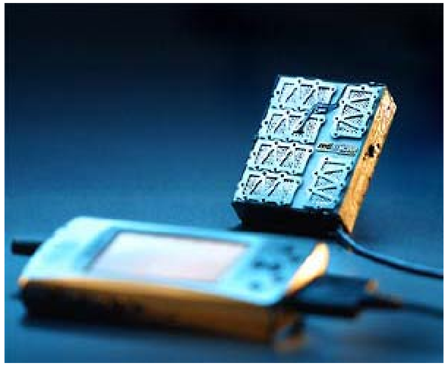
Fuel Cell Types Overview

Fuel Cell Types

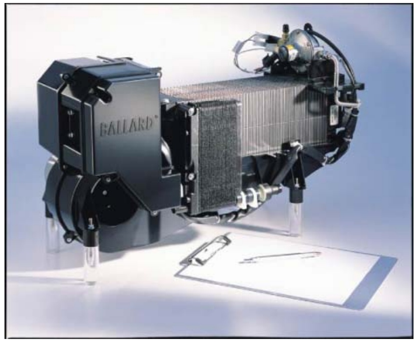
	PEMFC	PAFC	AFC	MCFC	SOFC
Electrolyte	Polymer Membrane	Liquid H_3PO_4 (Immobilized)	Liquid KOH (Immobilized)	Molten Carbonate	Ceramic
Charge Carrier	H^+	H^+	OH^-	$CO3^{2-}$	O^{2-}
Operating Temperature	80 °C	200 °C	60-220 °C	650 °C	600-1000 °C
Catalyst	Platinum	Platinum	Platinum	Nickel	Perovskites (Ceramic)
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.

Applications vs Power

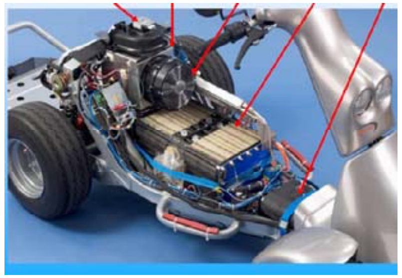


휴대전원

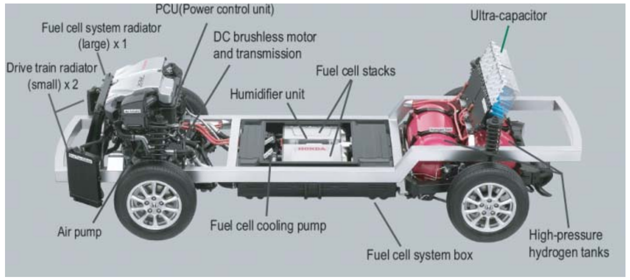


가정용 발전

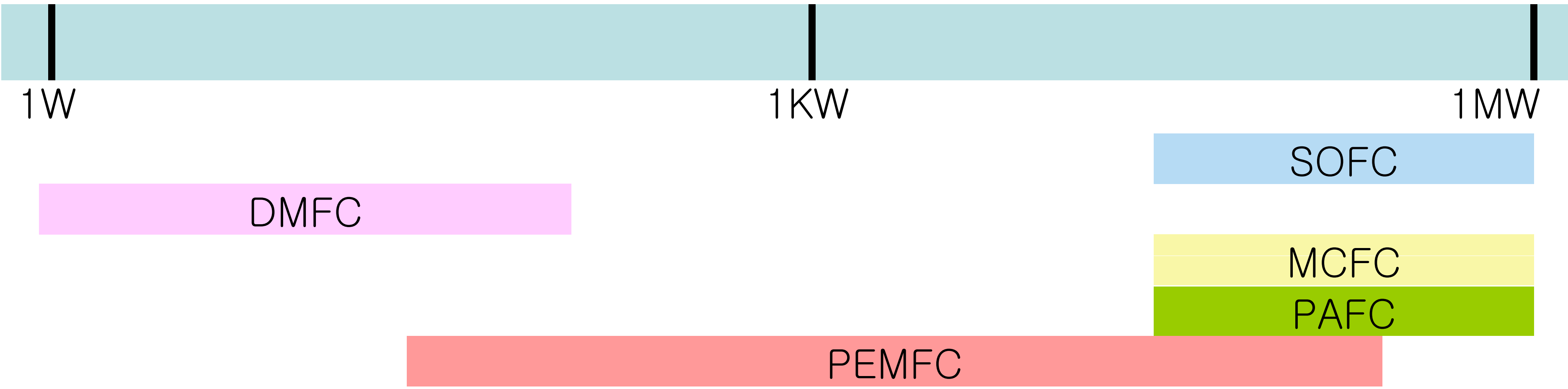
대형 발전



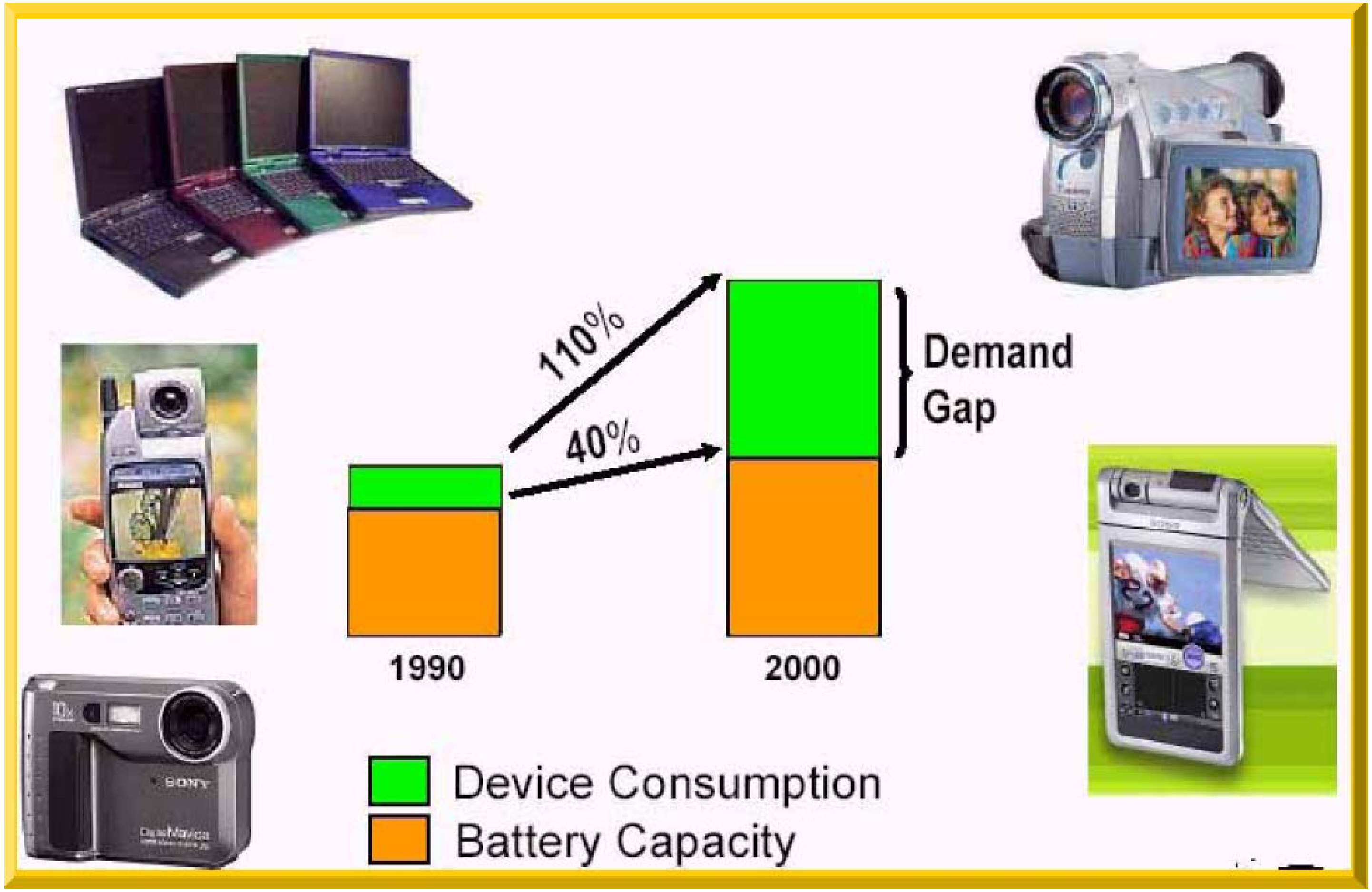
소형 운송수단



중 대형 운송수단

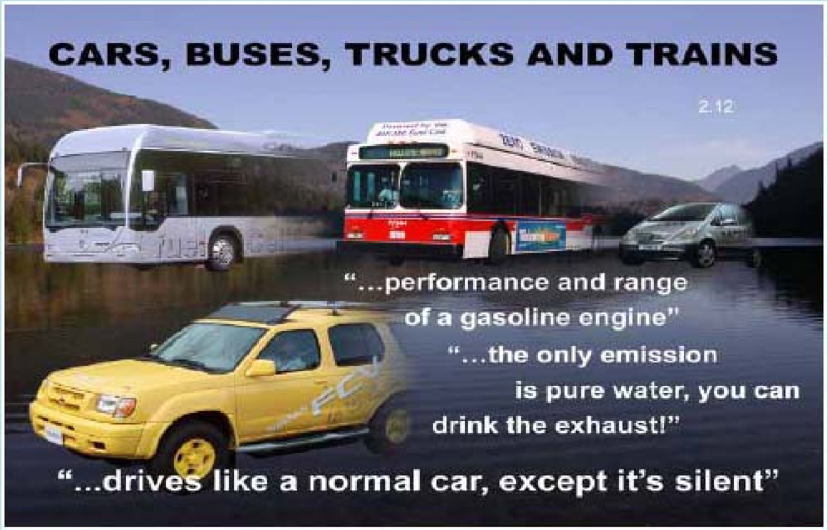


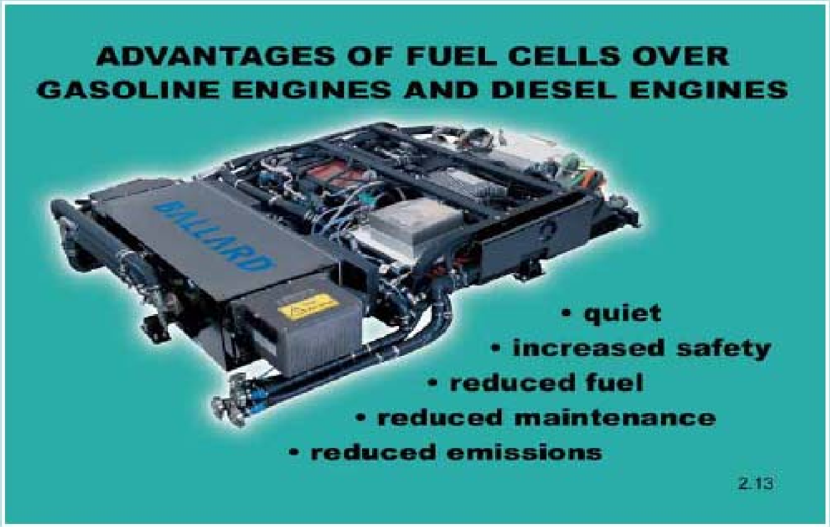
Mobile Application



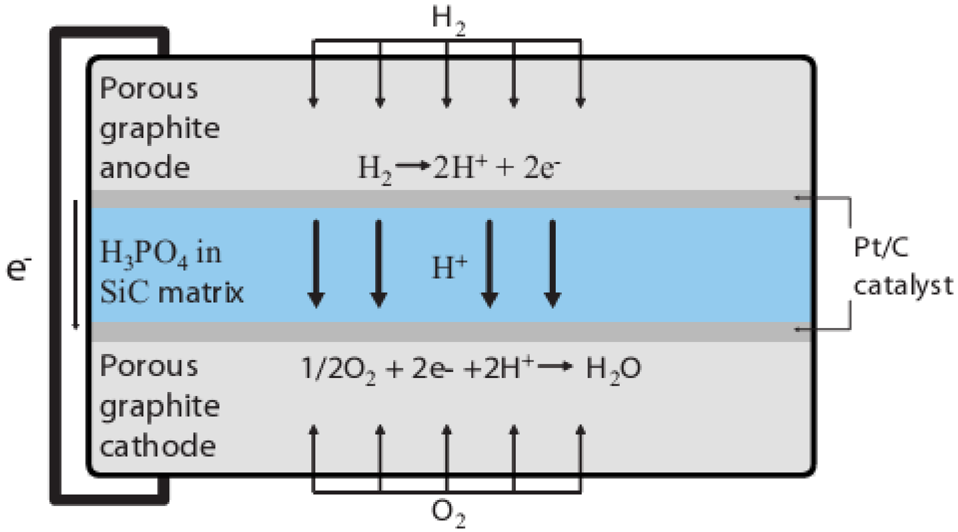
Stationary Application

Transportation Application





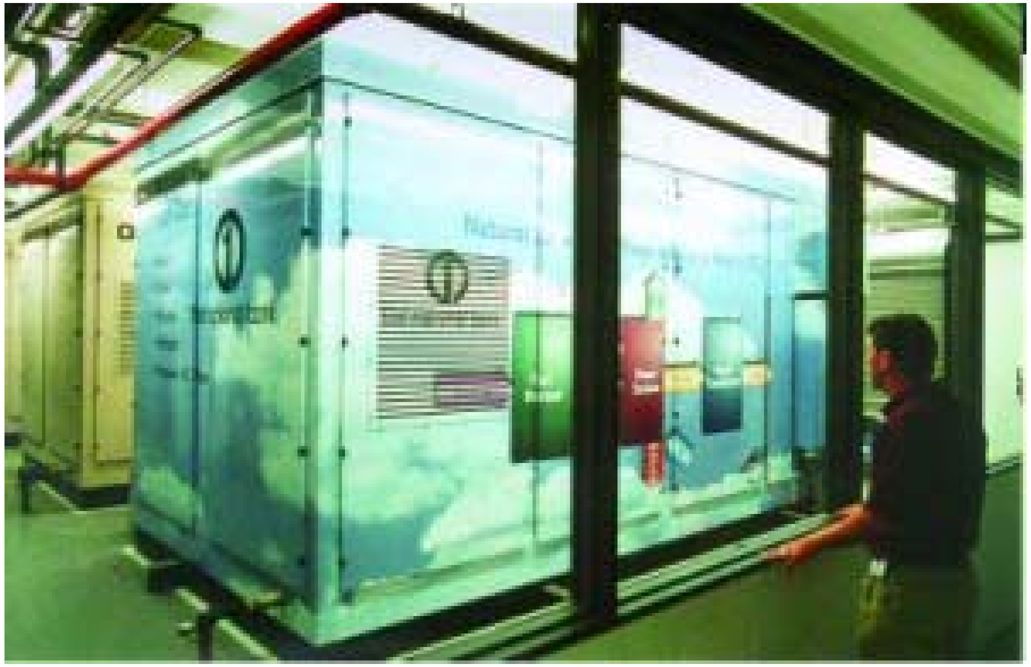
PAFC



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

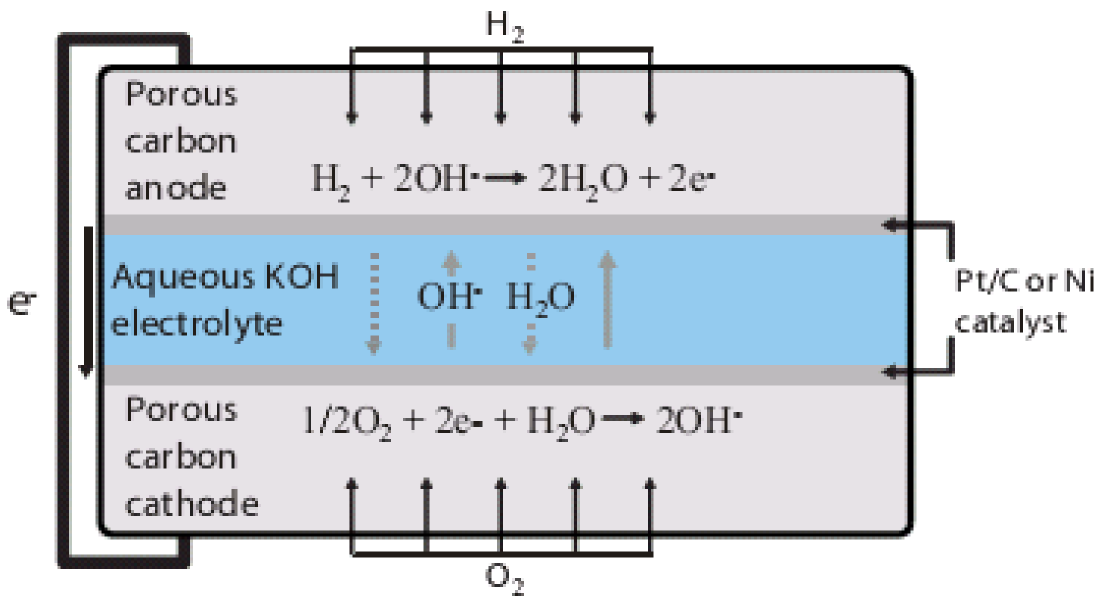
- Low T operation: 200
- Pt/C catalyst
- Solidified liquid electrolyte

PAFC



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

AFC

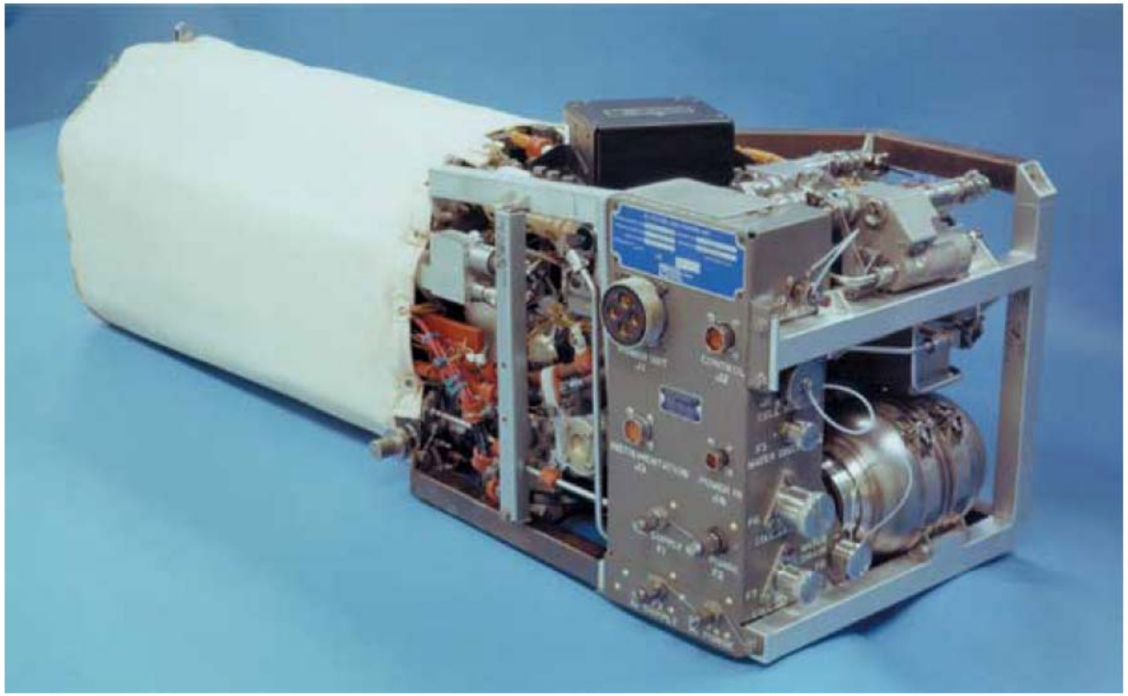


$$Anode:\ H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$$

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

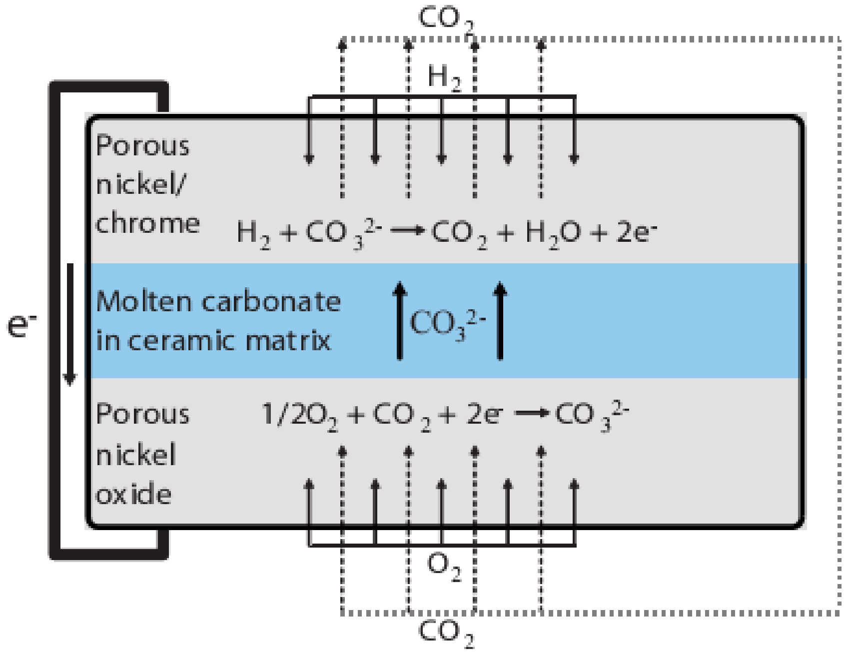
- Low T operation: 60~220
- Pt/C catalyst
- Solid electrolyte

AFC



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

MCFC



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

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

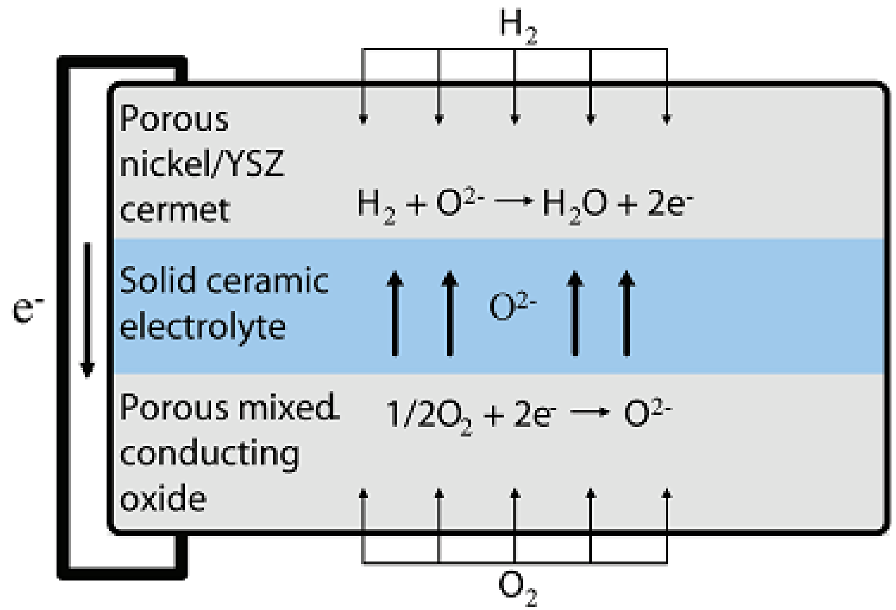
- High T operation: 650C
- Ni catalyst
- Immobilized Li2CO3 electrolyte in LiOAlO2
- CO2 recycling

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



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

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

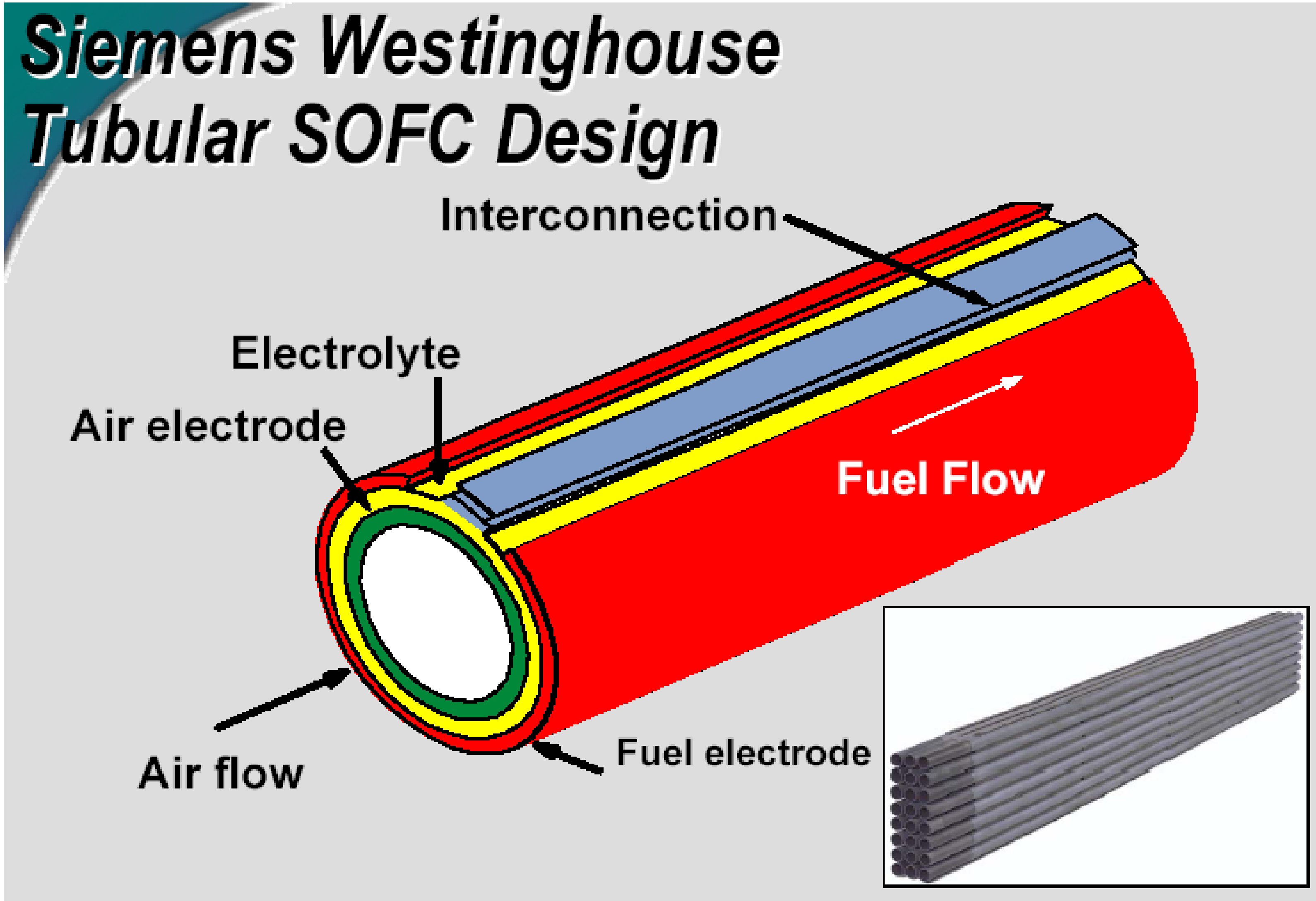
SOFC's

100kW Atmospheric SOFC

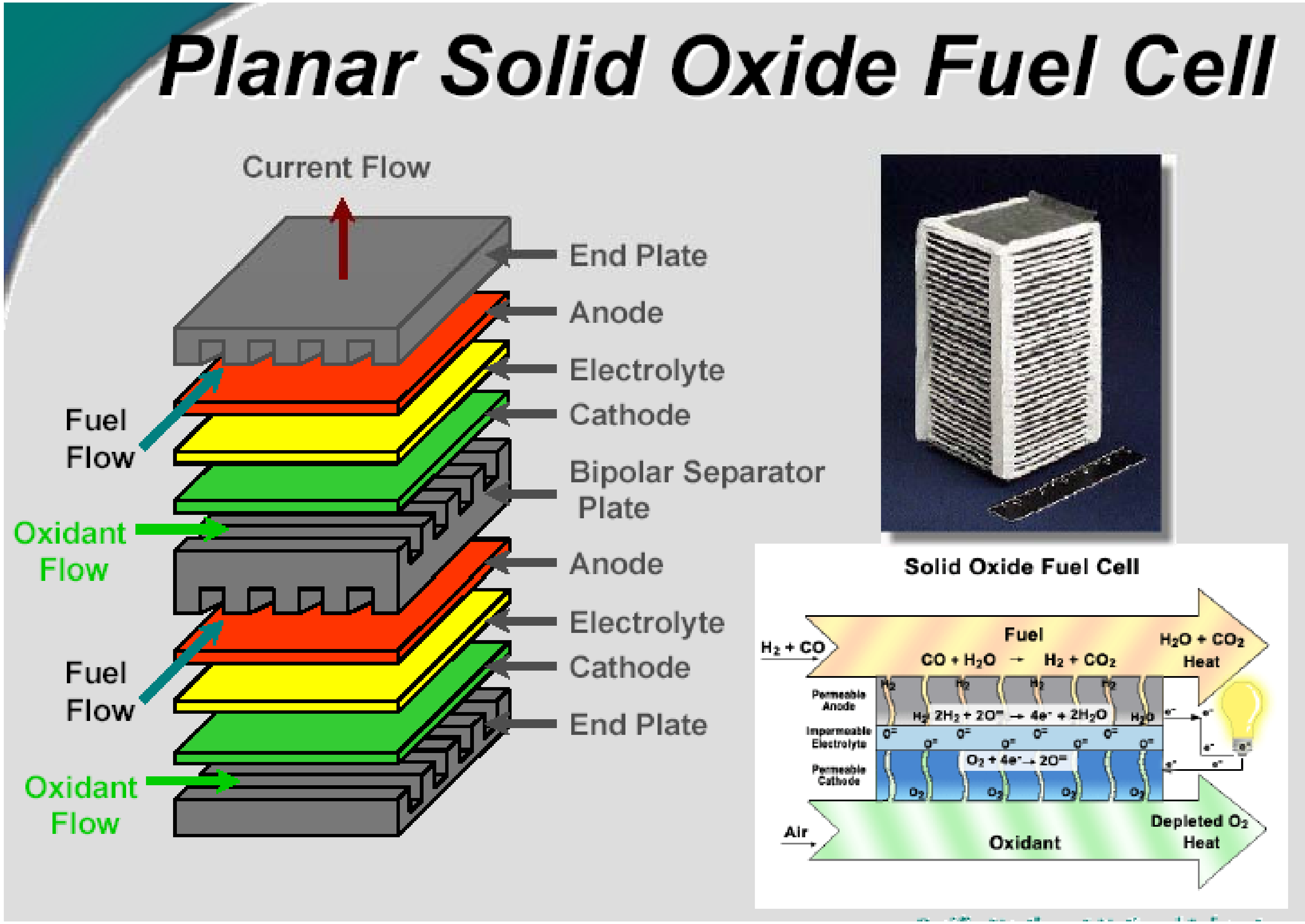
220kW Pressurized SOFC-GT Hybrid System

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

SOFC's


Siemens Westinghouse
Tubular SOFC Design
Interconnection
Electrolyte
Air electrode
Fuel Flow
Air flow
Fuel electrode

SOFC's


Planar Solid Oxide Fuel Cell
Current Flow
End Plate
Anode
Electrolyte
Cathode
Bipolar Separator Plate
Anode
Electrolyte
Cathode
End Plate
Fuel Flow
Oxidant Flow
Fuel Flow
Oxidant Flow
Solid Oxide Fuel Cell
H2 + CO
Fuel
CO + H2O → H2 + CO2
H2O + CO2
Heat
Air
Oxidant
Depleted O2
Heat

Design Comparison

	Tubular Cells	Planar Cells
Specific Power (W/cm^2)	Low (0.2-0.3)	High (0.6-2.0)
Volumetric Power (W/cm^3)	Low	High
Manufacturing Cost($/kW)	High	Low
High Temperature Seals	Not necessary	Required

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

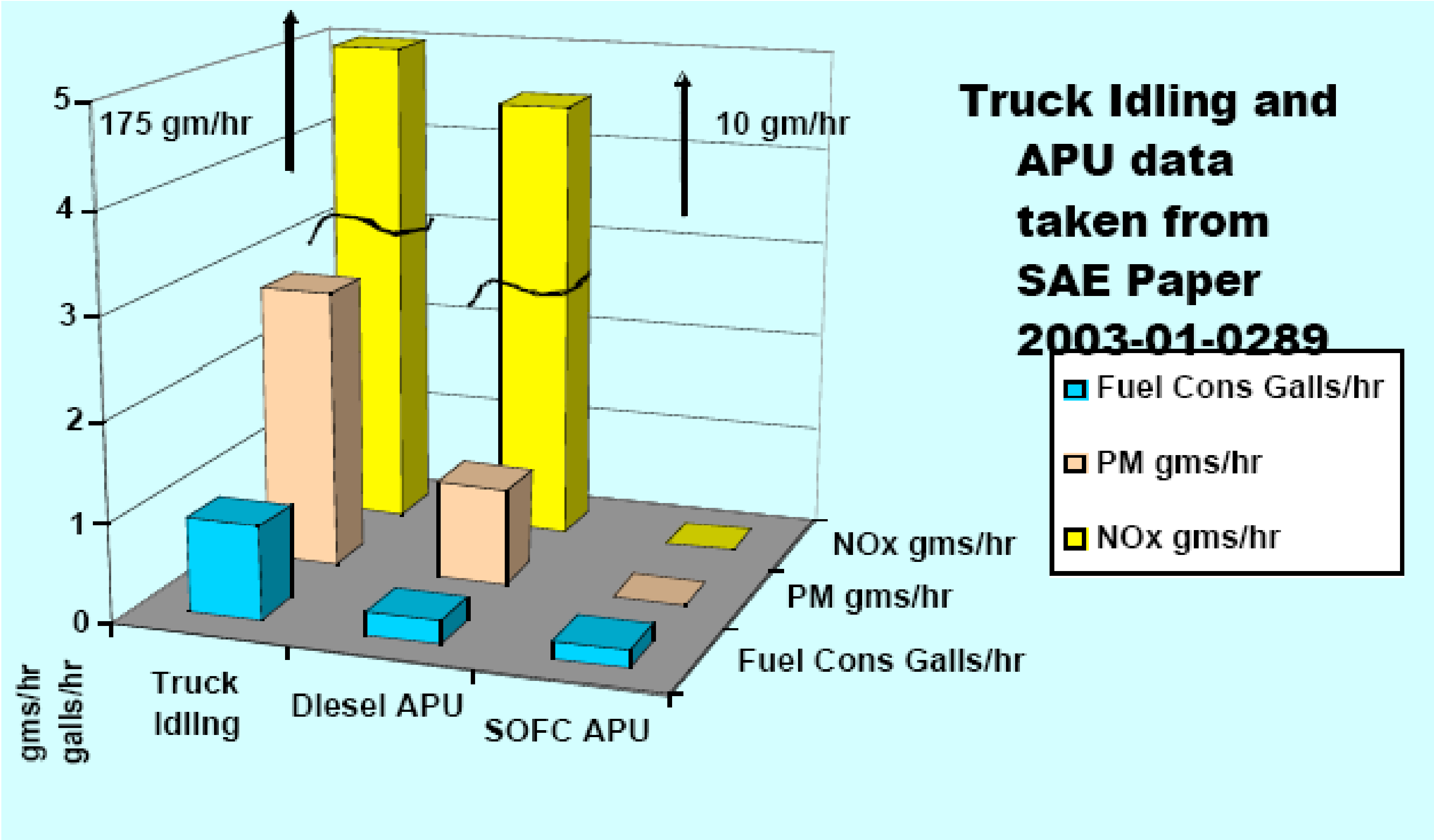
Pension und Cafe S. Simon

Commercial Power Units

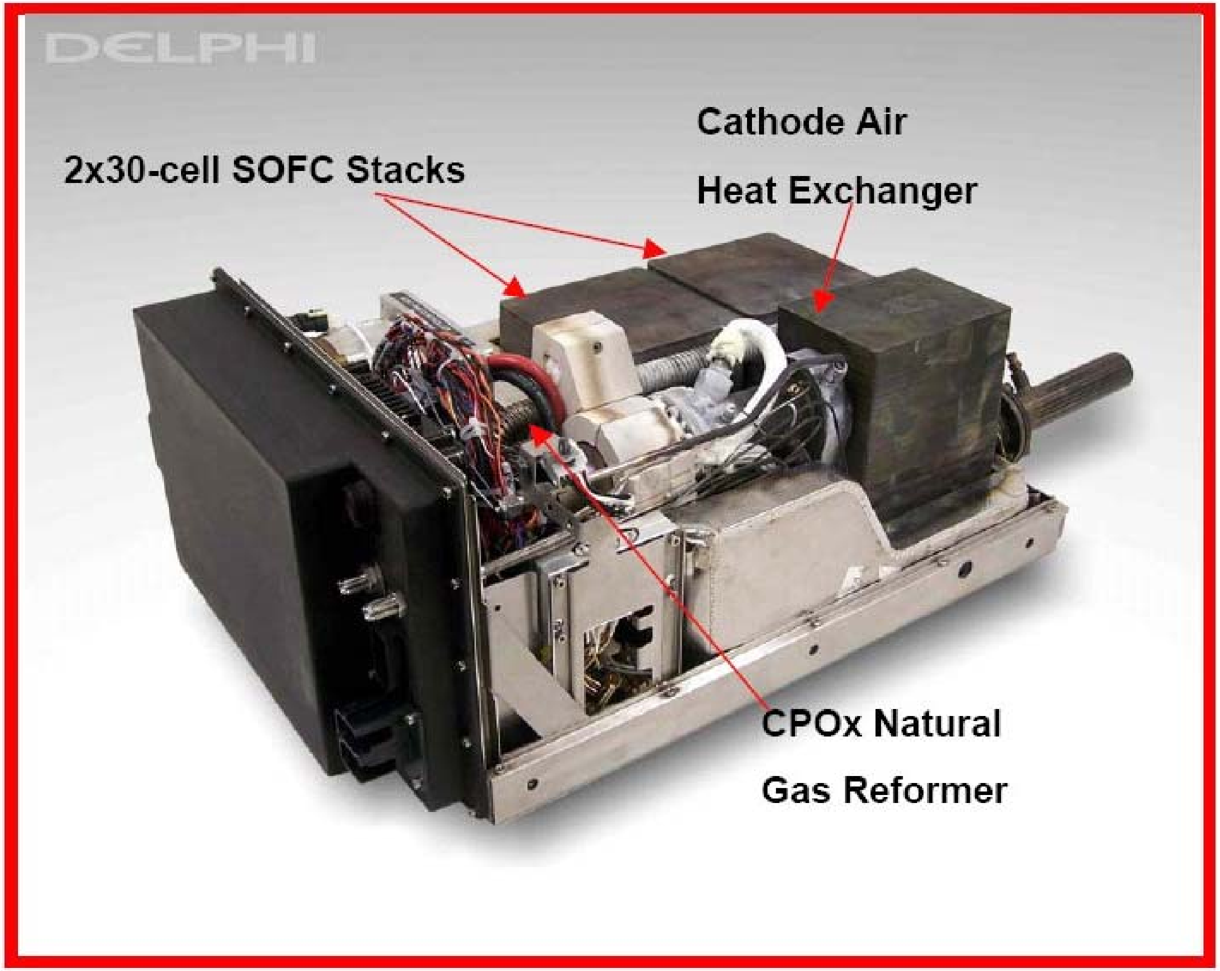
Annual US. Emissions Saved Using APUs in Class 8 trucks (vs.Idling)

- Diesel fuel saved:
  - 419 million gal./yr
- CO_2 reduced:
  - 4.64 million tons/yr
- Assumes
  - 2.1 million Class 8 trucks
  - 311,000 have overnight routes (APU candidates) SECA

Truck vs Diesel APU vs SOFC APU Emissions



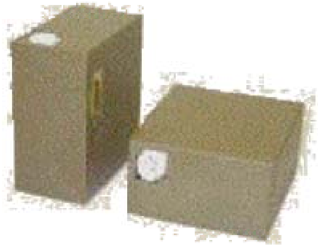
Delphi SOFC APU



Portable SOFC's for Military Power

Fuel Cell System

Propane powered



Military Batteries

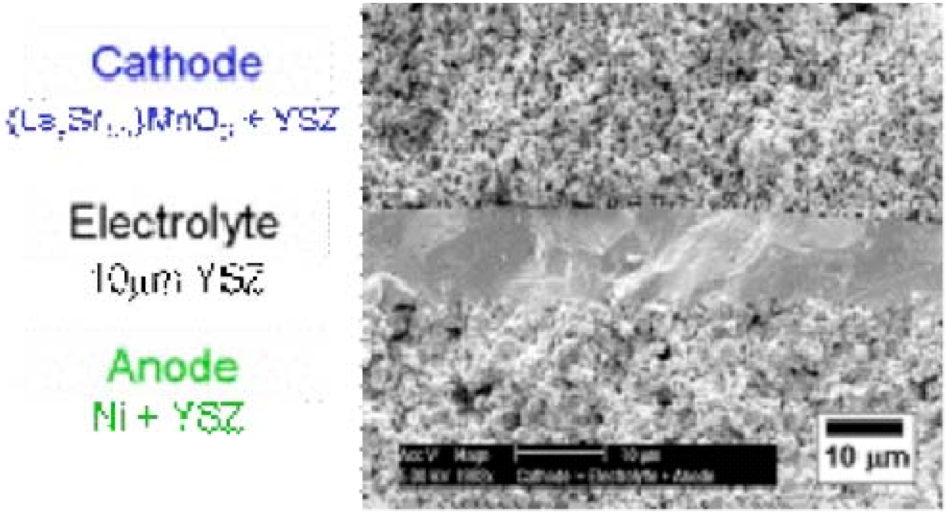
Three Day Mission

	Fuel Cell System	Military Batteries
	• 4.2 kg • 7.5 L • $7 fuel • $5,000 fuel cell system	• 23 kg • 20 L • $2,300 Battery cost

Life Cycle (1500 hrs)

	Fuel Cell System	Military Batteries
	• 38 kg • 68 L • $149 fuel • $5,149 fuel cell system	• 469 kg • 399 L • $46,900 Battery cost

20W Micro SOFC's



Adaptive Materials Inc

20W Portable SOFC

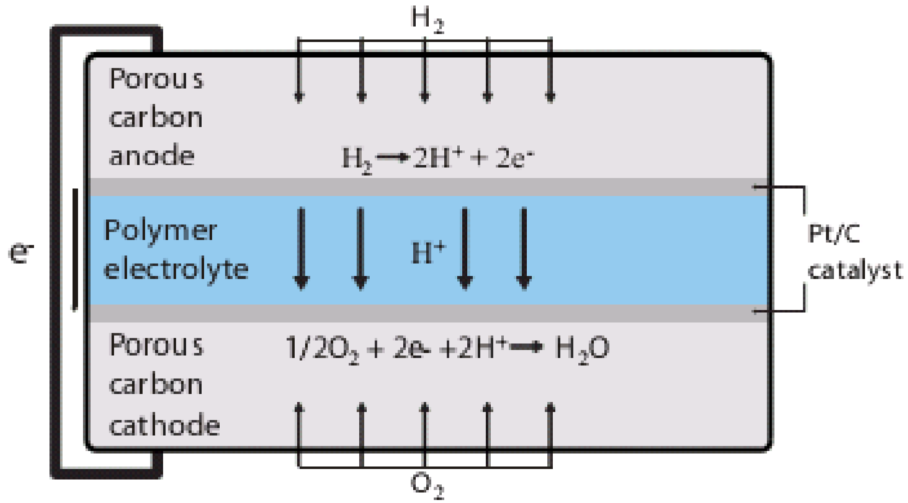
2006

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

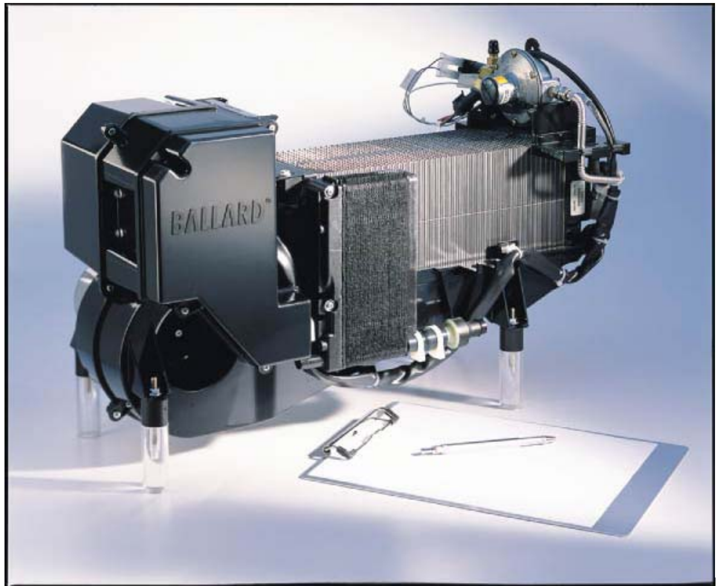


$$Anode:\ H_2 \rightarrow 2H^+ + 2e^-$$

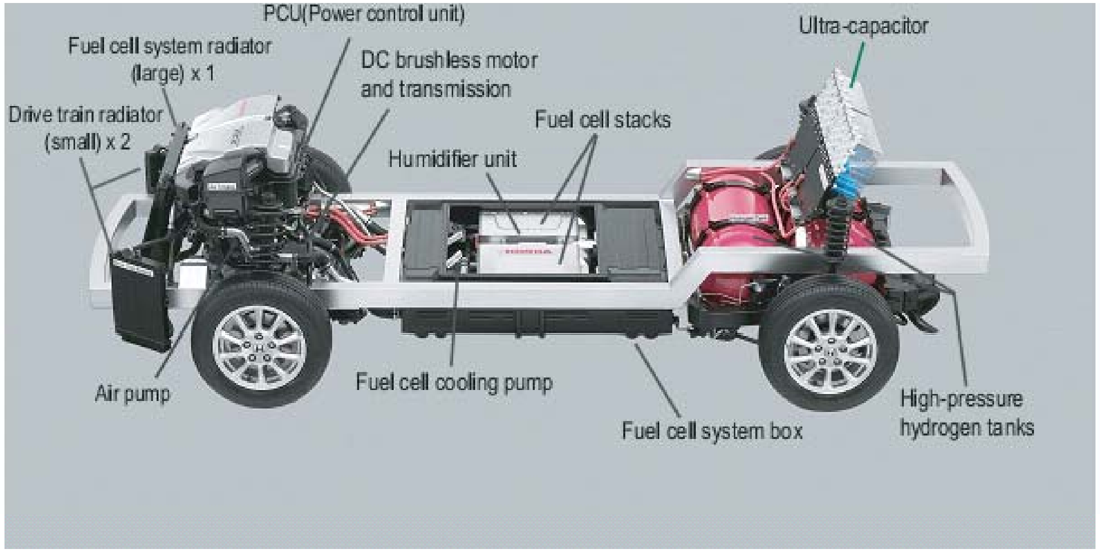
$$Cathode:\ \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

- 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



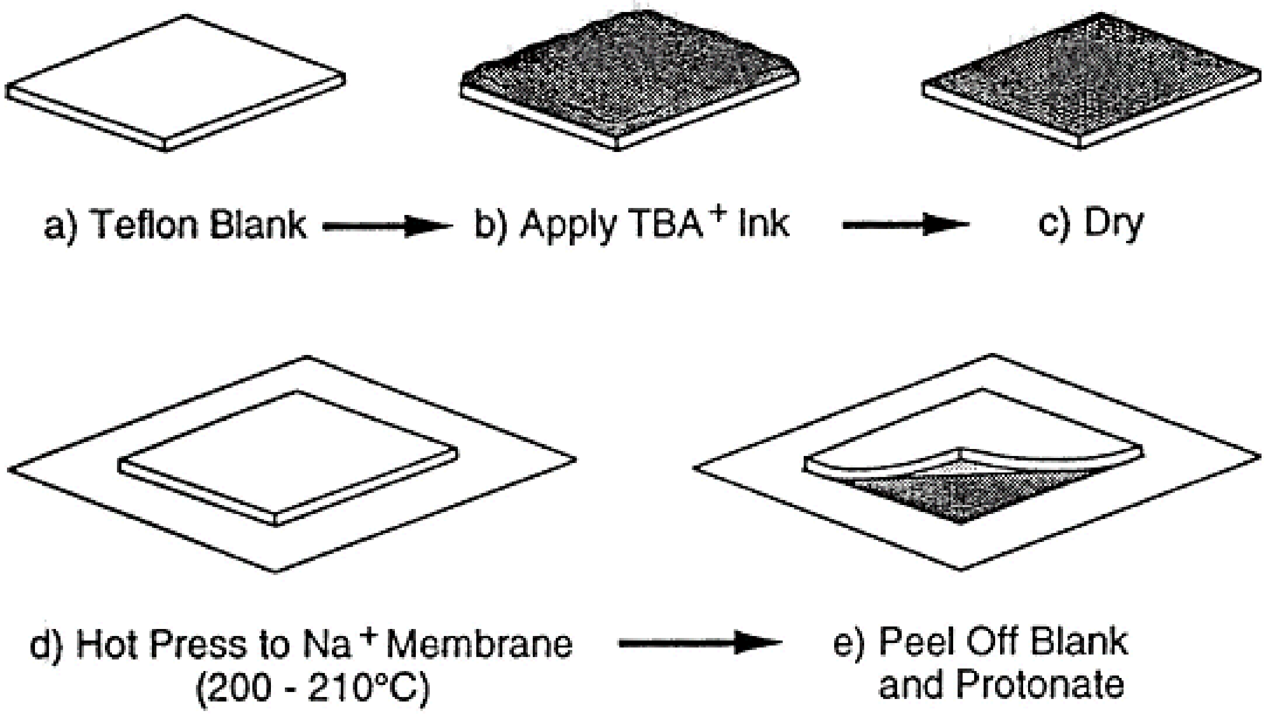
1.5kW portable PEMFC system by Ballard



Honda fuel cell car platform

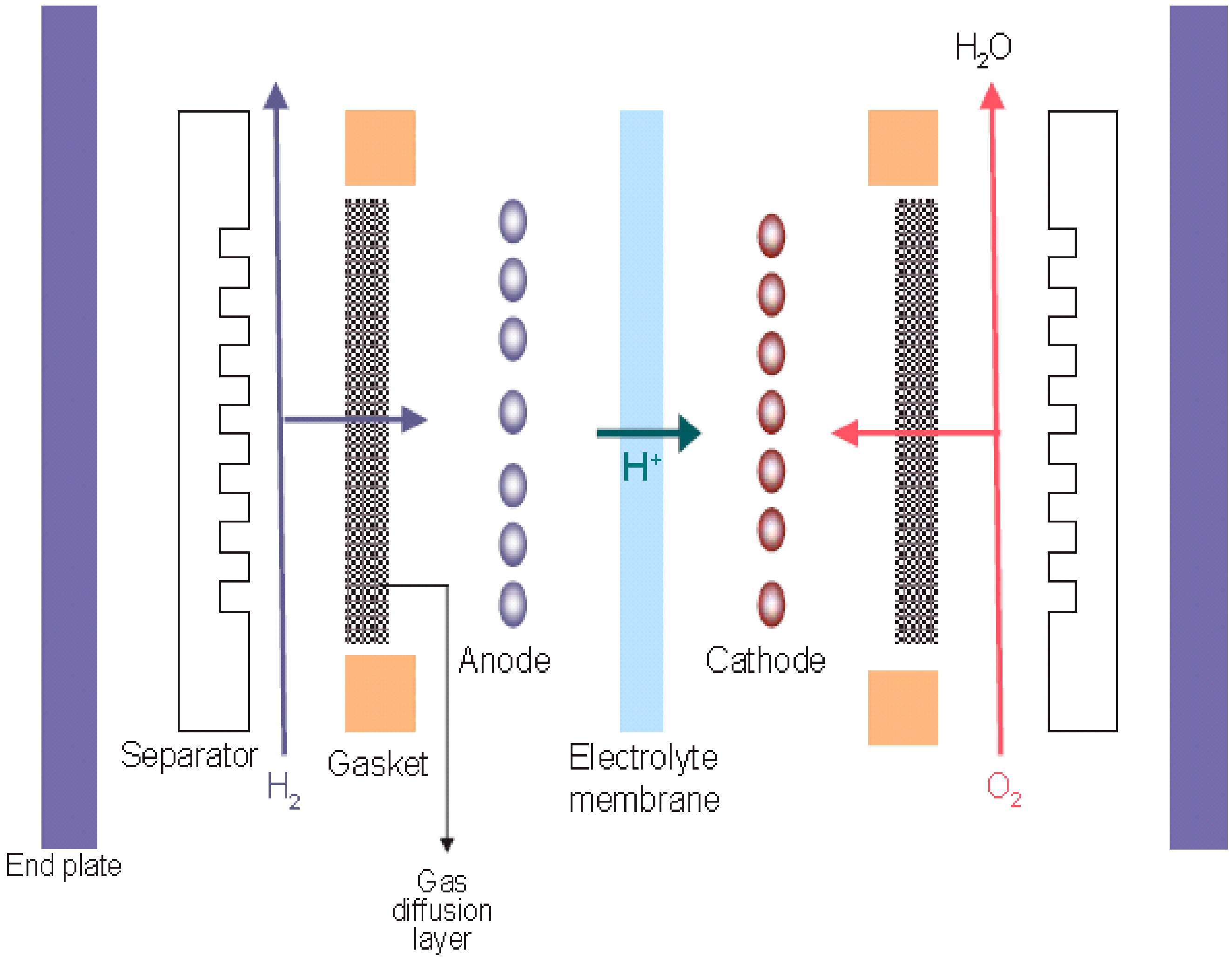
- Highest power density
- Fast start-up
- Low operating temperature makes it suitable for portable market.
- Poor CO & S tolerence
- Water management issue

PEMFC's

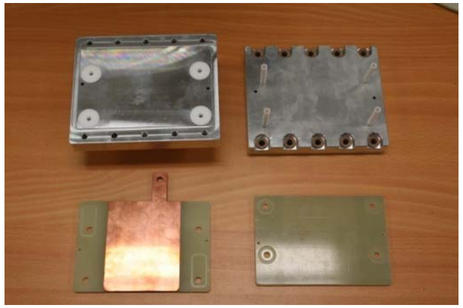


a) Teflon Blank
b) Apply TBA⁺ Ink
c) Dry
d) Hot Press to Na⁺ Membrane
(200 - 210°C)
e) Peel Off Blank
and Protonate

연료전지 구성: 단위 전지

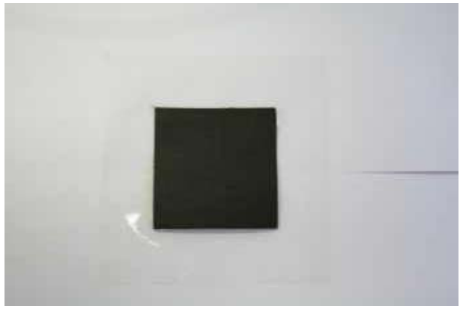


H2O
H+
Anode
Cathode
Separator
H2
Gasket
Electrolyte
membrane
O2
End plate
Gas
diffusion
layer



–Pressure Plate & Current Collector

- Pressure Plate
- Insulator
- Current Collector



– MEA

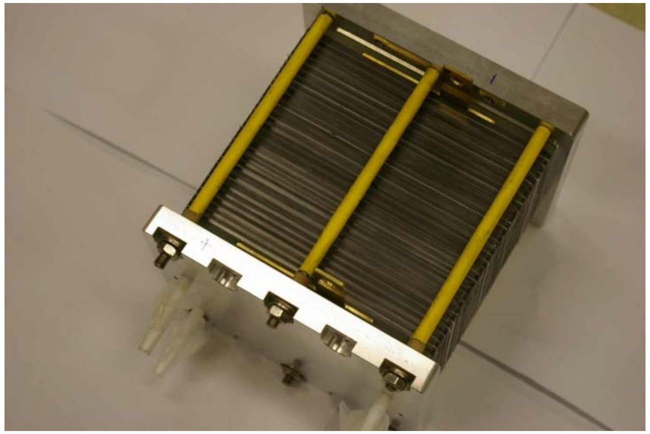
- Gas Diffusion Layers
- Catalyst Layers
- Membrane

– Separator

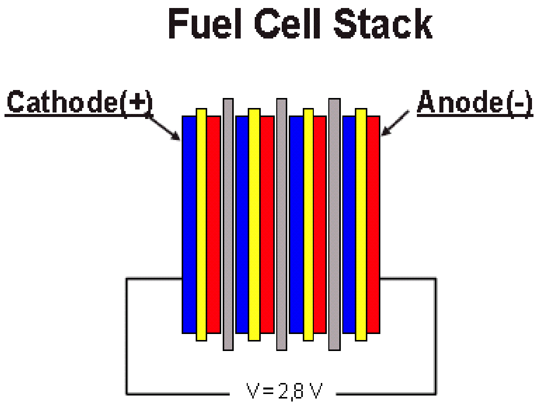
- Carbon Plate or etc.

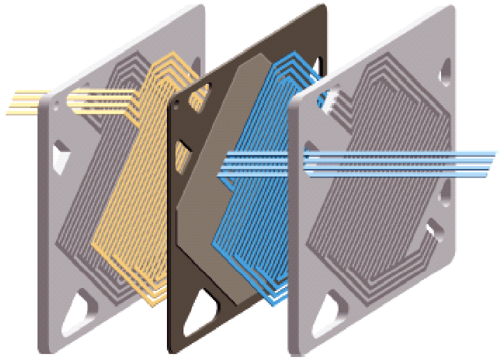
–Gasket

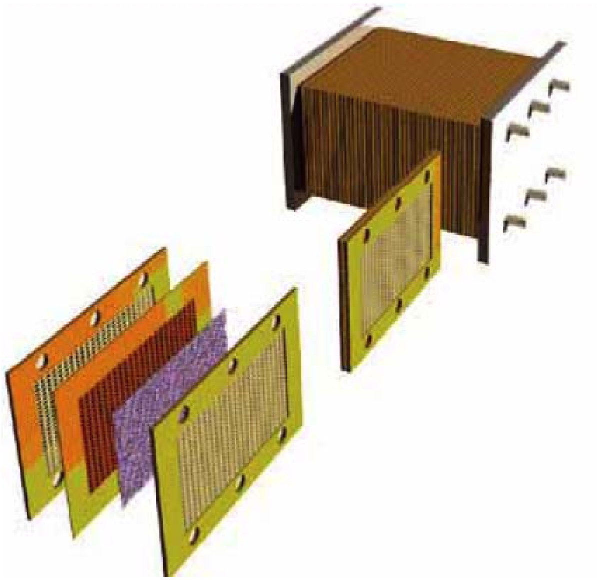
- Spacer

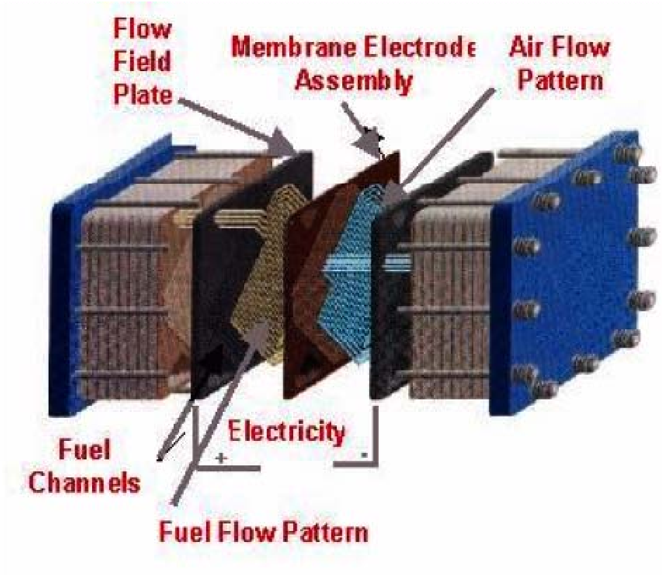


PEMFC Stack


Fuel Cell Stack
Cathode(+)
Anode(-)
V = 2,8 V






Flow Field Plate
Membrane Electrode Assembly
Air Flow Pattern
Electricity
+
-
Fuel Channels
Fuel Flow Pattern

PEMFC 스택 개발 현황

가압형(2~3기압)
•Ballard 사 Mark 902 등
•DC, Ford 등 적용
•스택효율 우수
•물관리 유리
•스택 기생전력 과다
  -교효율 공기압축기 요구: 스택출력의 10~25% 소비

상압형
•UTCFC 사 스택 등
•HMC, Nissan 등 적용
•시스템 기생전력 최소화
  - Air blower(토출압1.3bar 이하 적용시) 스택출력의 5% 미만 소모
•물관리 불리

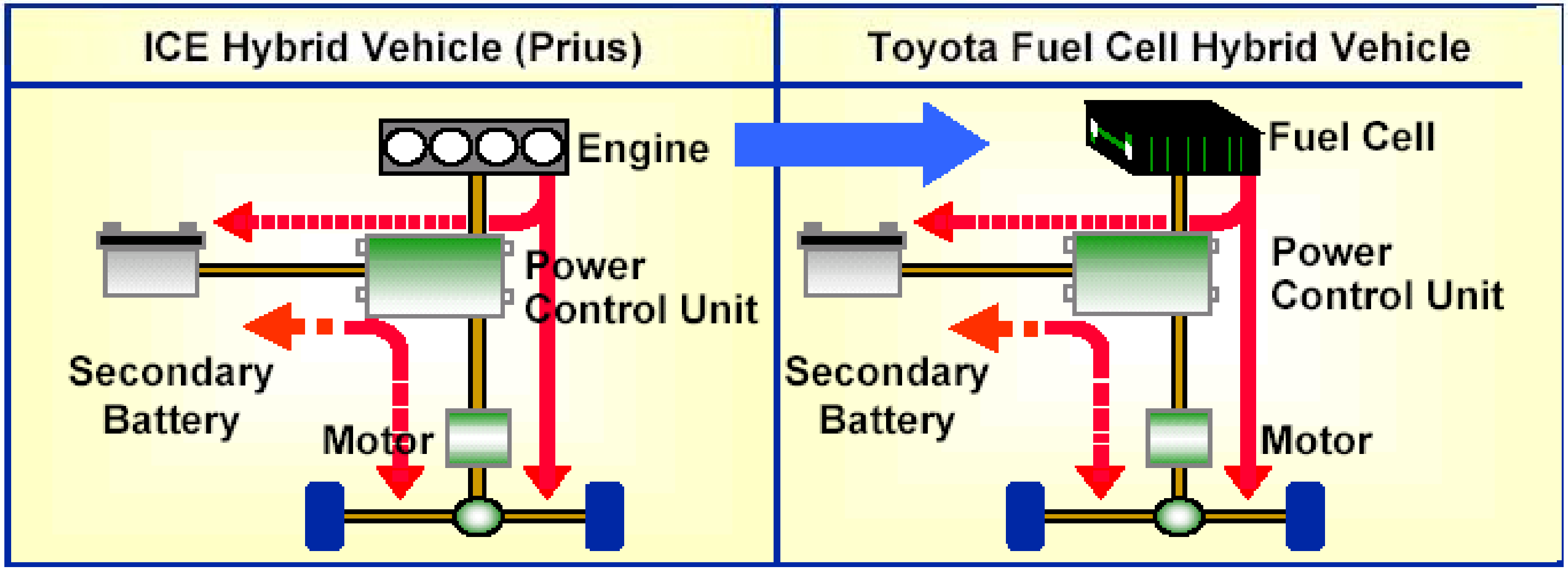
중압형(1.3~2기압)
•물관리 난점을 해결하고 소비전력 손해를 줄이는 절충형
•일부차량의 경우 고지 운전을 위해 적용

*수소연료전지사업단

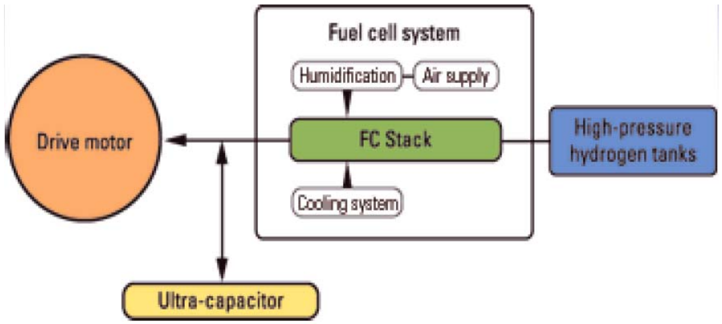
PEMFC's for Automotive

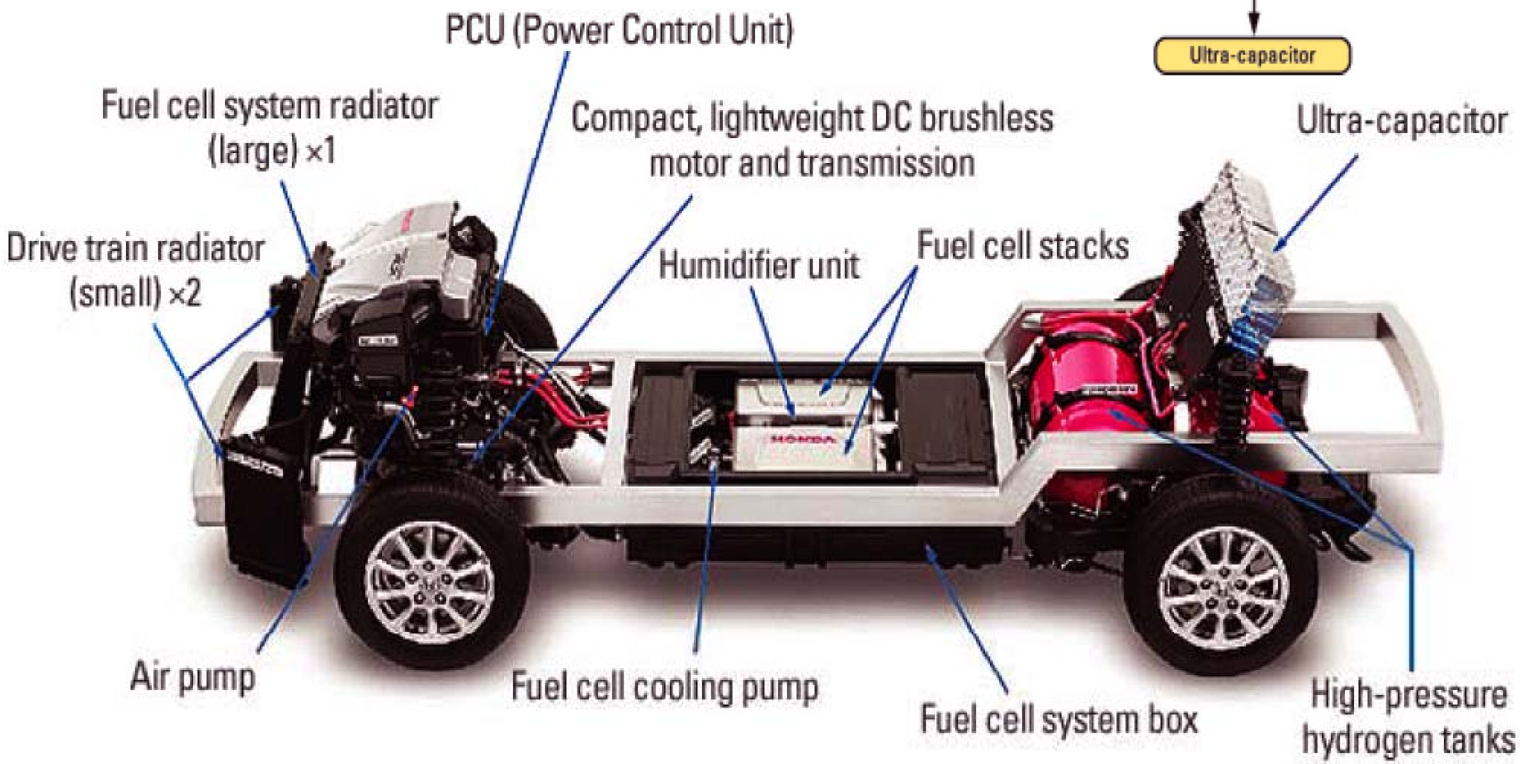
Prius

FCHV



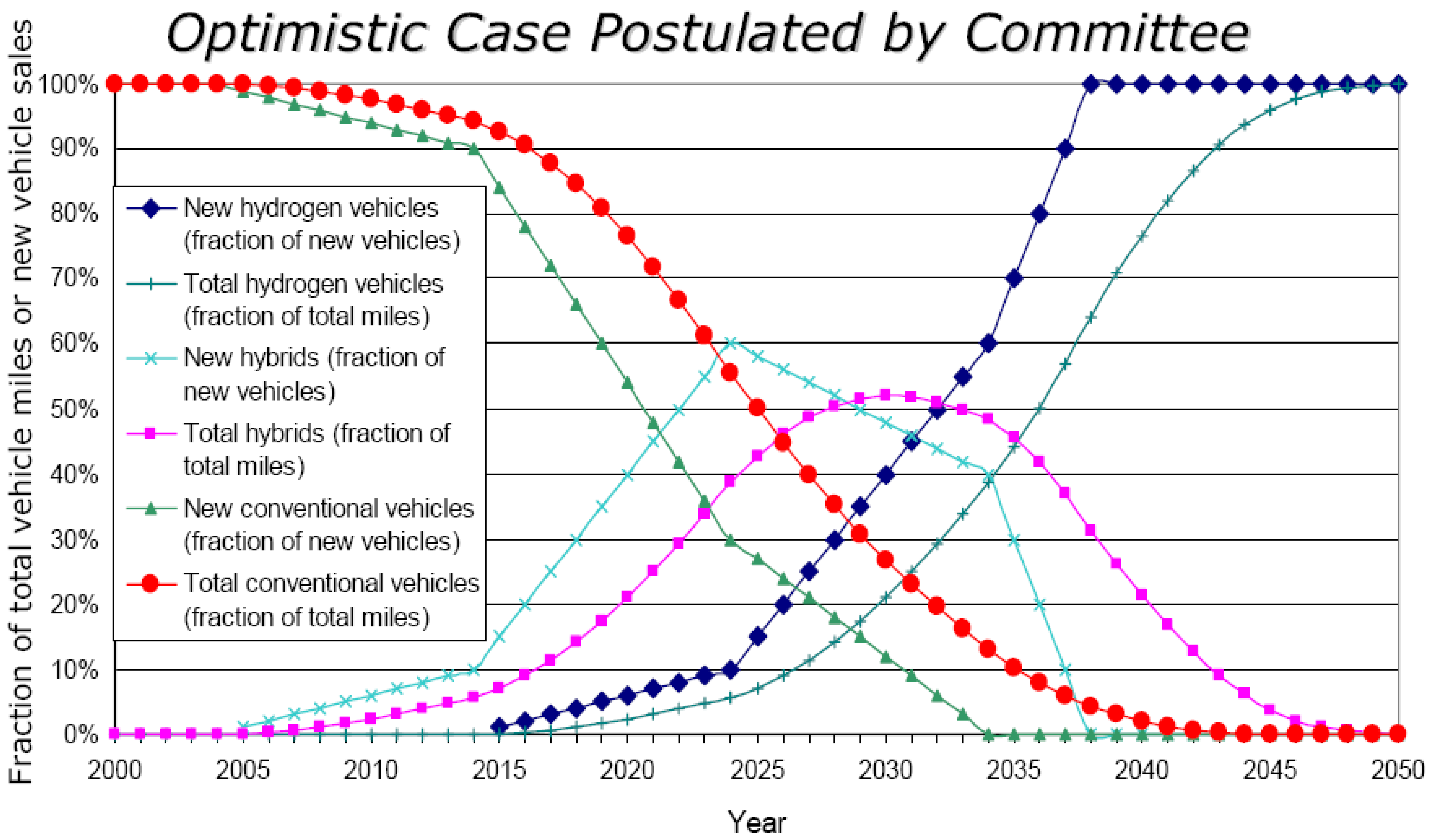
연료전지 자동차





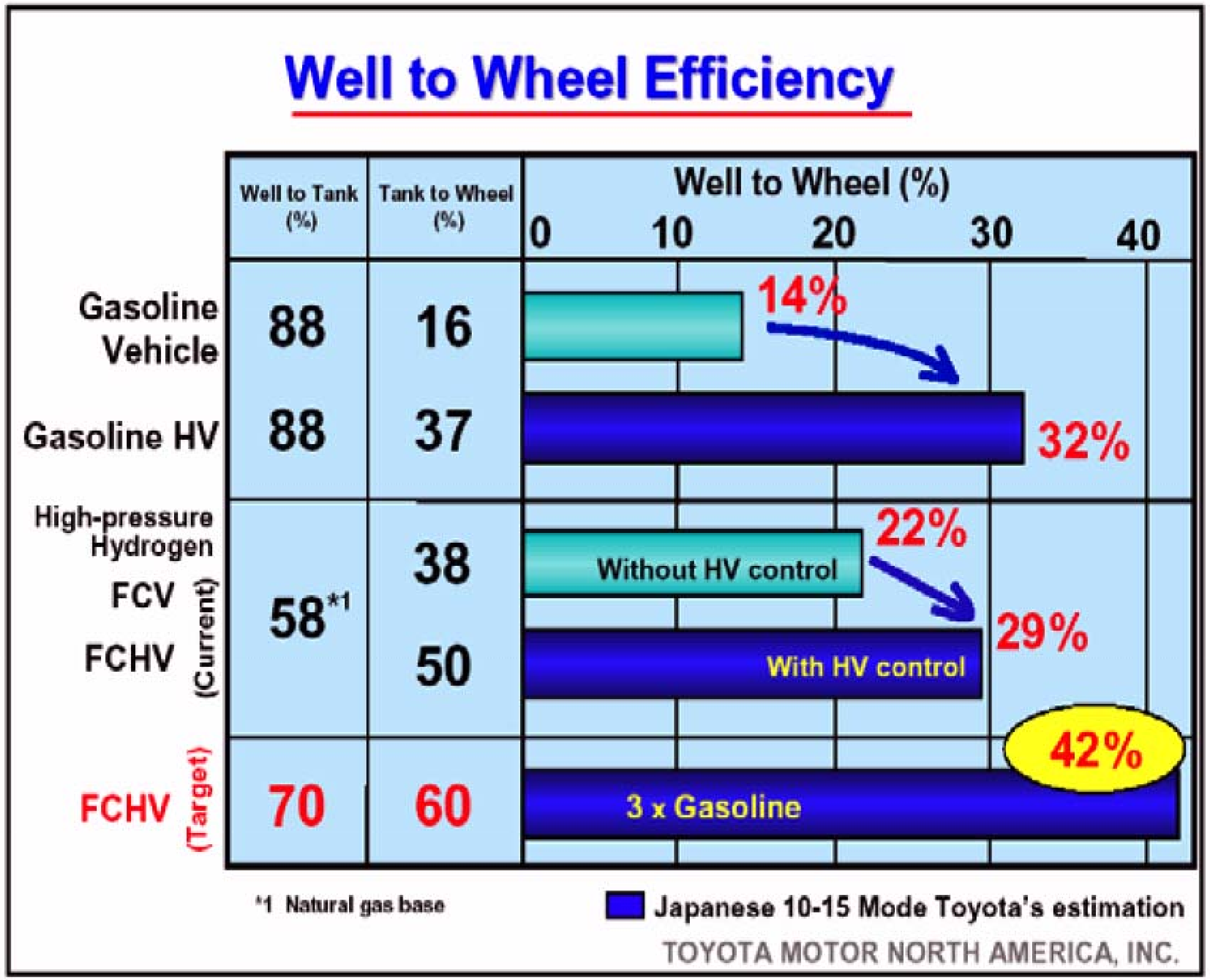
혼다 FCX

연료전지자동차 보급 예측



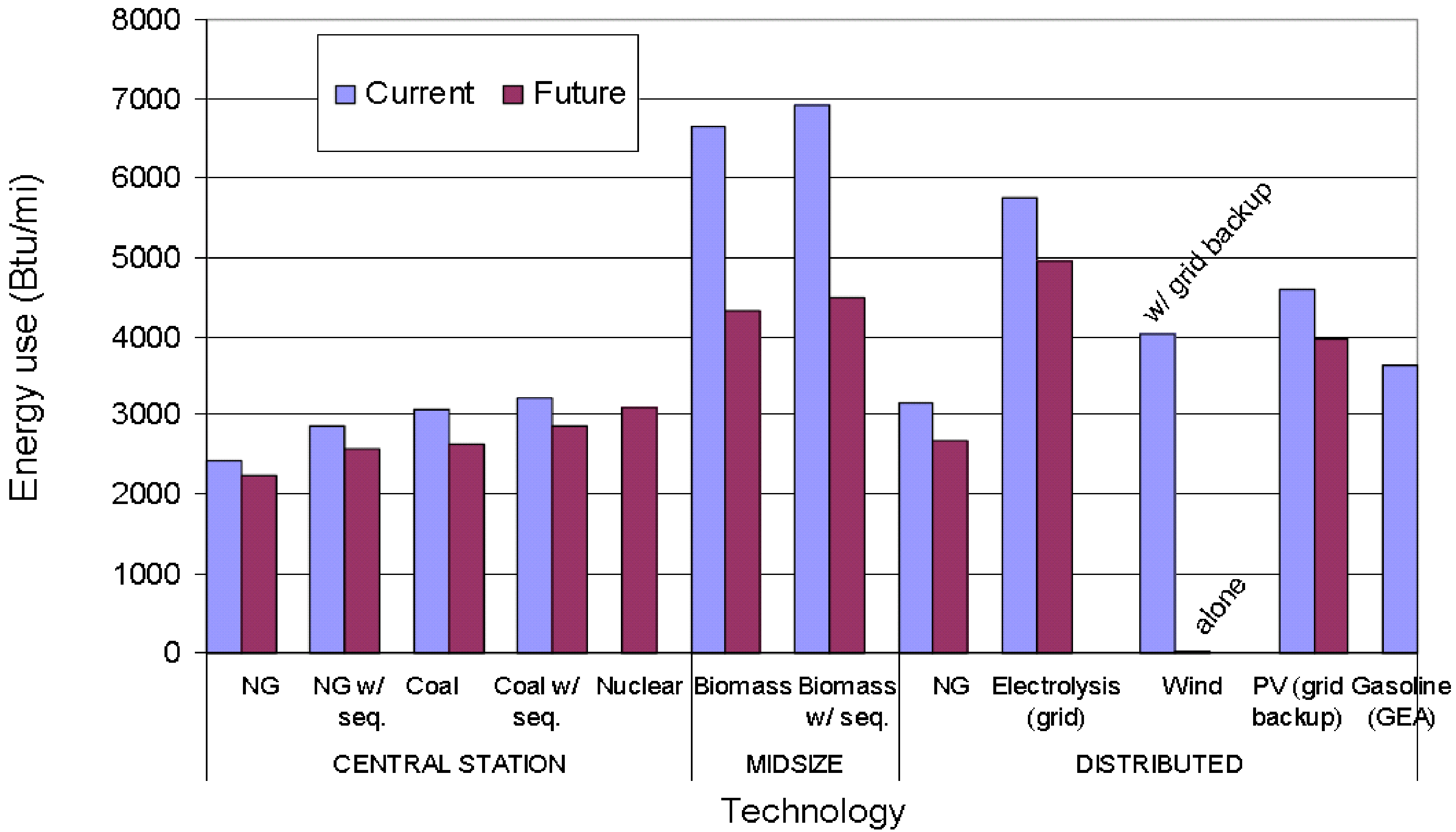
- *Complete replacement of ICE vehicles with fuel cell vehicles in 2050*

Well to Wheel Efficiency



수소생산 효율 및 연료전지 자동차 시스템 효율 개선 필요

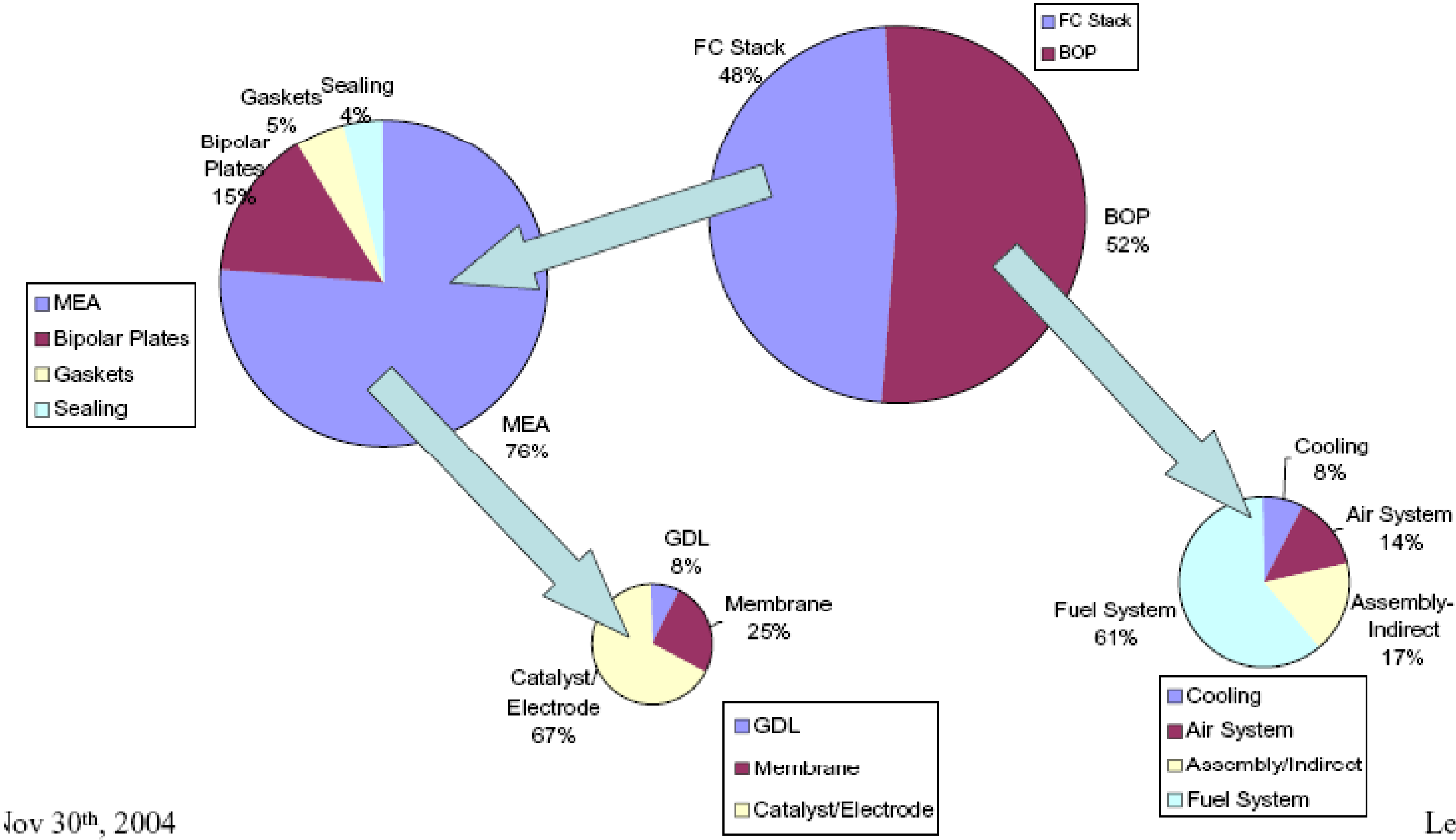
Well to Wheel Energy Use



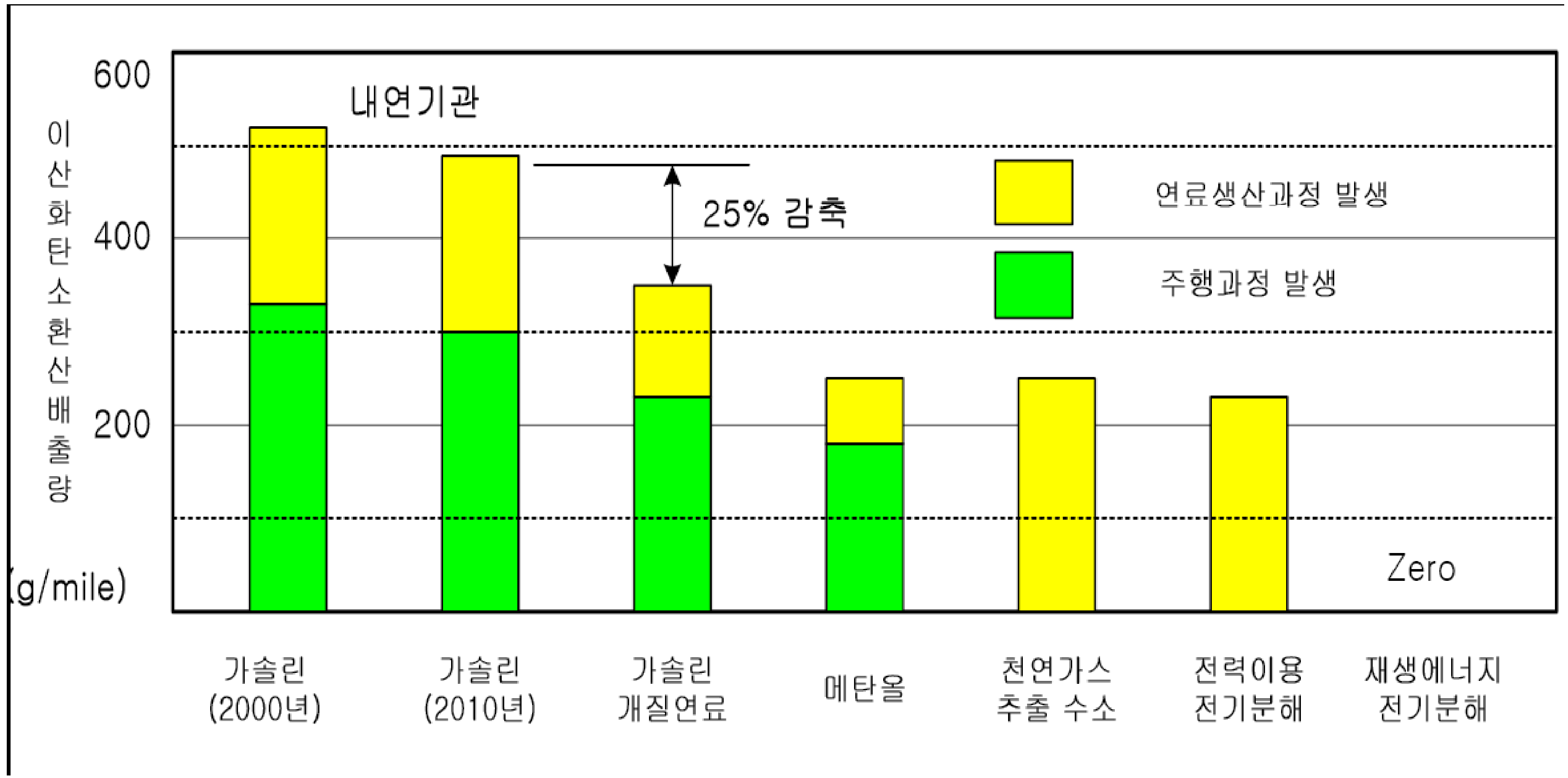
Fuel Cell System Cost Breakdown

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.)

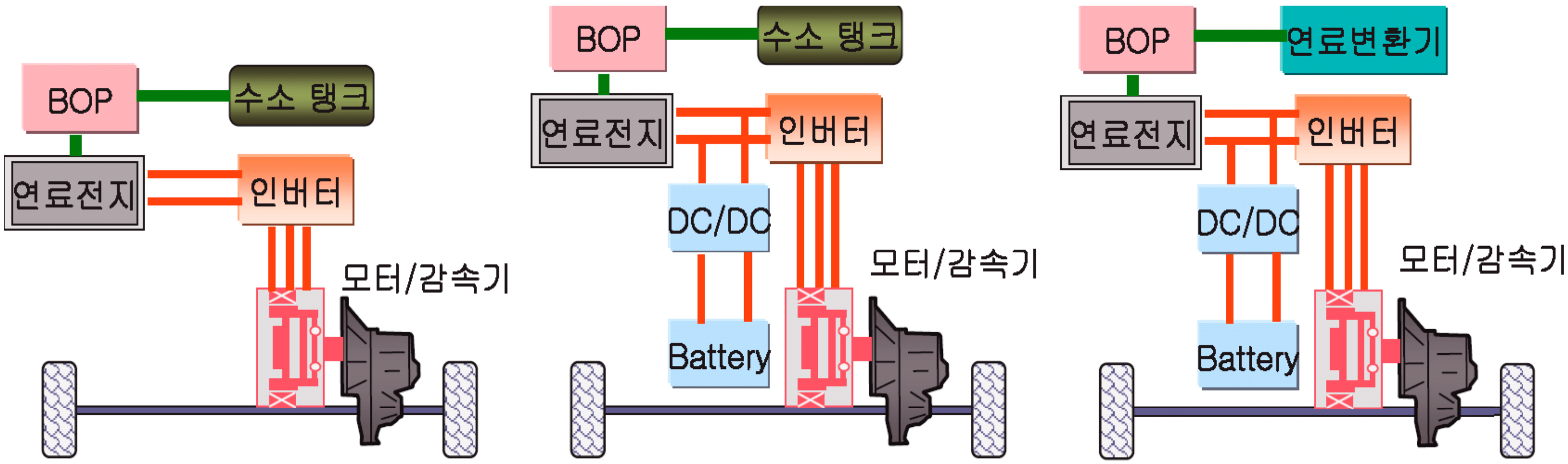


연료전지와 내연기관의 CO2 배출비교



*한국가스공사

연료전지 자동차동력 시스템 구성



순수수소 연료전지차	순수수소 하이브리드차	연료 개질형 하이브리드차
▪ 시스템 간단 ▪ 부하 추종형, 연료전지 전 출력 영역 운전	▪ 시스템 효율적 운전 가능 -> 연료전지 고효율 영역 (저출력 영역) 운전 -> 회생 제동 에너지 회수	▪ 기존 연료 인프라 사용 가능 ▪ 일충전 주행거리 만족 가능 ▪ 연료변환기 시동시간 및 부하 추종성 문제

스택 기술 개발 과제

상업화를 위한 기술적 과제

효율	가격	내구성
소재개발	조립 및 제조기술	출력밀도
운전제어기술(운전조건 등)	빙점이하보관 및 운전	저온 시동성

스택 부품

Membrane
Electrode
Assembly

문제점 및 개선사항

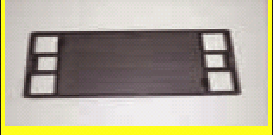
- 외부가습 삭제 또는 최소화
- 더 높은 스택 운전온도 구현
- 낮은 운전압력 영역에서의 스택출력 향상
- CO 내피독성 향상
- 촉매량 저감 / 내구성능 향상
- 저온특성 및 빙점이하 운전
- 새로운 이온 전도체를 통한 무가습 MEA개발
- 기계적 물성 개선 및 박막화
- 스택 조립성 및 장착성을 고려한 Gasket 및 GDM 과의 일체화

*수소연료전지사업단

스택 기술 개발 과제

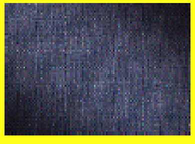
스택 부품 / 문제점 및 개선사항

Bipolar Plates



- 낮은 화학량론비에서의 운전
- 균일 냉각 및 공급기체 분산 (유로 Design)
- 절연 냉각수 개발
- 전기전도도 개선 (Composite Plastic의 경우)
- 내식성 향상 (Metal Plates)
- 저온특성 및 빙점이하 운전

Diffusion Media

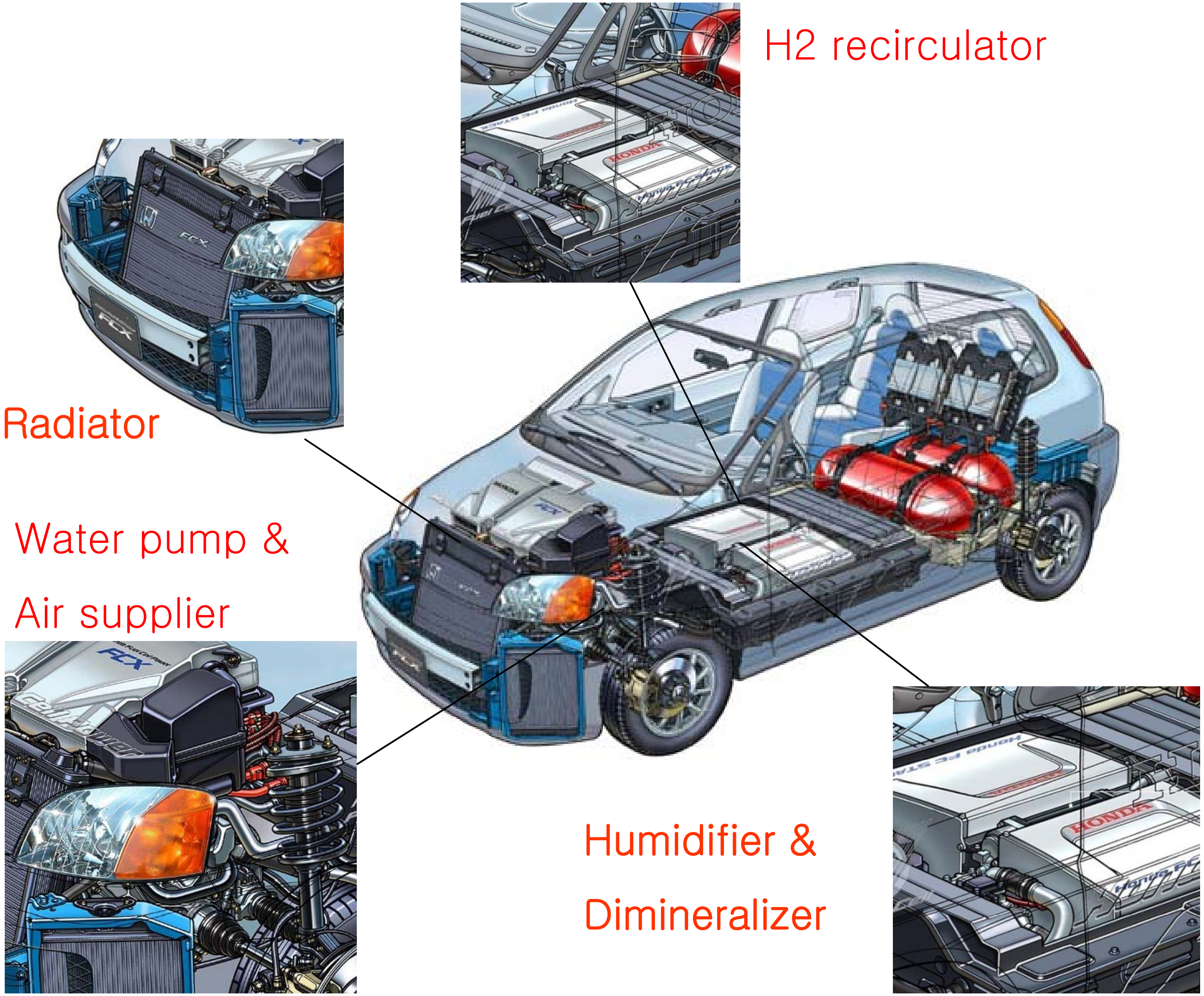


- 물 관리 기술
- 전기전도도 향상
- 스택 조립/체결 시 MEA보호

Cell Fixture

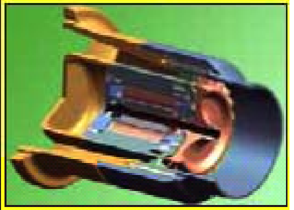
- 출력밀도 향상 : 경박 단소화
- 차량 장착성 &기계적 내구성 & 안전성
- 스택 조립성 향상
- 셀전압 측정기구 등 기능성 단품의 모듈화

운전장치 (Balance of Plant, BOP)



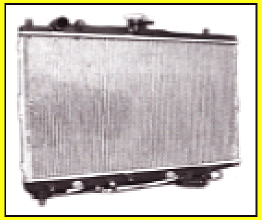
BOP 기술 개발 과제

Air Supplier



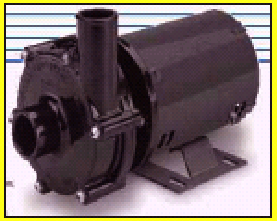
•연료전지 특성(압력/유량)을 충족시키는 사양 개발
•연료전지 시스템의 운전압력 결정
•Weight, Volume & Noise 저감
•최적의 Filter 개발

Radiator



•방열 성능 극대화 기술
•내부식성 소재 개발
•압력강하 최소화
•저온 및 빙점 이하 운전 기술
•Water Balance 확보

Water Pump



•내부식성 소재 개발
•BLDC 모터 개발

*수소연료전지사업단

BOP 기술 개발 과제

Demineralizer

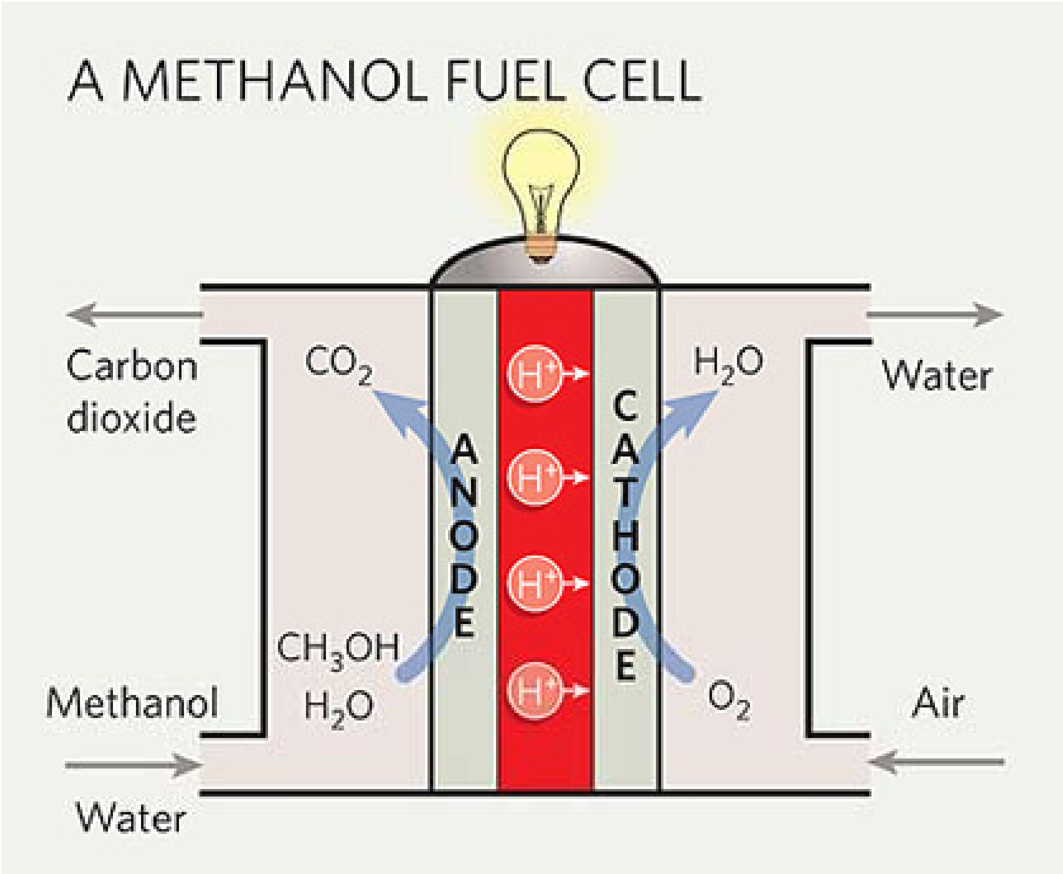
•냉각수 내 전기전도도 유지기술 확보
•고효율 이온제거 필터 개발
•고온용(70C 이상)필터 개발
•가격절감 및 내구성 확보

H2 Recirculation System

•최적의 수소 재순환 기술 확보
•내식성 소재 개발
•안전성 확보 (Sealing 등)
•BLDC 모터 개발

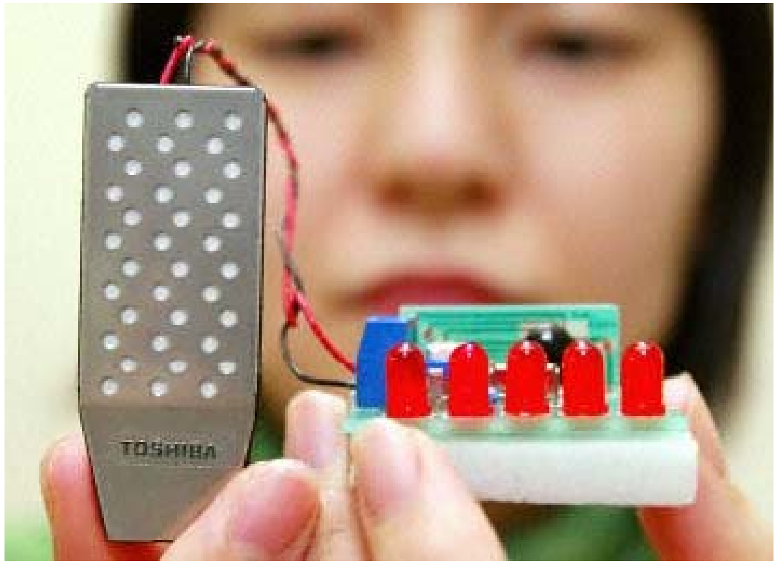
*수소연료전지사업단

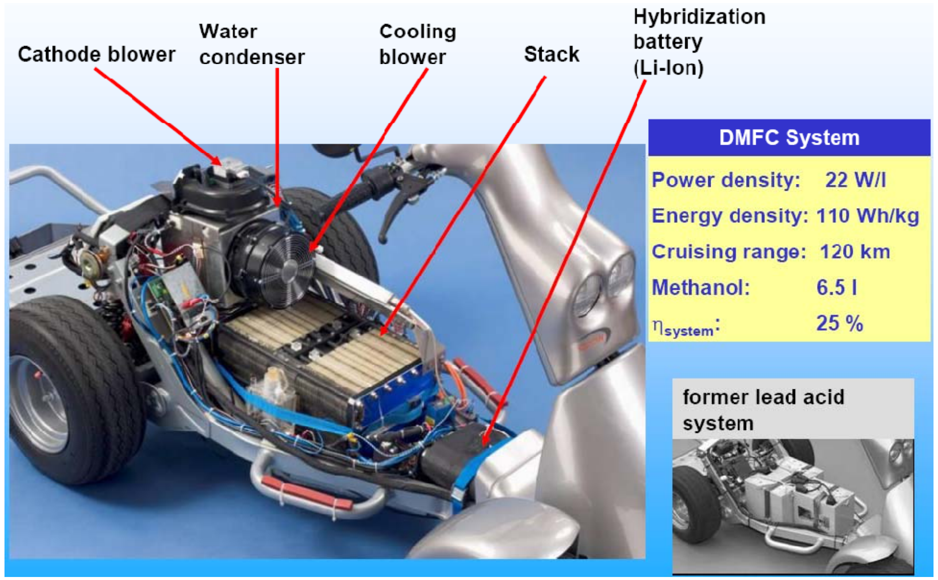
DMFC's


A METHANOL FUEL CELL
Carbon dioxide
CO_2
H^+
H_2O
Water
ANODE
CATHODE
CH_3OH
H_2O
Methanol
O_2
Air
Water

DMFC's

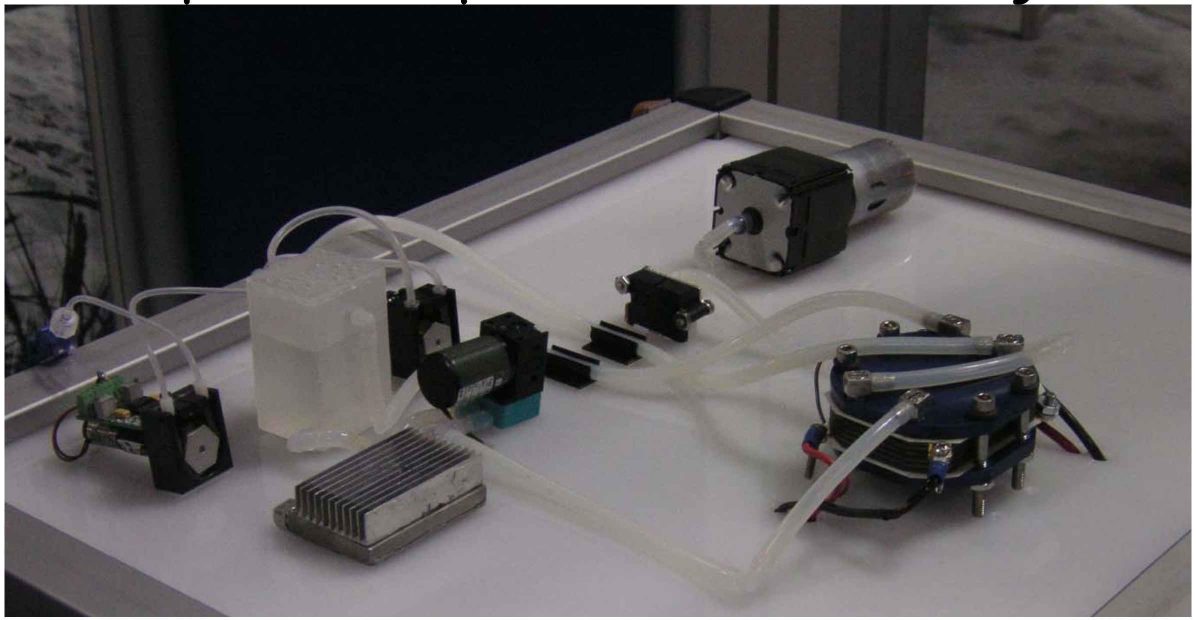

mobion

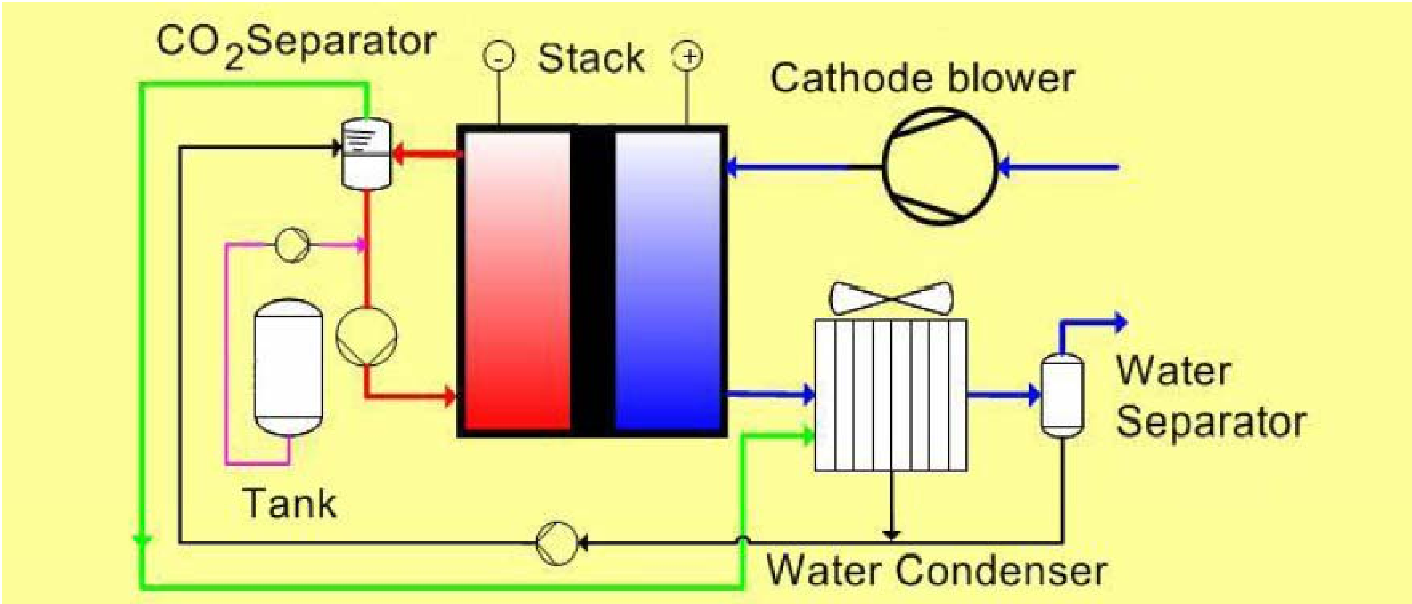

TOSHIBA


Cathode blower
Water condenser
Cooling blower
Stack
Hybridization battery (Li-Ion)
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


DMFC
VIEWIMAGES

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

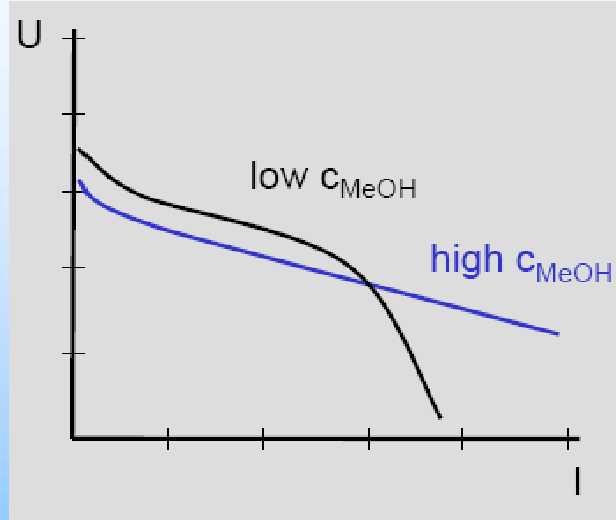
- **Reduce or eliminate precious metal catalysts**

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

Methanol Concentration Control

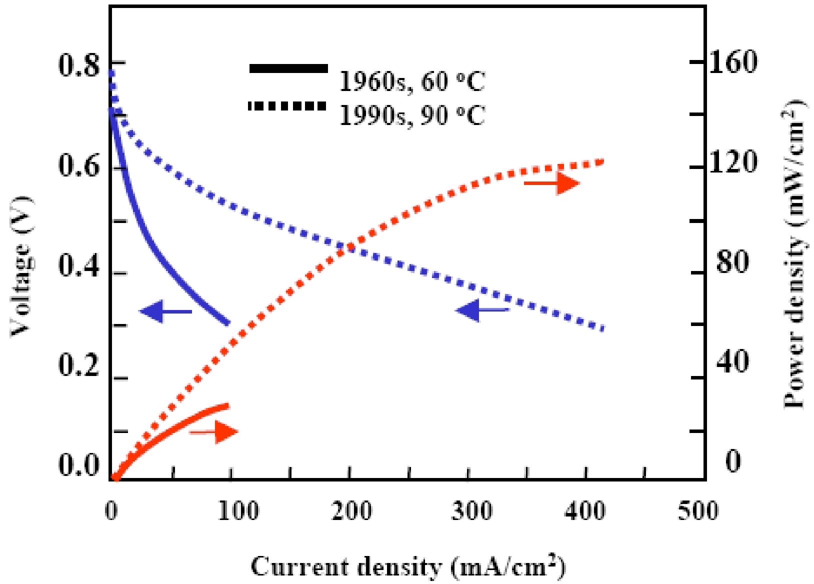
High methanol concentration
• low anode overpotential
• high methanol permeation
• high cathode overpotential (mixed potential)

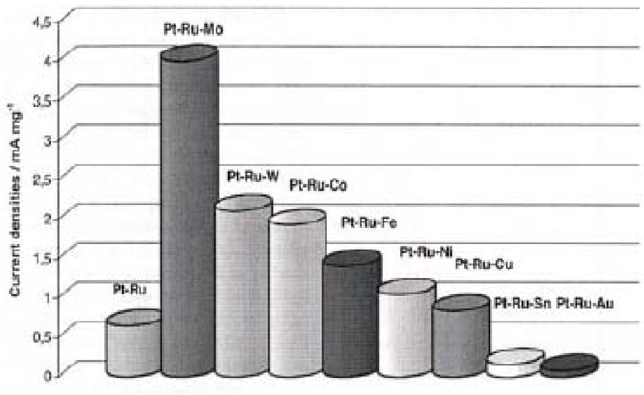
Low methanol concentration
• high anode overpotential
• low methanol permeation
• lower cathode overpotential

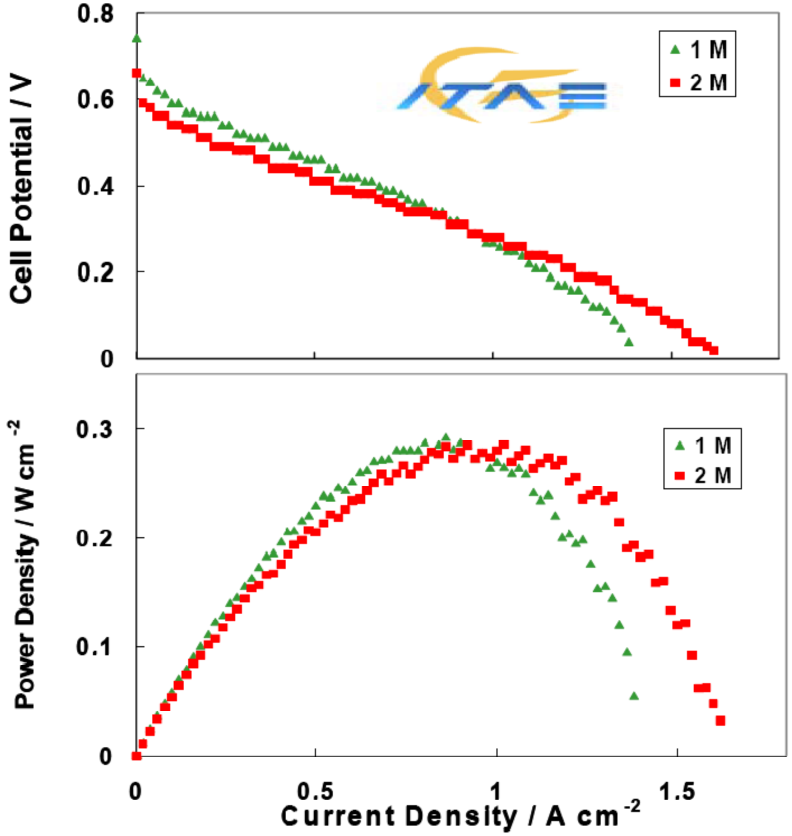


The **methanol concentration** is always a **compromise** between **cathode and anode** impact. It mainly depends on:
• current density
• temperature
• air flow rate

DMFC Performance







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

DMFC's for Portable Power

Single Cell/ Stack Developer	Power density	Temperature	Oxidant	Methanol Conc.	Anode Catalyst	Membrane Electrolyte	Cathode catalyst	# cells/Surface area
Motorola Labs	12-27 mW/cm^2	21°C	Ambient air	1M (0.45 ml/min.)	Pt/Ru alloy, 6-10mg/cm^2	Nafion 117	Pt, 6-10mg/cm^2	4 / 13-15cm^2 Planar stack
Energy Related Devices	3-5 mW/cm^2	25°C	Ambient air	1M -Pure	Pt/Ru alloy	Nafion	Pt	Planar stack
Jet Propulsion	6-10 mW/cm^2	20-25°C	Ambient air	1M	Pt/Ru alloy, 4-6mg/cm^2	Nafion 117	Pt, 4-6mg/cm^2	6 / 6-8cm^2 "Flat-pack"
Los Alamos National Labs	(300 W/L)	60°C	Air flowed at 3-5 times stoichiometry	0.5M	Pt/Ru, 0.8-16.6mg/cm^2	Nafion	Pt, 0.8-16.6mg/cm^2	5 / 45cm^2
Forschungszentrum Julich GmbH	45-55 mW/cm^2	50-70°C	3 atm O_2	1M	Pt/Ru, 2mg/cm^2	Nafion 115	Pt, 2mg/cm^2	40 / 100cm^2 Bipolar plate
Samsung Advanced Institute of Technology	10-50 mW/cm^2 (single cell)	25°C	Ambient air	2-5M	Pt/Ru	Hybrid membrane	Pt	12 / 24cm^2 Monopolar
Korea Institute of Energy Research	121-207 mW/cm^2	25-50°C	Ambient pressure, O_2 (300 cc/min)	2.5M	Pt/Ru/C metal powder	Nafion115 & 117	Pt-black	6 / 52cm^2 Bipolar
Korea Institute of Science & Technology	3-9 mW/cm^2	25°C	Ambient air		Pt/Ru, 8mg/cm^2	Nafion 117	Pt, 8mg/cm^2	15 / 90cm^2 Monopolar
More Energy Ltd.	60-100 mW/cm^2	25°C	Ambient air	30-45% Methanol	Pt/Ru	Liquid Electrolyte	Pt	/ 20cm^2

DMFC's for Transportation

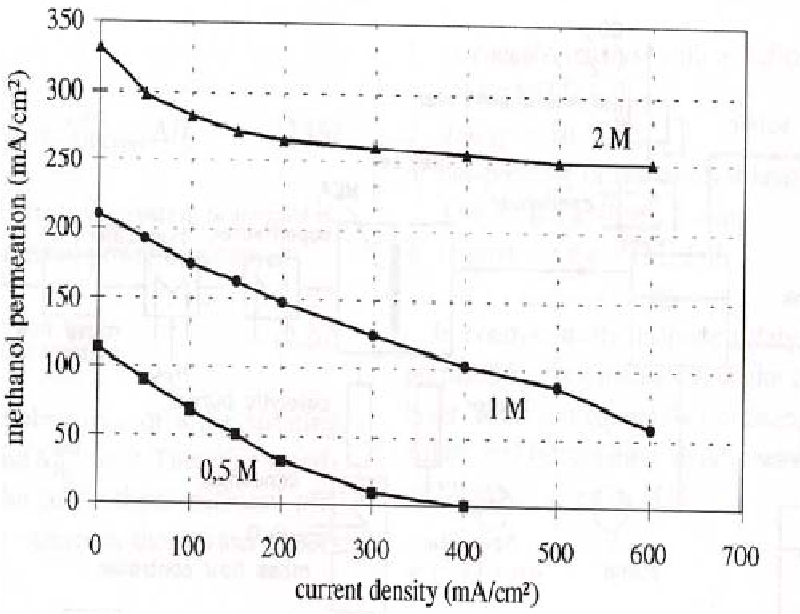
Single Cell/ Stack Developer	Power/ Power density	Temp (^oC)	Oxidant	MeOH Conc. (M)	Anode Catalyst	Membrane Electrolyte	Cathode catalyst	# cells/ Surface area (cm^2)
BALLARD POWER SYSTEMS, INC.	3 kW	100	air	1-pure	Pt/Ru	Nafion	Pt	-
IRD FUEL CELL A/S	100 mW/cm^2	90-110	1.5 atm Air	-	Pt/Ru	Nafion	Pt	4 / 154cm^2 Bipolar
THALES CNR-ITAE NUVERA FUEL CELLS	140 mW/cm^2	110	3 atm Air	1	Pt/Ru	Nafion	Pt	5 / 225cm^2 Bipolar
SIEMENS AG	250 mW/cm^2 (90)	110 (80)	3 atm O_2 (1.5 atm Air)	0.5	Pt/Ru	Nafion 117	Pt-black, 4mg/cm^2	3 cm^2 per cell
LOS ALAMOS NATIONAL LABS	(1 kW/L)	100	3 atm, Air	0.75	Pt-Ru	Nafion 117	Pt	30 / 45cm^2 Bipolar

DMFC Challenges (Half & Single Cell)

- **High activation loss (~400mV)**
  - -Electrooxidation of methanol
  - -Electroreduction of oxygen (ORR)
  - -High Pt-Ru and Pt loadings (~4.0 mg/cm2)

- **Poisoning of anode electrocatalyst by adsorbed intermediates;**
  - -CO, formaldehyde, formic acid

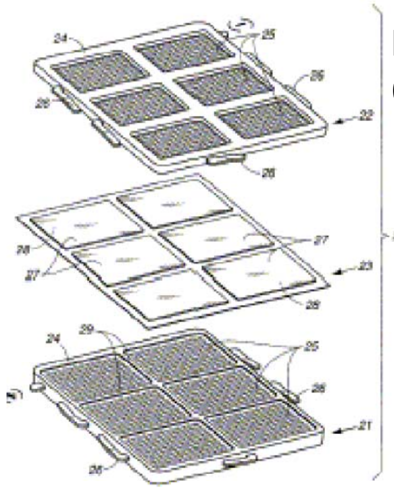
- **Methanol cross-over from anode to cathode**
  - -Coulombic efficiency losses (~30%)
  - -Increase of activation overpotential for ORR



Methanol permeation for different methanol concentrations. The methanol permeation is expressed as the parasitic current density. Operating conditions: 110 °C; pressure 3 bar absolute; oxygen as oxidant; measuring time per point 15-30 min. from: J. Power Sources 111 (2002) 268-282

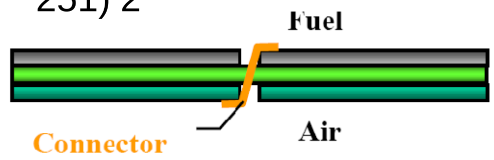
DMFC Challenges (Stack)

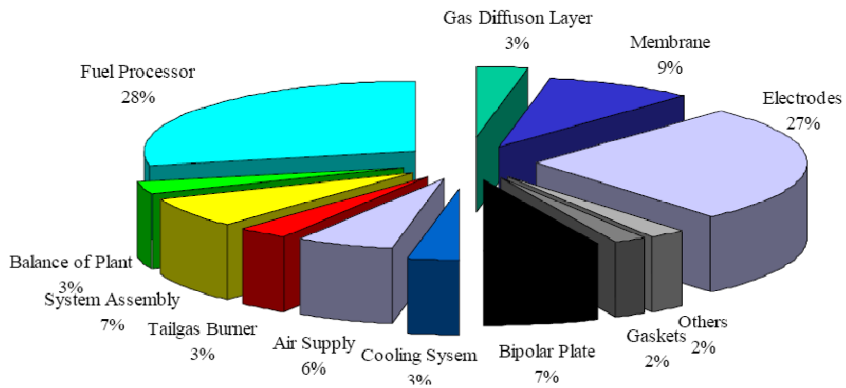
- **Low power density**
  - 350 mW/cm^2 (DMFC) vs. 900 mW/cm^2 (PEMFC)
- **Low methanol concentration**
  - Optimum of 1~2 M
  - Reduced energy density and specific energy
- **High cost**
  - Electrocatalysts ~$200/kW
  - PEM ~$600/kW
  - Fabrication of electrodes, MEAs, bipolar plates
- **Pressurization of gases**
  - Use of 3 atm air to minimize mass transport losses



Planar cell layout, Motolora Inc. (2000), US Patent, 6,127,058

Planar cell connection,J. Power Sources, 93 (2001) 251) 2





Cost break down, Small fuel cell seminar, Washington DC, April (2002)

DMFC Challenges (System)

• **Competition with existing technology**

-Lithium-ion batteries for small portable power sources (laptop computers, cellular phones, video camera's)

• **Size reduction**

-Difficulties in miniaturization of DMFCs and auxillaries for portable applications

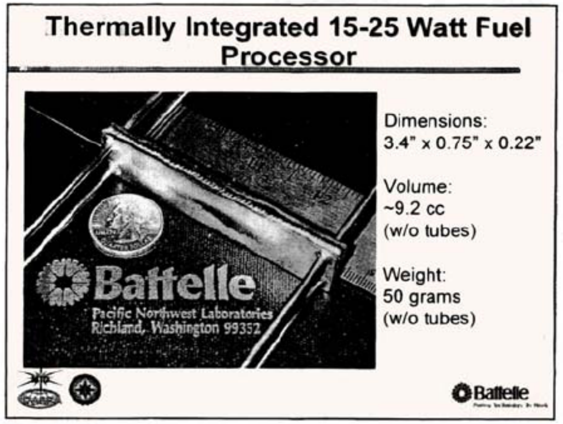
• **Air breathing limits power densities**

• **Lifetime issue**

-Unknown as compared with competing technologies

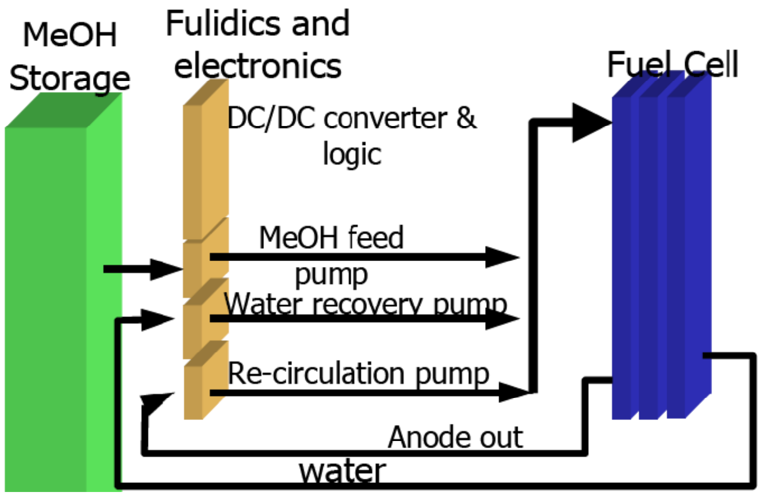
• **High capital costs**

- Portable power, transportations



Micro reformer, Battele in Small fuel cell seminar, Washington DC May (2002)

Water recovery system MTI in Small fuel cell seminar, Washington DC May (2002)



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

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

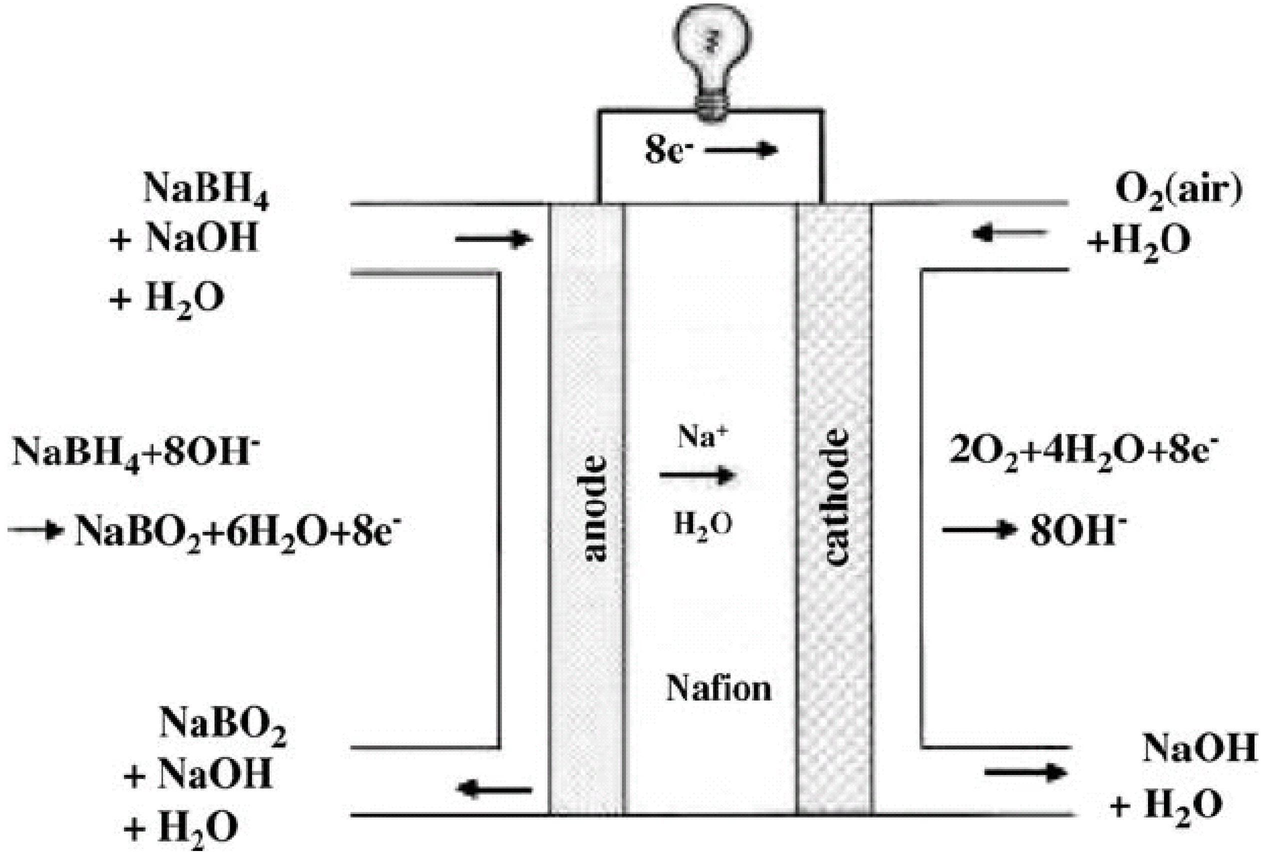
$$HCOOH + Pt^0 \rightarrow Pt{-}CO + H_2O \quad (2)$$

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

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

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

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

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

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

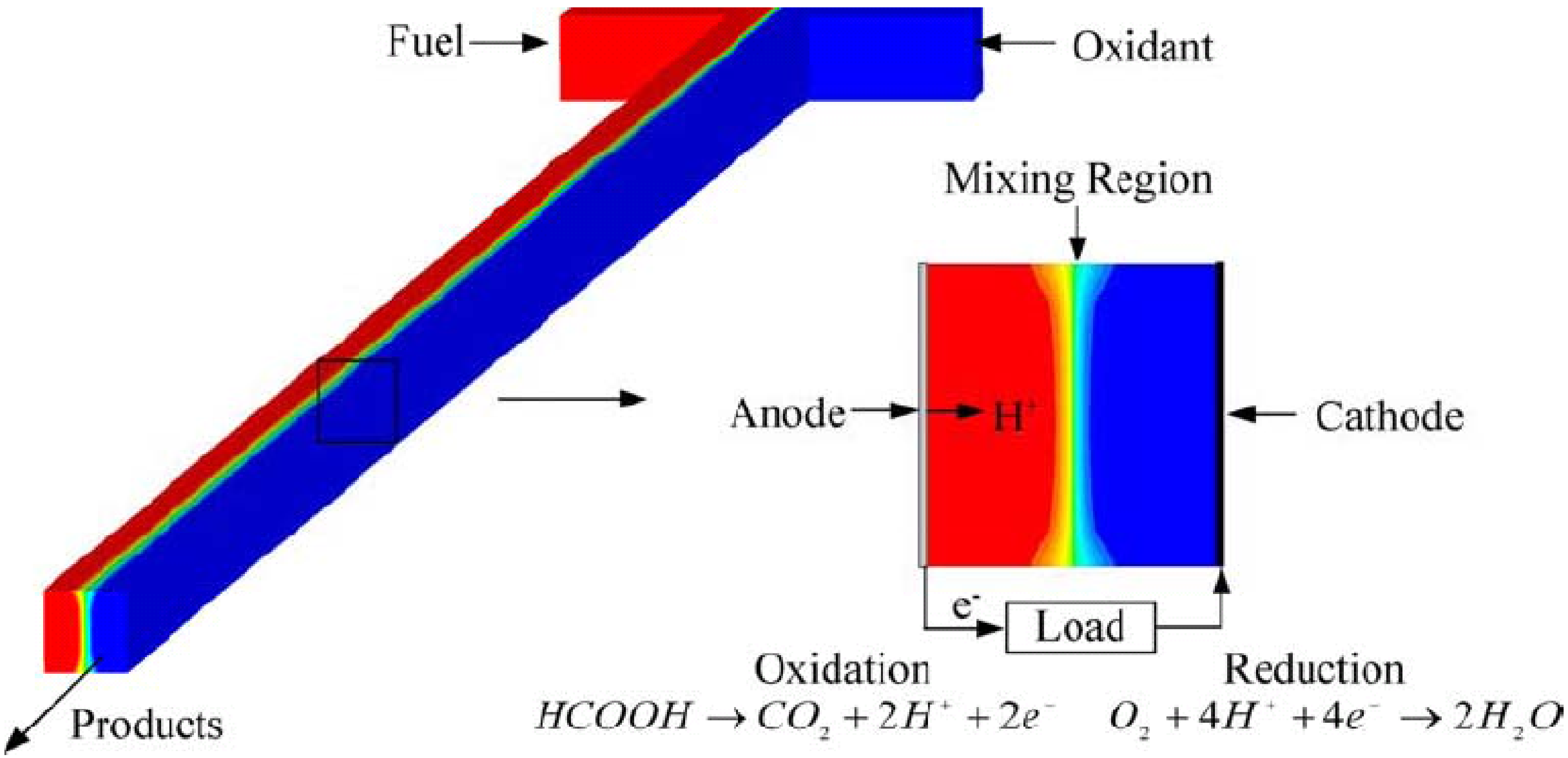
Cathode (positive electrode):

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

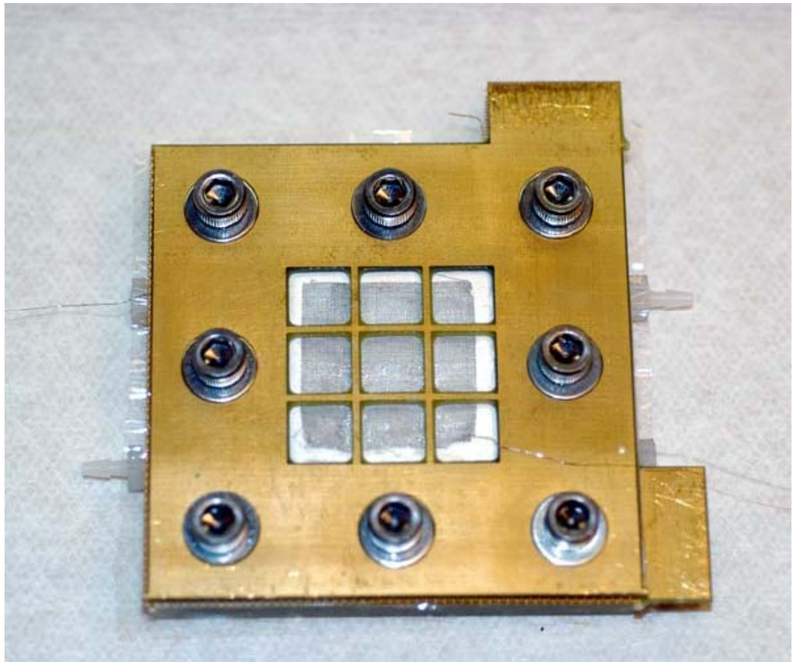
Overall:

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

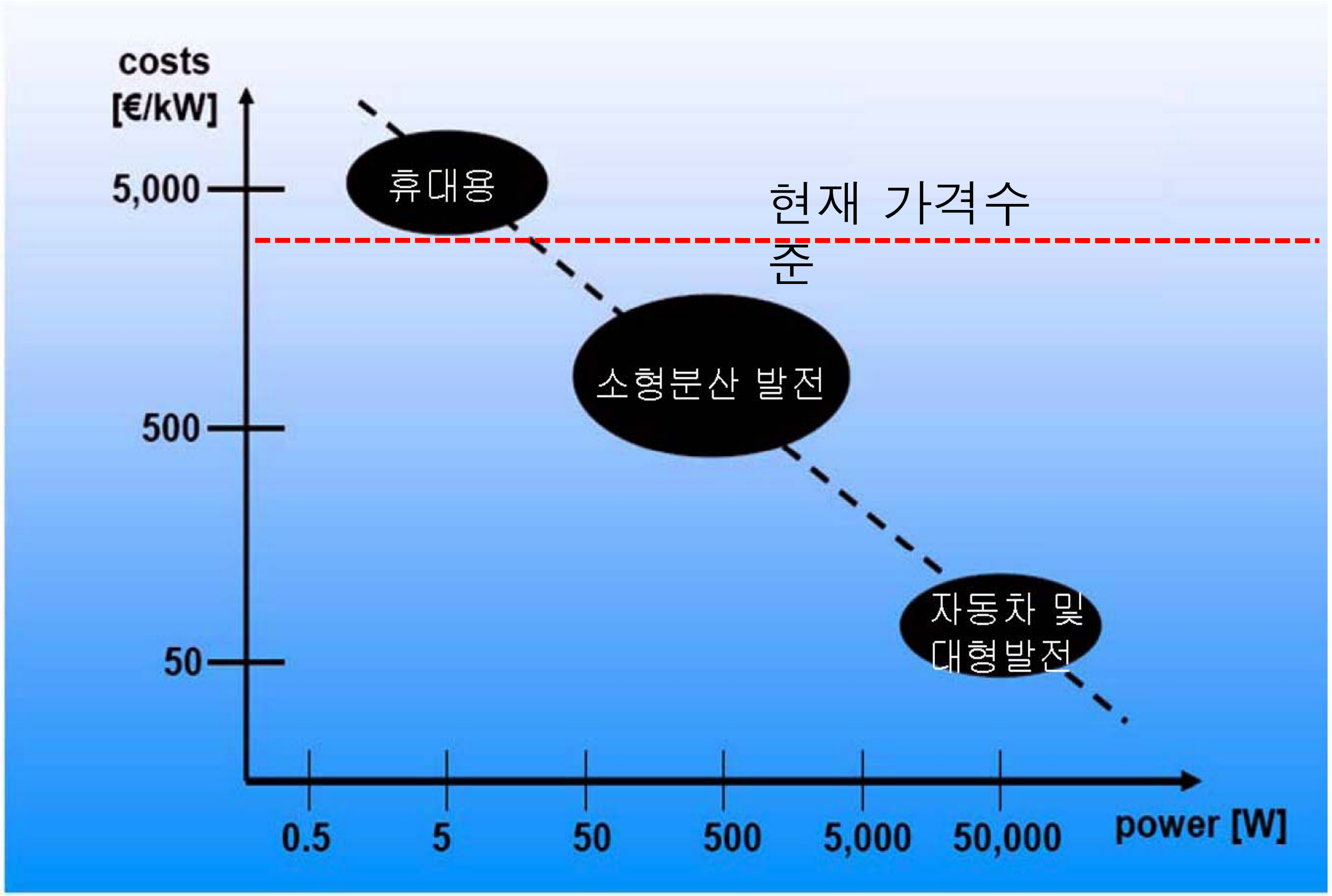
Membraneless Fuel Cells



Air Breathing Fuel Cells



Air-breathing passive fuel cell stack



상용화 분야에 따라 1/10~1/100의 가격 인하 필요