WEEK 1: Fuel Cell Introduction--INTERNALS

MECH-526

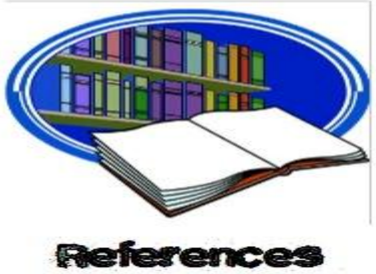
FUEL CELL SCIENCE & ENGINEERING

Center for FUEL CELL Systems & Powertrain Integration
Kettering University

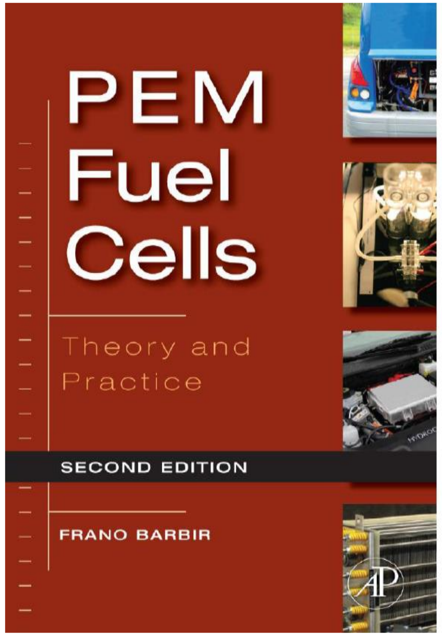
Dr. K. J. Berry. P.E.

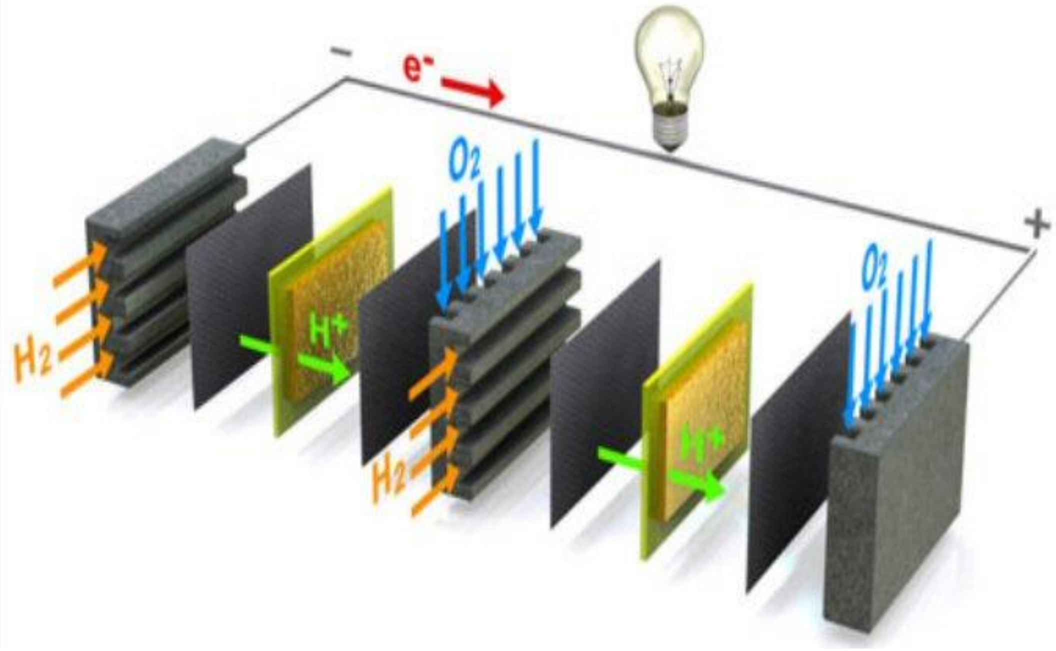
Mechanical Engineering
Kettering University
jberry@kettering.edu
www.DRKJBERRY.COM

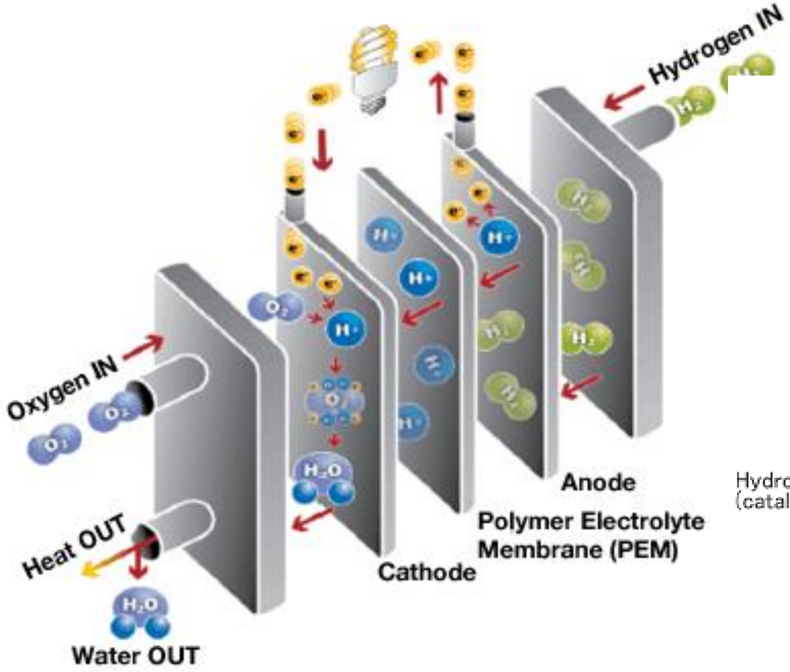
REFERENCES:

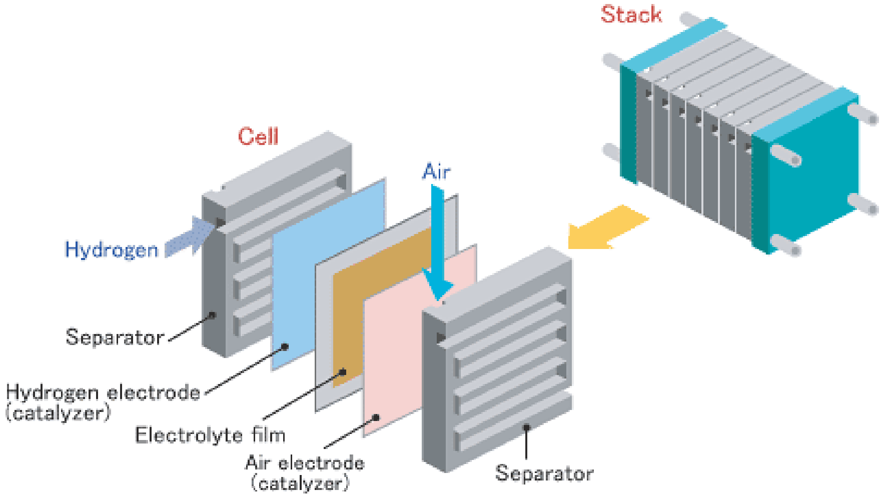


- PEM Fuel Cells: Frano Barbir, ELSEVIER.
- Fuel Cell Explained: Larmie & Dicks, WILEY.
- Fuel Cell Fundamentals: O’hayre, Cha, et al., WILEY.







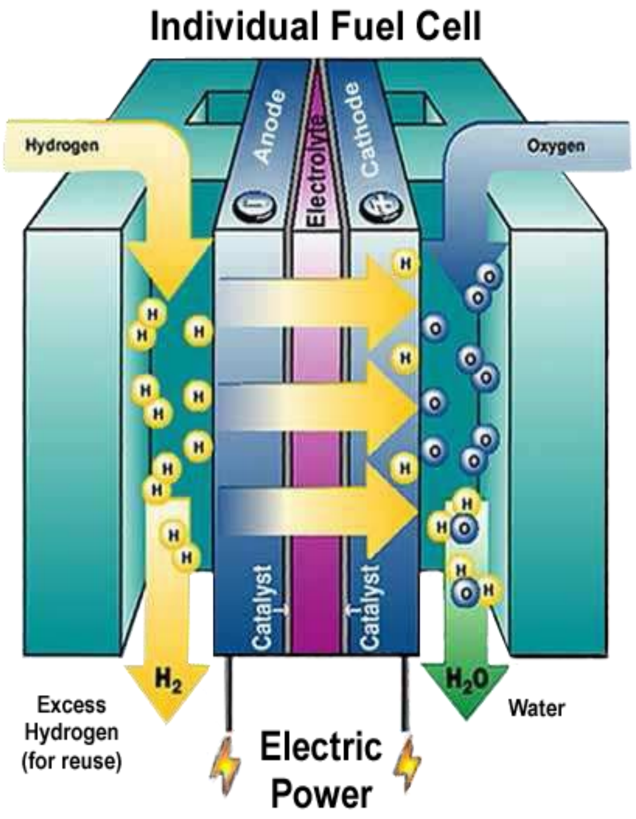


FUEL CELL FUDAMENTALS

WHAT IS A FUEL CELL ?

- A Fuel Cell is an ***ELECTROCHEMICAL*** device that operates like a battery. However, unlike a battery, a fuel cell requires re-fueling, and not recharging. ***NO COMBUSTION***.
- A fuel cell uses fuel — usually hydrogen extracted from natural gas, propane, or other carbon based fuels, and oxygen extracted from air — to produce electricity.
- Fuel cells will continue to produce energy in the form of electricity and heat as long as there is a constant fuel source.
- "PURE" Hydrogen fuel cells work simply, have no moving parts, and operate silently with water and excess heat as the only by-products.
- Fuel cells are a highly efficient, combustion-less, and virtually pollution free energy source that provides electricity to power a wide array of applications including ***buildings***, ***automobiles***, emergency ***back-up*** systems, ***laptop computers***, and numerous other ***consumer devices***.

- Fuel Cells Require:
  - *Hydrogen & Oxygen*



BASIC DEFINITIONS

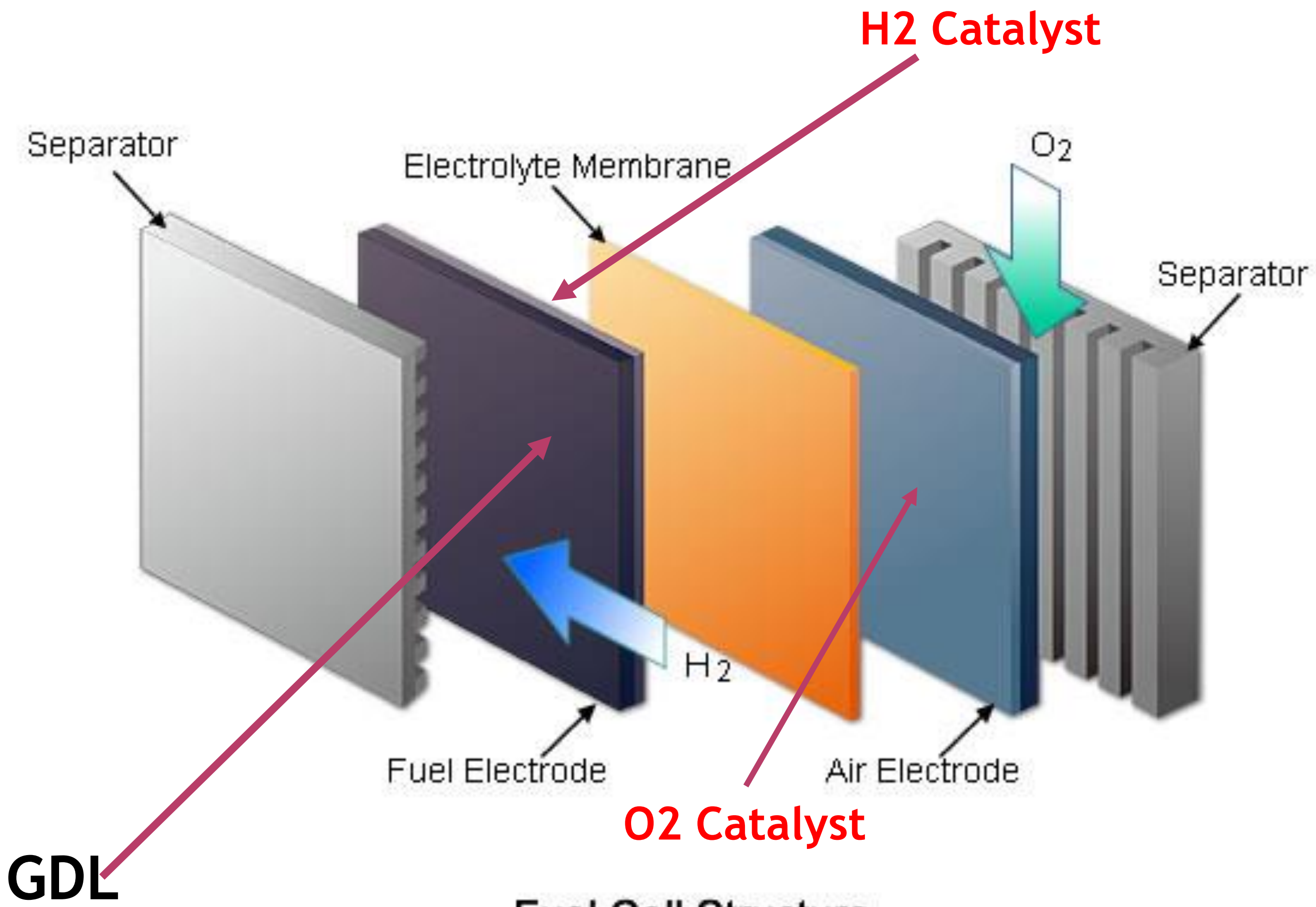
Fuel Cell = Electrochemical device (a galvanic cell) which converts **FREE ENERGY OF A CHEMICAL REACTION** into **ELECTRICAL ENERGY** (electricity); the byproducts are heat and water/steam. There is **NO COMBUSTION** in this process. It produces electricity on demand continuously as long as fuel and oxidant are supplied.

Primary Cell or Battery = Electrochemical ENERGY PRODUCING device (one-way chemical reaction producing electricity). Need to DISCARD once the battery is discharged.

Rechargeable or secondary battery = Electrochemical ENERGY STORAGE device (reversible chemical reaction producing or using electricity)

BASIC FUEL CELL COMPONENTS

Electrochemical reactions happen at the surface of the catalyst at the interface between the electrolyte and the membrane.



Fuel Cell Structure

COMPONENTS OF A FUEL CELL

- An **ANODE**: conducts electrons. It consists of
  - A porous Gas Diffusion Layer (GDL) as an electrode
  - An *Anodic Catalyst* layer

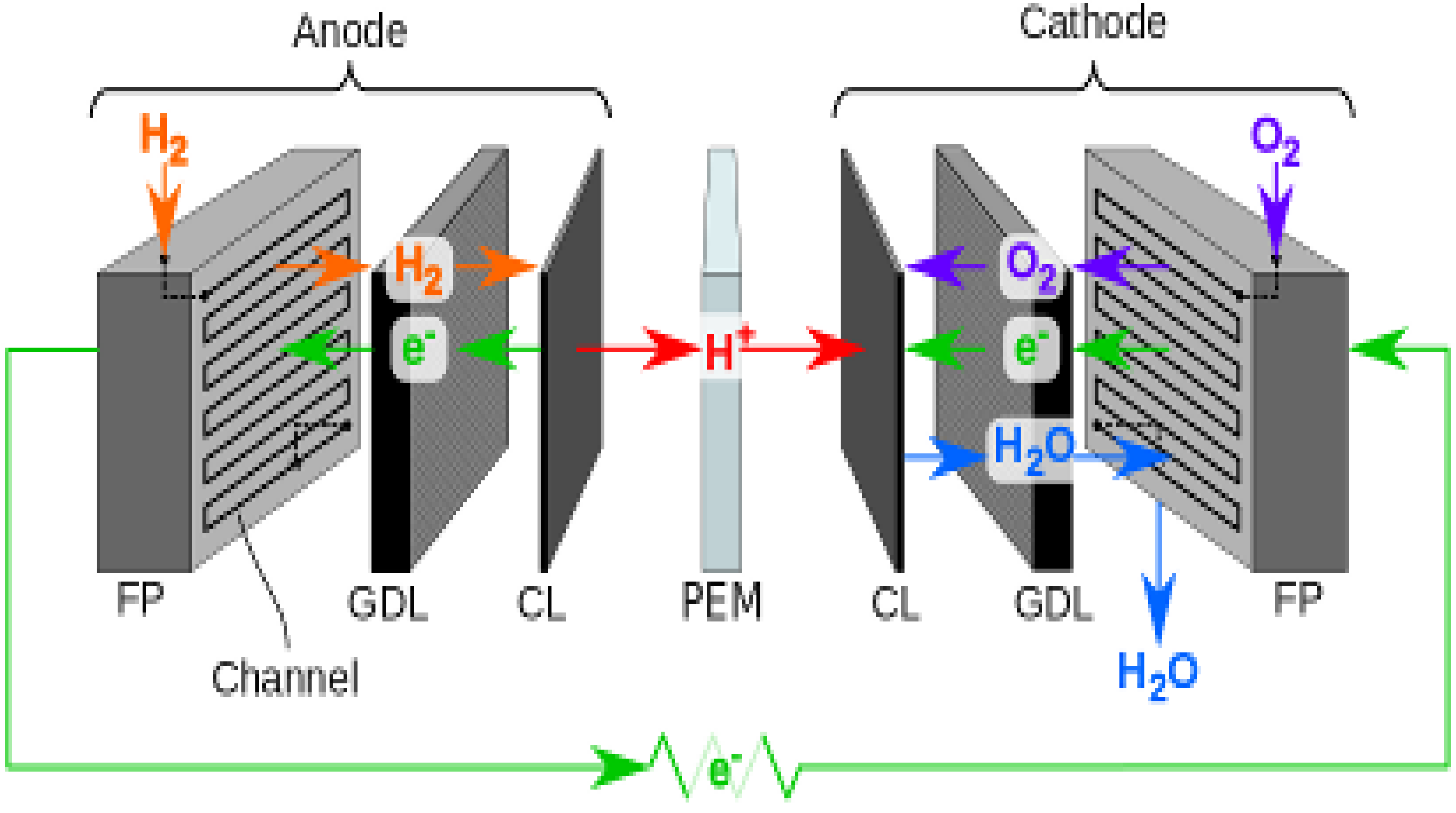
- A **MEMBRANE**: conducts PROTONS. It consists of
  - A solid membrane having a PROTON conducting medium (e.g., moisturized with water for PEMFC or DMFC) or
  - A solid matrix with a liquid electrolyte (e.g., PAFC, MCFC)
  - A solid ceramic matrix having proton conducting characteristics (e.g., SOFC)

- A **CATHODE**: conducts electrons. It consists of
  - A *Cathodic Catalyst* layer
  - A porous Gas Diffusion Layer (GDL) as an electrode

- Bipolar plates (or Interconnects)
  - Collect electrical current (ELECTRONS)
  - Distribute and separate reactive gases

MEA = CL(anode)+PEM+CL(cathode)+GDL

DETAILED ELECTRON FLOW



ANODE REACTION

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

CATHODE REACTION

$$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

OVERALL

$$H_2 + 1/2O_2 \rightarrow H_2O$$

MEMBRANE CATALYST

CATALYST LAYERS—INCREASES RATES OF REACTION

- A layer of **CATALYST** is added on **BOTH SIDES** of the membrane—the ANODE layer on one side and the CATHODE layer on the other.
- Catalyst layers include nanometer-sized particles of platinum dispersed on a high-surface-area carbon support. **PLATINUM** catalyst is mixed with an H2+ ION (**PROTON**)-conducting polymer (ionomer) and sandwiched between the membrane and the GDLs.
- On the ANODE side, the **PLATINUM** catalyst enables hydrogen molecules to be split into protons and electrons.
- On the CATHODE side, the **PLATINUM** catalyst enables oxygen reduction by reacting with the protons generated by the anode, producing water. The ionomer mixed into the catalyst layers allows the protons to

GDL

GAS DIFFUSION LAYERS (GDL)

- The GDLs sit outside the catalyst layers and facilitate **TRANSPORT** of reactants into the catalyst layer (ANODE), as well as **REMOVAL** of product water(CATHODE).

- Each GDL is typically composed of a sheet of carbon paper in which the carbon fibers are partially coated with POLYTETRA**FLUORO**ETHYLENE (PTFE). Gases diffuse rapidly through the pores in the GDL.

- These pores are kept open by the hydrophobic PTFE, which prevents excessive water buildup. In many cases, the inner surface of the GDL is coated with a thin layer of high-surface-area carbon mixed with PTFE, called the microporous layer.

- The microporous layer adjust the balance between **WATER RETENTION** (needed to maintain MEMBRANE CONDUCTIVITY) and **WATER RELEASE** (needed to keep the pores open so hydrogen and oxygen can diffuse into the electrodes).

FUEL CELL HARDWARE

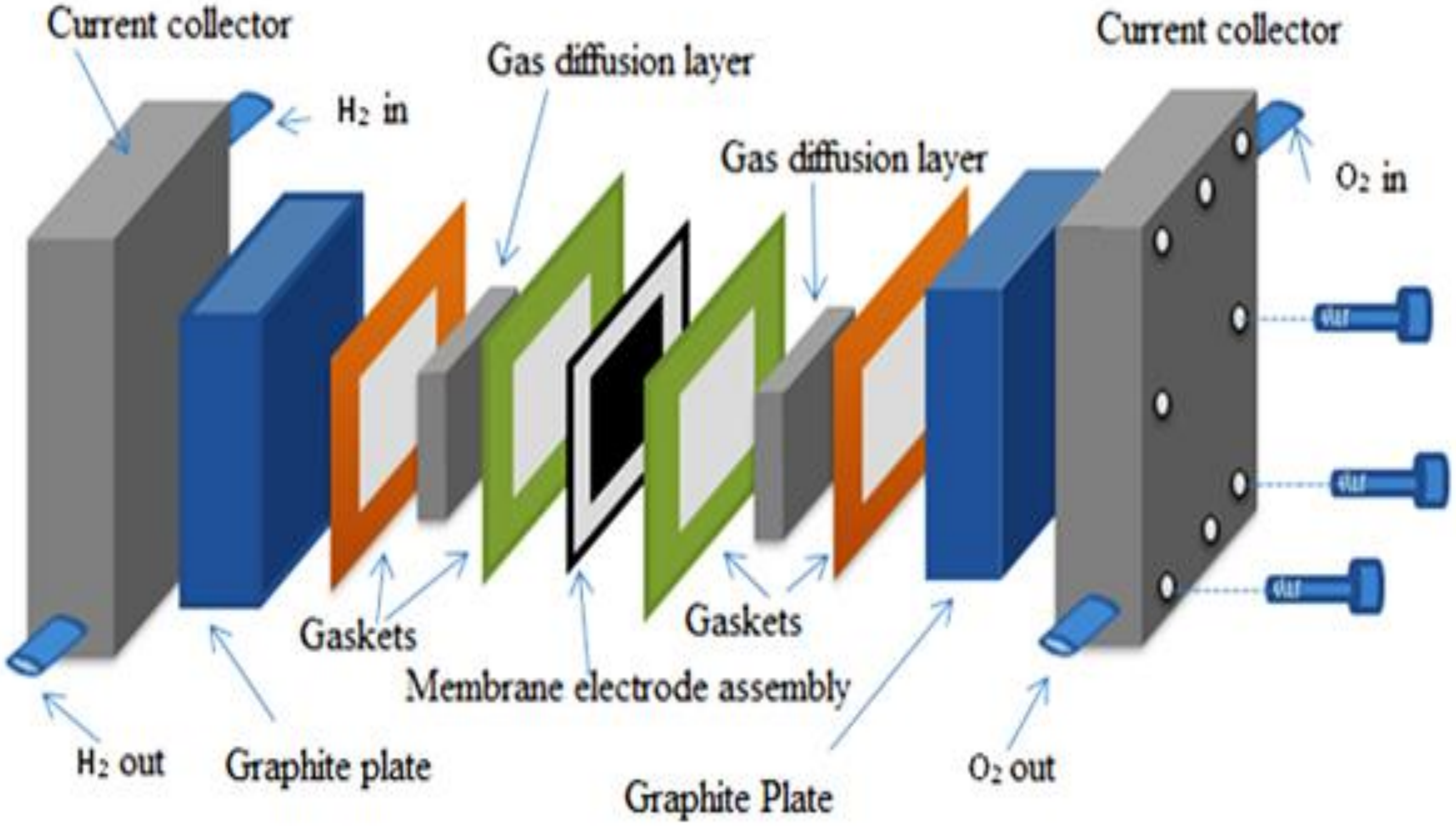
Hardware
The MEA is the part of the fuel cell where power is produced, but hardware components are required to enable effective MEA operation.

Membrane Electrode Assembly (MEA)
The **MEMBRANE**, **CATALYST** layers (anode and cathode), and **DIFFUSION** media together form the Membrane Electrode Assembly (**MEA**) of a PEM fuel cell.

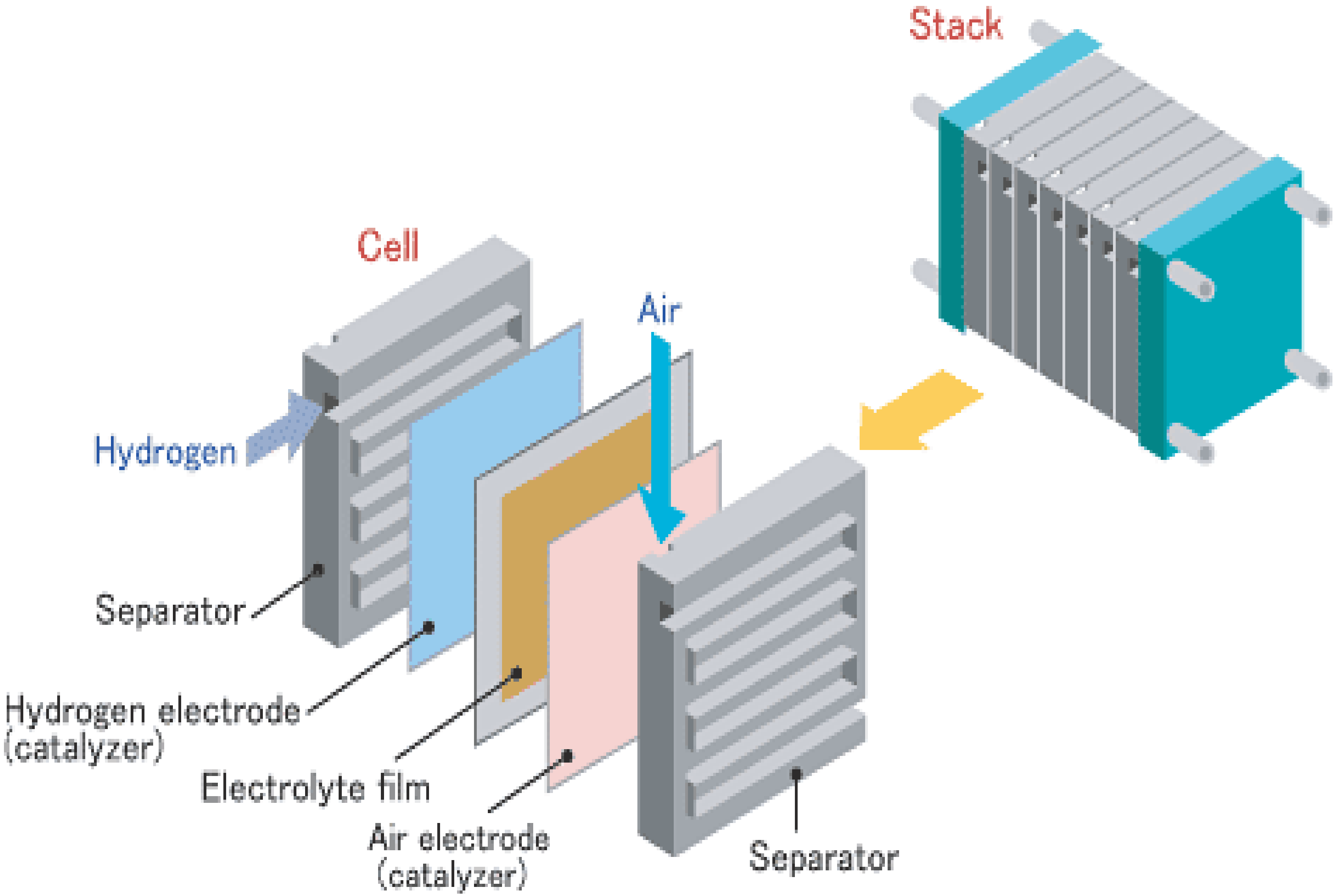
GASKETS
Each MEA in a fuel cell stack is sandwiched between two bipolar plates, but gaskets must be added around the edges of the MEA to make a gas-tight seal. These gaskets are usually made of a rubbery polymer.

BIPOLAR PLATES
MEA produces less than 1 V under typical operating conditions, but most applications require higher voltages. Therefore, multiple MEAs are connected in series by stacking in series to provide a usable output voltage. Each cell in the stack is between two bipolar plates to separate it from neighboring cells. The surfaces of the plates contain a “flow field,” which is a set of channels machined or stamped into the plate to allow gases to flow over the MEA.

DETAILED CELL COMPONENTS



FUEL CELL STACK ASSEMBLY



FUEL CELL OPERATION—GALVANIC CELL

- The ***anode reaction*** in fuel cells is "direct oxidation". "OXIDATION" is a process where electrons are "removed" from a species. "i.e. Negative Electrode".
- The ***cathode reaction*** is "oxygen reduction". "REDUCTION" is a process where electrons are "added" to a species. "i.e. Positive Electrode".
- **Electrons flow from ANODE (-) to CATHODE (+) for fuel cells (opposite for batteries).**
- For H2/O2 fuel cell, overall reaction is (GIBSS=max work possible)

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{HEAT} \qquad \text{with } \Delta G = -237.34\,\text{kJ/mol (GIBBS Free Energy)}$$

The product of this reaction is "water released" at the cathode or anode depending on the type of the fuel cell.

- The open circuit voltage E^0 at standard conditions of 25°C and 1 atmosphere pressure for the H2/O2 Fuel Cell is:

$$n = \frac{\text{moles of electrons}}{\text{moles of reaction}} = 2(\text{hydrogen moles/reaction})$$

$$F = \text{Faraday's Constant} = 96{,}485\frac{\textit{coulombs}}{\text{moles of electrons}}$$

$$\frac{\Delta G}{nF} = \frac{\dfrac{\text{Joules}}{\text{mole of reaction}}}{\dfrac{\text{moles of electrons}}{\text{moles of reaction}}\, x \,\dfrac{\textit{coulombs}}{\text{moles of electrons}}} = \frac{\text{Joules}}{\textit{coulombs}}$$

$$= \textit{Volts}$$

$$E^0_{\max} = \frac{-\Delta G}{nF} = 1.23V\,/\,cell$$

GIBBS FREE ENERGY

- The **Gibbs free energy** of a system at any moment in time is defined as the enthalpy of the **system** minus the product of the temperature times the entropy of the **system**. G = H - TS. H is enthalpy, T is temperature, and S is entropy.
- Used to calculate the **MAXIMUM** REVERSIBLE work that may be performed by a thermodynamic system at a constant temperature and pressure. **BUT NOT THE SPEED OF REACTION**.
- When using Gibbs free energy to determine the spontaneity of a process, we are only concerned with changes in "G", rather than its absolute value.
- When the process occurs under standard conditions (25C/1Bar/1M), we calculate the GIBBS free energy using the Standard Free Energy of Formation, ΔG_f^0

$$\Delta G = G_{Final} - G_{Initial};[J/kg]$$

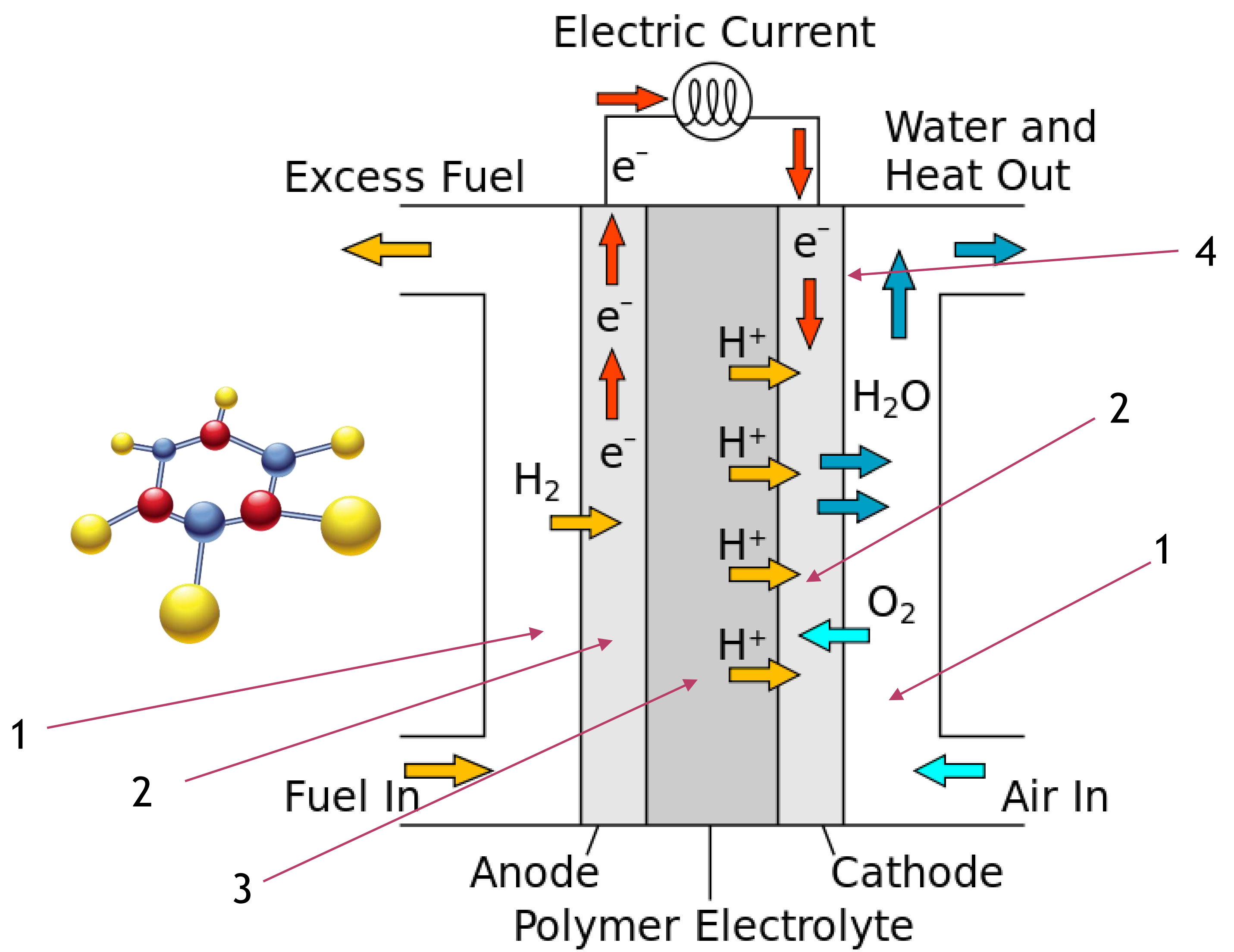
$$H_2 + 1/2O_2 \rightarrow H_2O + \text{Heat}$$

$$\Delta G_{System} = \Delta H_{System} - T\Delta S_{System}$$

$$if\ \ \Delta G_{System} < 0 \rightarrow \text{spontaneous (Exergonic)} \rightarrow \text{form more products}$$

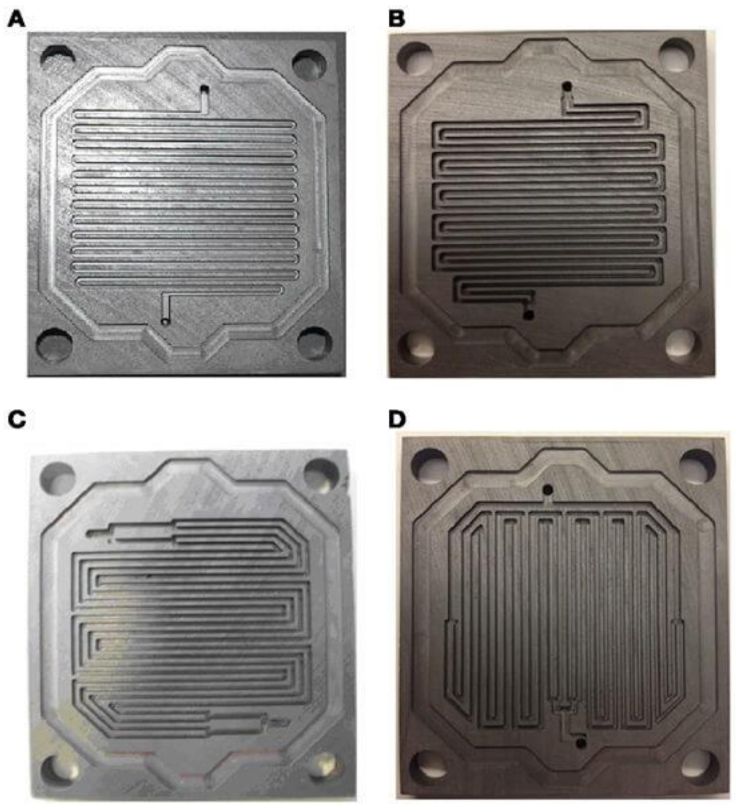
$$if\ \ \Delta G_{System} > 0 \rightarrow non-\text{spontaneous (Endergonic)} \rightarrow \text{form more starting materials}$$

POLYMER ELECTROLYTE MEMBRANE (PEM FUEL CELL): STEP-BY-STEP



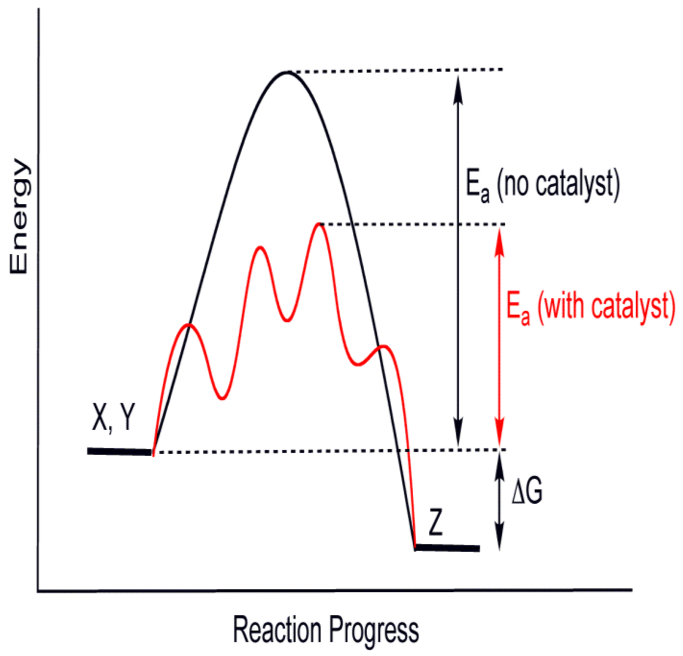
STEP-BY-STEP #1: REACTANT TRANSPORT

- Fuel Cells must have ‘fuel’ and ‘oxidant’ constantly. If the reactants are not supplied quickly enough to meet “current” demand, fuel cell will “**STARVE**”.
- Efficient delivery of reactants is done with “flow field plates” and porous electrode structures.
- Flow field plates contain channels to distribute reactants over the surface of the fuel cell. And shape, size, and flow field pattern can drastically affect performance.
- The material aspects of flow structures and electrodes are equally important. Components are held to stringent material constraints, including electrical, thermal, mechanical and corrosion requirements.



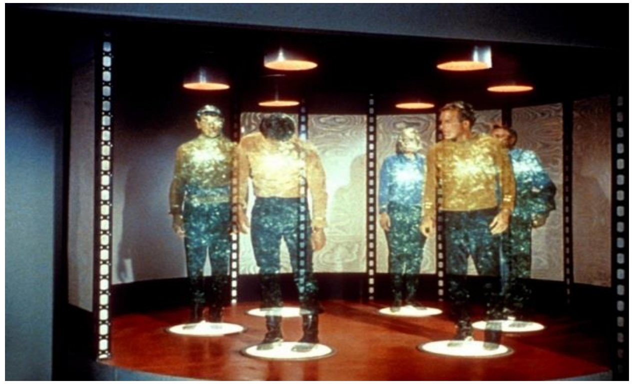
STEP-BY-STEP# 2: ELECTROCHEMICAL REACTION

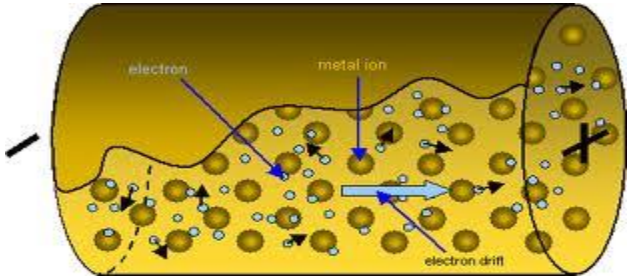
- Once reactants are delivered to electrodes, they must undergo electrochemical reaction via a **CATALYST**.
- Fast electrochemical reactions result is high current outputs.
- Catalysts work by providing an (alternative) mechanism involving a different transition state and **LOWER** activation energy. Hence, catalysts can "speed-up" reactions that would otherwise be blocked or slowed by a kinetic barrier.
- Fuel cell performance critically depends on choosing the right catalyst and carefully designing the reaction zones.
- Often, the kinetics of the electrochemical reactions represent the single greatest limitation to fuel cell performance.

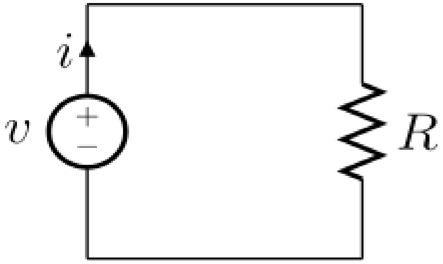


STEP-BY-STEP# 3: *IONIC (& ELECTRONIC) CONDUCTION*

- Electrochemical reactions in step# 2 either produce or consume ions and electrons. ***Ions & electrons*** produced at one electrode must be consumed at the other electrode.
- For charge balance, ions and electrons must be ***transported*** from the generations source to consumption source. Electrons are easy; external wire conductor.
- Ions are much larger and more massive than electrons and **REQUIRE** a **ELECTROLYTE** to provide pathways for ions to flow.
- IONIC transport can represent a significant resistance loss, reducing cell performance.
- Electrolytes in fuel cells are made as thin as possible to minimize the distance over which ionic conduction must occur, and therefore reducing resistance to flow.







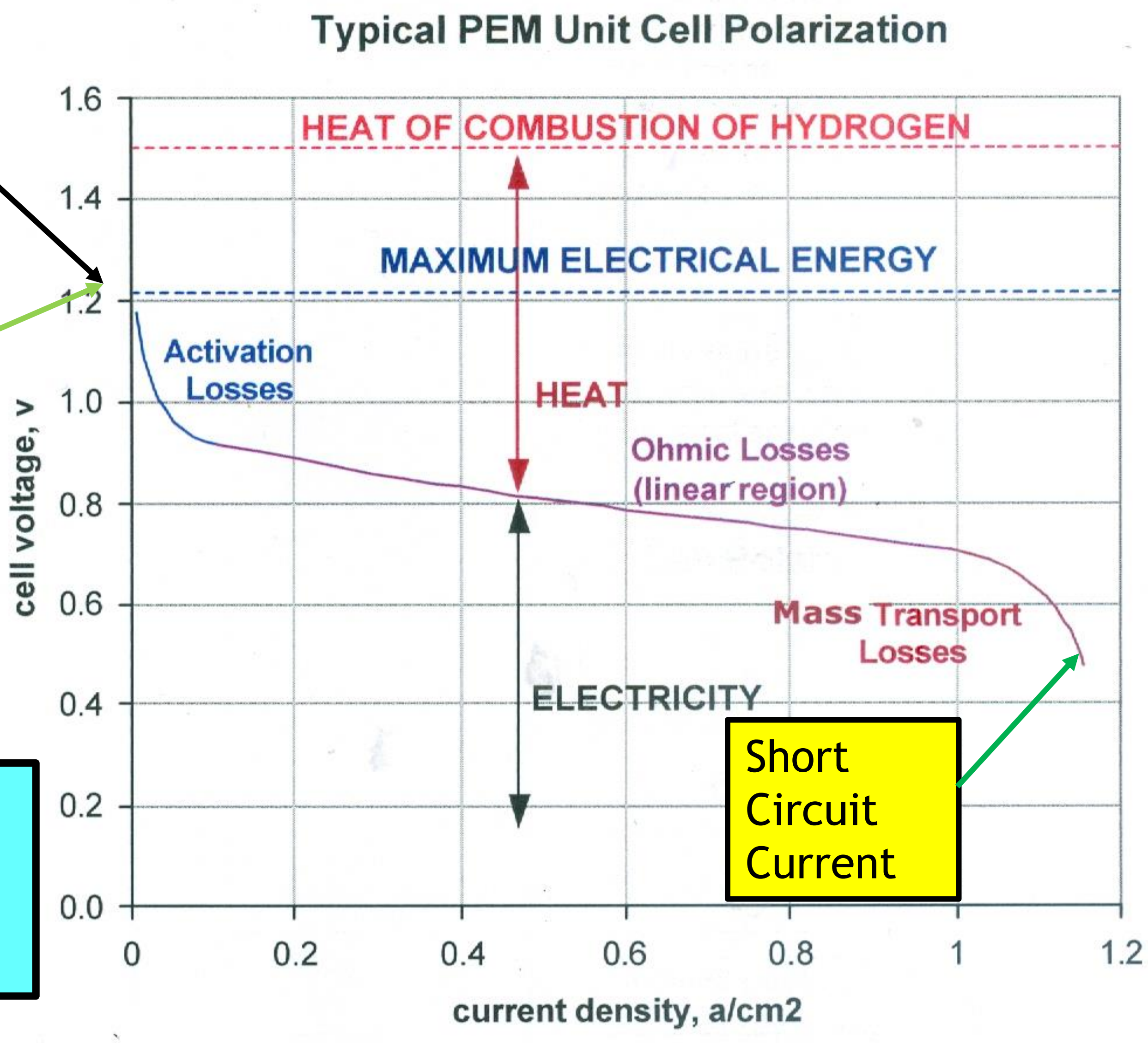
STEP-BY-STEP#4: PRODUCT REMOVAL

- In addition to electricity, all fuel cells generate at least one species; e.g. H2/O2 fuel cells generate water.
  - Hydrocarbon fuel cells also produce CO2.
- If not removed, over time water and species will "**strangle**" fuel cell, and preventing new fuel and oxidant form be able to react.
- The act of delivering reactants "into" the fuel cell often assist the removal of product species "out" of the fuel cell.
- The same mass transport, diffusion, and fluid mechanics issues important in optimizing reactant delivery can be applied to product removal.
- Important for PEMFC to prevent membrane "flooding", which can significantly hinder cell performance.

$$E^0 = \frac{-\Delta G}{nF} = 1.23V / cell$$

FUEL CELL I-V CURVE

Open Circuit Voltage



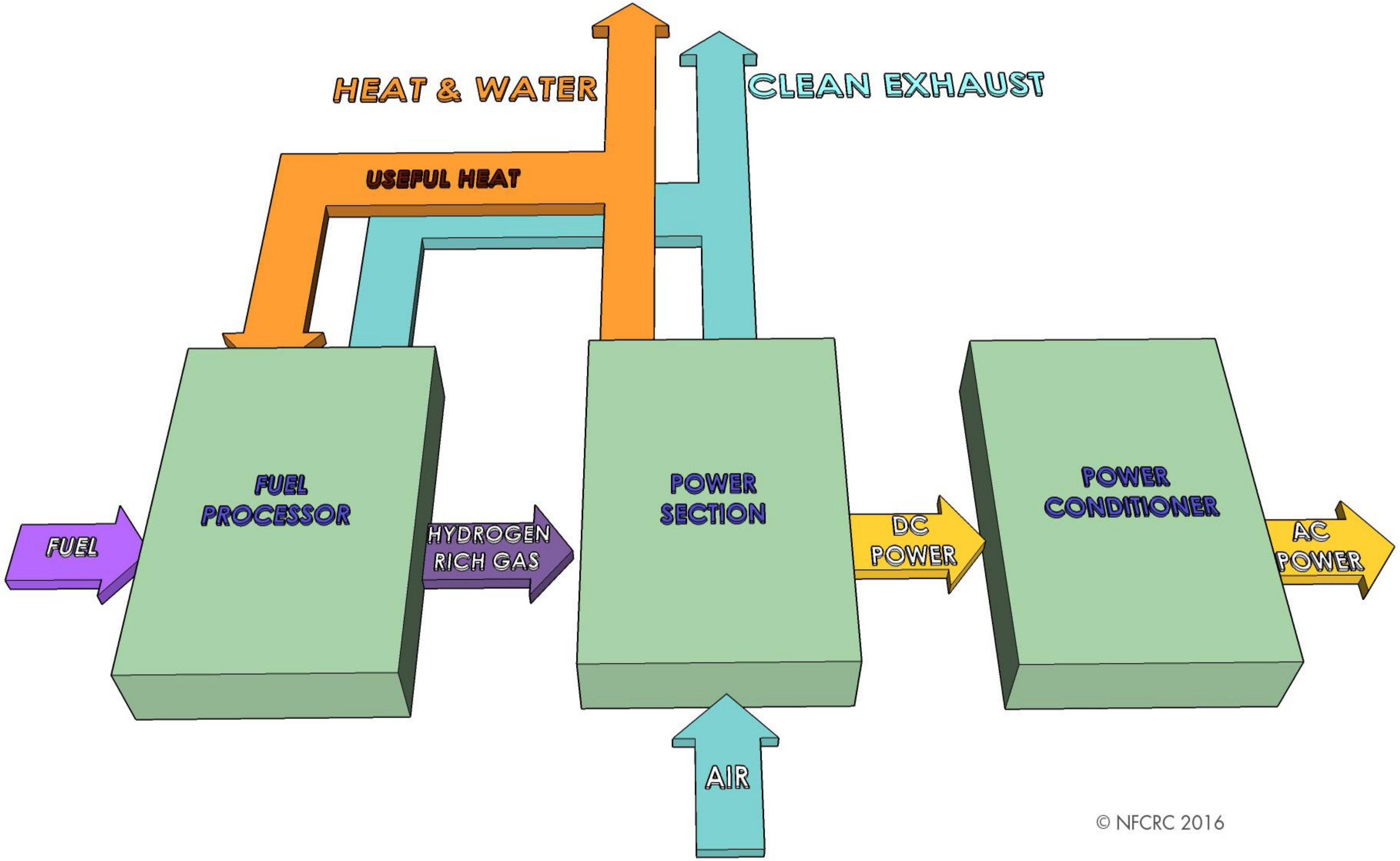
Short Circuit Current

We will be studying the different loss mechanisms

LOW TEMPERATURE PEM FUEL CELL

Product Water Management	Evaporative
Product Heat Management	50-70C, External Cooling Medium
Start-Up	Seconds
Power Density (kW/m2)	3.8-6.5
Efficiency	50-60%
Development Status	Mature, Systems up to 250kW
Catalyst	Platinum
Challenges	Lower Costs Catalyst & Electrolyte Improve Performance; High temperature CO tolerance; High current density
Applications	Auto/Bus Power; Telecom;Small Scale Back-up
Fuel	H2, Methanol
Anode Reaction	$H_2 \rightarrow 2H^+ + 2e^-$
Cathode Reaction	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$

FC POWER PLANT BOP COMPONENTS



FUEL CELL POWER PLANT

- Balance of Power Plant (BOP)
  - Fuel Reforming (Processor) System (includes fuel preheating if needed)
  - Fuel Storage
  - Air Management System (includes compressor, turbine, intercooler, pump/blower, etc. and air preheating if needed)
  - Water and Thermal Management System
  - Control Valves, Pressure Regulators, System Controllers, Electric Motors, etc.
  - Power Electronics and Power Conditioning (voltage regulator, DC/DC converter, DC/AC inverter, etc.

SUMMARY

The following topics have been covered in this lecture:

- The basic operation of a fuel cell.
- The components of a fuel cell and fuel cell systems.
- Basic description, comparison and contrast among various types of fuel cells, with more common types being PEMFC, AFC, PAFC, MCFC and SOFC.
- Various applications of fuel cell systems.