetration
Portable power and stationary/transport systems are validated; infrastructure investment begins with governmental policies

III. Expansion of Markets and Infrastructure
H_2 power and transport systems commercially available infrastructure business case realized

IV. Fully Developed Markets and Infrastructure
H_2 power and transport systems commercially available in all regions; national infrastructure

The timeframe is long and the investment is large to develop a hydrogen and transportation market that reduces our Nation's dependence on foreign sources of energy while minimizing environmental impacts.

Fuel Cells Fundamentals

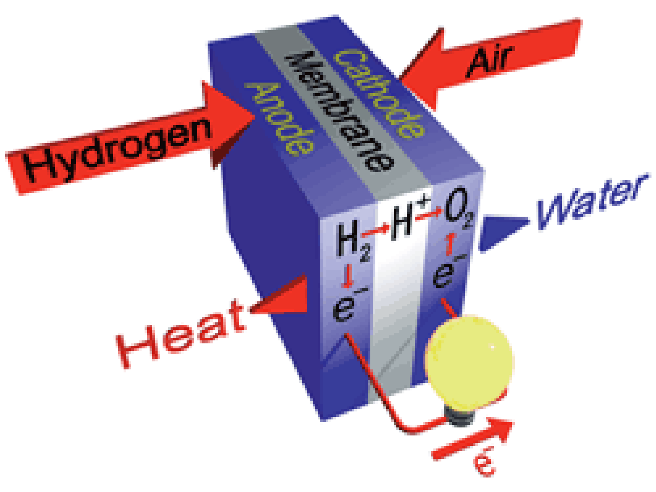
- Electrochemical Device
- “Steady Flow Battery”
- Electrochemical “Engine”
- Generate DC power
- # of cells (voltage) and active surface area (current)

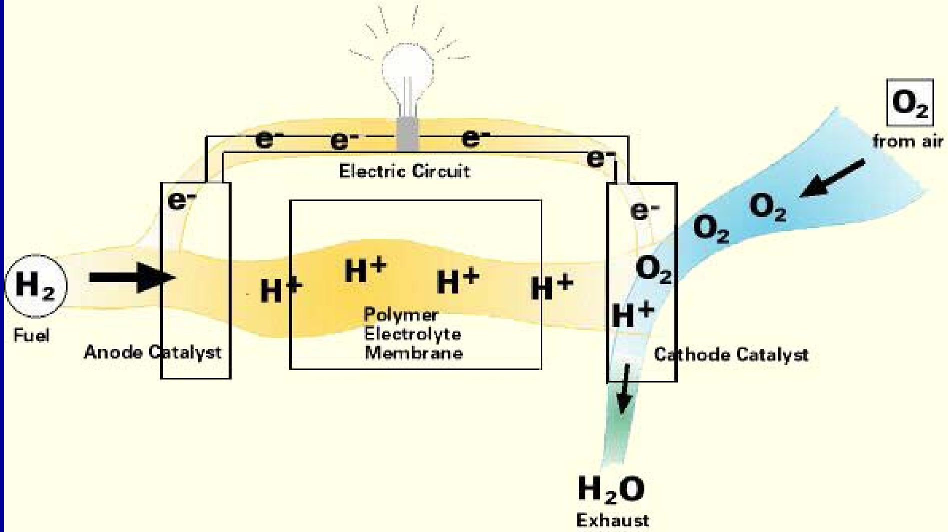
What is the Difference Between a Fuel Cell and a Rechargeable Battery ?

★ A fuel cell is able to operate for long periods of time without recharging or interruption because reactants are brought in from outside, while a rechargeable battery needs to be charged after discharge.

What is a fuel cell ?

A fuel cell is an electrochemical conversion device that converts hydrogen and oxygen into electricity, water, and heat.





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http://www.fuelcells.org/whatis.htm

Schematic Diagram of H_2/O_2 PEMFC

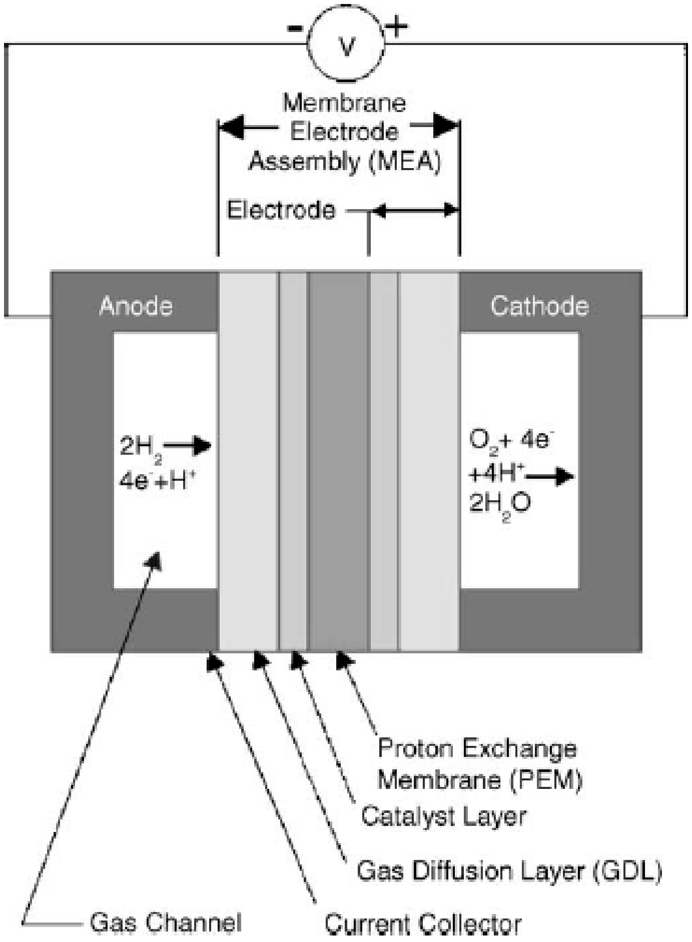
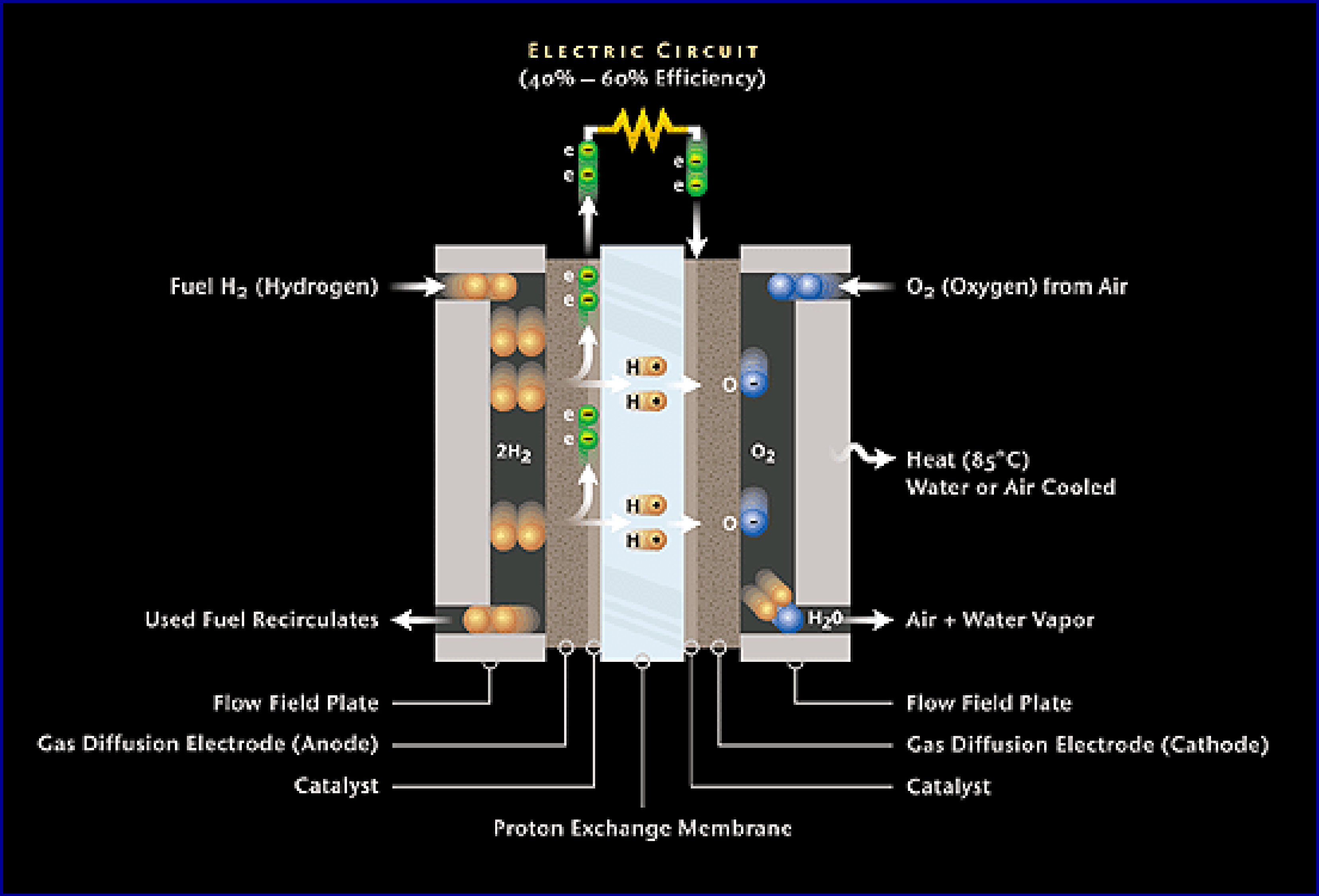
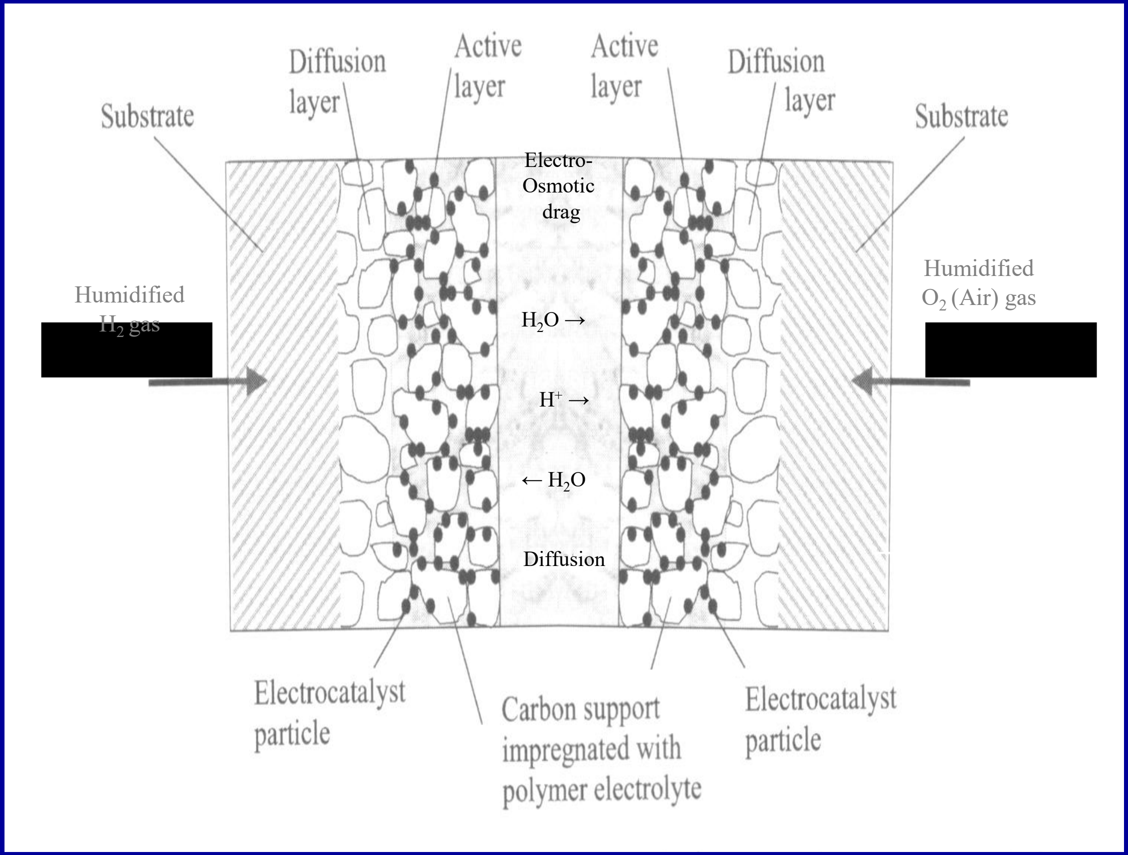


Fig. 1. Schematic of a single typical proton exchange membrane fuel cell.



*California Fuel Cell Partnership

Schematic Diagram of H_2/O_2 PEMFC



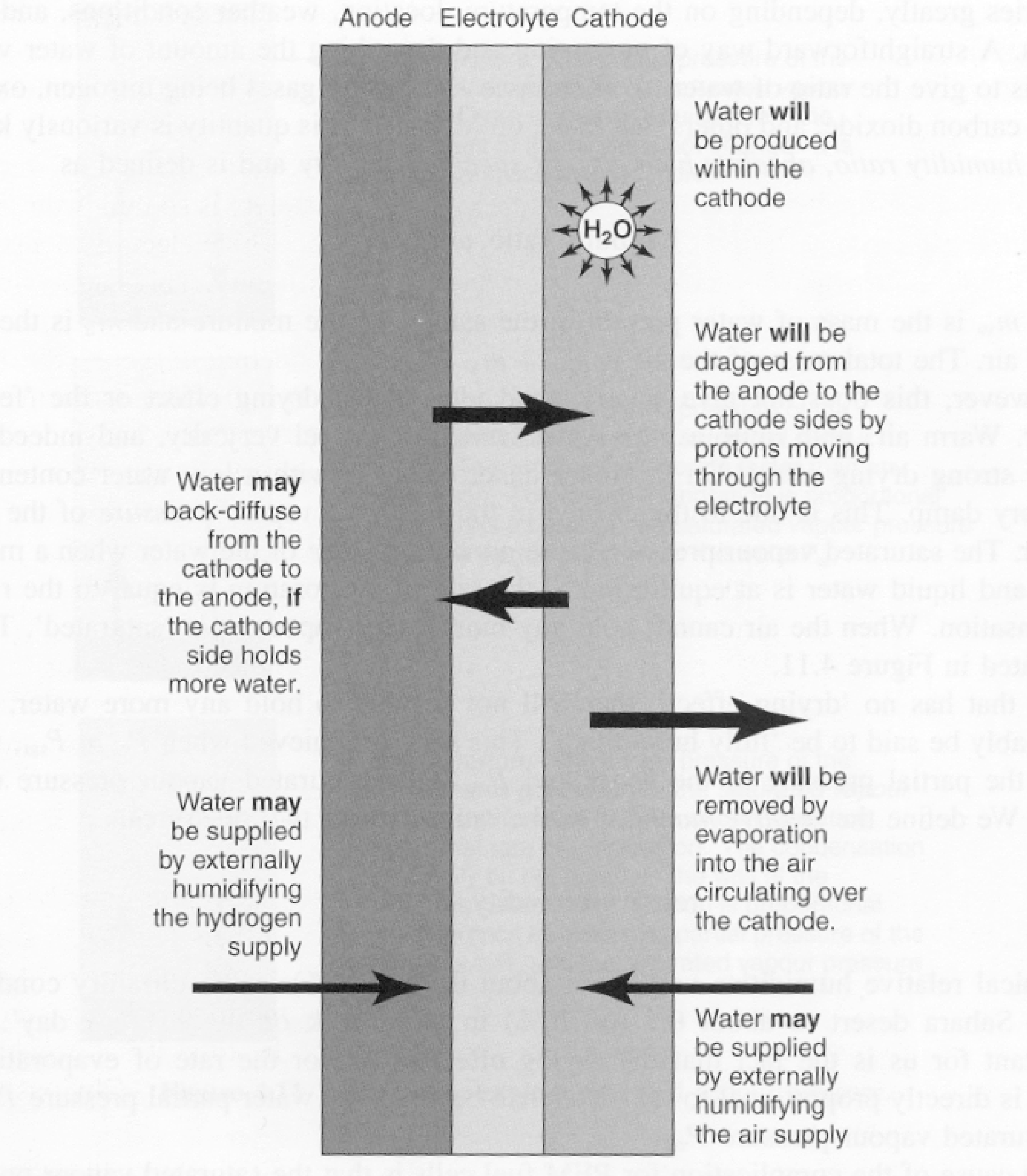
- ★ Anode: Hydrogen oxidation to protons
  $H_2 \rightarrow 2H^+ + 2e^-$

- ★ The protons migrate through the membrane to the cathode

- ★ Cathode: Oxygen reduction
  $1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$
  ($E_{o25}{}^{o}{}_{C}$=+1.23 V (vs. NHE)

- ★ Overall: $H_2 + ½ O_2 \rightarrow H_2O$

Water Management in the PEMFC



Water **will** be produced within the cathode

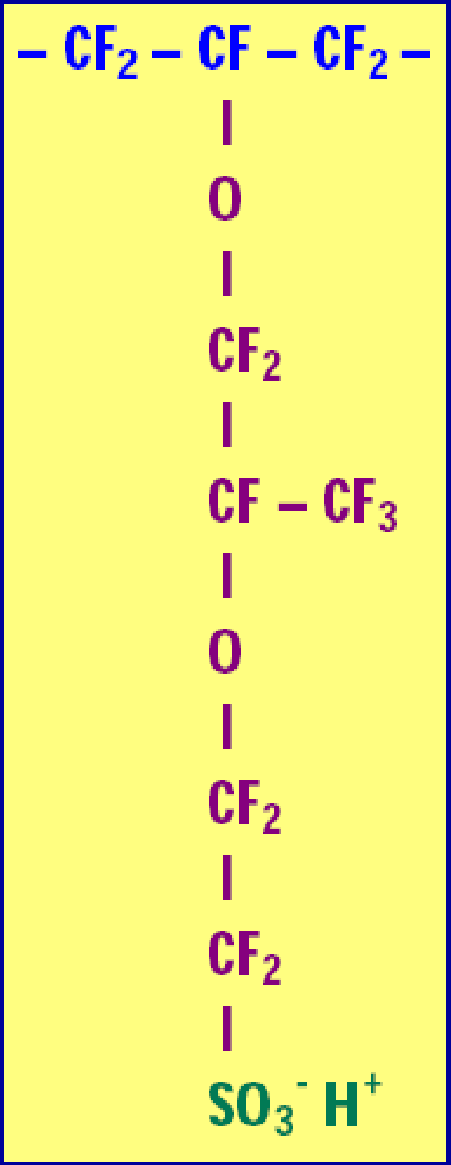
Water **will** be dragged from the anode to the cathode sides by protons moving through the electrolyte

Water **may** back-diffuse from the cathode to the anode, **if** the cathode side holds more water.

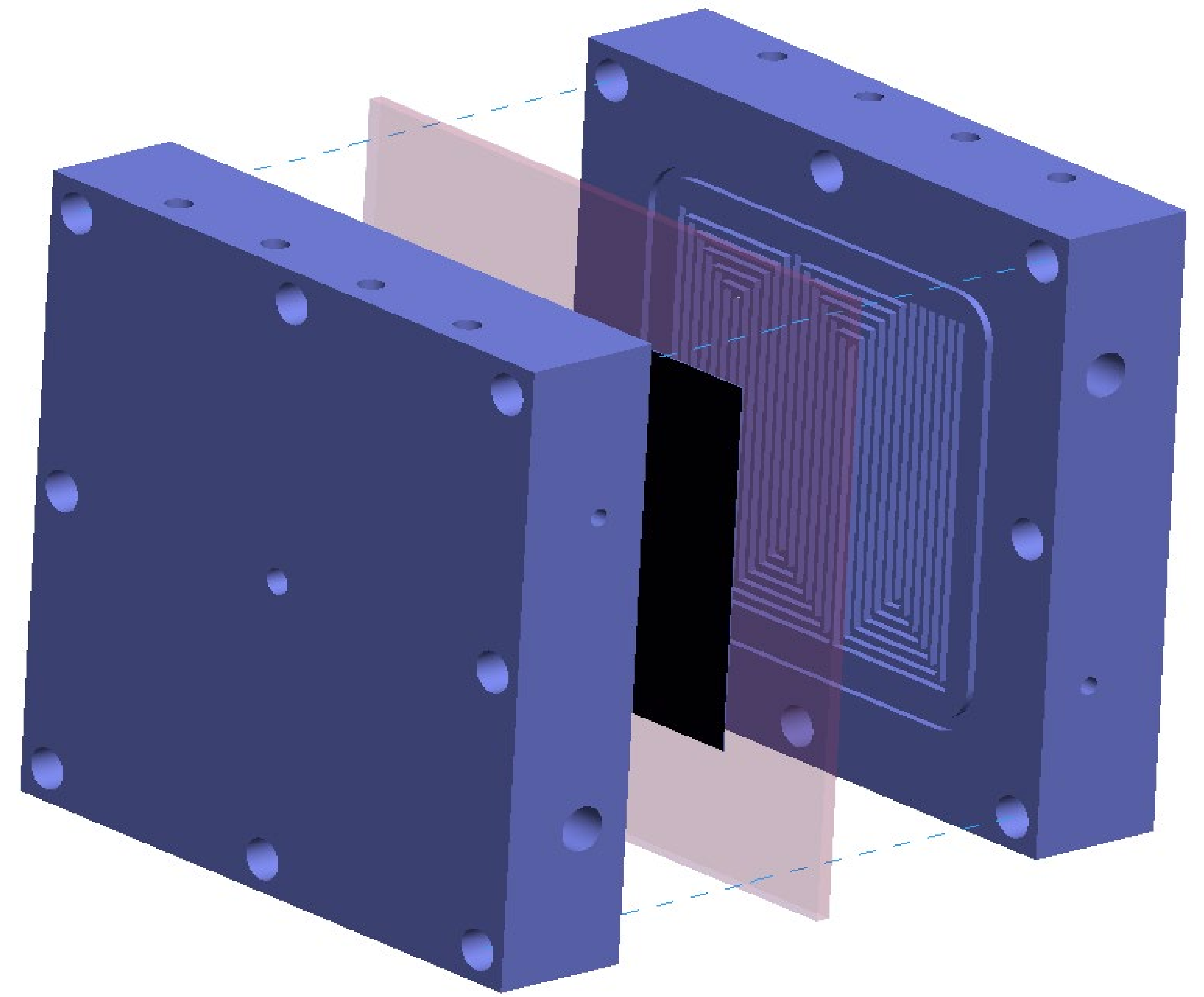
Water **will** be removed by evaporation into the air circulating over the cathode.

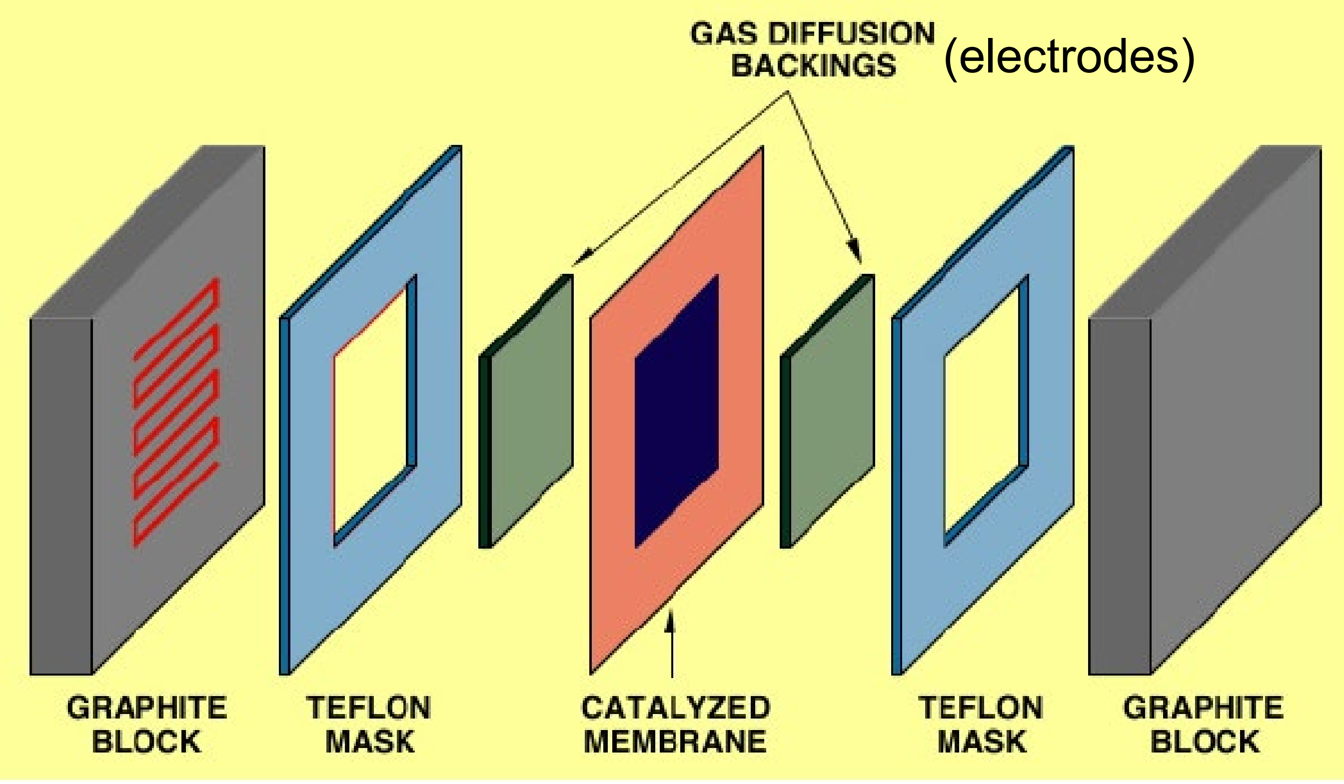
Water **may** be supplied by externally humidifying the hydrogen supply

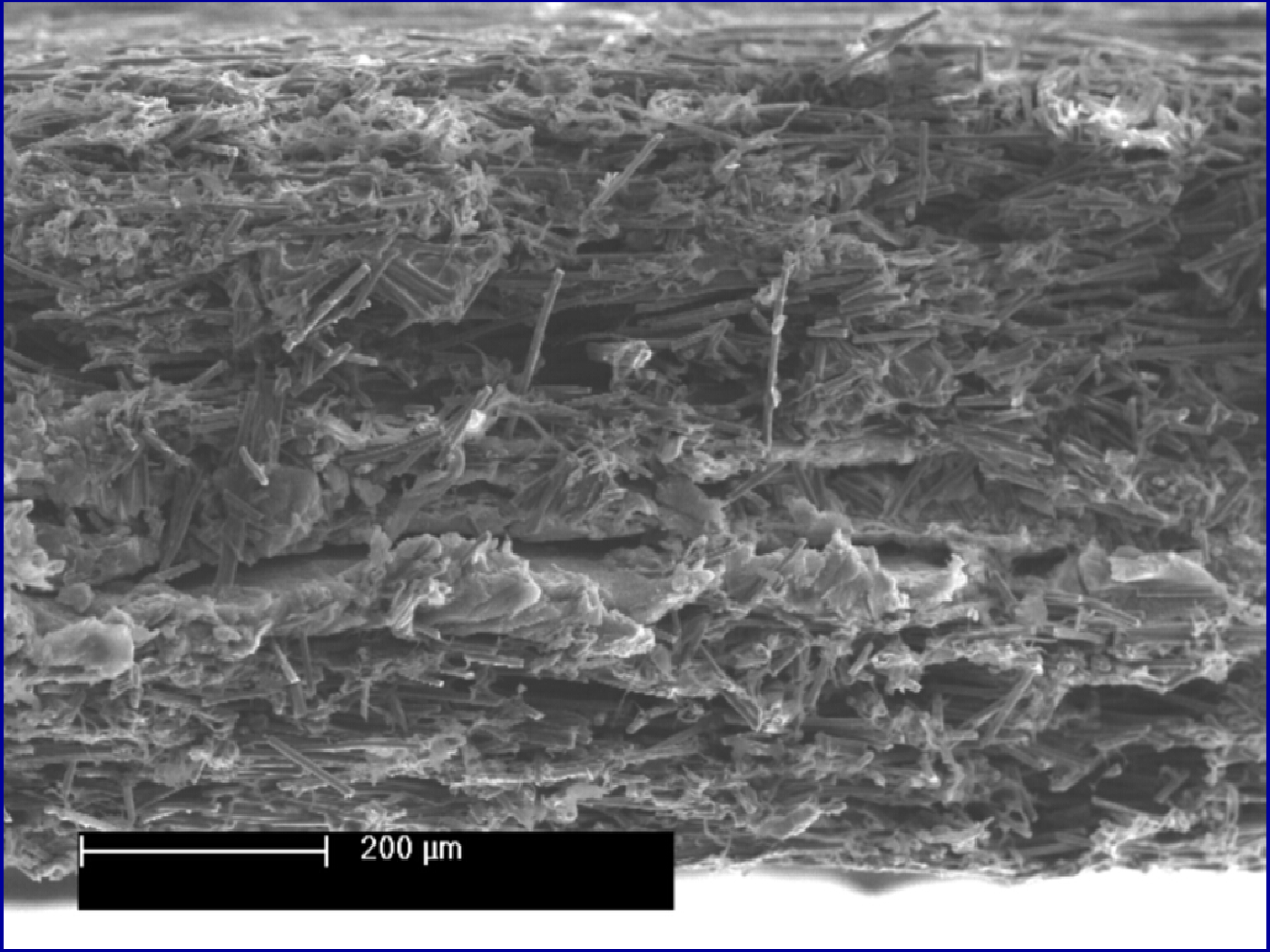
Water **may** be supplied by externally humidifying the air supply

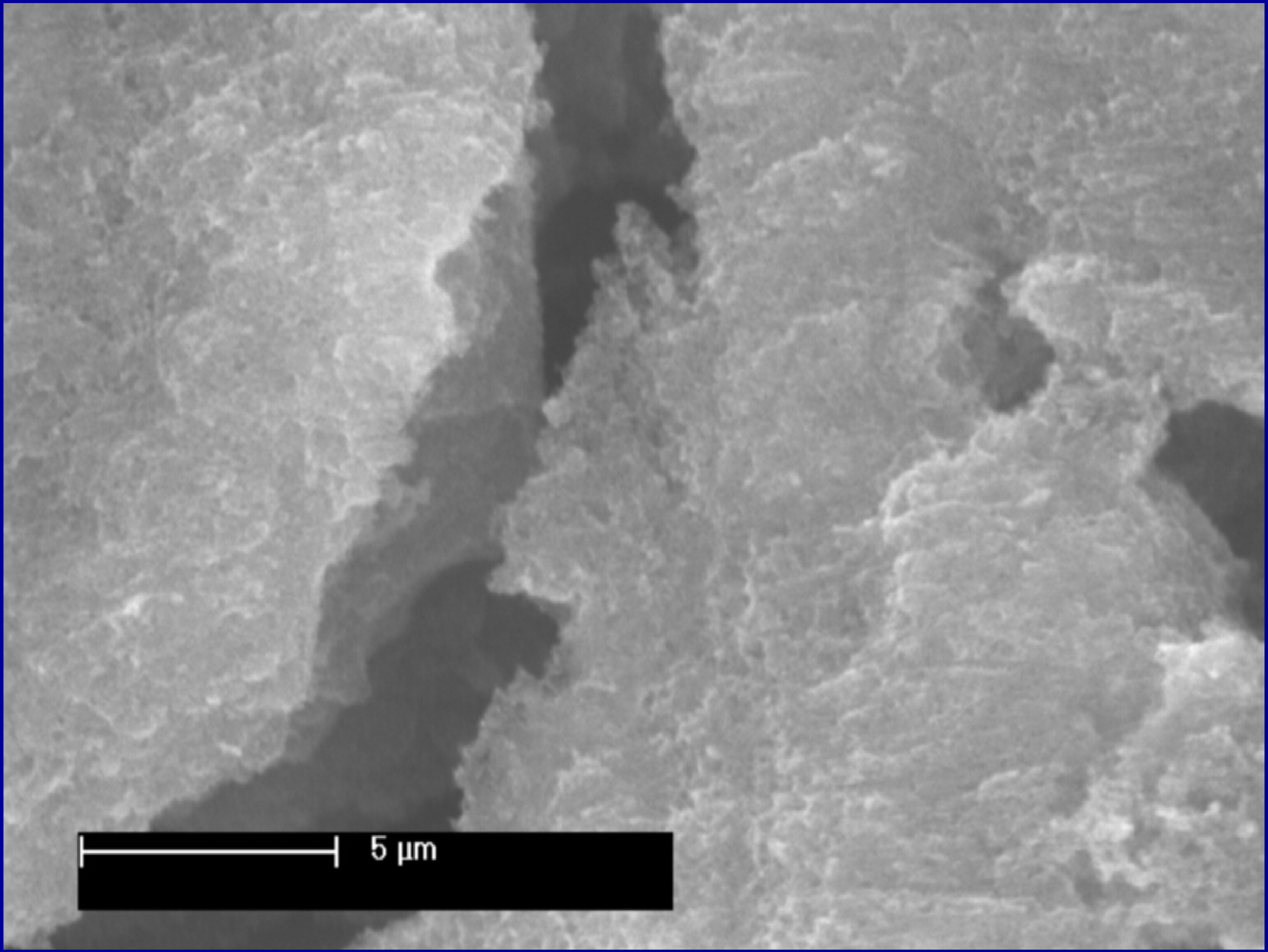


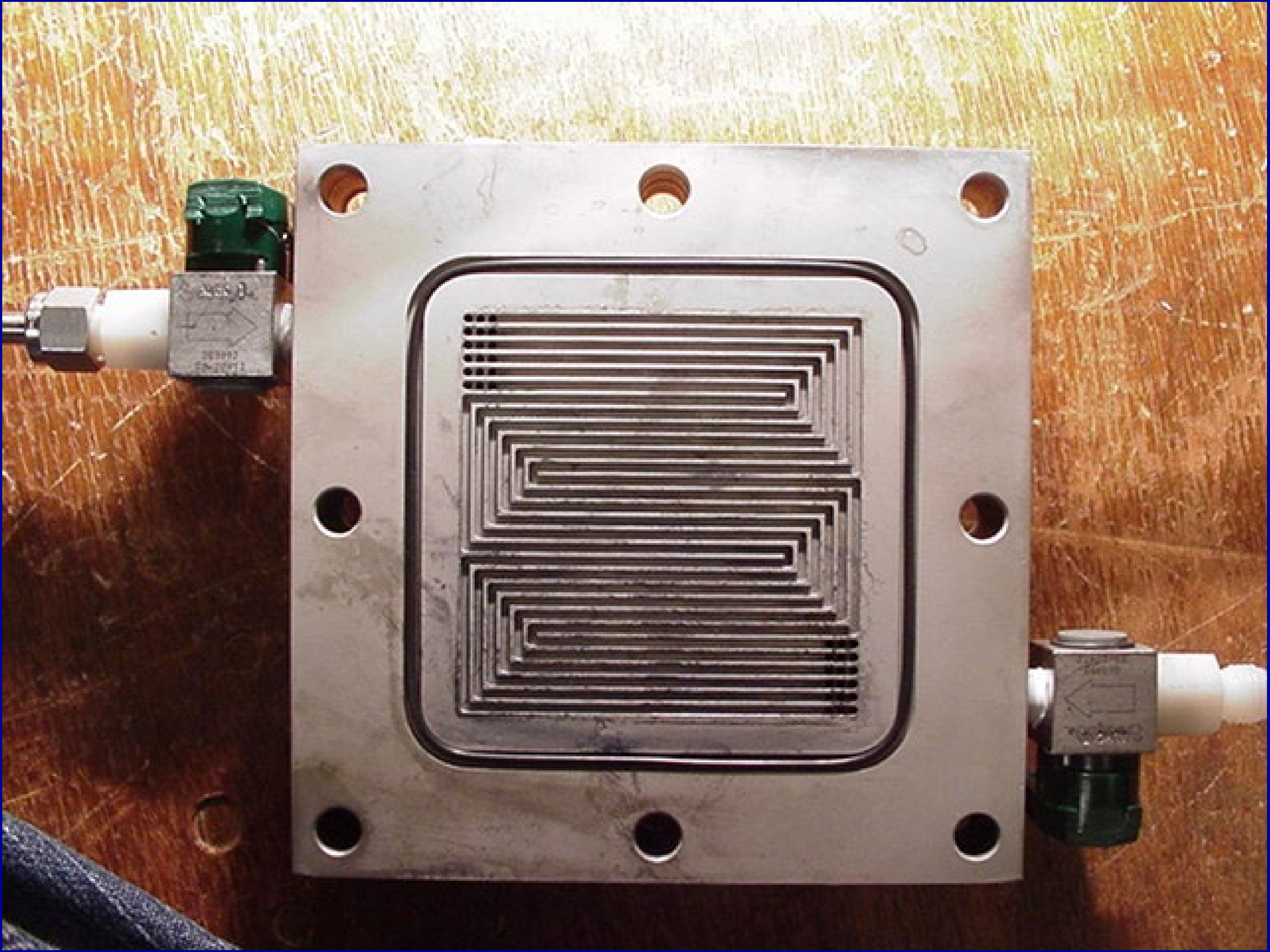
- Teflon Backbone (Hydrophobic)
- Side Chain (Hydrophilic)
- Sulfonic Group (weak, dilute acid)
- Solid Polymer Electrolyte

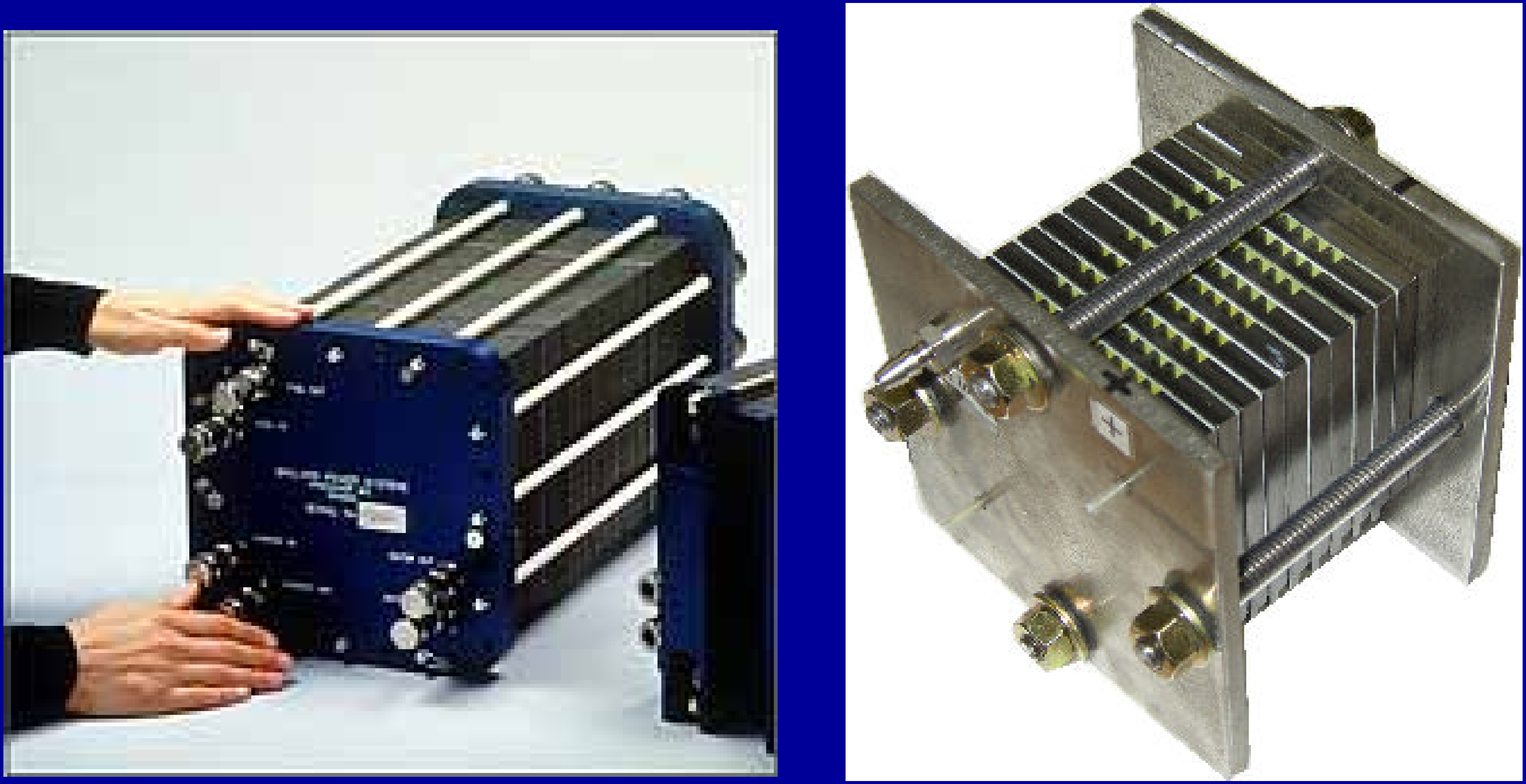



GAS DIFFUSION BACKINGS
(electrodes)
GRAPHITE BLOCK
TEFLON MASK
CATALYZED MEMBRANE
TEFLON MASK
GRAPHITE BLOCK


200 µm


5 µm





*Ballard Corporation

BOP

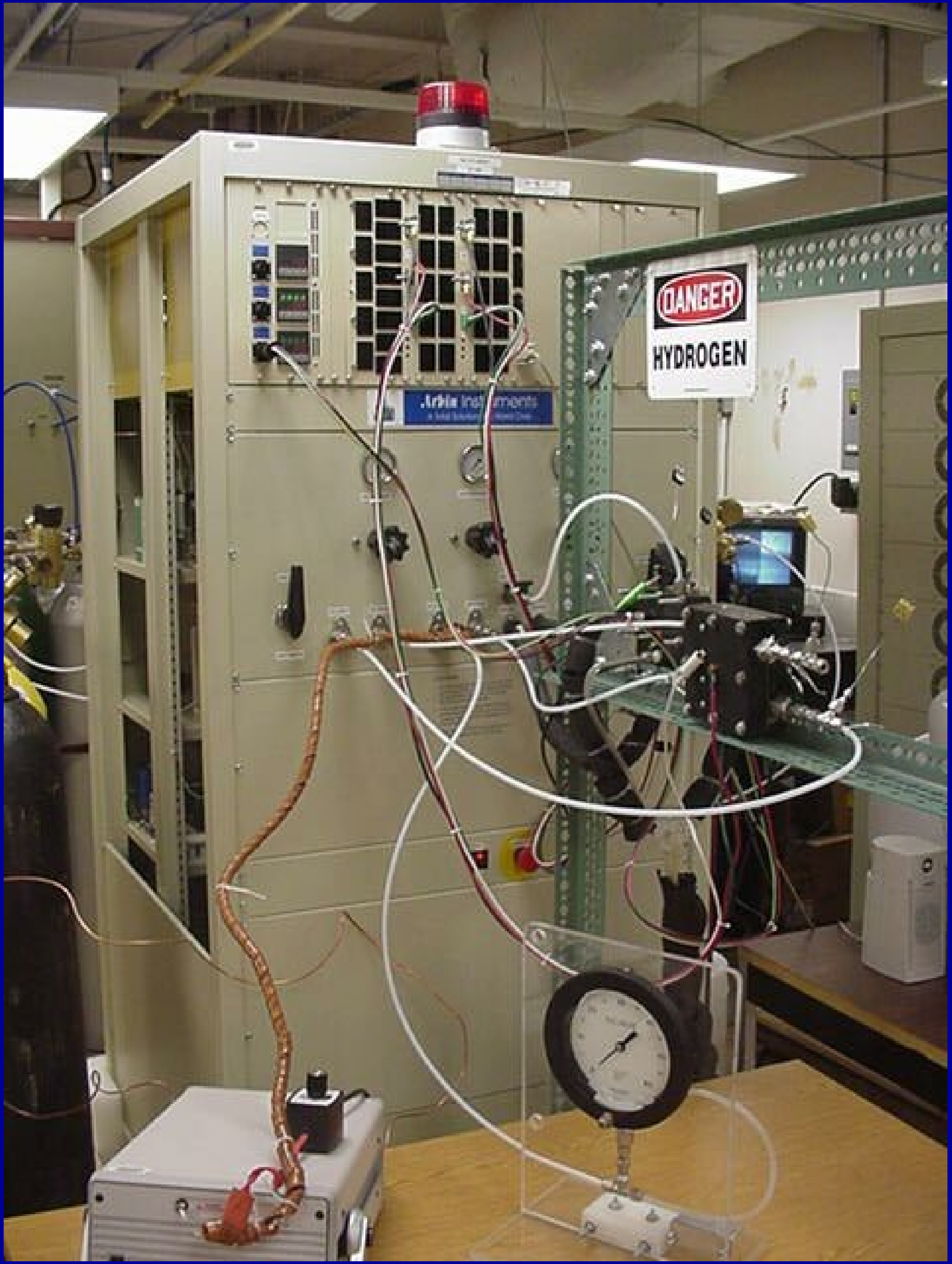
- In addition to the stack, practical fuel cell systems require several other sub-systems and components; the so-called balance of plant (BoP). Together with the stack, the BoP forms the fuel cell system. The precise arrangement of the BoP depends heavily on the fuel cell type, the fuel choice, and the application. In addition, specific operating conditions and requirements of individual cell and stack designs determine the characteristics of the BoP. Still, most fuel cell systems contain:

BOP

- Fuel preparation. Except when pure fuels (such as pure hydrogen) are used, some fuel preparation is required, usually involving the removal of impurities and thermal conditioning. In addition, many fuel cells that use fuels other than pure hydrogen require some fuel processing, such as reforming, in which the fuel is reacted with some oxidant (usually steam or air) to form a hydrogen-rich anode feed mixture.
- Air supply. In most practical fuel cell systems, this includes air compressors or blowers as well as air filters.
- Thermal management. All fuel cell systems require careful management of the fuel cell stack temperature.
- Water management. Water is needed in some parts of the fuel cell, while overall water is a reaction product. To avoid having to feed water in addition to fuel, and to ensure smooth operation, water management systems are required in most fuel cell systems.
- Electric power conditioning equipment. Since fuel cell stacks provide a variable DC voltage output that is typically not directly usable for the load, electric power conditioning is typically required.

- While perhaps not the focus of most development effort, the BoP represents a significant fraction of the weight, volume, and cost of most fuel cell systems

Fuel Cell with BOP



Introduction
FUEL CELL MODELING

Fuel Cell Model

Dehydration
flooding

- Model→prediction
- Stoichiometric Number: reflects the rate at which a reactant is provided to a fuel cell relative to the rate at which it is consumed. E.g., lamda=2 means that twice as much reactant as needed is being provided to a fuel cell. Choosing an optimal lamda is a delicate task. A large number is wasteful, resulting in parasitic power consumption and/or lost fuel. Too small number will result in reactant depletion effects. Two numbers are needed: for H2, and O2.

Fuel Cell Model

- Concept “Gibbs Free Energy”: the chemical energy released in a reaction can be thought of as consisting 2 parts: an entropy-free part called Gibbs Free Energy and a part that must appear as heat. The Gibbs free energy part can be converted directly into electrical or mechanical work, and thus corresponds to the maximum possible, entropy-free, electrical (or mechanical) output from a chemical reaction. For fuel cell, the ideal maximum efficiency is 83%.
- For fuel cell reaction, the Gibbs free energy is 237.2 kJ per mol of H2, which is the maximum electrical output at STP.

Fundamentals

$$H_2 \rightarrow 2H^+ + 2e^-$$

$$2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O$$

$$V_{ideal} = \frac{-\Delta\bar{h}_f}{2F} \qquad \eta = \frac{V_c}{V_{ideal}}$$

$V_{ideal} = 1.48$ V per cell at STP

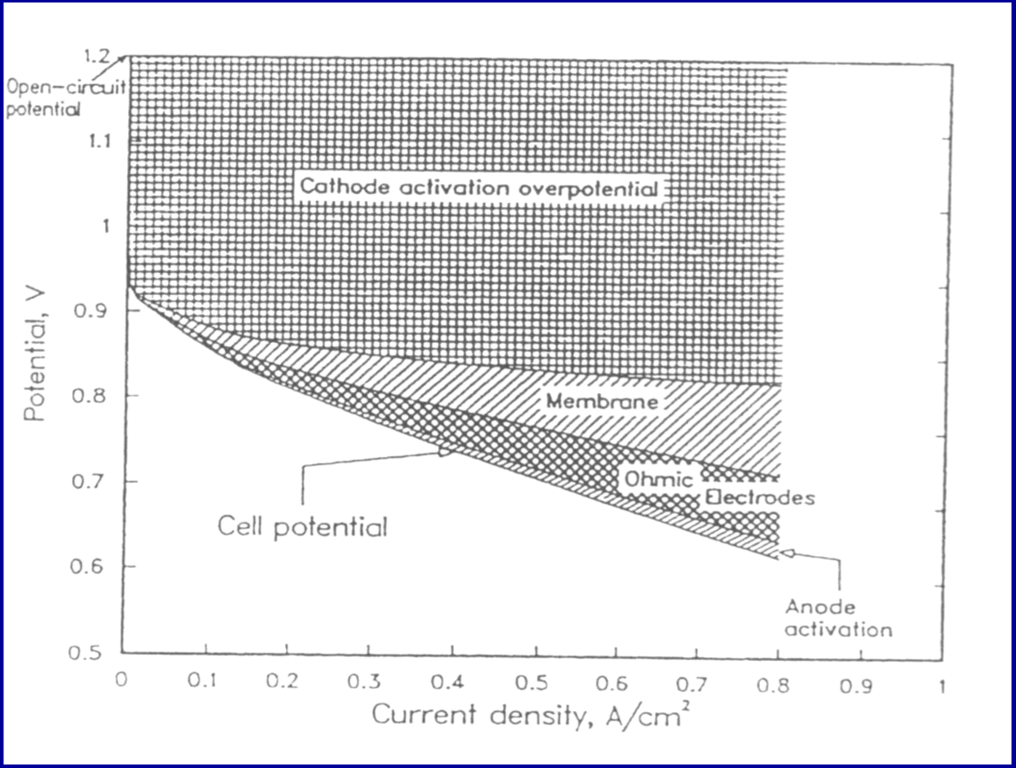
Electrochemical Reactions

$$H_2 \rightarrow 2H^+ + 2e^-$$

$$2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O$$ + HEAT

$$\boxed{H_2 + \frac{O_2}{2} \rightarrow H_2O}$$ **+ HEAT + electrical energy**

Cell potential vs. current density characteristic curve of a typical PEMFC

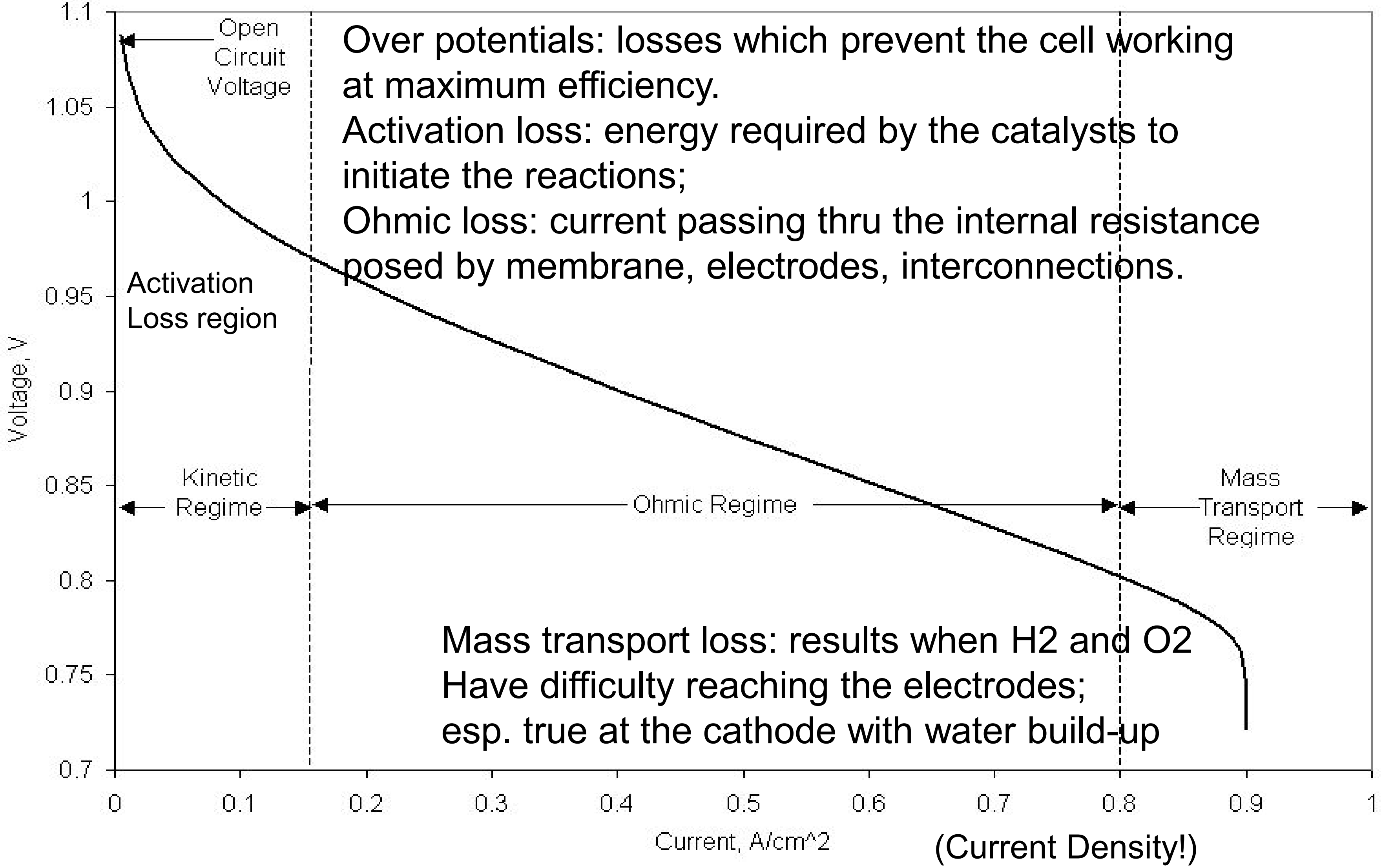


The reasons for a lower open circuit potential than the thermodynamic value for oxygen reduction on Pt:

★ Production of some peroxide
$O_2 + 2H^+ + 2e^- = H_2O_2$
$E^o_{25^oC} = +0.68V$ (Vs. NHE)

★ Formation of a range of possible platinum oxides at high potential
$Pt + H_2O = Pt\text{-}O + 2H^+ + 2e\text{-}$
$E^o_{25^oC} = +0.88V$ (Vs. NHE)

Fuel Cell Polarization



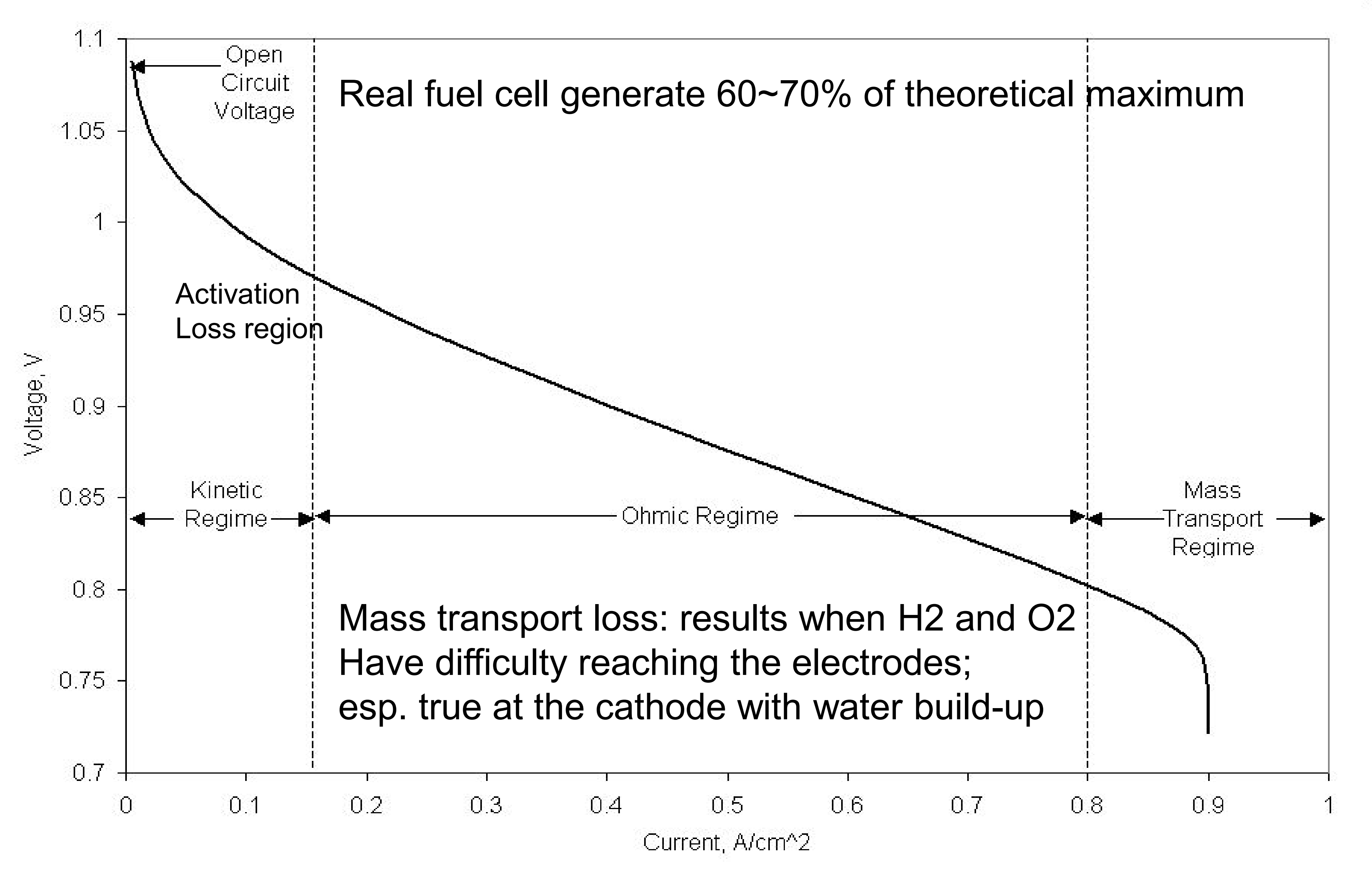
Over potentials: losses which prevent the cell working at maximum efficiency.
Activation loss: energy required by the catalysts to initiate the reactions;
Ohmic loss: current passing thru the internal resistance posed by membrane, electrodes, interconnections.

Activation Loss region

Mass transport loss: results when H2 and O2 Have difficulty reaching the electrodes;
esp. true at the cathode with water build-up

(Current Density!)

Fuel Cell Polarization



Real fuel cell generate 60~70% of theoretical maximum

Activation
Loss region

Mass transport loss: results when H2 and O2
Have difficulty reaching the electrodes;
esp. true at the cathode with water build-up

I-V curve linear equation

$$V = 0.85 - 0.25 J$$

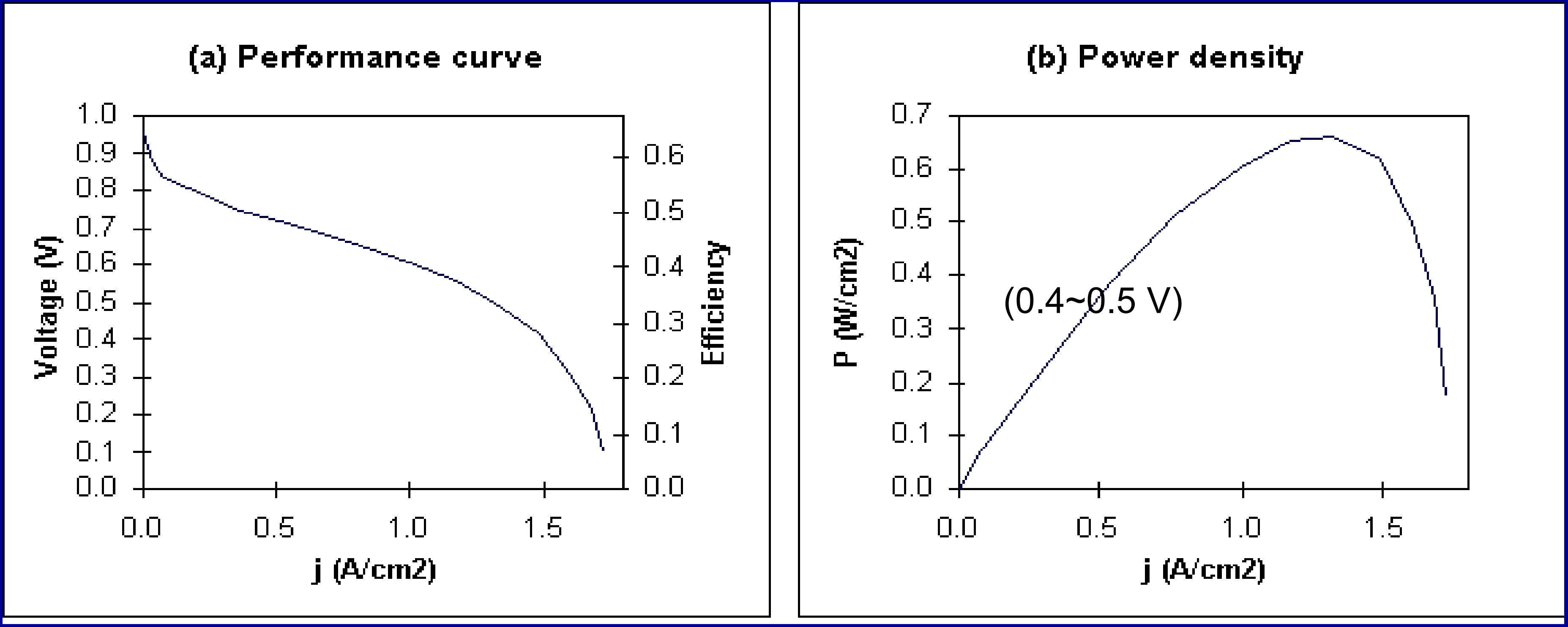
J: current density, equals I/A

Example: for a 1 kW fuel cell stack, which produces 48 V dc, each cell at 0.6 V, how many cells would be needed and what shaould be the memberance area of each cell?
Use the above approximate formula

Fuel Cell Polarization

- These losses are often referred to as polarization, overpotential or overvoltage, though only the ohmic losses actually behave as a resistance.
- Multiple phenomena contribute to irreversible losses in an actual fuel cell:
- Activation-related losses. These stem from the activation energy of the electrochemical reactions at the electrodes. These losses depend on the reactions at hand, the electro-catalyst material and microstructure, reactant activities (and hence utilization), and weakly on current density.
- Ohmic losses. Ohmic losses are caused by ionic resistance in the electrolyte and electrodes, electronic resistance in the electrodes, current collectors and interconnects, and contact resistances. Ohmic losses are proportional to the current density, depend on materials selection and stack geometry, and on temperature.
- Mass-transport-related losses. These are a result of finite mass transport limitations rates of the reactants and depend strongly on the current density, reactant activity, and electrode structure.

Power of Fuel Cells



Fuel Cell Ideal Open Circuit Voltage

- Nomenclature and physical constants:

q = charge on an electron = 1.602×10^{-19} coulombs

N =Avogadros number = 6.022×10^{23} molecules/mol

V = volume of 1 mole of ideal gas at STP

=22.4 liter/mol

n = rate of flow of H_2 into the fuel cell (mol/s)

I = current (A)

1A = 1Coulomb/s

V_R = ideal (reversible) voltage across the two electrodes (volts)

P = electrical power delivered (W)

1 Faraday constant = 1 mol of e– = 96,500 C

Fuel Cell Ideal Open Circuit Voltage

- For each molecule of H2 into an ideal fuel cell, two electrons will pass thru the electrical load. So the current flowing thru the load will be:

$$I(A) = n\left(\frac{mol}{s}\right)\cdot 6.022\times 10^{23}\left(\frac{moleculesH_2}{mol}\right)\cdot\frac{2electrons}{moleculeH_2}\cdot 1.602\cdot 10^{-19}\left(\frac{coloumbs}{electron}\right)$$

$$I(A) = 192{,}945n$$

Fuel Cell Ideal Open Circuit Voltage

- From the Gibbs free energy of fuel cell reaction, the ideal power in watts delivered to the load will be 237.2 kJ per mol of H2 times the rate of H2 use:

$$P(W) = 237.2\left(\frac{kJ}{mol}\right) \times n\left(\frac{mol}{s}\right) \times 1000\left(\frac{J}{kJ}\right) \cdot \frac{1W}{J/s}$$

$$P(W) = 237200n$$

- So the reversible voltage produced across the terminals of the ideal fuel cell will be:

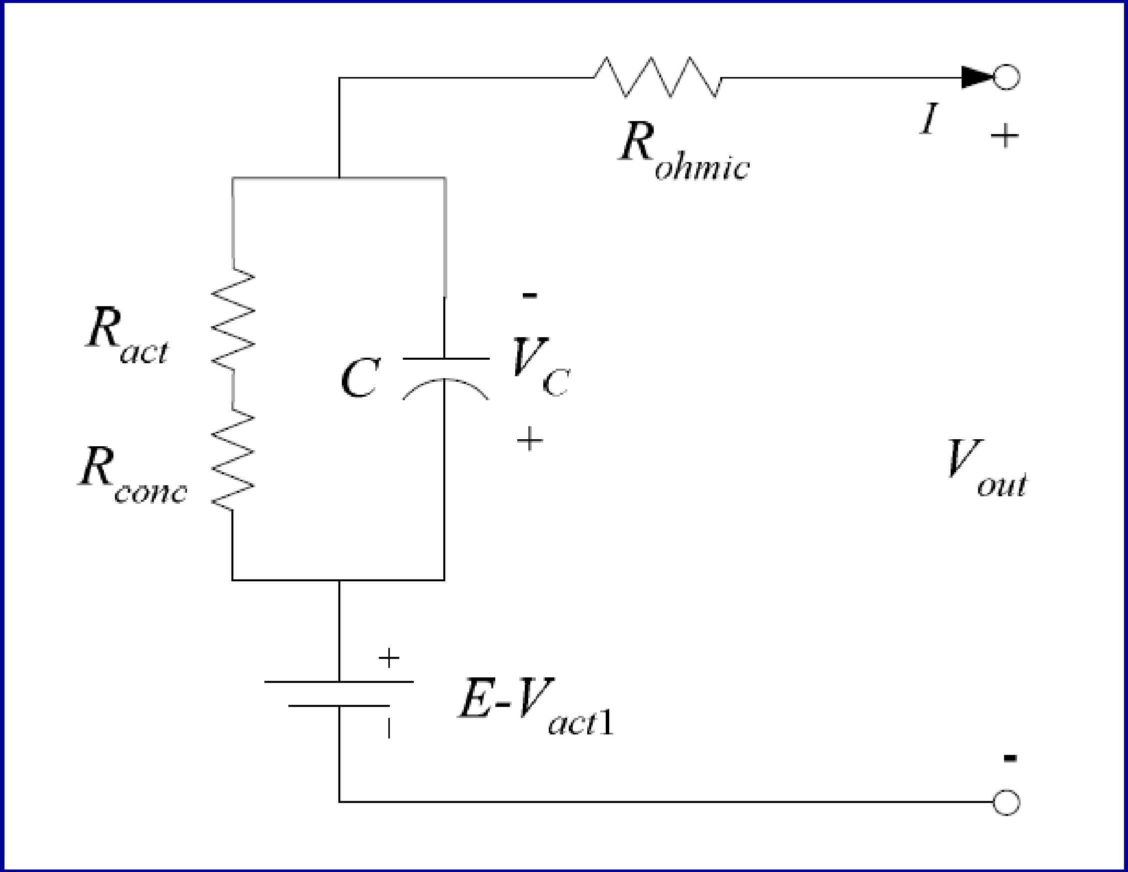
$$V_R = \frac{P(W)}{I(A)} = \frac{237200n}{192945n} = 1.229V$$

- Note that this voltage does not depend on the input rate of H2. But it depends on the temperature and partial pressure of the reactants since realistic operating condition is not STP.

Charge Double Layer

- The charge layer on both electrode-electrolyte interfaces (or close to the interface) is the storage of electrical charges and energy; so it behaves like an electrical capacitor.
- If the current changes, delay affects the activation and concentration potentials. (first-order)
- Time delay: t = CRa, C is the equivalent capacitance (few farads); Ra is the equivalent variable resistance to the activation and concentration losses.

Equivalent Circuit Model



$$P_{fc} = V_{cell} i_{fc}$$

Equivalent Circuit Model

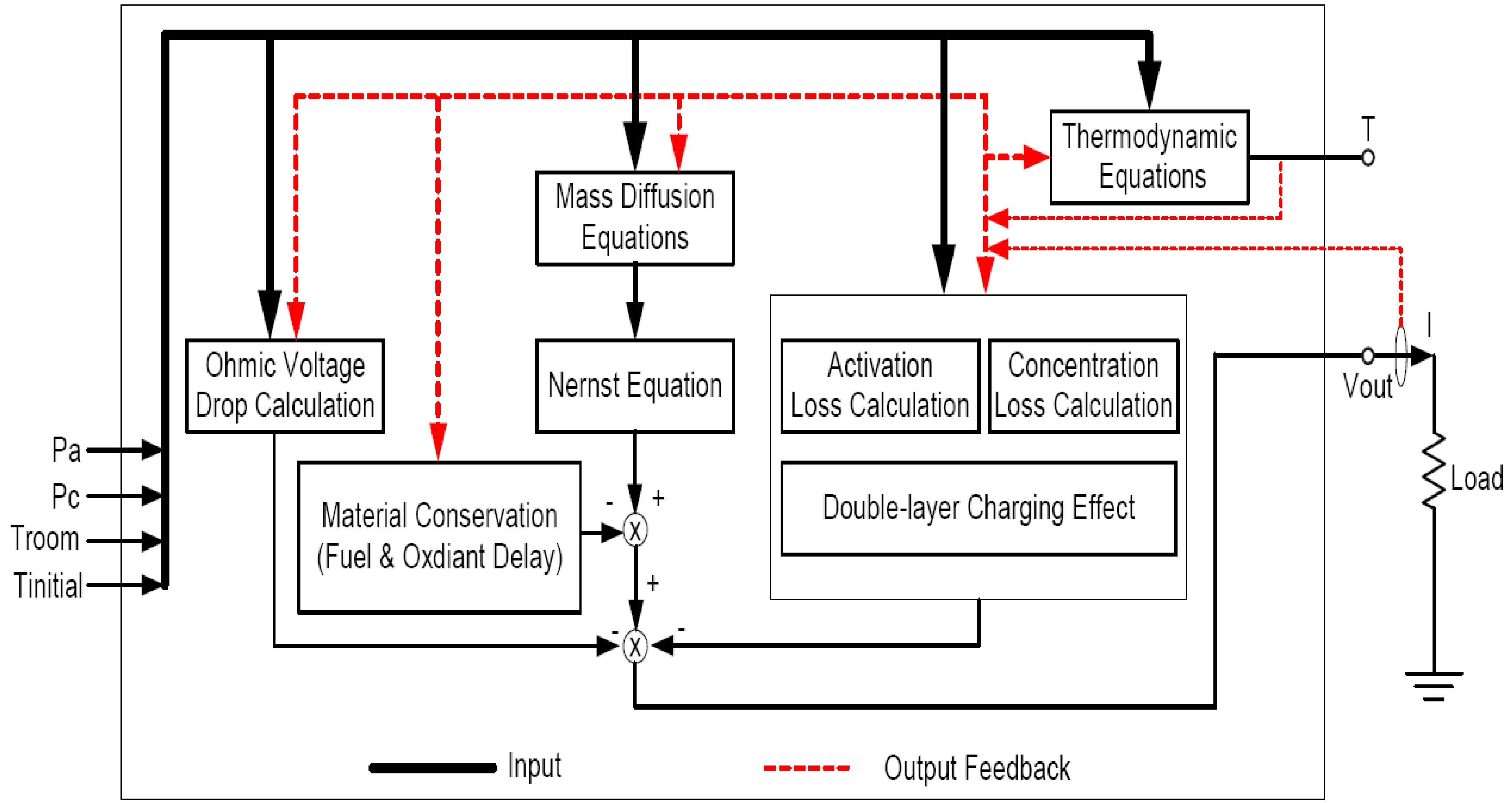
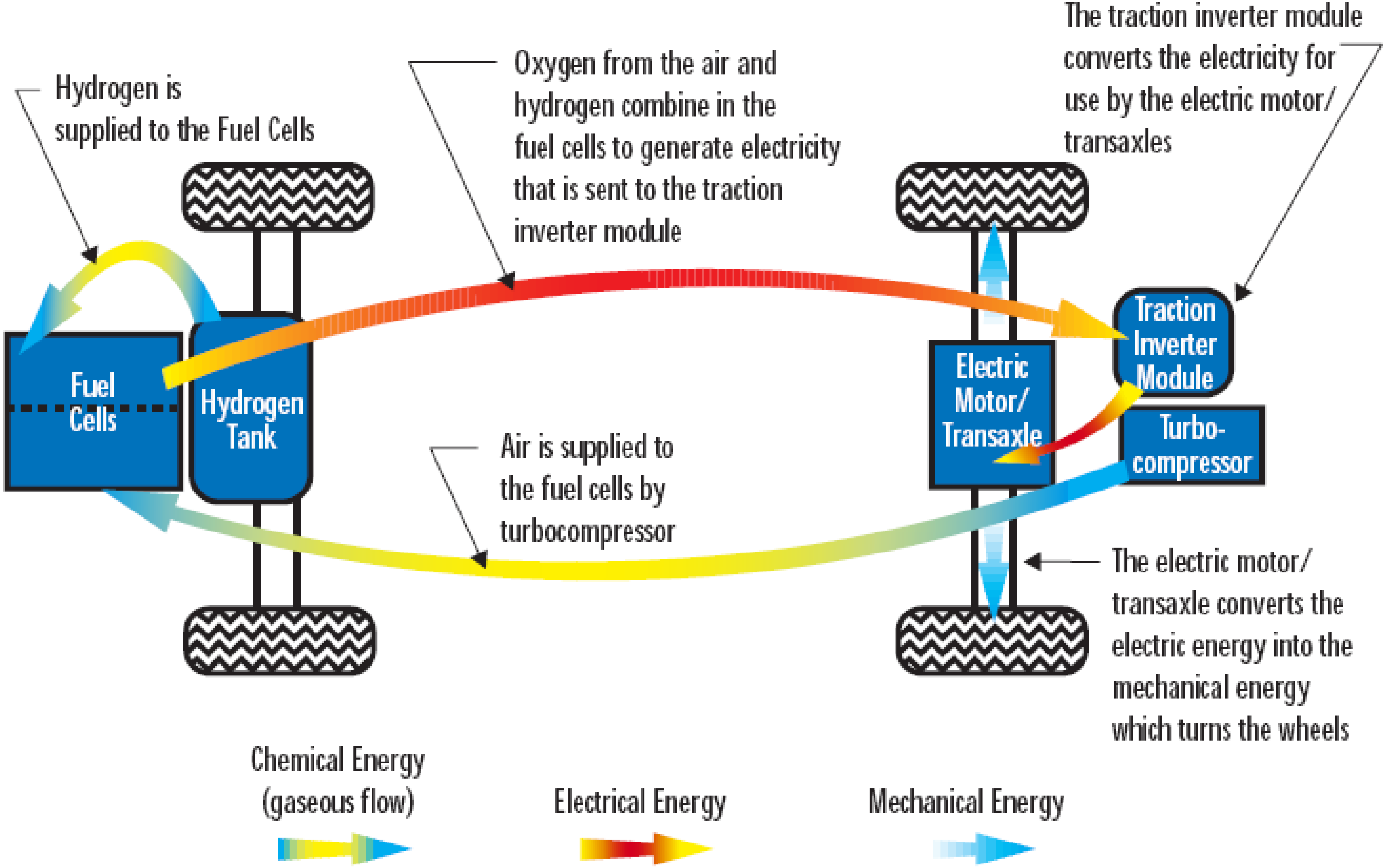


Diagram of building a dynamic model of PEMFC in SIMULINK

Introduction
FUEL CELL APPLICATION

Hydrogen Fuel Cell Car



Hydrogen is supplied to the Fuel Cells

Oxygen from the air and hydrogen combine in the fuel cells to generate electricity that is sent to the traction inverter module

The traction inverter module converts the electricity for use by the electric motor/ transaxles

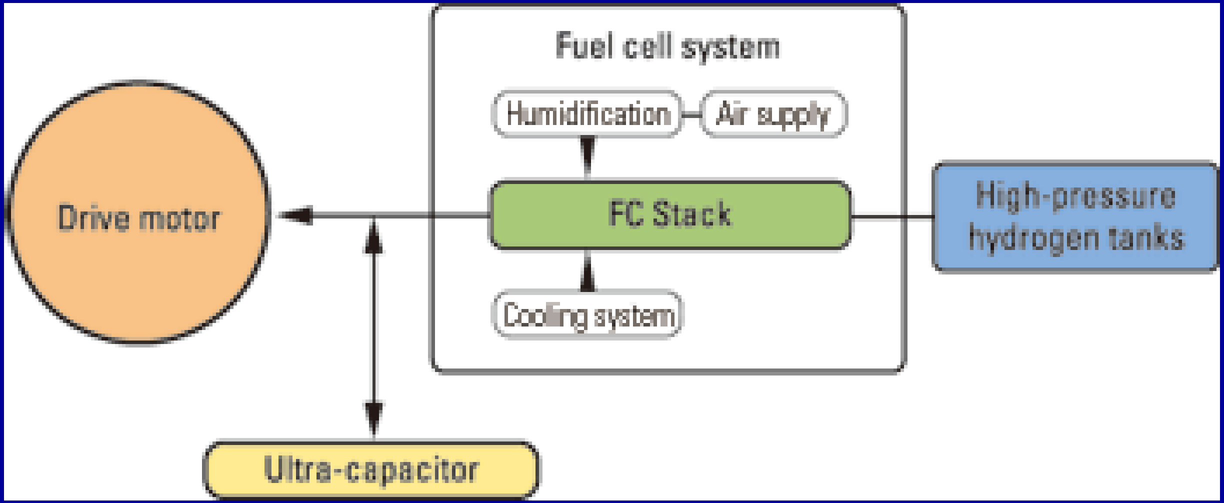
Air is supplied to the fuel cells by turbocompressor

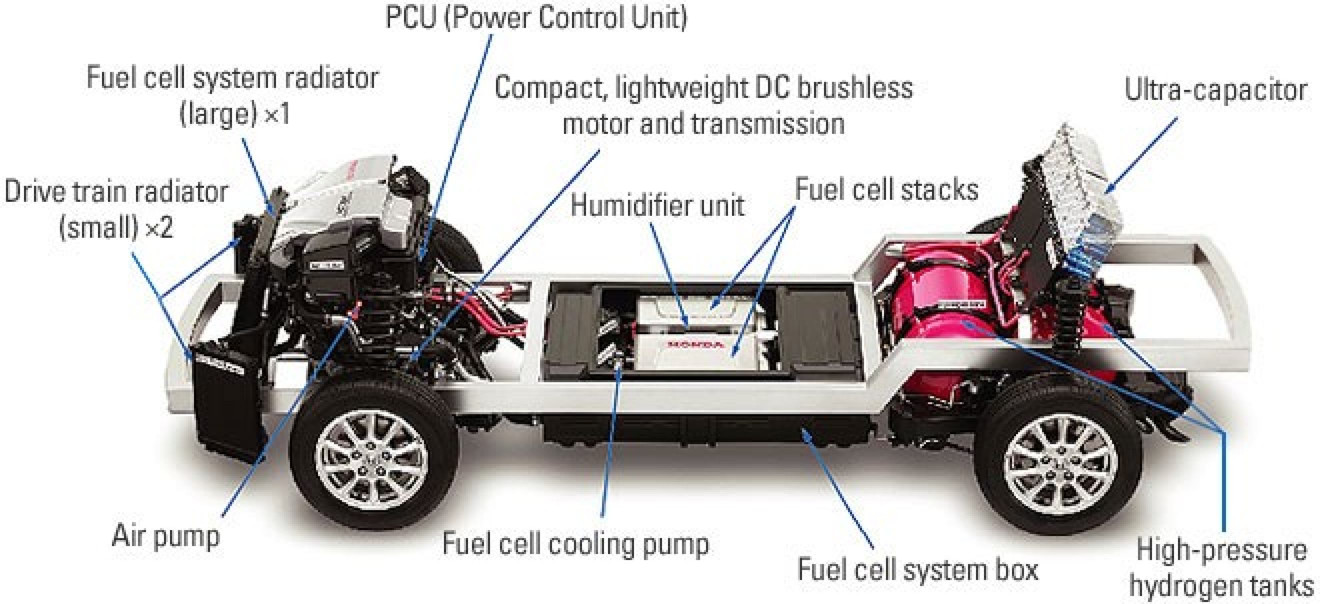
The electric motor/ transaxle converts the electric energy into the mechanical energy which turns the wheels

*Green Power, Los Alamos National Lab, LA-UR-99-3231

- FCV
- Entire Drive System Contained in “Skateboard”
- Interchangeable, Bolt on Body

- Single Center Electrical Connection
- Drive By Wire (Steering, Accelerator, Braking, etc.)





* Honda Motor Company

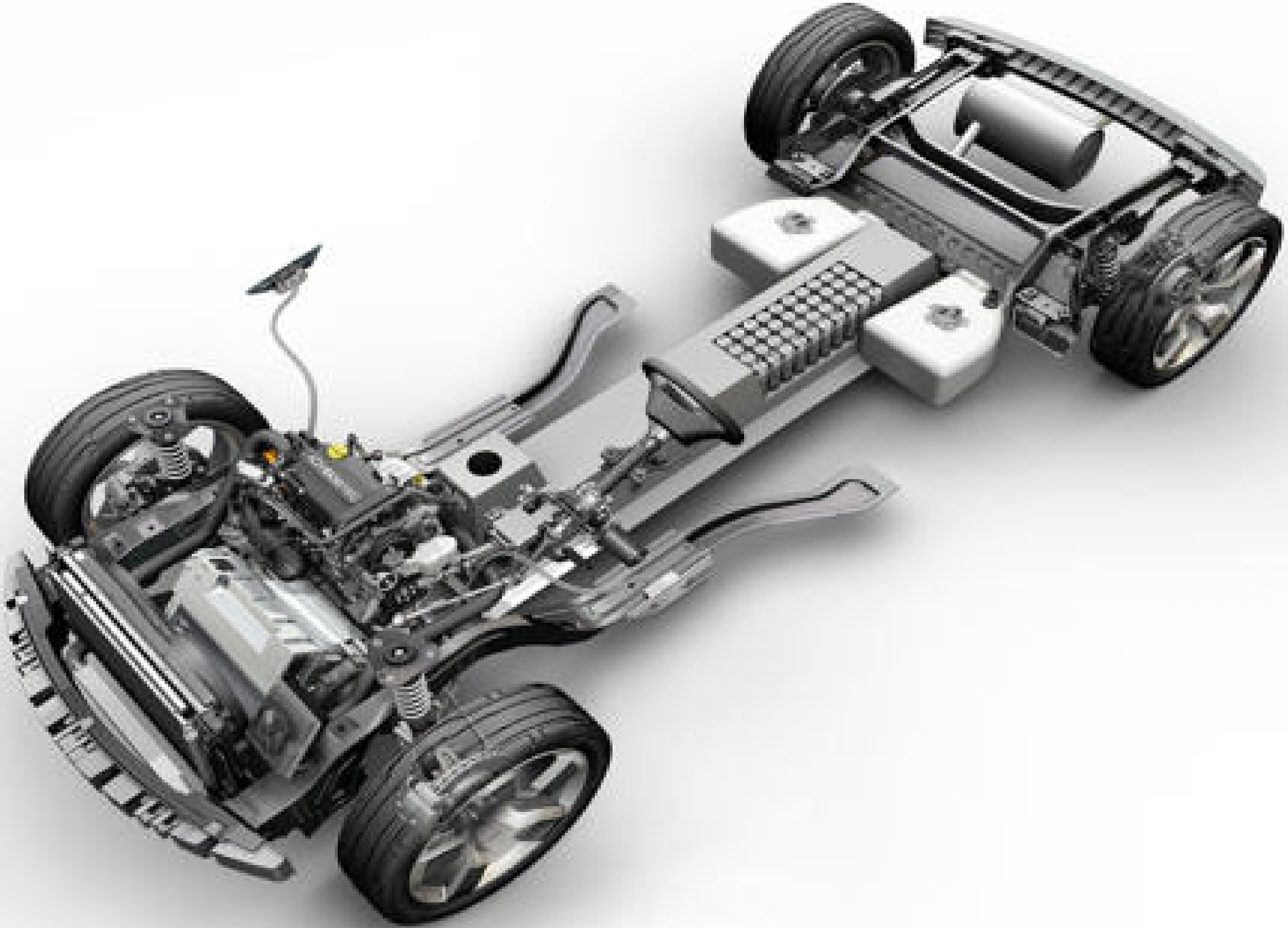

LIGHTNING BLUE
PSU ELECTRIC FIERO

Sequel, a fuel cell-powered vehicle from General Motors

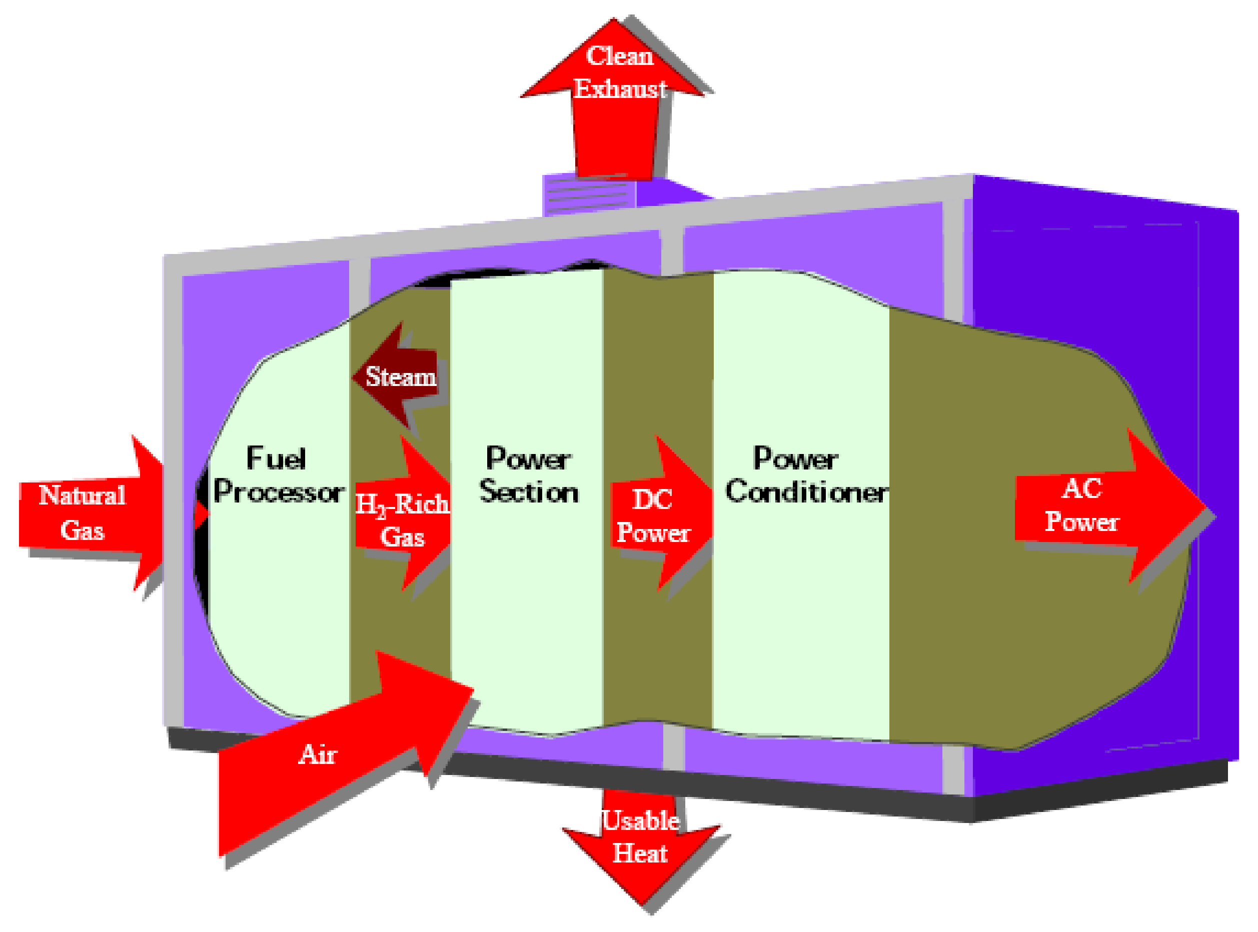
Ford Edge hydrogen-electric plug-in hybrid concept

The Boeing Fuel Cell Demonstrator powered by a hydrogen fuel cell

Hydrogen Bicycle



Fuel Cell Power Plant Major Processes



*Ocean County College, Toms River, NJ

Major issues in PEFC

- High cost of polymer membrane electrolyte
- Operation temperature limit of present polymer membrane electrolyte
- Reduce the loading of precious metal catalysts, ie. Pt, Ru
- Electro-osmotic drag of water and critical humidification level to maintain the conductivity
- Methanol permeation of the membrane
- Low CO tolerance of present catalysts

Challenges

- Cold Start
- Hydrogen Storage
  - High Pressure Composite Tanks
  - Cryogenic Storage
  - On-board Hydrocarbon Reforming?

- Carbon Monoxide Poisoning (when H2 is reformed from hydrocarbon fuels such as methanol)

Challenges

- Durability (up to 5,000 hrs and 40,000 hrs?)
- Clean H_2 Production
- Cost per kW (not just Pt)
- Size
- Weight
- End of Cycle Impact?
- Better than Hybrid Technology?
- Better than EV Technology?

Challenges

- Low power density compared to batteries
- Susceptible to high and widely variable currents
- Slow responsive action to step loads due to the FC's fuel delivery and regulatory system.

Challenges

- Current and fuel responsive problems can be remedied with a hybrid FC-Battery/Ultracapacitor system.

- FC > DC-DC Converter > Storage Device > Load

An experiment was conducted in order to see the advantages of a hybrid system over a stand-alone FC and converter.

Test included the following materials:

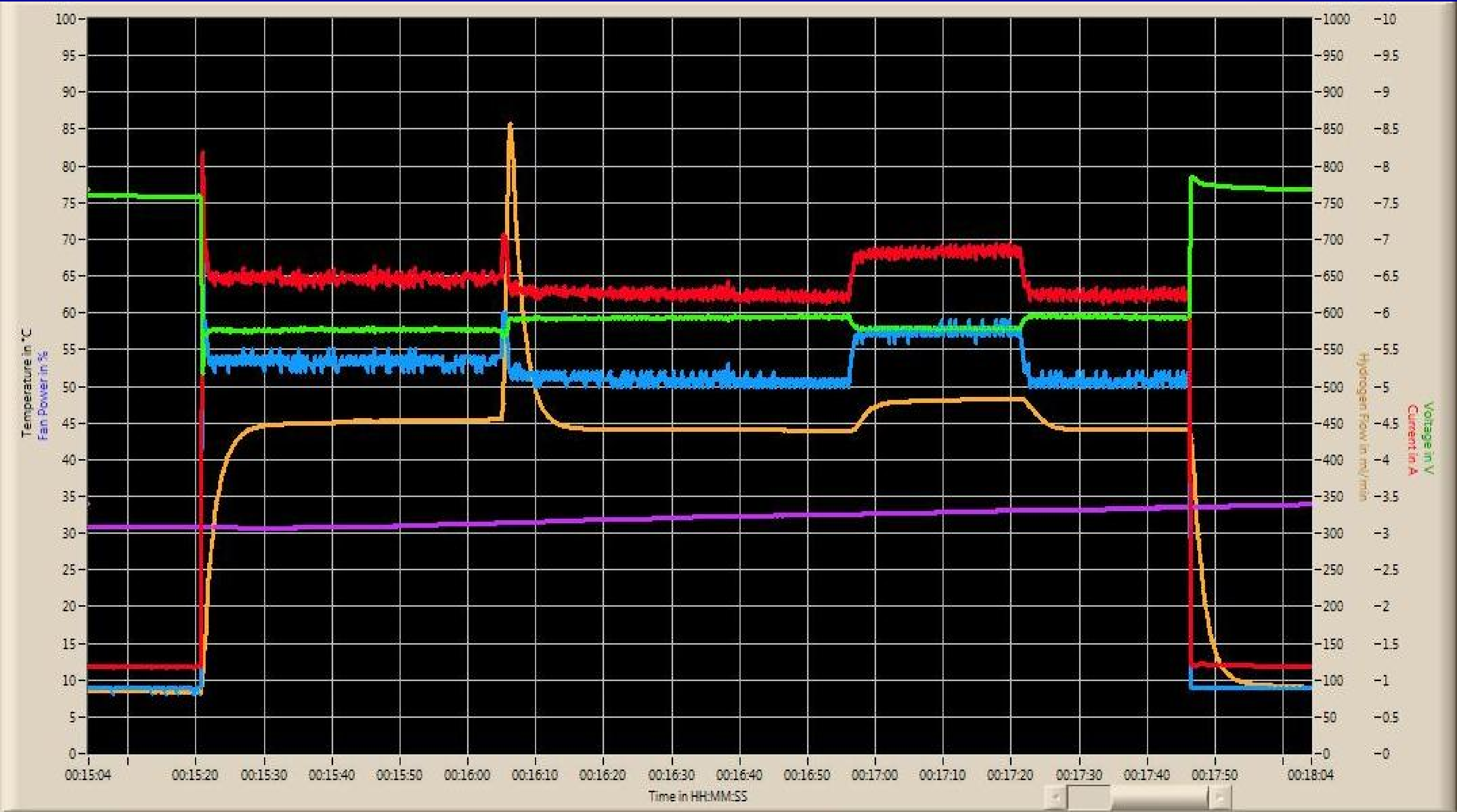
-50W PEMFC module by Hampden

- Passive 12V dc-dc boost converter module

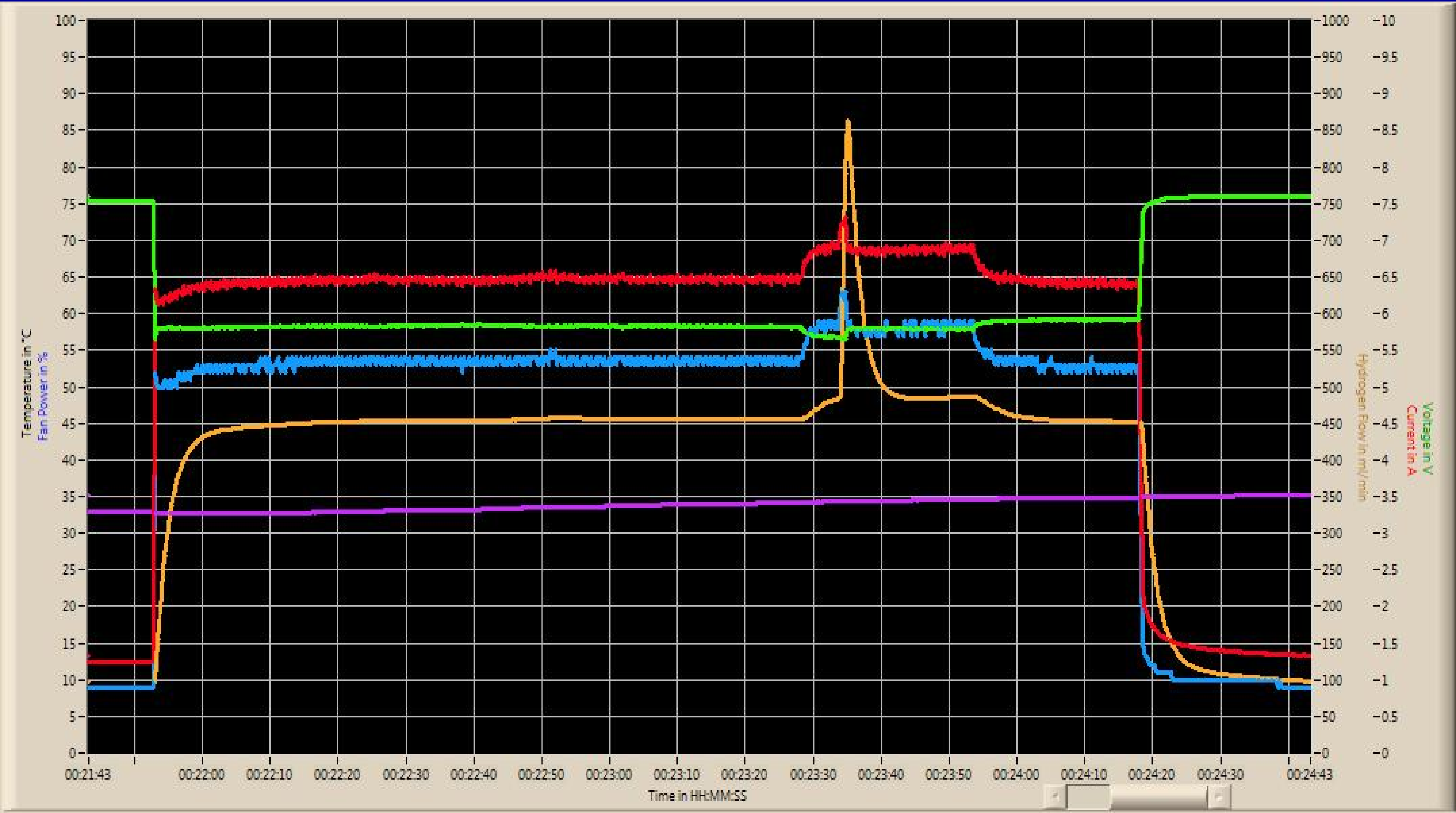
- 12V lead acid battery (the type found in electric scooters)

- Programmable variable speed DC motor system as the load

Example fuel cell system load characteristics without battery (use of passive 12V boost converter)

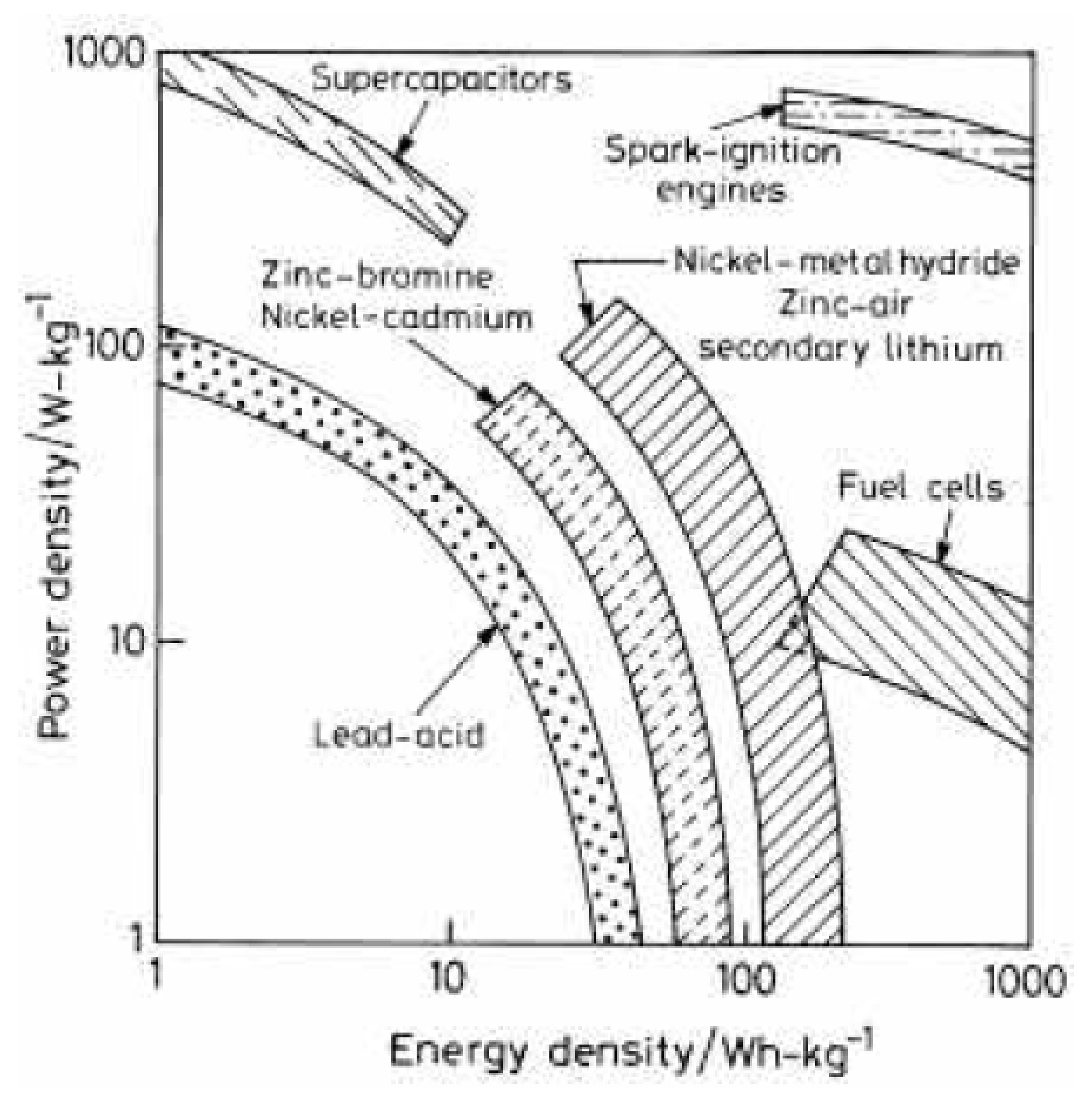


Example fuel cell system load characteristics with battery (use of passive 12V boost converter)

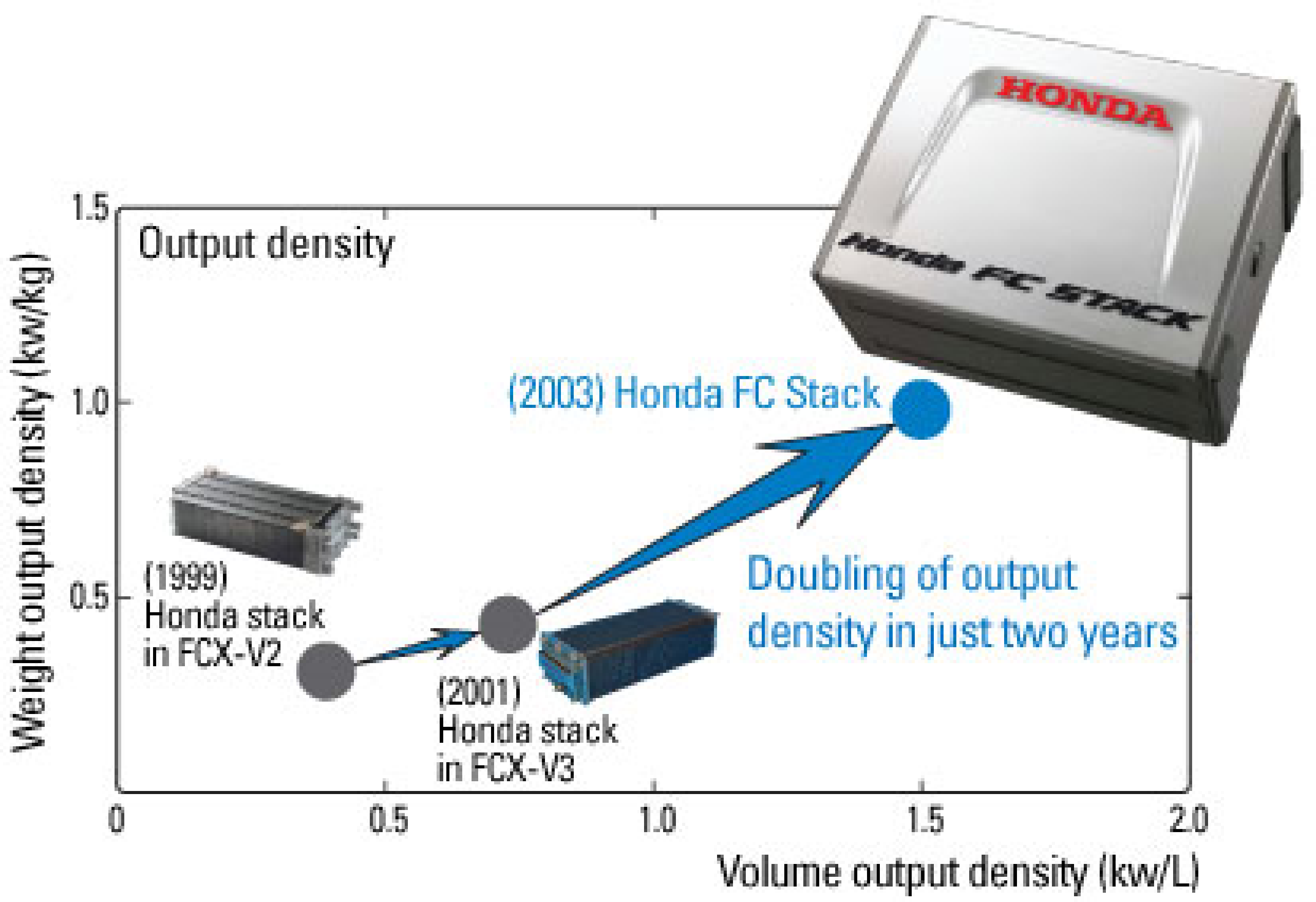


Challenges

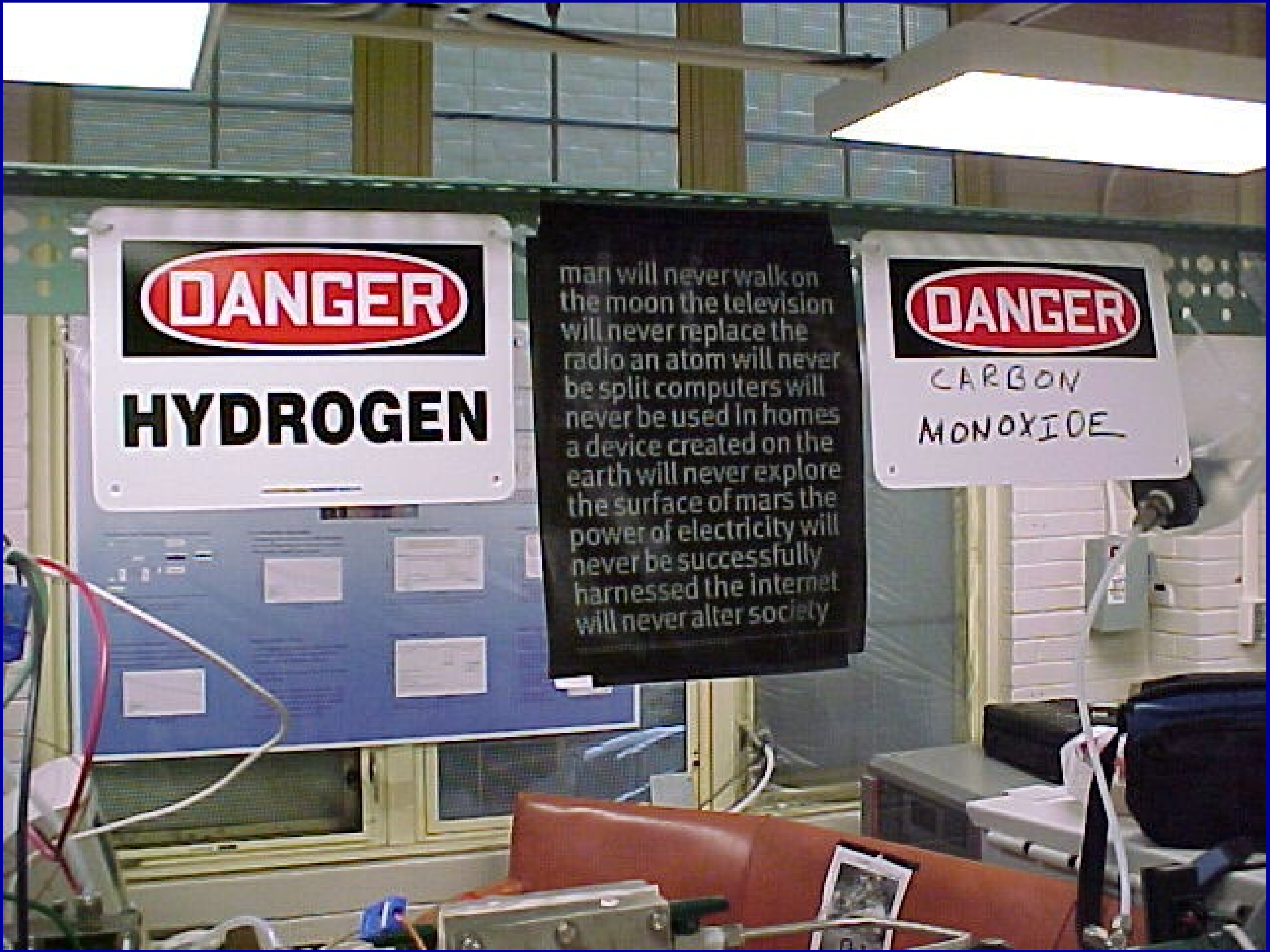
- A.D. Little study projects high volume production cost of \$14,700 or \$294/kW (60% Stack, 29% Processor, 11% BOP, Assembly, and Indirect) for fuel cell system
- Platinum cost alone is \$63/kW (21% of total \$)
- ICE engine cost?
- Fuel Cell Vehicle: cell, auxiliary equipment, H_2 storage, power inverters, and electric motors



* CURRENT SCIENCE, VOL. 77, NO. 9, 10 NOVEMBER 1999

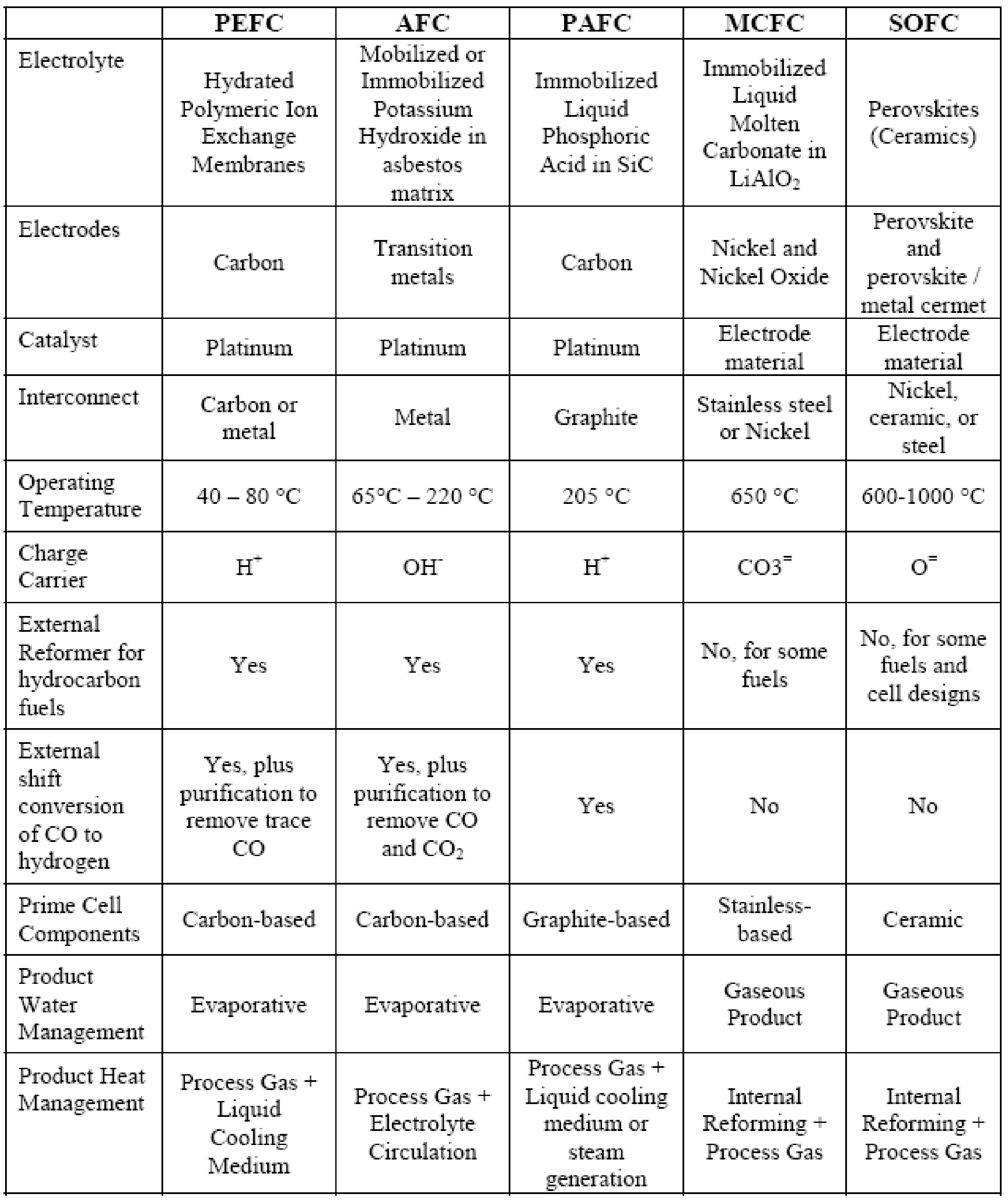


* Honda Motor Company


DANGER
HYDROGEN
man will never walk on the moon the television will never replace the radio an atom will never be split computers will never be used in homes a device created on the earth will never explore the surface of mars the power of electricity will never be successfully harnessed the internet will never alter society
DANGER
CARBON MONOXIDE

Various Types of Fuel Cells

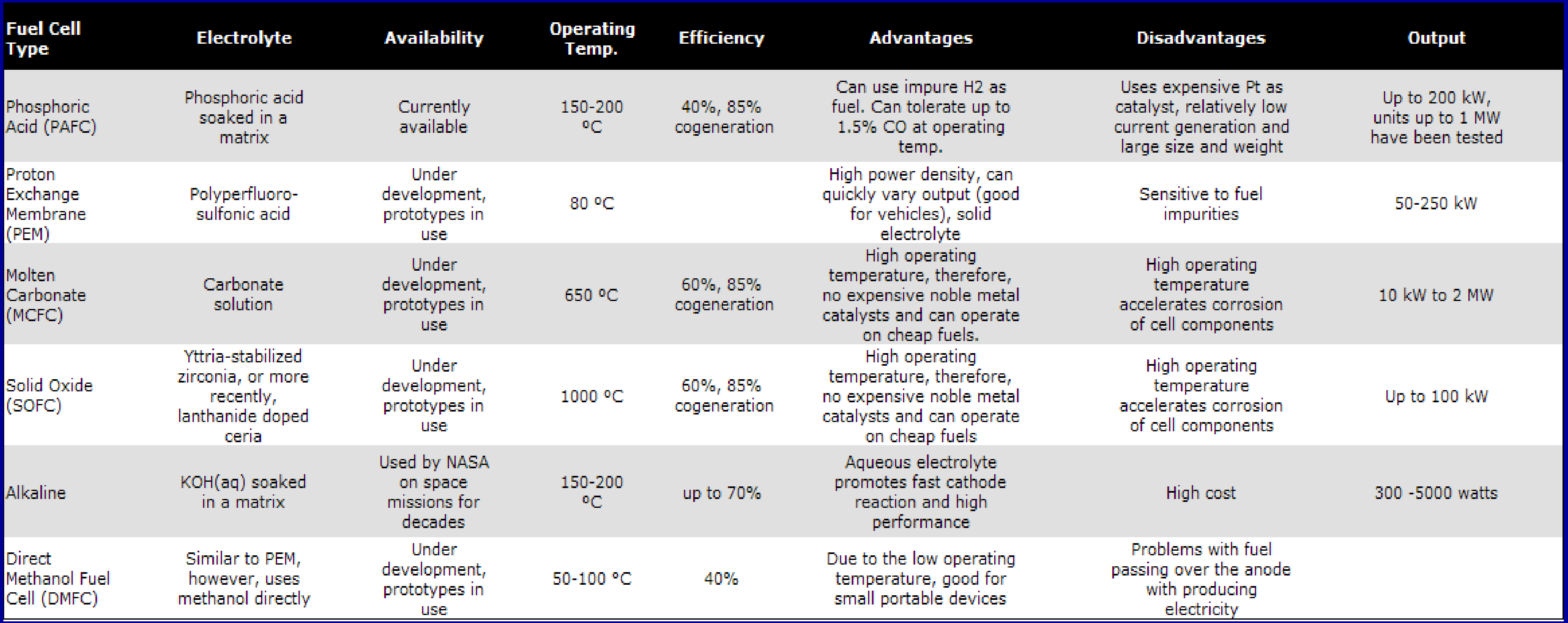
- PEMFC (Polymer Electrolyte FC)
- AFC (Alkaline FC)
- PAFC (Phosphoric Acid FC)
- MCFC (Molten Carbonate FC)
- SOFC (Solid Oxide FC)



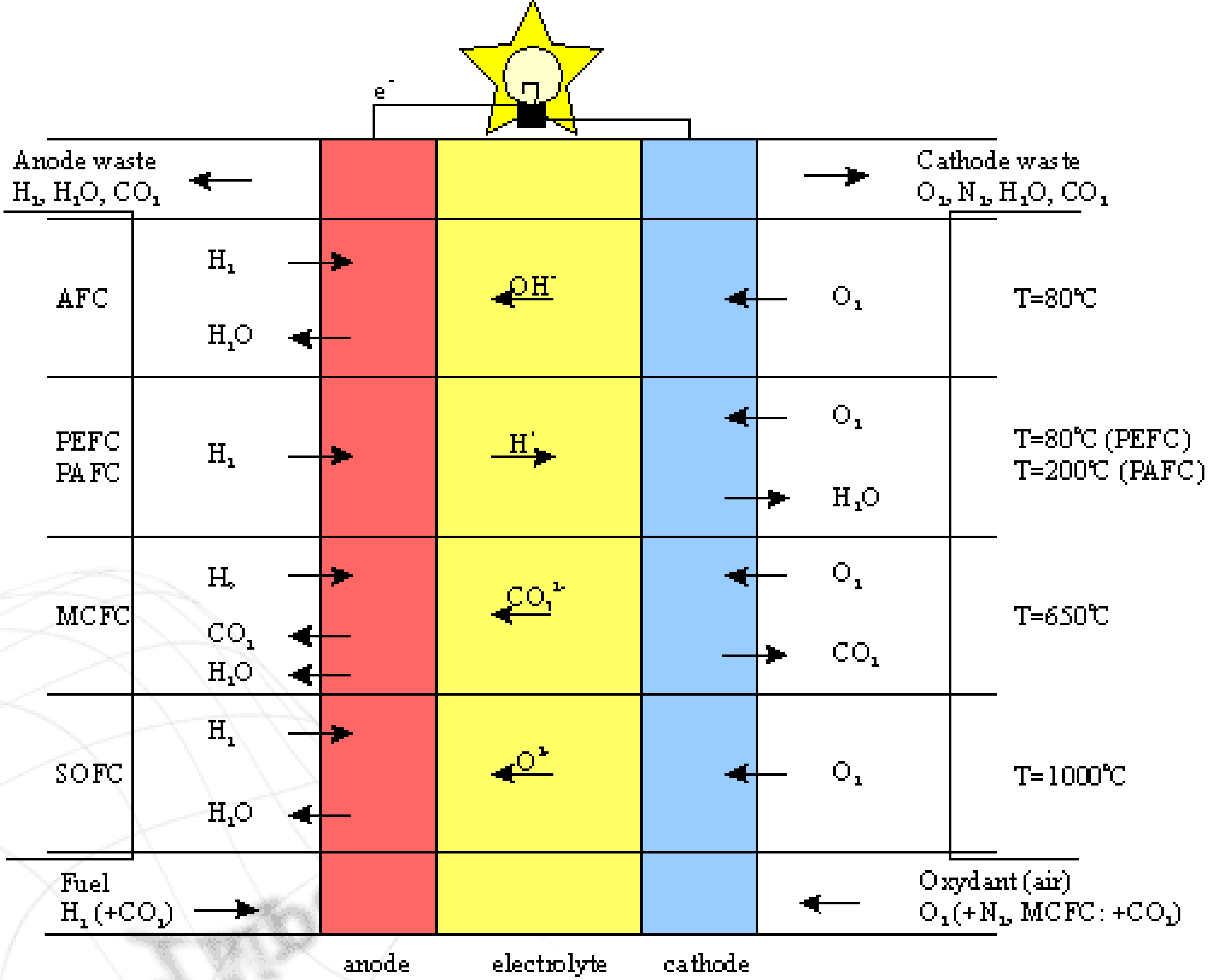
	PEFC	AFC	PAFC	MCFC	SOFC
Electrolyte	Hydrated Polymeric Ion Exchange Membranes	Mobilized or Immobilized Potassium Hydroxide in asbestos matrix	Immobilized Liquid Phosphoric Acid in SiC	Immobilized Liquid Molten Carbonate in $LiAlO_2$	Perovskites (Ceramics)
Electrodes	Carbon	Transition metals	Carbon	Nickel and Nickel Oxide	Perovskite and perovskite / metal cermet
Catalyst	Platinum	Platinum	Platinum	Electrode material	Electrode material
Interconnect	Carbon or metal	Metal	Graphite	Stainless steel or Nickel	Nickel, ceramic, or steel
Operating Temperature	40 – 80 °C	65°C – 220 °C	205 °C	650 °C	600-1000 °C
Charge Carrier	H^+	OH^-	H^+	$CO3^=$	$O^=$
External Reformer for hydrocarbon fuels	Yes	Yes	Yes	No, for some fuels	No, for some fuels and cell designs
External shift conversion of CO to hydrogen	Yes, plus purification to remove trace CO	Yes, plus purification to remove CO and CO_2	Yes	No	No
Prime Cell Components	Carbon-based	Carbon-based	Graphite-based	Stainless-based	Ceramic
Product Water Management	Evaporative	Evaporative	Evaporative	Gaseous Product	Gaseous Product
Product Heat Management	Process Gas + Liquid Cooling Medium	Process Gas + Electrolyte Circulation	Process Gas + Liquid cooling medium or steam generation	Internal Reforming + Process Gas	Internal Reforming + Process Gas

The most common classification of fuel cells is by the type of electrolyte used in the cells and includes 1) polymer electrolyte fuel cell (PEFC), 2) alkaline fuel cell (AFC), 3) phosphoric acid fuel cell (PAFC), 4) molten carbonate fuel cell (MCFC), and 5) solid oxide fuel cell (SOFC). Broadly, the choice of electrolyte dictates the operating temperature range of the fuel cell. The operating temperature and useful life of a fuel cell dictate the physicochemical and thermomechanical properties of materials used in the cell components (i.e., electrodes, electrolyte, interconnect, current collector, etc.).

Fuel Cell Characteristics Chart

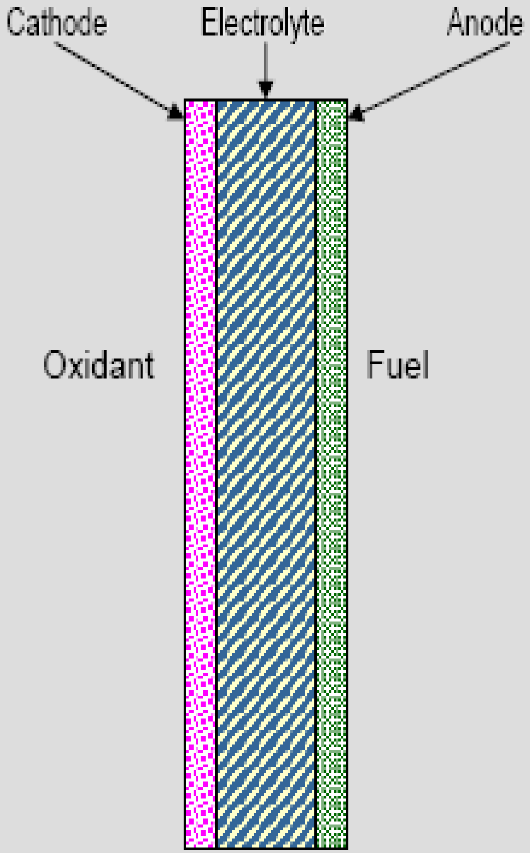


Fuel Cell Type	Electrolyte	Availability	Operating Temp.	Efficiency	Advantages	Disadvantages	Output
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	Currently available	150-200 °C	40%, 85% cogeneration	Can use impure H2 as fuel. Can tolerate up to 1.5% CO at operating temp.	Uses expensive Pt as catalyst, relatively low current generation and large size and weight	Up to 200 kW, units up to 1 MW have been tested
Proton Exchange Membrane (PEM)	Polyperfluoro-sulfonic acid	Under development, prototypes in use	80 °C		High power density, can quickly vary output (good for vehicles), solid electrolyte	Sensitive to fuel impurities	50-250 kW
Molten Carbonate (MCFC)	Carbonate solution	Under development, prototypes in use	650 °C	60%, 85% cogeneration	High operating temperature, therefore, no expensive noble metal catalysts and can operate on cheap fuels.	High operating temperature accelerates corrosion of cell components	10 kW to 2 MW
Solid Oxide (SOFC)	Yttria-stabilized zirconia, or more recently, lanthanide doped ceria	Under development, prototypes in use	1000 °C	60%, 85% cogeneration	High operating temperature, therefore, no expensive noble metal catalysts and can operate on cheap fuels	High operating temperature accelerates corrosion of cell components	Up to 100 kW
Alkaline	KOH(aq) soaked in a matrix	Used by NASA on space missions for decades	150-200 °C	up to 70%	Aqueous electrolyte promotes fast cathode reaction and high performance	High cost	300 -5000 watts
Direct Methanol Fuel Cell (DMFC)	Similar to PEM, however, uses methanol directly	Under development, prototypes in use	50-100 °C	40%	Due to the low operating temperature, good for small portable devices	Problems with fuel passing over the anode with producing electricity	



Fuel Cell Technologies

Fuel cell	Electrolyte	Charge carrier
PEMFC	Polymeric	H^+
AFC	KOH	OH^-
PAFC	Phos. Acid	H^+
MCFC	(Li,K..)Carbonate	$CO_3^=$
SOFC	Stab. ZrO_2	$O^=$

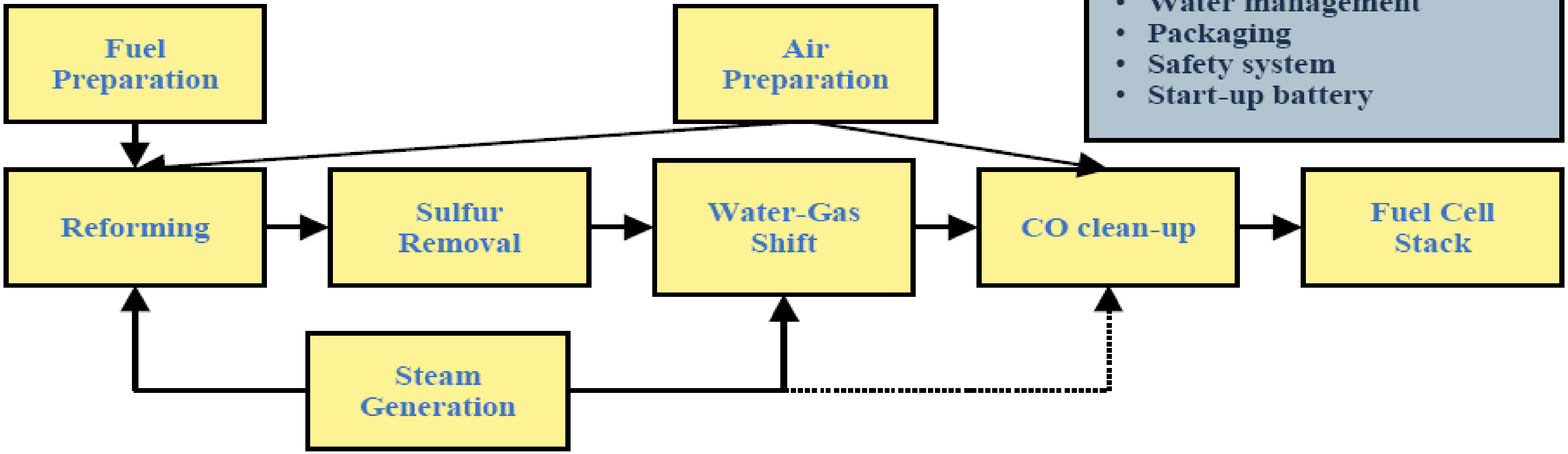


PEMFC and SOFC

- Two types of fuel cells have a very bright future. These are the PEMFC and the SOFC. The PEMFC has a bright future for use in automobiles due to the electrolyte and reactants used as well as its low operating temperature and material weight. The SOFC is and will continue to be utilized in distributed generation. The SOGC has a very high operating temperature of 750-1000 degrees Celsius and this waste heat can be used to create steam for turbines. As a result a duel generation can be implemented with this type of fuel cell.

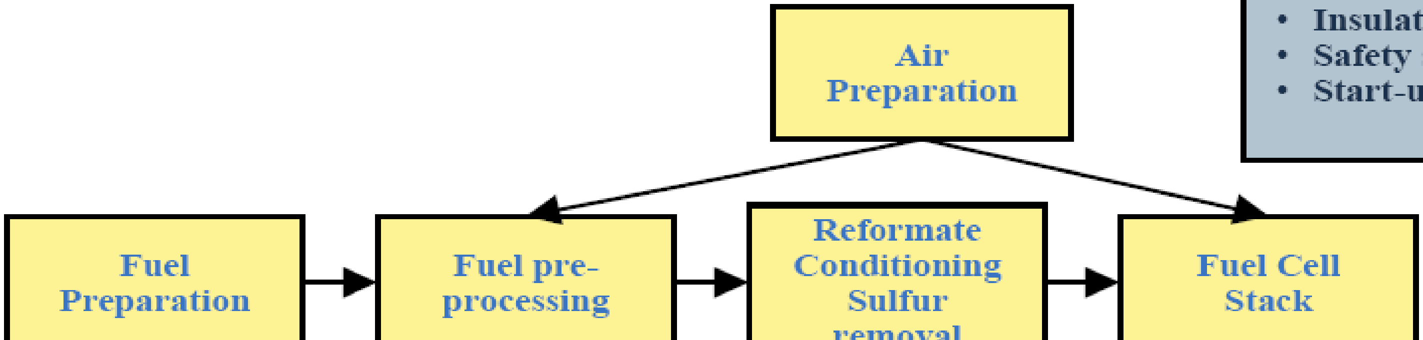
PEM-Based System

Balance of Plant:
- Compressor/Expander
- Pumps
- Controls
- Water management
- Packaging
- Safety system
- Start-up battery



SOFC-Based System

Balance of Plant:
- Compressor/Expander
- Pumps
- Controls
- Insulation & Packaging
- Safety system
- Start-up battery



SOFC

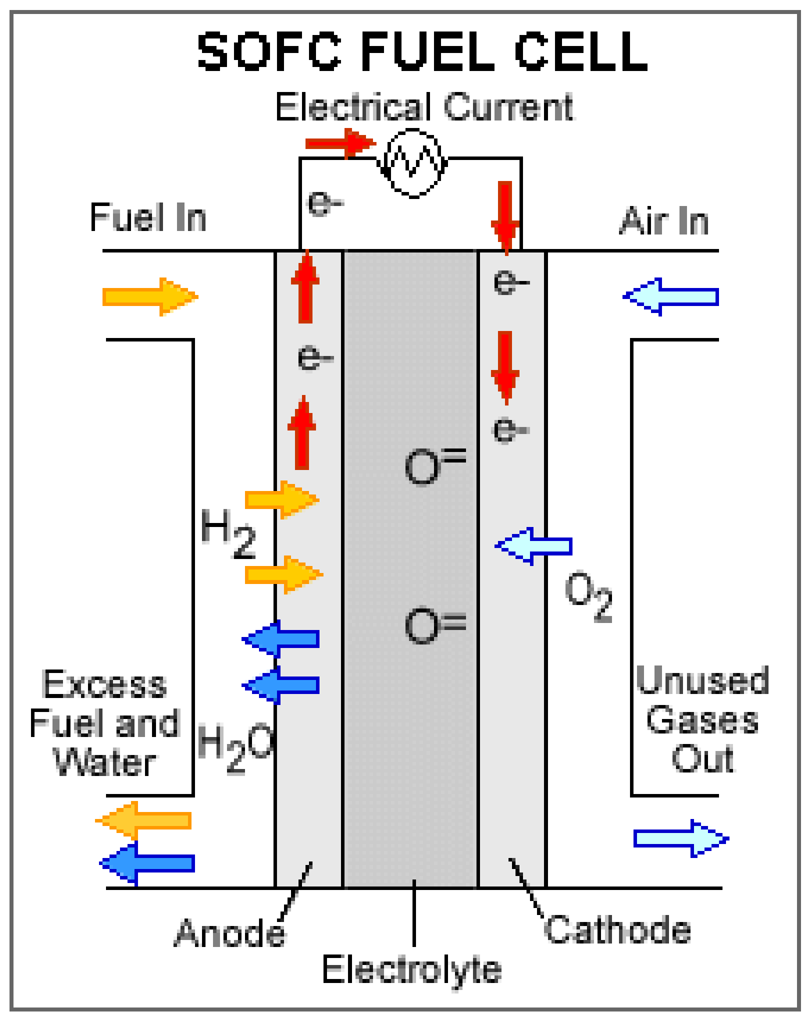
- High temperature: 750-1000 oC. Waste heat can be used for combined-cycle steam or combined cycle gas turbines.
- Electrolyte: solid ceramic material made of zirconia and yttria.
- Charge carrier that is transported across the electrolyte is oxide O2- ion, which is formed at the cathode when o2 combines with electrons from the anode.
- Reactions:

$$H_2 + O^{2-} \rightarrow H_2O + 2e^-$$

(Anode)

$$\frac{1}{2}O_2 + +2e^- \rightarrow O^{2-}$$

(Cathode)



$$H_2 + O^{2-} \rightarrow H_2O + 2e^-$$

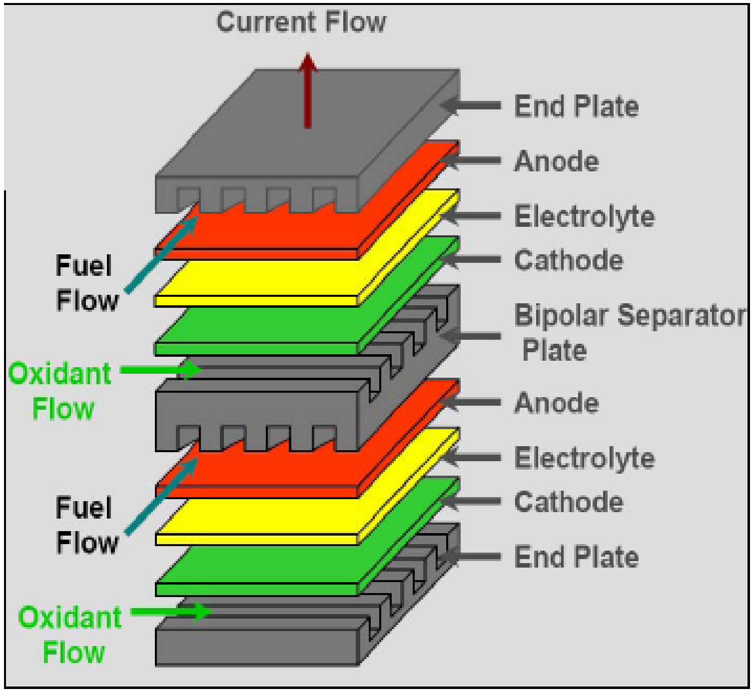
(Anode)

$$\frac{1}{2}O_2 + +2e^- \rightarrow O^{2-}$$

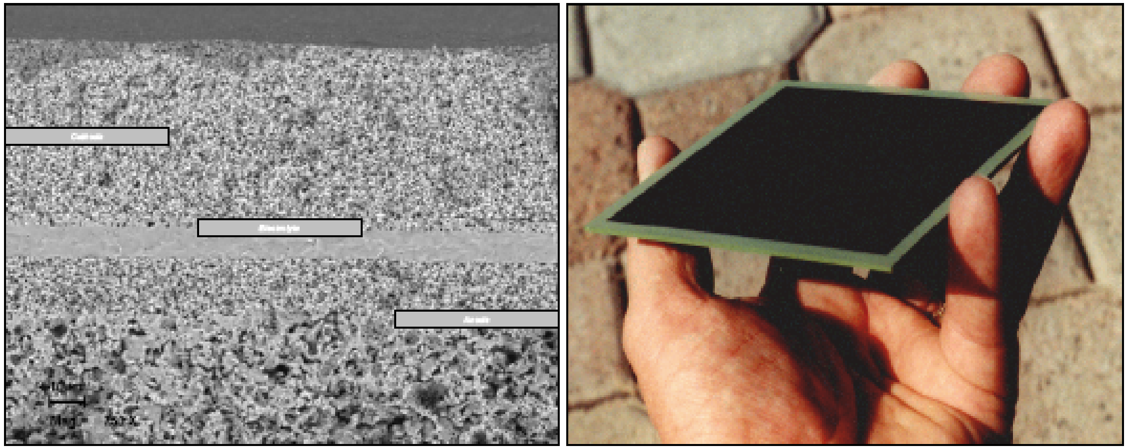
(Cathode)

SOFC Stacks

- SOFC Planar Construction
  - Solid electrolyte, supported by Anode material.
  - Cell interconnects made of stainless steel.

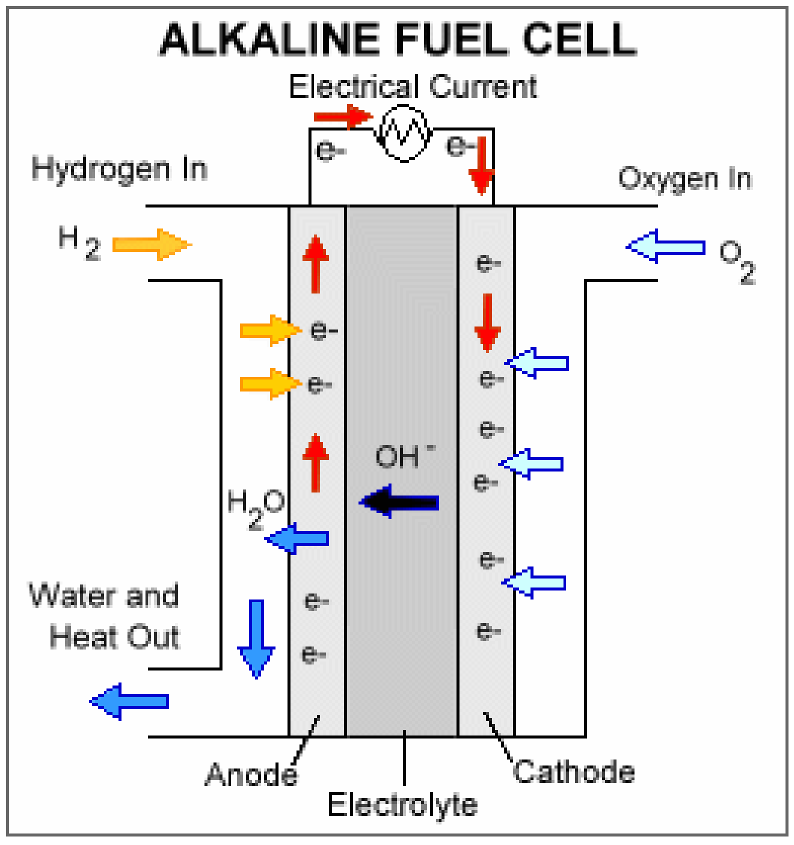


SOFC Cells



- *Anode* – nickel-zirconia cermet, ~ 1 mm thick
- *Electrolyte* – yttria-stabilized zirconia (YSZ), ~ 5 μm thick
- *Cathode* – conducting ceramic, ~ 50 μm thick

All Courtesy of Versa Power

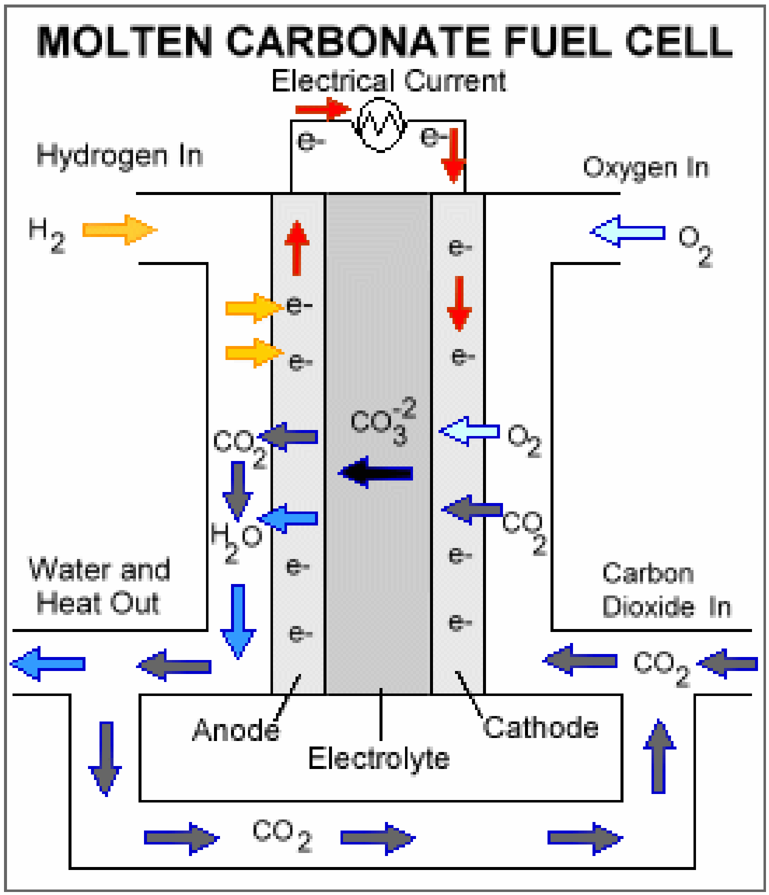


$$H_2 + 2\,OH^- \rightarrow 2\,H_2O + 2\,e^- \quad (anode)$$

$$\frac{1}{2}O_2 + H_2O + 2\,e^- \rightarrow 2\,OH^- \quad (cathode)$$

(intolerance of CO2)

http://fuelcellsworks.com/Typesoffuelcells.html
http://americanhistory.si.edu/fuelcells/basics.htm
http://www.azom.com/details.asp?ArticleID=2962
http://www.corrosion-doctors.org/FuelCell/Types.htm



$$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2\,e^- \quad (anode)$$

$$\frac{1}{2}O_2 + CO_2 + 2\,e^- \rightarrow CO_3^{2-} \quad (cathode)$$

(tolerance of CO)

H2 Production

- Methane Steam Reforming (MSR)
- Partial Oxidation (POX)
- Gasification of Biomass, Coal, or Wastes
- Electrolysis of Water