Class 10
Spacecraft Propulsion

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Typical Propulsion Requirements

Function	ΔV Requirements
Launch to LEO	8500 – 9000 m/s
LEO orbit raising	up to 1600 m/s
LEO drag makeup	up to 600 m/s
LEO deorbit	100 – 160 m/s
Interplanetary trajectories	> 3200 m/s

Nomenclature

- Words: engine, motor, rocket, thruster
  → all used in the same meaning
- engine – usually liquid rocket
- motor – usually solid rocket
- thruster – usually a small rocket

Classification of Rockets – Energy Source

Cold-gas thrusters (attitude control)

Chemical propulsion: liquid and solid

- **Liquid**
  - **monopropellant**: self reacts exothermically, i.e. with heat release
    hydrazine N_2H_4; hydrogen peroxide H_2O_2
  - **bipropellant**: two reactants: fuel and oxidizer
    fuel: kerosene (RP-1), H_2, methane (CH_4), hydrazine (N_2H_4)
    unsymmetrical dimethylhydrazine (UDMH) – $(CH_3)_2NNH_2$
    monomethylhydrazine (MMH) – CH_3NHNH_2
    oxidizer: O_2, nitric acid (HNO_3), nitrogen tetroxide (N_2O_4) (NTO)
- **Solid**: fuel and oxidizer are combined into a solid mixture called the grain
- **Hybrid** liquid and solid, for example solid fuel and liquid oxidizer

Solar

- generate electricity (for electric propulsion) or direct heating of the propellant

Nuclear (fission, fusion, radioactive isotope decay)

- generate electricity (for electric propulsion) or direct heating of the propellant

Nozzle Expansion

- exhaust/exit velocity, U_e
- propellant flow rate $\dot{m}$
- subscripts: **e** = exhaust/exit; **a** = ambient
- pressures P_e and P_a

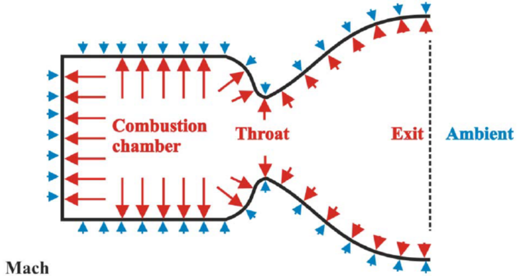
Transition from a subsonic flow to a supersonic flow can occur only at a throat (converging-diverging, or De Laval, nozzle)

$$\boxed{F_{TH} = \dot{m}U_e + A_e\left(P_e - P_a\right) = \dot{m}U_{eq}}$$

$P_e = P_a$ ⇔ correct or optimum expansion

$$\boxed{U_{eq} = U_e + \frac{A_e\left(P_e - P_a\right)}{\dot{m}}}$$

g_e is a coefficient relating mass and weight
g_e = 9.80665 m/s^2 or **g_e = 32.174 ft/s^2**
even if a rocket is fired at Mars, Jupiter, …



Mach number	M = 0	$M_t = 1$	$M_e > 1$
Pressure	$P = P_0$	$P_t \sim 0.5\, P_0$	$P_e < P_t$
Temperature	$T = T_0$	$T_t \sim (0.75\text{-}0.9)\, T_0$	$T_e < T_t$

Specific Impulse

$$\boxed{I_{SP} = \frac{U_{eq}}{g_E}}$$

$$\boxed{F_{TH} = \dot{m}U_{eq} = \dot{m}\, g_E I_{SP}}$$

$$I_{SP} = F_{TH} / \left(\dot{m} g_E\right)$$

- $[I_{SP}]$ = second
- straightforward characteristic of chemical rockets: the larger the better

Specific Impulse

Specific Impulse

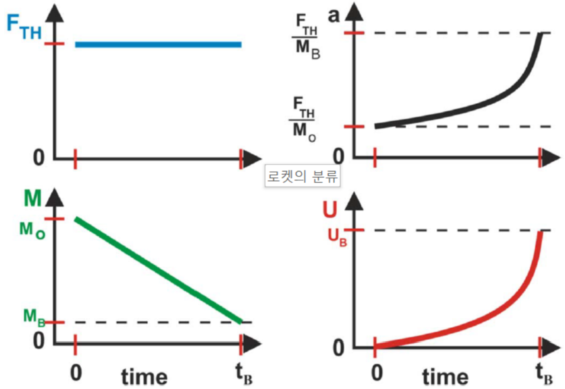
$$U_{eq} = g_E I_{SP}$$

$$U_{eq} = U_e + \frac{A_e (P_e - P_a)}{\dot{m}}$$

	I_{SP}, sec	thrust-to-weight ratio
cold gas (compressed)	60–100	
solid	220–300	up to > 1
monopropellant	150–230	10^{-1} – 10^{-2}
liquid hydrocarbon	250–350	up to > 1 (100)
$H_2 + O_2$	450	up to > 1 (100)
hybrid	350–380	up to > 1
electric	up to 5000 and more	up to 10^{-2}

Only chemical rockets are suitable for launch

Rocket Equation



$$R = \frac{M_0}{M_B}$$

$$\Delta U = u_{eq} \ln R$$

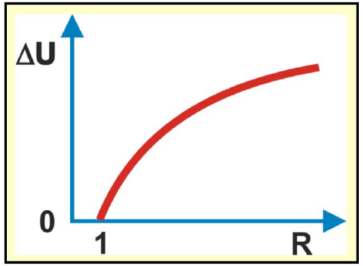
mass ratio R

$$u_{eq} = g_e I_{SP}$$

$$\Delta U = g_e I_{SP} \ln R$$

Assume

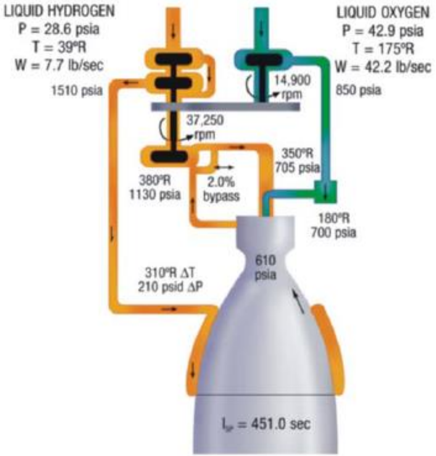
- no gravity
- no drag
- $\dot{m}$ = constant
- F_{TH} = constant
- t_B is the burnout time
- **U** is the rocket speed



- M_L – mass of the payload (satellite, warhead, ...)
- M_P – propellant mass; M_S – structural mass
- initial mass $M_0 = M_L + M_P + M_S$
- burnout mass (mass at the end of the thrust period)
  $M_B = M_L + M_S$

Rocket Heat Transfer and Basic Cooling Methods

- combustion temperatures of rocket propellants > melting points of common metals
- strength of most materials rapidly declines with temperature increase



Regenerative cooling
- long duration operation under thermal equilibrium
- used on all large liquid-propellant launch vehicle engines
- fuel or oxidizer used as a coolant (flowing in tubes on the chamber walls)
- increase in the exhaust velocity 0.1–1.5%

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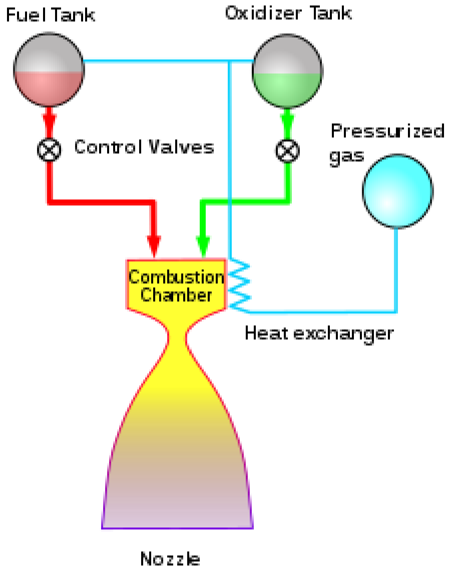
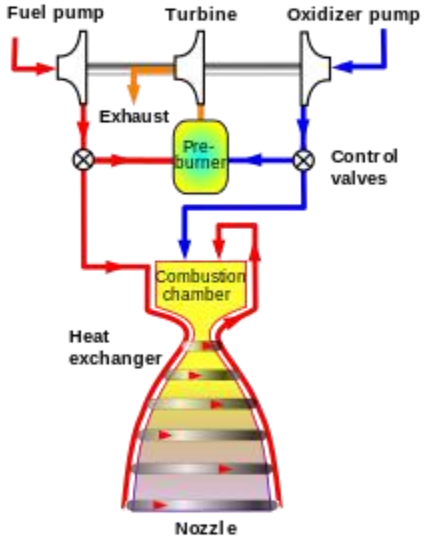
Propellant Feed Systems: Gas-Pressure Systems

- Gas-pressure systems



- Turbopump systems

  (Gas-generator cycle)



Thank you!