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Introduction to Alternative and Renewable Energy

EST1830

FESC Florida Energy Systems Consortium

FLATE
FLORIDA ADVANCED TECHNOLOGICAL EDUCATION CENTER
A National Science Foundation Regional Center For Advanced Technological Education

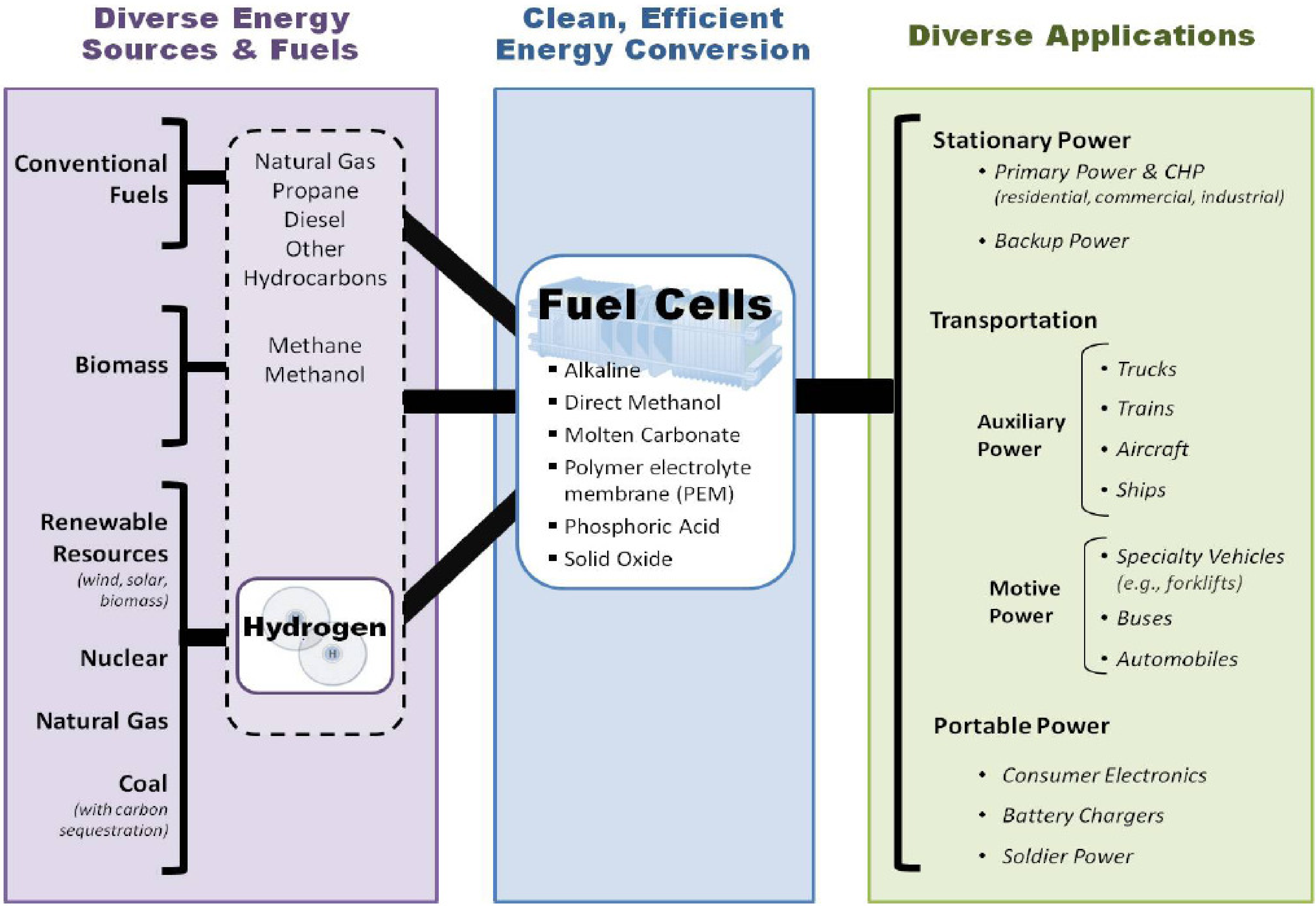
3. Energy Production

3.1 Renewable Energy Technologies
3.1.5 Fuel Cells
3.1.5.1 PEM
3.1.5.2 SOFC
3.1.5.3 Other Fuel Cells

Fuel Cell Types

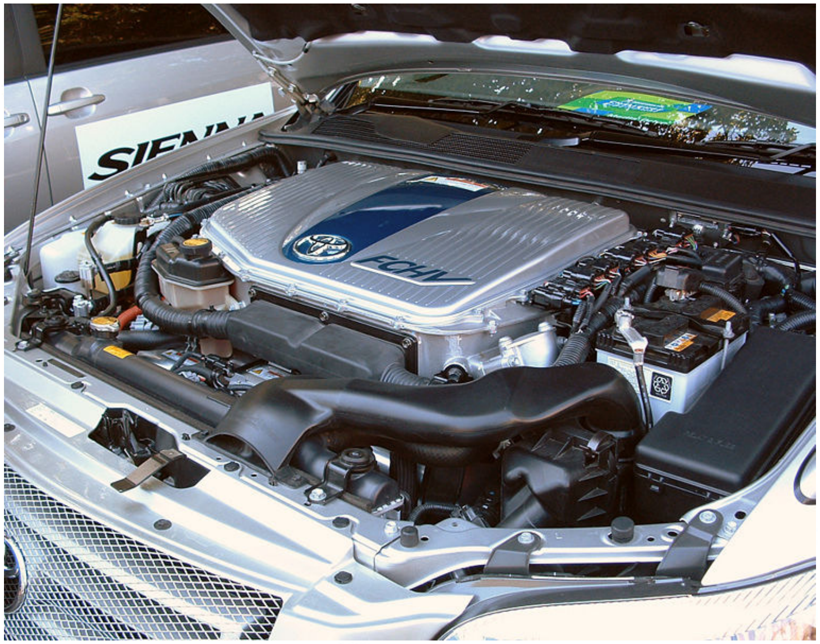
- Proton exchange membrane (PEM) fuel cells, 80°C
  - Automotive applications (50kW)
- Direct methanol fuel cells (<100°C)
- Alkaline fuel cells, 50 - 200°C
  - Space applications (1kW+)
- Phosphoric acid fuel cells, ~220°C
  - Commercially available for premium power applications (50kW+)
- Molten carbonate fuel cells, ~650°C
  - Industrial and commercial cogeneration systems (100kW+)
- Solid oxide fuel cells (SOFCs), 600 - 1000°C
  - Auxiliary power units (25kW) and stationary power applications (100kW+)

Science and Technology of Fuel Cells, Yang Shao-Horn, Energy Faculty Workshop, MIT, 6/2006



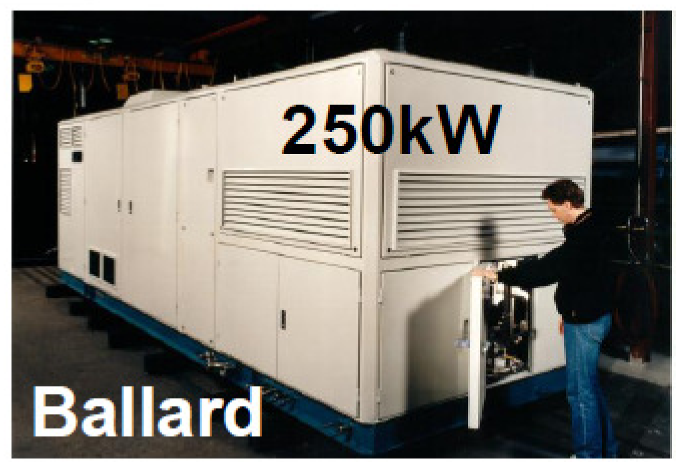
Hydrogen and Fuel Cell Technologies Update, *Dr. Sunita Satyapal, DOE, Fuel Cell Seminar & Exposition, San Antonio, TX, October 19, 2010*

Current Applications of Fuel Cells



Ballard Buses in Chicago

Stationary Power Units

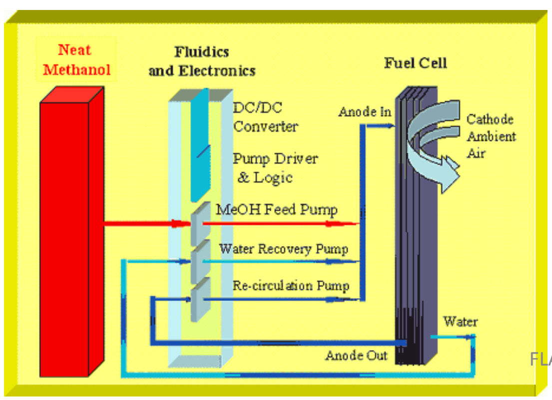


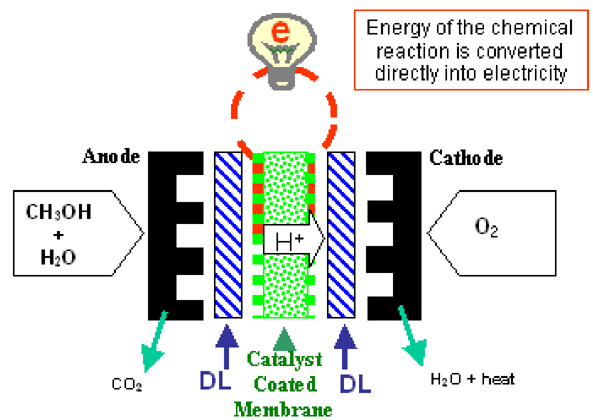
Science and Technology of Fuel Cells, Yang Shao-Horn, Energy Faculty Workshop, MIT, 6/2006

Direct Methanol FC

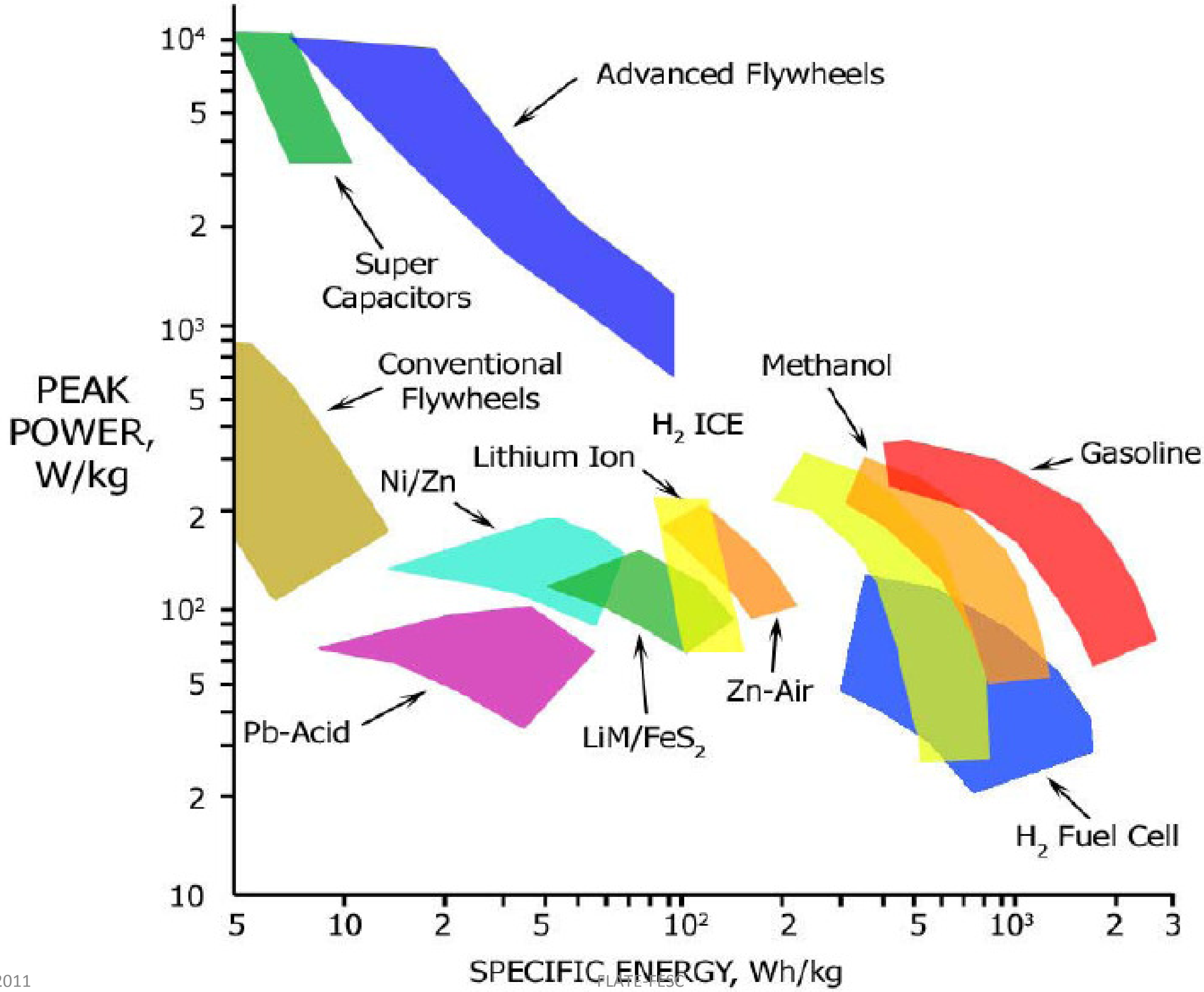
http://www.mtimicrofuelcells.com/news/img/mobionrf.jpg

External power-pack prototype capable of providing up to 25 hours of on-the-go power with each cartridge.





Ragone plot of Energy Storage



http://ocw.mit.edu/courses/chemical-engineering/10-391j-sustainable-energy-spring-2005/lecture-notes/0412se05ghoniem1.pdf

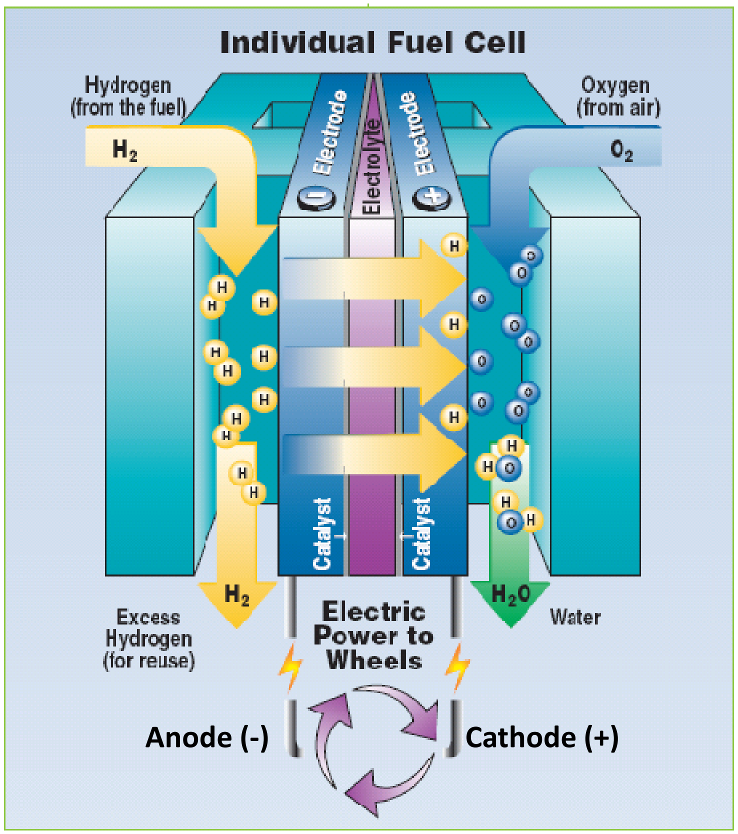
3.1.5.1 PEM Fuel Cells

Proton Exchange Membrane Fuel Cells

Proton Exchange Membrane FC

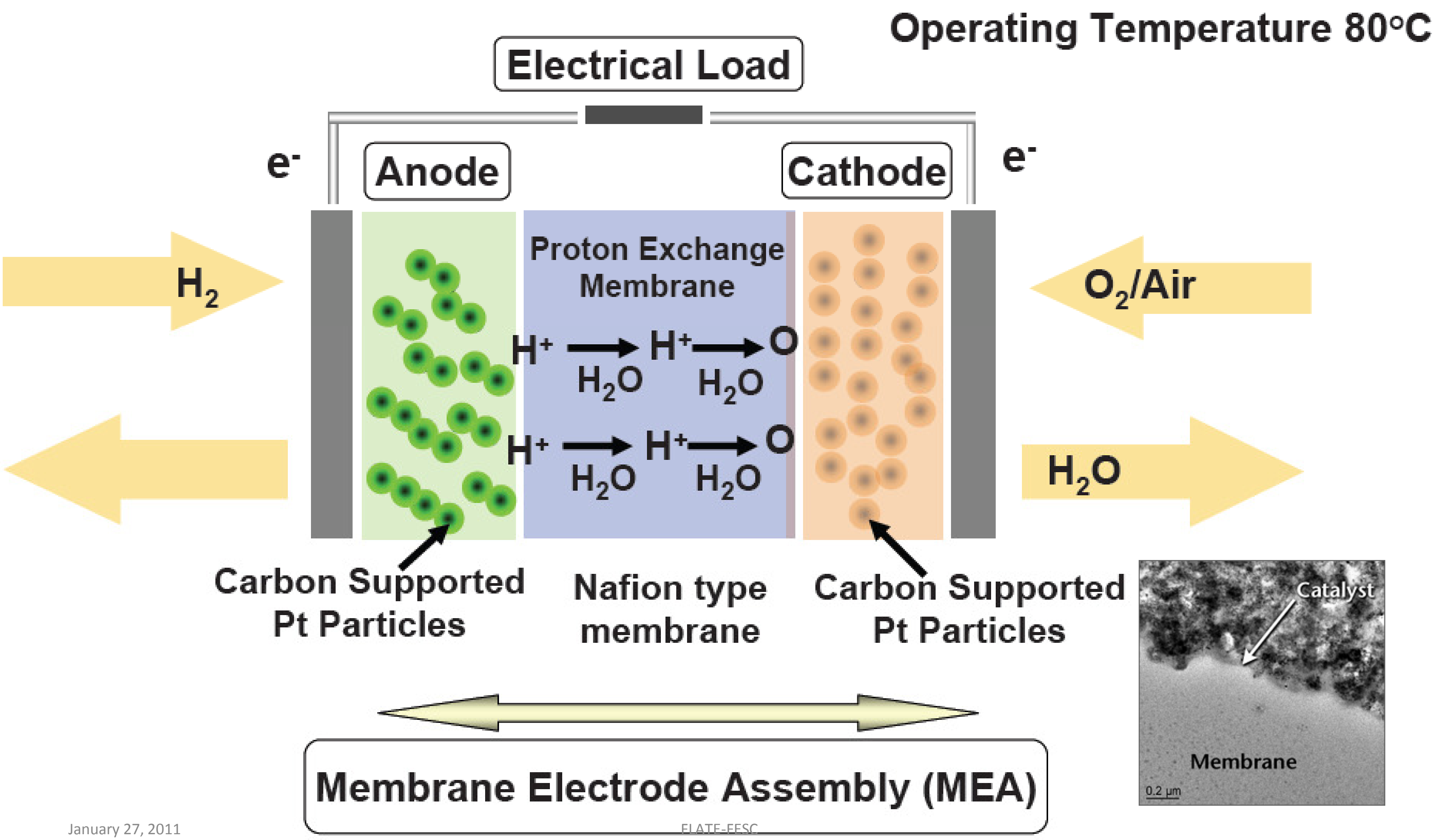
- Proton Exchange Membrane fuel cells (PEM)—also called Polymer Electrolyte Membrane—deliver high-power density and offer the advantages of low weight and volume, compared with other fuel cells.
- PEM fuel cells use a solid polymer as an electrolyte and porous carbon electrodes containing an expensive platinum catalyst.
- They need only hydrogen, oxygen from the air, and water to operate.
  - Do not require corrosive fluids like other fuel cells.
  - Hydrogen is typically supplied from storage tanks or on-board reformers.

PEM Fuel Cell Function



The platinum catalyst is extremely sensitive to CO poisoning because CO binds to the platinum catalyst at the anode, decreasing the fuel cell's efficiency. This makes it necessary to employ an additional reactor to reduce CO in the fuel gas if the hydrogen is derived from an alcohol or hydrocarbon fuel.

Proton Exchange Membrane Fuel Cells



Science and Technology of Fuel Cells, Yang Shao-Horn, Energy Faculty Workshop, MIT, 6/2006

Transportation: PEM FC

RECENT PROGRESS

Vehicles & Infrastructure

- 152 fuel cell vehicles and 24 hydrogen fueling stations
- Over 2.8 million miles traveled
- Over 114 thousand total vehicle hours driven
- 2,500 hours (nearly 75K miles) durability
- Fuel cell efficiency 53-59%
- Vehicle Range: ~196 – 254 miles

Buses

- DOE is evaluating real-world bus fleet data (DOT collaboration)
  - H_2 fuel cell buses have a 39% to 141% better fuel economy when compared to diesel & CNG buses

Forklifts

- Forklifts at Defense Logistics Agency site have completed more than 18,000 refuelings

Recovery Act

- DOE (NREL) is collecting operating data from deployments for an industry-wide report

Source: US DOE 09/2010

Hydrogen and Fuel Cell Technologies Update, *Dr. Sunita Satyapal, DOE, Fuel Cell Seminar & Exposition, San Antonio, TX, October 19, 2010*

PEM FC Challenges

Technology Barriers*

Fuel Cell Cost & Durability

Targets*:

- ***Stationary Systems:*** **$750 per kW, 40,000-hr durability**
- ***Vehicles:*** **$30 per kW, 5,000-hr durability**

Hydrogen Cost

Target: $2 – 4 /gge, delivered

Hydrogen Storage Capacity

Target: > 300-mile range for vehicles—without compromising interior space or performance

Technology Validation:

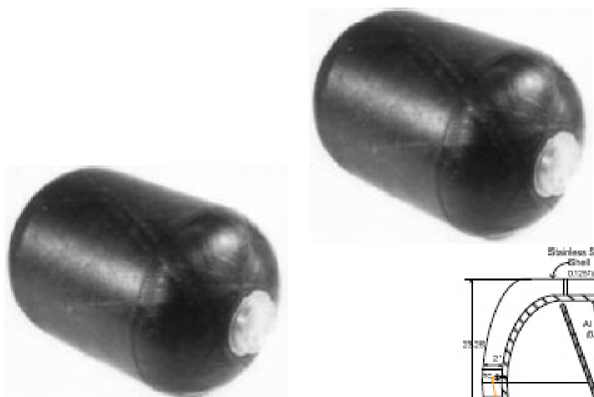
Technologies must be demonstrated under real-world conditions.

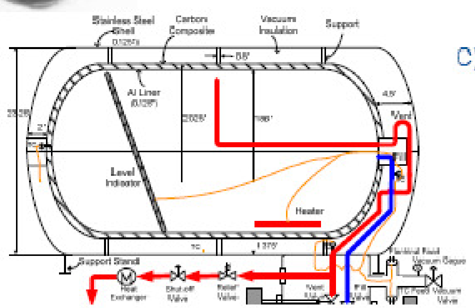
Hydrogen and Fuel Cell Technologies Update, *Dr. Sunita Satyapal, DOE, Fuel Cell Seminar & Exposition, San Antonio, TX, October 19, 2010*

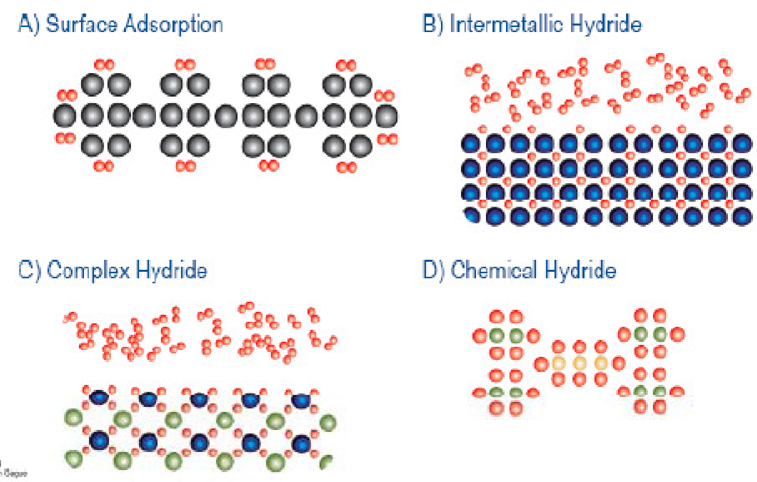
Vehicle H_2 Storage Challenge

Challenge: Providing a 300 mile driving range without sacrificing passenger and cargo space

Compressed 350 bar	Compressed 700 bar and Cryo-compressed	Low-pressure, Materials-based: Adsorbents; Metal Hydrides; Chemical Hydrides







Hydrogen and Fuel Cell Technologies Update, *Dr. Sunita Satyapal, DOE, Fuel Cell Seminar & Exposition, San Antonio, TX, October 19, 2010*

Near-term | Mid-term | Long-term

Modes of Use

PRODUCTS		FCvelocity™–9SSL	FCvelocity™–HD6	FCgen™–1020ACS	FCgen™–1300[1]	FCgen™–1030
						
COMMERCIAL INFORMATION	Market	Material Handling	Bus and Heavy Duty	Backup Power	Backup Power	CHP (Combined Heat & Power)
	Application	Forklift trucks – classes I, II and III	Transit buses	Emergency telecom network outages	Supplemental power for telecom networks	Residential Cogeneration
						
	Durability/ Lifetime Target	Up to 10,000 hrs	Up to 6,000 hrs	Up to 4,000 hrs	Up to 8,000 hrs	Up to 40,000 hrs
PHYSICAL CHARACTERISTICS	Length	107 – 313mm	1446mm	110 – 495mm	230 – 530mm[4]	347mm
	Width	760mm	871mm	103mm	490mm[4]	158mm
	Height	60mm	496mm	351mm	180mm[4]	259mm
	Weight (dry)	7.2 – 17 kg	250 – 355 kg	4 – 15kg	~6 – 29 kg	12 kg
	Number Cells (min/max)	25 – 110	Not applicable	10 – 80	25 – 125	46
PERFORMANCE	Rated Gross Power (beginning of life)	4.4 – 19.3 kW	75 and 150 kW	0.3 – 3.4 kW	2.3 – 11.3 kW[2]	1.2 kW
	Rated Current	300 Amps	240 Amps	65 Amps	135 Amps	40 Amps
	DC Voltage	15 – 64 Volts	313 – 626 Volts	6.4 – 51 Volts	17 – 84 Volts	31 Volts
	Cell Efficiency (reference to LHV)[3]	47 – 71%	62 – 71%	51 – 67%	54 – 64%	54 – 63%
	Fuel Composition[5]	Hydrogen	Hydrogen	Hydrogen	Hydrogen or reformate	Hydrogen or reformate (>72% H2, <10ppm CO typical)
	Oxidant Composition	Air	Air	Air	Air	Air

http://www.ballard.com/

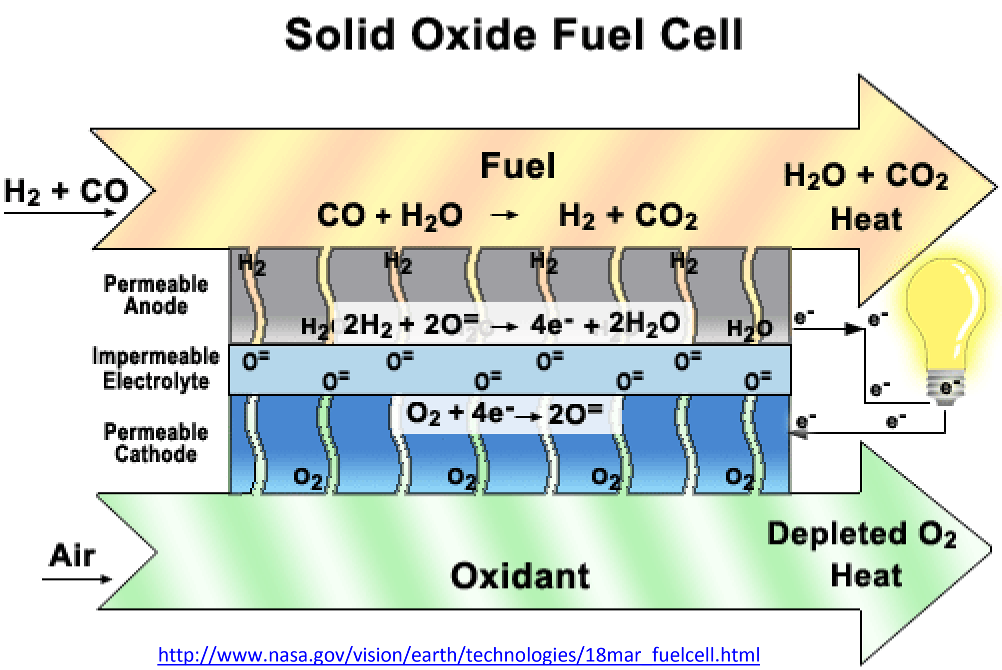
3.1.5.2 SOFC

Solid Oxide Fuel Cells

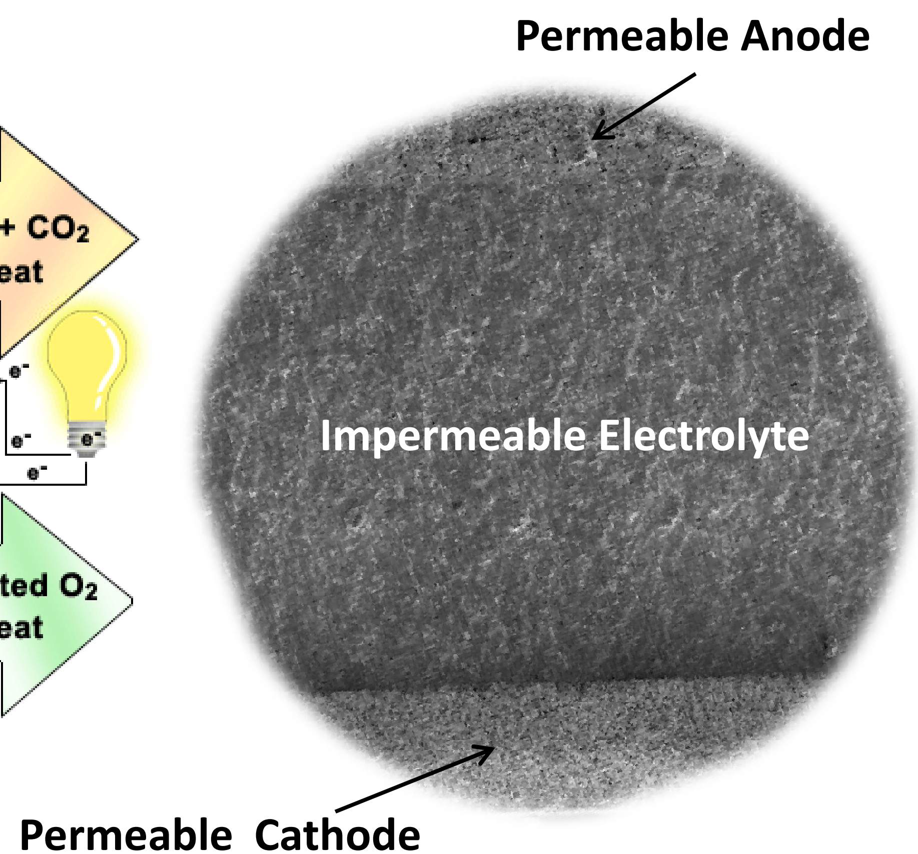
Solid Oxide Fuel Cell

- A **solid oxide fuel cell** (**SOFC**) is an electrochemical conversion device that produces electricity directly from oxidizing a fuel.
  - The SOFC has a solid oxide or ceramic, electrolyte.
  - Fuels: Biogas, Natural Gas, Methane, LP Gas, gasoline, diesel, jet fuels, biofuels.
- Advantages of this class of fuel cells include high efficiency, long-term stability, fuel flexibility, low emissions, and relatively low cost.
- The largest disadvantage is the high operating temperature which results in longer start-up times and mechanical and chemical compatibility issues.

SOFC Schematic



http://www.nasa.gov/vision/earth/technologies/18mar_fuelcell.html



http://en.wikipedia.org/wiki/Solid_oxide_fuel_cell

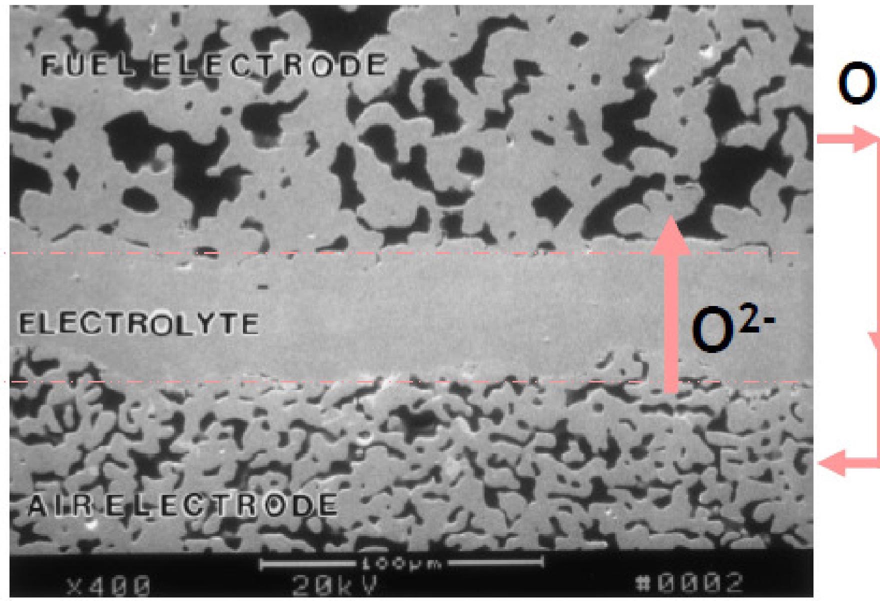
Solid Oxide Fuel Cells

- All-ceramic fuel cells with high operating temperatures (600-1000°C)

Anode (Ni/YSZ)

Electrolyte (YSZ)

Cathode (LSM)



$O^{2-} + H_2 \rightarrow H_2O + 2e^-$

$2e^-$

$E^o = \sim 1.0V$ at 800°C

$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$

LSM = $La_{1-x}Sr_xMnO_{3-d}$ (x~0.2-0.4)

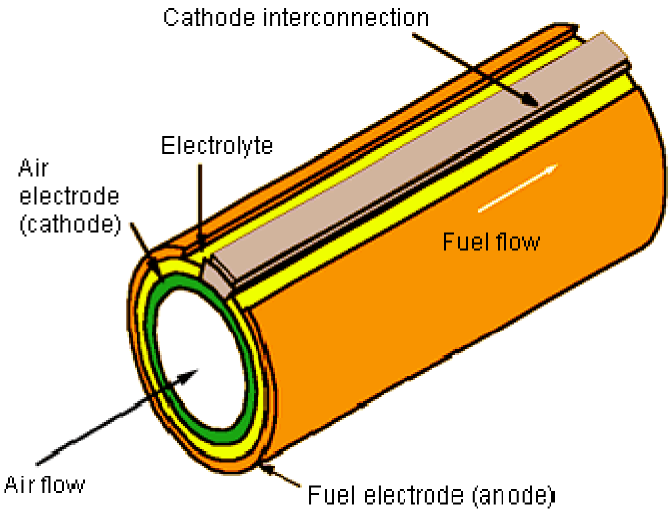
YSZ = $Y_{0.8}Zr_{0.92}O_{2-d}$

Singhal, S. C., Solid State Ionics 135(1-4): 305-313 (2000)

Science and Technology of Fuel Cells, Yang Shao-Horn, Energy Faculty Workshop, MIT, 6/2006

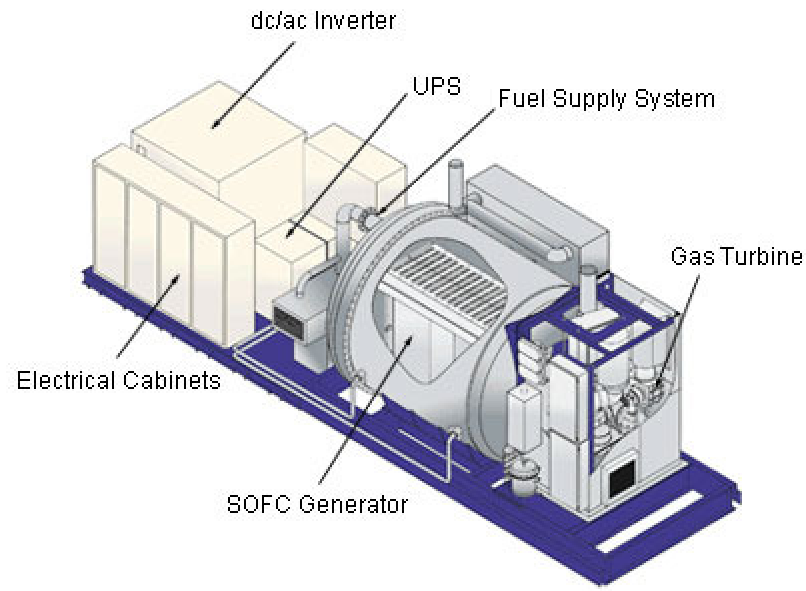
SOFC Designs

Siemens Energy Tubular SOFC Technology



In a tubular SOFC design, air flows through the interior of the cell, and fuel flows on the outside of the cell. At elevated temperatures, the oxygen in the air ionizes and the resulting ions flow through the electrolyte and combine with the fuel on the cell's exterior. This is an electrochemical reaction, so electrons are released. With proper connections, they can flow through an external circuit as electricity.

SOFC / Gas Turbine Hybrid



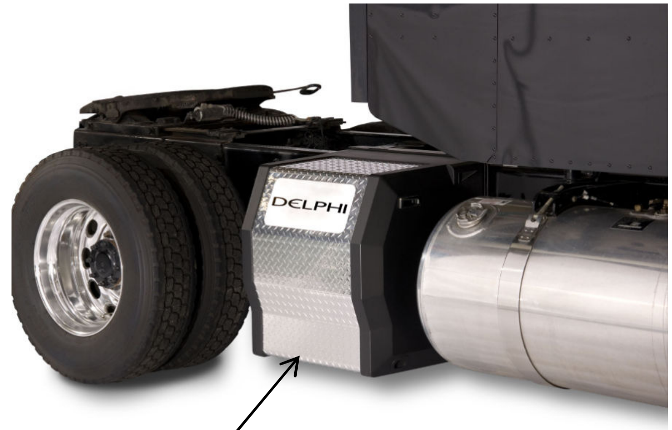
Since the SOFC stack operates at 1000°C it produces a high temperature exhaust gas. If operated at an elevated pressure, the exhaust becomes a hot pressurized gas flow that can be used to drive a turbine.

Analysis indicates that with such SOFC/GT hybrids an electrical efficiency of 55% can be achieved at power plant capacities as low as 250 kW, and ~60% as low as 1 MW using small gas turbines.

http://www.energy.siemens.com/hq/en/power-generation/fuel-cells/

Modes of Use

Stationary Power



Delphi offers its solid oxide fuel cell (SOFC) technology as an **auxiliary power unit (APU)** to provide up to 5 kW (6.7 hp) of electrical power for use on commercial vehicles during extended idling periods. http://www.sae.org/mags/sve/TOOLS/product/8402

Bloom Box

http://www.bloomenergy.com/

3.1.5.3 Other Fuel Cells

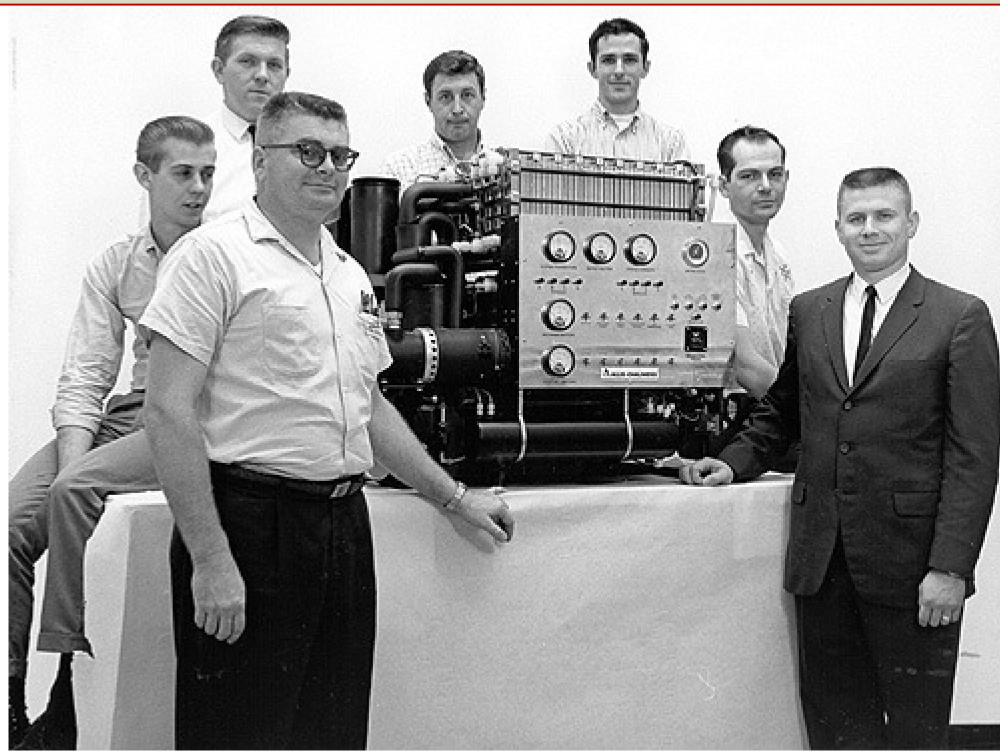
Phosphoric Acid

Molten Carbonate

Alkaline

Phosphoric Acid Fuel Cell

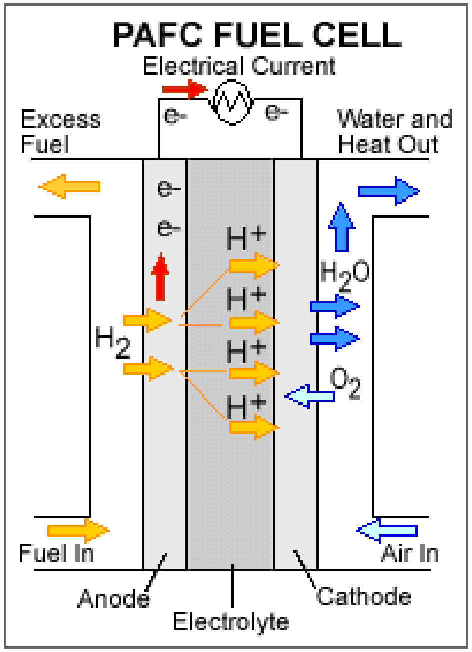
Phosphoric Acid Fuel Cells (PAFC) were the first fuel cells to be commercialized. Developed in the mid-1960s and field-tested since the 1970s, they have improved significantly in stability, performance, and cost.



Project team for 5kw phosphoric acid fuel cell system, Allis-Chalmers, 1965."

http://americanhistory.si.edu/fuelcells/phos/pho1.htm

Phosphoric Acid Fuel Cell



Phosphoric acid fuel cells use liquid phosphoric acid (H_3PO_4) as an electrolyte—the acid is contained in a Teflon-bonded silicon carbide matrix—and porous carbon electrodes containing a platinum catalyst.

A 250-kilowatt phosphoric acid fuel cell powers a police station and electric vehicle recharging station in New York's Central Park

http://www.fossil.energy.gov/programs/powersystems/fuelcells/fuelscells_phosacid.html

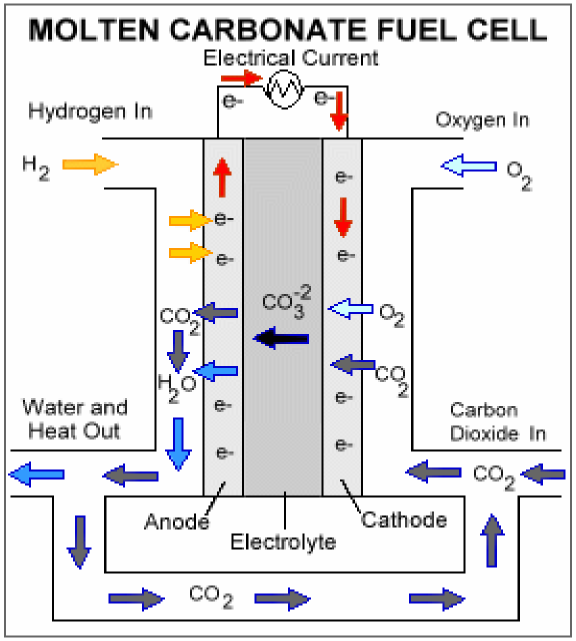
The ionic conductivity of phosphoric acid is low at low temperatures, so PAFCs are operated at the upper end of the range 150ºC–220ºC.

PAFCs are more tolerant of impurities in fossil fuels that have been reformed into hydrogen than PEM cells. They are 85% efficient when used for the co-generation of electricity and heat but less efficient at generating electricity alone (37%–42%).

PAFCs are also less powerful than other fuel cells, given the same weight and volume. So they are typically large and heavy. Plus also expensive. Like PEM fuel cells, PAFCs require an expensive platinum catalyst.

http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html

Molten Carbonate FC

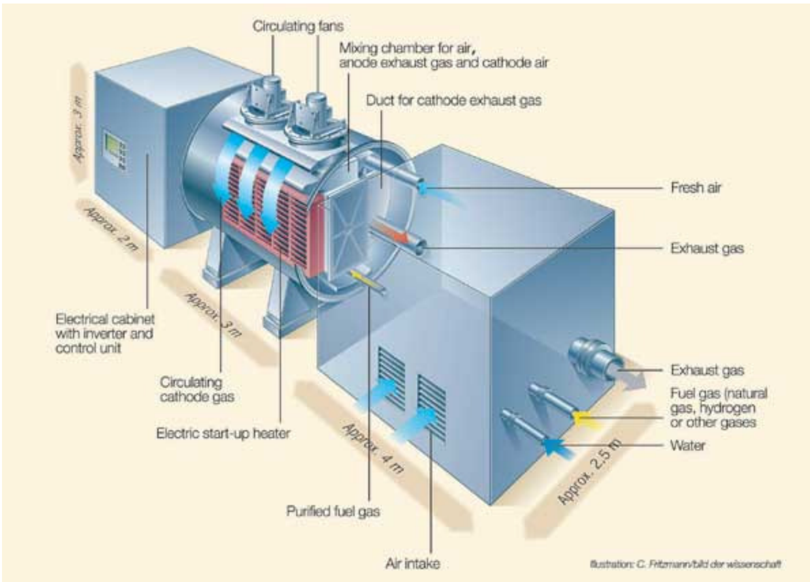


MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide ($LiAlO_2$) matrix. Because they operate at extremely high temperatures of 650°C (roughly 1,200°F) and above, non-precious metals can be used as catalysts at the anode and cathode, reducing costs.

Molten carbonate fuel cells can reach stand-alone efficiencies approaching 60%, considerably higher than the 37%–42% efficiencies of a phosphoric acid fuel cell plant. When the waste heat is captured and used, overall fuel efficiencies can be as high as 85%.

The primary disadvantage of current MCFC technology is durability. The high temperatures at which these cells operate and the corrosive electrolyte used accelerate component breakdown and corrosion, decreasing cell life.

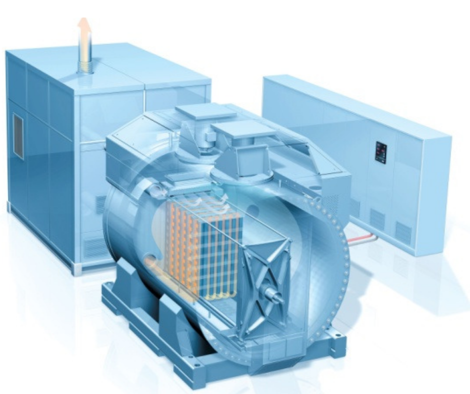
Molten Carbonate FC



MTU

http://www.fuelcelltoday.com/reference/image-bank/Schematics/MTU-HotModule-Schematic

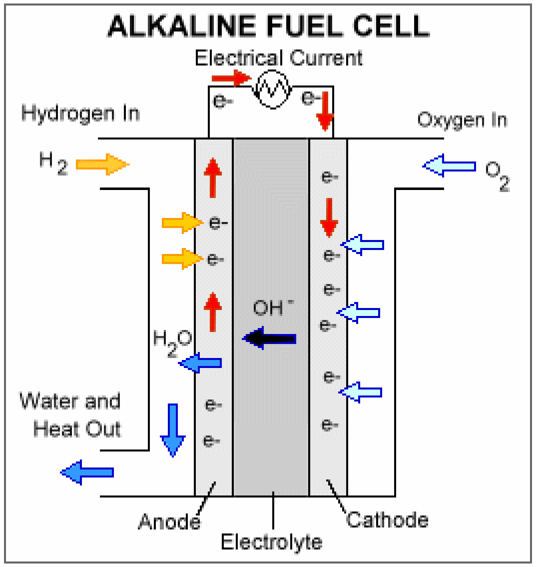
T-Systems is using this Molten Carbonate Fuel Cell to power part of its Munich data center with biomethane. The system generates 245 kilowatts of power.



http://www.t-systems.de/tsi/servlet/content/t-systems.de/en/228788

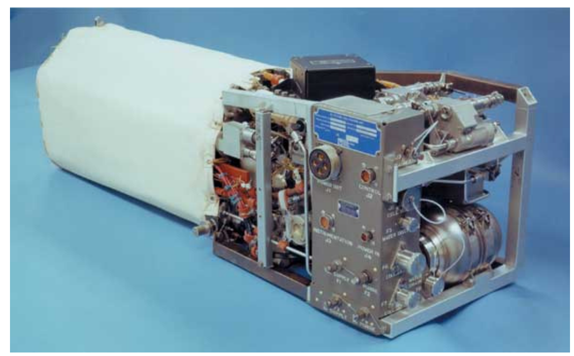
Alkaline FC

Alkaline fuel cells (AFCs) were one of the first fuel cell technologies developed, and they were the first type widely used in the U.S. space program to produce electrical energy and water on-board spacecrafts.



- These fuel cells use a solution of potassium hydroxide in water as the electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode.
- High-temperature AFCs operate at temperatures between 100°C and 250°C (212°F and 482°F).
- However, newer AFC designs operate at lower temperatures of roughly 23°C to 70°C (74°F to 158°F)

Space Shuttle Alkaline Fuel Cell Power Plant



Supplied to NASA by UTC Fuel Cells, three of these 12kW systems provide auxiliary power and drinking water in each spacecraft in the space shuttle fleet.

AFCs' high performance is due to the rate at which chemical reactions take place in the cell. They have also demonstrated efficiencies near 60% in space applications.

The disadvantage of this fuel cell type is that it is easily poisoned by carbon dioxide (CO_2). In fact, even the small amount of CO_2 in the air can affect this cell's operation, making it necessary to purify both the hydrogen and oxygen used in the cell.

http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html

Comparison of Fuel Cell Technologies

DOE Hydrogen Program

Fuel Cell Type	Common Electrolyte	Operating Temperature	System Output	Electrical Efficiency	Combined Heat and Power (CHP) Efficiency	Applications	Advantages
Polymer Electrolyte Membrane (PEM)*	Solid organic polymer poly-perfluorosulfonic acid	50 - 100°C 122 - 212°F	<1kW – 250kW	53-58% (transportation) 25-35% (stationary)	70-90% (low-grade waste heat)	▪ Backup power ▪ Portable power ▪ Small distributed generation ▪ Transportation ▪ Specialty vehicles	▪ Solid electrolyte reduces corrosion & electrolyte management problems ▪ Low temperature ▪ Quick start-up
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90 - 100°C 194 - 212°F	10kW – 100kW	60%	>80% (low-grade waste heat)	▪ Military ▪ Space	▪ Cathode reaction faster in alkaline electrolyte, leads to higher performance ▪ Can use a variety of catalysts
Phosphoric Acid (PAFC)	Liquid phosphoric acid soaked in a matrix	150 - 200°C 302 - 392°F	50kW – 1MW (250kW module typical)	>40%	>85%	▪ Distributed generation	▪ Higher overall efficiency with CHP ▪ Increased tolerance to impurities in hydrogen
Molten Carbonate (MCFC)	Liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600 - 700°C 1112 - 1292°F	<1kW – 1MW (250kW module typical)	45-47%	>80%	▪ Electric utility ▪ Large distributed generation	▪ High efficiency ▪ Fuel flexibility ▪ Can use a variety of catalysts ▪ Suitable for CHP
Solid Oxide (SOFC)	Yttria stabilized zirconia	600 - 1000°C 1202 - 1832°F	<1kW – 3MW	35-43%	<90%	▪ Auxiliary power ▪ Electric utility ▪ Large distributed generation	▪ High efficiency ▪ Fuel flexibility ▪ Can use a variety of catalysts ▪ Solid electrolyte reduces electrolyte management problems ▪ Suitable for CHP ▪ Hybrid/GT cycle

**Direct Methanol Fuel Cells (DMFC) are a subset of PEM typically used for small portable power applications with a size range of about a subwatt to 100W and operating at 60 - 90°C.*

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U.S. Department of Energy Hydrogen Program
www.hydrogen.energy.gov