

Electrochemistry for Materials Technology

ENERGY APPLICATIONS

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Electrochemistry – Energy Applications

Converting fuels *continuously* to electricity & useful heat:

•FUEL CELLS



Converting fuels to electricity and vice-versa (*size-limited*):

•BATTERIES

e.g. storage



Converting electricity to fuels and chemicals

•ELECTROLYSIS

e.g. H₂ production



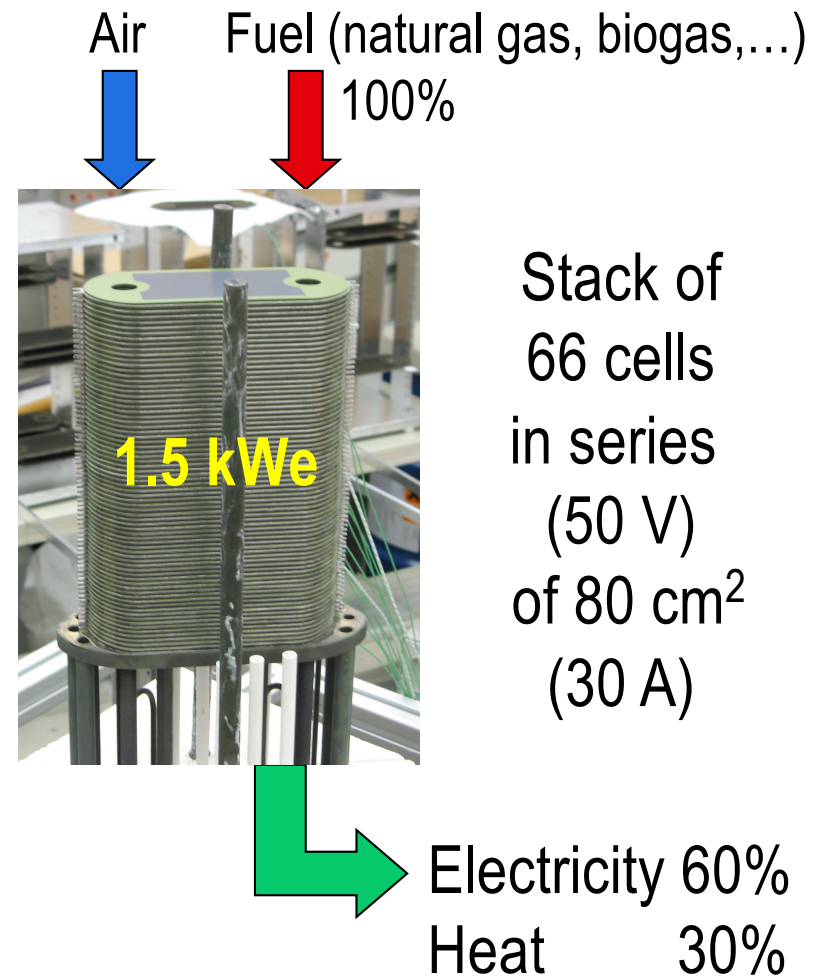
e.g. Al production

FUEL CELLS – General aspects

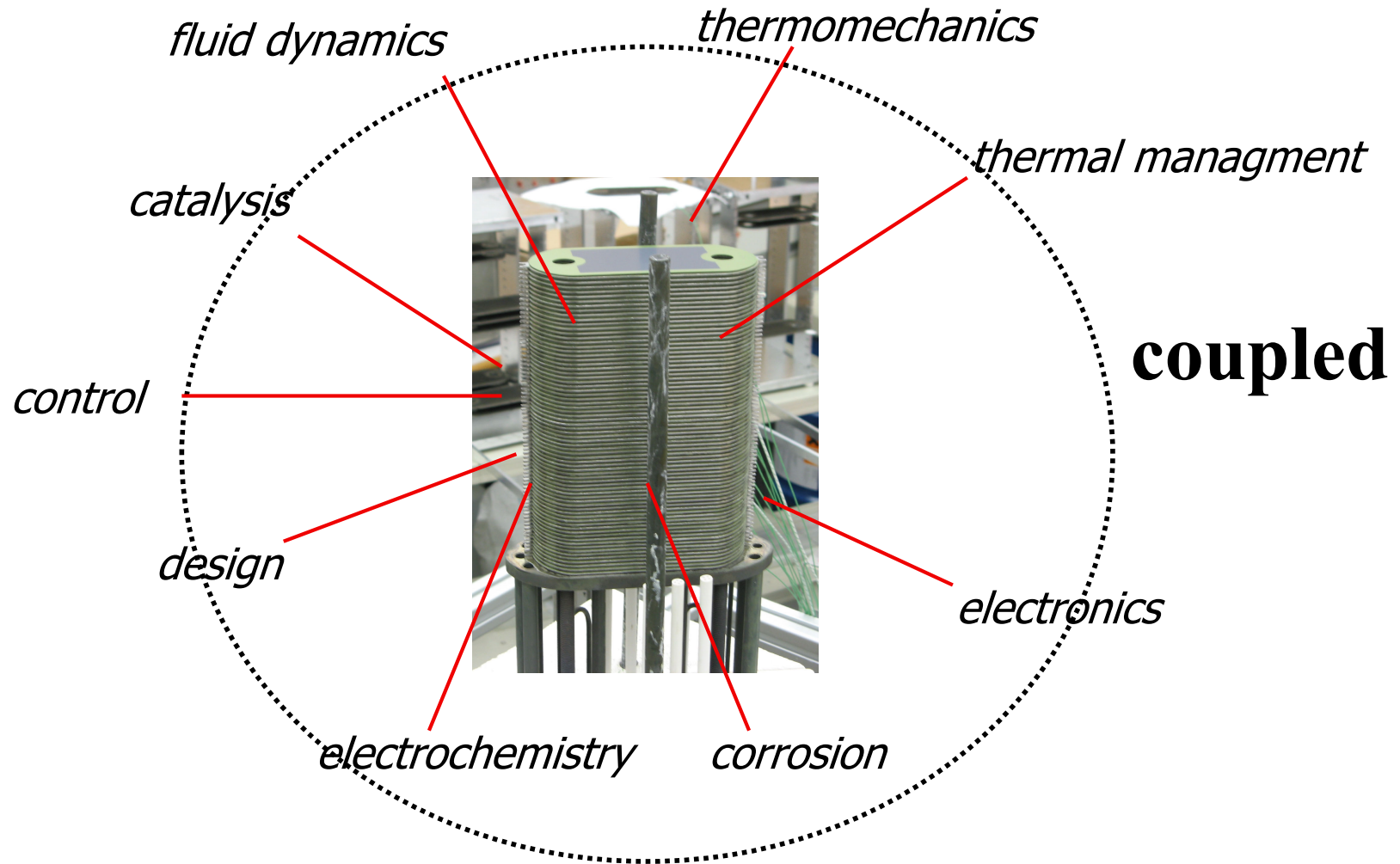
Principles, types, applications, strengths, efficiency

A Fuel Cell in a nutshell:

- works like a **battery**, fed with **gas**
- fuel is **directly** converted into electricity and useful heat
- typical sizes:
 - 1-20 W_e / H_2 , MeOH / portable electronics
 - 1 kW_e / natural gas / a house
 - 20 kW_e / H_2 / an electric car
 - 1 MW_e / biogas / CHP
- status: pilot & demonstration, R&D, pre-commercial



Highly pluridisciplinary topic



*At the crossroads of mechanics, chemistry, **materials science** and electrical engineering*

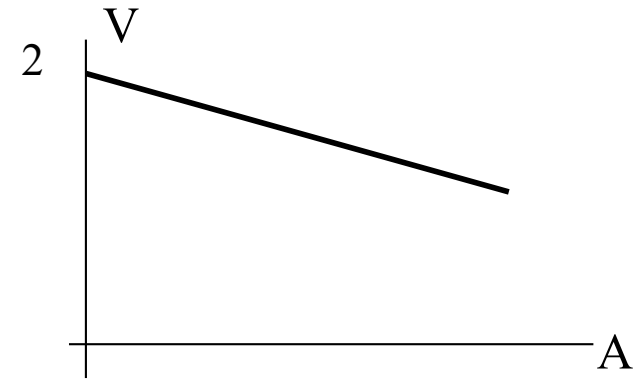
Components of a fuel cell (=a 'gas battery')

- 2 solid electrodes (+,-) of **electronic** conduction
- **ionic** conductor (*solid* or *liquid*), electronically insulating, that separates the 2 electrodes
- at both interfaces between **electronic** and **ionic** conductors, there is
 - charge transfer (electrons)
 - mass transfer (molecules)to complete the circuit and sustain current flow (& mass flow), so as to deliver electricity

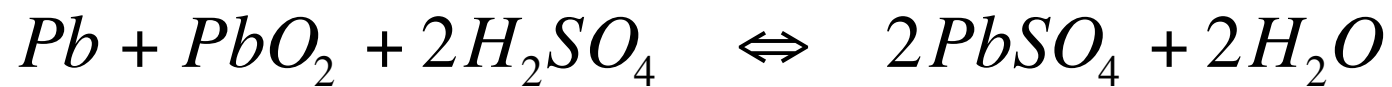
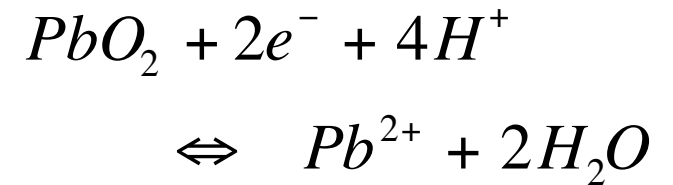
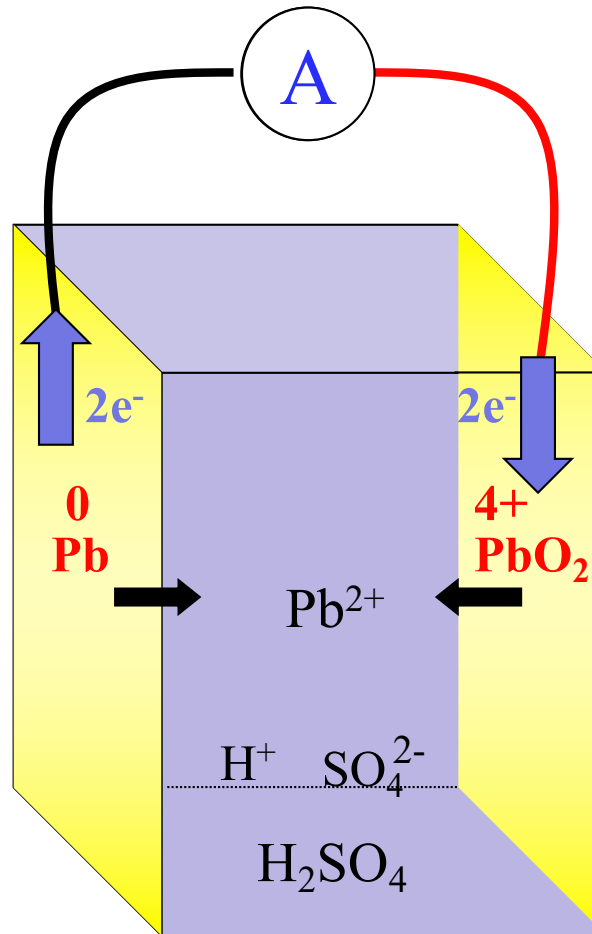
Operating principle

- we first describe the operating principle of a classical **battery** (lead - sulfuric acid)
- and then explain the similarities and differences with a **fuel cell** ('gas battery')
- we consequently introduce different fuel cell **types**, one by one (5 in total), depending on the **materials** used
 - the fuel cell type (name) is designated by its **electrolyte** material,
 - which can be solid or liquid,
 - and conduct charge depending on the **operating temperature (RT to 1000C!)**

Lead acid battery



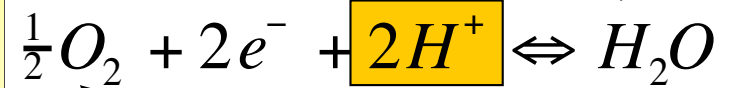
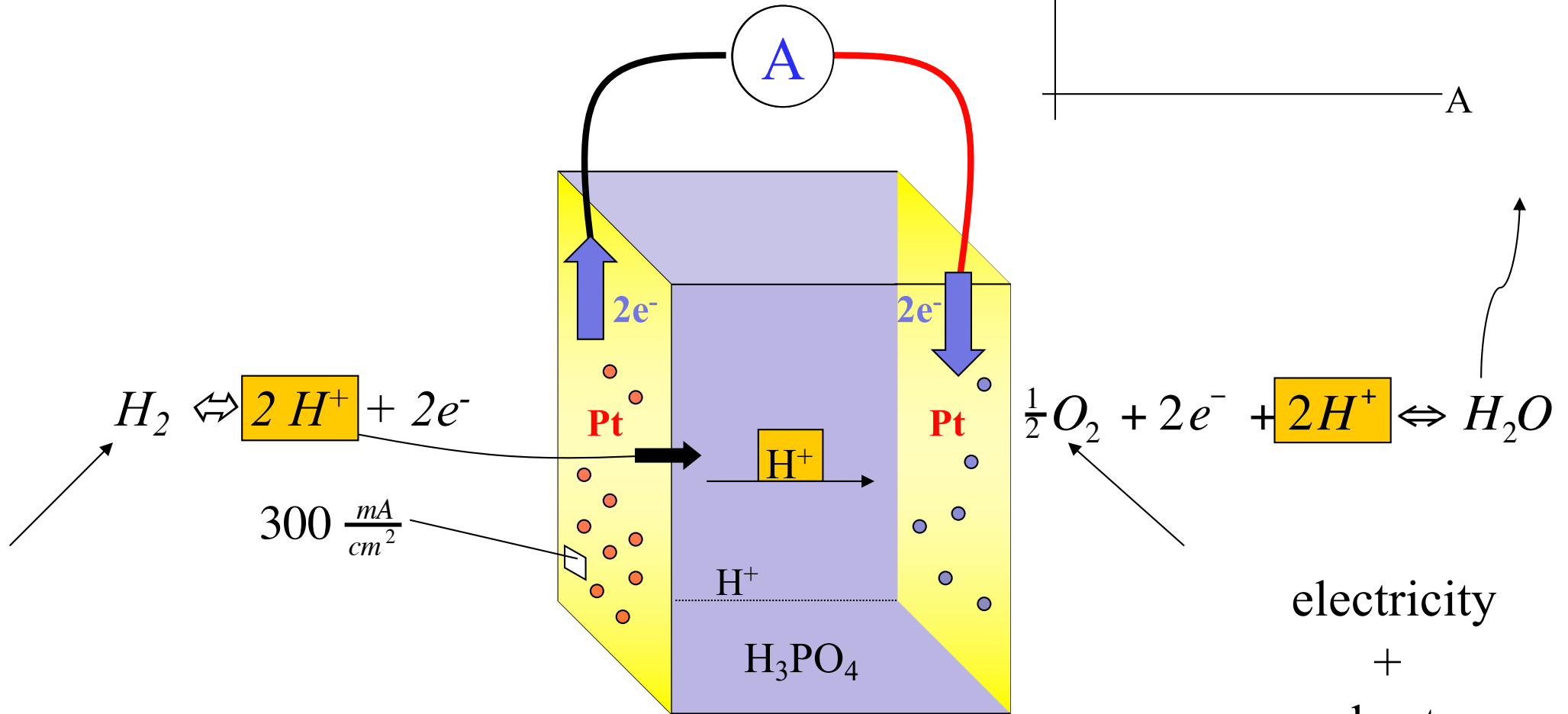
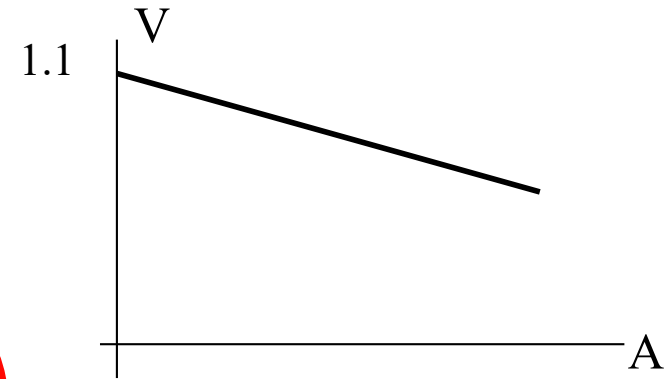
< 2 V



 Electrode consumption (« active masses »)

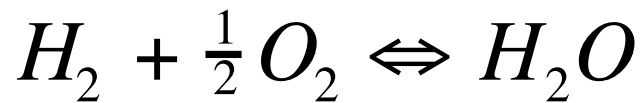
1. Phosphoric acid fuel cell (PAFC)

< 1 V



electricity
+
heat

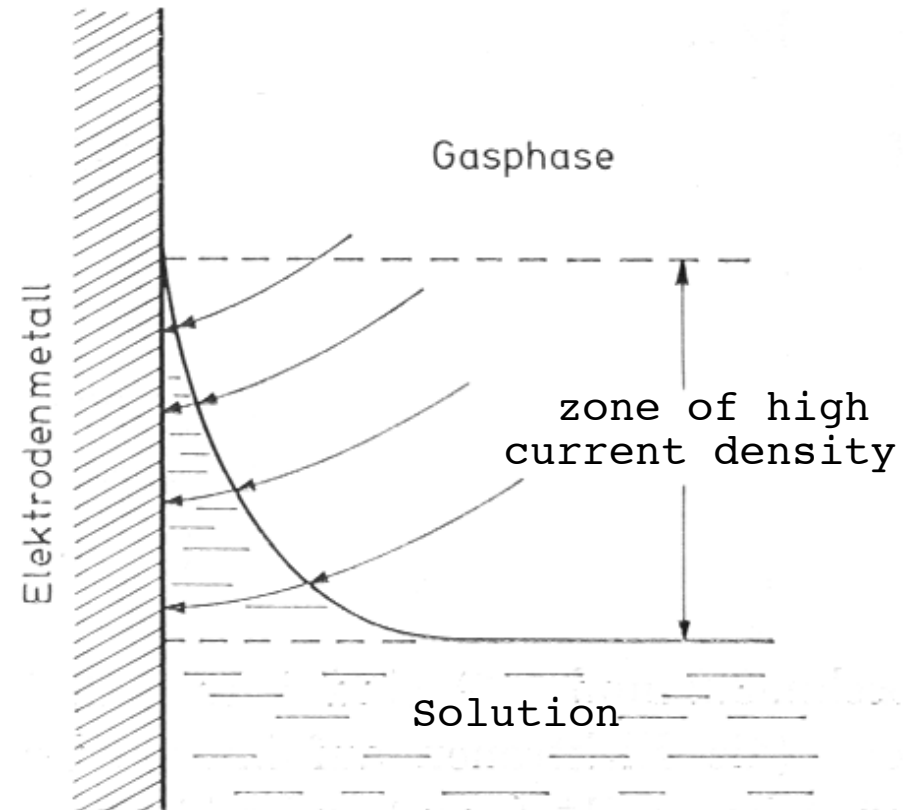
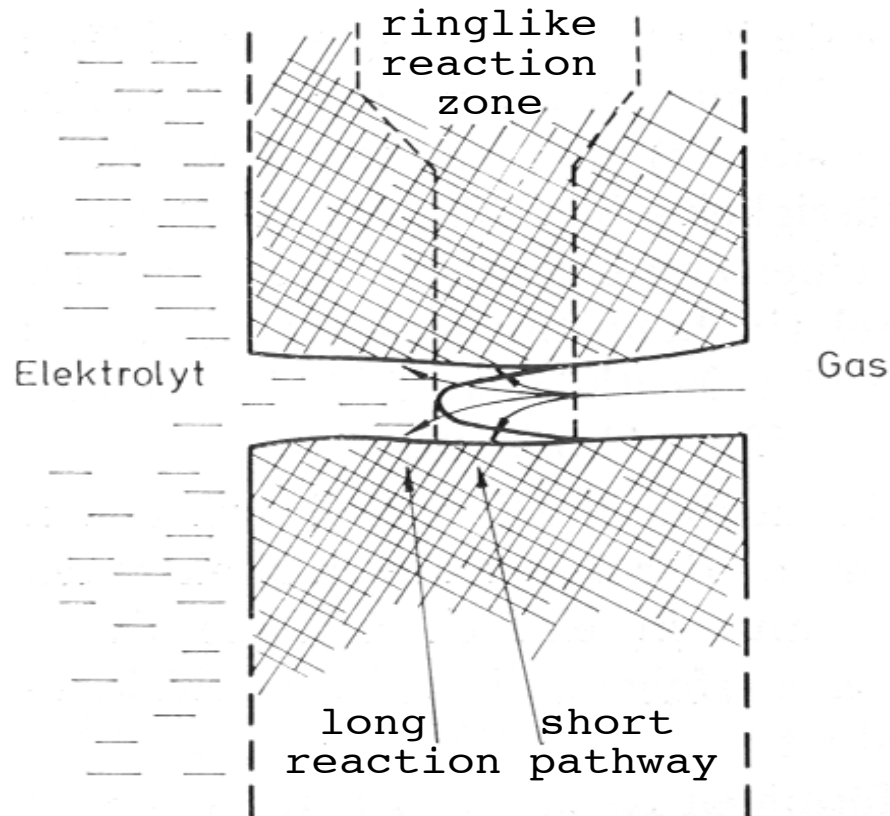
200C

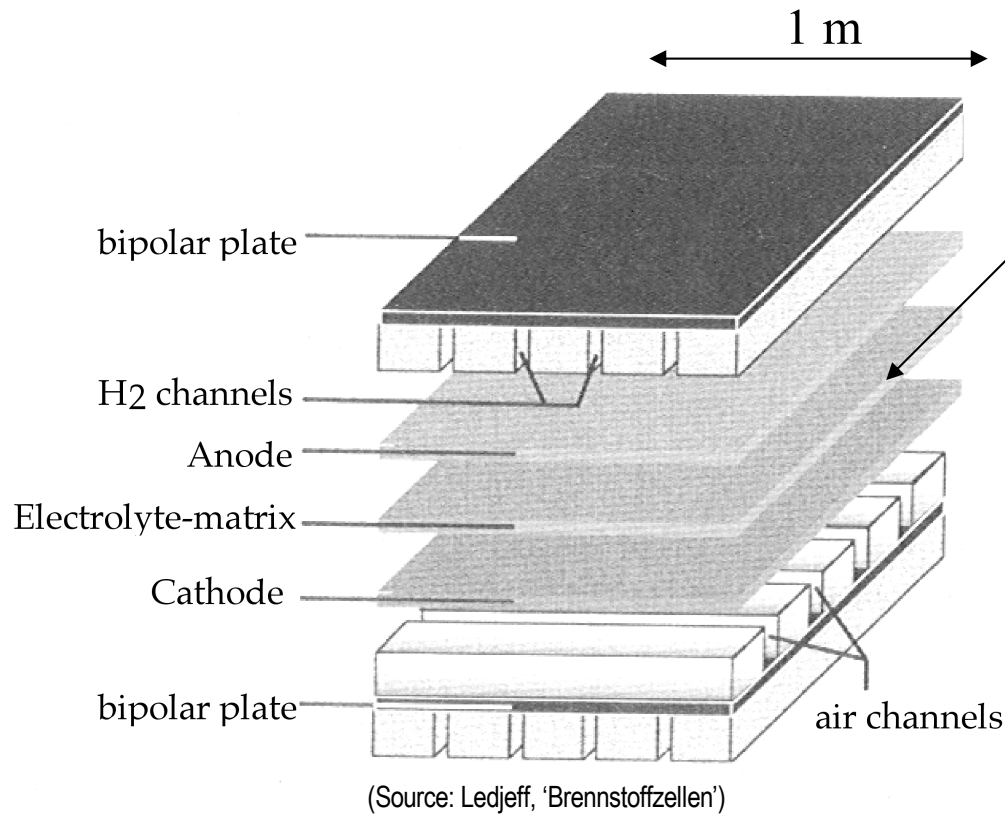


- consumption of gases
- electrodes are invariant (catalysts)

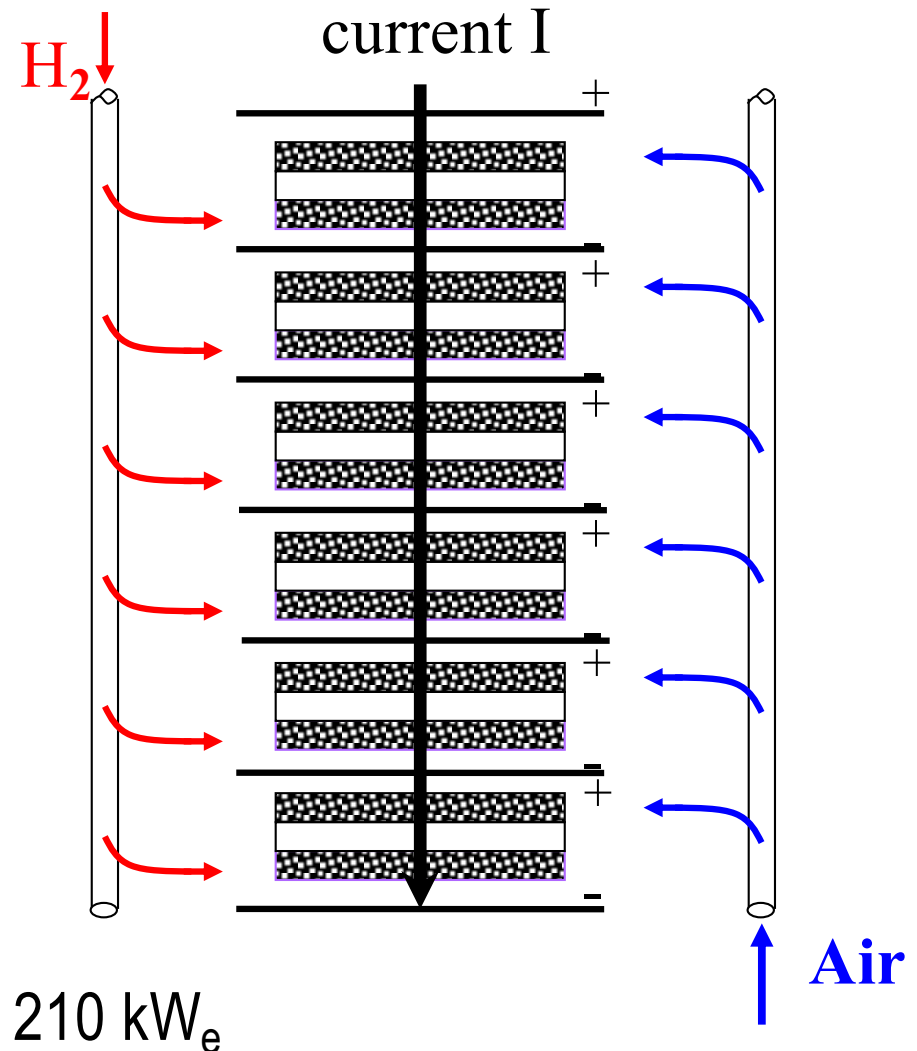
Gas diffusion electrodes

- allow to inject (extract) a gas into (from) a liquid
- reaction zone = “triple phase boundary” (gas/liquid/solid)





Increase electrode surface :
 → high **current I (A)**



Series connection :
 add up the **voltages (V)**

Electric **power** $P = V * I$
 f.ex. 100 cells of 1 m² surface

$$70 \text{ V} * 3000 \text{ A} = 210 \text{ kW}_e$$



Units exist from 50 kW_e to several MW_e

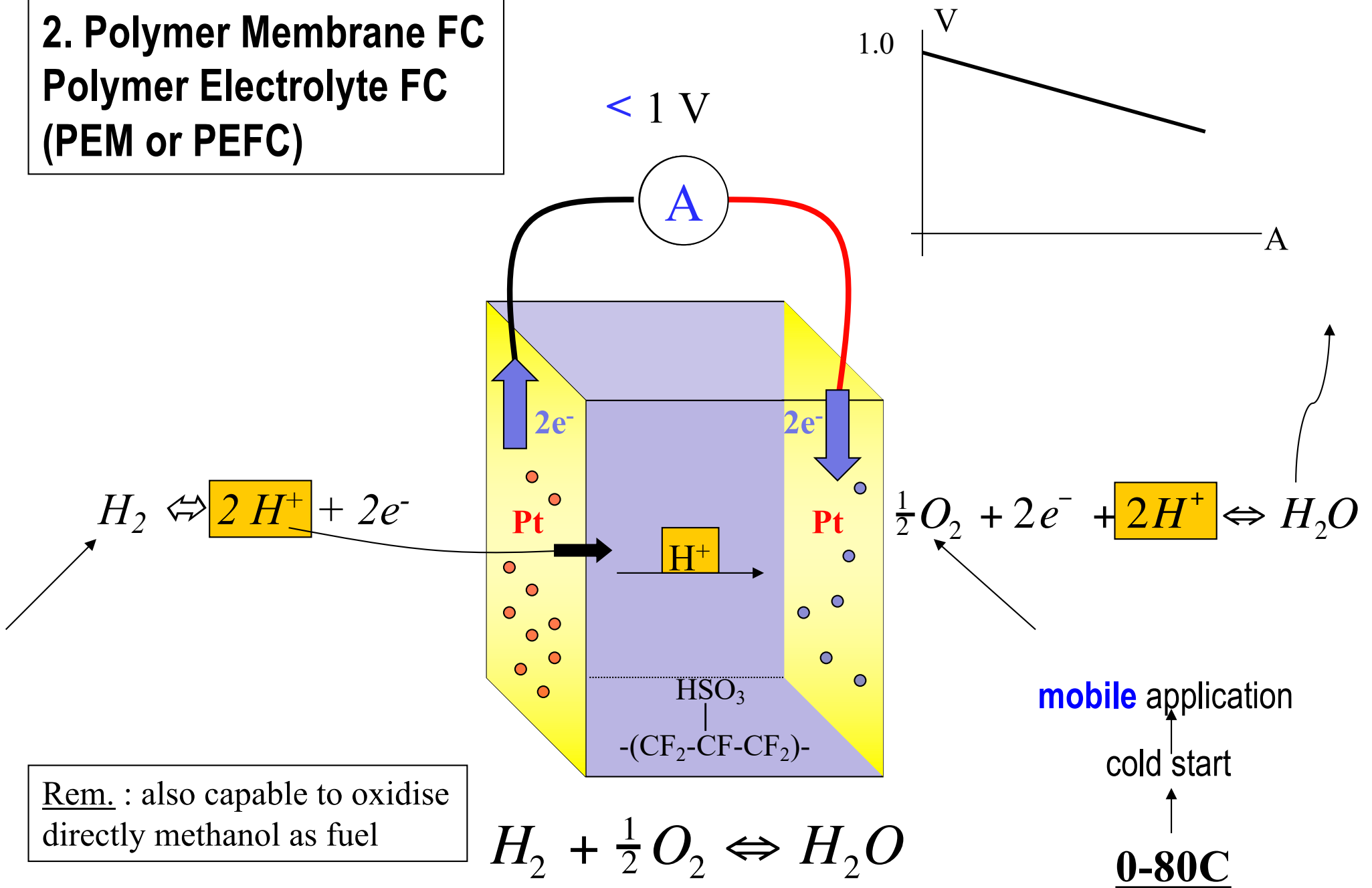


Typical size is 200 kW_e or 400 kW_e, operated on natural gas (NG)



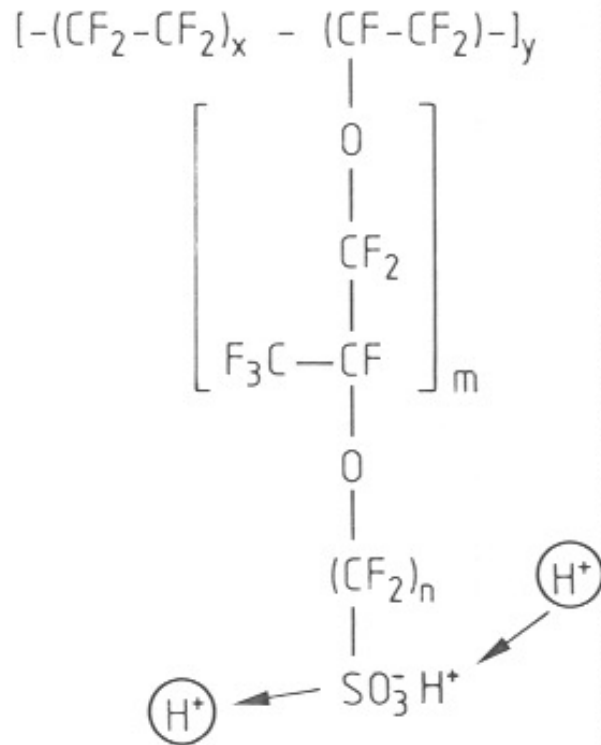
(source : Thoma & Renz AG, Basel, CH)

**2. Polymer Membrane FC
Polymer Electrolyte FC
(PEM or PEFC)**

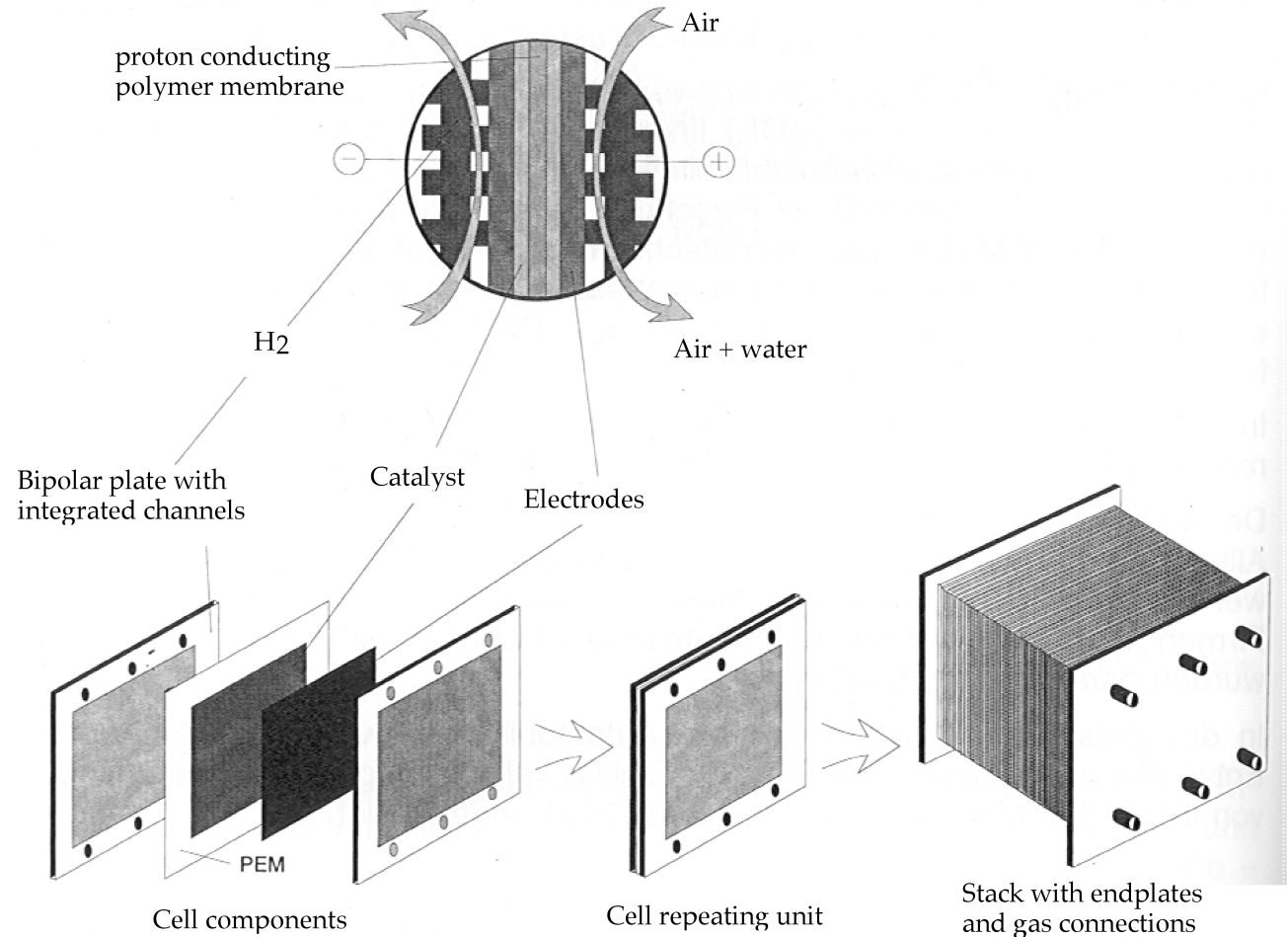


Rem. : also capable to oxidise directly methanol as fuel

polymer membrane (50 μm thin)



series connection (« stack »)

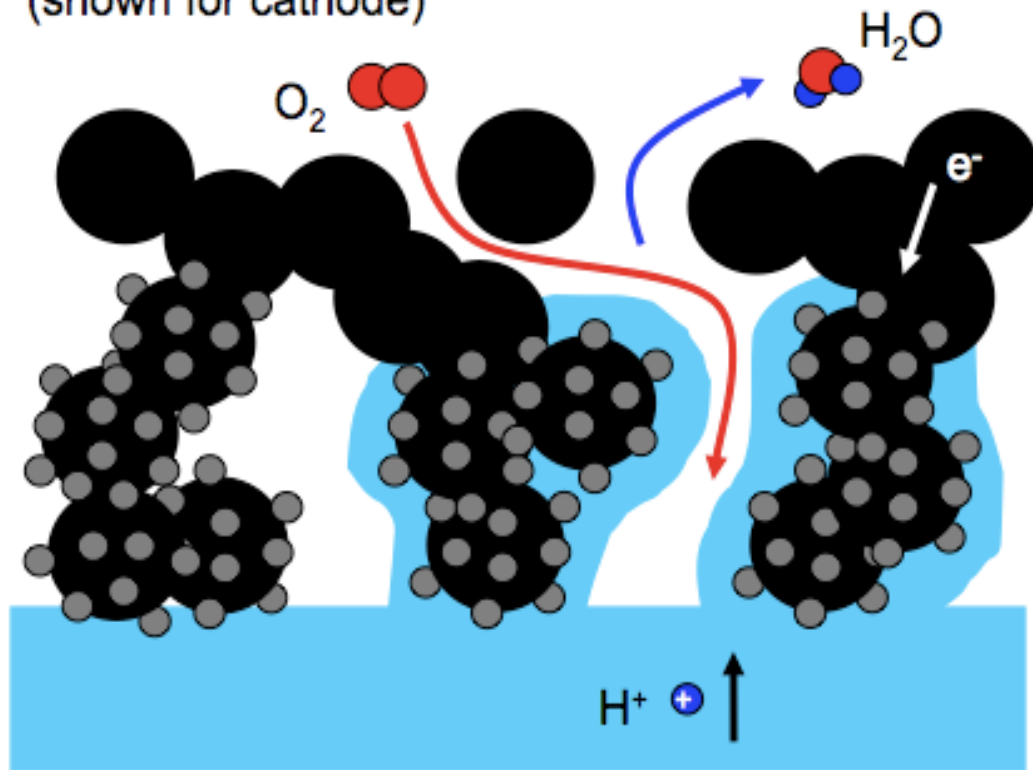


<http://www.youtube.com/watch?v=yowRvfFtMgQ>

'Triple phase boundary' concept

Copied from G.G. Scherer, PSI, European Fuel Cell Forum, Lucerne, Tutorial Course

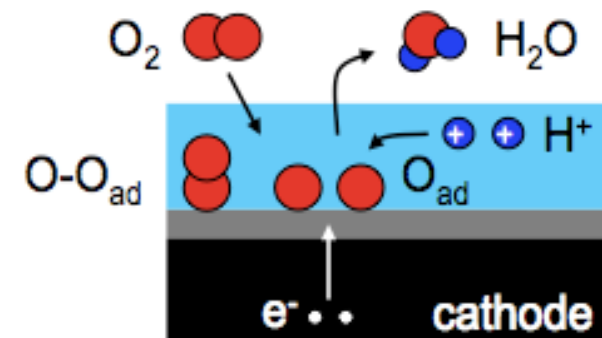
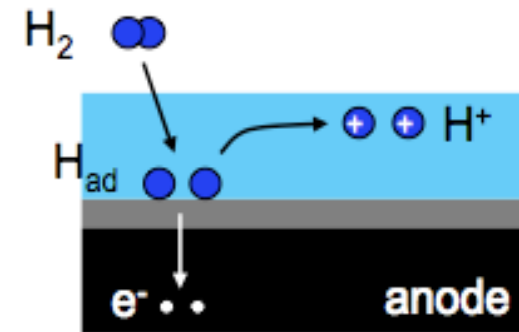
(shown for cathode)



3 phases **must** meet: gas (pores), catalyst (electrons) and electrolyte membrane (ions)

access of:

1. electrons
2. protons
3. reactants / products

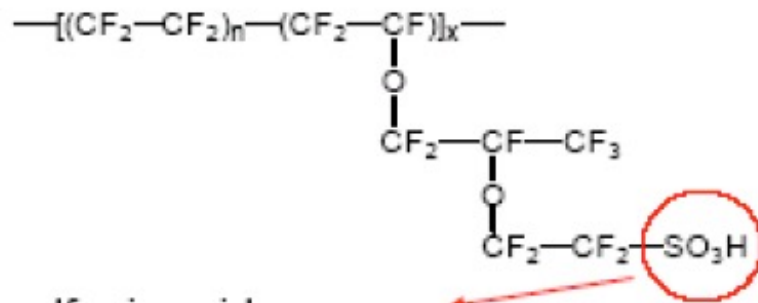


Polymer membrane morphology

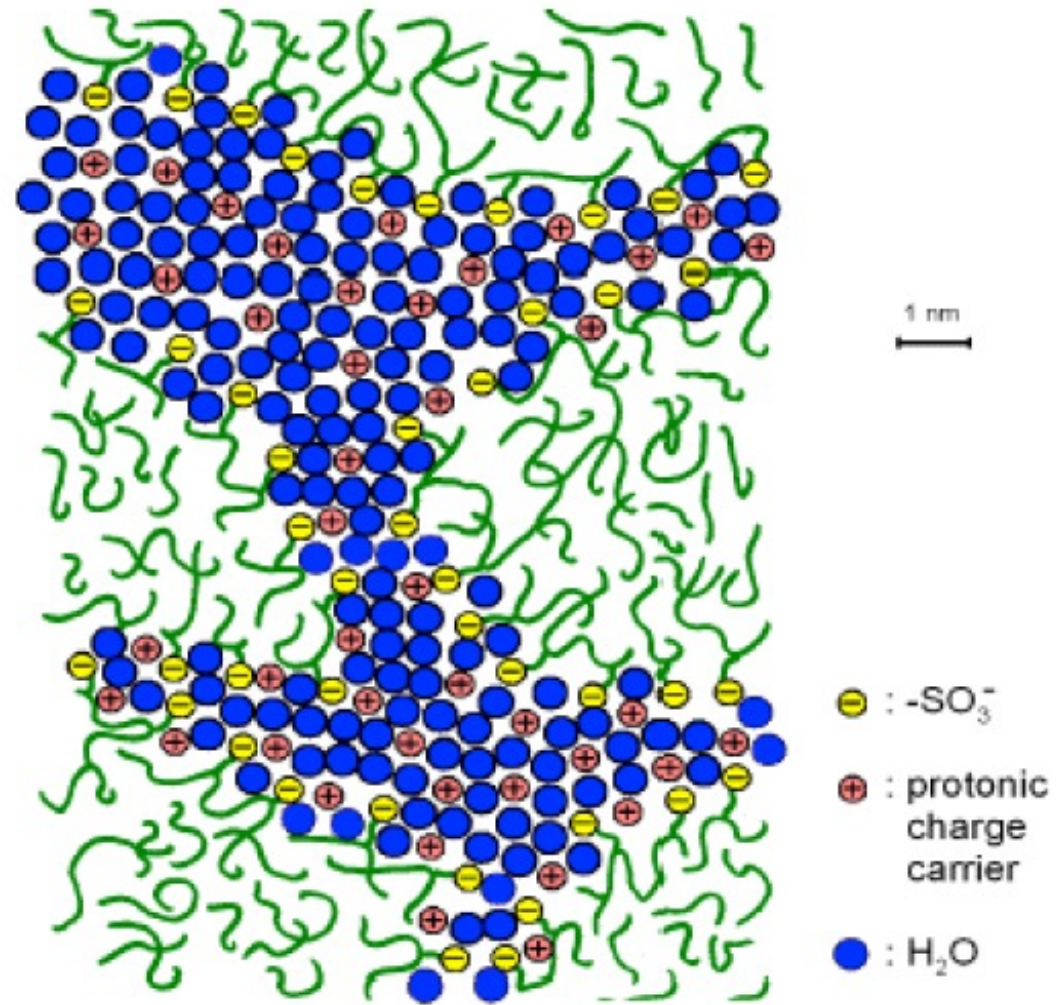
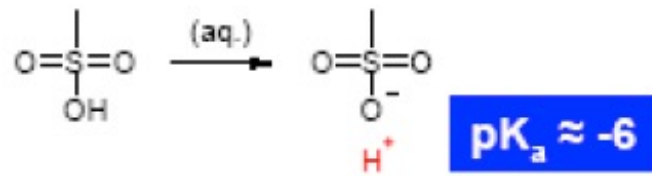
bi-continuous nano-phase separated microstructure

- hydrophobic backbone provides mechanical integrity
- proton transport occurs via water filled channels

e.g. Nafion®:



sulfonic acid group:



Copied from G.G. Scherer, PSI, Fuel Cell Tutorial, European Fuel Cell Forum, Lucerne

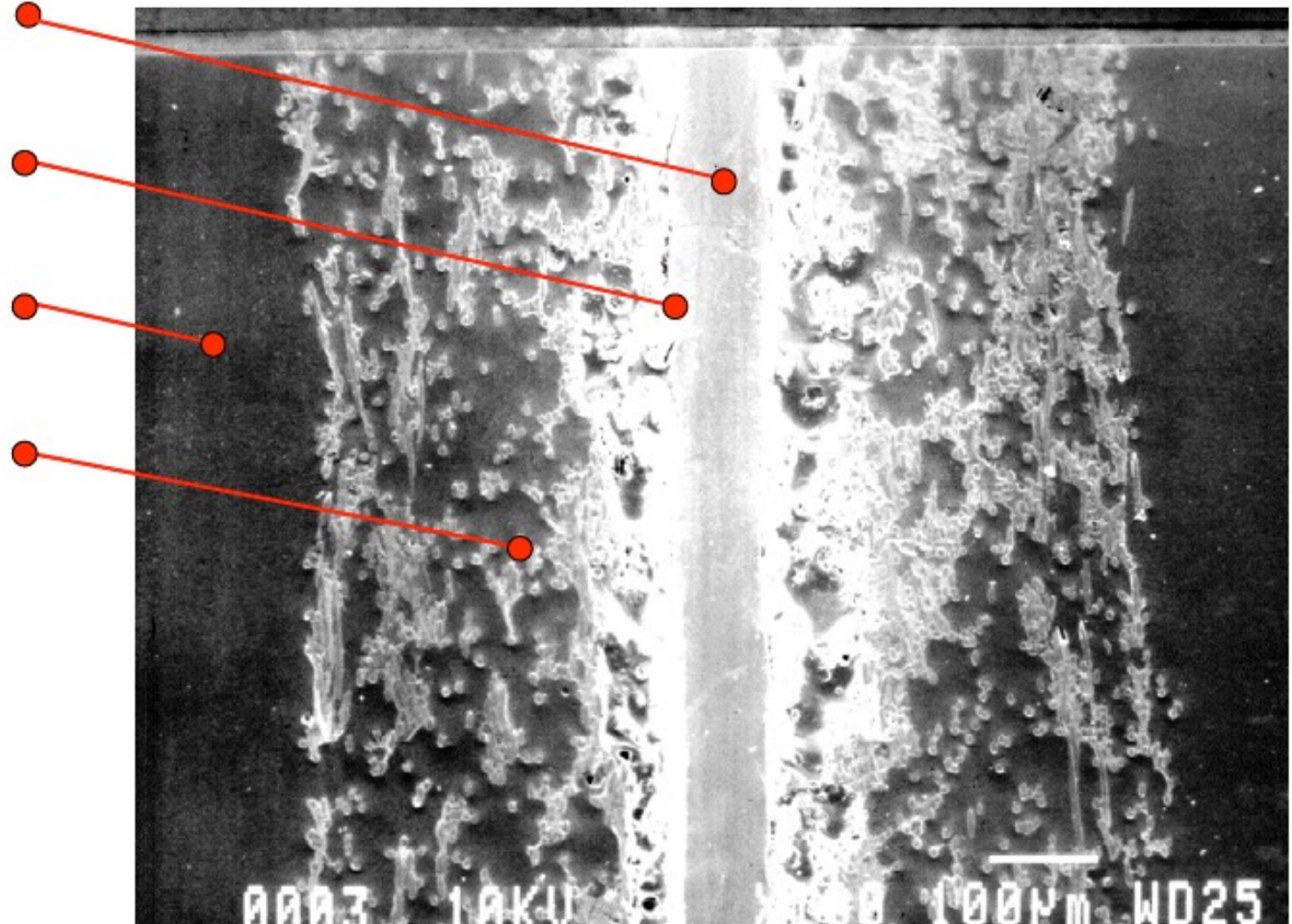
Membrane electrode assembly (MEA)

polymer
electrolyte

Pt-catalyst

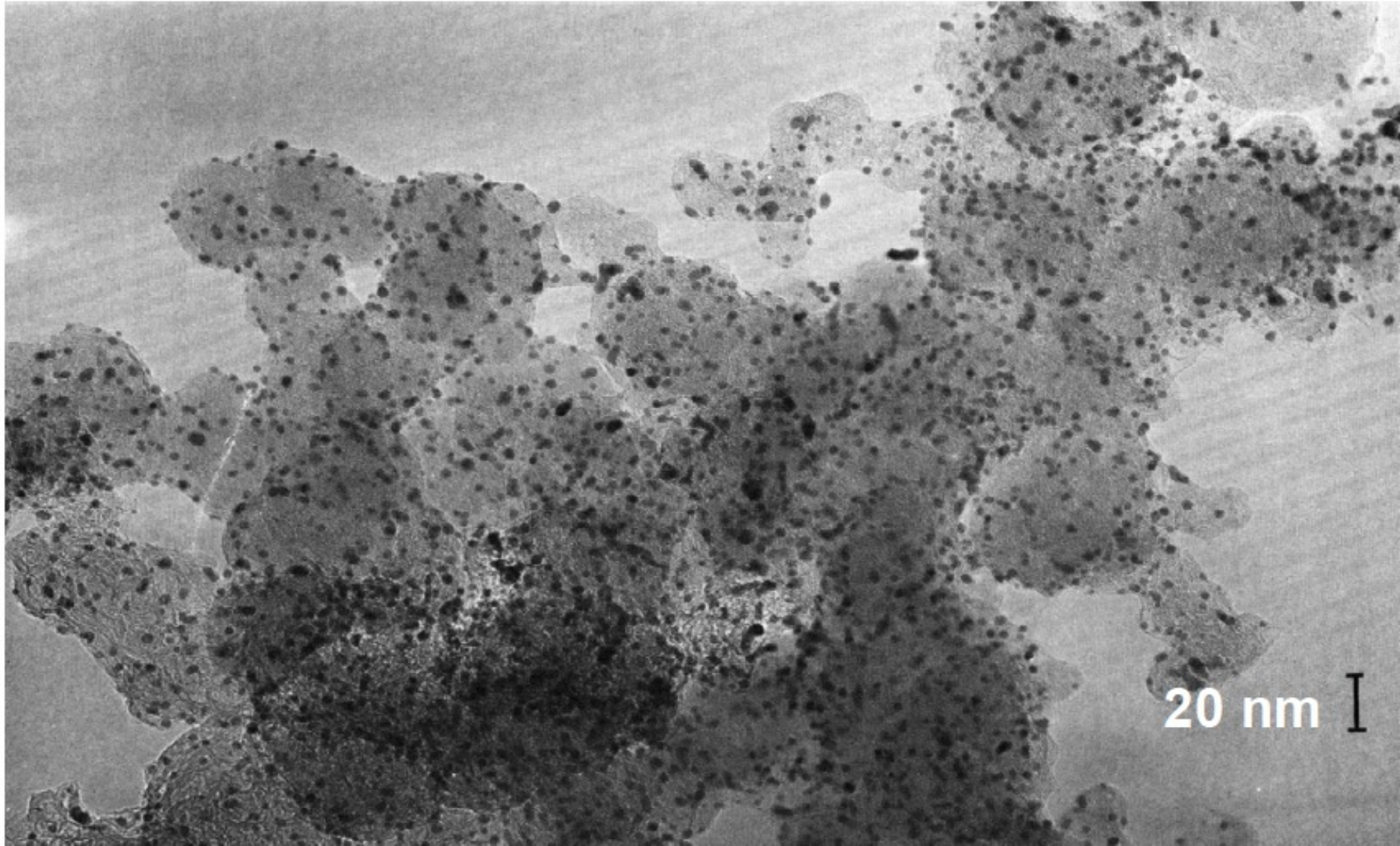
cell frame /
bipolar plate

current collector /
gas diffusion layer



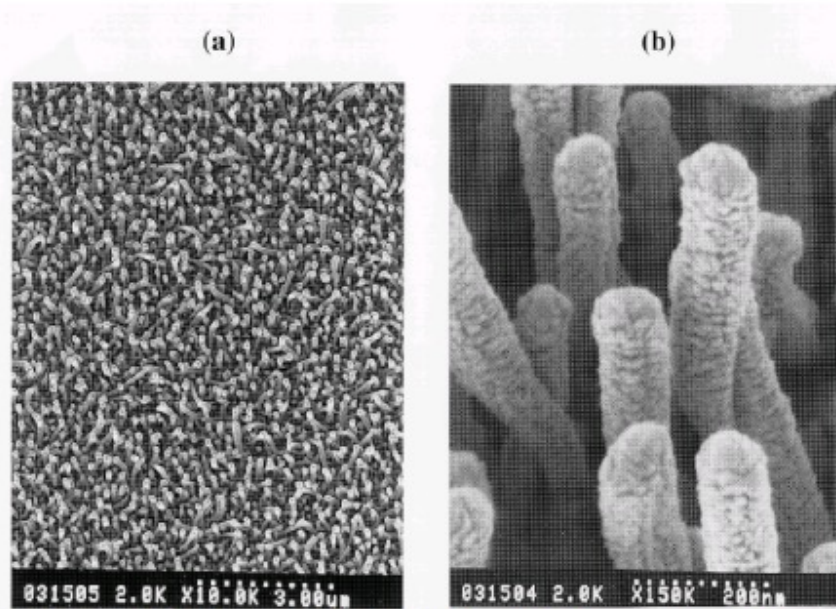
Copied from G.G. Scherer, PSI, Fuel Cell Tutorial, European Fuel Cell Forum, Lucerne

Platinum nano particles supported on carbon particles



Copied from G.G. Scherer, PSI, Fuel Cell Tutorial, European Fuel Cell Forum, Lucerne

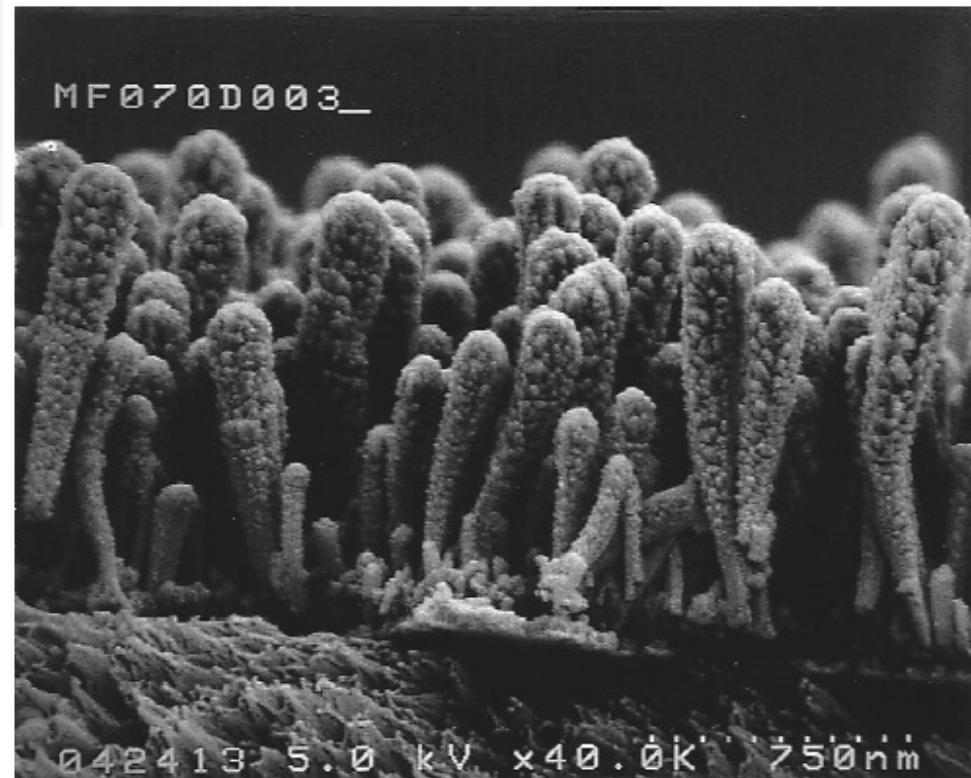
Example of commercial catalyst (3M)



Pt coated nanostructured whisker supports (0.25 mg/cm^2), at 10,000 X plan view (left) and 150,000 X, 45° view (right).

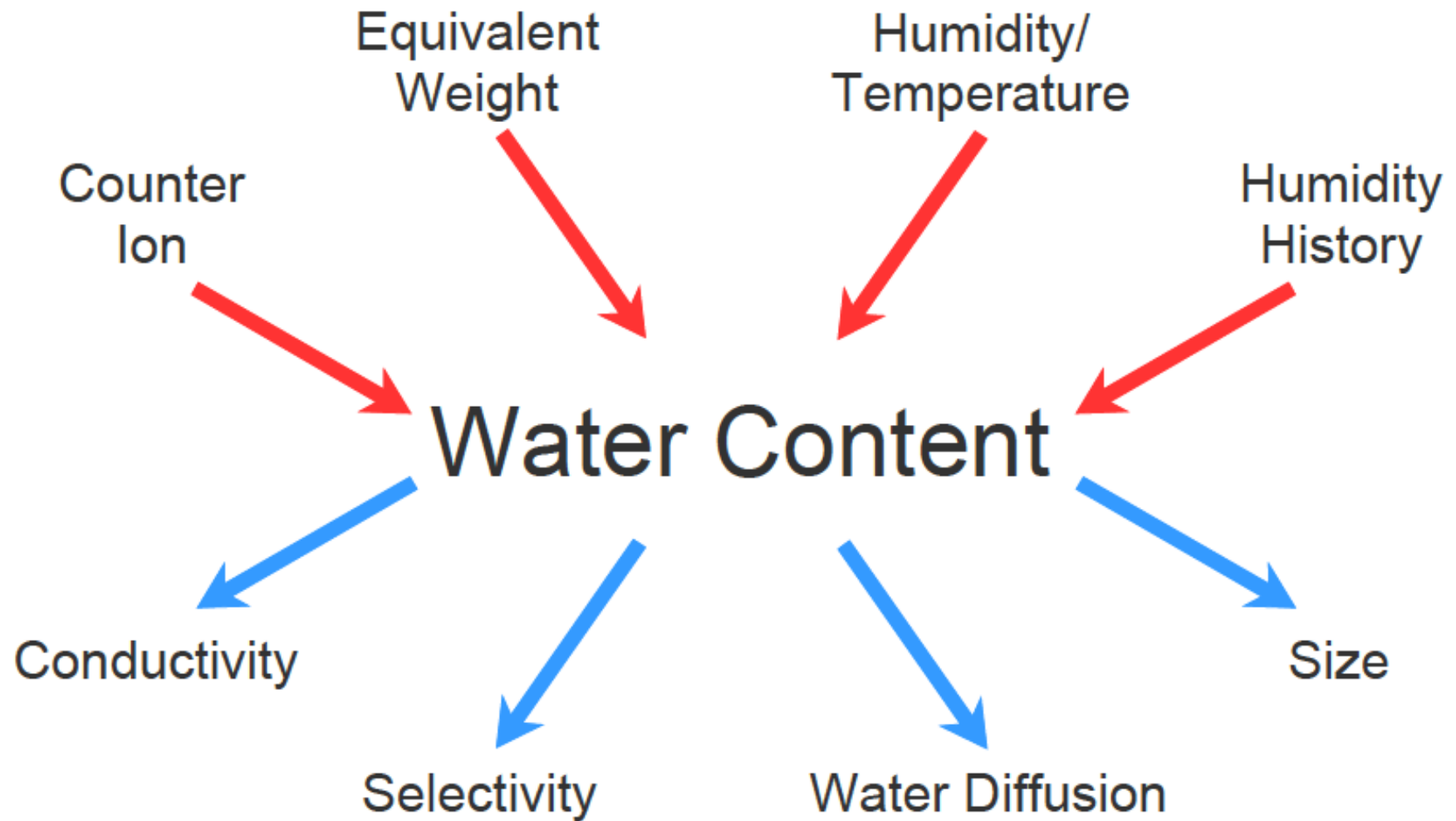
Low platinum loading

No ionomer impregnation

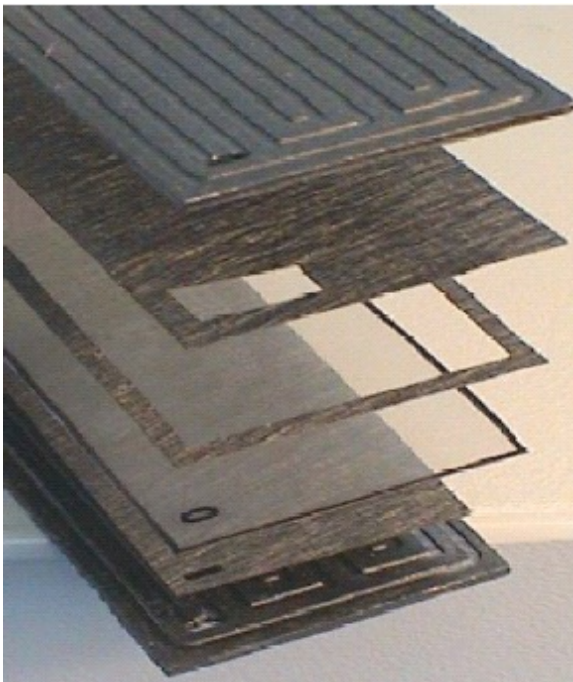


Copied from G.G. Scherer, PSI, Fuel Cell Tutorial, European Fuel Cell Forum, Lucerne

PEFC : critical water management



Copied from G.G. Scherer, PSI, Fuel Cell Tutorial, European Fuel Cell Forum, Lucerne



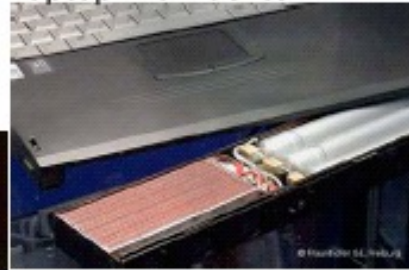
70 kW_e



2 kW_e

5 - 50 W_e

Laptop with fuel cell



Fuel cell camcorder



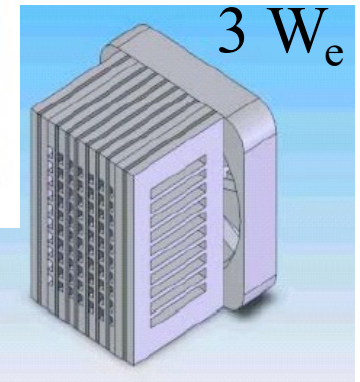
Professional camera with fuel cell



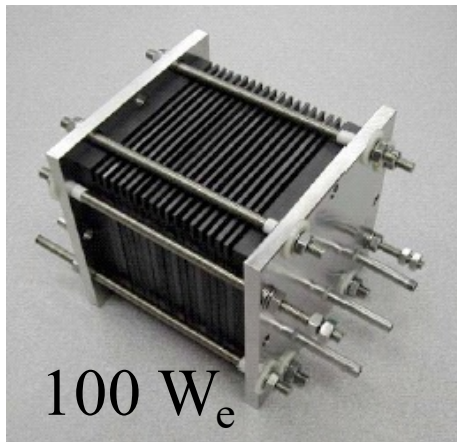
5 kW_e



Fuel cell power box



3 W_e



100 W_e

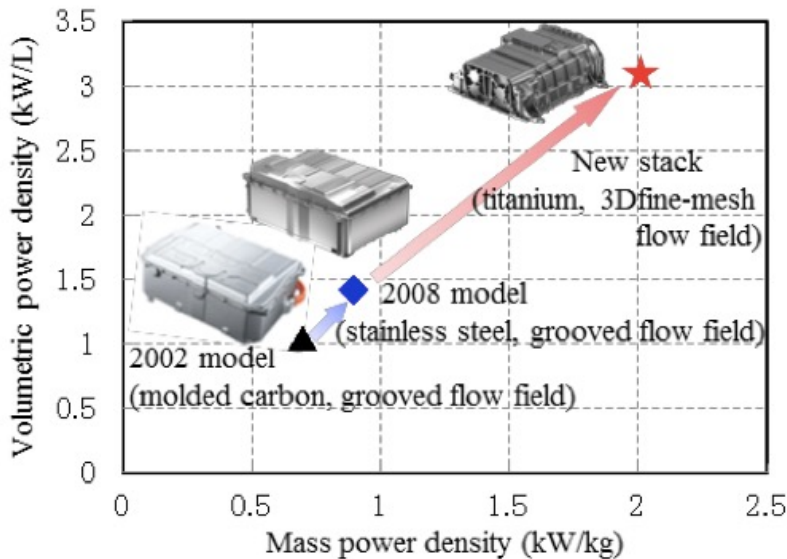
PEFC applications

Toyota Mirai

On the market since January 2015
 Many 1000 vehicles sold.

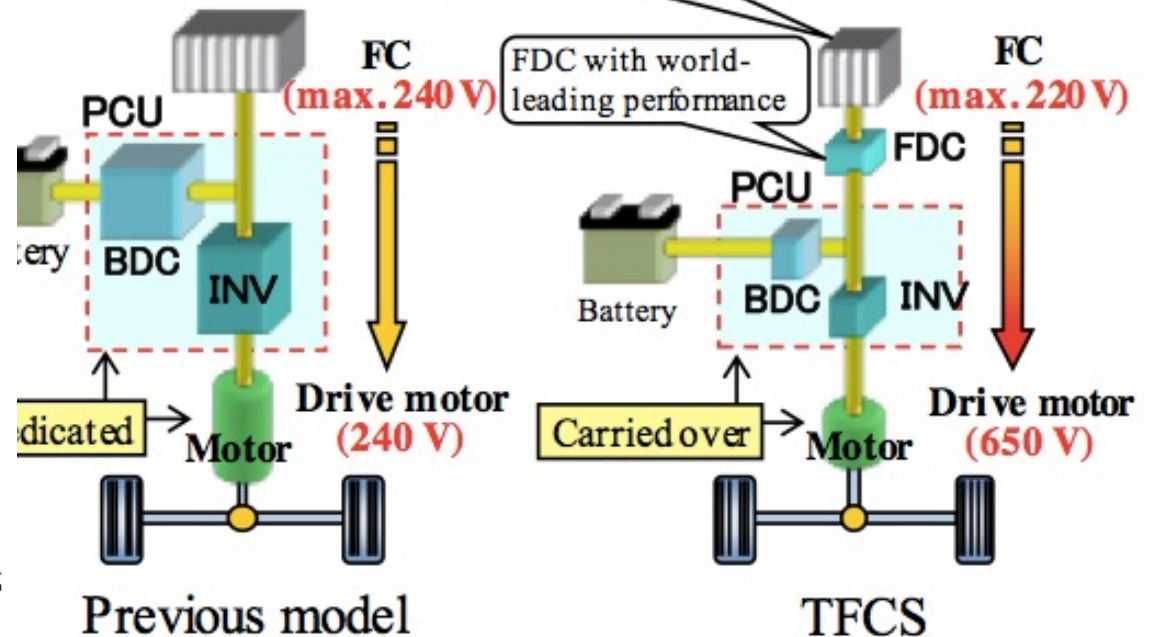


<https://www.youtube.com/watch?v=vmk15ZjgFXg>



FDC: FC boost converter
 BDC: Battery boost converter

Compact and low-cost
 (fewer layered cells)



Some facts

- Toyota invested 15 billion Fr in developing the Mirai car
- Hyundai employs 4000 fuel cell system engineers
- A fuel cell car consumes 0.8 kg H₂ per 100 km
 - 1 kg H₂ = 33 kWh
 - 1 L gasoline = 9 kWh
 - hence this is equivalent to <3 L gasoline /100 km
- **Cost:**
 - H₂ price = 10 €/kg (future target : 5 €/kg)
 - Gasoline price = 1.7 Fr/L
 - hence this high H₂ cost is even cheaper than a 6 L/100 km gasoline car

Comment: (1) H⁺ conduction

- The 2 former **fuel cell types** use **proton (H⁺) conduction**, in a liquid (**acid**) or a wet membrane (**polymer**)
- They operate at 200C (acid) or below 100C (polymer)
- At such '**low**' **temperature**, the **only fuel** reactive enough to be (electrochemically) oxidized is **hydrogen (H₂)**
 - ...and methanol (MeOH), but with much reduced power output
- Moreover, the **only electrodes** capable to catalyze this reaction ($\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$) in **acidic** medium at such low temperature are the **noble metals** (Pt-group) – cf. activation overpotential (charge transfer at cathode) and exchange current density j_0

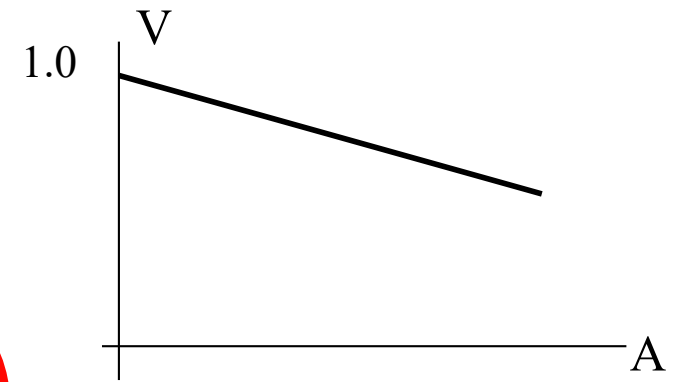
=> limited to H₂ and Pt

Comment: (2) oxygen conduction

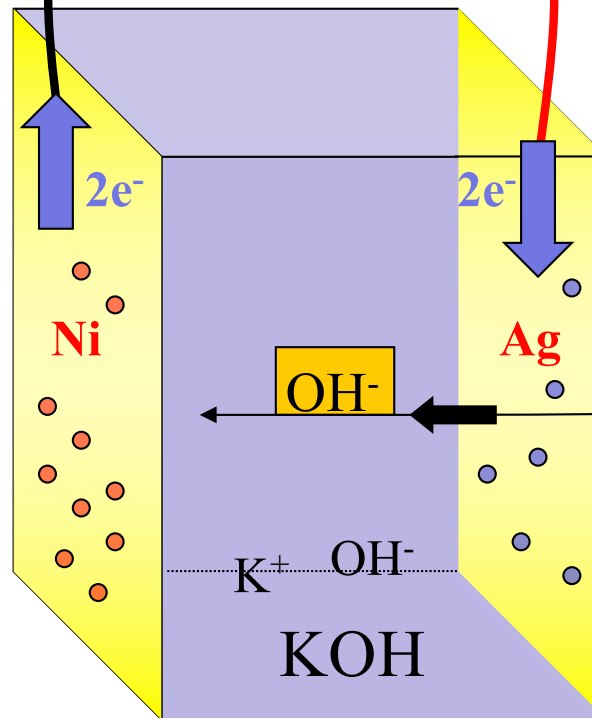
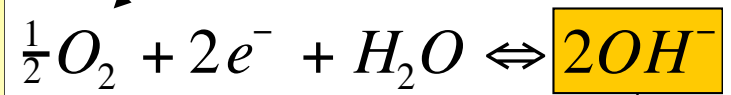
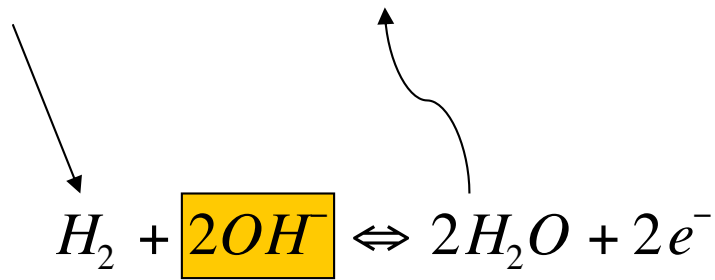
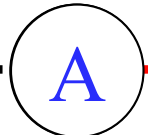
- The following **3 fuel cell types** use a form of **oxygen ion conduction**
- Two use a ceramic resp. molten salt conductor, which operate at high temperature (>600C)
- At such **high temperature**, **other fuels than H₂** become reactive enough for (electrochemical oxidation) (CO, CH₄,...)
- Moreover, high temperature is favorable for fast electrode kinetics, making **cheaper catalysts** than noble metals possible (Ni, oxides,...)

=> possible with hydrocarbons, on Ni catalyst

3. Alkaline Fuel Cell (AFC)



< 1 V



application:
transport, or
low cost stationary

↑

80C



on-board 12 kW_e

Alcaline FC

- requires pure H₂, air without CO₂ (carbonatisation of KOH electrolyte)
- ...but CO₂ is easily scrubbed out
- cheaper catalysts possible, as alternative to Pt (Ni anode, Ag cathode)
- robust
- can be mass-manufactured
- 60% efficiency based on H₂
 - Varta batteries (D)
 - Siemens (transport)
 - Univ. Graz (AUT, Prof. Kordesh)
 - **AFC Energy (UK) => 0.5-1 MWe systems**
(market: H₂ byproduct from NaCl salt electrolysis)

AFC example from Apollo Spacecraft (1970'ies)

Manufacturer: Pratt & Whitney Aircraft Division of United Aircraft Corporation

3 fuel cells stacks on board

pure liq H_2 and O_2

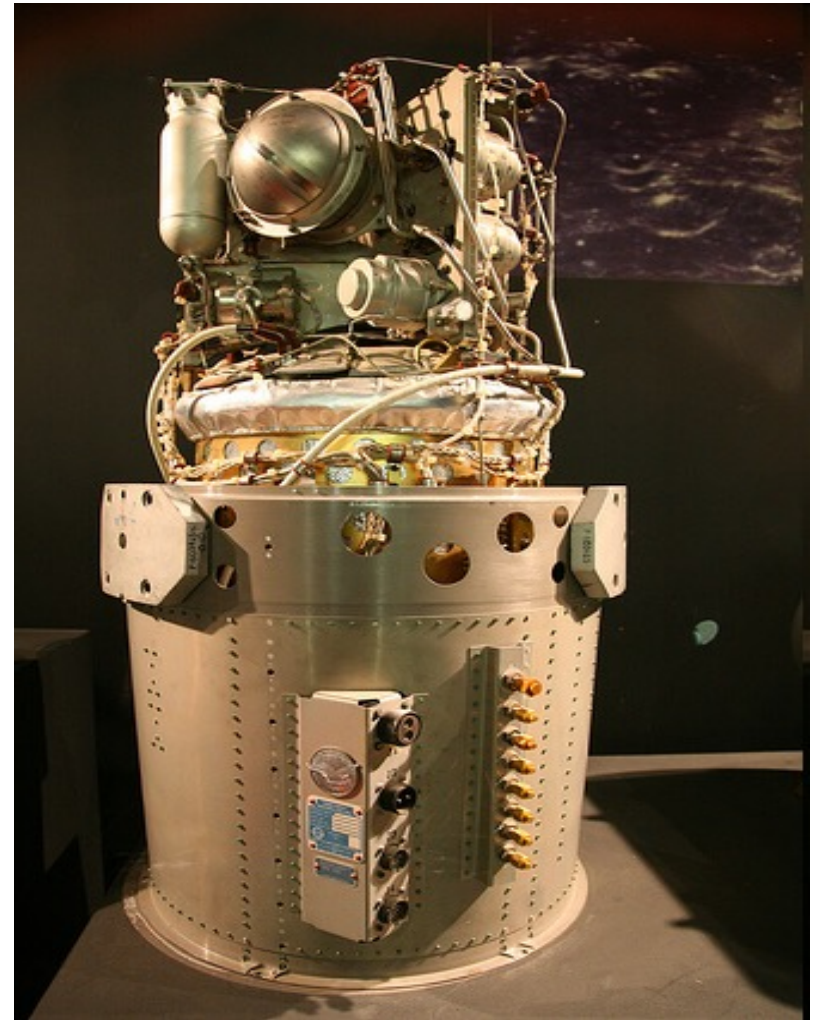
operating T $206^\circ C$

efficiency 70% !

31 cells in series operating at 27-31 V for a power output of 0.56-1.42 kW, and a max of 2.3 kW (each stack)

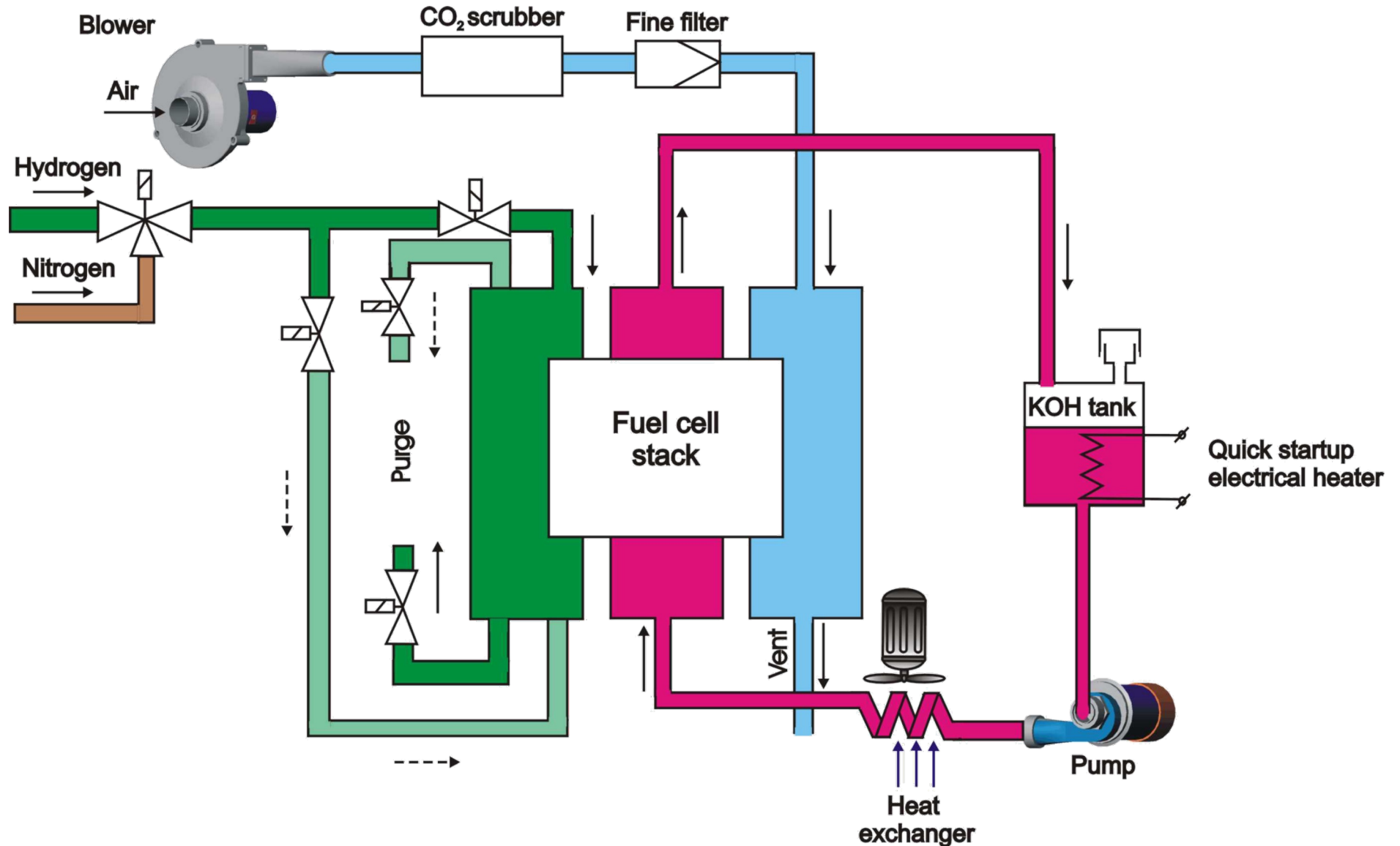
Construction materials: Ti, stainless steel, Ni
Electrodes: Ni with Pt catalyst

(no limit on noble metal use for space application!!)

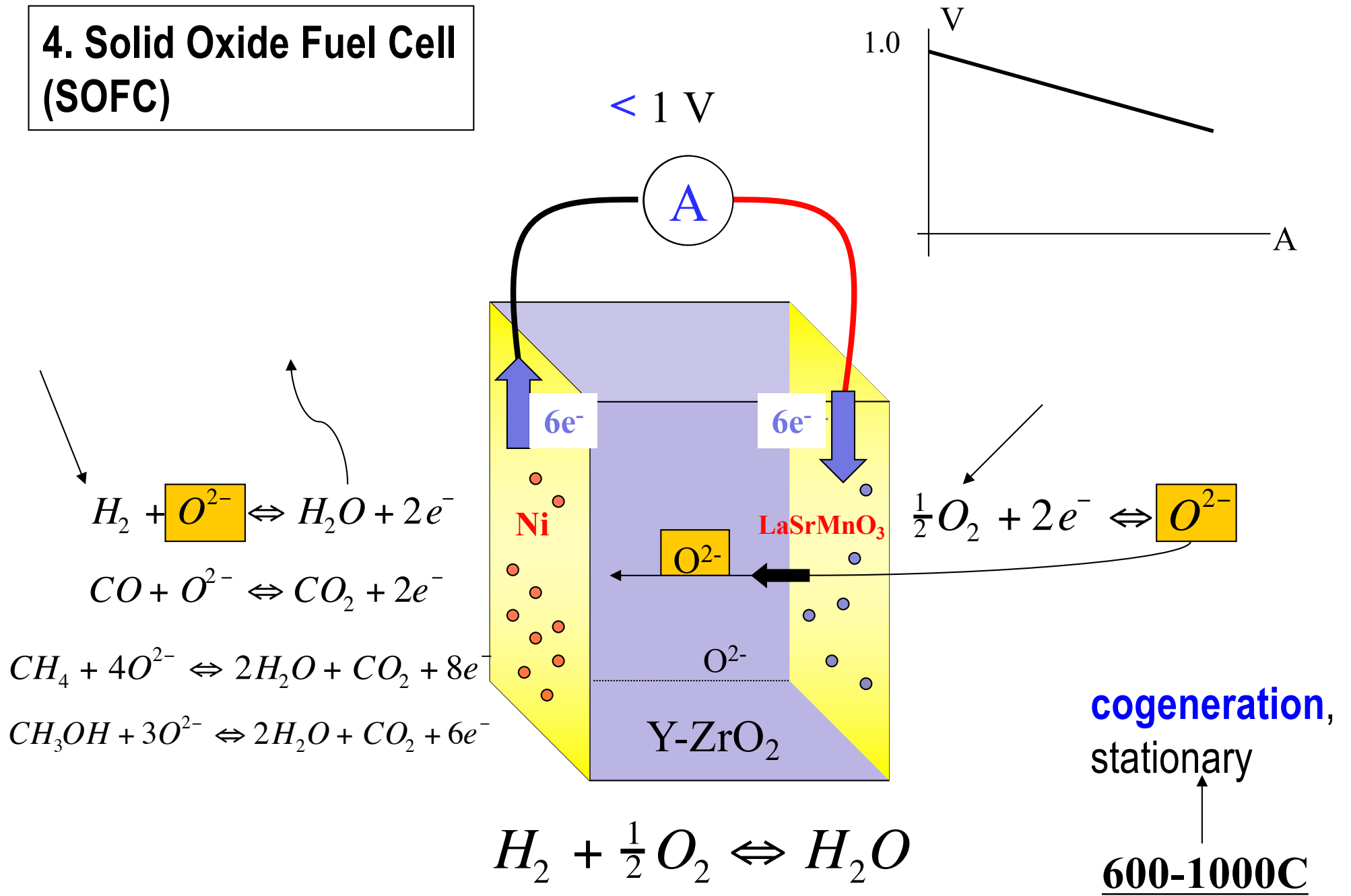


AFC system

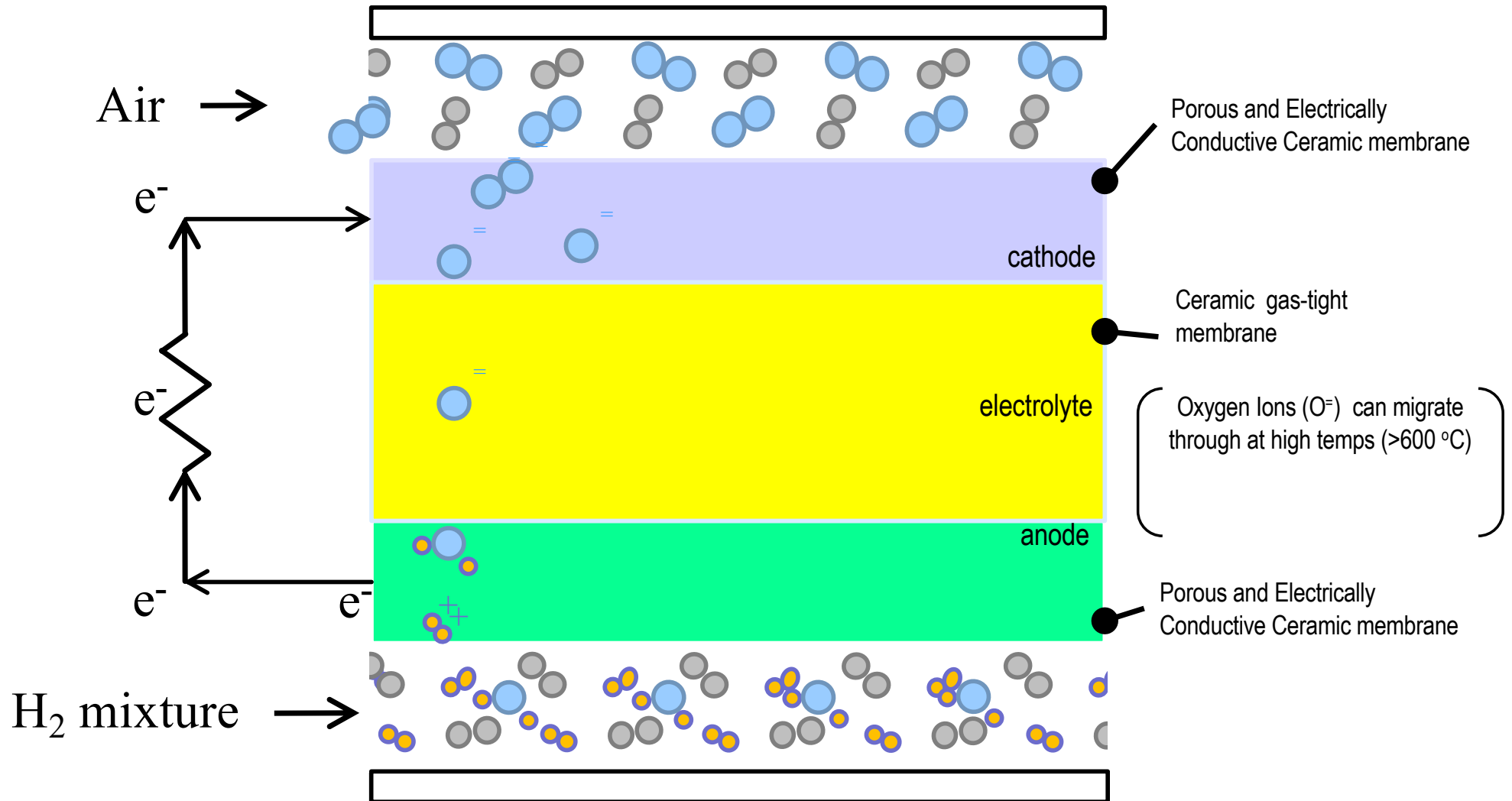
characterised by a circulating electrolyte



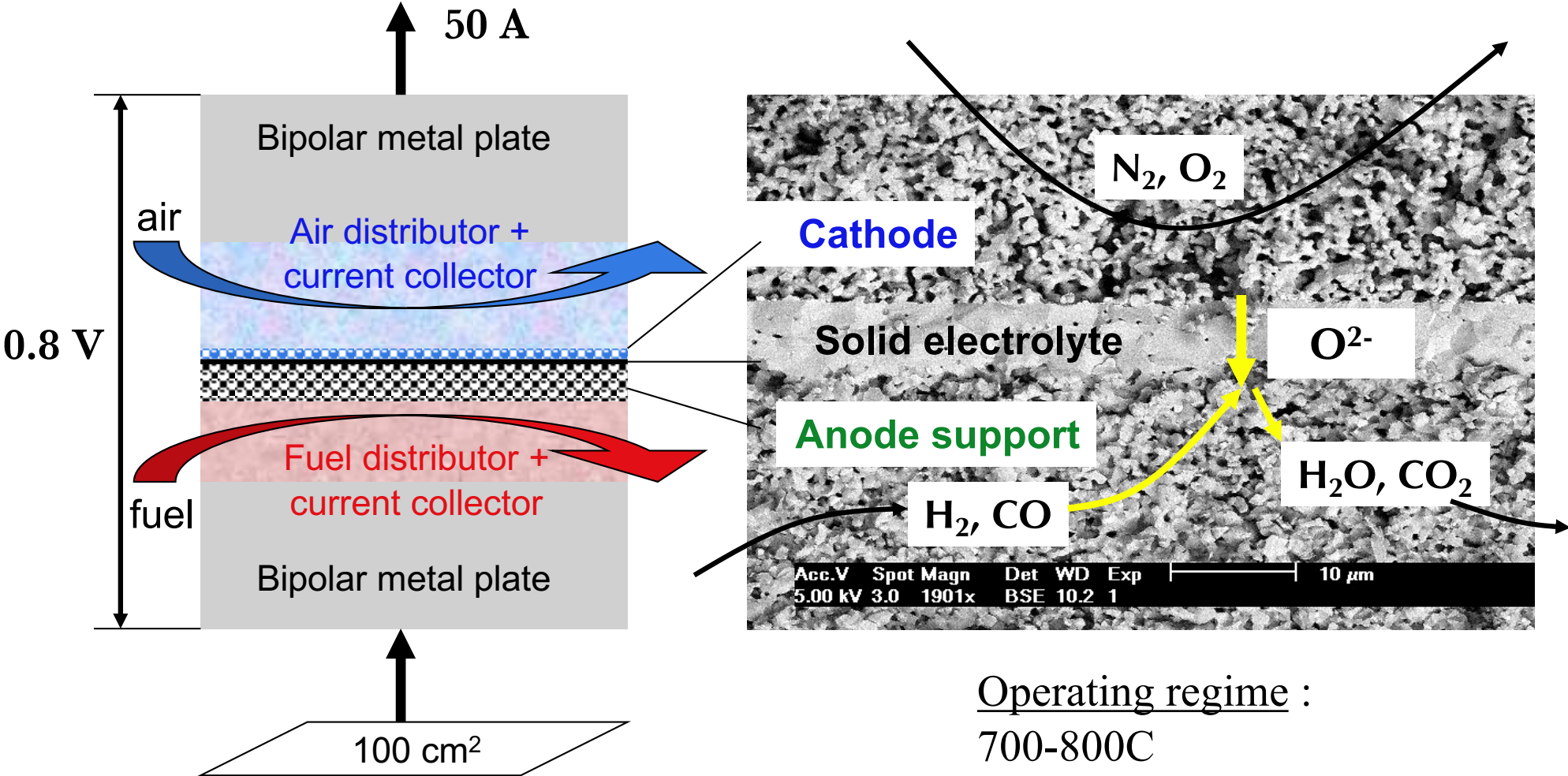
4. Solid Oxide Fuel Cell (SOFC)



FC operation



SOFC interfaces detail



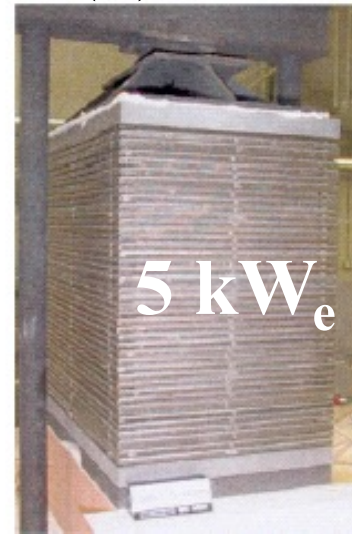
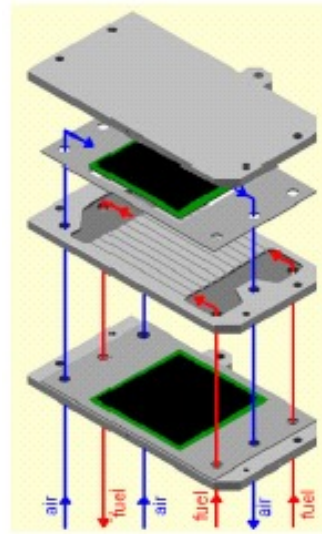
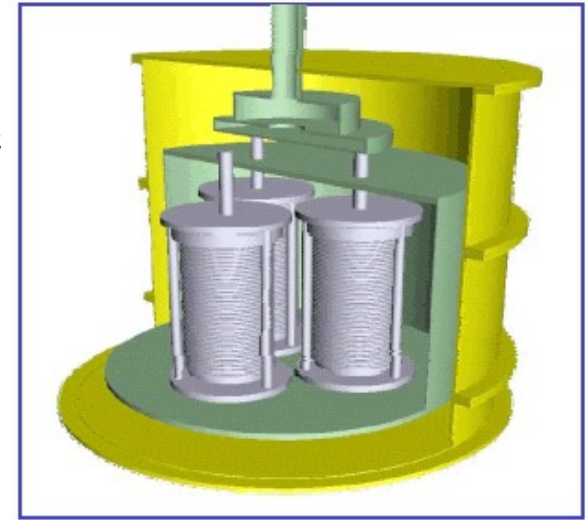
Operating regime :
 700-800C
 1 bar (to 5 bar)



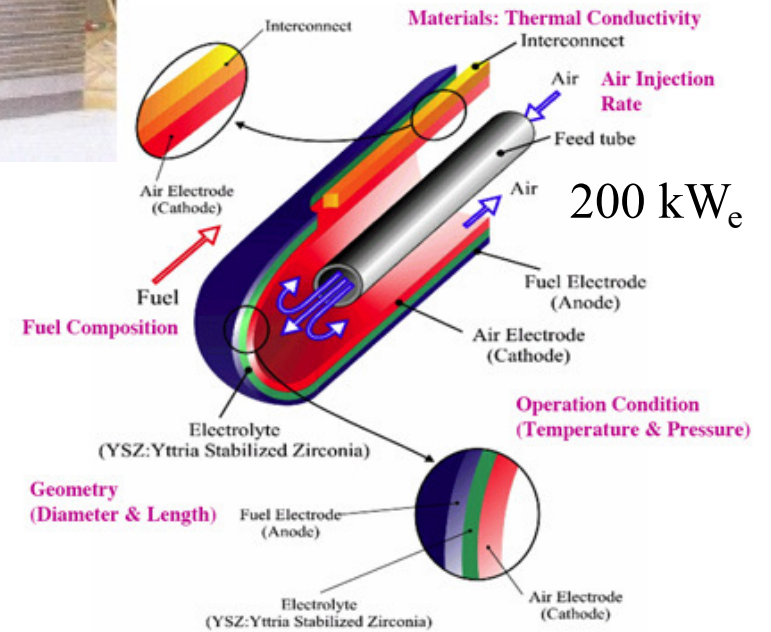
TOHO
GAS
1 kW_e

Kansai
Electric
3 kW_e

FZJülich (D)



RollsRoyce Power (UK)



Siemens-Westinghouse

2 kWe net 63% ac efficient SOFC system



Performance			
	Min	Optimum	Max
Electrical Output	500 W	1500 W	2000 W
Electrical Efficiency	36 %	60 %	57 %
Thermal Output	Approx. 400 W*	Approx. 540 W*	Approx. 1000 W*
	* Based on exhaust gas cooled to 30 °C		
Power Output Modulation	From 0 % to 100 %		
System Efficiency	60 % to 85 % Depending on heat and condensate recovered		

<https://www.dailymotion.com/video/x2p2rmd>

Multi-100 kWe SOFC



Inputs	
Fuels	Natural Gas, Directed Biogas
Input fuel pressure	15 psig
Fuel required @ rated power	0.661 MMBtu/hr of natural gas
Water required (for startup only)	120 gallons municipal water
Outputs	
Rated power output (AC)	100 kW
Electrical efficiency (LHV net AC)	> 50%
Electrical connection	480V @ 60 Hz, 4-wire 3 phase
Physical	
Weight	10 tons
Size	224" x 84" x 81"
Emissions	
NOx	< 0.07 lbs/MW-hr
SOx	negligible
CO	< 0.10 lbs/MW-hr
VOCs	< 0.02 lbs/MW-hr
CO ₂ @ specified efficiency	773 lbs/MW-hr on natural gas, carbon neutral on Directed Biogas

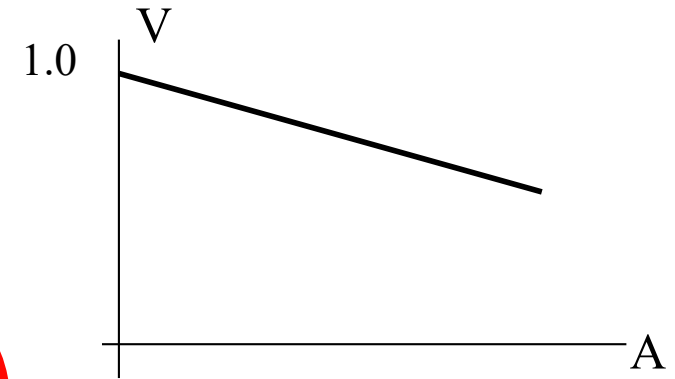
60-65%

www.bloomenergy.com/products

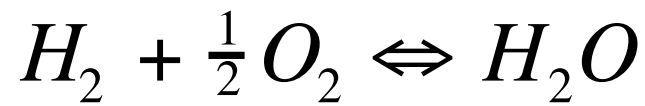
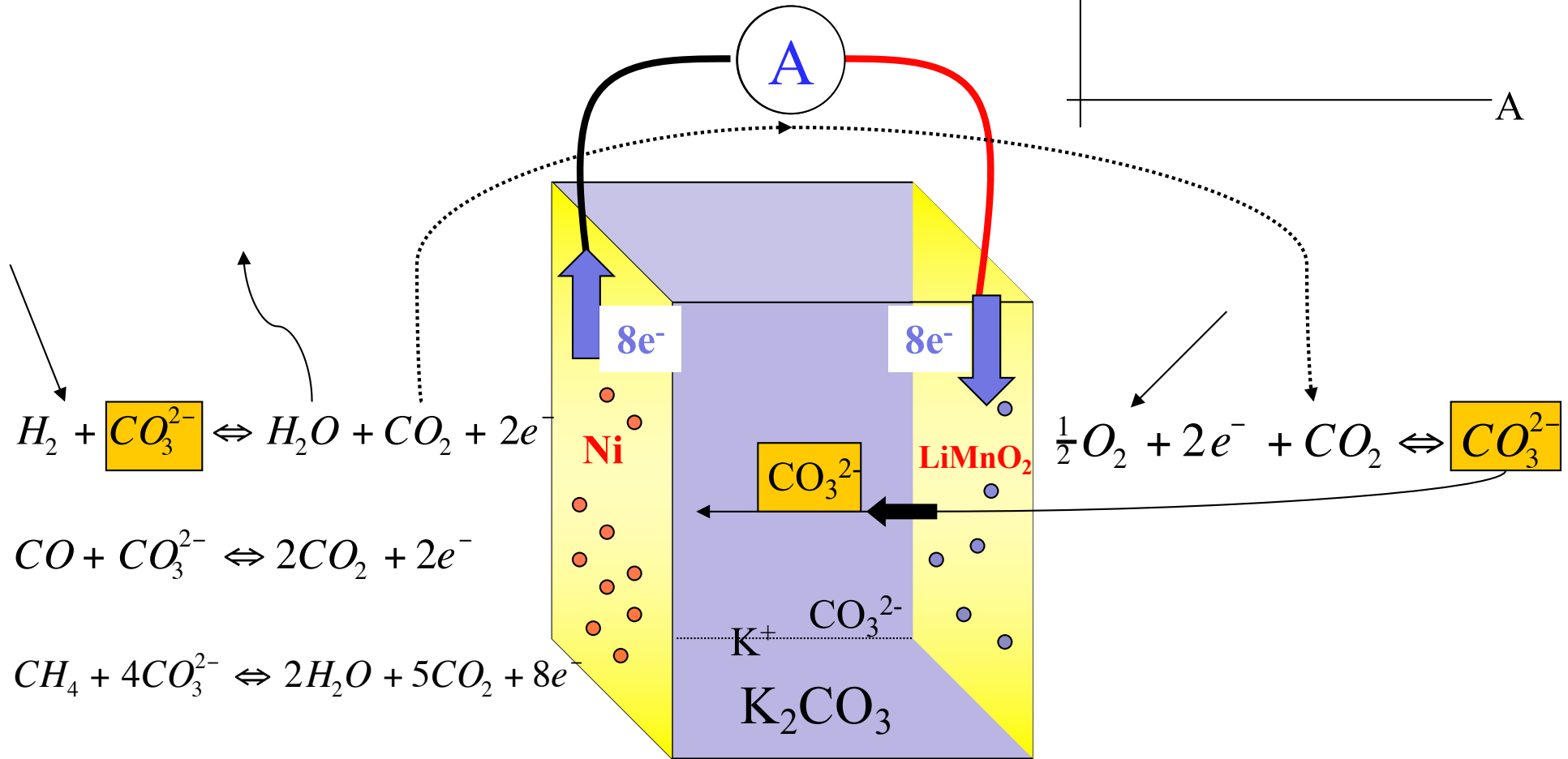
SOFC characteristics

- tubular : robust (>12 yr proven lifetime), but expensive
goal = few MWe in a hybrid cycle with a micro-gasturbine
- planar : proven lifetime 70'000 h, with **mass-manufacturing** potential;
typically 1-10 kW_e modular units, demonstrated up to MWe
- **60% η_{el}** achieved for both designs
- fuel : NG, LPG, diesel, biogas, NH₃, alcohols, wood gas,...
- **Materials challenges** :
 - FeCr steel interconnect corrosion
 - electrode poisoning from CrO_x steel vapors
 - anode (Ni) reoxidation (=> NiO : expansion) during operation
 - differential thermal expansion, layer delaminations
 - imperfect sealing (leaks)
 - electrode microstructure coarsening, e.g. Ni particle growth
 -

5. Molten Carbonate fuel cell (MCFC)



< 1 V

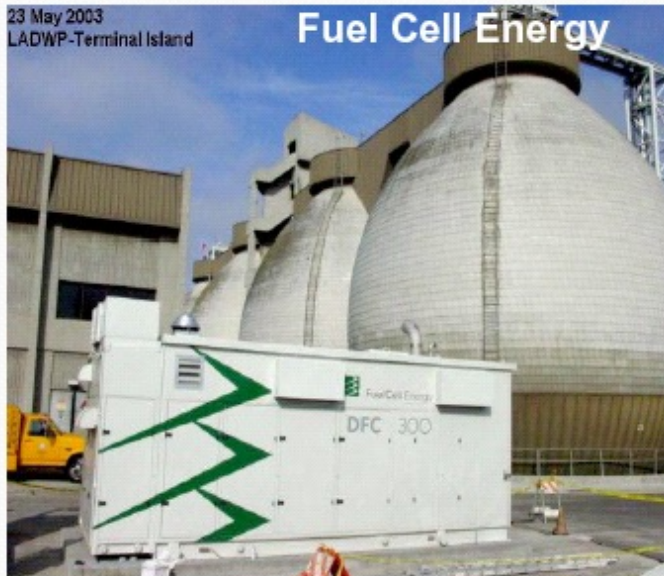


650° C

Photos courtesy of: FCE, AFC, MTU, NEDO, KEPRI

23 May 2003
LADWP-Terminal Island

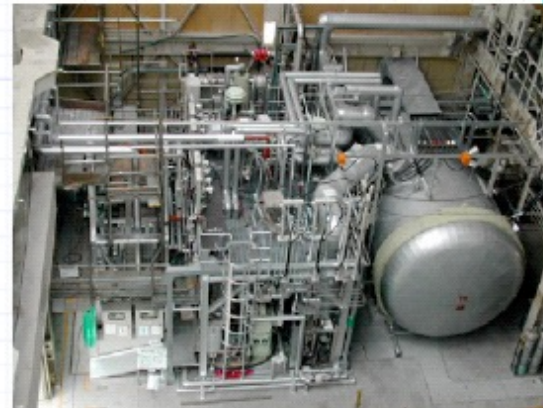
Fuel Cell Energy



Rhon-Klinikum Hospital (MTU)
Bad Neustadt & Bad Berka,



Ansaldo Fuel Cells S.p.A.



Full View of 300kW-class Compact System
in KAWAGOE Test Station

NEDO



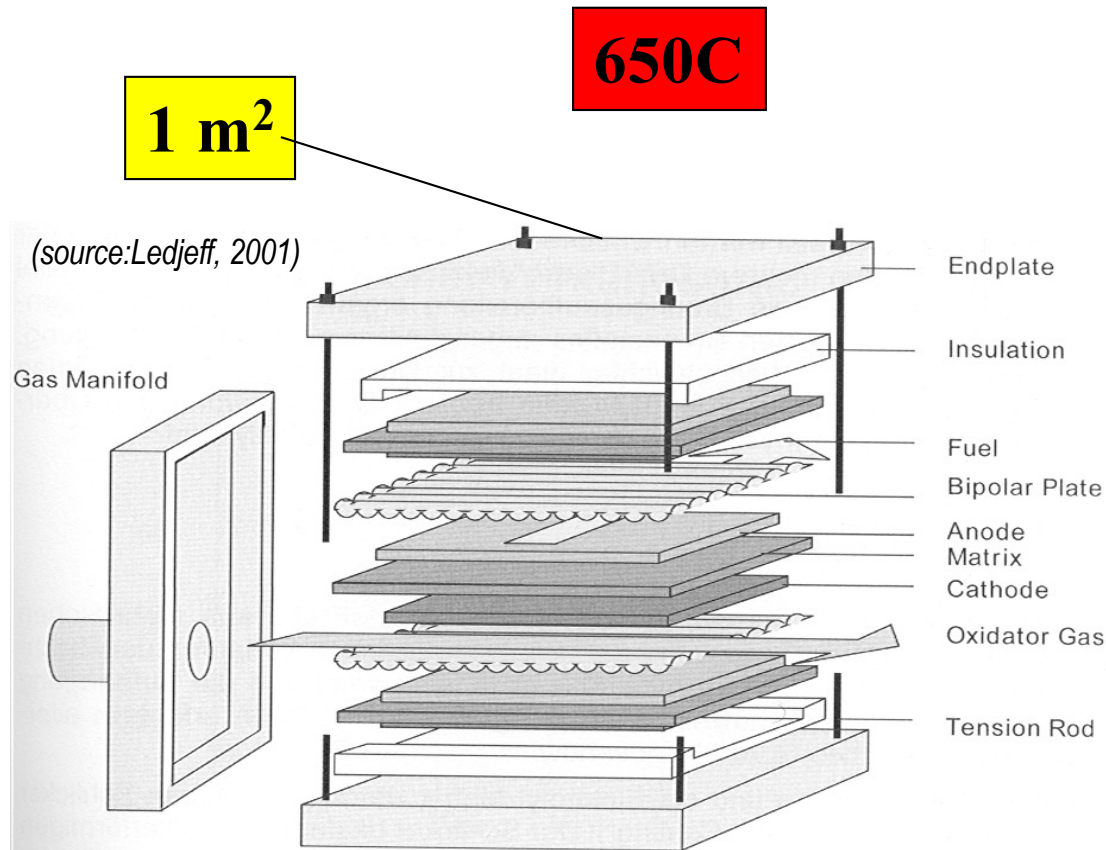
KEPRI

MCFC cogeneration units of 250 kW_e - 1 MW_e

MCFC design & materials

World leading : FUEL CELL ENERGY company :

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

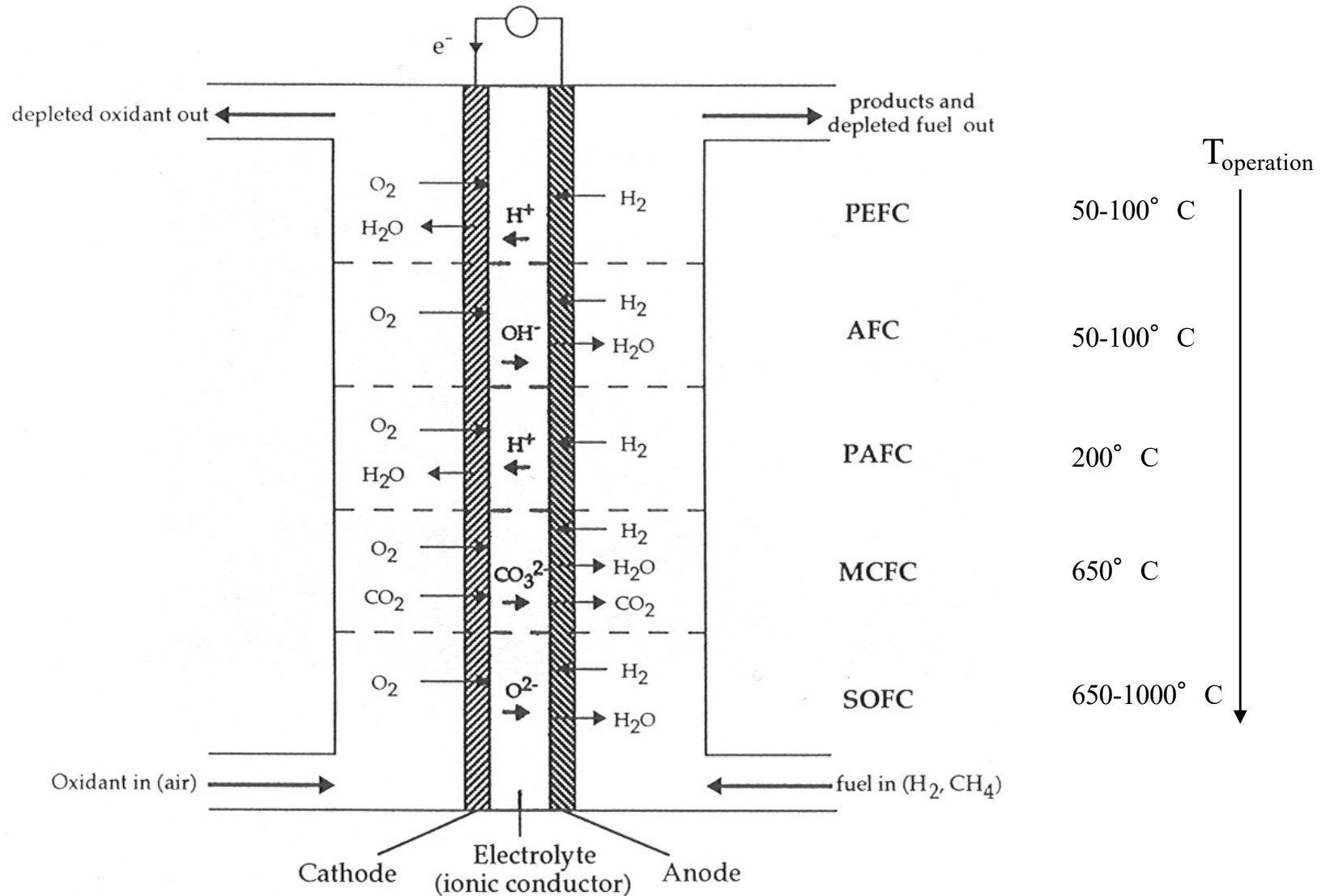


- electrolyte = Li_2CO_3 or Na_2CO_3 mixed with K_2CO_3 , molten at $600\text{-}700^\circ\text{C}$, in a porous ceramic matrix of LiAlO_2
- anode : NiCr or NiAl
- cathode : Li-doped NiO
- interconnection : stainless steel

- CO_2 recirculation imposes a minimal size on the system (250 kW_e)
- 4 modules are combined to one 1 MWe unit etc.

The 5 FC types (summarised)

(according to $T_{\text{operation}}$ and the ionic conductor)



Fuels: distinction low vs. high T (H_2 vs C_xH_y)

Type	Electrolyte	Temperature	Fuel
AFC	Alcaline solution	20-100° C	H_2
PEFC DMFC ←	Polymere membrane	20-100° C	H_2 methanol
PAFC	liquid acide	20° C	H_2 (nat. gas)
MCFC	Molten salt	650° C	C_xH_y
SOFC	Solid ceramic	600-1000° C	C_xH_y

“direct” methanol

Materials in fuel cells: low vs high T (Pt vs Ni)

Type	Electrolyte	Cathode	Anode	Interconnect	Dimensions
AFC	KOH	Ag	Ni	conducting composite	flat, 50-500cm ²
PEFC	« Nafion » («sulfonated teflon »)	Pt on C	Pt(-Ru)	graphite	flat, 5-500 cm ²
PAFC	H ₃ PO ₄	Pt on C	Pt on C	graphite	flat, 1 m ²
MCFC	(Na,K,Li) ₂ -CO ₃	NiO or LiCoO ₂	Ni	inox	flat, 1 m ²
SOFC	90% ZrO ₂ + 10% Y ₂ O ₃	LaSrMnO ₃ LaSrFeO ₃ LaSrCoO ₃	Ni	Ferritic Cr or high Cr steel	flat, 10-400 cm ² tubes / (2 m long * 2 cm diam.)

SOFC stack assembly (movie)

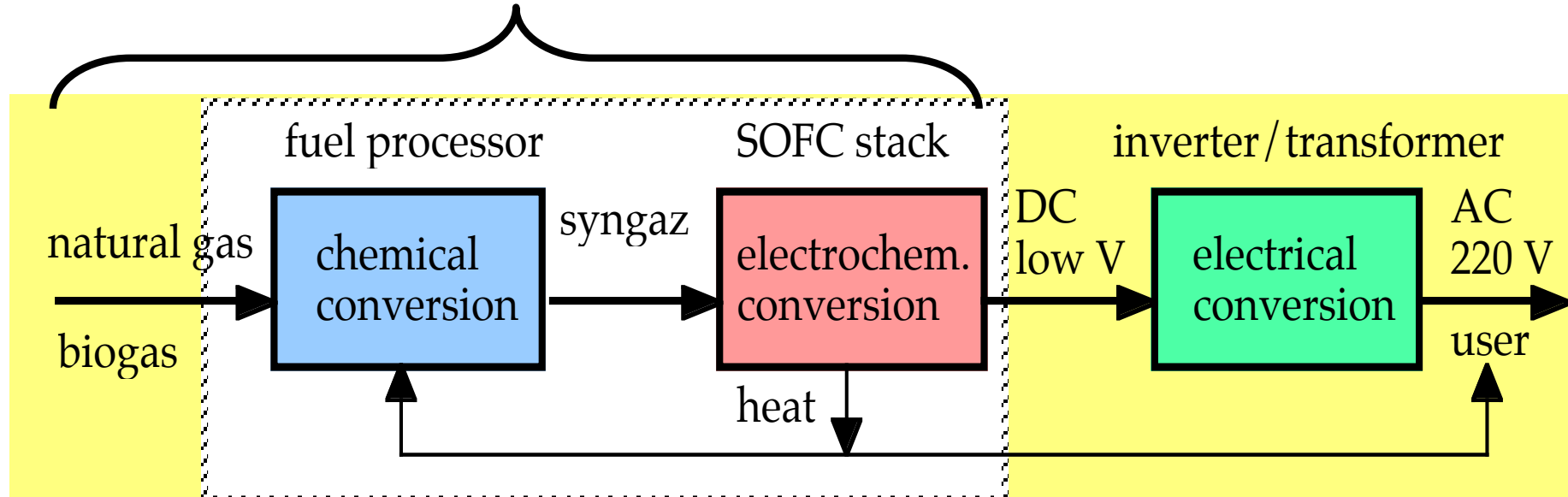
APPLICATIONS OVERVIEW

Portable	0.1-100 W	electronics (competing with batteries)	DMFC, PEFC
Small cogen.	1 kW - 100 kW	«best» range (lower competition from μ T or diesel engines)	SOFC, PEFC
Transport	10 kW - 200 kW > 1 MW	vehicles, buses ships	PEFC, DMFC, AFC MCFC, SOFC
Medium cogen.	0.2 MW - 3 MW	offices, schools, hotels, hospitals, supermarkets; industry (chem./ steel/ foods)	PAFC, AFC MCFC SOFC

Power size

FUEL CELL SYSTEM

“conversion chain”



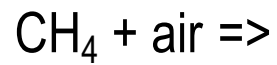
A system of 3 series converters :

1. FUEL PROCESSOR (fuel treatment)
2. FUEL CELL STACK
3. Electrical conditioning (DC/AC, DC/DC)

ADVANTAGES of Fuel Cells

- I. High **electrical efficiency**
 - a) for small power size (1 We - 1 MWe)
 - b) especially at *partial* load
- II. Low chemical and acoustical **emissions**
- III. **Cogeneration** of electricity & heat
- IV. **Modularity**
- V. Fuel **flexibility**
 - a) **fossils** (natural gas, diesel, coal gas,...)
 - b) **renewables** (biogas, biodiesel, woodgas, ethanol,...)

Electrical efficiency: combustion vs electrochemistry



combustion



polluting emissions

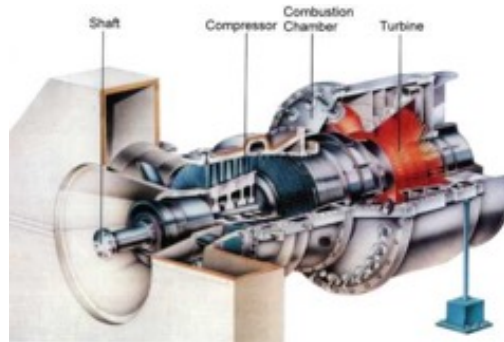
ENGINES



http://www.sdeciepower.com/8.3L_Natural_Gas_Engine.htm

0.1 – 5 MW_{el}
η_{EL} 33-45%

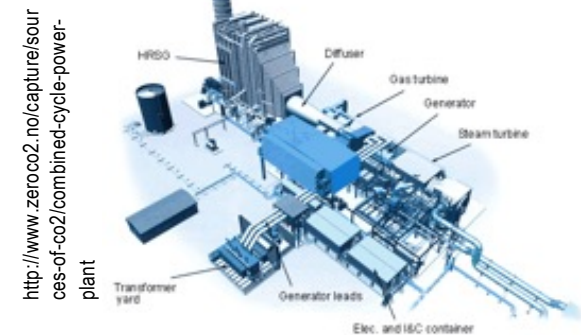
TURBINES



<http://www.wartsila.com/sv/kraftverk/learning-center/gas-turbine-for-power-generation>

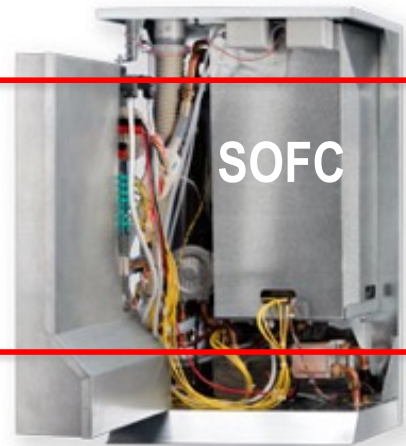
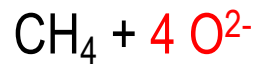
5-100 MW_{el}
η_{EL} 27-40%

COMBINED CYCLES



<http://www.zeroCO2.no/capture/sources-of-co2/combined-cycle-power-plant>

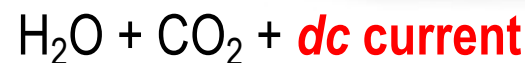
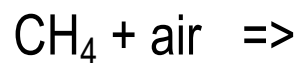
50-500 MW_{el}
η_{EL} 50-60%



electrochemical
"combustion"

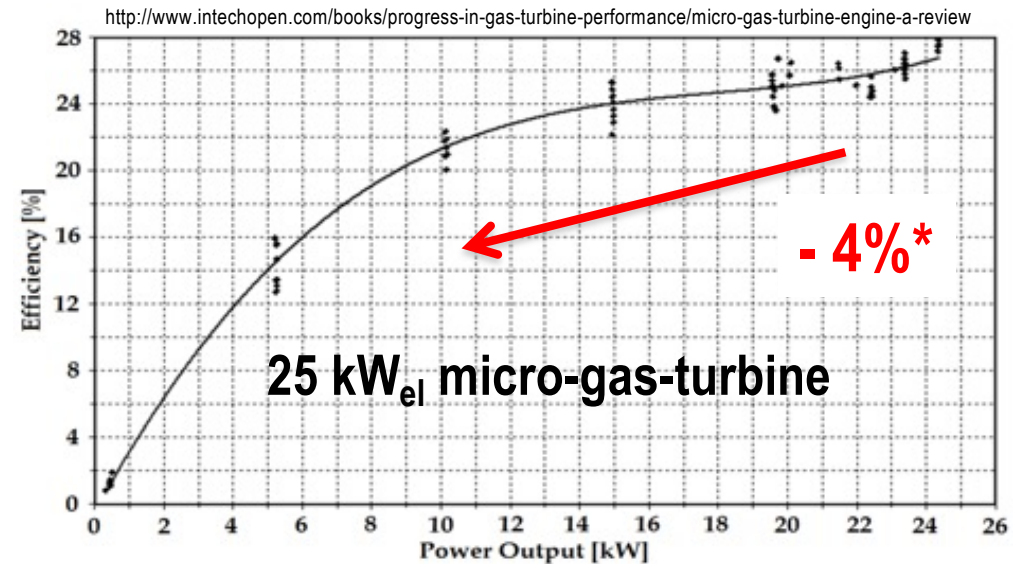
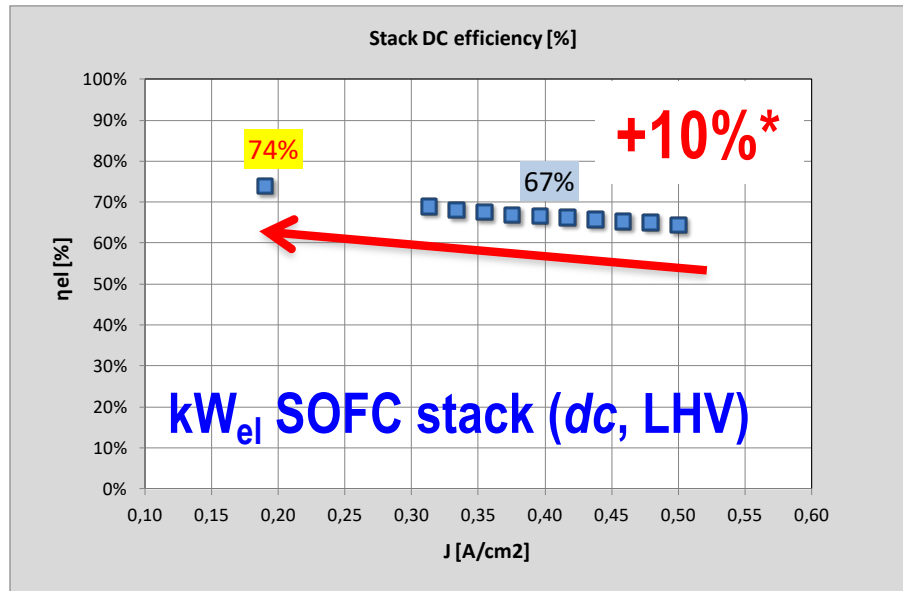
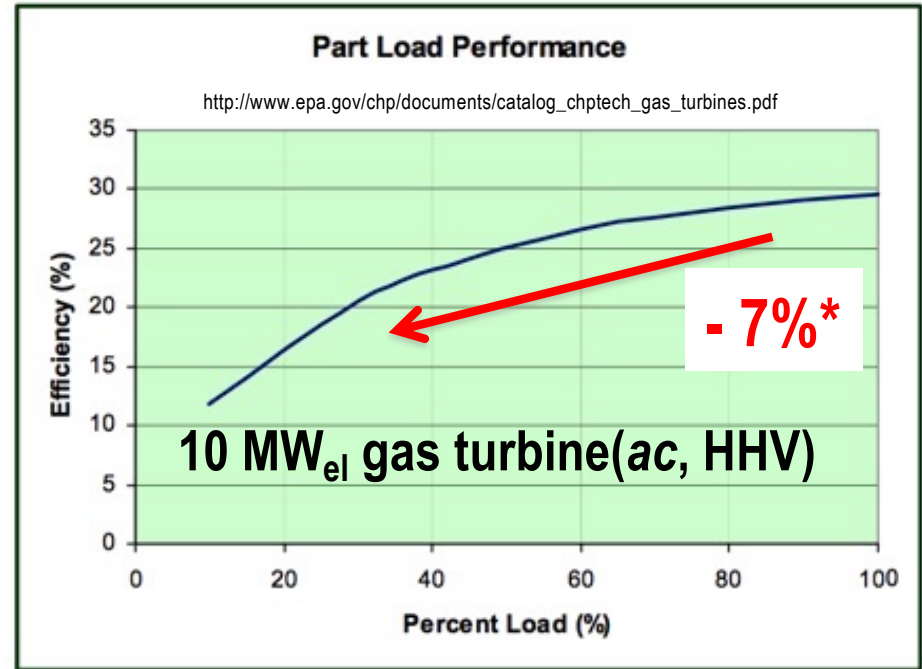
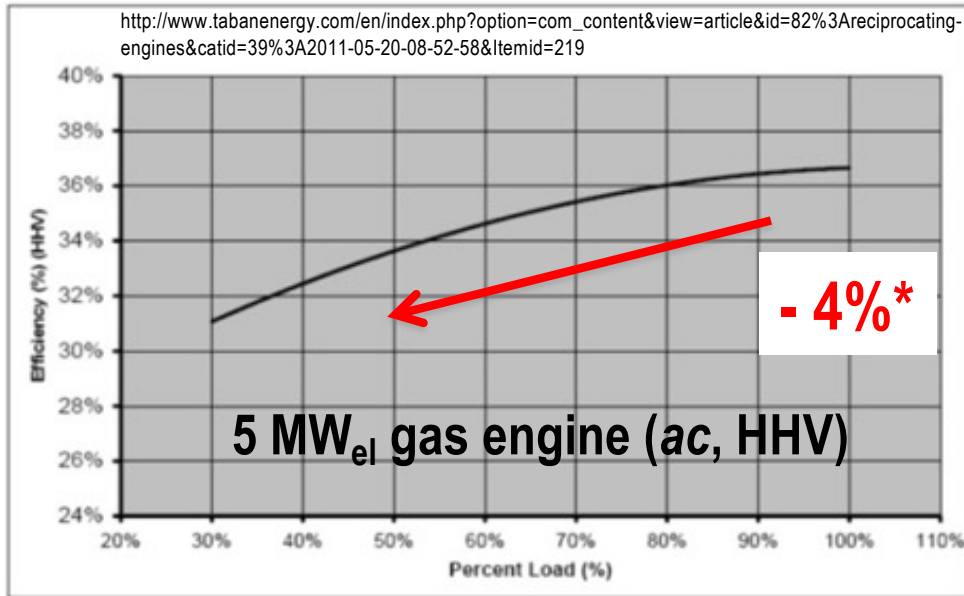
1 – 100 kW_{el}
η_{EL} 50-60%

no pollution



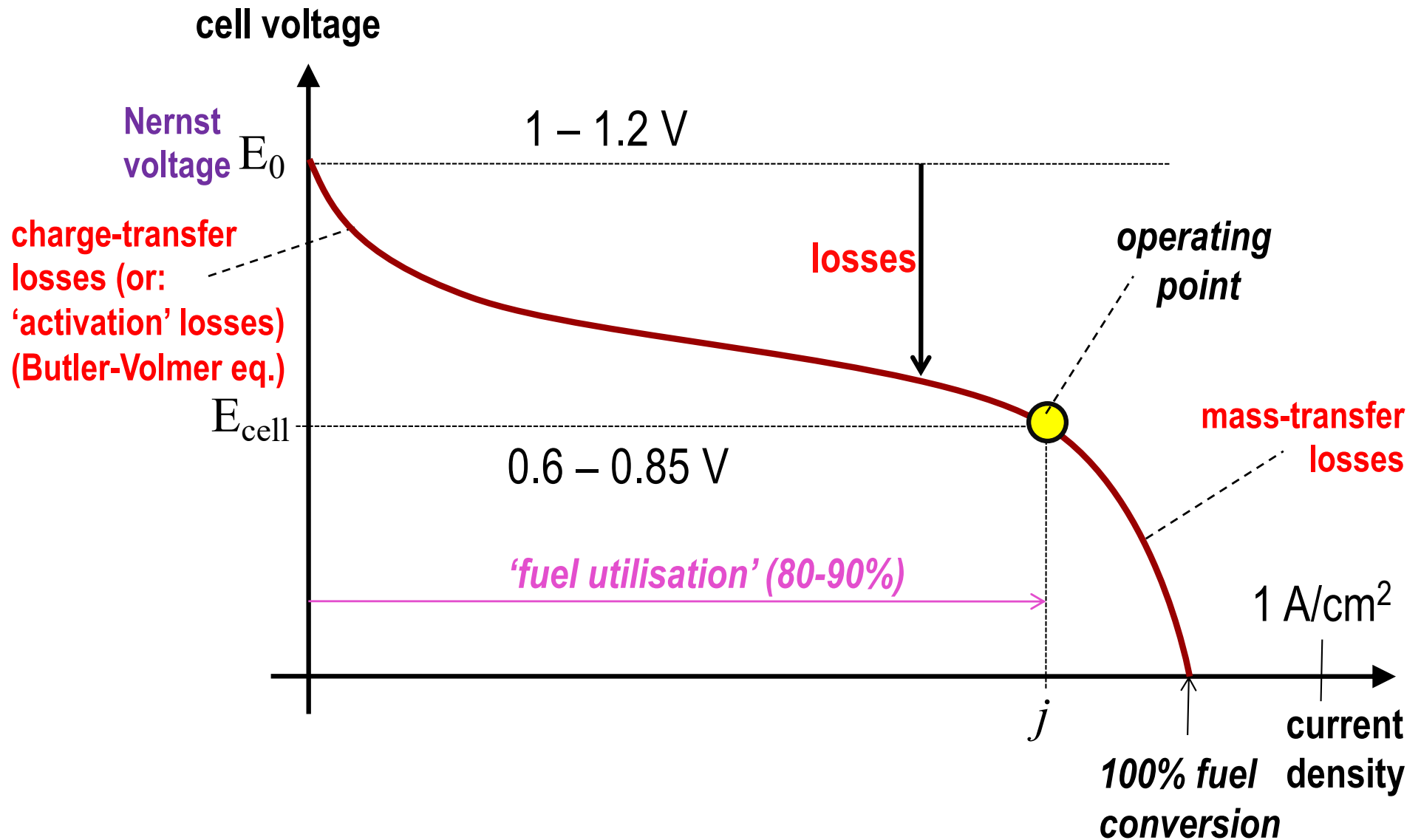
+ cogenerated useful heat

Part load: technology comparison



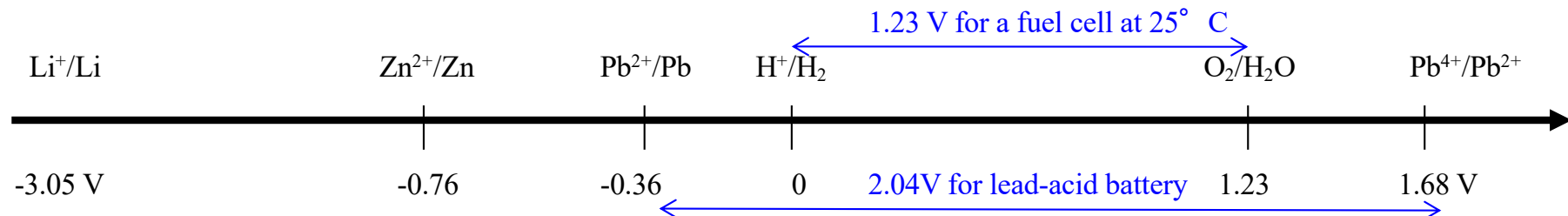
*from 100% to 40% power modulation

Characteristic i-V (current-voltage) curve



Nernst equilibrium voltage and thermodynamics

- in a fuel cell at equilibrium (start-up, no net external current), fed with H₂/O₂ (air), the **Nernst voltage** is characteristic for the reaction H₂/O₂ : **1.229 V** (at 298K and 1 atm)
- the useful **work (electricity)** exploitable from this reaction H₂/O₂ is given by the **Gibbs free enthalpy** of the corresponding chemical reaction $\Delta G_r = \Delta H_r - T \Delta S_r$:
 for H₂ + 0.5 O₂ -> H₂O
 where $\Delta G_r^0(298K, 1 \text{ atm}) = -237' 150 \text{ J/mole}$
- the link between ΔG_r (J/mole) and the Nernst voltage, E (or V, or U) is the amount of charge (in Coulomb, C) exchanged across this voltage :
 $\Delta G_r = - nF.E$
 (with n = 2 exchanged electrons for H₂, F = Faraday constant = 96484 C / mol e⁻),
 which leads to the value $E^0 = 1.229 \text{ V}$ (for H₂/O₂ at 1 atm, 298 K)



Efficiency

$$\Delta H_{\text{reaction}}$$



$$\Delta G_{\text{reaction}}$$



$$\Delta G = -nFE_{\text{Nernst}}$$

$$E_{\text{Nernst}}$$



$$V_{\text{cell}}$$

total enthalpy = total chemical (**heat**) energy at inlet
= heating value of the used fuel (kJ/mol, kJ/kg)

free enthalpy = theoretical useful **work** (kJ/mol, kJ/kg)

↓
in a fuel cell: electrical work

F: Faraday constant 96500 C/mol
n: number of electrons released per fuel molecule

equilibrium voltage (V) $i = 0$

operating voltage (V) $i \neq 0$

- includes all **losses** in the internal circuit

Total (ΔH) and free (ΔG – Gibbs) enthalpy

Fundamental thermodynamics equation for any reaction:

$$\Delta H_r(T) = \Delta G_r(T) + T \cdot \Delta S_r(T)$$

here: electrical

- ΔG_r = the fraction of ΔH_r theoretically convertible in **work**
- $T \cdot \Delta S_r$ = **inevitable heat loss** during the conversion (S : entropy)

$$\Delta H_r(T) = \sum_{prod} \nu_{prod} \Delta H_f(T) - \sum_{react} \nu_{react} \Delta H_f(T) \quad \Delta S_r(T) = \sum_{prod} \nu_{prod} S_f(T) - \sum_{react} \nu_{react} S_f(T)$$

v = stoichiometric factors of the reaction

products (H₂O, CO₂,...) educts (H₂, CO, CH₄, O₂,...)

$$\Delta H_f(T) = \Delta H_f^0(298K) + \int_{298}^T C_p(T) dT \quad S_f(T) = S_f^0(298K) + \int_{298}^T \frac{C_p(T)}{T} dT$$

thdynam. tables $C_p(T) = a + b \cdot T + c / T^2$ thdynam. tables

- ➔ ΔG_r for any reaction at any T can be computed from thermodynamic tables
- ➔ The equilibrium voltage E^0 for any reaction at any T can be computed

The effect of concentrations : the mass action law & Nernst equation

To take account of species concentrations (=molar fractions) participating in the reactions :

$$\Delta G_r(p, T) = \Delta G_r^0(T) + RT \ln K$$

all species at 1 atm

equilibrium constant K

$$K = \prod_i \left(\frac{x_i P}{p^0} \right)^{\nu_i} = \frac{x_{H_2O}}{x_{H_2, anode} \sqrt{x_{O_2, cathode}}} \left[\frac{P_{cathode}}{p^0} \right]^{\sum \nu_{cathode}} \left[\frac{P_{anode}}{p^0} \right]^{\sum \nu_{anode}}$$

$\nu_{H_2} = -1, \nu_{O_2} = -0.5, \nu_{H_2O} = 1$ $x = \text{molar fractions at anode and cathode}$ 1 atm

Since $E = -\Delta G_r / nF$, one obtains :

$$E^{SOFC} = E^0 + \frac{RT}{2F} \ln \left(\frac{x_{H_2}^{anode} \sqrt{x_{O_2}^{cathode}}}{x_{H_2O}^{anode}} \right) \left[\frac{P^{cathode}}{p^0} \right]^{\frac{1}{2}}$$

$$E^{PEFC} = E^0 + \frac{RT}{2F} \ln \left(\frac{x_{H_2}^{anode} \sqrt{x_{O_2}^{cathode}}}{x_{H_2O}^{cathode}} \right) \left[\frac{P^{anode}}{p^0} \right] \left[\frac{P^{cathode}}{p^0} \right]^{-\frac{1}{2}}$$

Nernst equation

=> useful cell power

$$E_{pile} = E_{Nernst}(p, T) - (i \cdot R_{ohmique} + |\eta_{cathode}| + \eta_{anode})$$

$$P_{\acute{e}l} = E_{pile} \times i$$

Typical current density: 0.4 A/cm²

Typical useful voltage E_{pile} : 0.75 V

Series connection of cells ("stack") to increase E_{tot}

Example of PAFC :

- 240 cells in series (170 V)
- electrodes of 0.66 m x 0.66 m (1300 A)
- the stack module (1 m³) delivers 200 kW_{él} (and 200 kW heat)

with electrical efficiency : 40%

and global efficiency (cogeneration) >80%

Fuel cell electrical efficiency expression

$$\eta_{cell} = \frac{P[W]}{f[mol/s] \cdot \Delta H_{293K}[J/mol]} \quad \longrightarrow \quad \eta_{cell} = \frac{I \cdot E_{cell}}{f[mol/s] \cdot \Delta H_{293K}[J/mol]} \frac{\Delta G(p,T)}{\Delta G(p,T)}$$

$$\eta_{cell} = \frac{I[A]}{f[mol/s] \cdot nF[C/mol]} \frac{E_{cell} [V]}{E_{Nernst} [V]} \frac{\Delta G(p,T)[J/mol]}{\Delta H_{293K}[J/mol]}$$

$$\eta_{cell} = \eta_I \cdot \eta_V \cdot \eta_{THDYN}$$

current efficiency,
"fuel utilisation"

voltage efficiency

thermodynamic
efficiency

Efficiency H₂ vs. CH₄, with air

	H ₂ , 80C (PEFC)	H ₂ , 800C (SOFC)	CH ₄ , 800C (SOFC)
Fuel utilisation	1	0.85	0.8
* Voltage efficiency	0.65	0.8	0.8
* Thermodynamic efficiency (LHV)	0.93	0.78	1
= Electrical efficiency (LHV)	0.6	0.53	0.64

- these values have been achieved in real systems.
- there is usually co-generation of useful heat, for total efficiencies of $\approx 90\%$.
- CH₄ has the intrinsic benefit of presenting **no entropy loss**.
- H₂ carries an additional intrinsic loss as it has to be synthesized first.

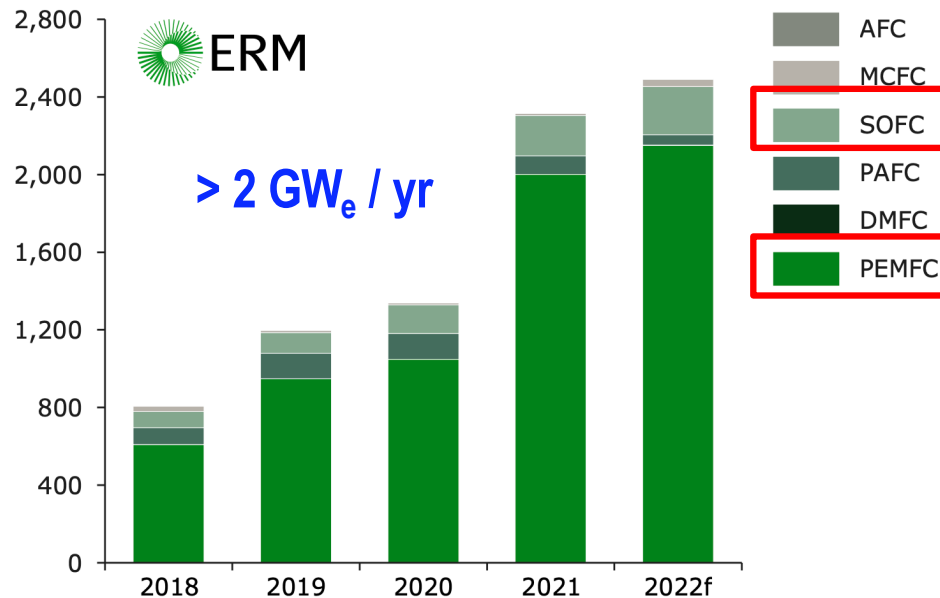
➔ **Methane-FC (natural gas, biogas) are (in principle) more efficient than H₂-FC.**

Worldwide fuel cell deployment: by type, MWe, units

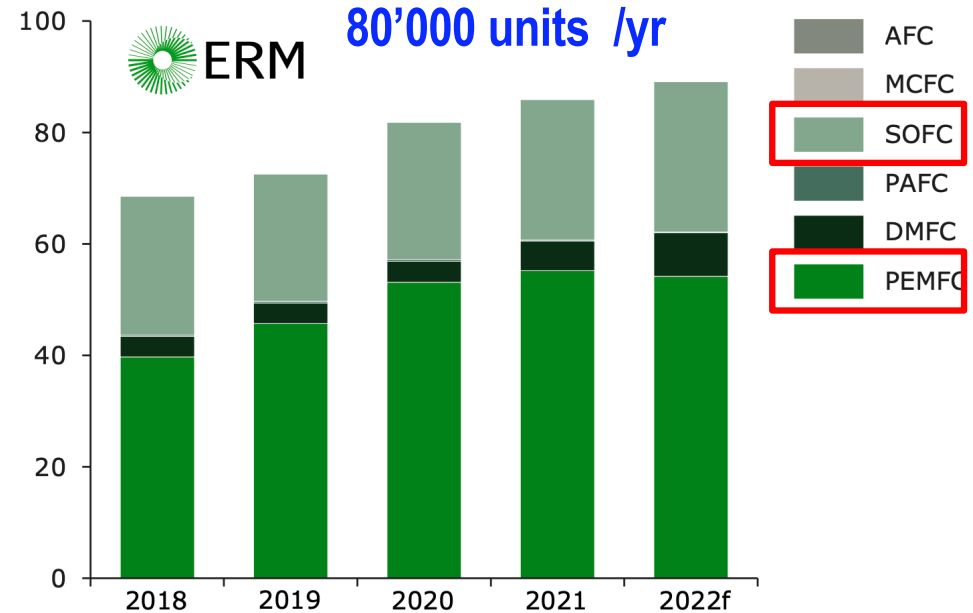
Installed power >10 GWe

>750'000 units

Megawatts by fuel cell type 2018 - 2022



Shipments by fuel cell type 2018 - 2022 (1,000 units)



SOFC, MCFC, PAFC : stationary
 PEMFC : mobility
 DMFC : portable

Summary

- great progress in Fuel Cells since 2 decades
 - H₂-cars and buses (50 – 200 kW_e PEFC)
 - residential micro-CHP (1-2 kW_e SOFC, natural gas)
 - efficient clean cogeneration plants (MW_e-sized SOFC + MCFC, incl. biogas)
- big effort in R & D continues
- competition (engines, batteries,...) progresses a lot too!
- issue of the H₂-storage & distribution, H₂-society
- electrolysers (reverse fuel cells) are coming up strongly (combined with renewable electricity increase (PV, wind))