

Power Sources for Marine Systems

Characteristics of Power Systems for Marine Applications

- “Main Supply” of power – energy source must be carried on board; has to last days, months, years.
- Weight and volume constraints *may* be significantly reduced compared to terrestrial and esp. aeronautical applications.
- Reliability and safety critical due to ocean environment.
- Capital cost, operating costs, life cycle analysis, emissions are significant in design, due to large scale.

This Lecture

- Fuel Engines
 - Characteristics of typical fuels; combustion
 - Internal combustion engines
 - Brayton cycle (gas turbine) engines
- Batteries and Fuel Cells
 - Electrochemical processes at work
 - Canonical battery technologies
 - Fuel cell characteristics
- NOT ADDRESSED: Nuclear power sources, renewable energy, emissions, green manufacturing, primary batteries, generators ... !

Engines transform *chemical* energy into *heat* energy into *mechanical* or *kinetic* energy.

1 MegaJoule is:

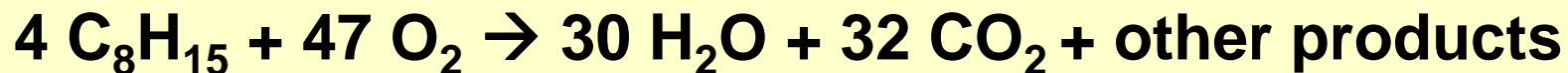
1 kN force applied over 1 km;

1 Kelvin heating for 1000 kg air;

1 Kelvin heating for 240 kg
water;

10 Amperes flowing for 1000
seconds at 100 Volts

Reaction for gasoline:



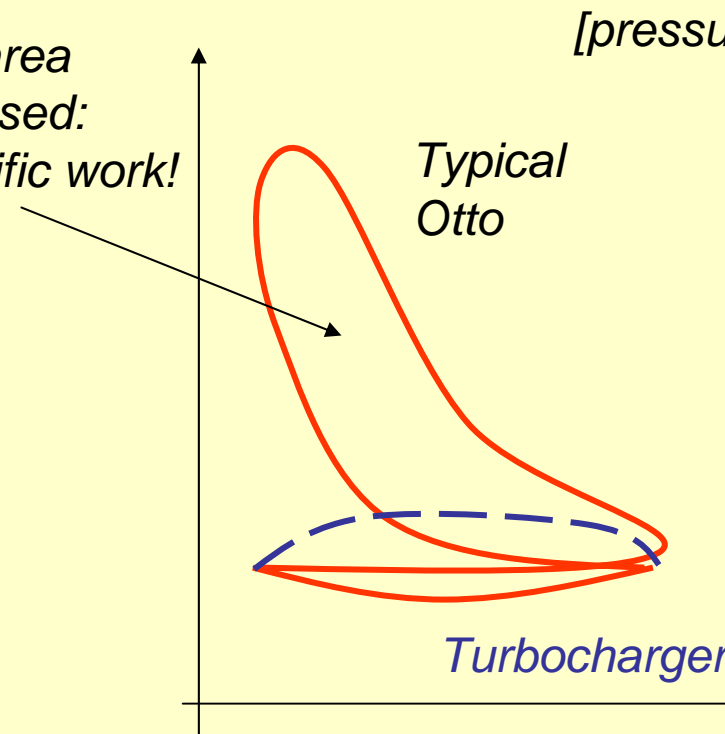
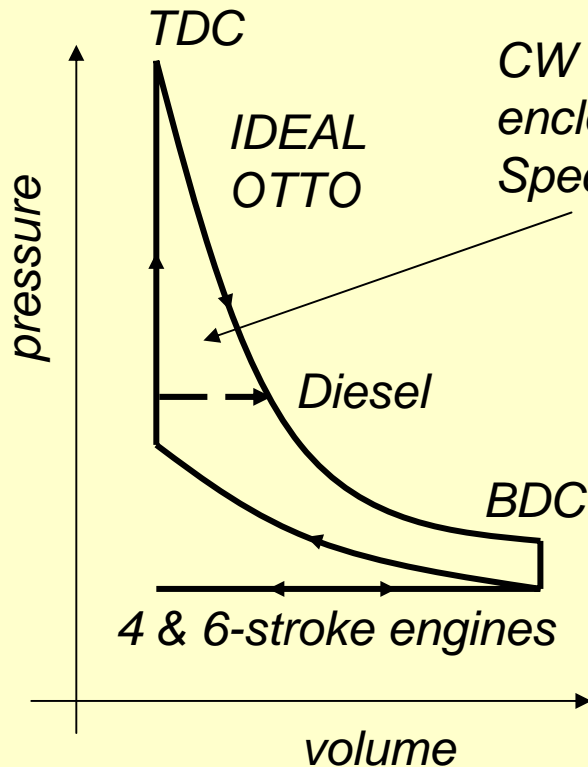
Fuel	Heat Content MJ/kg
Gasoline*: C_8H_{15}	45
Diesel*: $\text{C}_{13}\text{H}_{23}$	42
Propane: C_3H_8	48
Hydrogen: H_2	130
Ethanol: $\text{C}_2\text{H}_5\text{OH}$	28

**Approx.: complex mixtures
Pulkrabek, p. 444*

Otto and Diesel Cycles

Four-stroke engine:

- 1: TDC to BDC, bring air into cylinder
- 2: BDC to TDC, compress air
ADD FUEL and IGNITE!
- 3: TDC to BDC, expand heated air (power stroke)
- 4: BDC to TDC, blow out products of combustion



$$[\text{pressure} * \text{volume}] = \text{N/m}^2 * \text{m}^3/\text{kg} = \text{Nm/kg} = \text{Energy/mass}$$

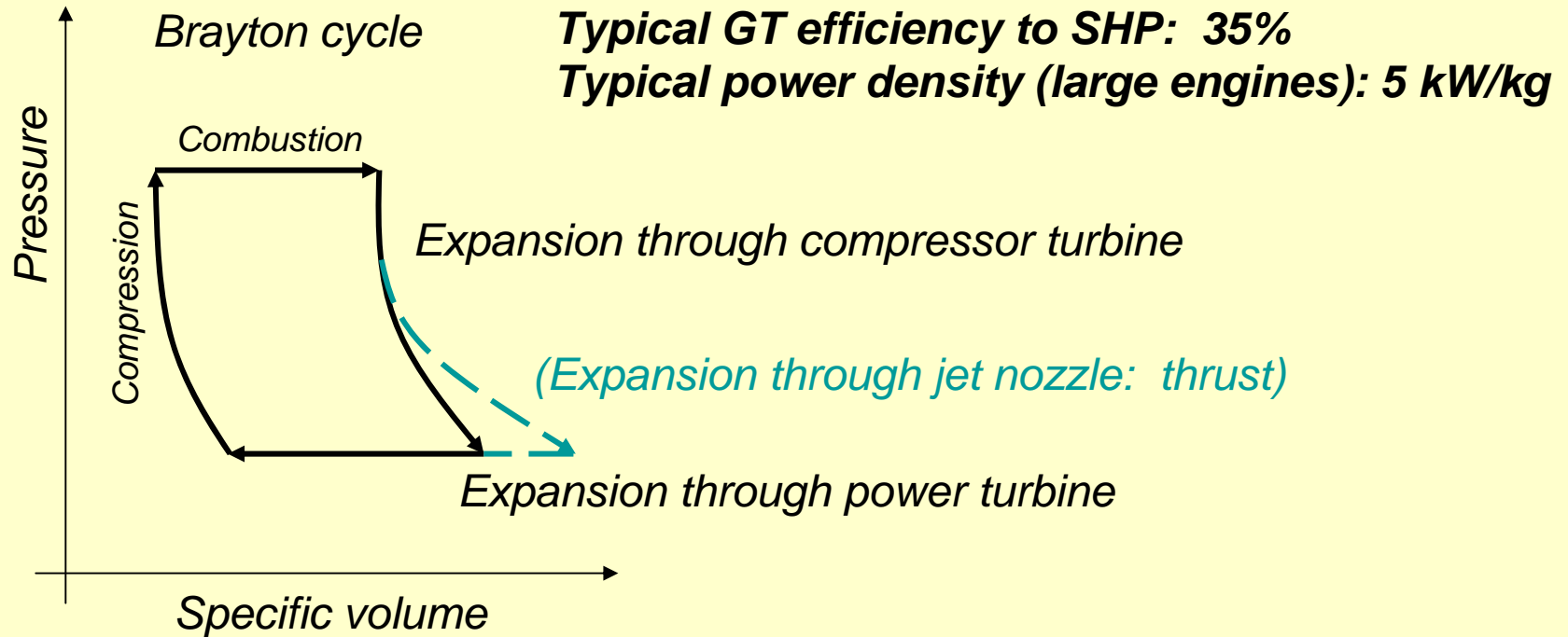
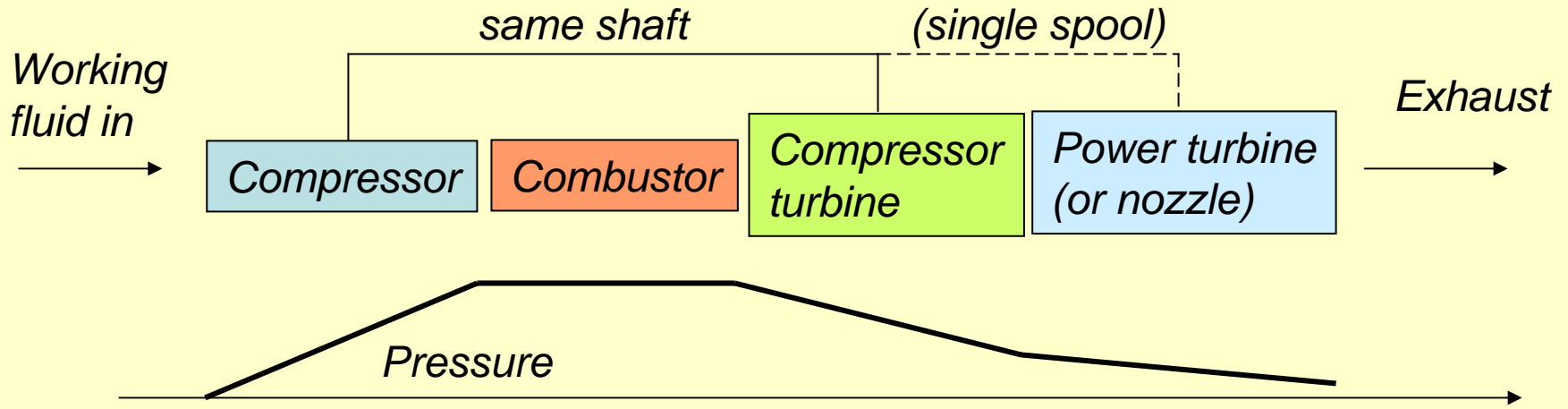
Typical ICE efficiency to BHP: 30%

Typical power density: 0.05-0.4 kW/kg

LM2500 Specifications - Quoted

“ Output: 33,600 shaft horsepower (shp)
Specific Fuel Consumption: 0.373 lbs/shp-hr
Thermal Efficiency: 37%
Heat Rate: 6,860 Btu/shp-hr
Exhaust Gas Flow: 155 lbs/sec
Exhaust Gas Temperature: 1,051°F
Weight: 10,300 lbs
Length: 6,52 meters (m)
Height: 2.04 m

Average performance, 60 hertz, 59°F, sea level, 60% relative humidity, no inlet/exhaust losses, liquid fuel, LHV=18,400 Btu/lb ”

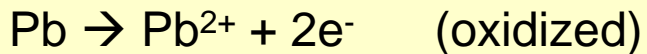


Battery Technologies

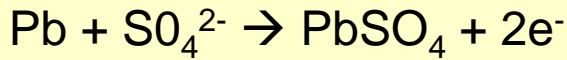
Electrochemical Cells

Lead-acid battery has two electrode reactions (discharge):

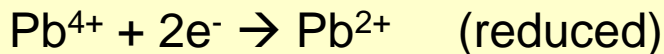
Releasing electrons at the negative electrode:



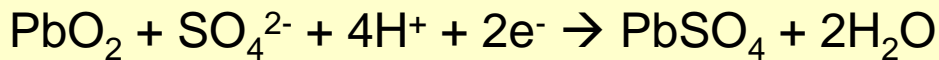
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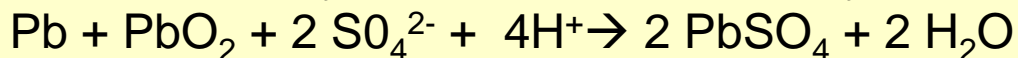
Gathering electrons at the positive electrode:



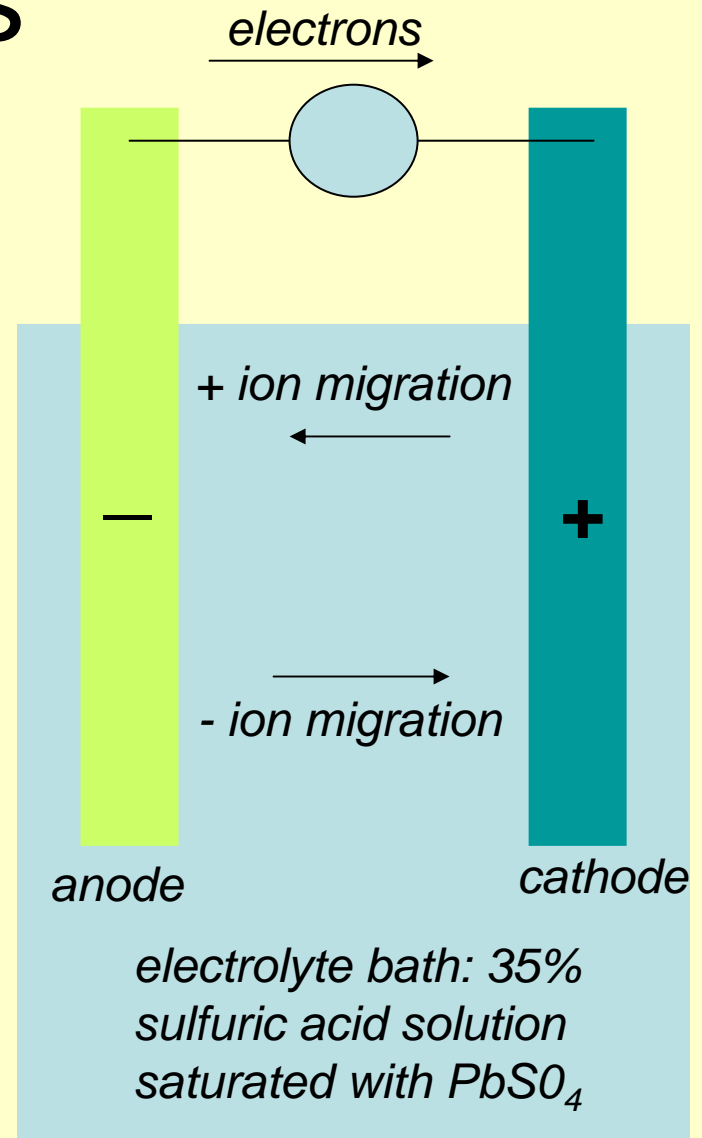
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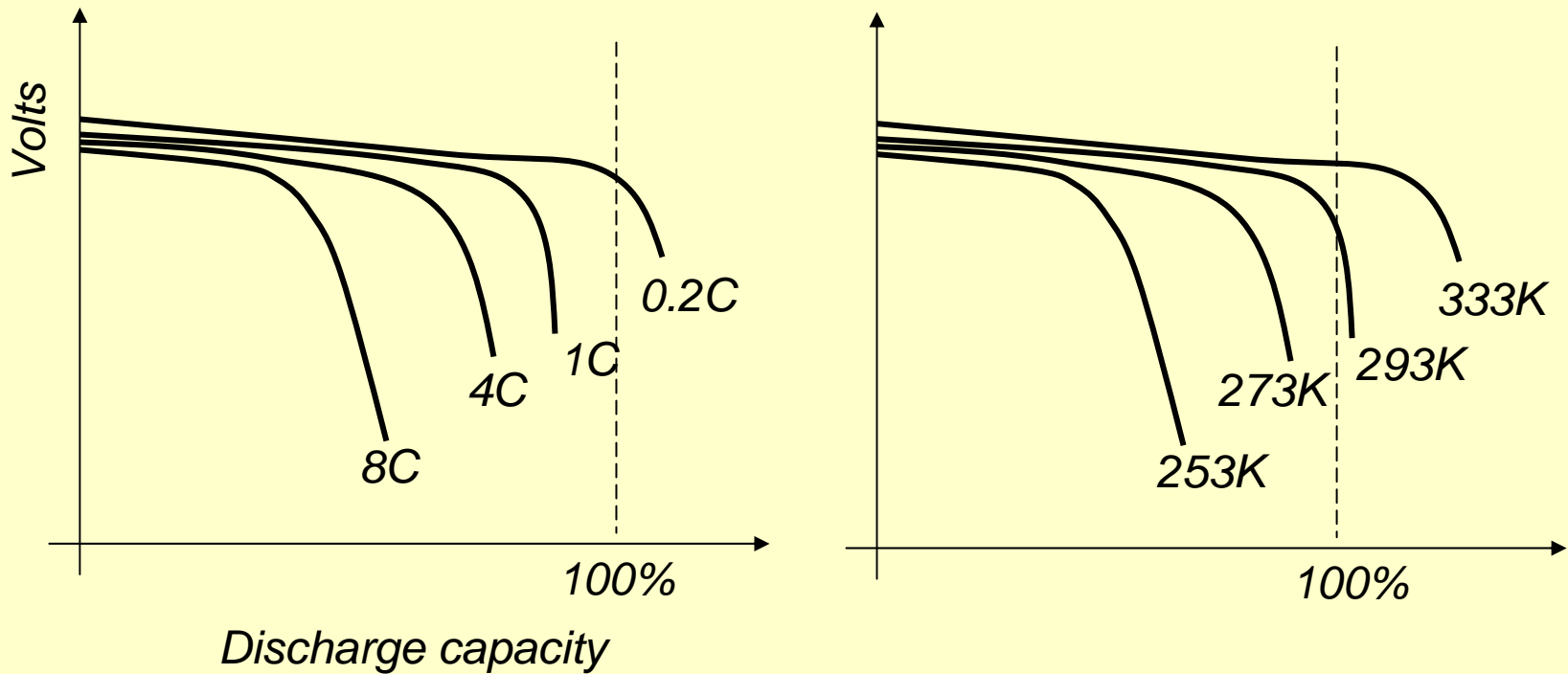
Total Chemistry of the Lead-Acid battery:



Theoretical limit of lead-acid energy density: 0.58MJ/kg



Overall Discharge Dependence on Current and Temperature



Nominal discharge rate C is capacity of battery in Ah, divided by one hour (typical).

Some variation of shapes among battery technologies, e.g., lithium lines more sloped.

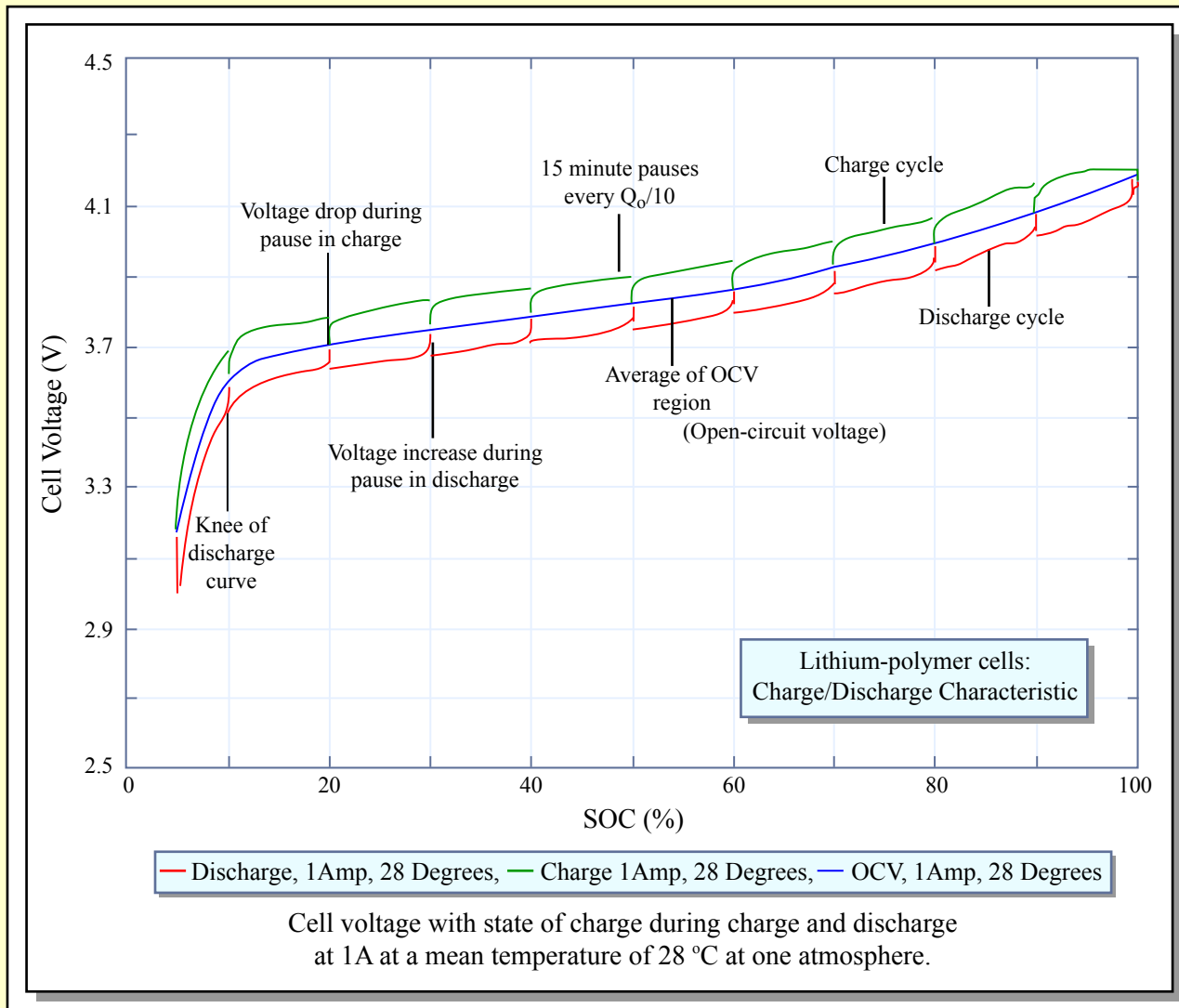


Figure by MIT OCW.

Comparison of Battery Performance for Mobile Applications

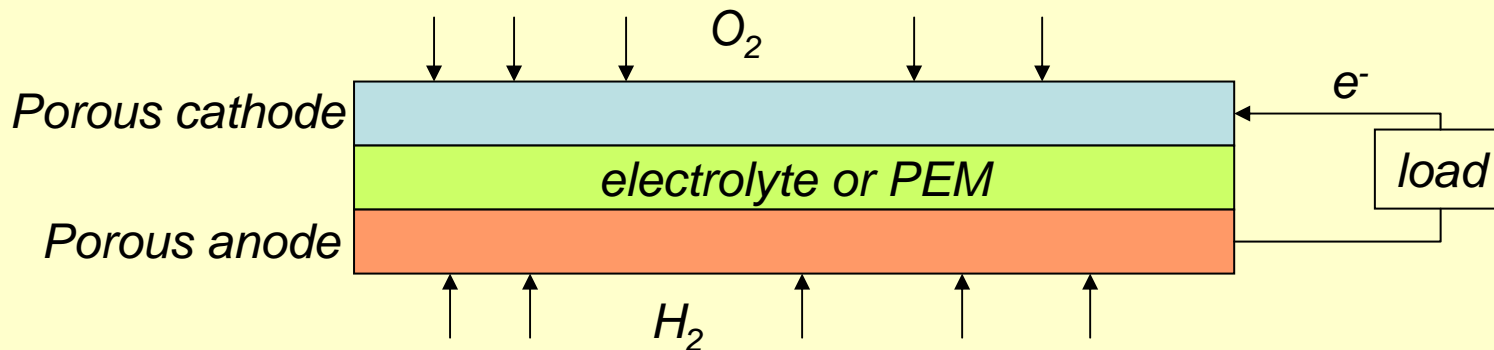
	Energy density, MJ/kg, MJ/l	Memory effect	Maximum current	Recharge efficiency	Self-discharge, %/month at 293K
Lead-acid	0.14, 0.36	No	20C	0.8-0.94	??
Ni-Cd	0.24, 0.72	Yes	3C	0.7-0.85	25
NiMH	0.29, 1.08	Yes	0.6C		<20
Li-ion	0.43-0.72, 1.03-1.37*	No	2C		12

All have 300+ cycles if max current is not exceeded.

** Lithium primary cells can reach 2.90 MJ/l*

Fuel Cells

- Electrochemical conversion like a battery, but the fuel cell is defined as having a *continuous supply of fuel*.
- At anode, electrons are released: $2\text{H}_2 \rightarrow 4\text{H}^+ + 4\text{e}^-$
- At cathode, electrons are absorbed:
$$\text{O}_2 + 4\text{e}^- + 4\text{H}^+ \rightarrow 2\text{H}_2\text{O}$$
- Proton-exchange membrane (PEM) between electrodes allows H^+ to pass, forcing the electrons around outside the battery – the load. PEMFC operates at 300-370K; a low-temperature fuel cell. ~40% efficient.



Some Fuel Cell Issues

- High sensitivity to impurities: e.g., PEMFC is permanently poisoned by 1ppb sulfide.
- Weight cost of storage of H₂ in metal hydrides is 66:1; as compressed gas: 16:1.
- Oxidant storage: as low as 0.25:1
- Reformation of H₂ from other fuels is complex and weight inefficient: e.g., Genesis 20L Reformer supplies H₂ at ~ 0.05 kW/kg
- Ability of FC to change load rapidly.
- ***Typical Overall Performance Today:***
0.025 kW/kg, 0.016 kW/l

State of the Art 2005

- Gas turbines for large naval vessels due to extremely high power density, and the high thermal energy content of traditional fuels
- Li-based batteries now available at $\sim 0.65\text{MJ/kg}$ (180kWh/kg); gold standard in consumer electronics and in autonomous marine vehicles
- Fuel cells are still power-sparse and costly for most mobile applications, but continue to be developed. More suitable are power generation plants in remote locations.

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