Some Important Power Sources

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 *mechanica*l 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

Fuel	Heat Content MJ/kg
Gasoline*: C_8H_{15}	45
Diesel*: $C_{13}H_{23}$	42
Propane: C_3H_8	48
Hydrogen: H_2	130
Ethanol: C_2H_50H	28

**Approx.: complex mixtures*

Pulkrabek, p. 444

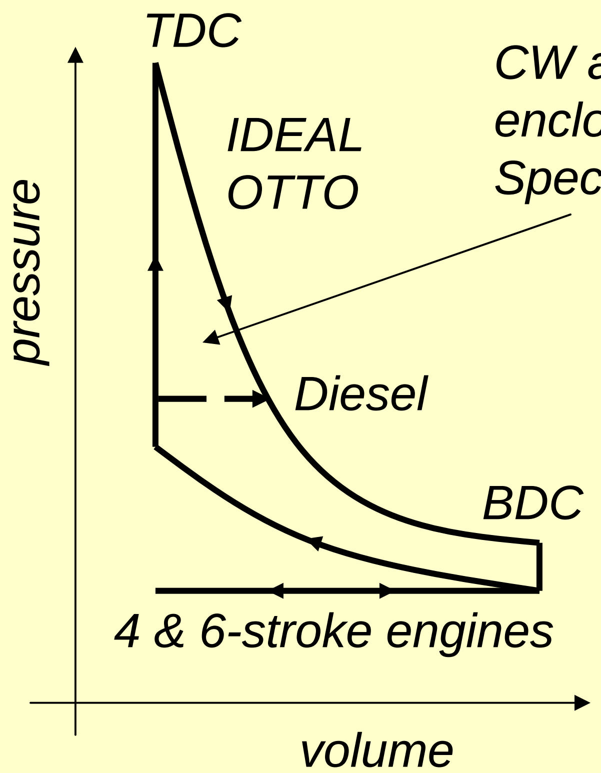
Reaction for gasoline:

$4\ C_8H_{15} + 47\ O_2 \rightarrow 30\ H_2O + 32\ CO_2$ + other products

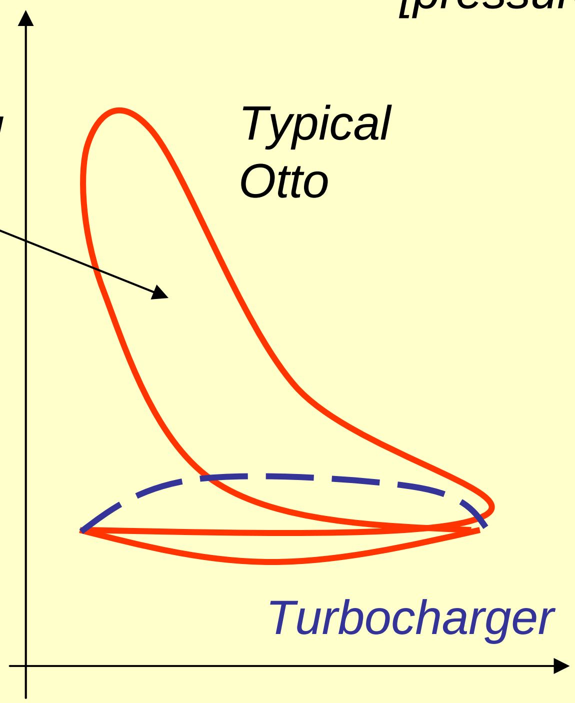
Otto and Diesel Cycles

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



CW area enclosed: Specific work!



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

Typical ICE efficiency to BHP: 30%

Typical power density: 0.05-0.4 kW/kg

Pulkrabek p. 88, 111.

Photo of the 9H rotor
removed due to copyright restrictions.

GE LM2500 gas turbine: 22kW for marine propulsion

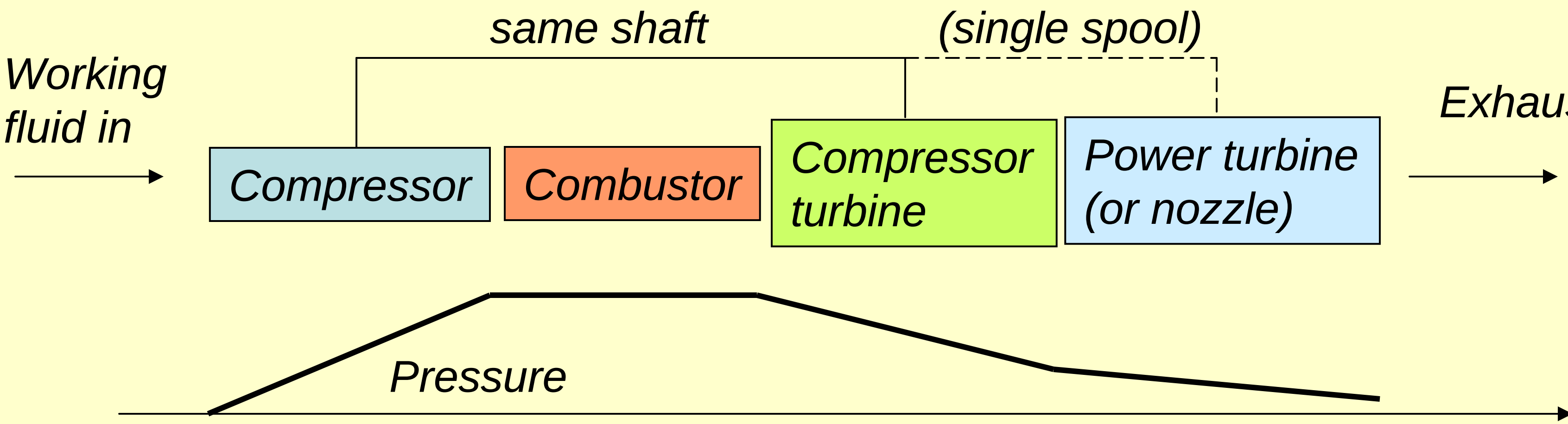
Photo of a LM2500 gas turbine
removed due to copyright restrictions.

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

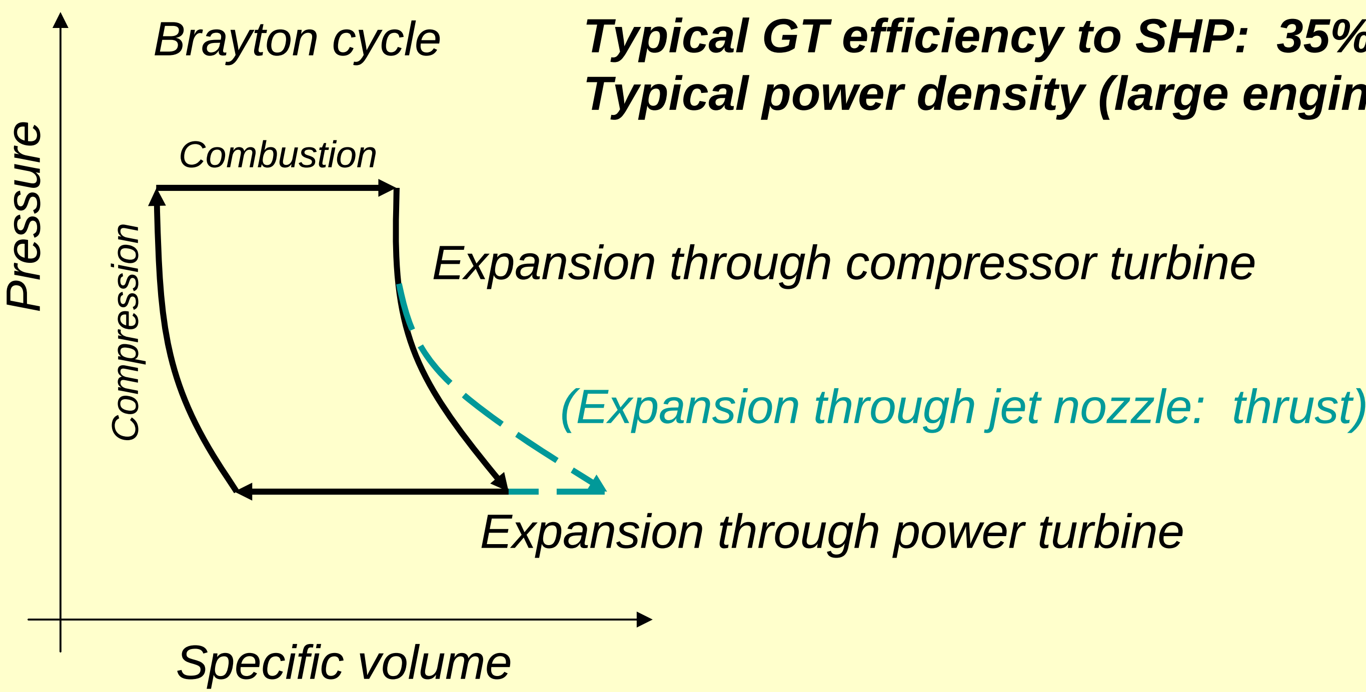
Average performance, 60 hertz, 59°F, sea level, 60% relative humidity, no inlet/exhaust losses, liquid fuel, LHV=18,400 Btu/lb ”

http://www.geae.com/aboutgeae/presscenter/marine/marine_200351.html



Typical GT efficiency to SHP: 35%

Typical power density (large engines): 5 kW/kg



Giampaolo, p. 46, 52

Battery Technologies

Electrochemical Cells

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

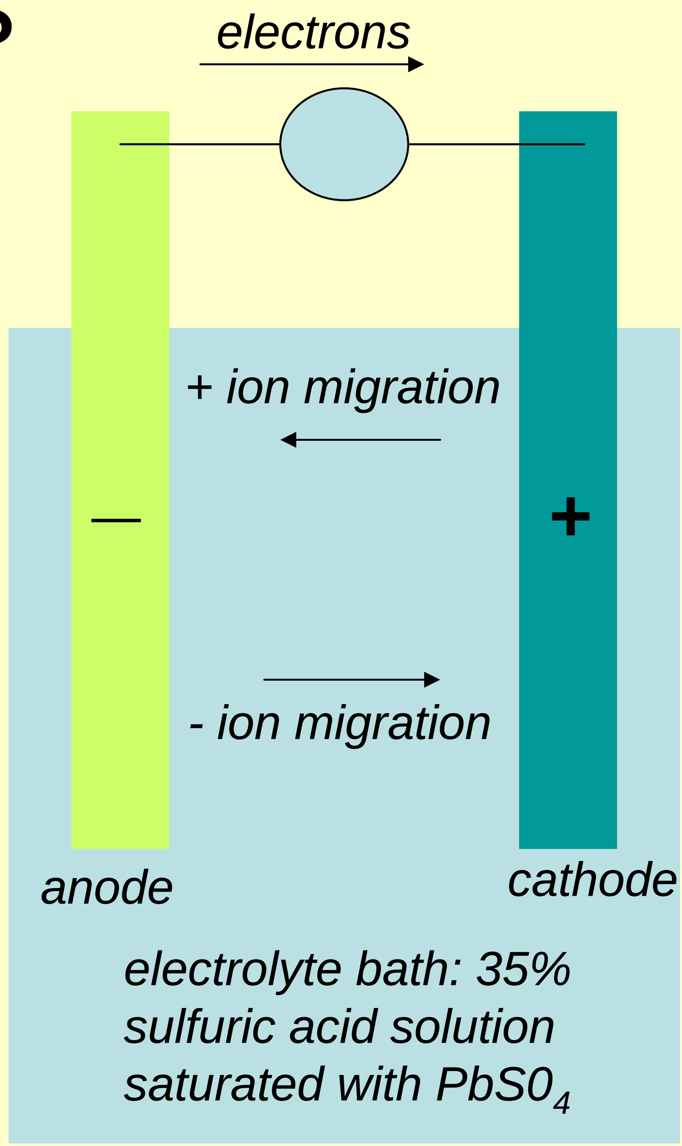
Releasing electrons at the negative electrode:

$Pb \rightarrow Pb^{2+} + 2e^-$ (oxidized)
or
$Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$

Gathering electrons at the positive electrode:

$Pb^{4+} + 2e^- \rightarrow Pb^{2+}$ (reduced)
or
$PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$

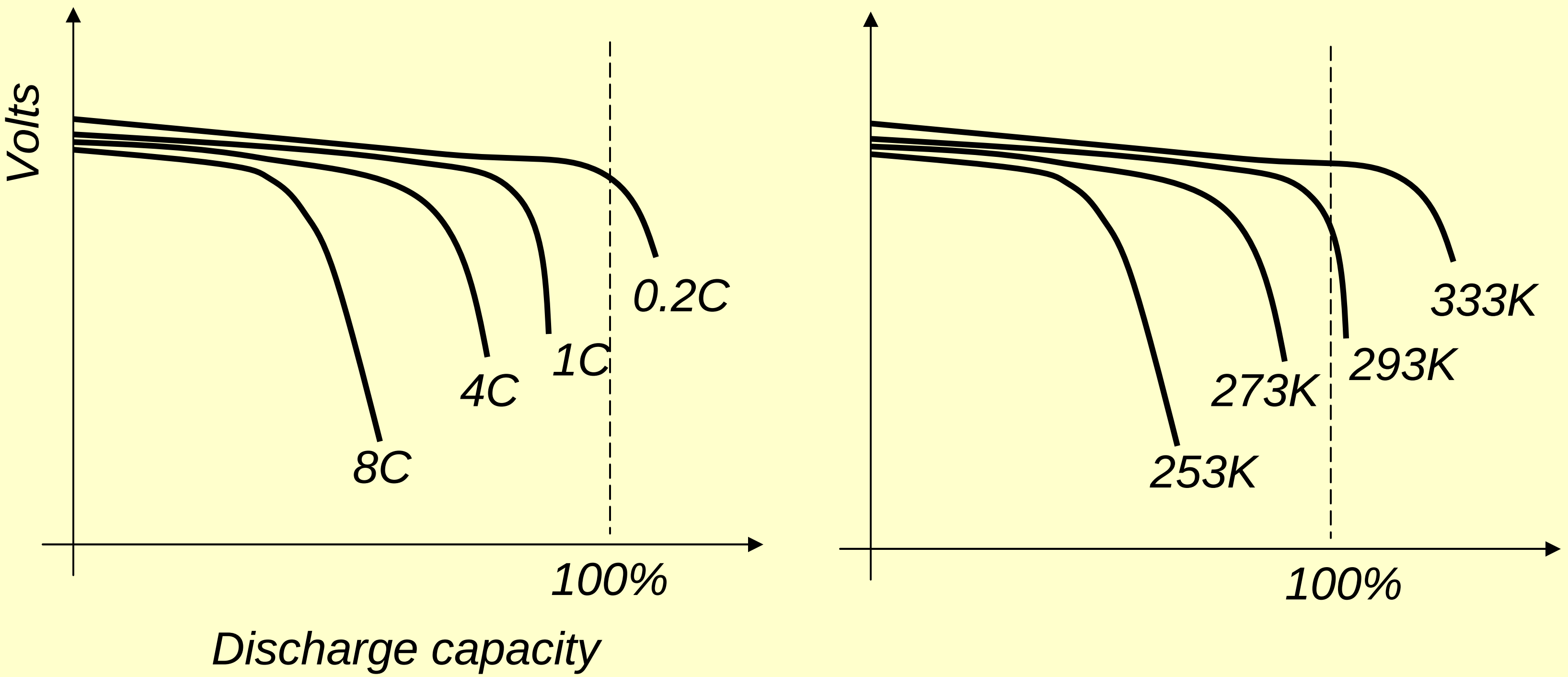
Total Chemistry of the Lead-Acid battery:
$Pb + PbO_2 + 2\ SO_4^{2-} + 4H^+ \rightarrow 2\ PbSO_4 + 2\ H_2O$



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

Berndt, p. 36, 43

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.

Osaka & Datta, p. 30, 61, 63

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Please see Fig. 3 in Rutherford, K., and D. Doerffel.
"Performance of Lithium-Polymer Cells at High Hydrostatic Pressure."
Proceedings of the Symposium on Unmanned Untethered Submersible Technology, 2005.

From Rutherford & Doerffel

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*

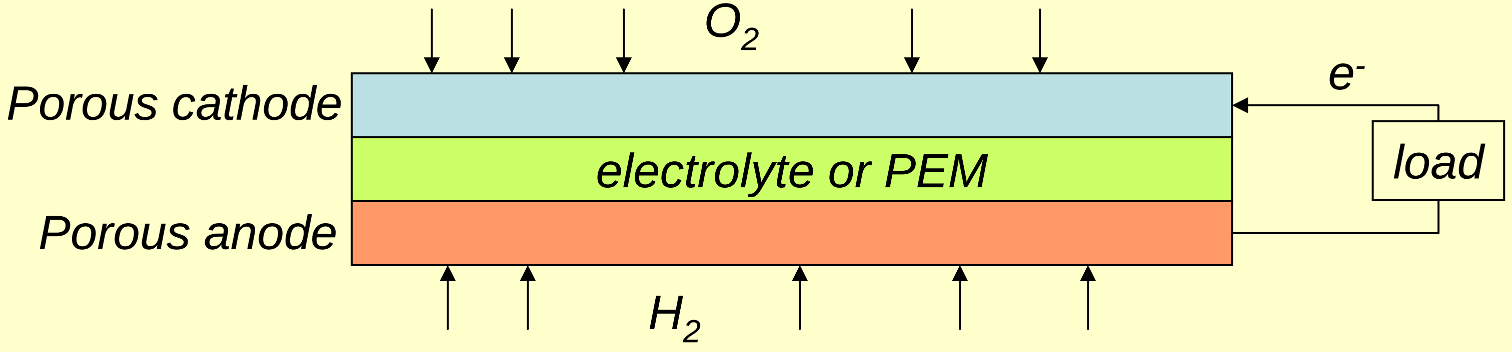
Osaka & Datta, p. 41, 449; Berndt p. 254

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: $2H_2 \rightarrow 4H^+ + 4e^-$
- At cathode, electrons are absorbed:

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_20$$

- 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.



Larminie & Dicks

Some Fuel Cell Issues

- High sensitivity to impurities: e.g., PEMFC is permanently poisoned by 1ppb sulfide.
- Weight cost of storage of H_2 in metal hydrides is 66:1; as compressed gas: 16:1.
- Oxidant storage: as low as 0.25:1
- Reformation of H_2 from other fuels is complex and weight inefficient: e.g., Genesis 20L Reformer supplies H_2 at ~ 0.05 kW/kg
- Ability of FC to change load rapidly.
- ***Typical Overall Performance Today:***

0.025 kW/kg, 0.016 kW/l

Larminie & Dicks, ch. 8, Griffiths et al.

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 ~0.65MJ/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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