1MG11: FUEL CELL VEHICLES
Part 1: Fuel Cell Technology

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References

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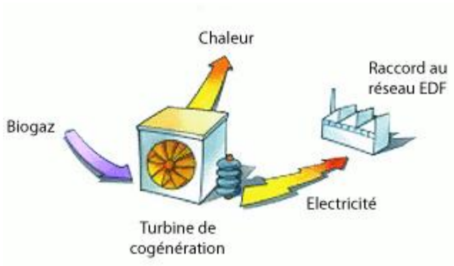
- Fuel cell org: www.fuelcell.org

Introduction

Energy: A sustainable approach

- Reduction of the energy consumption
  - Reduction of the energy needs: modification of the way of life and energy consumption usage

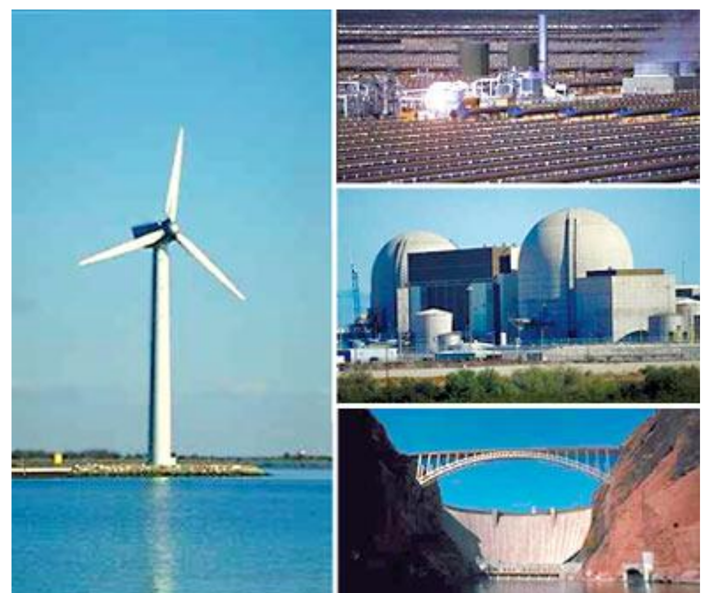
  - Combination of several energy usages
    - Integrating the processes
    - E.g. combined heat and electricity production



  - Reduction of the energy losses
    - Insulation of buildings
    - Reducing the friction losses

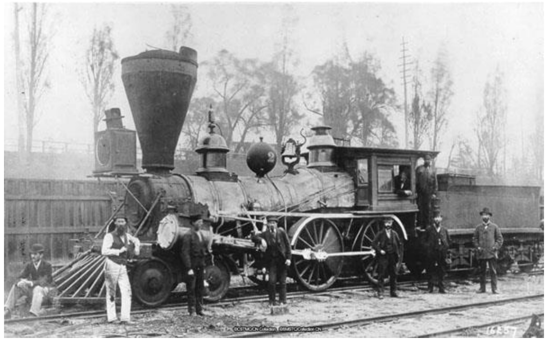
Energy: A sustainable approach

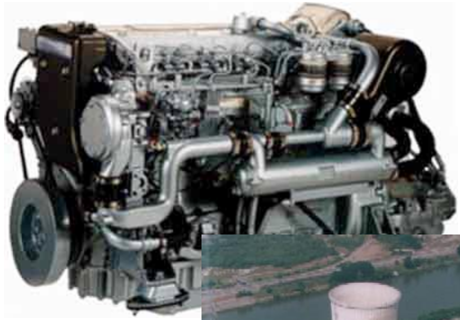
- Exploitation of alternative energy sources
- Alternative energy sources
  - Biomass
  - Waste (energy valorization of wastes : burning wastes, heat valorization of exhaust by burning gases)
- Solar energy
  - Photovoltaic conversion
  - Thermal conversion
  - Wind energy
  - Hydro-electric production
- Nuclear:
  - A new start?



Improving the energy conversion efficiency

- Steam engine (1850): 3%
- Gas turbine (1945): 10%
- Internal combustion engine (1950): 20%
- Electric power plant (1960): 41%
- Turbine gas steam (1990): 51%
- Fuel cell (2000): 50%
- Solid Oxide FC + gas turbine (2005): >75%
- Fuel cell + cogeneration (2019) > 90%





Improving the energy conversion efficiency

- Question:
  - How to convert the chemical energy of the fuel into electricity?

- Classical (thermodynamic) approach :
  - Combustion
  - Thermal engine
  - Generator

- Efficiency limited by Carnot
  - Carnot principle

$$W = \eta \, \Delta H$$

$$\eta_{max} = 1 - T_c / T_h$$

Improving the energy conversion efficiency

- Question:
  - How to convert the chemical energy of the fuel into electricity?

- Electrochemical route:
  - Direct transformation of the chemical energy into electric work
  - Efficiency = Quantity of energy theoretically recoverable / Quantity of Energy at play during the Transformation

$$\eta = \frac{\Delta G}{\Delta H}$$

- Fuel Cell H2-O2:

$$\Delta G = -229\, kJ/kmol$$

$$\Delta H = -242\, kJ/kmol$$

$$\eta = \frac{\Delta G}{\Delta H} = 95\,\%$$

Direct conversion

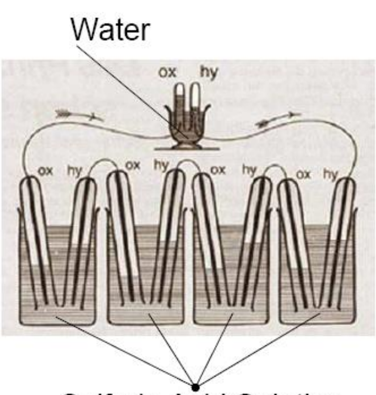
- Electrochemical systems
  - Volta batteries:
    - Closed system, irreversibility
    - Consumption of the reactant chemicals

  - Rechargeable batteries
    - Closed system but reversible
    - Regeneration of reactants

  - Fuel Cells
    - Open system
    - Reactants are continuously supplied, while reaction products are continuously eliminated

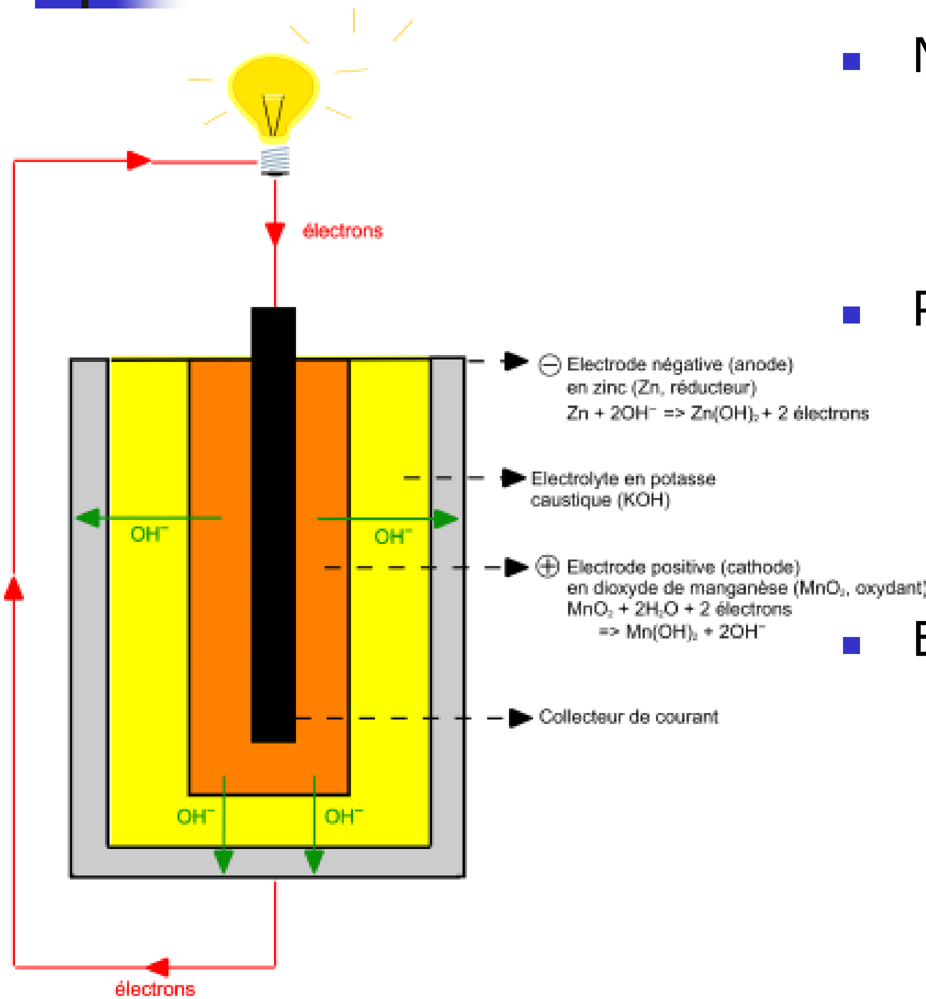
Fuel Cell - History

W. Groove



- In 1839 Christian Schönbein, a German scientist discovers the fuel cell effects
- From 1839 to 1842, The Welsh scientist William Groove makes the first lab implementation of a fuel cell
- From 1932, F. Bacon restarts study of fuel cells and shows prototypes of 1 kW in 1953 and 5 kW in 1959.
- Thomas Grubb and Leonard Niedrach from GE brings new improvements related to the sulfonated membranes and the platinum deposition on electrodes ➔ Grubb-Niedrach fuel cell will be the basis for space exploration fuel cells developed by NASA and Mac Donell Aircraft for Gemini program.
- The first hydrogen fuel cell application was made by Roger Billing in 1991.

Working principle of alkaline batteries



- Negative electrodes (anode)
  - Oxidation of Zinc
  - $Zn + 2\ OH^- \rightarrow Zn(OH)_2 + 2\ e^-$
- Positive electrode (cathode)
  - Manganese dioxide MnO_2
  - $MnO_2 + 2\ H_2O + 2\ e^- \rightarrow Mn(OH)_2 + 2\ OH^-$
- Electrolyte
  - Caustic potash
  - KOH

Working principle of alkaline batteries

- Direct conversion of chemical energy into electrical energy

- Closed system:
  - At the beginning: given amount of reactants (oxidants and reductant)
  - At the end: the quantity of reactants is used, and the reaction product remain in the battery
  - Reaction stops when the materials are used

- Irreversible process
  - No recharge is possible

What is a Fuel Cell?

- Direct conversion of the chemical fuel into electricity using an electrochemistry process
  - Electrochemical reaction (oxidoreductase) without combustion (flame)

- Open system
  - Reactants are continuously fed, converted and then eliminated
  - Reaction products are removed continuously

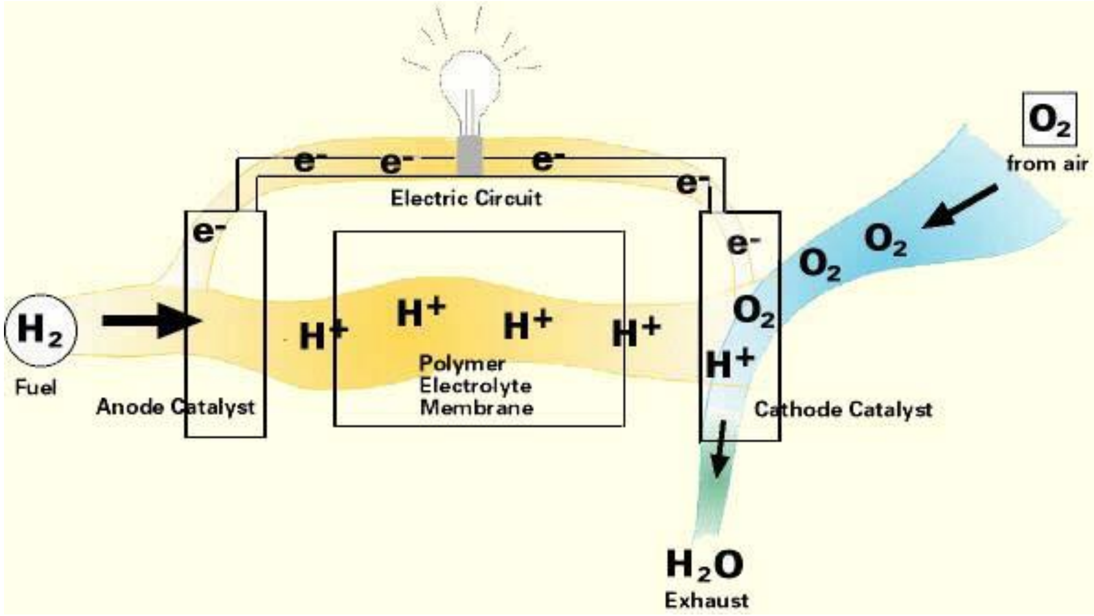
- Electrolyte
  - Protons / ions are carried out from one electrode to the other one through the electrolyte (liquid or solid)

What is a Fuel Cell?

- External circuit
  - Close to each electrode, highly conductive plates collect and drain the current to external circuit.
  - Electrons that are exchanged during the reaction are conducted through the external electrical circuit, creating a current in the external circuit.
  - Electrical work is developed by the external current in the circuit

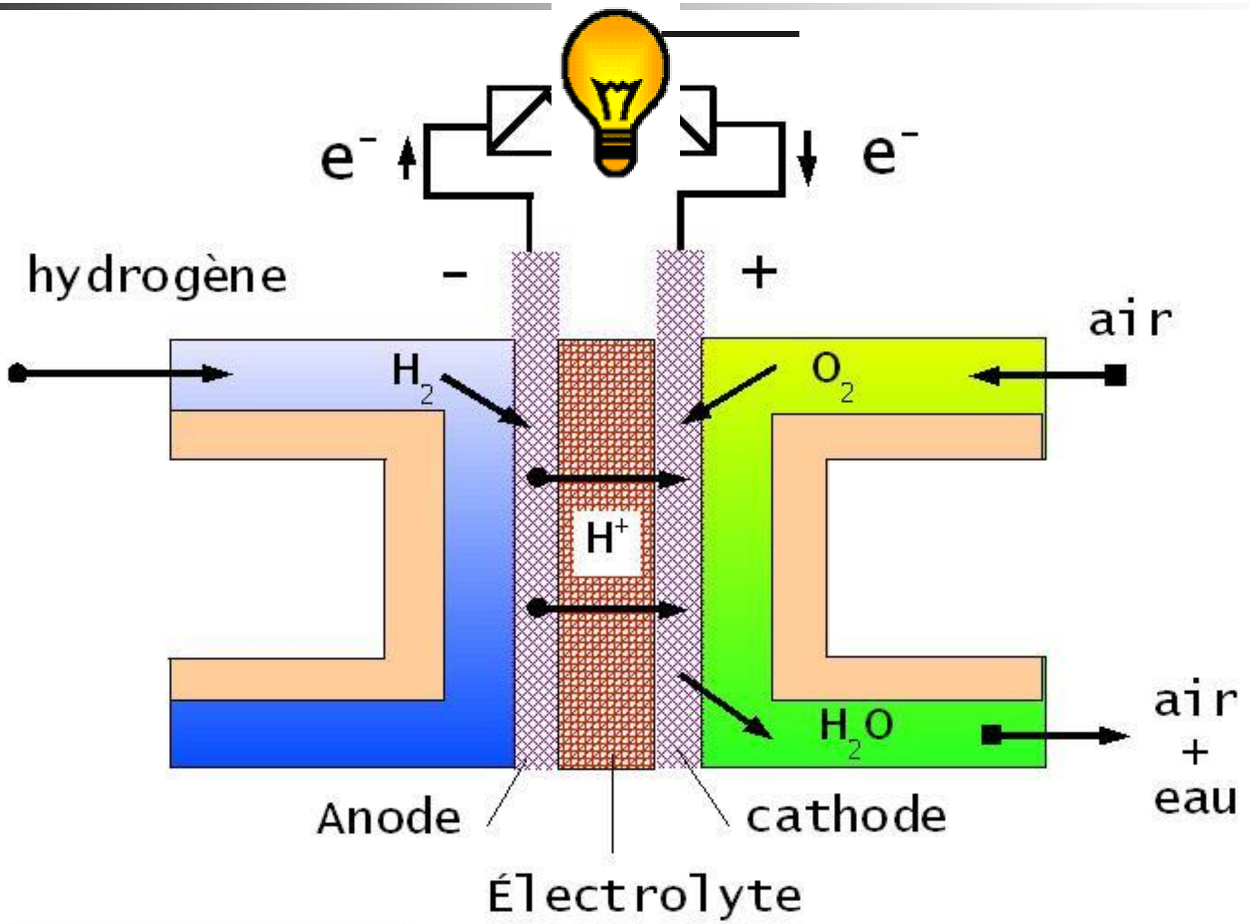
Working principle of fuel cells

- The H_2-O_2 fuel cell
  - The fuel: generally (di)hydrogen H_2
  - Oxidizer: oxygen (often from air) O_2
  - Hydrogen + Oxygen → water (steam) + electricity + heat
  - Electricity: direct current



Working principle of H_2 –O_2 fuel cell

Working principle of H_2 –O_2 fuel cell



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

$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

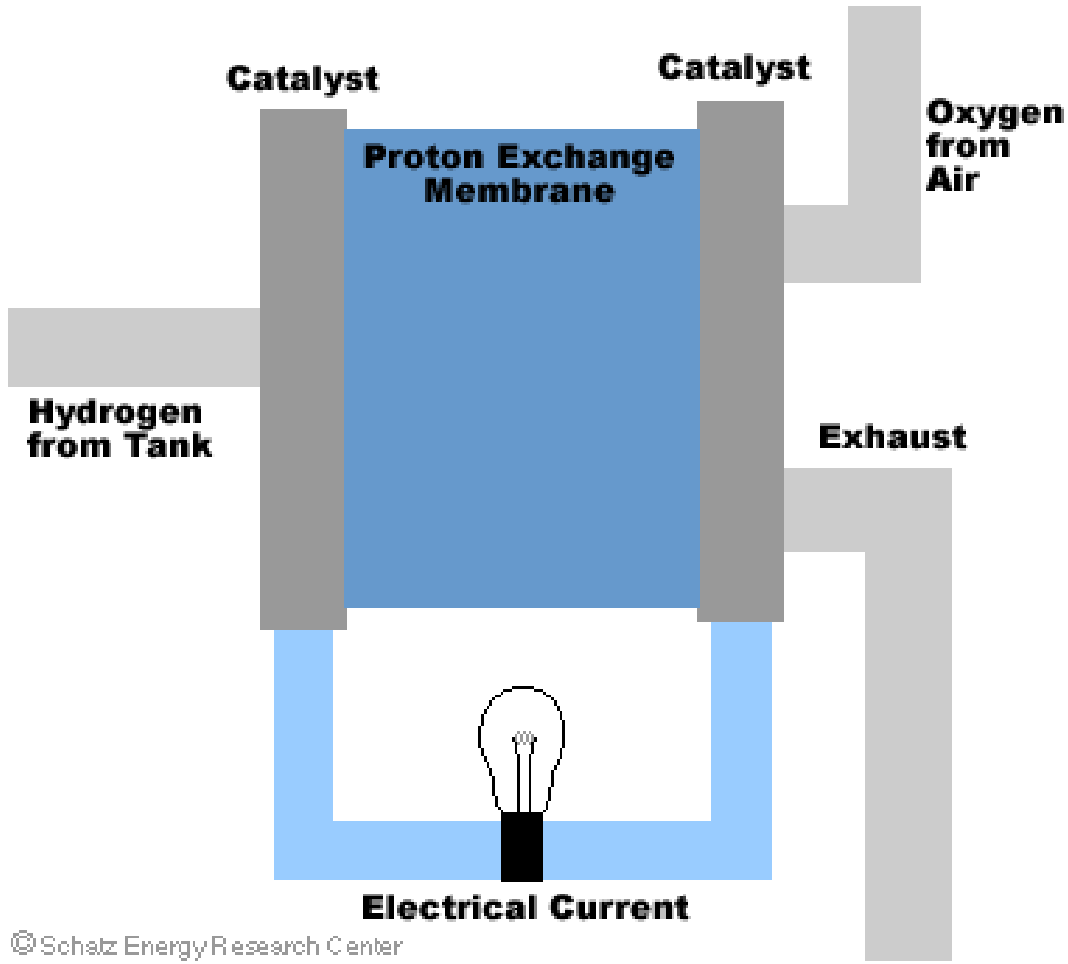
Working principle of H_2 –O_2 fuel cell

- <u>At anode</u>: oxidation of hydrogen (catalyzed reaction)
  - $H_2 \longrightarrow 2\ H^+ + 2\ e^-$ *Acid electrolyte*
  - $H_2 + 2\ OH^- \longrightarrow 2\ H_2O + 2\ e^-$ *Basic electrolyte*

- <u>At cathode</u>, reductase of oxygen (catalyzed reaction)
  - $1/2\ O_2 + 2\ H^+ + 2e- \longrightarrow H_2O$ *Acid electrolyte*
  - $1/2\ O_2 + H_2O + 2e- \longrightarrow 2\ OH^-$ *Basic electrolyte*

- Balance
  - $H_2 + 1/2\ O_2 \longrightarrow H_2O + \text{heat}$

Work scheme of a single cell



Source: Schatz Energy Research Center

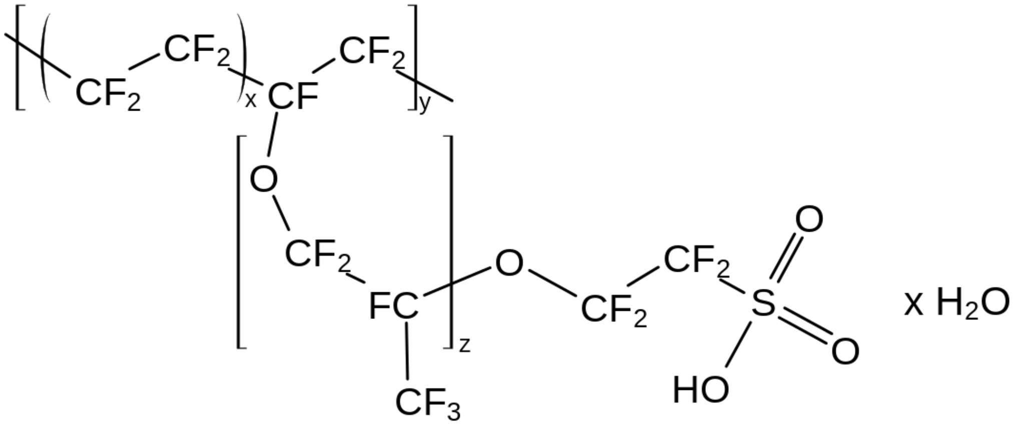
Working principle of H_2 –O_2 fuel cell

- The fundamental working principle is the inverse reaction of water electrolysis
- This chemical reaction is exothermic at 25 C.
- Free enthalpy of the reaction is -237 or -229 kJ/mol depending on the fact that the produced water is under liquid or gaseous form.
- This corresponds to theoretical voltages of 1,23 and 1,18 V. The voltage depends also of the temperature.
- The reaction requires the presence of catalyst (Pt or Pt/Ru) to activate (accelerate) the reaction speed.

Working principle of H_2 –O_2 fuel cell

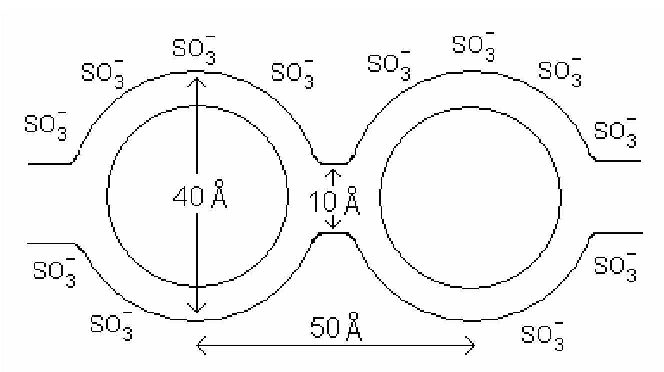
- Every electrochemical systems require an electrolyte to transfer ions from one electrode to the other.

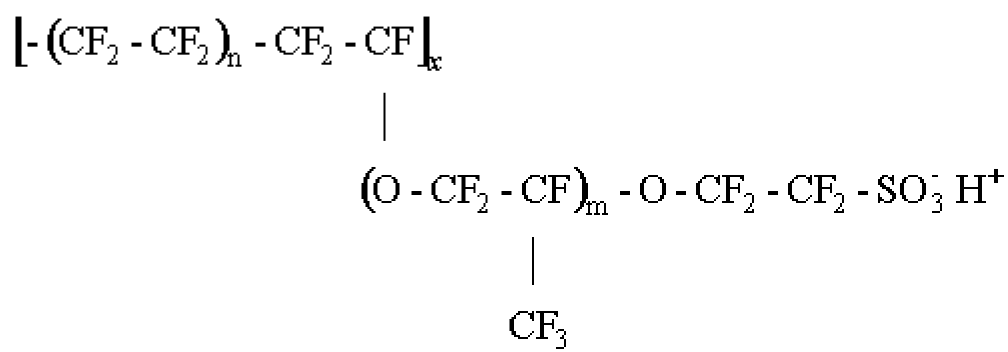
- For Proton Exchange Membrane (PEM) fuel cells
  - Solid electrolyte
  - Ions H+
  - Polymer membrane (Nafion)



Working principle of H_2 –O_2 fuel cell

- Nafion is a sulfonated tetrafluoroethylene based fluoropolymer-copolymer discovered in the late 1960s by Walther Grot of DuPont.
- First of a class of synthetic polymers with ionic properties which are called ionomers.
- Nafion's unique ionic properties are the result of incorporated perfluorovinyl ether groups terminated with sulfonate groups onto a tetrafluoroethylene (Teflon)





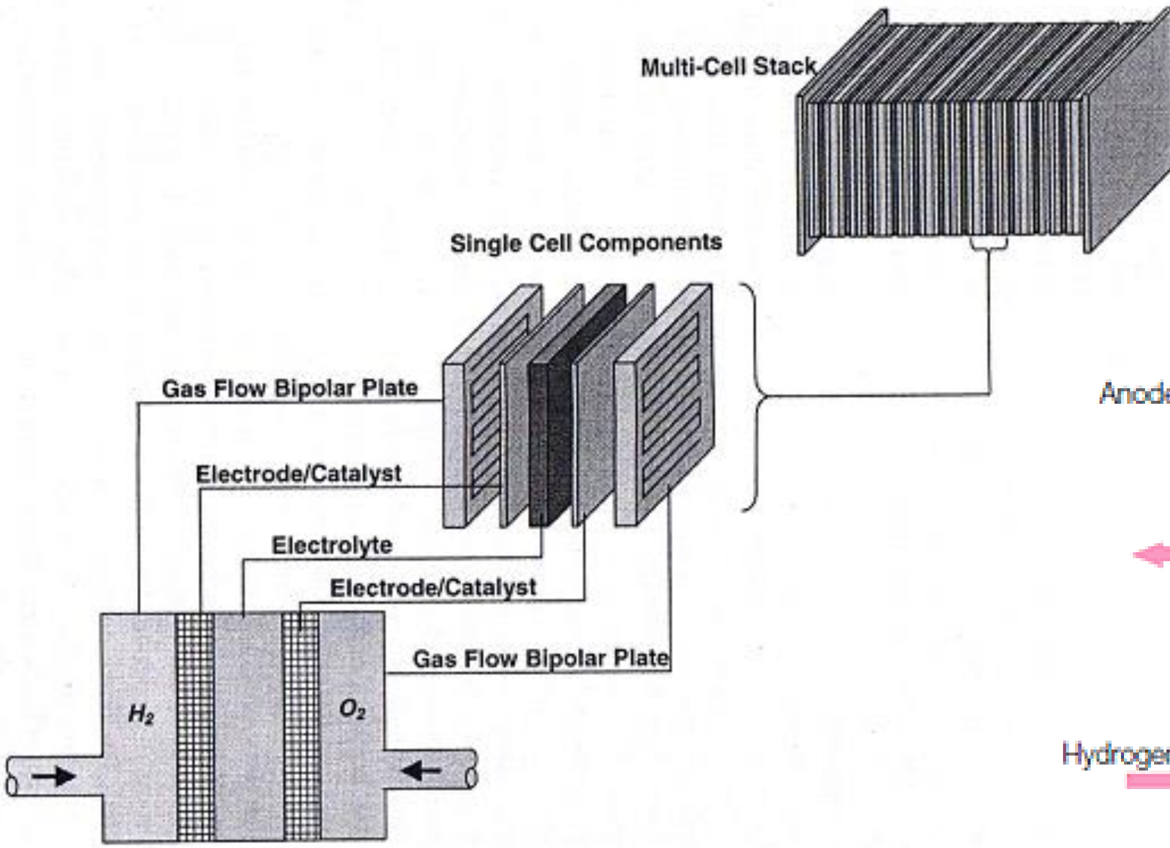
Source Wikipedia

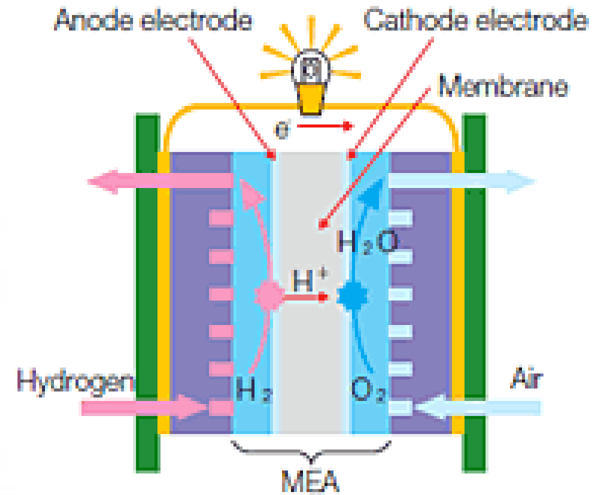
Working principle of H_2 –O_2 fuel cell

- Advantages:
  - Operating generally at low or moderate temperatures
  - Silent operation
  - High theoretical efficiency (η_{th}~92%)

- Drawbacks:
  - Cost of electrodes (Pt)
  - Purity of the fuel
  - Limited power density

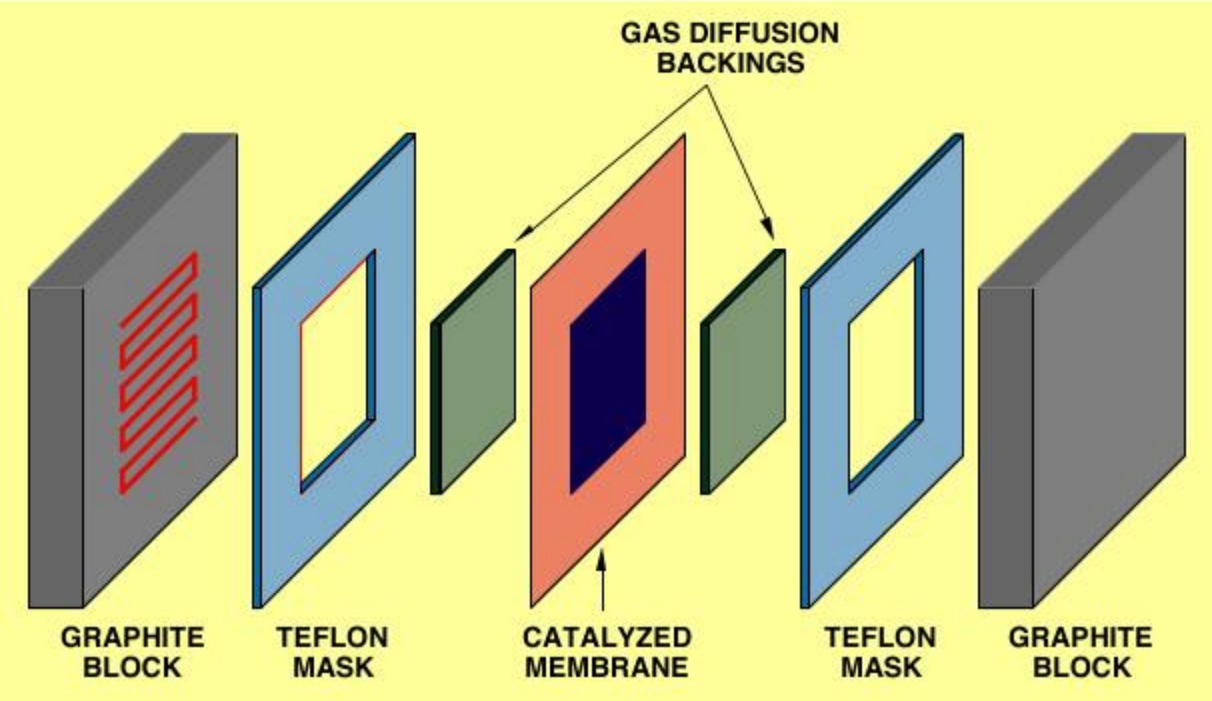
From MEA to single cell and fuel cell stack



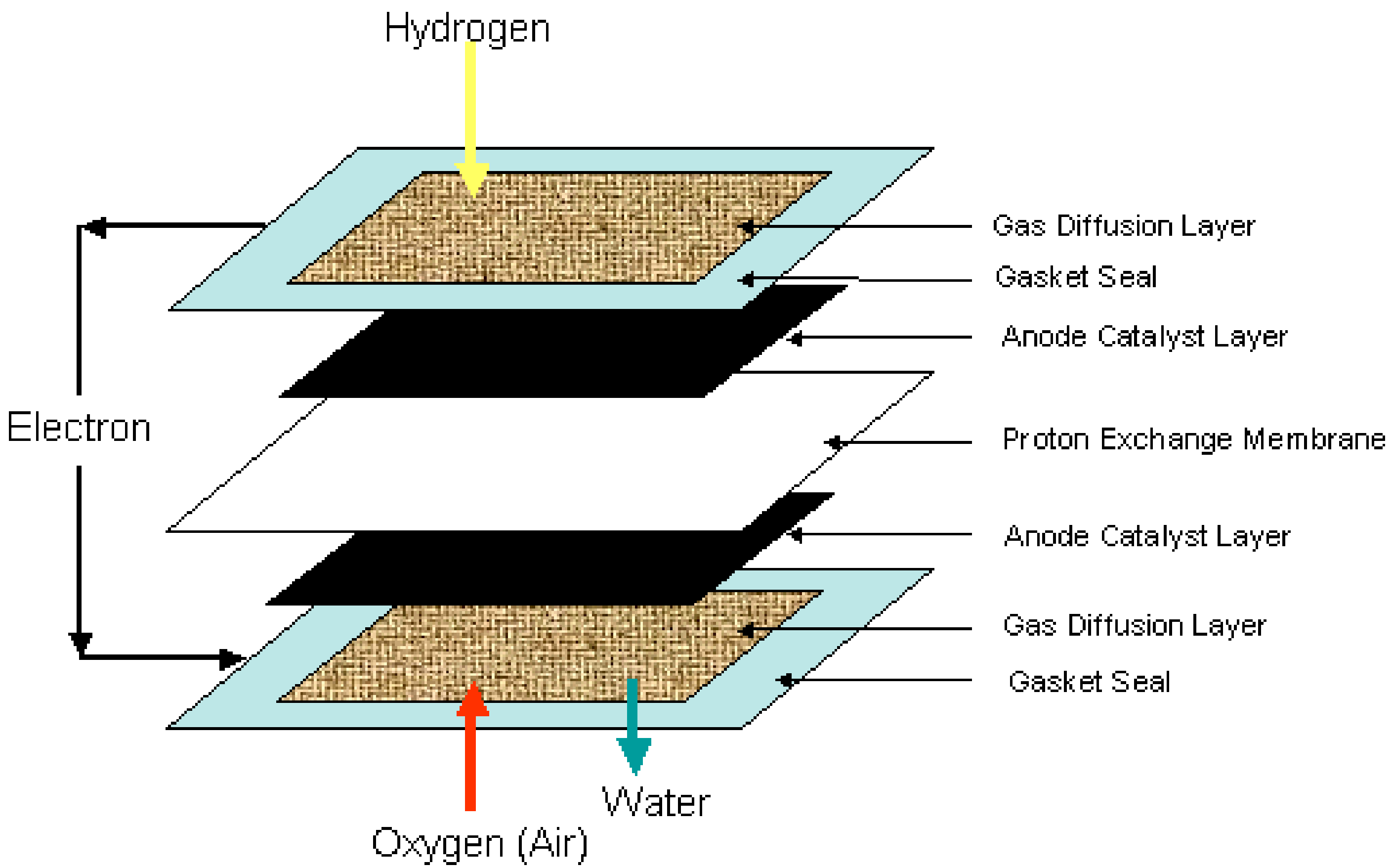


Single cell scheme

SINGLE CELL HARDWARE



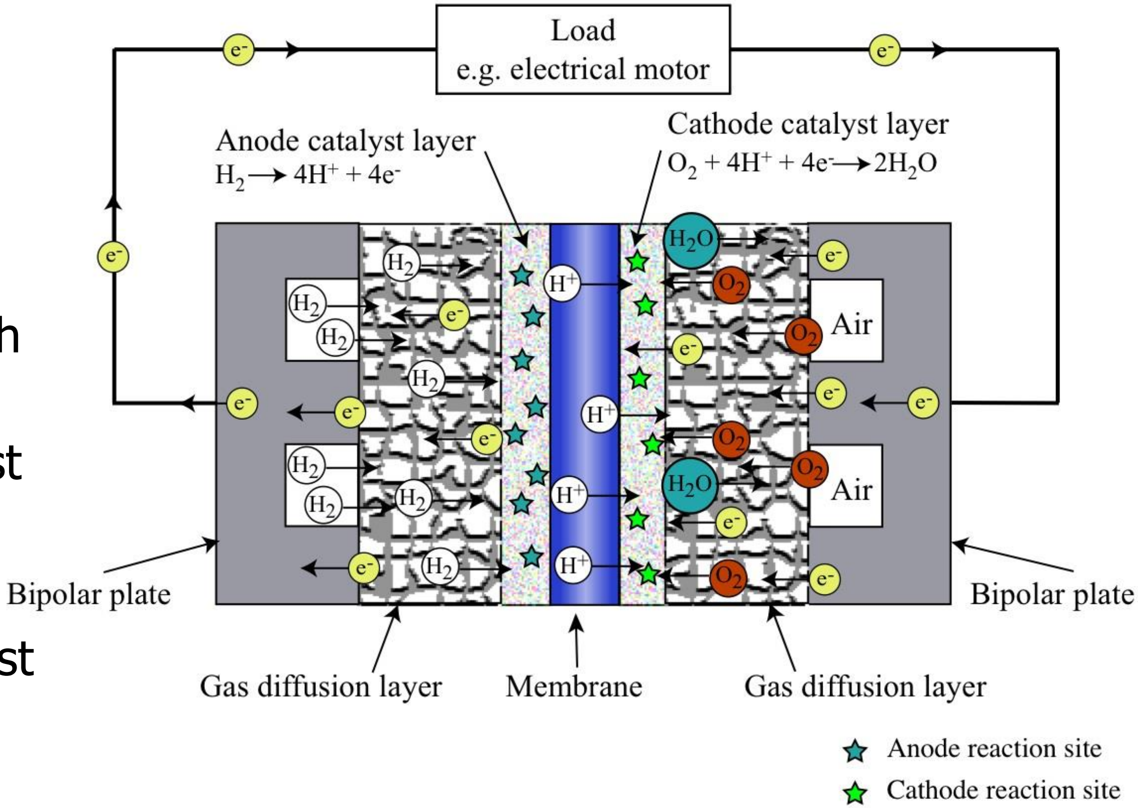
Membrane Electrode Assembly (MEA)



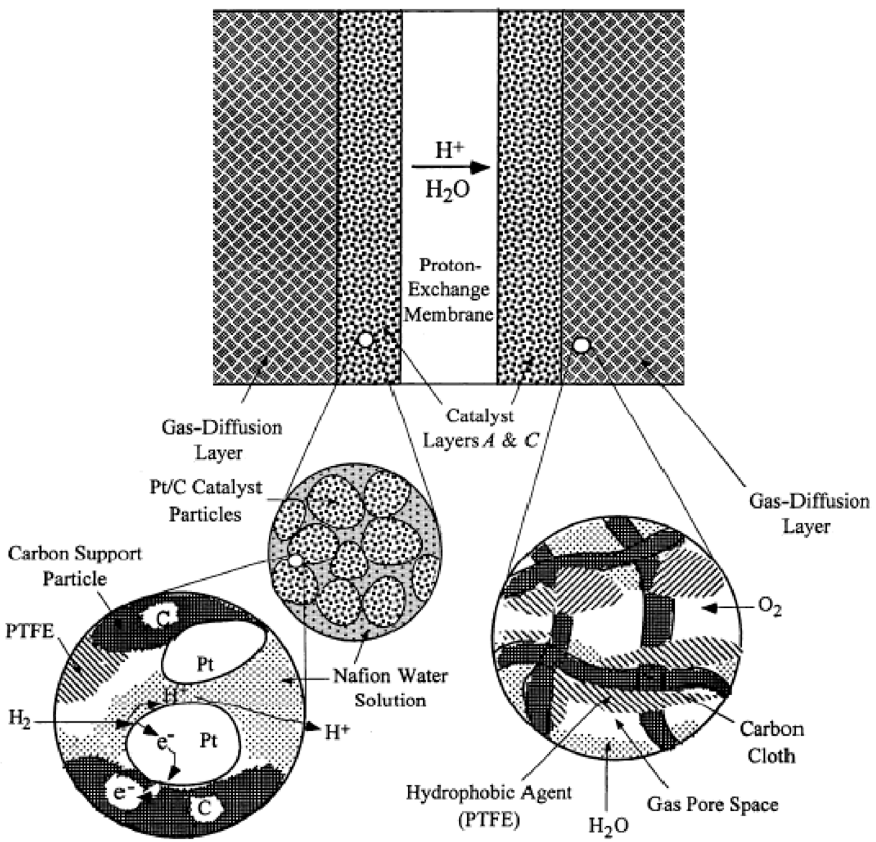
■ Construction of MEA (Membrane Electrode Assembly)

Single cell mechanisms

- Mechanisms at electrodes:
  - Reactants are brought by convection
  - Diffusion towards the reaction anode sites through gas diffusion layer
  - Reaction of H_2 using catalyst
  - Dissolution into the electrolyte
  - Reaction H_2-O_2 using catalyst
  - Diffusion of products towards the gaseous phase
  - Elimination by convection



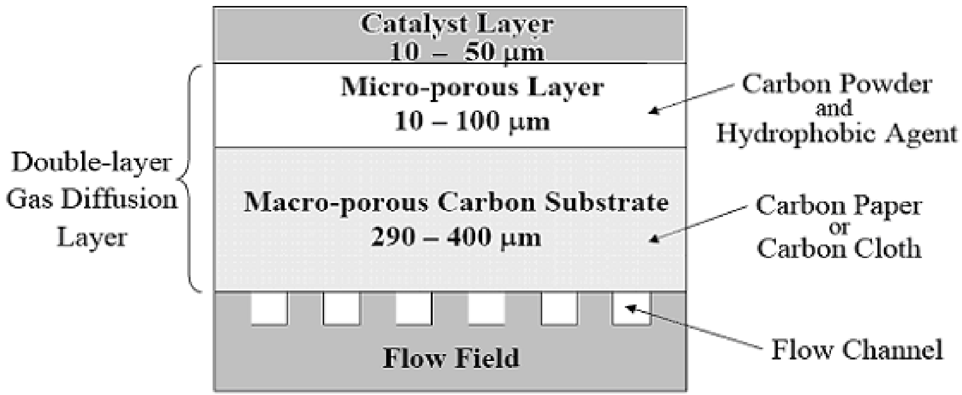
Membrane Electrode Assembly



Catalysts and catalyst layers

- Considerable effort has been made in researching efficient electro catalysts.
- To date, the best PEM fuel cell anode and cathode catalysts are still platinum-based.
- To maximize platinum utilization and minimize cost, platinum is finely dispersed on an electrically conducting, relatively chemically inert support such as a *carbon black*. In this manner the amount of active platinum exposed to the reactants is maximized, greatly increasing power density.

Membrane Electrode Assembly



Gas Diffusion Layer

- The gas diffusion layer (GDL) or backing layer is a critical component in an MEA.
- GDL's main function is to distribute the reactant gases while providing a good electronic conductivity, porous conductors such as carbon cloth or paper are commonly used.
- Secondary functions: minimize water flooding and maximize the electronic contact at the interface with the catalyst layer.
- The GDL serves in water management as it removes product water away from the catalyst layer.
- The GDL usually has a dual layer structure :
- 1/ A microporous layer next to the catalyst layer and made from carbon powder and a hydrophobic agent (PTFE).
- 2/ The second layer is a macroporous carbon substrate consisting of the carbon paper or cloth.

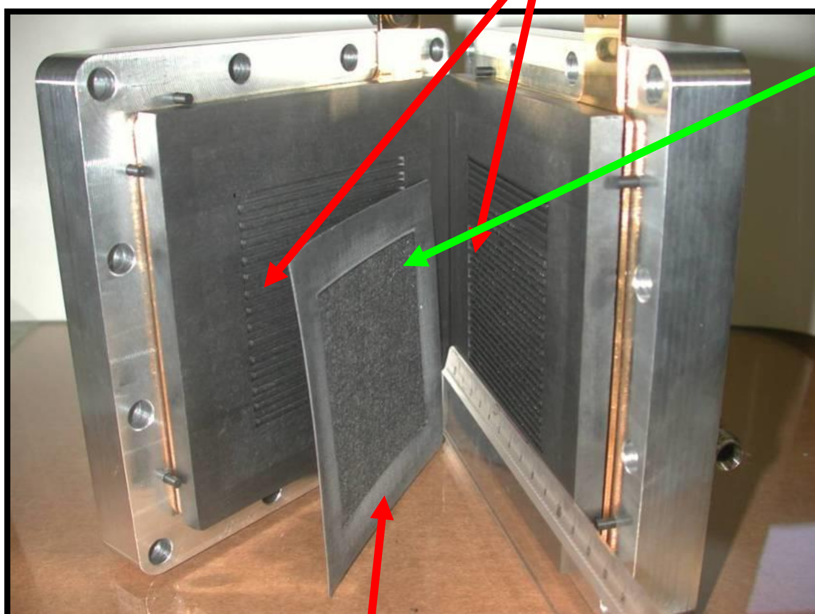
Membrane Electrode Assembly (MEA)

- Anodes:
  - Metal catalyst (Pt, Pd, Rh, etc.) supported on active C
  - Ni of Raney (alkaline fuel cells)
  - Fe, Co, Ni at high temperature (sintered metals or cermet)
- Cathodes:
  - Precious metals at low temperature
  - Ni sintered (or melted carbonates)
  - Mixed oxides (high temperature fuel cells)

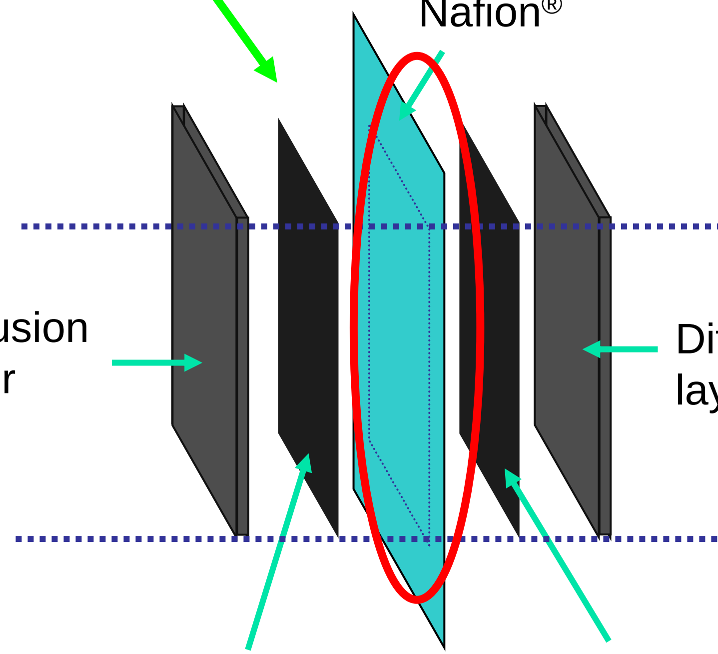
Design of Membrane Electrode Assembly (MEA)

Gas distribution channels carved in the current collectors (graphite)

MEA: Membrane-Electrode Assembly

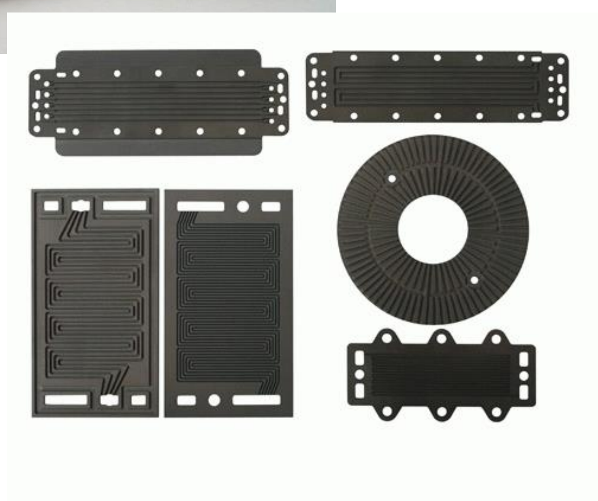


gaskets



Design of Membrane Electrode Assembly

Design

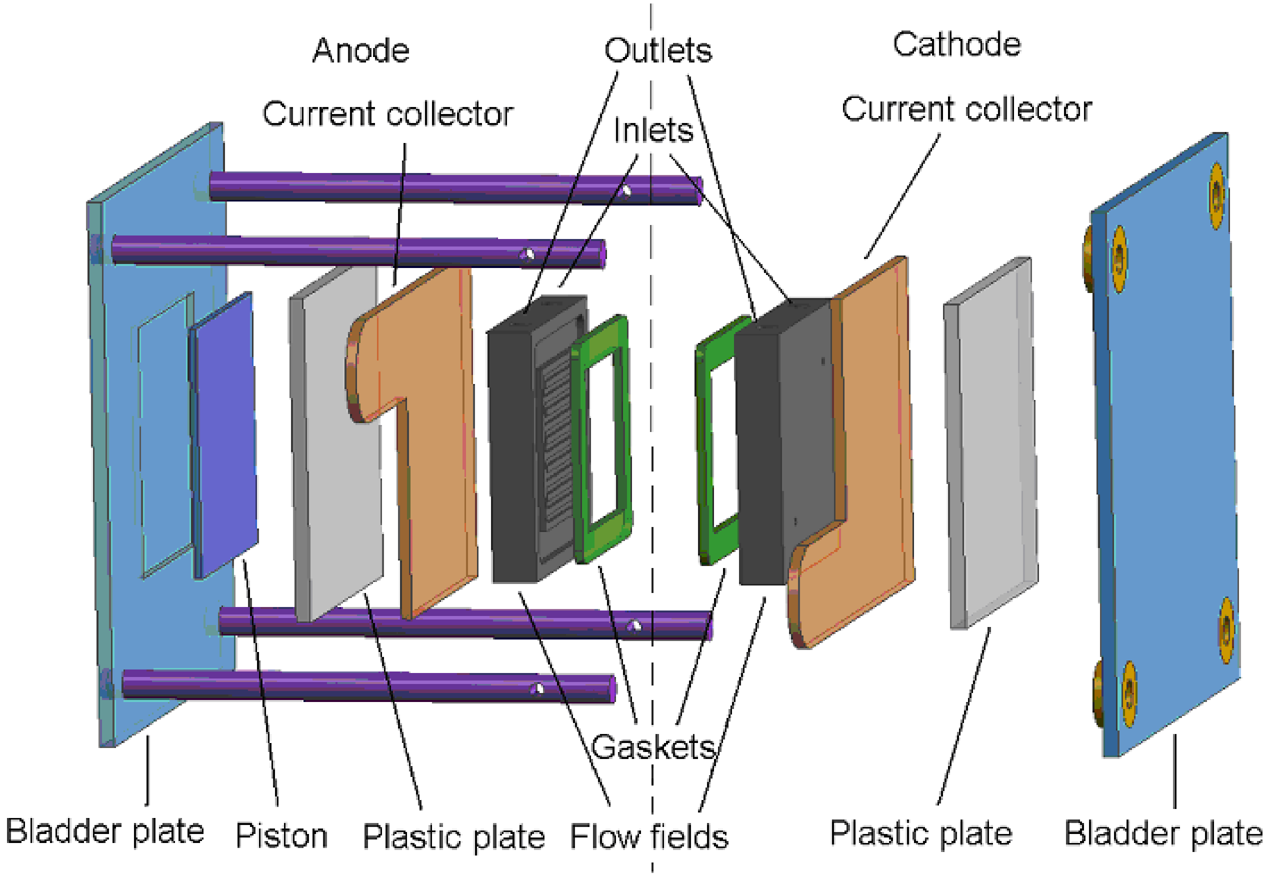


Bipolar plates in carved graphite

COST !

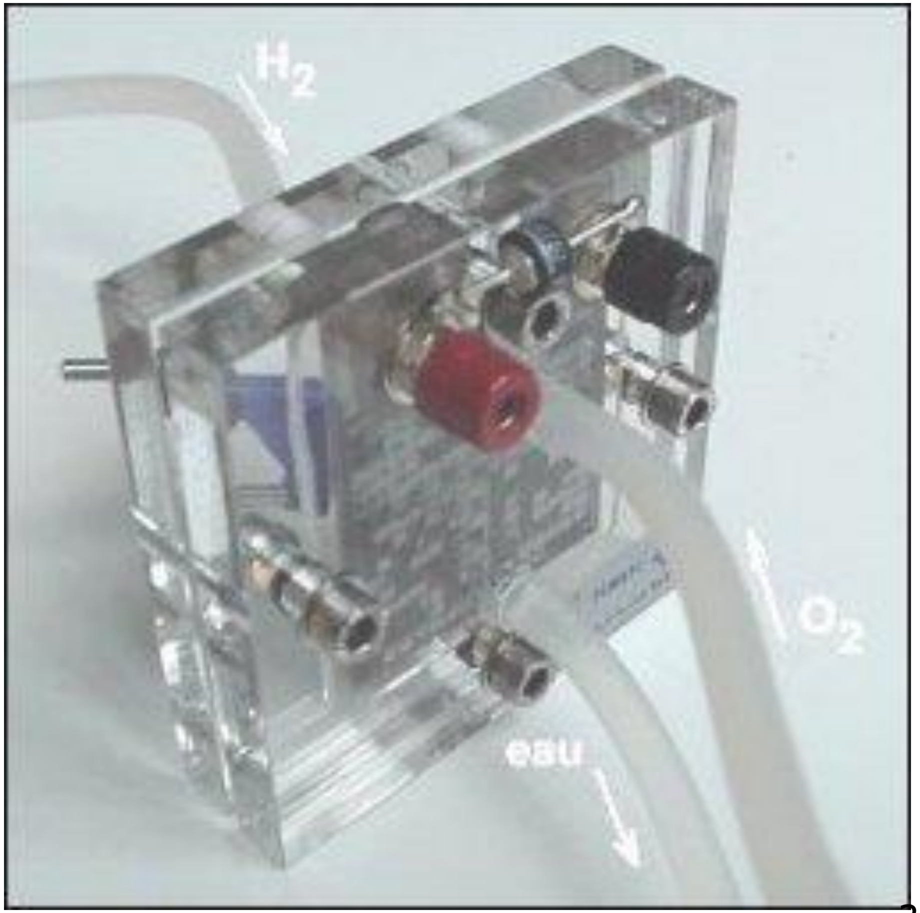
Metal bipolar plates

Fabrication of a single cell

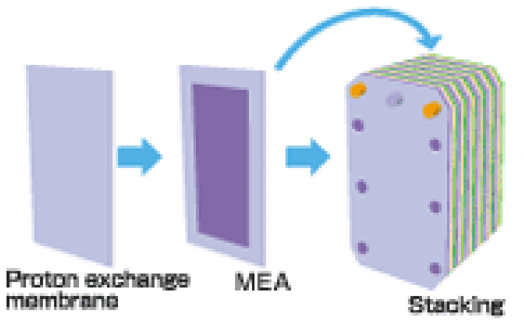


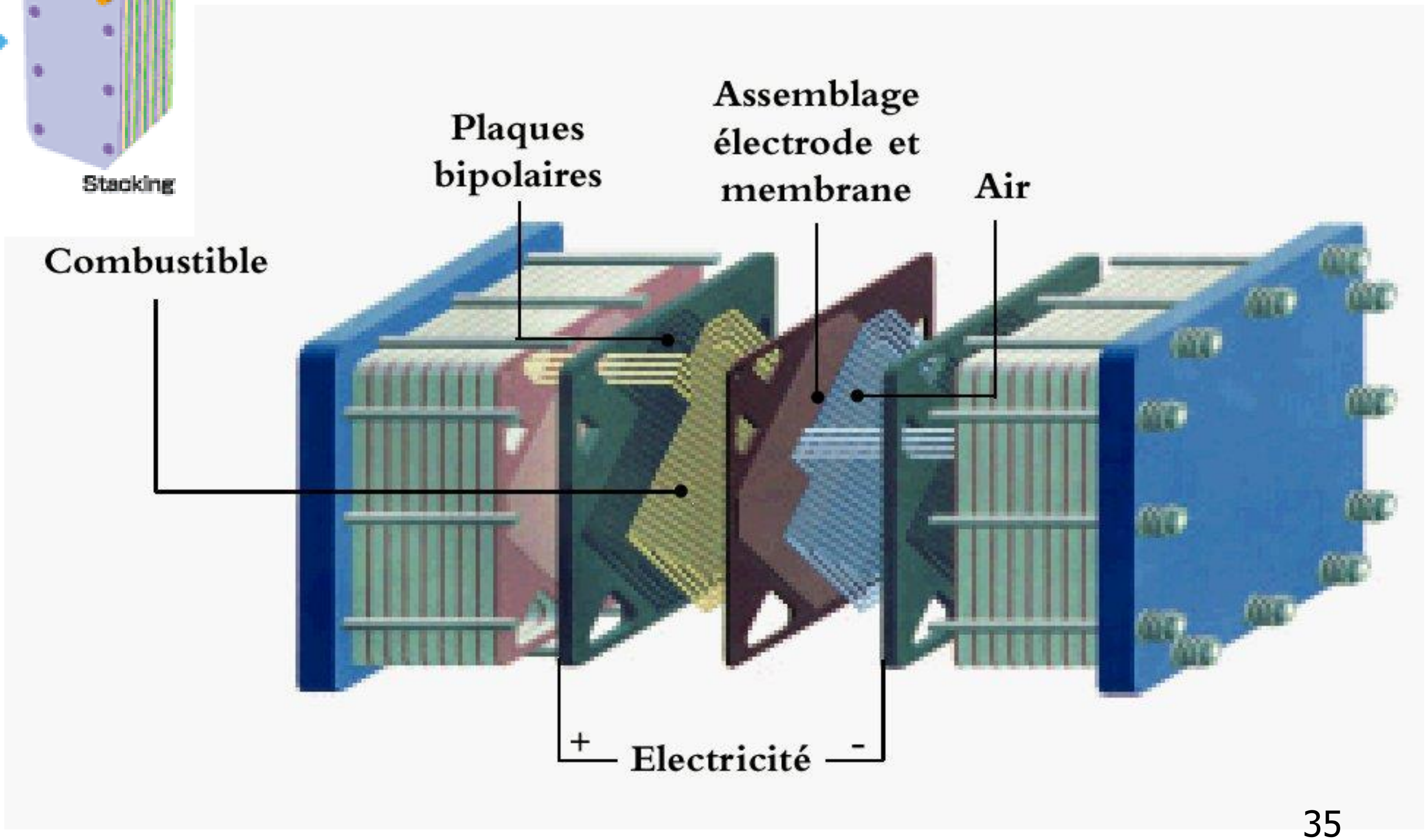
Exploded view of single PEM fuel cell.

Fabrication of a single cell

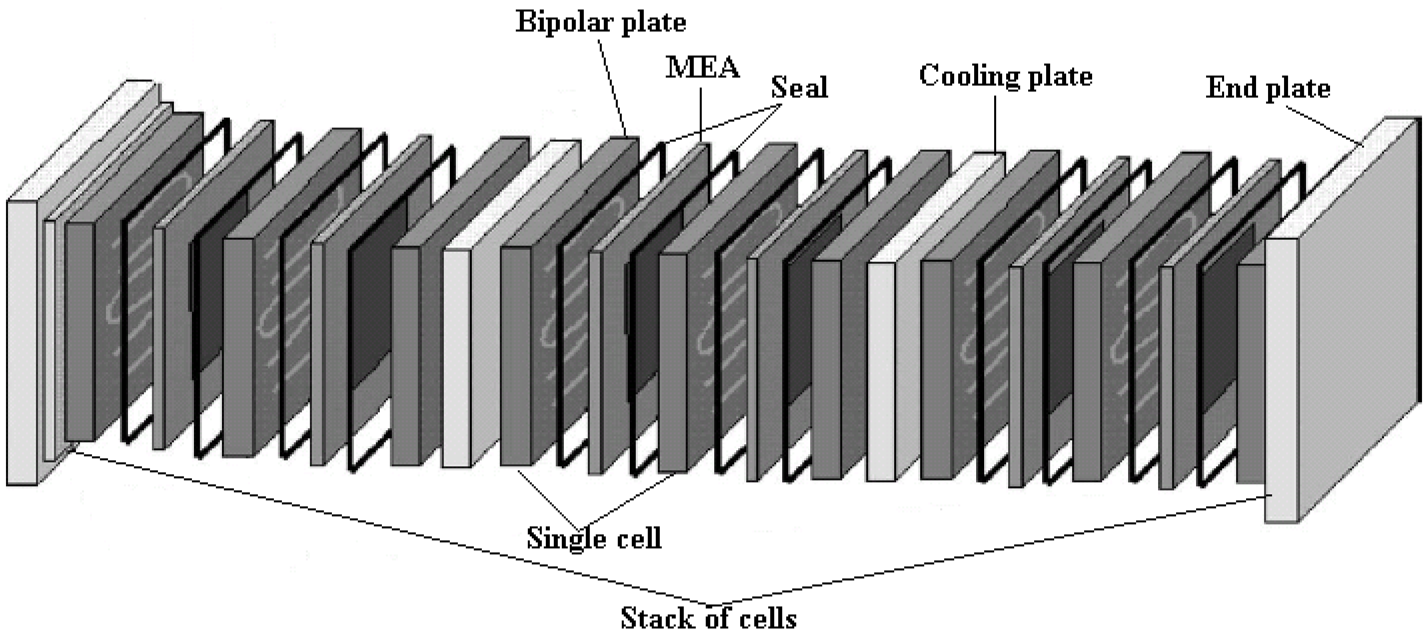


Assembly of a fuel cell stack





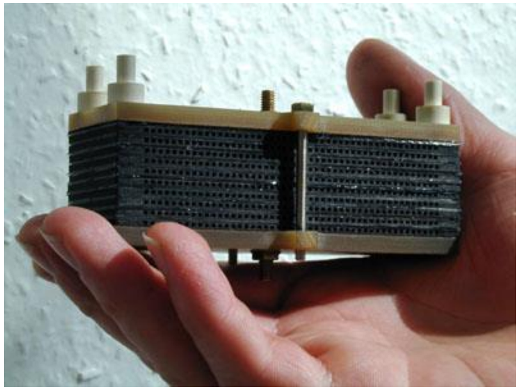
Assembly of a fuel cell stack

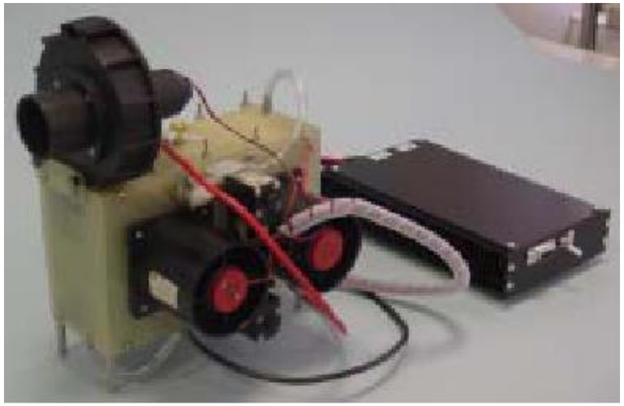


Exploded view of PEM fuel cell stack

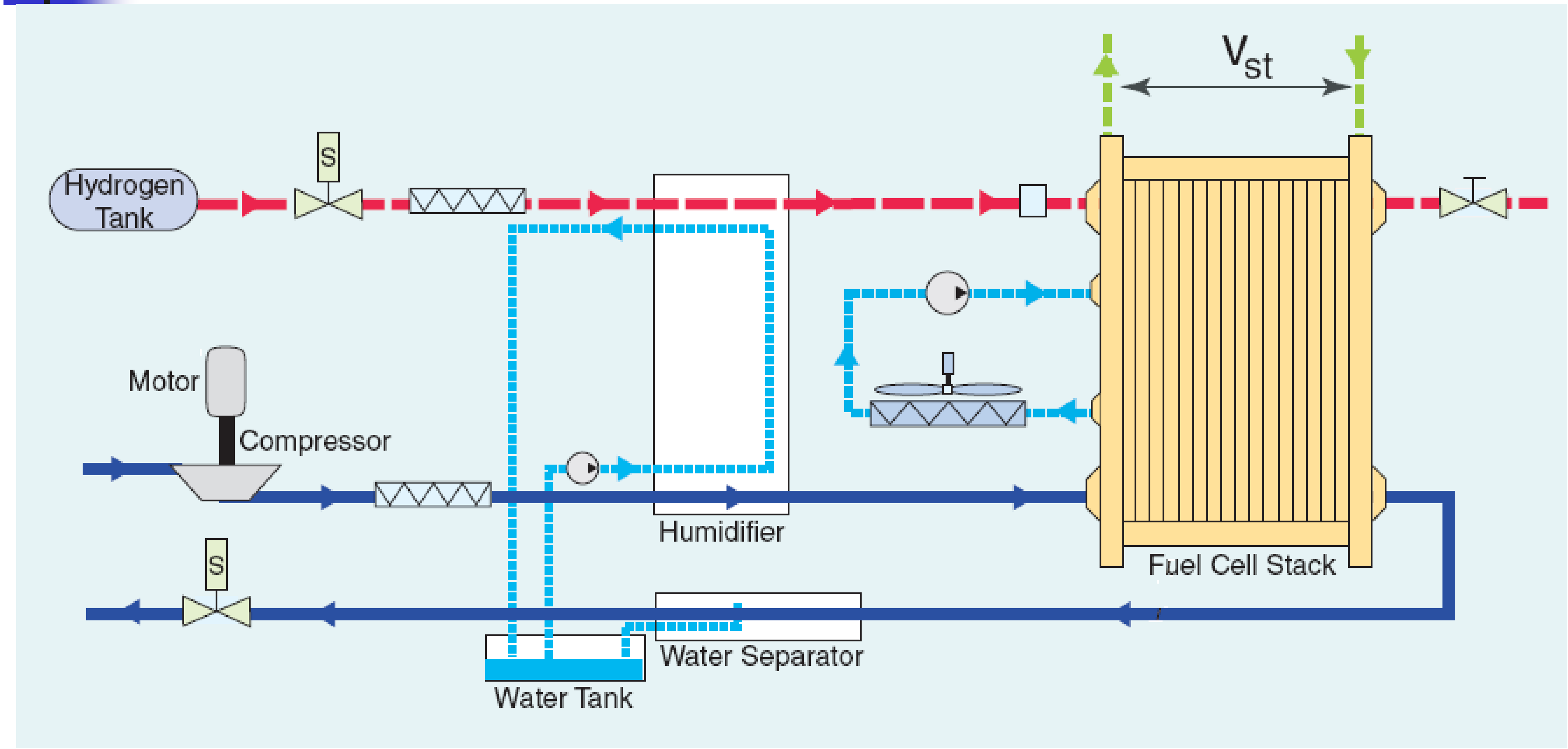
Assembly of a fuel cell stack

- In practice, the single cells are stacked in parallel or serial assembly to shape a fuel cell stack.
- The fuel cell stack power depends on the number and the surface of fuel cells that are compiled.
- The range of power of the stack can span from a few W to several MW.
- One can find miniaturized fuel cell stacks of a few Watts.





Fuel cell systems



Schematic of hydrogen PEM fuel cell system.

Fuel cell systems

- Hydrogen reformer or hydrogen purification. Hydrogen gas rarely occurs naturally on the earth's surface and has to be made from other chemical fuels. Once the hydrogen fuel is made, impurities such as carbon monoxide poisons the cell, necessitating purification and detection systems.
- Air supply. Oxidant must be supplied to the cathode at a specific pressure and flow rate. Air compressors, blowers, and filters are used for this.
- Water management. The inlet reactant gasses must be humidified, and the reaction produces water. Management of water must also consider relative amounts of the two phases.
- Thermal management. Stack temperature must be monitored and controlled through an active or passive stack cooling systems as well as a separate heat exchanger in the case of an active system.

Conversion efficiency of a Fuel Cell

Characteristics of an elementary fuel cell

- Work of the fuel cell = variation of free energy (Gibbs)

$$W_{max} = -\Delta G$$

$$W_{utile} = nF(E_a - E_c) \quad F = 96500 \text{ C/mol}$$

- Maximum voltage

$$(E_a - E_c) = -\frac{\Delta G}{nF}$$

- Example: $H_2 + 1/2\, O_2 \rightarrow H_2O(g)$
  - ΔG = -229 kJ/mol $H_2(g)$ ΔG = -237 kJ/mol $H_2(l)$
  - E_{max} = 1,18 V E_{max} = 1,23 V

Characteristics of an elementary fuel cell

- The maximum voltage at the fuel cell depends also of the temperature. Indeed

$$\Delta G = \Delta H - T\Delta S$$

$$(E_a - E_c) = -\frac{\Delta H - T\Delta S}{nF}$$

- In case of a reduction of the number of molecules (case of fuel cells H_2/O_2), there is a reduction of entropy $\Delta S<0$ and the absolute value of ΔG is reduced with the temperature.

- Example H_2/O_2
  - 25°C: 1,18V 650°C: 1,02V 1000°C: 0,92V

Characteristics of an elementary fuel cell

- <u>Energy efficiency</u>

$$\eta = \frac{W_{elec}}{\Delta H} \qquad \qquad \eta = 1 - \frac{T\,\Delta S}{\Delta H}$$

- Example $H_2 + 1/2\,O_2 \rightarrow H_2O(g)$

  - ΔH = -242 kJ/mol (PCI)
  - ΔG = -229 kJ/mol
  - η = 95% à 25°C (74% à 1000°C)

- In practice the efficiency is inferior to this theoretical value because of irreversibilities

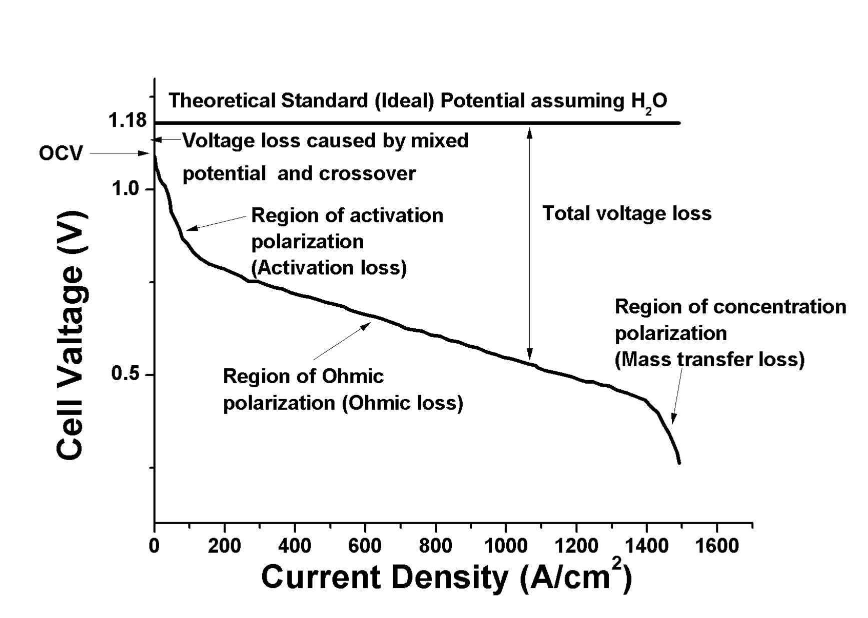
Characteristics of an elementary fuel cell

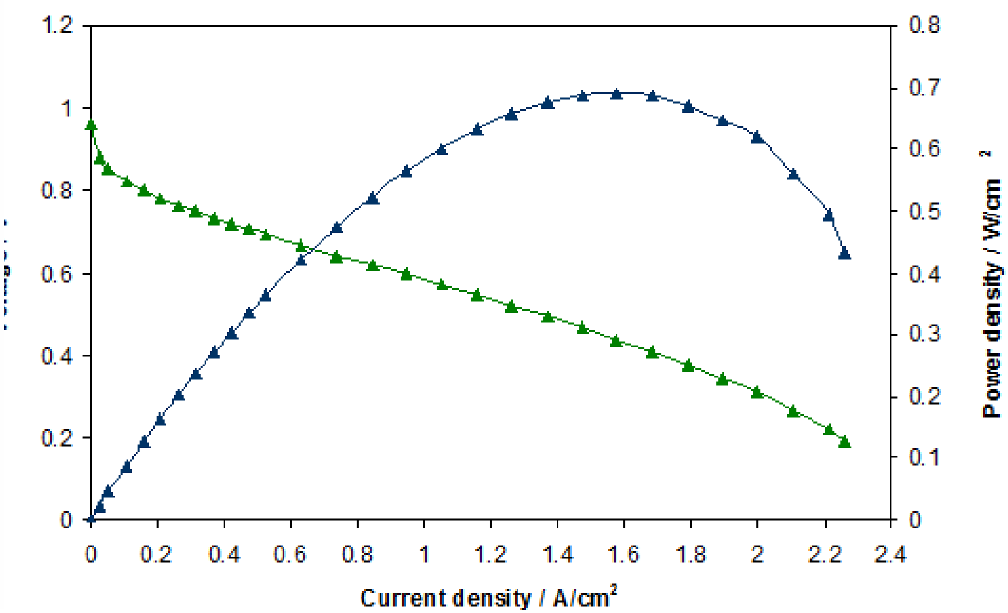
Efficiency of the H_2/O_2 fuel cell compared to the Carnot efficiency (Tu=300K)

Characteristics of fuel cells

- Real characteristics of fuel cells → Limitations of fuel cells
- Irreversibility : gradients & friction
  - Gradient of concentrations
  - Gradient of temperatures
  - Gradient of pressure
  - Joule effects
  - Other factors

Characteristics of an elementary fuel cell

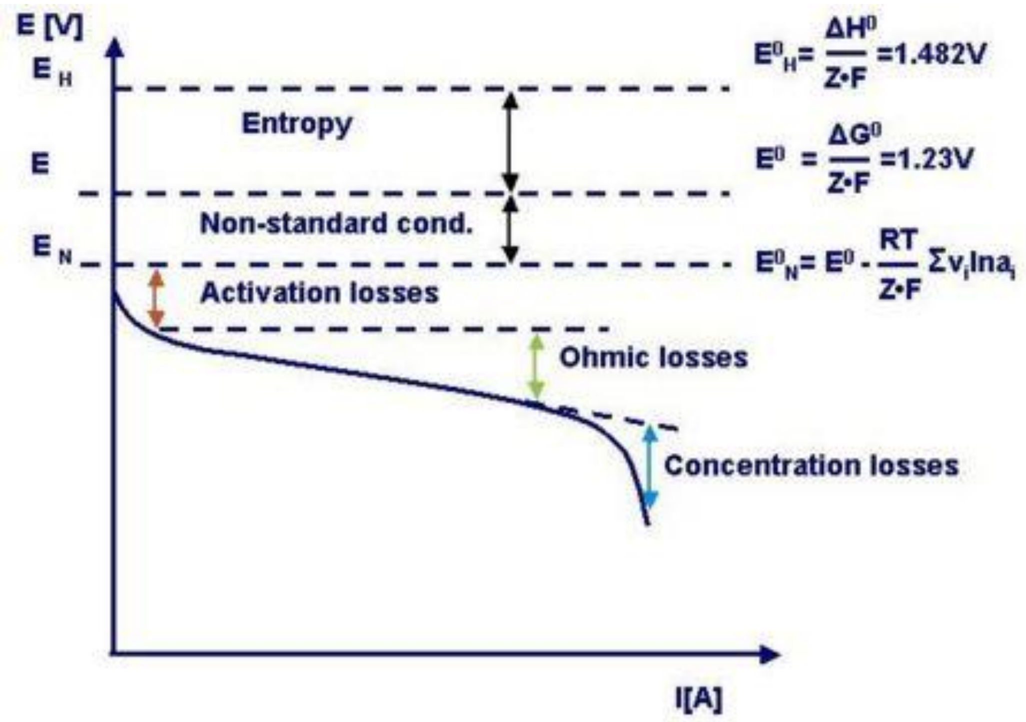




Polarization curve of the FC: voltage-current density curve

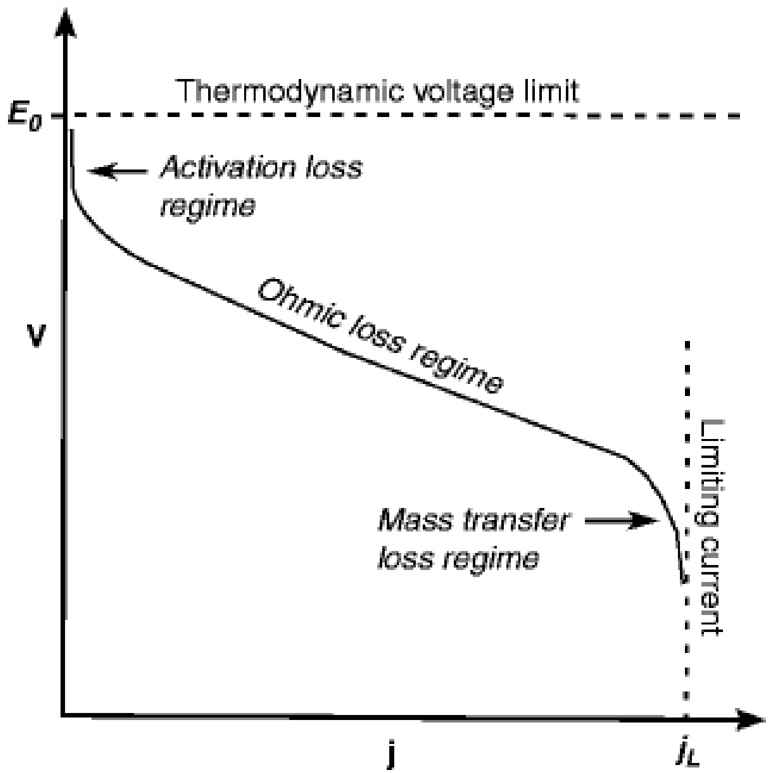
Characteristics of an elementary fuel cell

- Loss of efficiency due to over tension and polarization, and the reduction of voltage:
  - Open circuit losses: ΔG instead of ΔH (entropy) and nonstandard conditions ($T \neq T_0$, $p \neq p_0$).
  - Operational losses: Activation losses, Ohmic losses, Concentration polarization



Characteristics of an elementary fuel cell

$$U_{FC} = U_{rev} - U_{act} - U_{Ohm} - U_{conc}$$



Polarization curve of the FC: voltage-current density curve

- Generally, on distinguishes three domains in the experimental voltage-current curves of FC. There are three main operational losses are often referred to as
  - Activation polarization: kinetic and activation energy related to the irreversibility of reactions
  - Ohmic losses: resistance of the ionic conduction
  - Concentration polarization losses: mass transfer resistance of reactants and products

Characteristics of an elementary fuel cell

- 1/ Activation loss regime: Even for zero and very low currents, there are irreversible losses. These stem from the activation energy of the electrochemical reactions at the electrodes [mainly at cathode electrode (oxygen)].
- These losses depend on the reactions at hand, the electro-catalyst material and microstructure, reactant activities (and hence utilization), and weakly on current density. They are related to the energy required to initiate the reactions and the finite speed (kinetic) of electrochemical reactions.
- The activation losses related to charge transfer are ruled by the Butler Volmer law. This law can be approximated by the semi empirical Tafel law

$$U_{act} = c_0 + c_1 \ln(i_{FC}(t))$$

- Or it's empirical approximation

$$U_{act} \simeq c_0(1 - e^{-c_1 i_{FC}(t)})$$

Characteristics of an elementary fuel cell

- 2/ Ohmic loss regime: For intermediate current density, where the FC is generally used, the losses increase linearly with the current density. It is typical from ohmic losses due to internal resistance of the ion current across the electrolyte and the membrane, and the electronic resistance in the electrodes, current collectors and interconnects, and contact resistances.
- Ohmic losses are proportional to the current density.
- They depend on materials selection and stack geometry, and on temperature.

$$U_{Ohm} = i_{FC}\,\bar{R}_{FC}$$

Characteristics of an elementary fuel cell

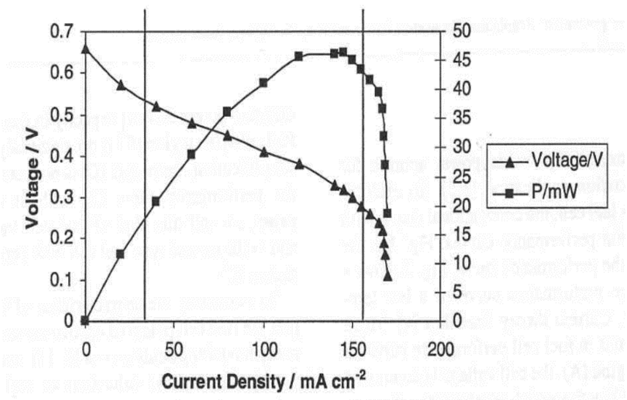
- 3/ Mass transfer loss regime: For high current densities, the losses increase drastically.
- The over tensions result from the finite mass transport limitations rates of the reactants and the products of the reaction to and from the electrodes.
- These losses depend strongly on the current density, reactant activity, and electrode structure. It is therefore also denominated as the concentration polarization.
- Concentration loss are generally expressed by the law

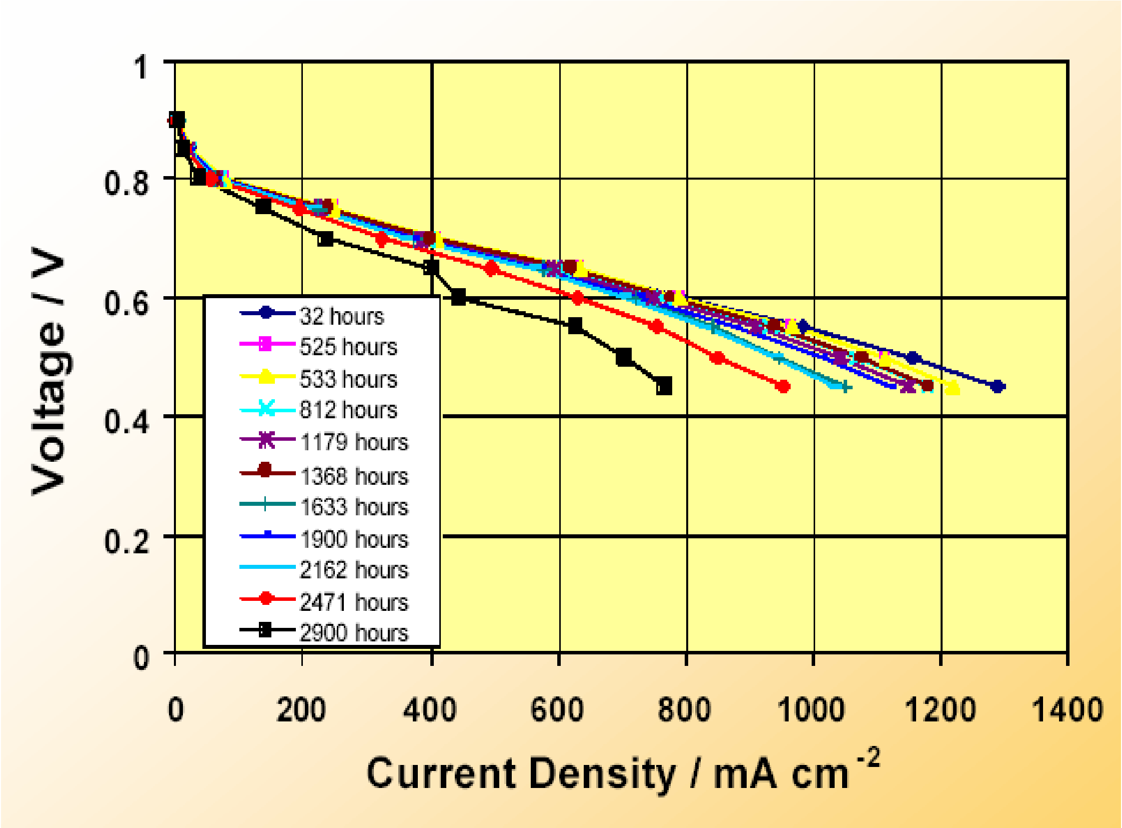
$$U_{conc} = c_2 \, i_{FC}^{c_3}(t)$$

- Or alternatively

$$U_{conc} = c_2 \, e^{c_3 \, i_{FC}(t)}$$

Characteristics of an elementary fuel cell





Loss of efficiency

- The reversible efficiency is calculated as the ratio between the theoretical (reversible) voltage and the actual voltage measured at the ports:

$$\eta_{elec} = \frac{U}{E_{rev}}$$

- This efficiency also depends on the catalyst, the health state of electrodes, material selection, choice of oxidant (pure oxygen of from air), ambient conditions (temperature, pressure)

Loss of efficiency

- Faradic efficiency
  - Take care of the number of electrons actually participating to the electrochemical reaction compared to the electrons liberated by the oxidoreductase per mole of fuel
  - For hydrogen H_2: efficiency is close to 1,0
  - For methanol FC, one has secondary reactions (formaldehydes, formic acid) ➔ efficiency can drop to 0,66 or even 0,33
  - Account also for internal short circuits

- Material efficiency
  - Take into account for the (uncompleted) usage of the input fuel at the level of electrodes
  - Generally one admits more than the stoichiometric fraction ratio of air (1,7) and of H_2 (1,4)
  - H_2 is not fully utilized

Loss of efficiency

- System efficiency
  - In mobile and stationary applications, the fuel cell does not work isolated.
  - Several auxiliaries are necessary: air compressors, control systems, thermal control, reforming and purification of H_2 (desulfuration, Hydrogen purification, heat exchangers)
  - Generally they have a global efficiency of 80%

Global efficiency of the FC system

- Global efficiency of the fuel cell

$$\eta_{FC} = \eta_{elec}\,\eta_u\,\eta_f\,\eta_m\,\eta_{sys}$$

- Numerical example H_2/O_2 @ 80°C, PEMFC with actual voltage of 0,7V for 350 mA/cm²
  - Reversible efficiency (thermodynamics) : 0,936
  - ➔ Electrical efficiency : 0,60
  - Faradic efficiency: 1
  - Material efficiency: 0,9
  - System efficiency: 0,8
  - <u>Total: 40,4%</u>

Fuel cell technologies

Fuel cell technologies

- One distinguishes 6 types of fuel cells:
  - AFC: Alkaline Fuel Cell
  - PEMFC: Polymer Exchange Membrane Fuel Cell
  - DMFC: Direct Methanol Fuel Cell
  - PAFC : Phosphoric Acid Fuel Cell
  - MCFC: Molten Carbonate Fuel Cell
  - SOFC: Solid Oxide Fuel Cell

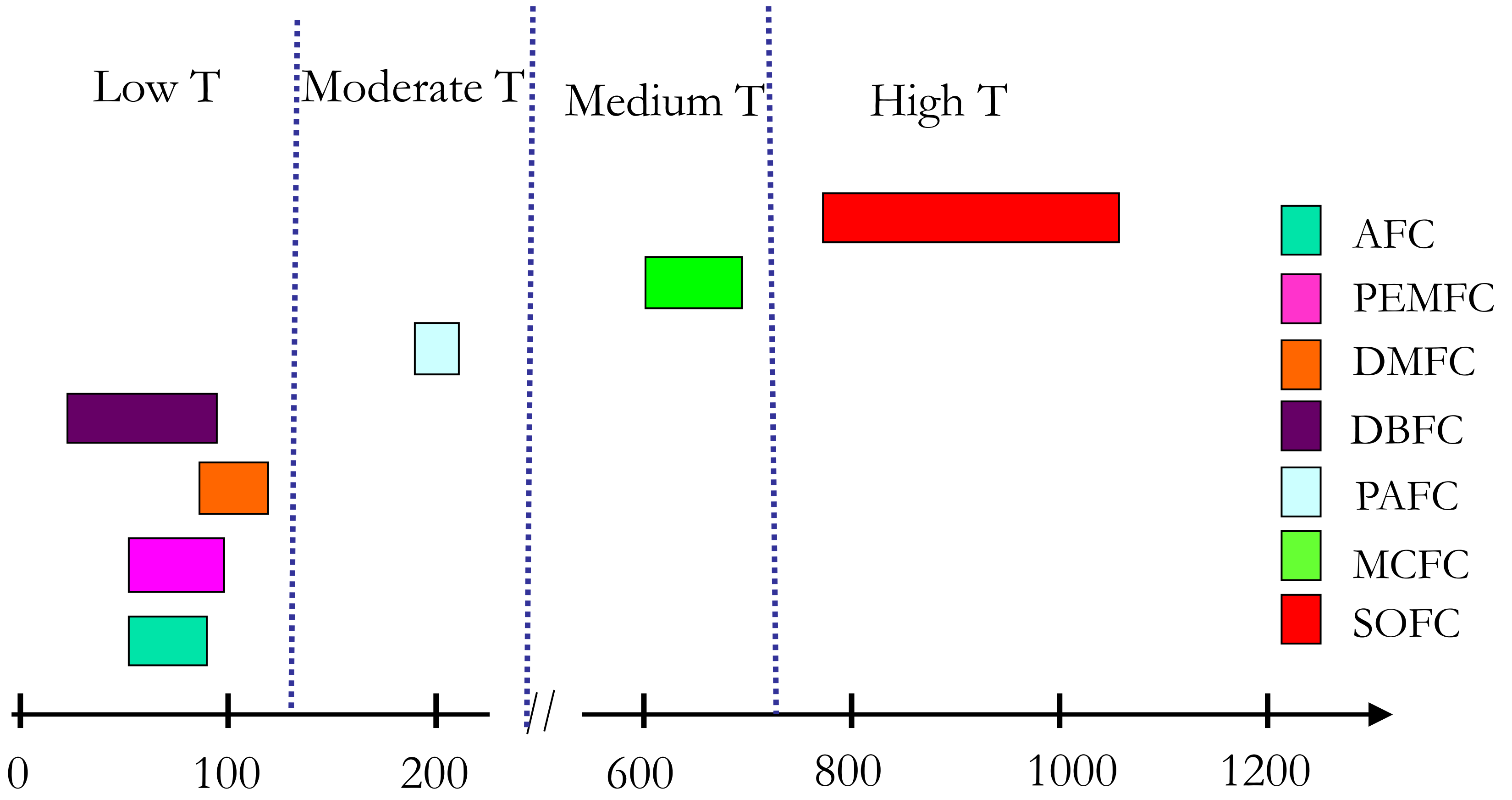
Fuel cell technologies

- The different fuel cell technologies are characterized by:
  - The type of fuel: hydrogen, methanol, natural gas
  - The nature of the electrolyte
  - The kind of the transported ions: H^+, OH^- or carbonate $CaCO_3$--
  - The operating temperature
  - The architecture of the fuel
  - The size of the application (buildings, vehicle, electricity power plant, computer, portable communication equipment and by the nature of the application (mobile or stationary))
  - The typical power range
  - The conversion efficiency
  - The technology maturity or technological readiness level (TRL)
  - The cost per kW

Fuel cell technologies

Fuel cell name	Electrolyte	Qualified power (W)	Working temperature (°C)	Efficiency (cell)	Efficiency (system)	Status	Cost (USD/W)
Direct borohydride fuel cell	Aqueous alkaline solution		70			Research	
Alkaline fuel cell	Aqueous alkaline solution	10 – 100 kW	< 80	60–70%	62%	Commercial / Research	
Direct methanol fuel cell	Polymer membrane (ionomer)	100 mW – 1 kW	90–120	20–30%	10–20%	Commercial / Research	
Reformed methanol fuel cell	Polymer membrane (ionomer)	5 W – 100 kW	250–300 (Reformer) 125–200 (PBI)	50–60%	25–40%	Commercial / Research	
Proton exchange membrane fuel cell	Polymer membrane (ionomer)	100 W – 500 kW	50–120 (Nafion) 125–220 (PBI)	50–70%	30–50%	Commercial / Research	30–35
Phosphoric acid fuel cell	Molten phosphoric acid (H_3PO_4)	< 10 MW	150-200	55%	40% Co-Gen: 90%	Commercial / Research	4–4.50
Molten carbonate fuel cell	Molten alkaline carbonate	100 MW	600-650	55%	47%	Commercial / Research	

Fuel cell technologies

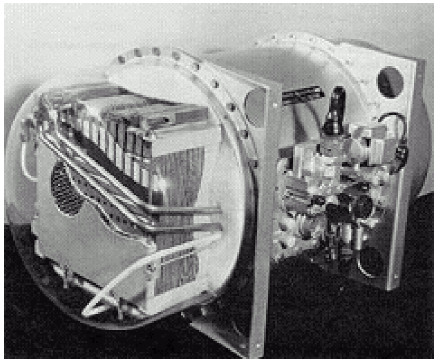


Fuel cell technologies

- Low temperature T (80-90°C)
  - Proton Exchange membrane FC (PEM)
  - Alkaline fuel cell (AFC)
  - Direct methanol FC (DMFC)
- Moderate temperature (200°C)
  - Phosphoric Acid FC (PAFC)
- Medium temperature(600-700°C)
  - Melted Carbonate FC (MCFC)
- High temperature (900-1000°C)
  - Solid Oxide FC (SOFC)

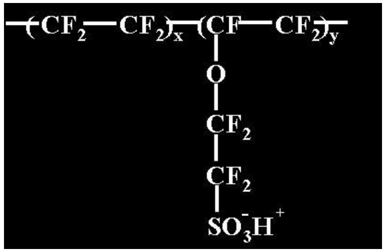
Piles alkaline fuel cells

- Electrolyte: KOH solution 30-45%
- Temperature 60-90°C at atmospheric pressure (T higher at higher pressure)
- Electrodes: Ni or Pt at anode and coal +Ag at cathode
- Fuel: H_2 and oxidizer: O_2
- Ions: OH^-
- Power: 70-100 mW/cm²
- Low tolerance: a few ppm of CO and CO_2 in H_2 and air
  - CO is a poison of KOH → K_2CO_3
- Developed in Belgium by HYDROGENICS
- Examples of application:
  - Spaceship vessels (Gemini, Apollo)
- Technological Readiness Level: industrial level



Polymer exchange membrane

- Temperature 60-100°C; pressure between 1 and 5 bars
- Fuel: H_2 pure or from reforming - Oxidizer: O_2 (air)
- Ions H^+
- Electrolyte: conducting polymer membrane
  - Thickness: 50-100µm
  - Sulfonated tetrafluoroethylene based fluoropolymer-copolymer (Nafion)
  - High cost: 500€/m²
  - Hygrometric constraint: water saturation
- Catalyst of anode: Pt (0,5 – 2 mg/cm²)
- Inter connection plate: graphite machine tooled
- Tolerant of a few ppm of CO



Polymer exchange membrane

- Power: 200-400 mW/cm²
- Examples of applications: vehicles, portable systems, cogeneration, marine
- Manufacturers: ex. Ballard (Canada), Horizon, MES…
- Development level : prototype or pre industrial level
- Prototypes 250 kW (env. 1kW / litre)

Application: Ballard
250 kW + heat
Alsthom, Promocell

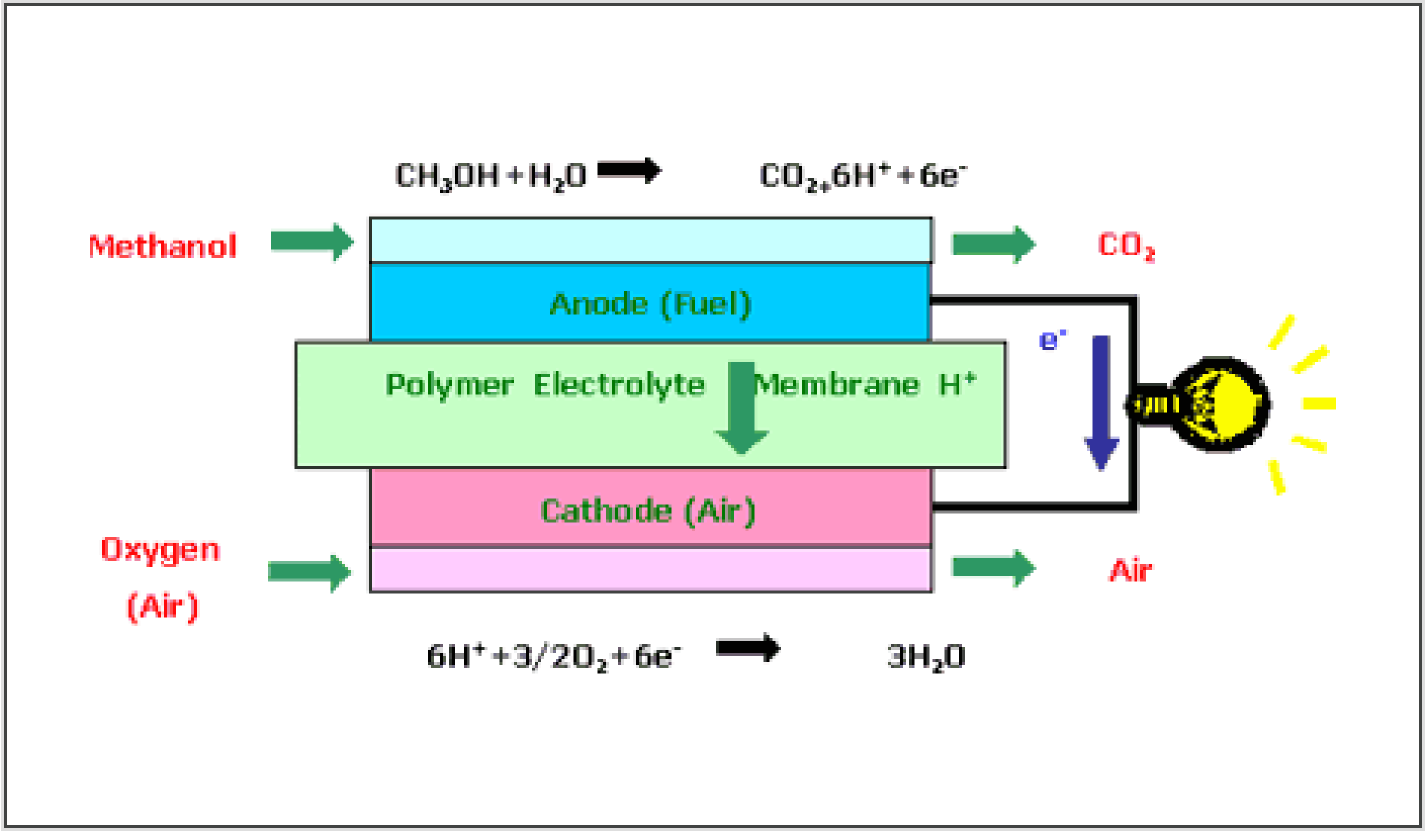
Direct Methanol Fuel Cell

- Anode: methanol supply (CH_3OH)

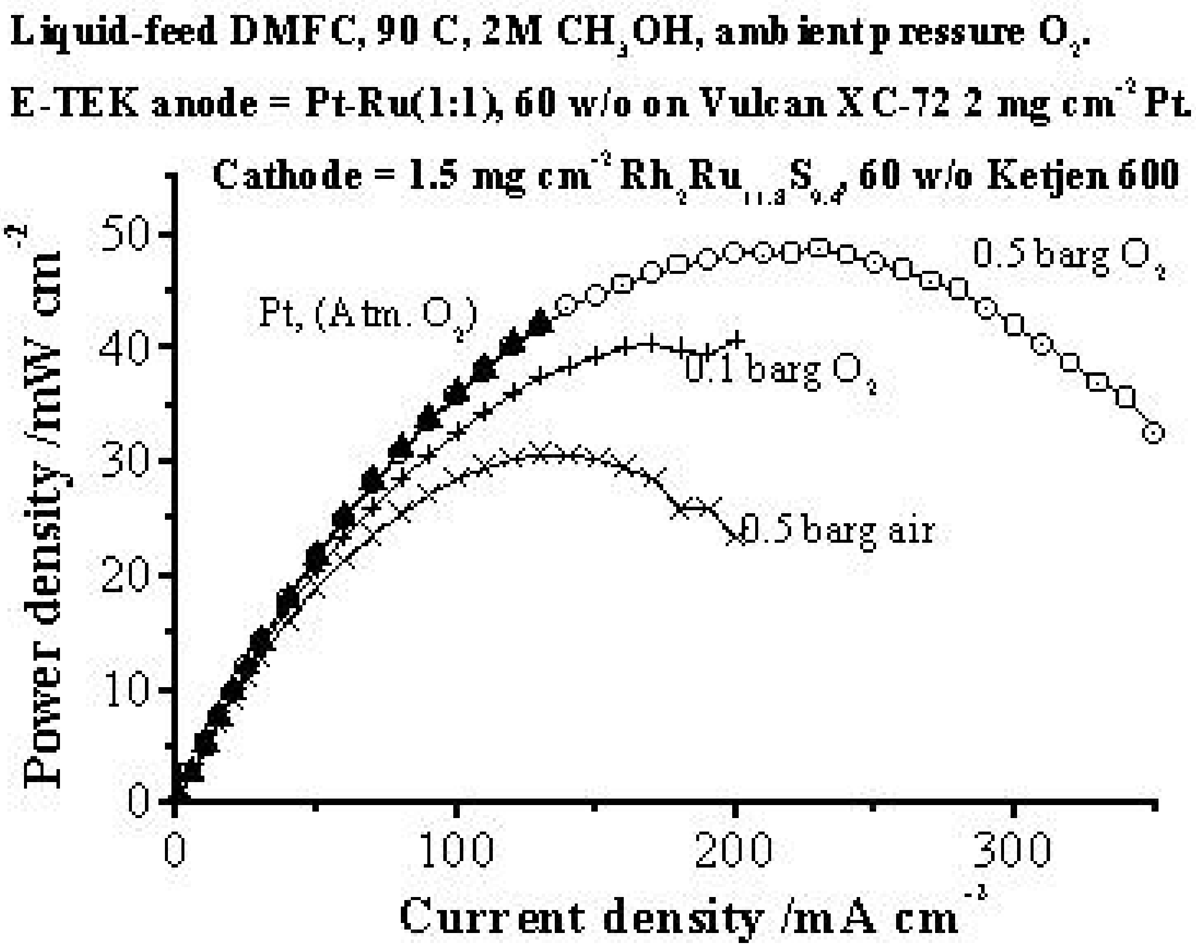
$$CH_3OH + H_2O \rightarrow CO_2 + 6\,H^+ + 6\,e^-$$

- Cathode: oxygen oxidizer (O_2)
- Temperature 60-100°C; pressure between 1 and 5 bars
- Fuel: methanol - Oxidizer: O_2 (air)
- Ions H+
- Electrolyte: polymer exchange membrane

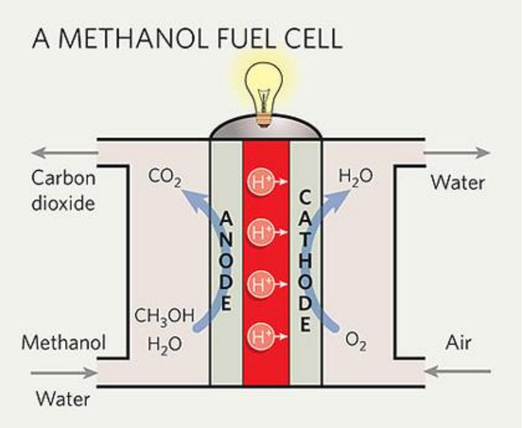
Direct Methanol Fuel Cell



Direct Methanol Fuel Cell



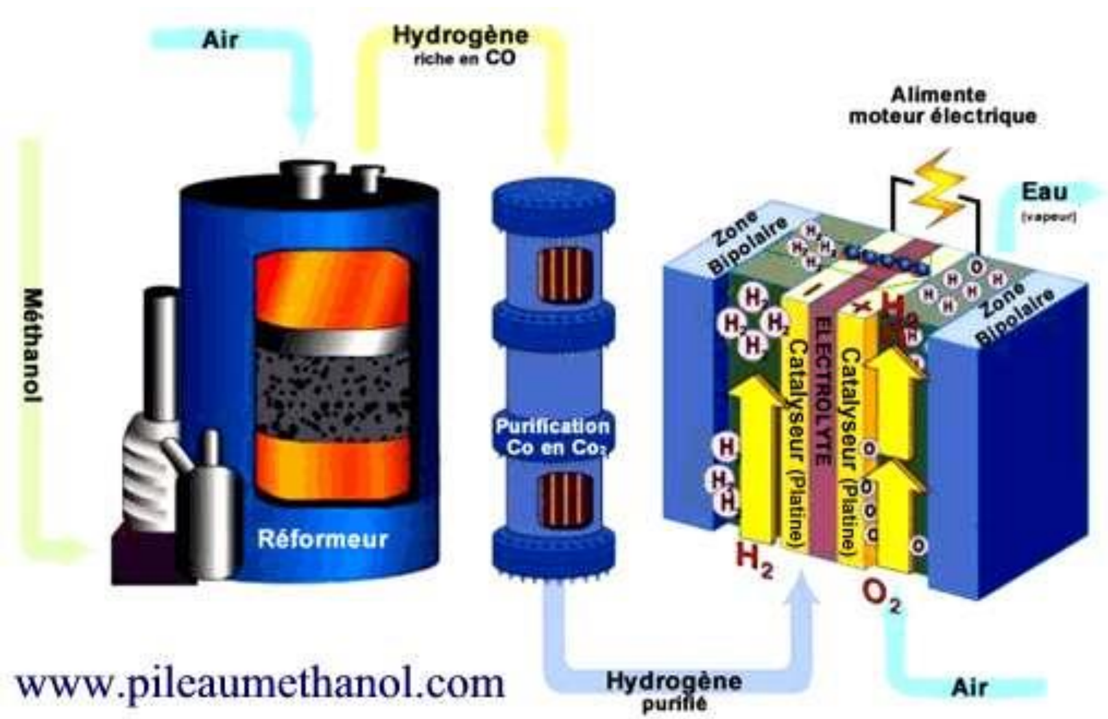
Direct Methanol Fuel Cell



- Disadvantages:
  - Activity of methanol is lower than H_2
  - Secondary reactions
  - Lower efficiency than PEMFC with H_2 (2/3 à 1/3!)
- Advantages:
  - Methanol is liquid so that it is easier to transport, to store and to refuel compared to H_2 (gas)
- Applications: portable equipment (GSM, PC)
- TRL: prototype

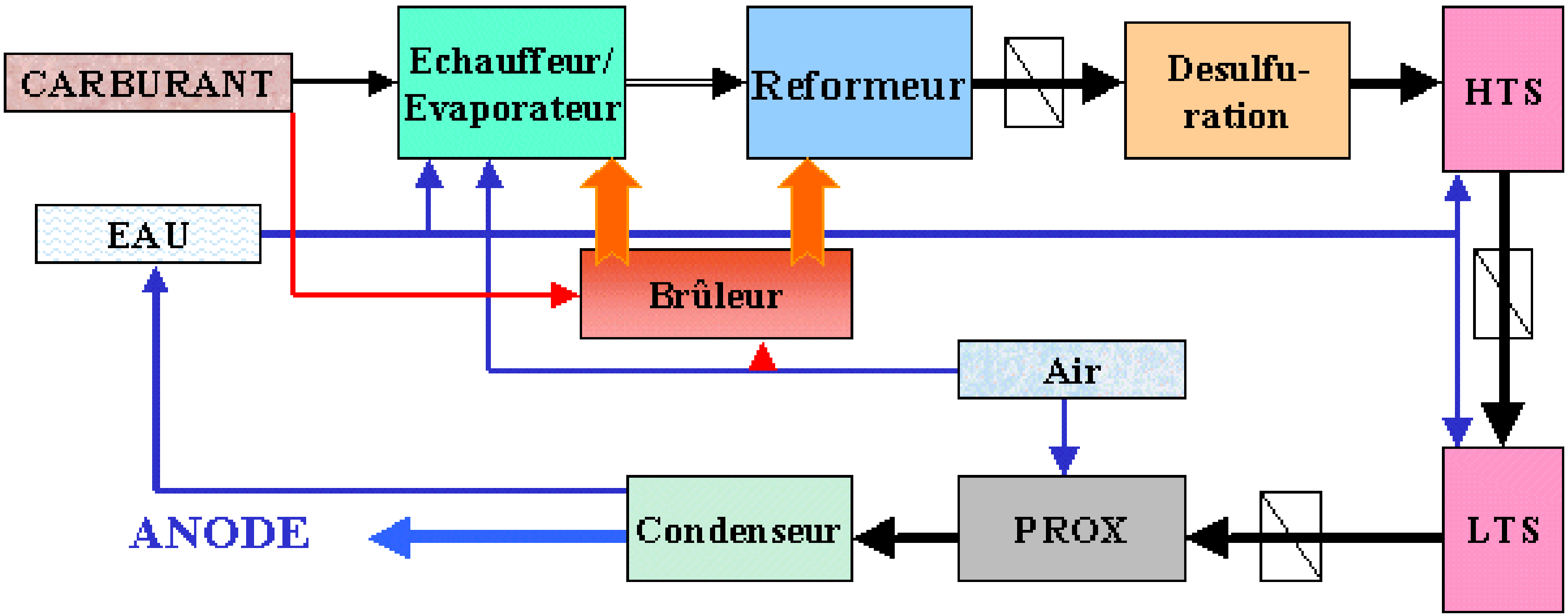
Other H_2 supply: PEM with methanol reforming

- Production of H_2 from methanol using reforming



Principe de la pile à combustible au méthanol

Other H_2 supply: PEM with methanol reforming



PAFC: phosphoric acid fuel cells

- Electrolyte: phosphoric acid H_3PO_4 100%
- Temperature 180-220°C
- Fuel: H_2 pure or from reforming - Oxidizer: O_2 (air)
- Ions H^+
- Power density: 100 – 300 mW/cm²
- Tolerance: 1% CO
- Applications: cogeneration
- TRL: mature technology

PAFC: phosphoric acid fuel cells

Nous ne pouvons pas afficher l'image.

Geometry of phosphoric Acid Fuel Cell

PAFC: phosphoric acid fuel cells

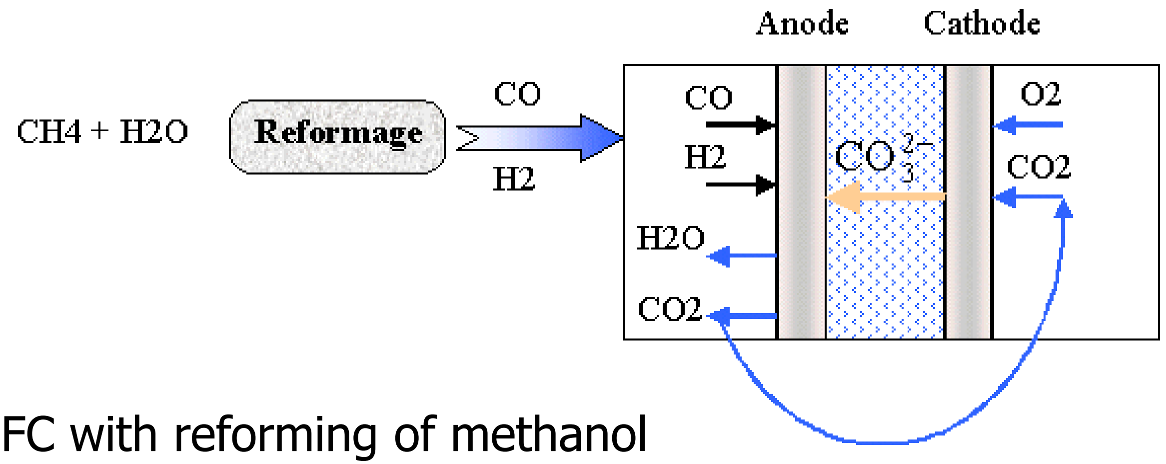
A fuel cell O.N.S.I. of 200 kWe and 200 kWth was installed in France in Celles by E.D.F. and G.D.F., for a demonstration project. It consumes natural gas provided by G.D.F and provides electrical energy as well as heat up to 80° C

MCFC: Molten Carbonate Fuel Cell

- Molten Carbonate Fuel Cell : K_2CO_3, Li_2CO_3 melted in a matrix of $LiAlO_2$ (thickness 0,4 mm)
- Electrolytes: CO_3^{2-}
- Fueling in H_2 or natural gas CH_4:
  - Anode: $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$
  - Cathode: $O_2 + 2CO_2 + 2e^- \rightarrow 2\,CO_3^{2-}$
- Regeneration loop of CO_2 between anode and cathode
- Temperature : 600-660°C
- Catalysts:
  - Anode: Ni + Cr
  - Cathode: NiO + Li
- Connection plates made of Ni

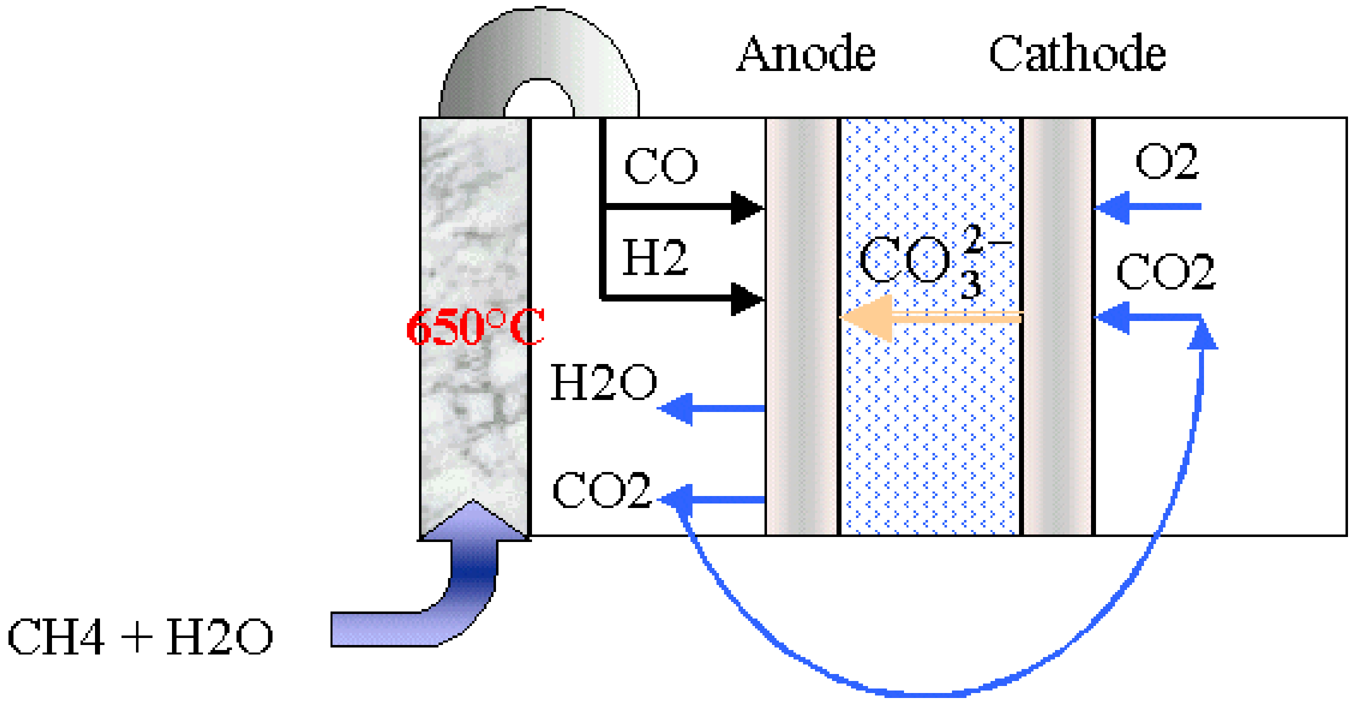
MCFC: Molten Carbonate Fuel Cell

- Tolerant to CO
- Corrosion problems
- Stationary applications for high powers (800 kW to 2 MW) : cogeneration, centralized production of electricity, marine applications
- TRL: prototypes pre-industrial



MCFC with reforming of methanol

MCFC: Molten Carbonate Fuel Cell

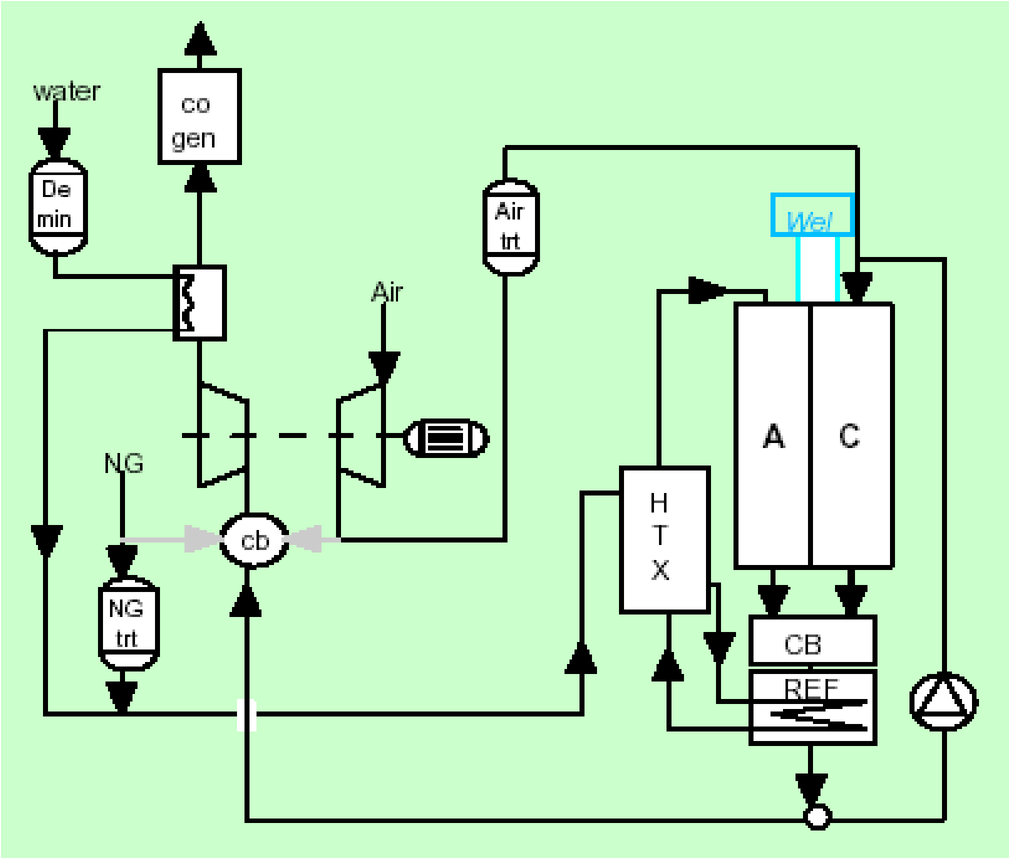


MCFC with internal reforming

MCFC: Molten Carbonate Fuel Cell

- Several advantages of MCFC
  - High electrical efficiency (60%),
  - Utilization of produced heat for cogeneration or internal reforming and combination with gas turbine,
  - Possible to use fuels as methane, methanol, ethanol or gasified coal...
  - Possible to use nonprecious metal as catalyst metals in electrodes.

MCFC: Molten Carbonate Fuel Cell



Design of combined cycle (Ansaldo)

MCFC: Molten Carbonate Fuel Cell

Application: MCFC of 2MW in Santa Clara, California. Operation time: 4000h. Other system: MCPower system of 250 kW used as a cogeneration unit in Miramar, California (See figure)

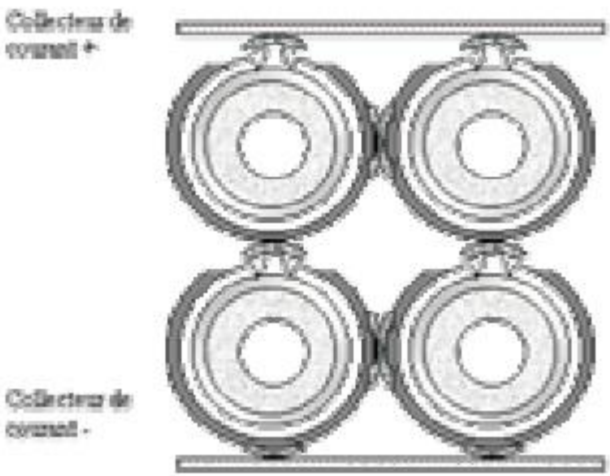
Solid Oxide Fuel Cell : SOFC

- Conducting electrolyte: Zirconium doped with Yttrium: ZrO_2 and Y_2O_3.
- Ions: O^{2-}.
- Temperature: 700-1000°C
- Fuel: supply in pure H_2 or from reforming, natural gas CH_4, CO or other fossil fuel (very interesting)
- Oxidizer: O_2 (air)
- Reactions:
  - Anode: $H_2 + O^{2-} \rightarrow H_2O + 2\,e^-$
  - Cathode $1/2\,O_2 + 2\,e^- \rightarrow O^{2-}$

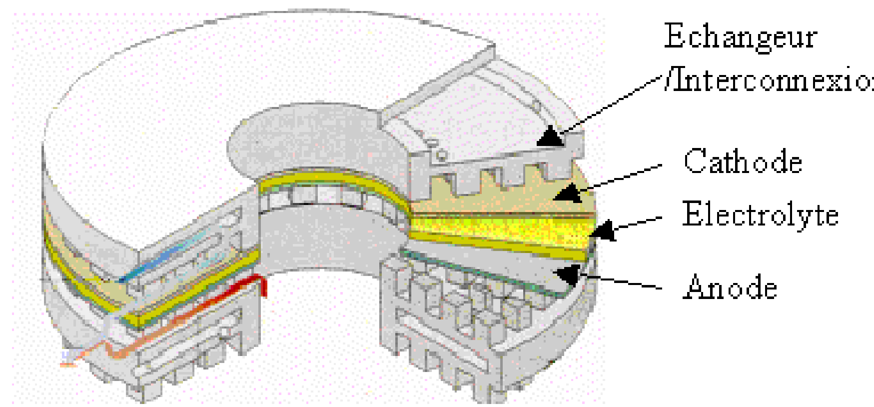
Solid Oxide Fuel Cell : SOFC

- Stationary and mobile application
- Vast application power (2,5 kW to 100 MW)
- Technical difficulties
  - Corrosion
  - Materials : fragile behavior and sensitivity w.r.t. to thermal shocks
  - Reduction of voltage with temperature T
- TRL: prototypes

Solid Oxide Fuel Cell : SOFC



SOFC fuel with a tubular structure



SOFC Fuel Cell by Suzer Hexis

Hydrogen as a fuel

Fuel treatment

- H_2: difficulty of storage and distribution network
- CH_3OH: reforming process is a classical technology but remains costly
- Natural gas (CH_4):
  - De sulfuration
  - Reforming
  - Elimination of CO_2 and of CO (except MCFC)
  - Utilization of unreacted H_2
- Compression: energy loss
- Opportunity for partial oxidation-based systems

Hydrogen production paths

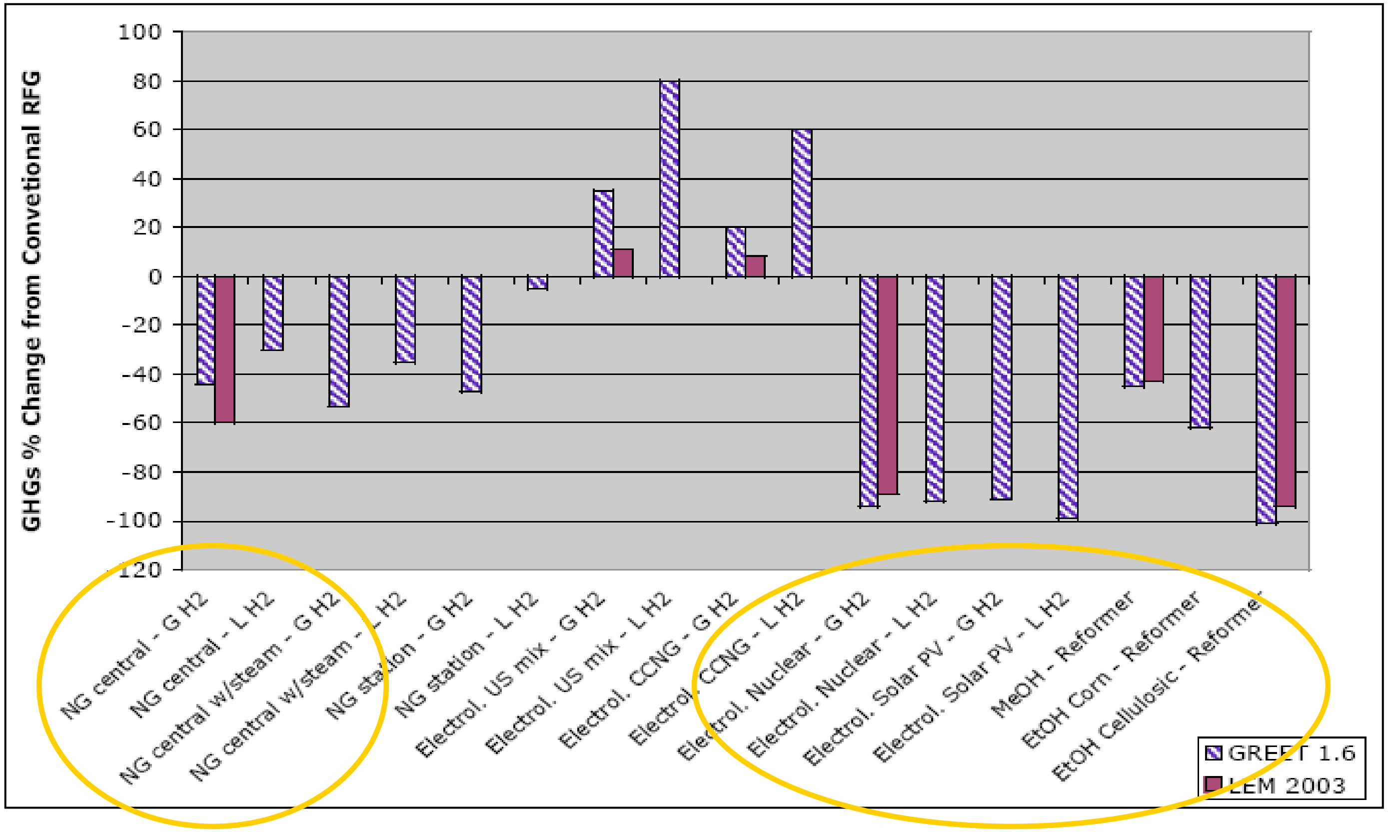
- **Water electrolysis**
  - Environmental impact depends on the CO_2 emission of electrical network
  - Low overall efficiency (<60%)
  - Advantages: enables a massive energy storage of green electricity and allows to level the production peeks

- **Reforming of fossil fuel** from natural gas or oil
  - Production of CO_2 and dependency to oil
  - Emissions in upstream level
  - Is considered as the best option currently

- **Hydrogen « lost » in industrial processes (chemical industry in processes)**

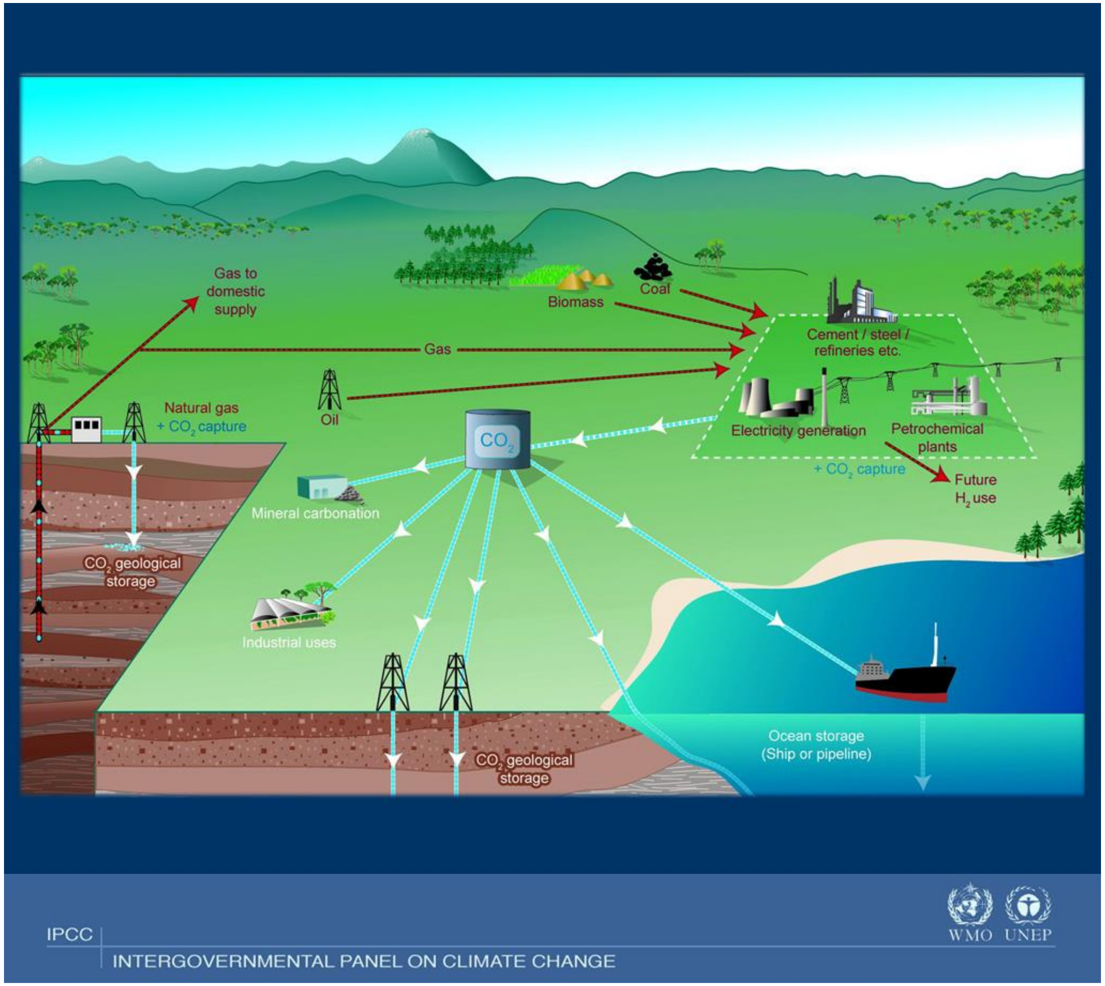
- **Poly generation**
  - Production of heat, energy, and fuel in large scale energy systems. Possibility to perform Carbone capture & sequestration (CCS) as well as pollutants

Hydrogen production: GHG efficiency



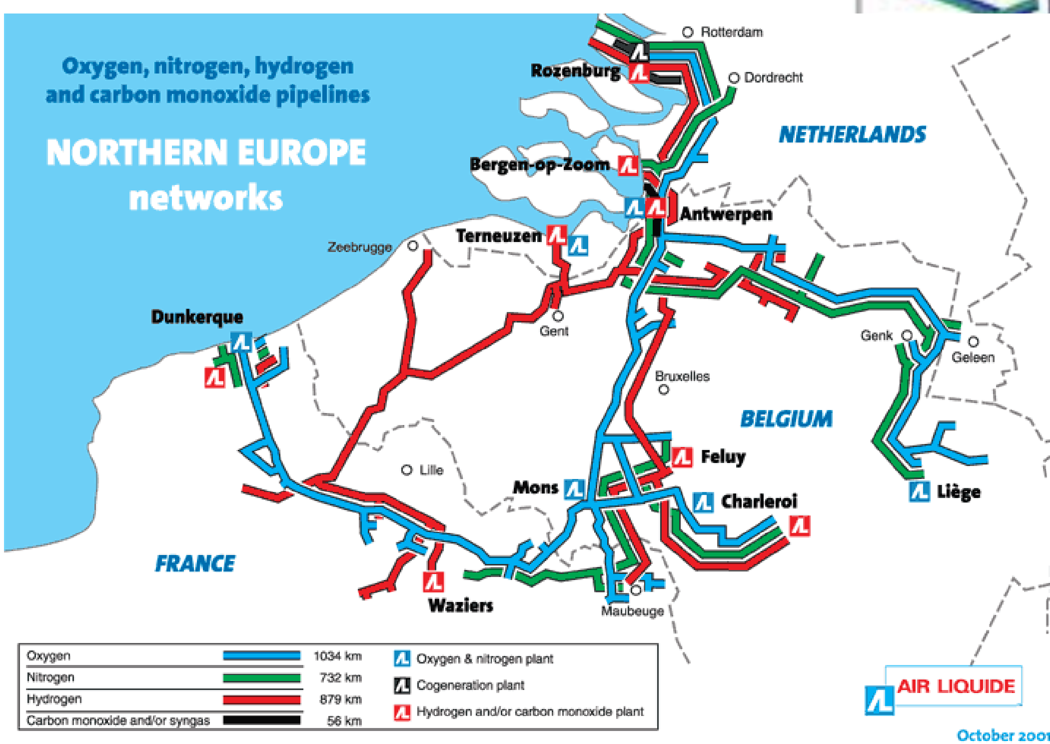
CO_2 and GHG emissions compared to the reforming in USA situation

Hydrogen production: the IPCC vision



Hydrogen route

Hydrogen network



IS HYDROGEN A SAFE FUEL?

Fuel leakage Simulation. Dr. Michael Swain.
Experiment on fuel leakage and burning car conducted with the University of Miami at Coral Gables.

Lighter than air

Fuel tank punctured 0 seconds

Fuel set on fire 3 seconds

Fuel tank burning 60 seconds

Hydrogen storages

Hydrogen storage

	Specific energy (Wh/kg)	Energy density (Wh/l)
H_2 compressed gas (T amb. et p=20 Mpa)	33600	600
H_2 liquefied (T cryo. et p=0.1 Mpa)	33600	2400
Mg-H2	2400	2100
Vanadium hydride	700	4500
Methanol	5700	4500
Petrol	12400	9100