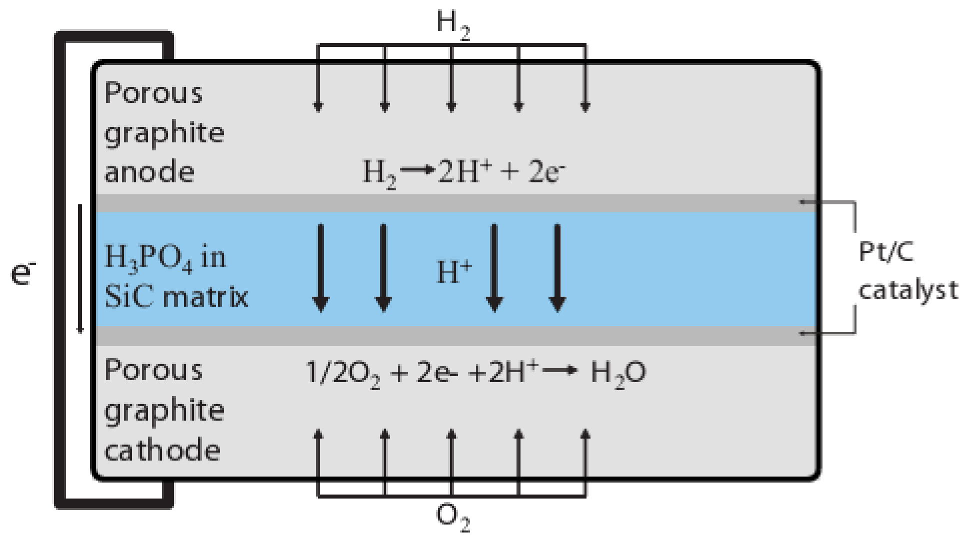
Fuel Cell Types Overview

Fuel Cell Types

	PEMFC	PAFC	AFC	MCFC	SOFC
Electrolyte	Polymer Membrane	Liquid H_3PO_4 (Immobilized)	Liquid KOH (Immobilized)	Molten Carbonate	Ceramic
Charge Carrier	H^+	H^+	OH^-	$CO3^{2-}$	O^{2-}
Operating Temperature	80 °C	200 °C	60-220 °C	650 °C	600-1000 °C
Catalyst	Platinum	Platinum	Platinum	Nickel	Perovskites (Ceramic)
Cell Components	Carbon-based	Carbon-based	Carbon-based	Stainless-based	Ceramic-based
Fuel Compatibility	H_2, Methanol	H_2	H_2	H_2, CH_4	H_2, CH_4, CO

- Electrolyte determines the type of fuel cells and operation temperature.
  - Operation temperature significantly affects the use of other components such as catalyst.

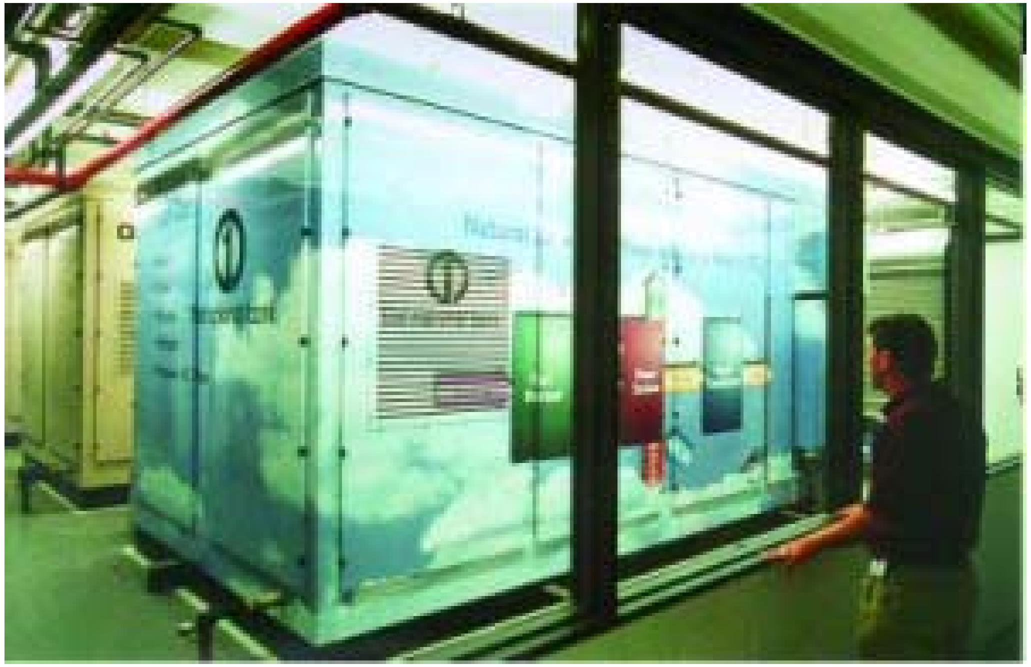
PAFC



$$Anode:\ H_2 \rightarrow 2H^+ + 2e^-$$
$$Cathode:\ \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

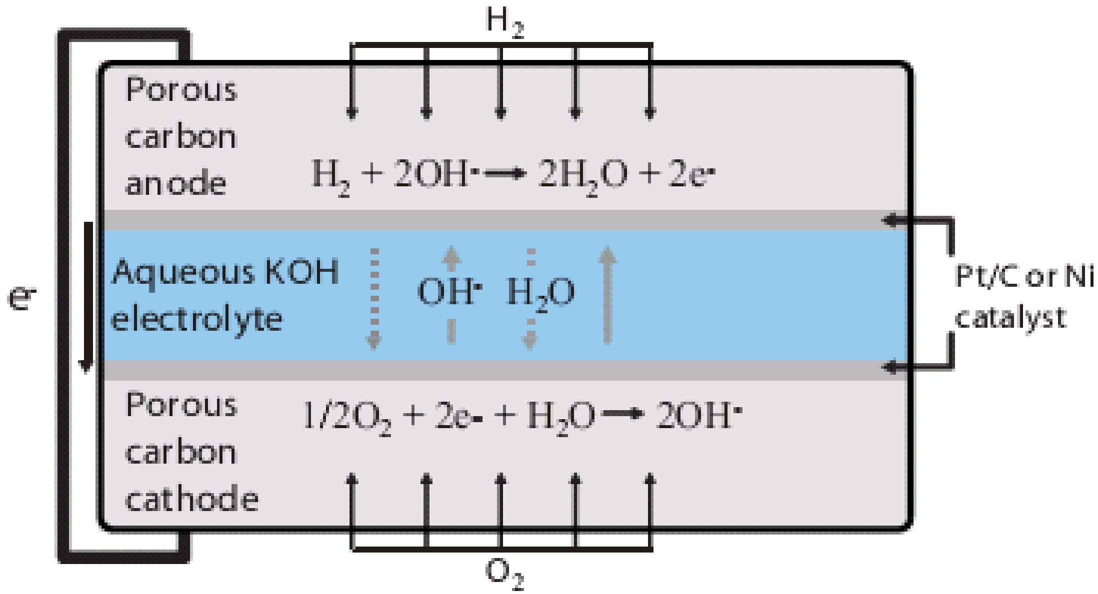
- Low T operation: 200
- Pt/C catalyst
- Solidified liquid electrolyte

PAFC



- Electrolyte evaporation
- CO, S poisoning
- Moderate success in commercialization (cost barrier, maintenance)
- Emergency power generation

AFC

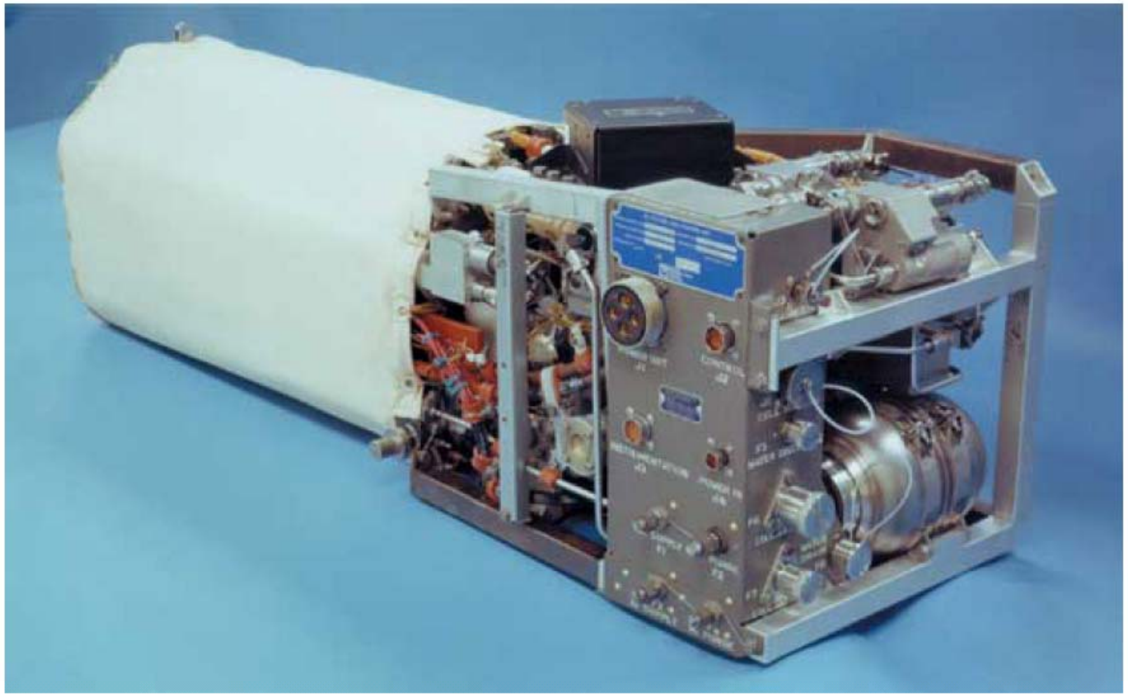


$$Anode: \ H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$$

$$Cathode: \ \tfrac{1}{2}O_2 + 2e^- + H_2O \rightarrow 2OH^-$$

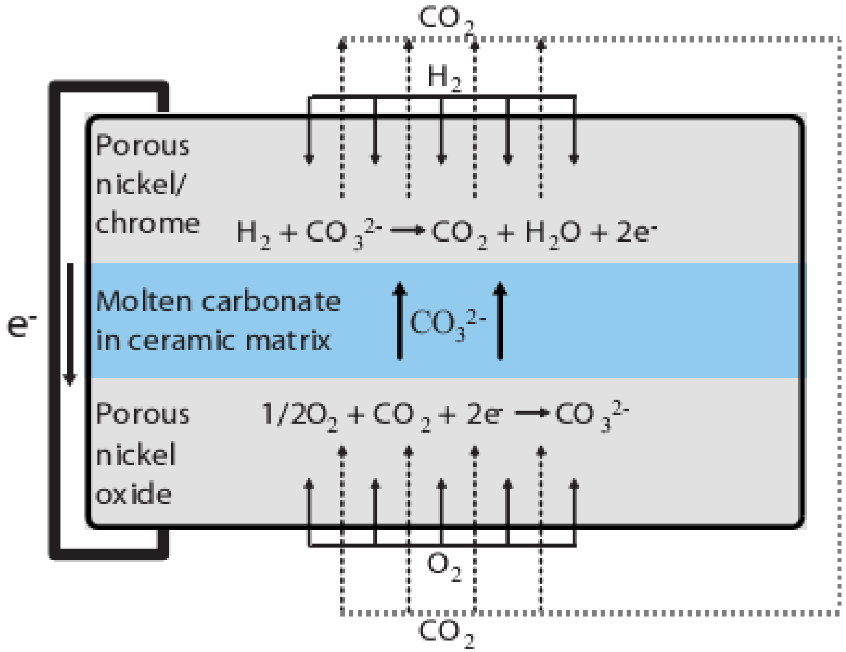
- Low T operation: 60~220
- Pt/C catalyst
- Solid electrolyte

AFC



- Carbon dioxide poisoning
- Pure hydrogen & air (oxygen) only
- Special applications such as space mission (Gemini project)

MCFC



$$Anode:\ H_2 + CO_3^{2-} \rightarrow CO_2 + H_2O + 2e^-$$

$$Cathode:\ \frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$$

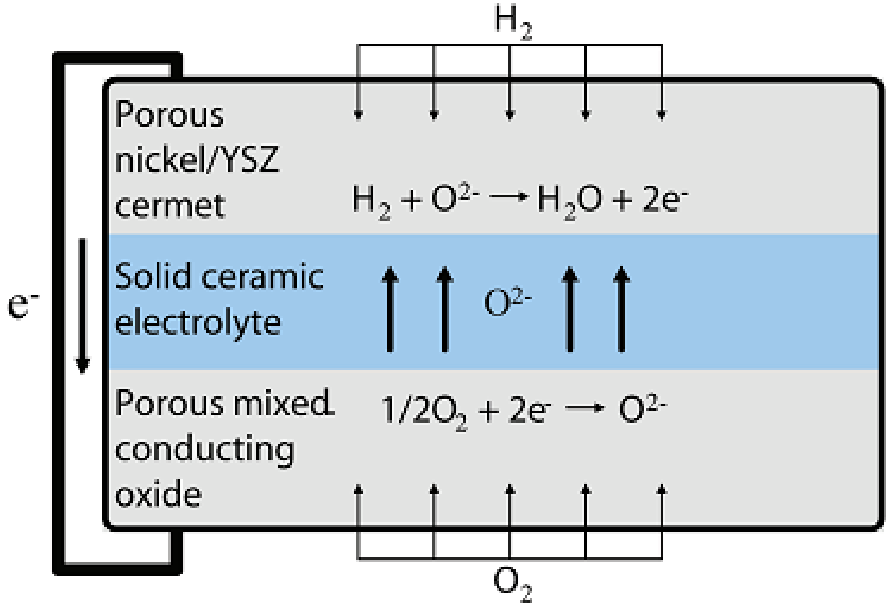
- High T operation: 650C
- Ni catalyst
- Immobilized Li2CO3 electrolyte in LiOAlO2
- CO2 recycling

MCFC

25kW Pressurized MCFC System operated by KEPRI since 2000

- Stationary power generator
- Demonstration upto MW
- Well demonstrated technology
- High efficiency (50%> for CHP system)
- No CO issues (CO as fuel)
- Difficult to increase power density

SOFC's



$$Anode:\ H_2 + O^{2-} \rightarrow H_2O + 2e^-$$
$$Cathode:\ \frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$$

- High T operation: 600~1000C
- Ceramic electrolyte: YSZ, SDZ, SDC, GDC, LSGM...
- Anode: Ni/YSZ
- Cathode: LSM, LSC, LSF, LSCF

SOFC's

100kW Atmospheric SOFC

220kW Pressurized SOFC-GT Hybrid System

- Stationary power generator
- Demonstration upto MW
- Fuel flexibility
- High efficiency (50%> for CHP system)
- Relatively high power density
- Relatively expensive components/fabrication

SOFC's

Picture removed for possible copyright infringement

SOFC Potential Markets

Automotive APU

Residential Power Units with Combined Heat and Power.

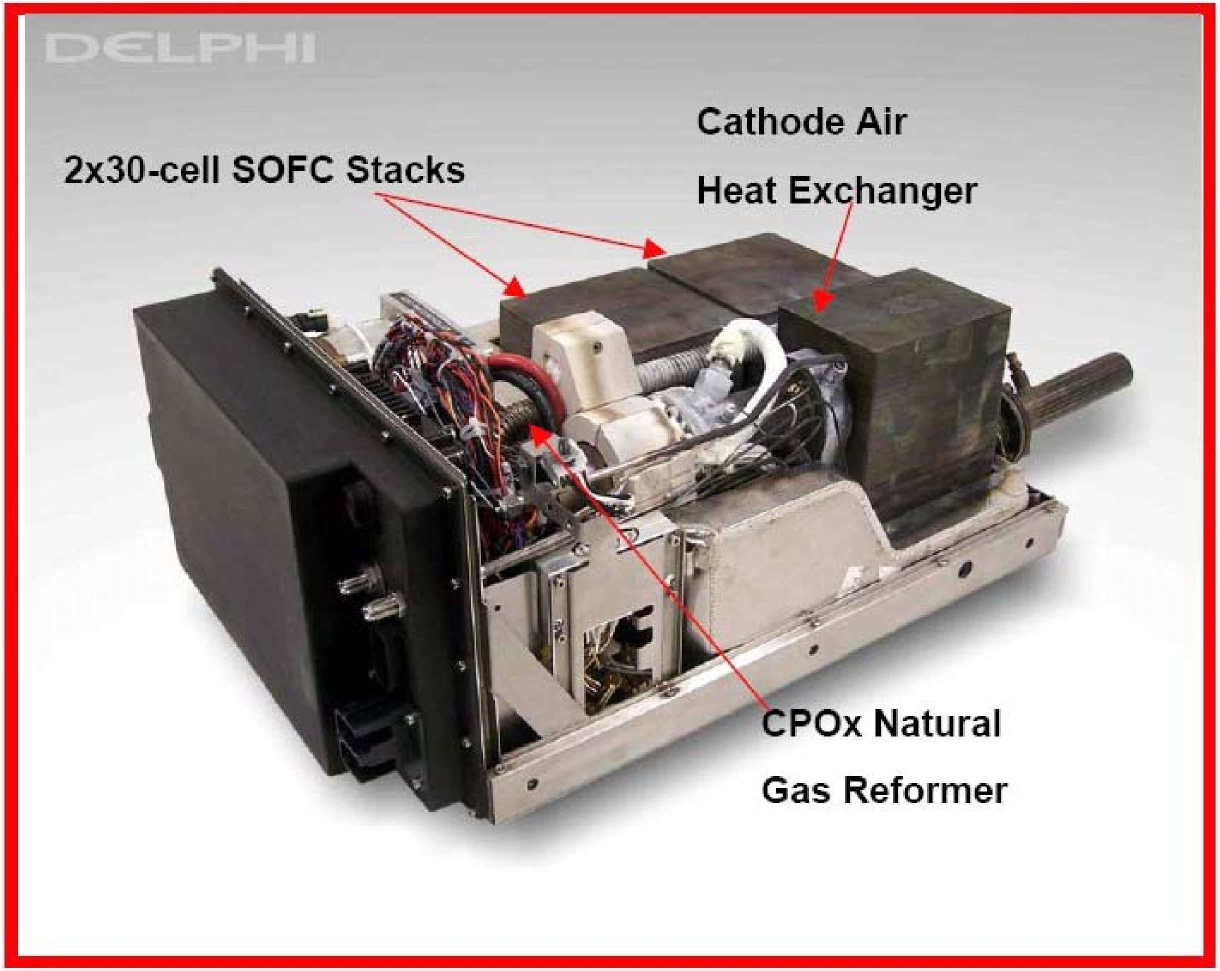
Heavy Duty Truck APU to eliminate long term idling or EPU as part of Electric Truck Architecture

Military uses are similar to that in mobile applications with modifications for High Sulfur fuels: JP8

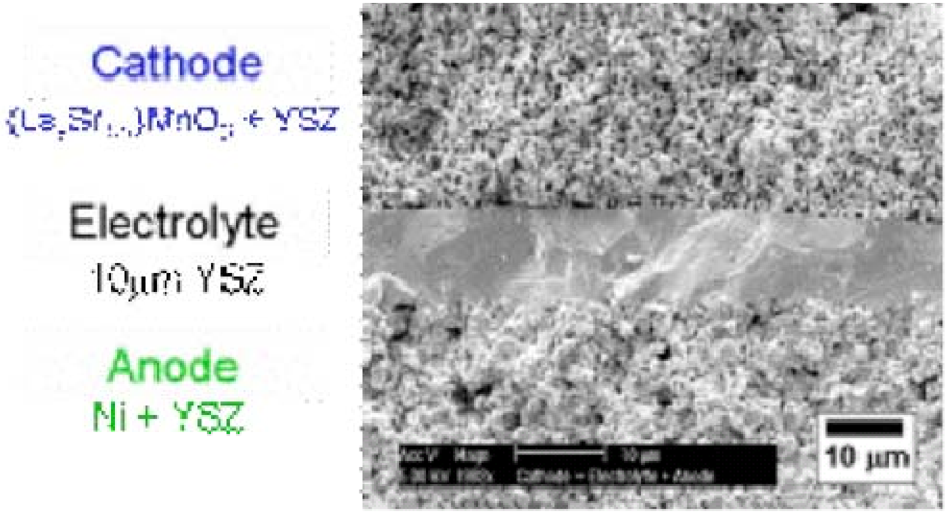
Pension und Cafe S. Simon

Commercial Power Units

Delphi SOFC APU



20W Micro SOFC's



Adaptive Materials Inc

20W Portable SOFC

2006

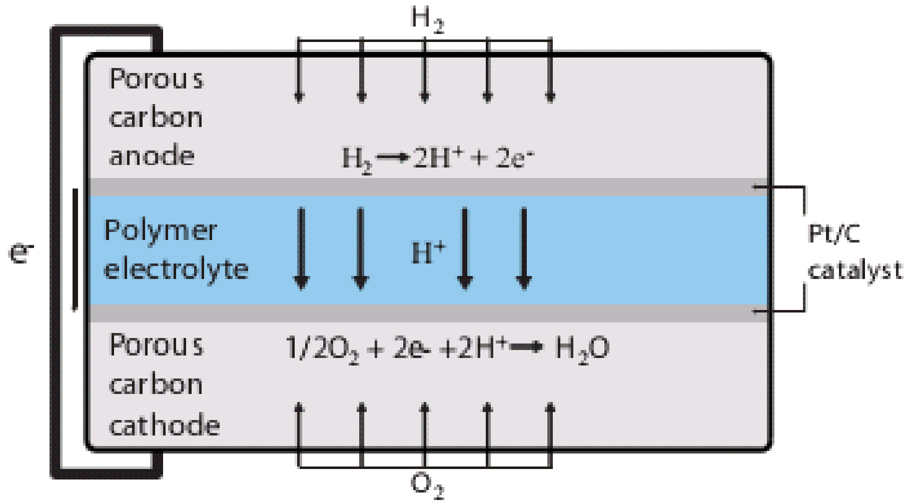
Generation 2.0 Prototype

SOFC System	
Dry Weight, kg	0.97
Volume, liters	1.3
Net System Efficiency	27%

Hydrocarbon Fuel Tank	
Fuel Tank	0.15
Fuel Loading, kg	0.35
Fuel Tank, kg	0.5
Net Fuel Energy, Whr	1219
20 Watt Run Time, hr	61

Specific Energy	
3 Day Mission, Whr/kg	**923**
10 Day Mission, Whr/kg	**1633**

PEMFC's

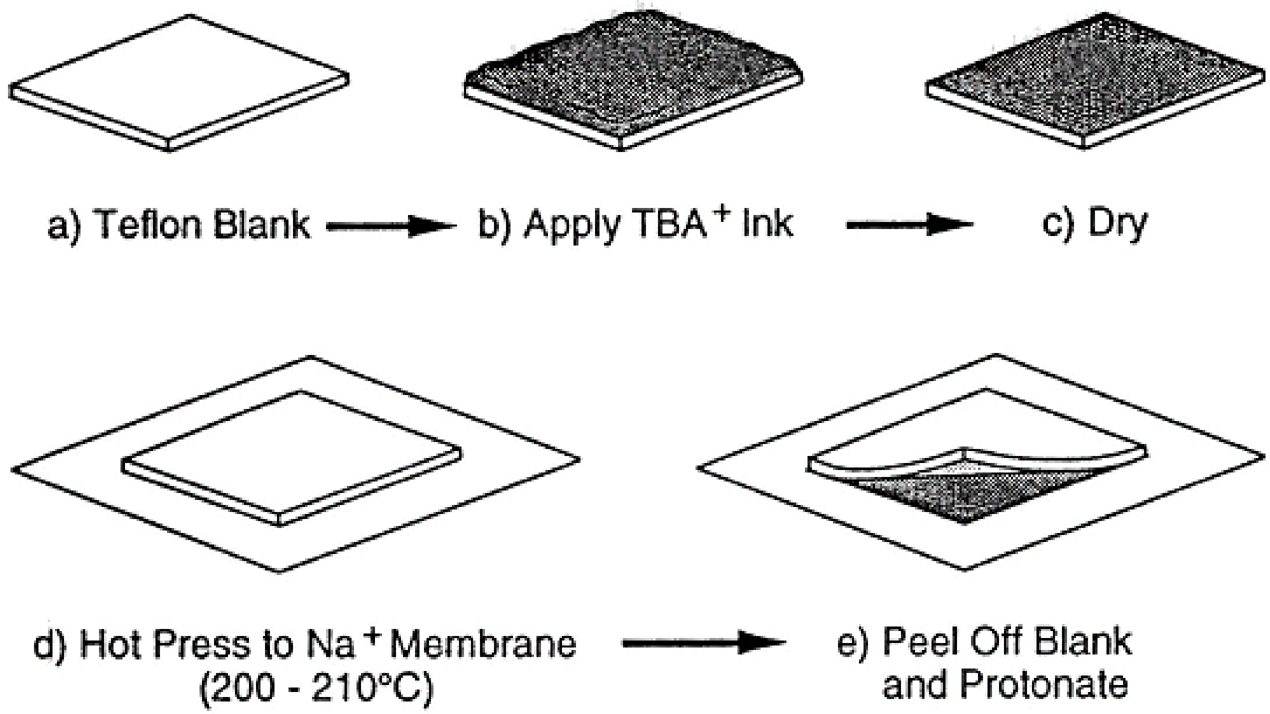


$$Anode: \; H_2 \rightarrow 2H^+ + 2e^-$$

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

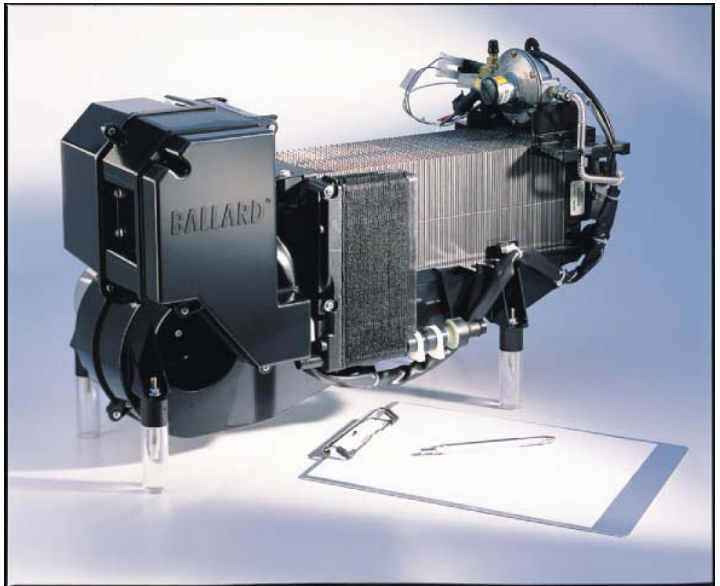
- Low T operation: 30~130C
- Pt/C catalyst
- Polymer membrane: Sulfonated PTFE(Nafion, Dow, Membrane-S, Gore..), PBI(Celanese), PEEK, Polymide...
- Carbon cloth (paper) electrode

PEMFC's

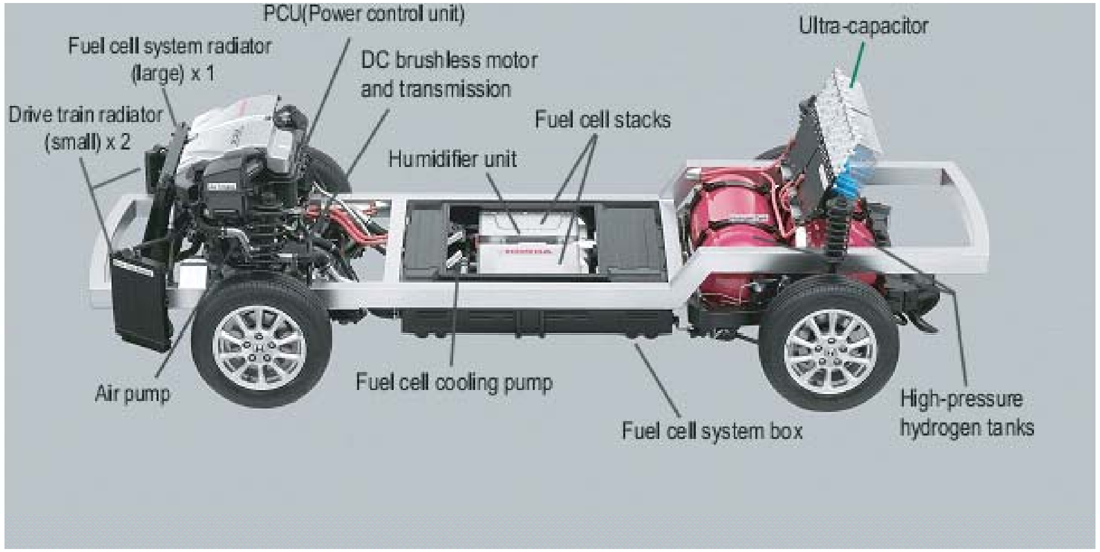


a) Teflon Blank
b) Apply TBA + Ink
c) Dry
d) Hot Press to Na + Membrane (200 - 210°C)
e) Peel Off Blank and Protonate

PEMFC's



1.5kW portable PEMFC system by Ballard



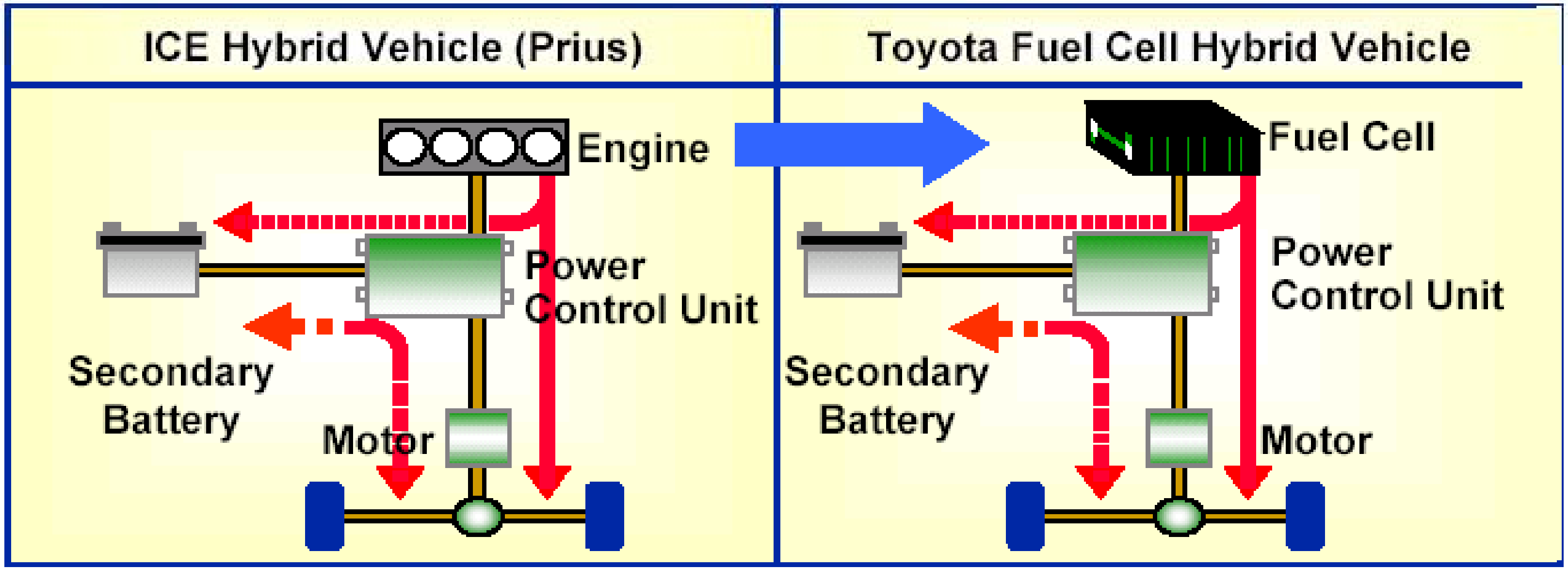
Honda fuel cell car platform

- Highest power density
- Fast start-up
- Low operating temperature makes it suitable for portable market.
- Poor CO & S tolerence
- Water management issue

PEMFC's for Automotive

Prius

FCHV



PEMFC's for Automotive

Well to Wheel Efficiency

	Well to Tank (%)	Tank to Wheel (%)	Well to Wheel (%)
Gasoline Vehicle	88	16	14%
Prius (Gasoline HV)	88	32	28%
Hydrogen FCV	58*1	38*2	22%
FCHV	58*1	50*2	29% With HV control
FCHV (Target)	70	60	42% 3 x Gasoline, 1.5 x HV

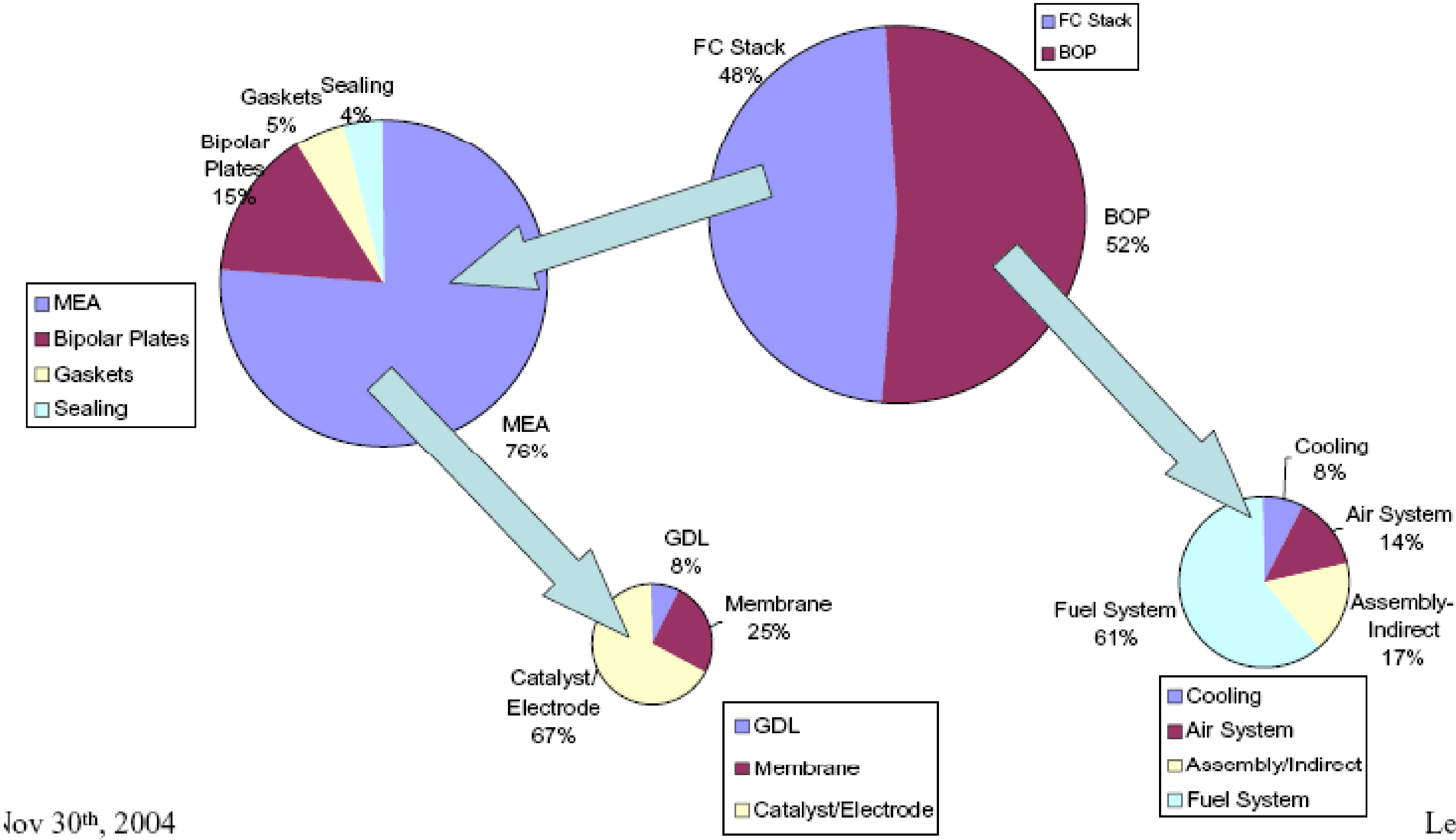
Japanese 10-15 Mode   Toyota estimate

*1 Natural gas base   *2 electric efficiency

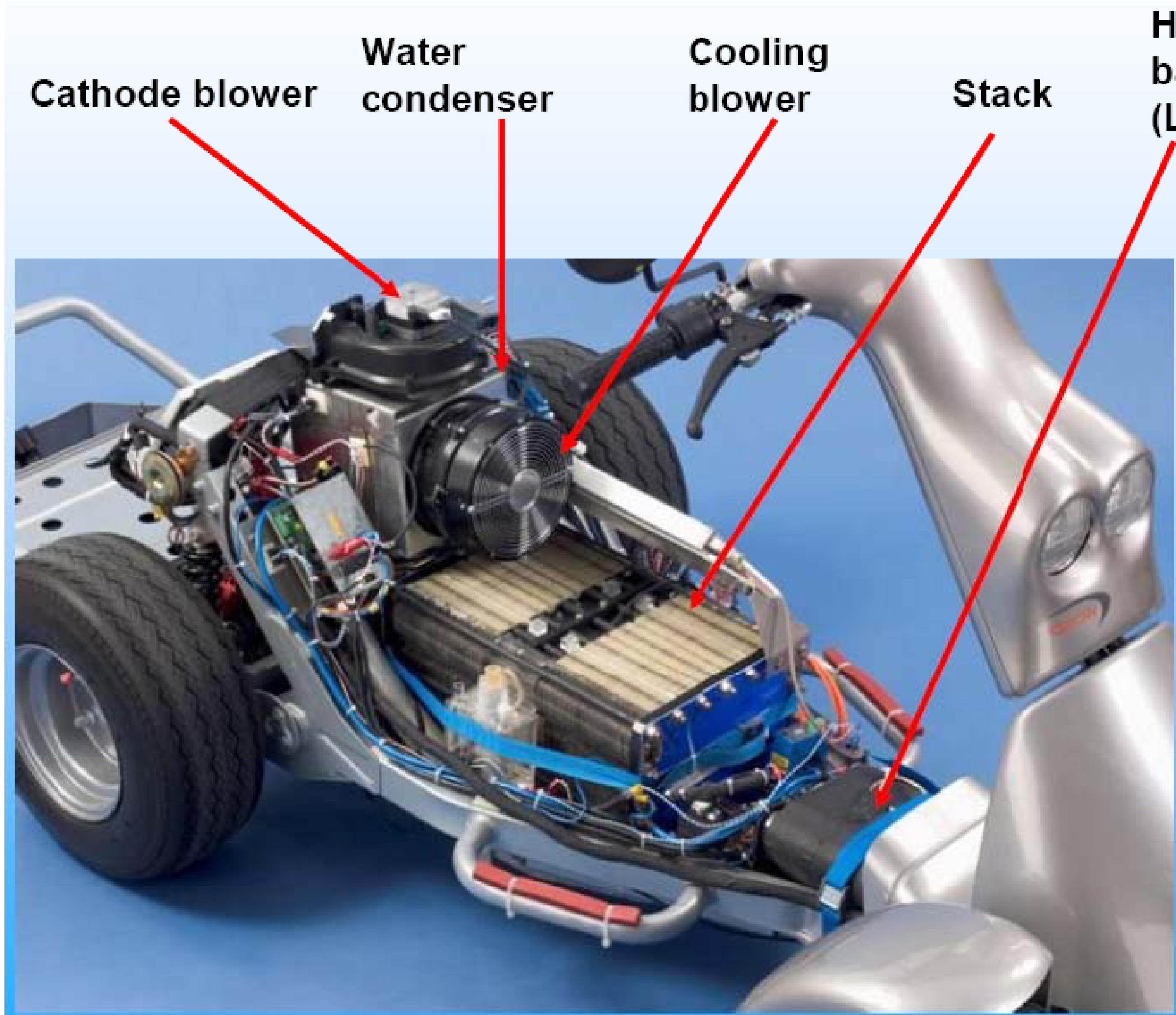
Fuel Cell System Cost Breakdown

Light Duty Fuel Cell Car Example

(Data from Arthur D. Little, Inc. "Cost Analysis of Fuel Cell Systems for Transportation", Final Report to the DOE, March 2000.)



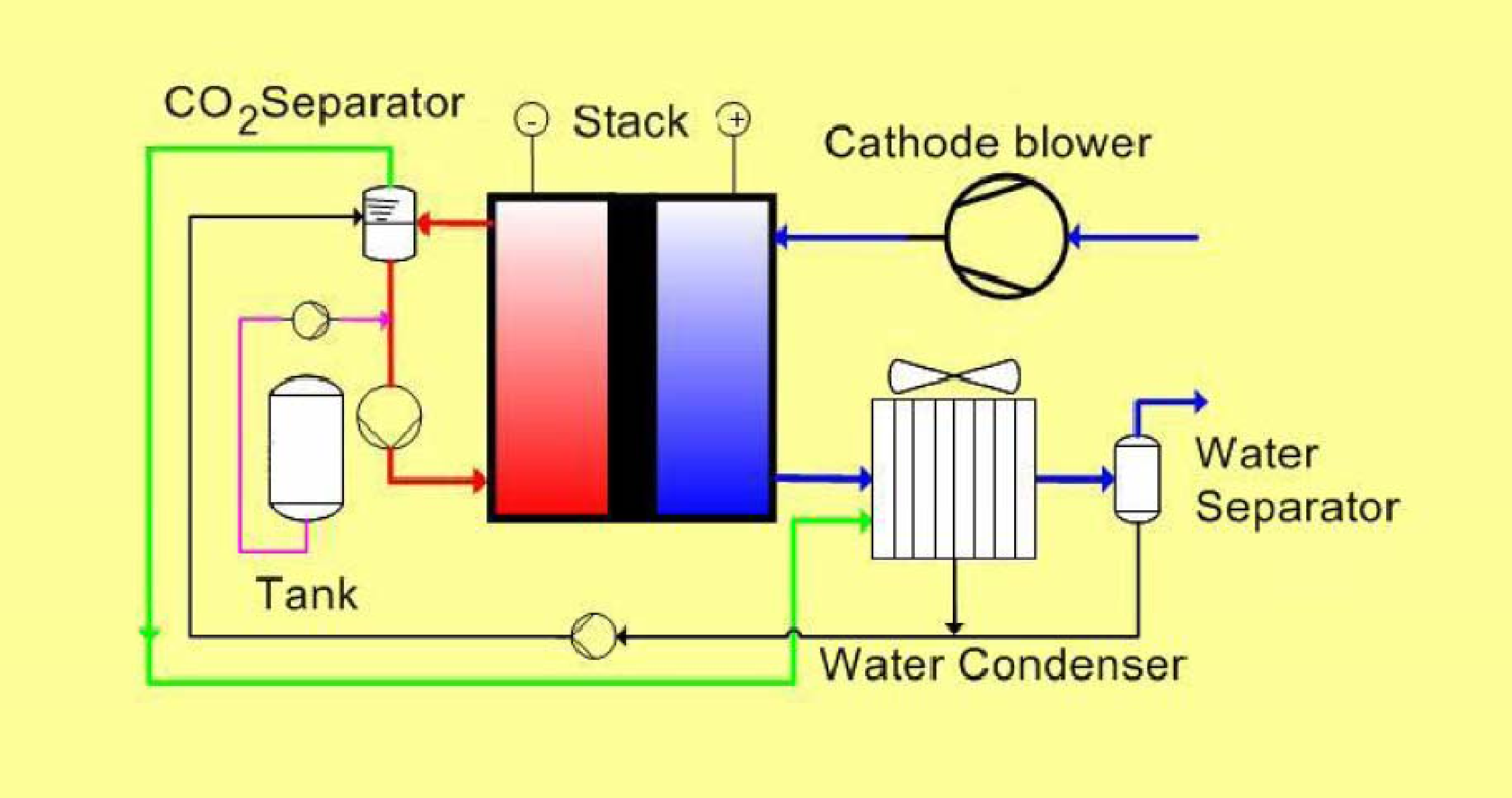
DMFC's



DMFC System	
Power density:	22 W/l
Energy density:	110 Wh/kg
Cruising range:	120 km
Methanol:	6.5 l
η_{system}:	25 %

former lead acid system

Simple Liquid DMFC System



DMFC Electrode Reaction Steps

Anode Reaction

$CH_3OH + s_1^* \rightarrow CH_3OH_{(ad)1}$

$CH_3OH_{(ad)1} \rightarrow CO_{(ad)1} + 4\,H^+ + 4\,e^-$

$H_2O + s_2^* \rightarrow OH_{(ad)2} + H^+ + e^-$

$CO_{(ad)1} + OH_{(ad)2} \xrightarrow[rds]{} CO_2 + H^+ + e^- + s_1^* + s_2^*$

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

Cathode Reaction

$3/2\,O_2 + 6\,H^+ + 6\,e^- \rightarrow 3\,H_2O$

Problems with Nafion DMFC

- **Methanol crossover from anode to cathode**

  - Dilution (5-15% in water)
  - Electro-osmotic drag of water
  - Reduces fuel utilization
  - Competing reactions at the cathode
  - Polarizes the cathode (poisons catalytic sites for O_2)
  - Reduces overall cell potential

- **Poor oxidation kinetics**

  - Anode polarization dominates cell performance
  - Need for good anode catalyst

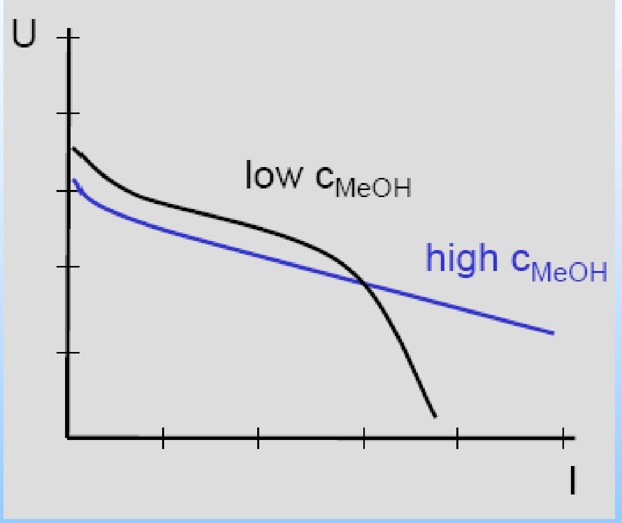
- **Reduce or eliminate precious metal catalysts**

Best performance : 0.4 Ω/cm^2 at 130 ^oC using 3 atm. O_2 at cathode

Methanol Concentration Control

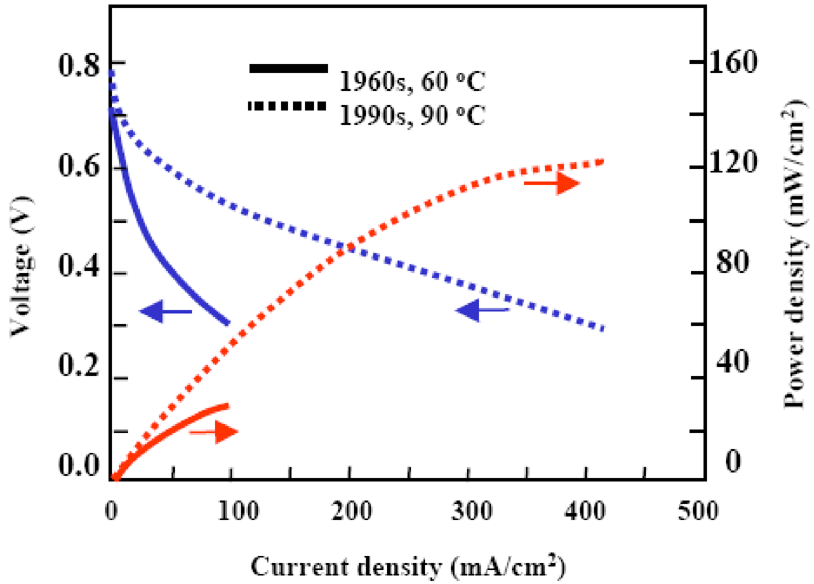
High methanol concentration
- low anode overpotential
- high methanol permeation
- high cathode overpotential (mixed potential)

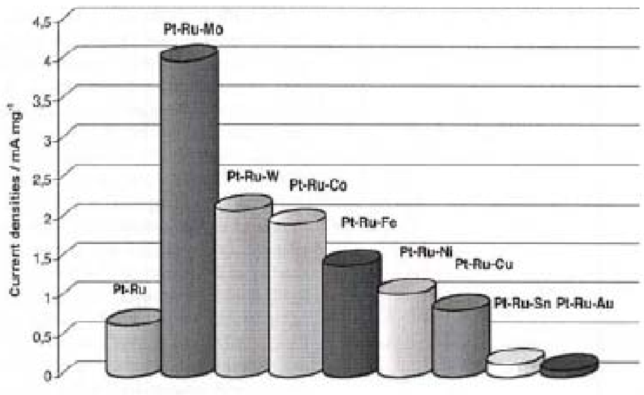
Low methanol concentration
- high anode overpotential
- low methanol permeation
- lower cathode overpotential

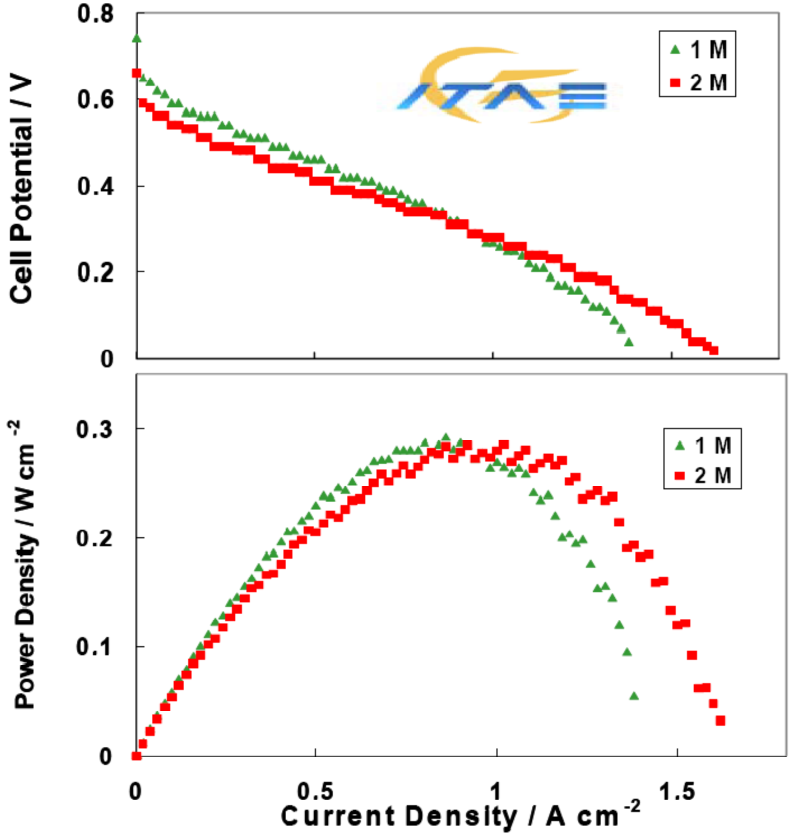


The **methanol concentration** is always a **compromise** between **cathode and anode** impact. It mainly depends on:
- current density
- temperature
- air flow rate

DMFC Performance







CNR-TAE Unsupported Pt-Ru 1:1 alloy catalyst
Air=3 atm, 130 °C, Max Power 300 mW cm^{-2}

DMFC Prognosis

- Stiff challenges from competing technologies
  - Cost
  - Reliability
  - Lifetime
  - Maintenance
  - Batteries, Small IC engines...
- Low power densities
  - Impressive progress in technology recently
  - Most suitable for small portable applications in near term
- High activation overpotential
  - Considerable reduction is essential for higher power applications (stationary, transportation)
- Operations temperature
  - High T operation (~150 C) can enhance prospects of higher power level applications

Direct Formic Acid Fuel Cells

$$HCOOH \rightarrow CO_2 + 2H^+ + 2e^- \quad (1)$$

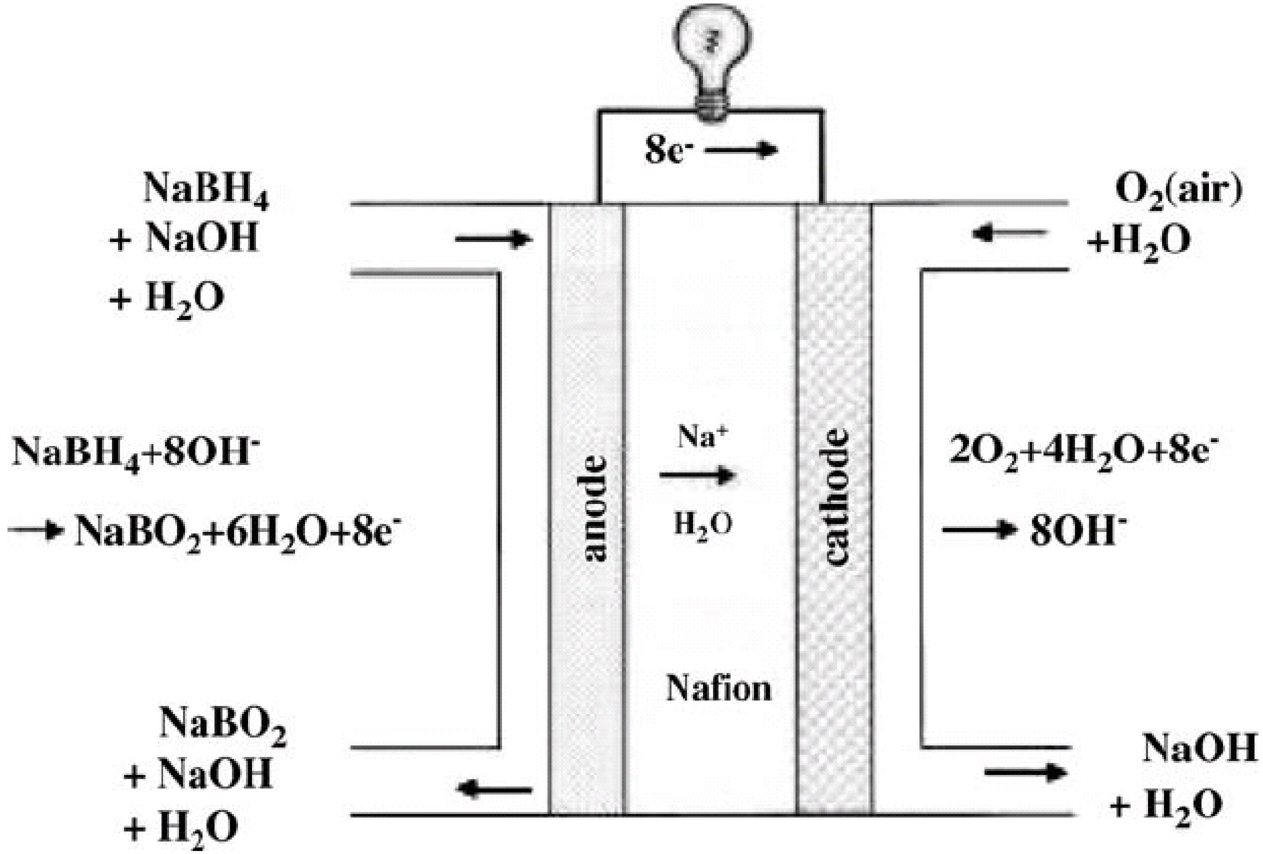
$$HCOOH + Pt^0 \rightarrow Pt{-}CO + H_2O \quad (2)$$

$$Pt^0 + H_2O \rightarrow Pt{-}OH + H^+ + e^- \quad (3)$$

$$Pt{-}CO + Pt{-}OH \rightarrow 2Pt^0 + CO_2 + H^+e^- \quad (4)$$

$$\text{Overall :} \quad HCOOH \Rightarrow CO_2 + 2H^+ + 2e^- \quad (5)$$

Borohydride Fuel Cells



Borohydride Fuel Cells

Anode (negative electrode):

$$NaBH_4 + 8OH^- \rightarrow NaBO_2 + 6H_2O + 8e^-, \quad E^o = 1.24\,V \tag{4}$$

Cathode (positive electrode):

$$2O_2 + 4H_2O + 8e^- \rightarrow 8OH^-, \quad E^o = 0.40\,V \tag{5}$$

Overall:

$$NaBH_4 + 2O_2 \rightarrow NaBO_2 + 2H_2O, \quad E^o = 1.64\,V \tag{6}$$

Borohydride Fuel Cells

$$NaBH_4 + 6OH^- \rightarrow NaBO_2 + 4H_2O + H_2 + 6e^-,$$

$$E^o = -1.38\ V$$

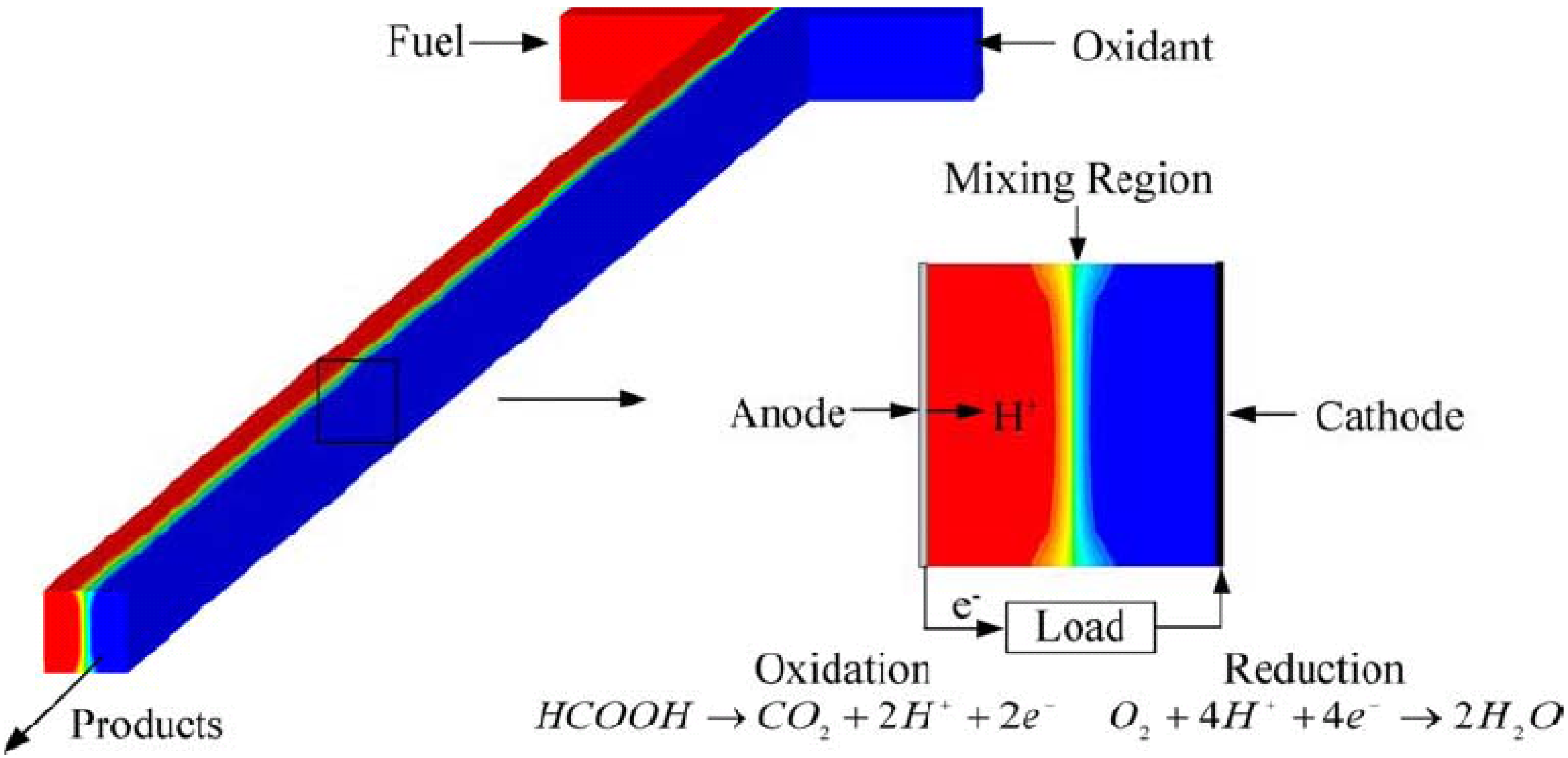
Cathode (positive electrode):

$$\frac{3}{2}O_2 + 3H_2O + 6e^- \rightarrow 6OH^-, \quad E^o = 0.40\ V$$

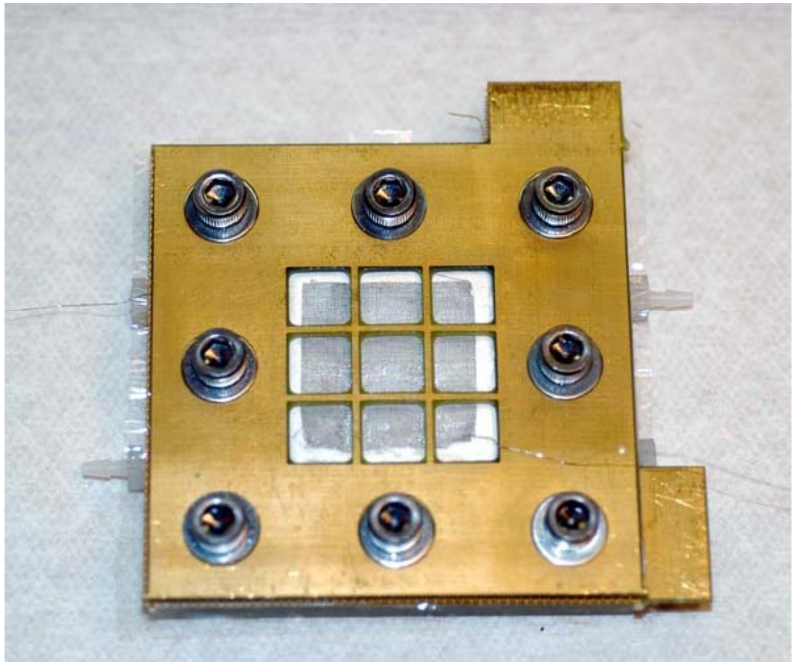
Overall:

$$NaBH_4 + \frac{3}{2}O_2 \rightarrow NaBO_2 + H_2O + H_2, \quad E^o = 1.78\ V$$

Membraneless Fuel Cells



Air Breathing Fuel Cells



Air-breathing passive fuel cell stack