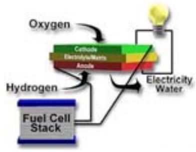
Fuel Cell Technologies and Applications



S.A. Klein
Solar Energy Laboratory
University of Wisconsin - Madison

Headlines

Europe Pushes for Alternatives to Fossil Fuel (NY Times)

"Fuel Cells Turn the Corner"….*Power*

"Step on the hydrogen" … *Wisc. Journal*

"Taking on the Energizer Bunny"…*Sci. Am.*

"The Coming of Age of Fuel Cells"….*Mech. Eng.*

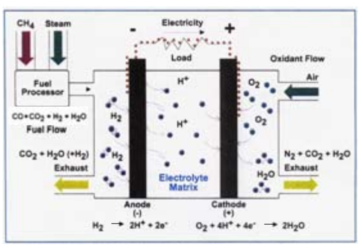
"The Automaker's Big-Time Bet on Fuel Cells"…*Fortune*
($750 million investments by Ford & Daimler-Benz)
"GM's Billion Dollar Bet"

"…Company Uses Fuel Cell to Get Energy From Gasoline"…*NY Times*

Application Scales

Battery Sized →	Residential →	Transportation →	Comm./Industrial →	Utility
(mW - W)	(1-10 kW)	(25 - 250 kW)	(25 kW - 10 MW)	(100+ MW)

What is a Fuel Cell?



Converts chemical energy to electrical power - like a battery
Electrochemical process - Avoids Carnot limitations
Fuel is continuously supplied to electrodes
Charge carriers: H^+, CO_3^{-2}, or O^{-2}

Thermodynamics

Energy balance: (steady state)
$$\sum_i^R \dot{n}_i h_i - \sum_j^P \dot{n}_j h_j + \dot{Q} - \dot{W}_{elec} = 0$$

Entropy balance:
$$\sum_i^R \dot{n}_i s_i - \sum_j^P \dot{n}_j s_j + \dot{Q}/T + \not{\sigma} = 0$$

$$\dot{W}_{elec,ideal} = \left(\sum_i^R \dot{n}_i h_i - \sum_j^P \dot{n}_j h_j\right) - T\left(\sum_i^R \dot{n}_i s_i - \sum_j^P \dot{n}_j s_j\right)$$

$$\dot{W}_{elec,ideal} = -\dot{n}_{fuel} \Delta g_R$$

Gibb's energy difference between products and reactants per mole of fuel

Electrical

$$\dot{W}_{elec} = iV \qquad \dot{W}_{elec,ideal} = iV_{ideal}$$

For 1 mole of fuel: $W_{elec,ideal} = Q_c V_{ideal}$

Q_c = #coulombs / mole of fuel
= # of electrons * electron charge / mole of fuel
= N_c * 6.023E23 electrons/mole electrons * 1.602E-19 coulomb/electron
= N_c * F

where
N_c = moles of electrons per mole of fuel consumed
F = Faraday's constant = 96,487 kJ/V-kmole

$$V_{ideal} = -\frac{\Delta g_R}{N_c F}$$

Half-Reactions Determine N_c

Example: $H_2 + 1/2\ O_2 = H_2O$
Anode: $H_2 = 2\ e^- + 2\ H^+$
Cathode: $2\ H^+ + 2\ e^- + 1/2\ O_2 = H_2O$
N_c=2

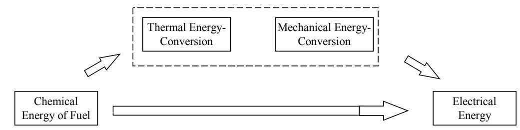
Example: $CH_4 + 2\ O_2 = CO_2 + 2\ H_2O$
Anode: $CH_4 + 2\ H_2O = CO_2 + 8\ e^- + 8\ H^+$
Cathode: $8\ H^+ + 8\ e^- + 2\ O_2 = 4\ H_2O$
N_c=8

The electrolyte transports the ions. Acidic electrolyte transports H^+.
Basic electrolyte transports OH^- or CO_3^{-2} (carbonate ion)
Electrolyte may be non-aqueous, as the proton exchange membrane

Why All The Interest?

- Becoming Technically Viable
- Highest Efficiency of Any Prime Mover (35-60+%)
- Emissions (Unparalleled)
- Part-Load Performance
- Modular Nature (independ. of size)
- Low Maintenance (no moving parts)
- Fuel Diversity (for some types)
- Cogeneration Potential (for some types)

Direct vs Thermal Energy Conversion Processes



Combustion

- Highly irreversible --> *(explosive, uncontrolled oxidation)*
- Large Temperature Gradients
- Result is Low Electric Efficiency

Oxidation in a Fuel Cell

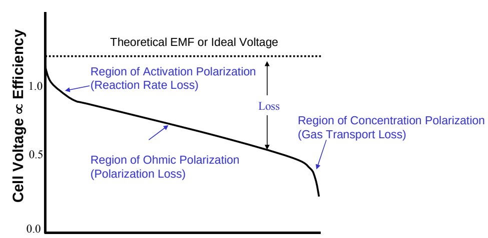
- Reactant ions are first passed thru electrolyte reducing the chemical driving force (i.e., "controlled" oxidation process)
- Oxidation of fuel occurs at higher temperatures (for some fuel cells)
- Result is higher electric efficiencies, but at lower power densities

Major Types of Fuel Cells

	Proton Exchange Membrane (PEM)	Phosphoric Acid Fuel Cell (PAFC)	Molten Carbonate Fuel Cell (MCFC)	Solid Oxide Fuel Cell (SOFC)
Operating Temperature	80°C (200°F)	200°C (400°F)	650°C (1200°F)	600-1000°C (1100-1800°F)
Expected Early Market	Available	1992 Reintroduction (2007)	Pre-commercial	Available (small systems)
System Electric Efficiency Ranges (HHV)*	20-45%	35-40%	40-60%	30-70%
Size Range	0.1 – 250 kW	200-400 kW	250 kW – 3 MW	1 kW – 1 MW
Cost (est.) / Cost Target	$1,500 - 4,000/kW / $25-50/kW	$6,000/kW / $1,800/kW	? / $400/kW	? / $400-$800 /kW (2010)
Applications	Stationary Vehicles Portable	Stationary / Cogen	Stationary / Cogen Marine	Stationary / Cogen Portable

*System efficiency depends on fuel type, fuel processing method, and manufacturer's design

Ideal and Actual Fuel Cell Voltage/Current Characteristics

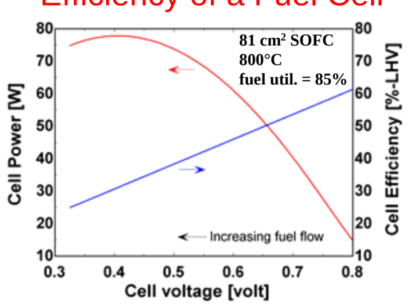


Nernst Voltage $E = E^\circ + \left(\frac{RT}{2F}\right)\ln\left(\frac{P_{H_2}P_{O_2}^{1/2}}{P_{H_2O}}\right)$

Gibbs of reaction

Correction for Fuel Composition

Efficiency of a Fuel Cell



- Higher power density: lower cell cost vs. cell cooling issues
- Lower power density: lower parasitics vs. larger stacks (higher costs)
- Cell efficiency is usually between 25%-60% (based on HHV)
- System efficiency vs. load affected by part-load efficiency of BOP

Disadvantages of Fuel Cells for Vehicles

- Hydrogen as Fuel
  - large tanks and limited distance on tank
  - new infrastructure required for refilling
- Liquid Fuels
  - requires reforming
  - CO must be eliminated
  - lower efficiency
  - poor time response
- Difficult Design Problem
  - size, shocks, temperature extremes, reliability...

Proton Exchange Membrane Fuel Cells (PEMFCs)

History

- Conceived in 1959, developed by GE for the Gemini Space Program
- Discarded in favor of the Alkaline cell in Apollo and Space Shuttle missions
- *low power density*, *membrane dehydration*, and *high platinum catalyst loading*.
- Major breakthrough in 1987 by Ballard Power Systems that quadrupled the power density of the cell to roughly 2 kW/ft² of cell.

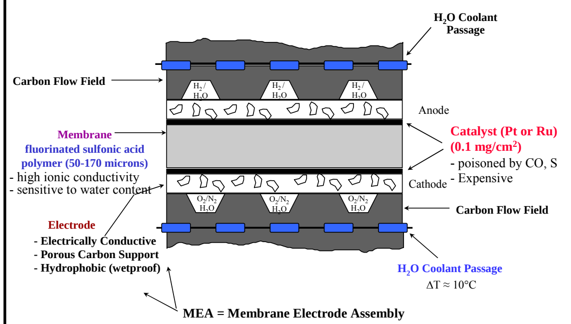
Presently

- Fast startup and excellent load following characteristics => Transportation appls.
- Ballard Power is the technology leader. Several automobile (NECAR and NEBUS), and stationary demonstrations (10, 30, and 250 kW) have taken place.
- Development is proceeding quickly and vehicular target dates are about 2004.

Characteristics

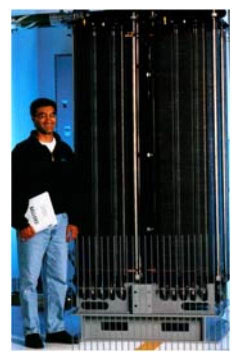
- High power density, low weight, and low-temperature operation.
- Requires hydrogen as a fuel (can be reformed from natural gas)
- CO intolerant and low-temp operation makes system integration difficult.

PEM Stack Cross-Section



Plug Power Residential (7 kW)

Ballard 250 kWe Stack



PEM Characteristics & Focus of R&D Efforts

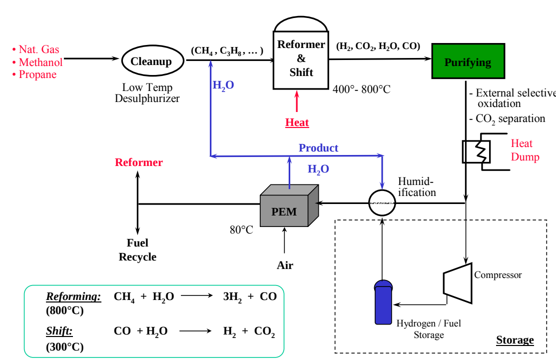
Characteristics:

Solid Polymer Electrolyte	0.2 mm thick	Simplest in conception
High Power Density	~ 1 kW/kg	Compact / light
Low Temperature	~ 80°C	Rapid transients / poor cogen
Performance is very sensitive to CO	≤ 10 ppm	Extensive fuel processing req'd

R&D Efforts

1) Electrocatalyst tolerance to low-level CO concentrations in the fuel feed gas
2) Water management and membrane operating temperature limits
3) Systems integration
   – Thermal integration of system (esp. high temperature fuel reformer)
   – Dynamic (transient) performance of system, particularly fuel reformer
   – Thermal management of cell stacks
4) Membrane and balance-of-plant (BOP) costs
5) Manufacturing costs (stack and cell components)

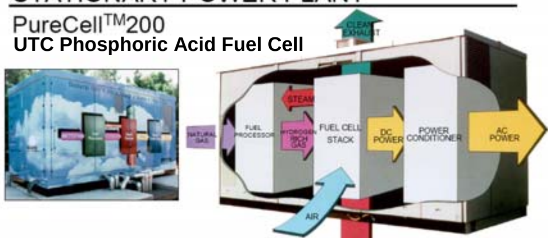
Fuel Processing System for PEMs



STATIONARY POWER PLANT Phosphoric Acid System

PureCell™200

UTC Phosphoric Acid Fuel Cell



- Indoor/outdoor installation
- Grid connect/grid independent
- Automatic, unattended operation
- Remote monitoring, control and diagnostics
- Wide range of operating temperatures (-40°F to 120°F)
- Negligible air emissions
- Quiet operation
- 38% avg. electric efficiency
- 85% total efficiency

Solid Oxide Fuel Cells (SOFCs)

History

- In development since the late 1950s (longest of all types)
- Has roots in: (1) oxygen sensor (measures O_2 partial pressure via voltage)
  (2) steam electrolysis for hydrogen production
- Exotic materials (Yttria, zirconium, lanthanum, maganite, cobalt chromite, etc.)

Present

- Much activity by numerous developers (Westinghouse's Tubular design)
- Solid electrolyte; many different cell designs
- High (1000°C) and Intermediate (700 - 800°C) temperature designs
- Several pilot plants have been started recently (25 - 100 kWe).

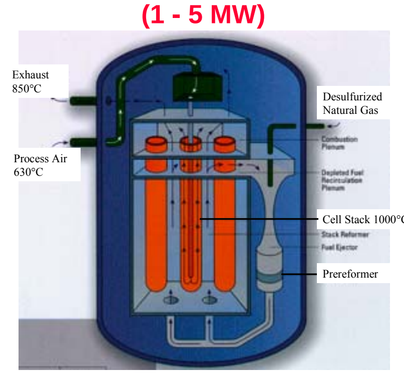
Some Advantages *(of high temperature operation)*

- Fast electrode kinetics = no expensive electrocatalysts required.
- Internal Reforming of fuel → better heat management and system efficiency
- High grade heat available for cogeneration.

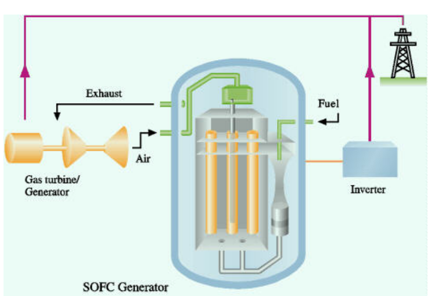
SOFC Technology and Research Issues

- Lower operating temperature (allows less expensive materials; (1,000°C ⇒700°C)
- Match CTE of materials to reduce degradation during transient operation and improved sealing techniques
- Improved reliability (sintering, catalyst degradation, shorts, etc.)
- Thermal Management (heat rejection)
- Systems Integration
  - cogeneration
  - gas turbines
  - reduce parasitic blower power consumption

Westinghouse/Siemens Tubular Design (1 - 5 MW)



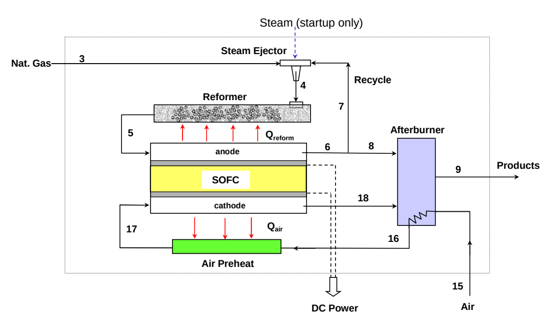
Combined Gas Turbine / Fuel Cell System



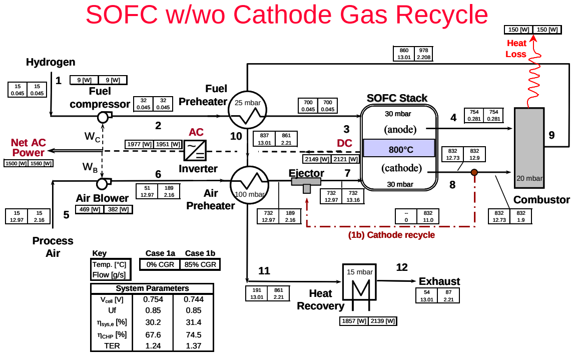
Demonstrated electrical efficiency is 60% at 220 kW

Planar Stack Process Design Concept

SOFC with Indirect Internal Reforming and Anode Gas Recirculation

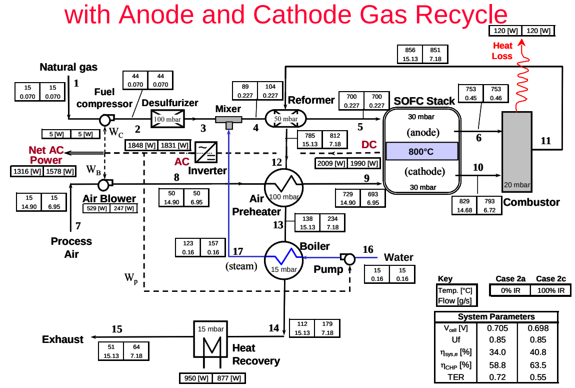


Process Flowsheet for Hydrogen-fueled SOFC w/wo Cathode Gas Recycle



from R.J. Braun et al., J. Power Sources, 2005 in press

Process Flowsheet for CH_4-fueled SOFC with Anode and Cathode Gas Recycle



from R.J. Braun et al., J. Power Sources, 2005 in press

Results from the Simulation Study

- Higher electrical efficiency is possible with natural gas vs hydrogen
- Largest irreversibilities occur in air preheater and combuster
- Internal reforming reduces air flow and thus blower power but lowers CHP efficiency
- Cathode gas recycle improves system efficiency by reducing blower power and size of air preheater
- Best performance occurs with natural gas using combined internal reforming and anode gas recycle

What are the Driving Forces For Fuel Cell Development?

- Efficiency
- Emissions
- Others?

Conclusions

- Fuel cell technology is improving rapidly
- Stationary applications provide easier integration
- Fuel cell systems will not be producing utility scale power for years
- There are economic advantages to central power
- Distributed power offers cogeneration possibilities
- Fuels are needed by all energy conversion systems (including fuel cell systems)