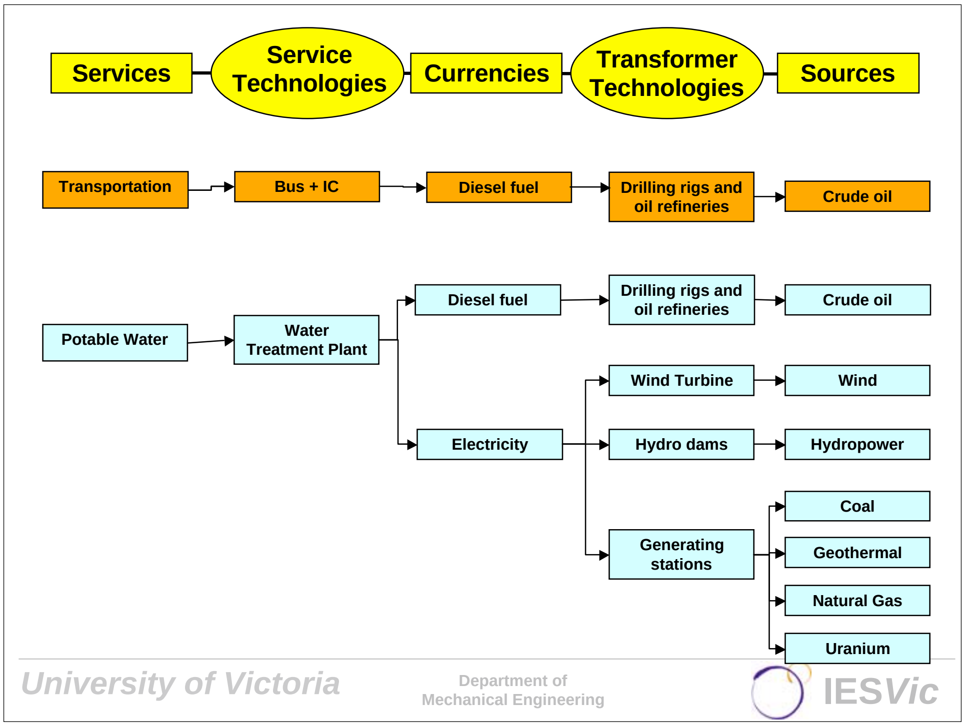
Mech 549
Fuel Cell Technology

Lecture 1

Today

- Energy, hydrogen and fuel cells: Introductory overview
- Course outline: topics, grading, etc.
- A brief history of fuel cell development
- Operating principles and classification
- Structure of a fuel cell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Currencies
Transformer Technologies
Sources
Transportation
Bus + IC
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Drilling rigs and oil refineries
Crude oil
Potable Water
Water Treatment Plant
Diesel fuel
Drilling rigs and oil refineries
Crude oil
Wind Turbine
Wind
Electricity
Hydro dams
Hydropower
Coal
Generating stations
Geothermal
Natural Gas
Uranium
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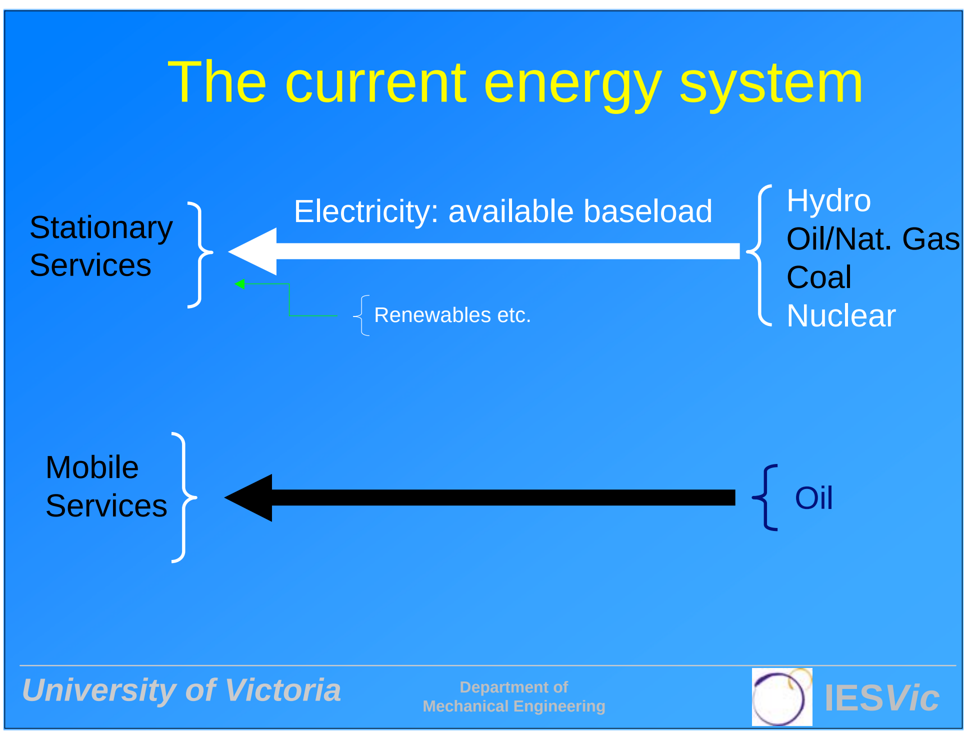
The current energy system
Stationary Services
Electricity: available baseload
Hydro
Oil/Nat. Gas
Coal
Nuclear
Renewables etc.
Mobile Services
Oil
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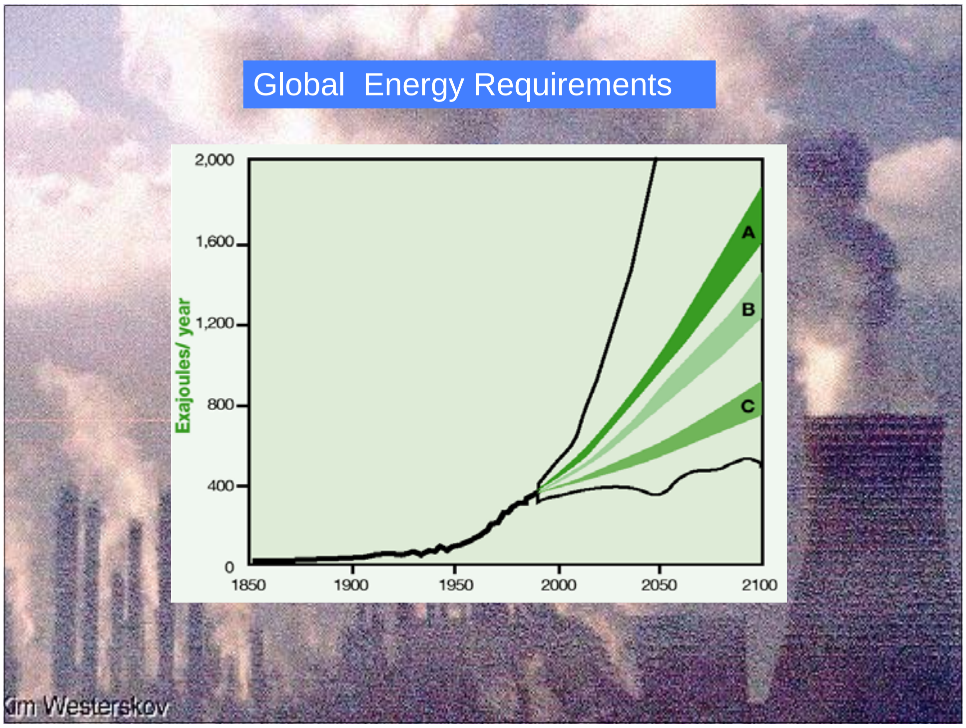
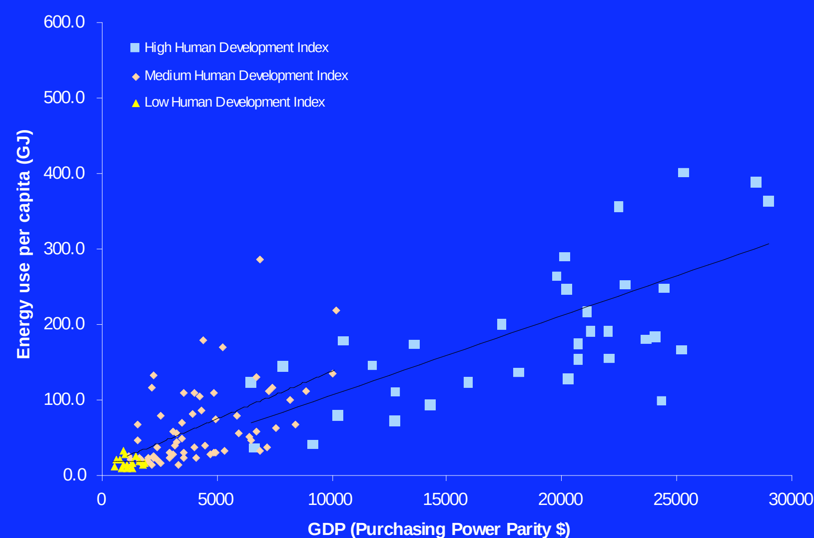


How much energy do we "need" ?



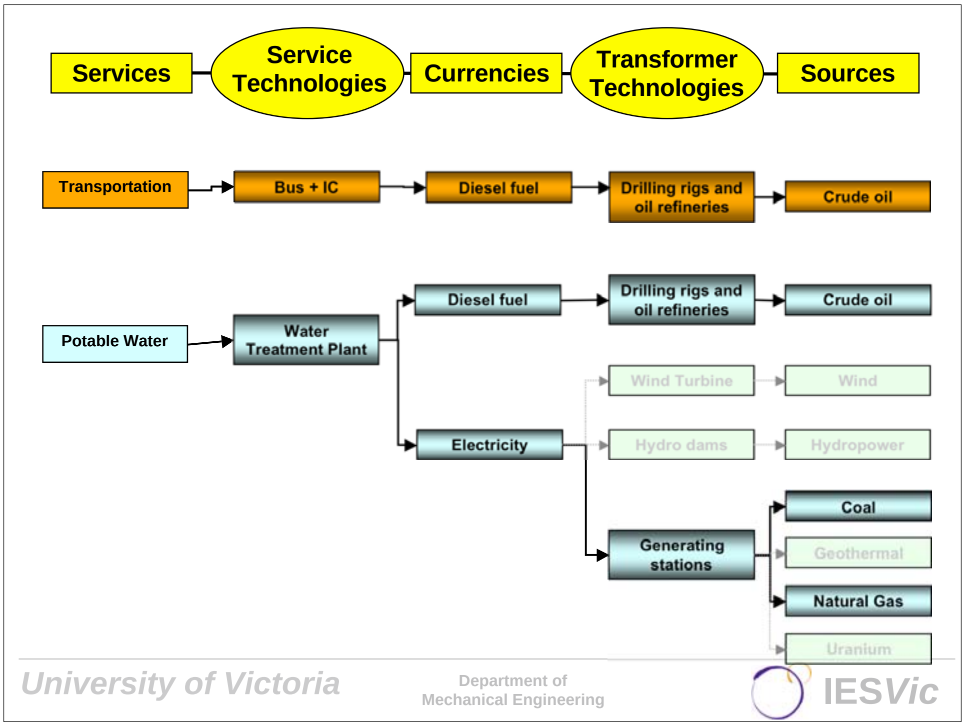
- “Standards of living” (economic prosperity; quality of life; social progress; infant mortality…) correlate very well with per capita energy consumption.

- Is increasing supply of energy per capita a prerequisite for continued progress?

“You cannot train China and India to conserve energy, because they want the same standard of living that we enjoy. And that is based on largely on energy consumption per capita.

… But to see energy conservation as a means or mechanism by which we solve our world’s problems is just putting your head in the sand”

Geoffrey Ballard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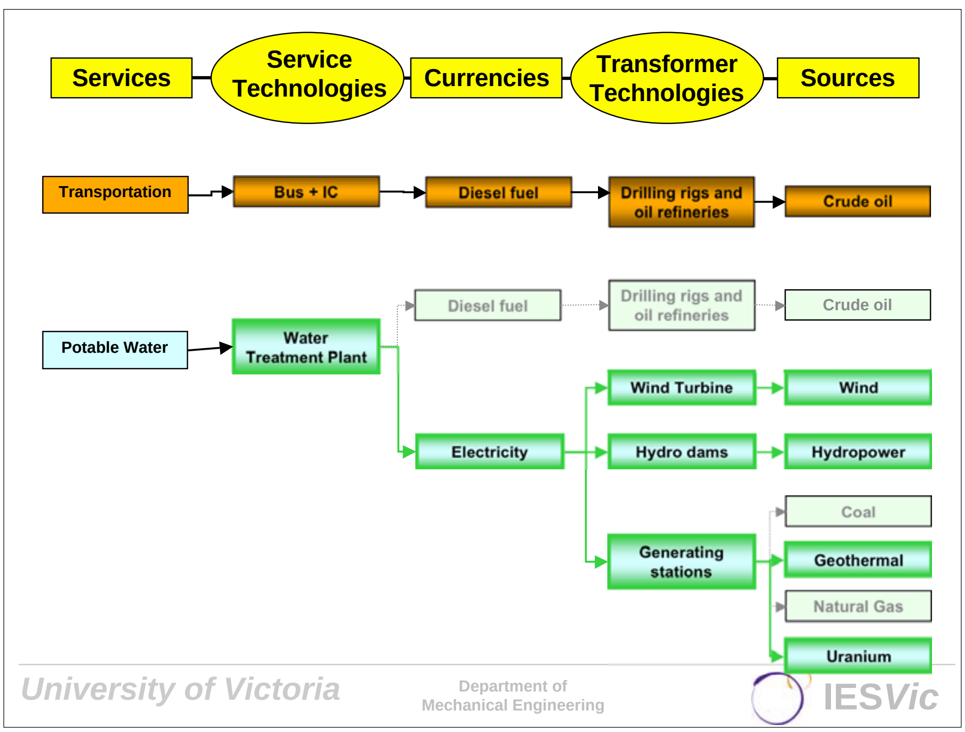
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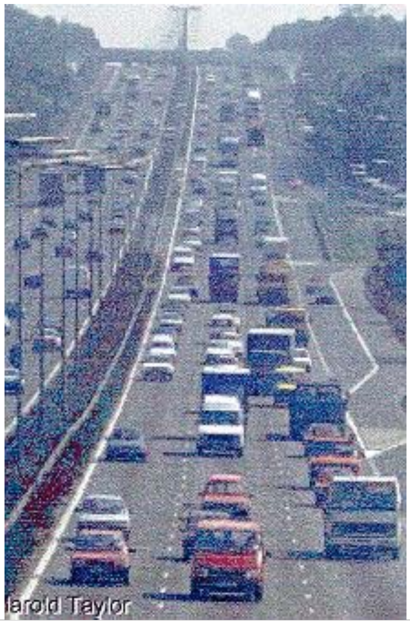
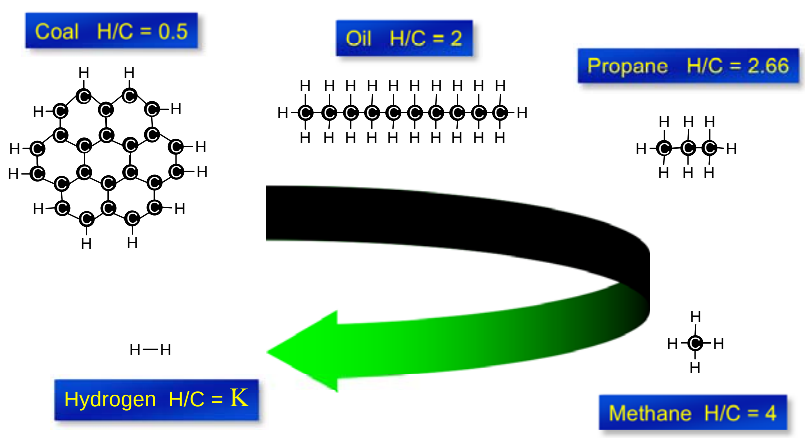
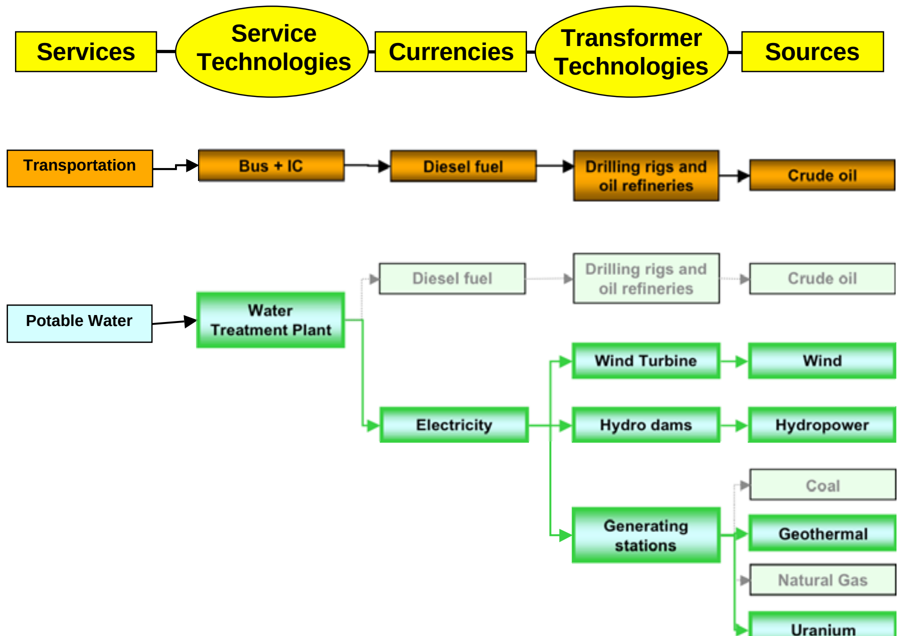


How can we meet our needs for energy services and reduce emissions ?

→ Decarbonization & New ET

Pathway: Decarbonization

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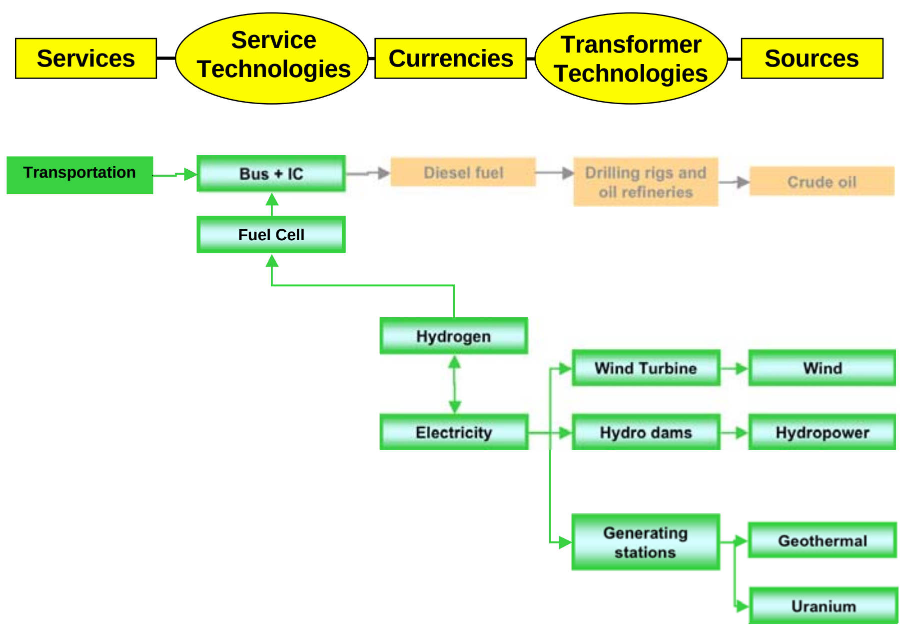
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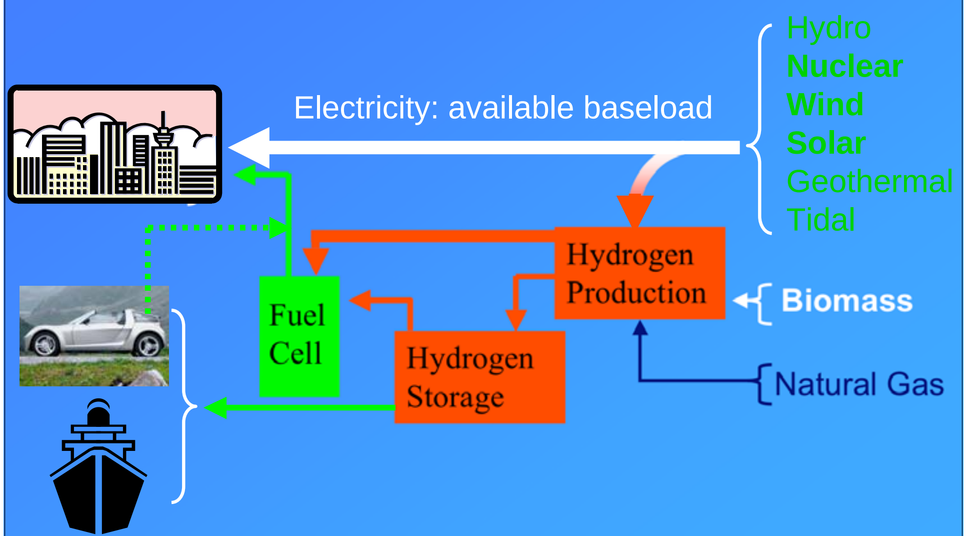
The emerging energy system



'Fuel Cells seem to have been on the verge of capturing world markets as well as the imagination ever since my postwar years in Cambridge …'

P.G. Ashmore, Professor of Physical Chemistry, UMIST, 1972

Dr. Harry Karl Ihrig tilling hard dry earth with a plow and fuel cell–driven tractor in the fall of 1959.

1959

Fuel Cell Application Areas

- Transportation
- Off-Grid Power
- Grid-Integrated Power
- Portable Electronics

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Some Applications…

…

Fuel Cell Vehicles: Transit Bus

Fleet operation: Vancouver & Chicago

- 40 passengers
- Zero Emission (ZEV)
- 275 hp (205 kW)
- 400 km range

European FC Bus Program

Motorized Bicycles

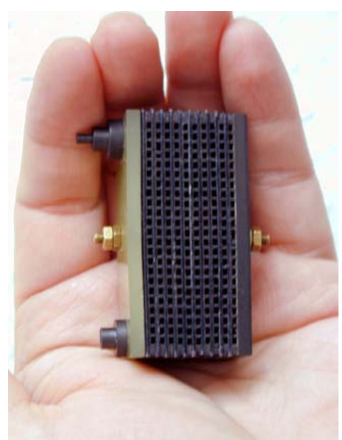
Asian market:

- 2-stroke IC ban
- 1.5 M E-bikes & Scooters
- 20 Kg batteries
- 6-8 hrs recharge

Fuel Cells in the Ocean…

& in Space

Range of Power Applications



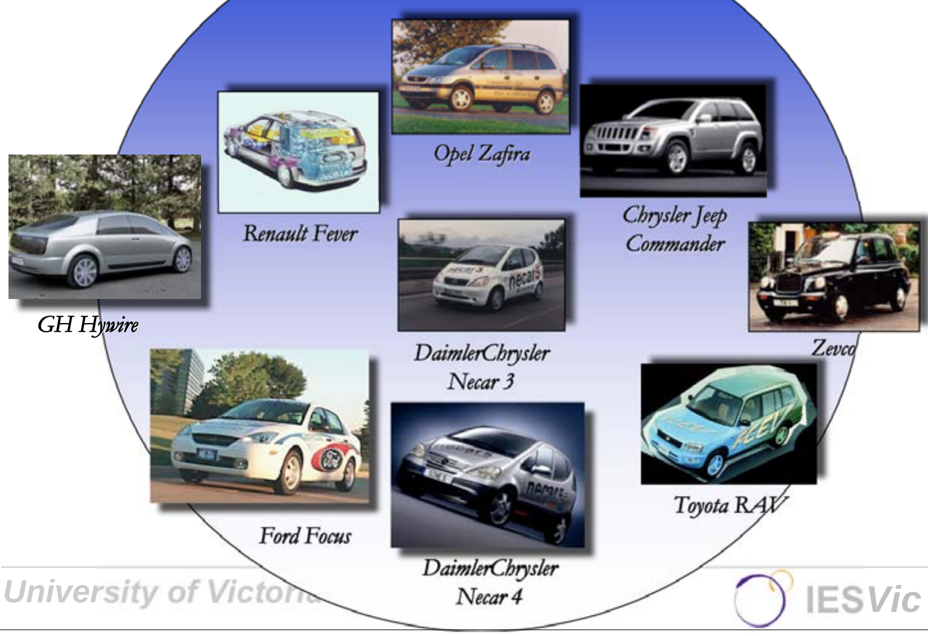
MW ⟶ mW

Karl Kordesch's Austin

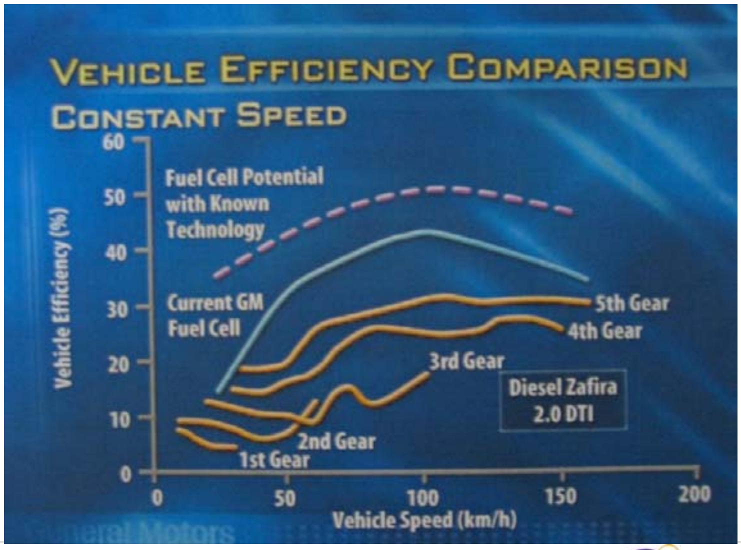
6 kW Alkaline Fuel Cell

Lead Acid Batteries

Fuel Cell Vehicles



Why Fuel Cells for Vehicles?



Commuting in the 21st Century … Could be fun

Bombardier's Embryo FCV

Canadian FC Sector

- Angstrom
- Ballard Power Systems
- Cellex Power*
- Fuel Cell Technologies
- General Hydrogen
- Hydrogenics*
- Palcan
- QuestAir
- Stuart Energy Systems*

Topics

- Overview of Fuel Cell Systems & Fundamentals
- Proton Exchange Membrane Fuel Cells
- Micro/Mini Fuel Cells
- Solid Oxide Fuel Cells
- Fuelling & Fuel Cell Systems

References

- J. Larminie & A. Dicks, *Fuel Cell Systems Explained*, Wiley, 2003
- F. Barbir, *PEM Fuel Cells*, Elsevier, 2005.
- X. Li, *Principles of Fuel Cells*, Taylor & Francis, 2005.
- W. Vielstich, A. Lamm, H. A. Gasteiger (Eds.), Handbook of fuel cells: fundamentals, technology, and applications, Wiley, 2003
- *Fuel Cell Handbook-7th Edition*, US Department of Energy, (2004). Available at www.netl.doe.gov
- S. Sunden & M. Faghri (Eds.), *Transport Phenomena in Fuel Cells*, WIT Press, 2005

Project

- analysis or design of a fuel cell related process, system or component
- grade for the project will be based on submission of a progress report, a final report and an oral presentation
- details on suitable topics, expectations and grading will be provided during the second week of classes.

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Paper Discussion and Critique

- Each student will present a critical summary and lead a discussion on an assigned paper.
- All students will be expected to read the paper and participate in the discussion.
- Mark based on critical summary and participation

Grading

Project Progress Report	10 %
Project Final Report	45 %
Project Presentation	15 %
Paper Discussion	10 %
Oral Examination	20 %
Total	**100**

Course Web Site

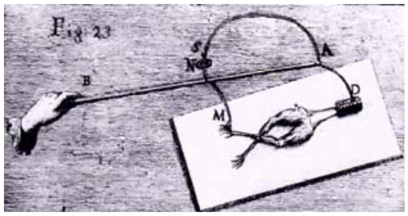
www.me.uvic.ca/~ndjilali/MECH549/mech549.html

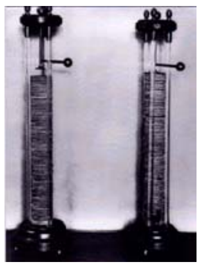
- Course outline
- Project outline
- Lectures, supplementary notes & reading material
- Assignments & solutions
- Selected links

Part II

- A brief history of fuel cell development
- Operating principles and classification
- Structure of a fuel cell

Where is the connection ?

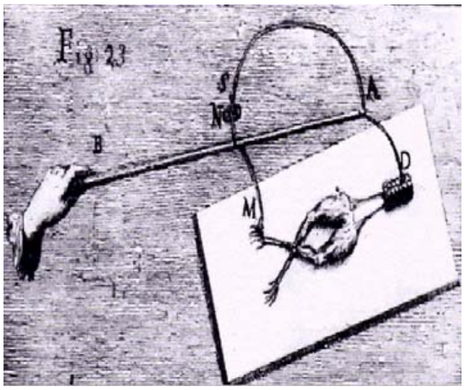




Electricity and Batteries

-Some Historical Highlights-

Galvani: The Concept of “Animal Electricity”



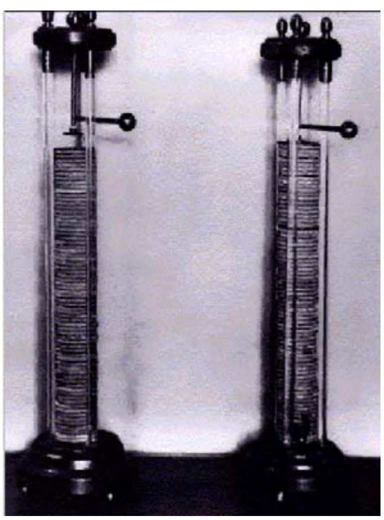
How a perchance occurrence in the laboratory of 18th-century Italian scientist Luigi Galvani - culminated in the development of the concept of voltage & invention of battery.

The year was 1780

- one lab assistant observed twitching
- another thought he saw lightning

Galvani thought that the “twitching effect” was due to the transfer of a special fluid from the animal and called it "*animal electricity*,".

Volta: No such thing as Animal Electricity!



Alessandro Volta (1745-1827).

- Was not convinced with the theory of *animal electricity*
- Developed Voltaic piles -- a stack of alternating discs of Zn and Cu or Ag separated by felt soaked in brine.

The Voltaic Cell provided, for the first time, a simple source of stored electrical energy that didn't rely on mechanical means – this was 1800

Davy: Electricity & Electrolysis

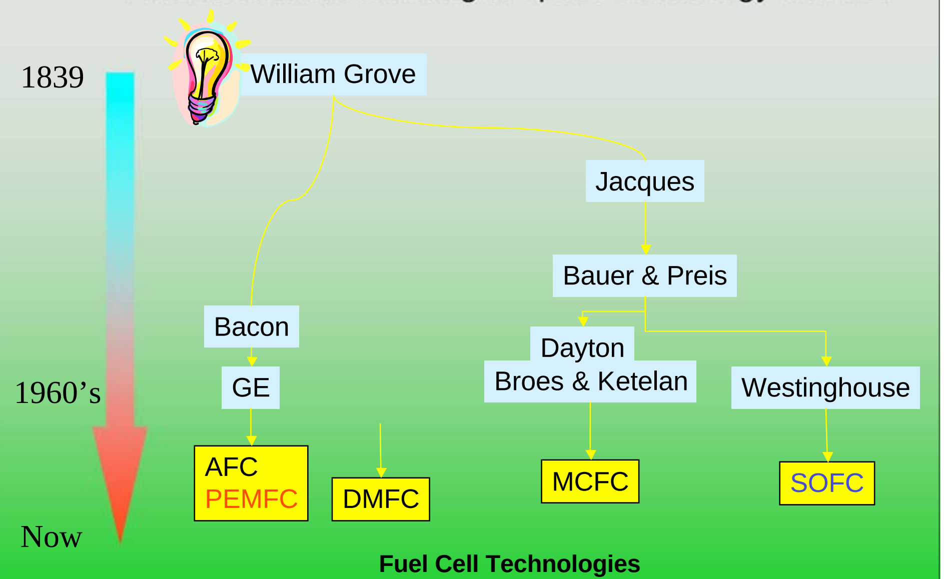
In **1813**, Sir Humphrey Davy concocted a giant battery in the basement of Britain's Royal Society - made of *2,000 pairs of plates* and occupied *889 square feet*.

He found that when he passed electrical current through some substances, these substances decomposed, (a process later called *electrolysis*).

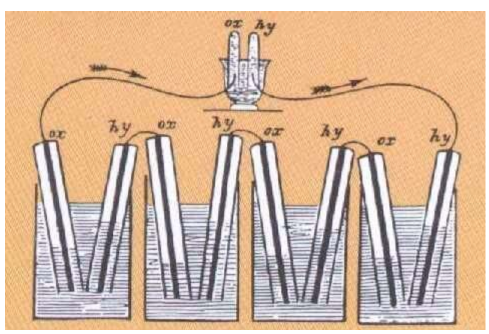
Later, when *Grove* experimented with his fuel cell, the production of electricity was demonstrated by electrolysis of water.

A Brief History of Fuel Cells

From basement tinkering to space technology and …?



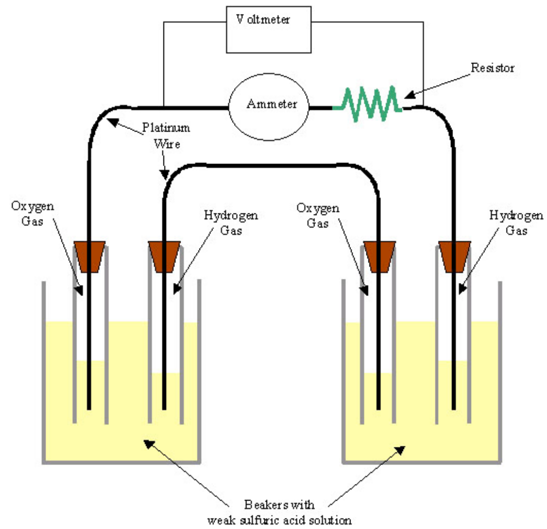
Sir William Grove & His Gas Voltaic Battery



Philos. Mag., *Ser. 3*, **1839**, *14*, 127.

Grove's Device: Oxygen and hydrogen in the tubes over the lower reservoirs react in sulfuric acid solution to form water. That is the energy producing chemical reaction. The electrons produced electrolyze water to oxygen and hydrogen in the upper tube that was actually used as a voltmeter.

Sir William Grove & His Gas Voltaic Battery



Did Grove really invent the first fuel cell ?

- **1802**: Sir Humphrey Davy created a simple fuel cell that allowed him to give himself a feeble electric shock. However, this result was not well documented.
- **1830's**: Sir William Grove was working on series and parallel connections for his powerful platinum-zinc battery.
- **January 1839**: The basic operating principle of fuel cells was decribed by Christian Friedrich Schönbein who published his article about the hydrogen-oxygen "fuel cell" in the *Philosophical Magazine*.
- **February 1839**: In the post-scriptum to his article published also in the *Philosophical Magazine*, Grove noted the possibility of using the hydrogen-oxygen reaction to generate electricity.
- **1842**: Grove presented the Gas Voltaic Battery (now known as a Fuel Cell) in all its details.

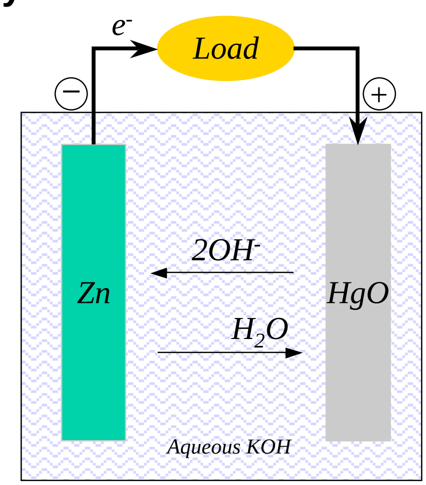
Battery

- Anode (oxidation)
  $Zn + 2OH^- \rightarrow Zn(OH)_2 + 2e^-$
  $\rightarrow ZnO + H_2O + 2e^-$

- Cathode (reduction)
  $HgO + H_2O + 2e^- \rightarrow Hg + 2OH^-$

- Cell reaction
  $Zn + HgO \rightarrow ZnOH + Hg$

- Reaction stops when electrode material is depleted

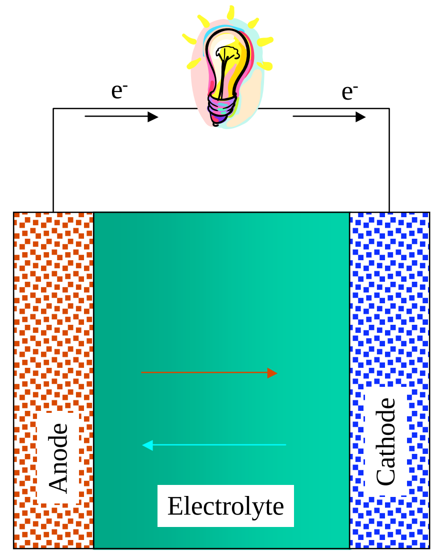


Battery versus Fuel Cell

- Both battery and fuel cells have three key components –
  - *an anode*
  - *a cathode*
  - *an electrolyte.*

- How does a fuel cell differ from a battery?
  "A fuel cell is a battery that produces electricity continuously as long as it is fed which the fuel and reactant"

Key Components of a Fuel Cell



<u>At anode:</u>

You always *produce* electrons

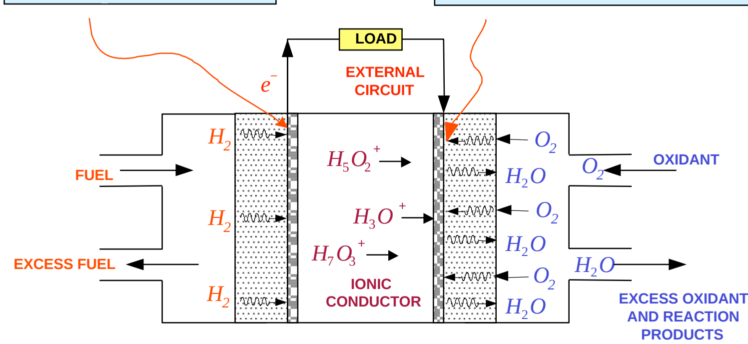
<u>At cathode</u>

You always *consume* electrons

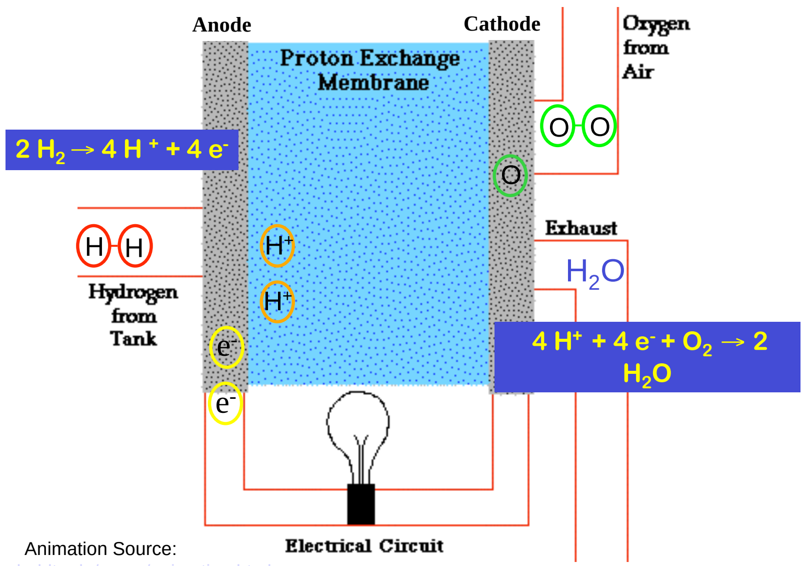
PEM Fuel Cell Operation (<u>acidic electrolyte</u>)

ANODE: $H_2(g) \rightarrow 2H^+ + 2e^-$

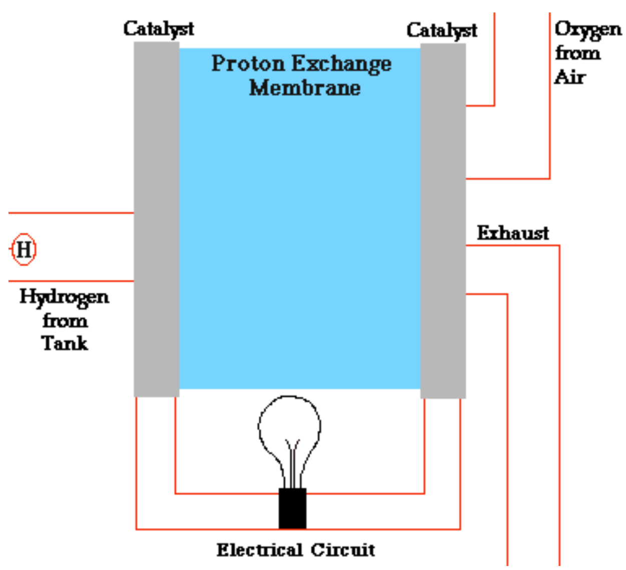
CATHODE: $\frac{1}{2}O_2(g) + 2H^+ + 2e^- \rightarrow H_2O(l)$



OVERALL REACTION: $H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l) \qquad \Delta G^o = -273 \text{ kJ/mol}$



Animation Source:
www.humboldt.edu/~serc/animation.html



SOFC Operating Principle

For H_2-O_2 operation

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

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

Overall reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

Carbon monoxide (CO) and hydrocarbons such as methane (CH4) can be used directly as fuels in SOFCs. In the high temperature environment of SOFCs steam reforming and water gas shift can take place:

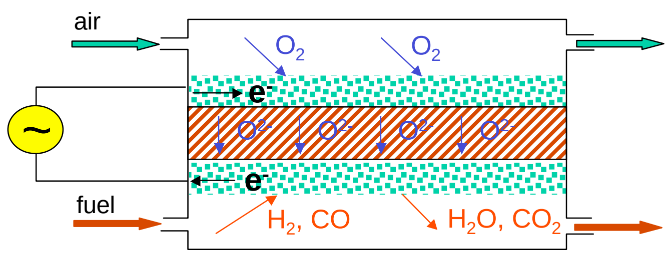
$$CH4 + H2O \rightarrow 3H2 + CO$$

$$CO + H2O \rightarrow H2 + CO2$$

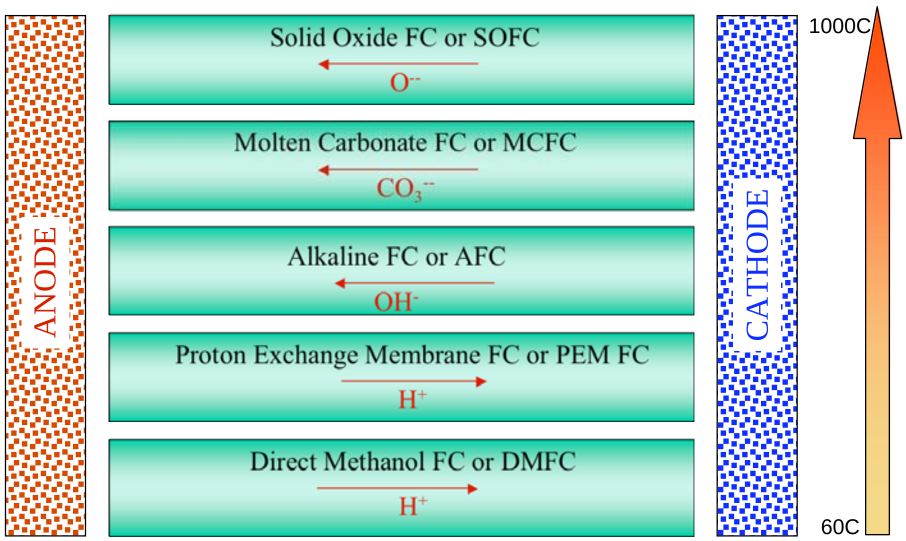
Direct oxidation of CO contained in reformed hydrogen is possible.

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

  $aH_2 + bCO + (a+b)O^{2-} \rightarrow aH_2O + bCO_2 + 2(a+b)e^-$
- Cathode: $\frac{1}{2}(a+b)O_2 + 2(a+b)e^- \rightarrow (a+b)O^{2-}$
- Overall cell reaction: $\frac{1}{2}(a+b)O_2 + aH_2 + bCO \rightarrow aH_2O + bCO_2$



Fuel Cell (FC) Classification



Fuel Cell Technologies

	PEFC	PAFC	MCFC	SOFC
Electrolyte	Ion Exchange Membrane	Immobilized Liquid Phosphoric Acid	Immobilized Liquid Molten Carbonate	Ceramic
Operating Temperature	80°C	205°C	650°C	800-1000°C now, 600-1000°C in 10 to 15 years
Charge Carrier	H^+	H^+	$CO3^=$	$O^=$
External Reformer for CH_4 (below)	Yes	Yes	No	No
Prime Cell Components	Carbon-based	Graphite-based	Stainless Steel	Ceramic
Catalyst	Platinum	Platinum	Nickel	Perovskites

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Reactions by Types of Fuel Cell

Fuel Cell	Anode Reaction	Cathode Reaction
Proton Exchange Membrane	$H_2 \rightarrow 2H^+ + 2e^-$	$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Alkaline	$H_2 + 2(OH)^- \rightarrow 2H_2O + 2e^-$	$\frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$
Phosphoric Acid	$H_2 \rightarrow 2H^+ + 2e^-$	$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Molten Carbonate	$H_2 + CO_3^= \rightarrow H_2O + CO_2 + 2e^-$ $CO + CO_3^= \rightarrow 2CO_2 + 2e^-$	$\frac{1}{2} O_2 + CO_2 + 2e^- \rightarrow CO_3^=$
Solid Oxide	$H_2 + O^= \rightarrow H_2O + 2e^-$ $CO + O^= \rightarrow CO_2 + 2e^-$ $CH_4 + 4O^= \rightarrow 2H_2O + CO_2 + 8e^-$	$\frac{1}{2} O_2 + 2e^- \rightarrow O^=$

CO - carbon monoxide
CO_2 - carbon dioxide
$CO_3^=$ - carbonate ion
e^- - electron
H^+ - hydrogen ion
H_2 - hydrogen
H_2O - water
O_2 - oxygen
OH^- - hydroxyl ion

Modern Developments
(from the 50's on…)

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GE’s Fuel Cell (Ion Exchange Membrane) for the Gemini Spacecraft

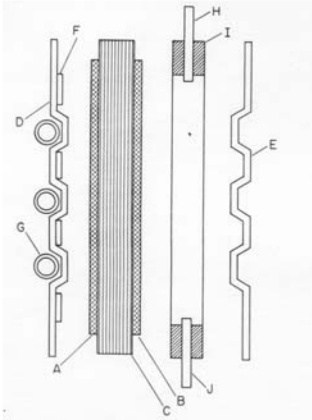


Figure X.2. Schematic diagram of the hydrogen-oxygen cell of the General Electric Company, Schenectady, N.Y., U.S.A. (after Cohen[11]). (A) Oxygen electrode, (B) hydrogen electrode, (C) membrane (electrolyte), (D) and (E) current collectors for hydrogen and oxygen electrodes respectively, (F) wick for water collection, (G) cooling coils, (H) H_2 feed tube, (I) frame, (J) H_2 purge tube.

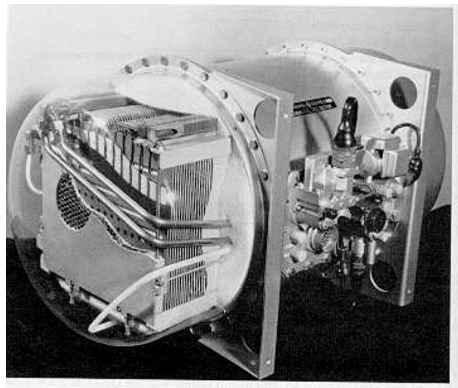
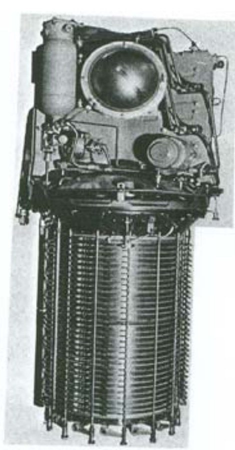


Figure 11.2. GE 1-kW Gemini SPFC module.

- 26 V at 13 A (36 mA/cm2)
- 300 Watts
- Produced 215 cm3 /hr of water

Used an ion-exchange membrane

Pratt & Whitney’s – Alkaline (Bacon-type) fuel cell for Apollo Missions



- 0.9V at 200 mA/cm^2
- Total voltage output – 27V
- Operated for 1000 hours – three times more than originally designed for

Used an alkaline (KOH) electrolyte

Terrestrial Applications of Fuel Cells

Other Early Applications of Fuel Cells - Lighting in Buoys

Figure X.18. 30 watt (6 V) methanol–air battery with alkaline electrolyte for servicing the light buoy illustrated opposite (after Guth, Haase, Plust and Vielstich[33]). Capacity per filling, 180 kW/hr.

- H_2/O_2 fuel cell
- 2 seconds ON; 4 seconds OFF
- lasted for 13 months

Methanol/Air system with alkaline electrolyte

Other Applications: Powering High Altitude TV Relay Station

- In Winter of 1965/66, Swiss Television used fuel cells to relay TV programs
- FC designed by Brown Boveri Company
- 320 cells; 20 Watts for 7000 hrs

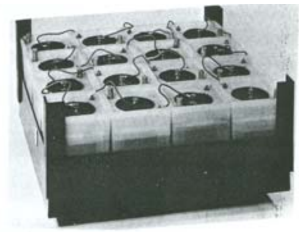


Figure X.21. Left: Television station over Visp (Oberwallis) in winter[3*]. Energy supply by a 20 (40) watt methanol-formate battery (Brown, Boveri u. Cie.).
Right: Battery of 16 individual fuel cells, of box form, suitable for combination to form indefinitely large units. 20 such batteries (320 cells) were used at high altitude; each cell provided 0.2 W at 0.6 V for about 7000 hr.

Methanol/Air system with alkaline electrolyte

Progress on Molten Carbonate Fuel Cells

- Dutch scientists G.H.J. Broers and J.A. Katelaar experimenting with molten carbonate salts [instead of solid electrolytes used by Bauer and his group]
  - 1960: demo MCFC operated for 6 months
- Bacon was also working on MCFCs during that time
- US Army's Mobility Equipment Research was interested in using available fuel (gasoline) in fuel cells – they tested MCFCs that provided power output of 0.1 to 1 W

Progress on Solid Oxide Fuel Cells

- Poor performance of Bauer's SOFCs dissuaded many to continue research in this area but not the researchers at
  - Central Technical Institute, Netherlands
  - Consolidation Coal Company, Pennsylvannia
  - General Electric, NY
  - Westinghouse Research Lab.

100 Watts SOFC developed by Westinghouse Research laboratories (circa 1960)
– 20 batteries of 20 cells each
– Open circuit voltage = 200 V
– Current = 1.2 A
–H2/O2 system

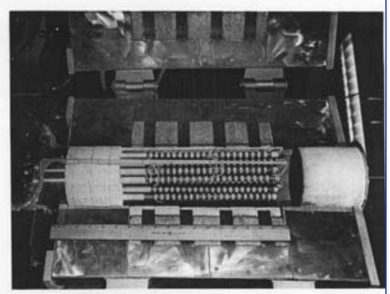
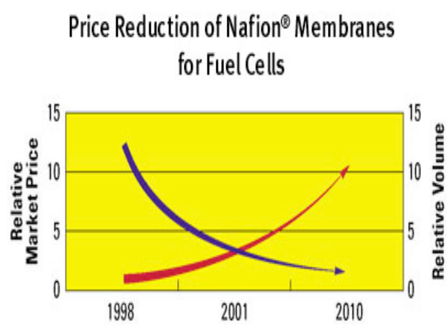


Figure IV.69c. Solid-electrolyte, 100 watt fuel cell power system with furnace door open. (Westinghouse Res. Lab.)

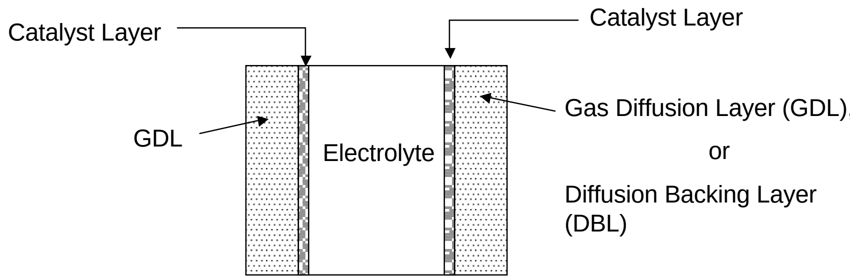
Progress in PEMFC: Invention of Nafion

- Stability of GE's ion exchange membrane used in Gemini project was a major issue
- A breakthrough occurred when DuPont developed perfluoro-sulfonic membrane- NAFION



Membrane Electrode Assembly

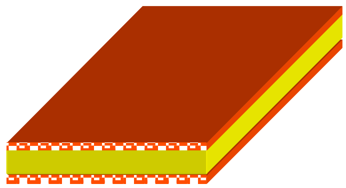
- MEA = Membrane Electrode Assembly
  - This is a PEM term, reflecting the polymer membrane electrolyte
  - A more general term would be EEA, Electrolyte Electrode Assembly



Structure of a PEMFC

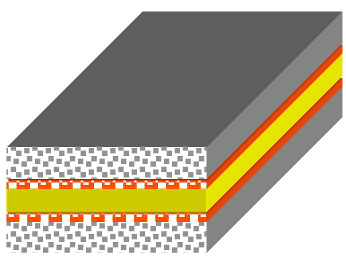
Begin with an Electrolyte (Nafion)

Structure of a PEMFC



Add Catalyst (Platinum on Carbon Black)

Structure of a PEMFC



Add Gas Diffusion Layer (Carbon Paper/Cloth)

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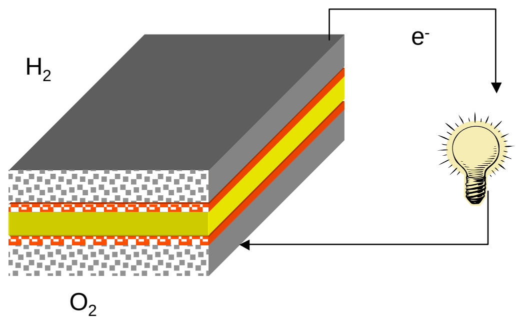
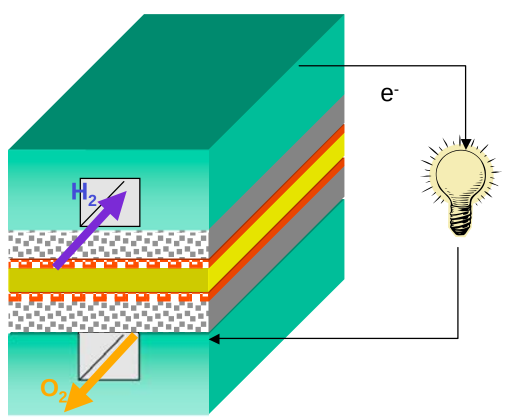
Department of Mechanical Engineering
IESVic

Structure of a PEMFC



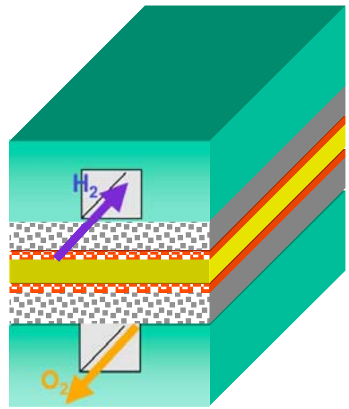
At this point we technically have a fuel cell and could add a load, fuel and oxidizer … but a practical system still needs more..

Structure of a PEMFC



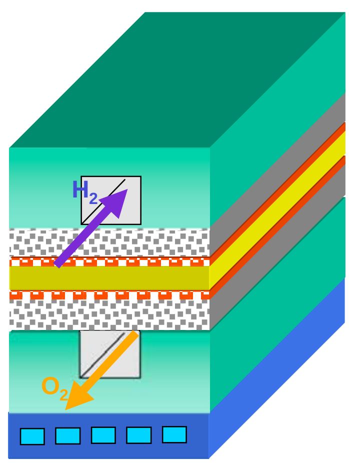
And again, we have our Fuel Cell (Current Collected from plates)

Structure of a PEMFC



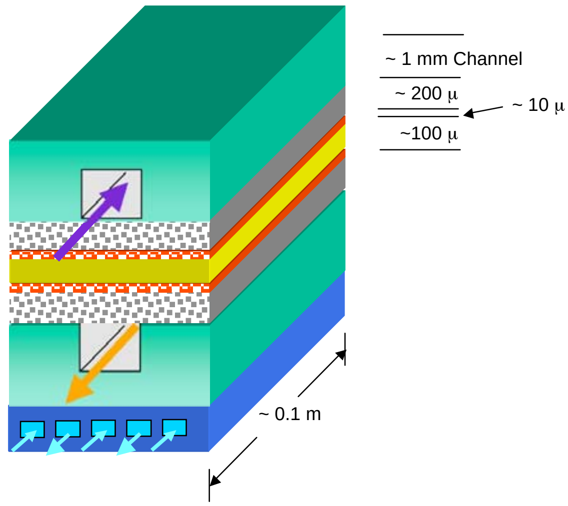
In a practice cooling is required as the reaction generates heat

Structure of a PEMFC

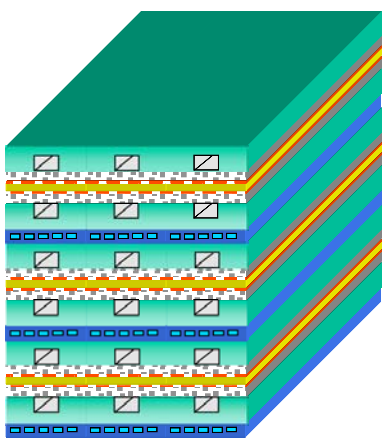


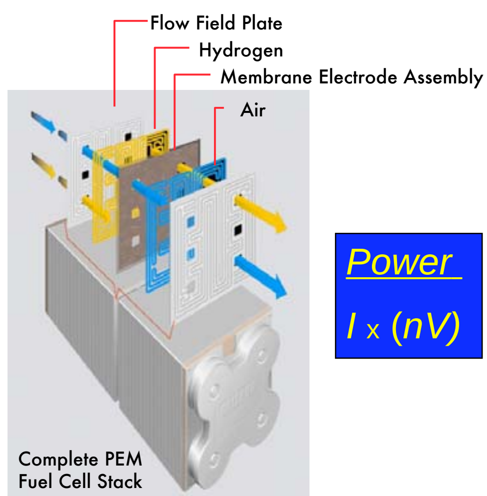
In a practice cooling is required as the reaction generates heat

Structure of a PEMFC



Structure of a PEMFC Stack





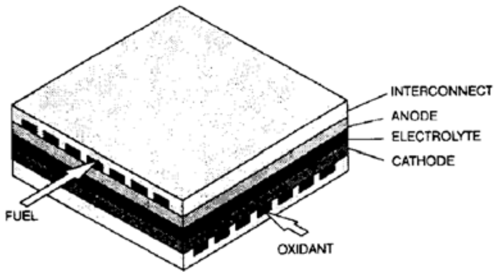
Power

$I \times (nV)$

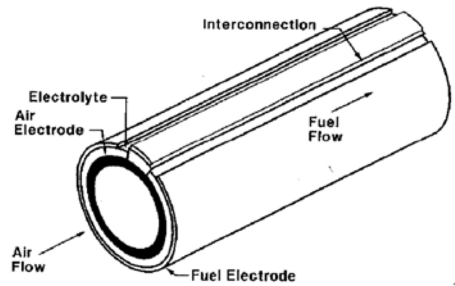
Increase Area: higher *current*
Increase # cells: higher *voltage*

Structure of SOFCs

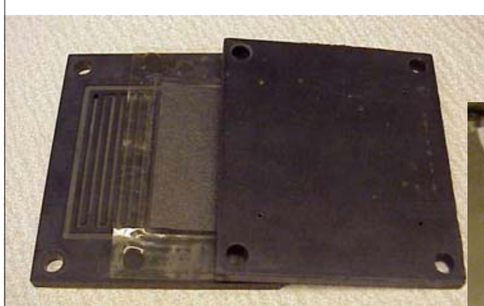
Planar

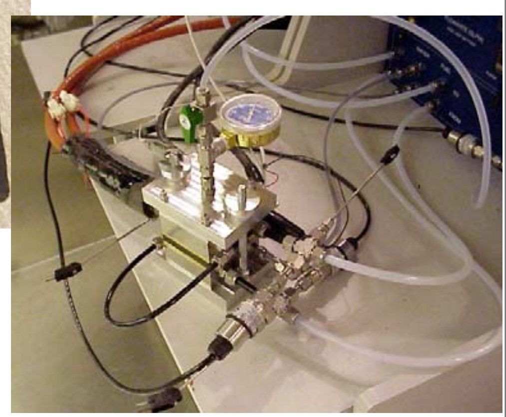


Tubular



A cell in operation





Some of the Challenges

- Improved understanding of effect of operating conditions
- Reduction in catalyst loading and improved tolerance to poisoning
- Development of improved/cheaper electrolyte materials
- Development of stack designs and manufacturing techniques suitable for low cost mass production
- Development of efficient balance of plant components and Improved system integration
- Reduction of system costs
- Durability
- Cold start

Summary

- From Galvani to Grove:

  electricity → batteries → electrolysis → fuel cells
- Components/operations of fuel cells
- Modern developments & applications : From Space to Earth
- Nafion and structure of PEMFCs
- From cell to stack