EPFL

EPFL Space Center eSpace

Space Propulsion ENG-510

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Lecture # 2
Part # 2
Introduction in Propulsion Systems

Brief overview on all space propulsion systems

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What is the principle of Space Propulsion?

Basic Working Principle for Propulsion:

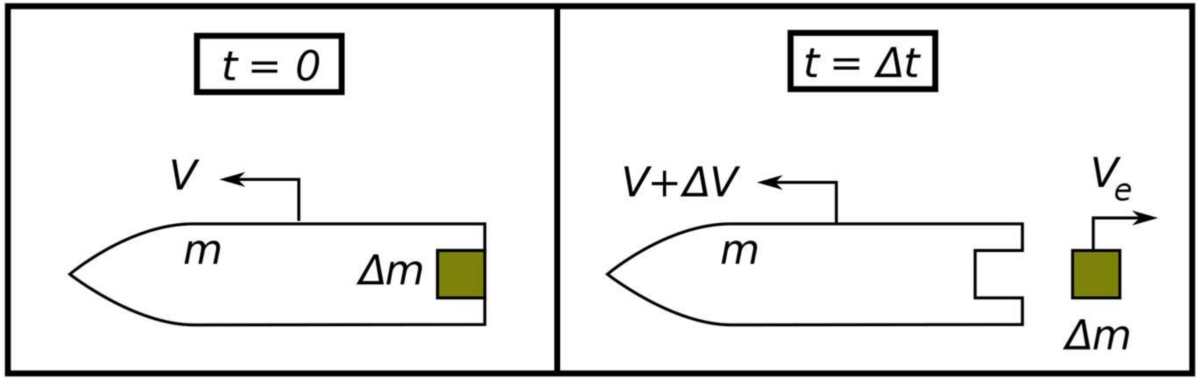
- In its simplest form, a propulsion system accelerates matter to provide a force of thrust that moves or rotates a vehicle
- Example: Small row boat on the lake of Geneva
- Basic rocket equation (Tsiolkovsky rocket equation):
  The basis principle of a classical rocket engine is to eject mass with a high velocity. The recoil of this ejection is then increasing the velocity of the Spacecraft (S/C) including the Payload (P/L) as well as the remaining propellant

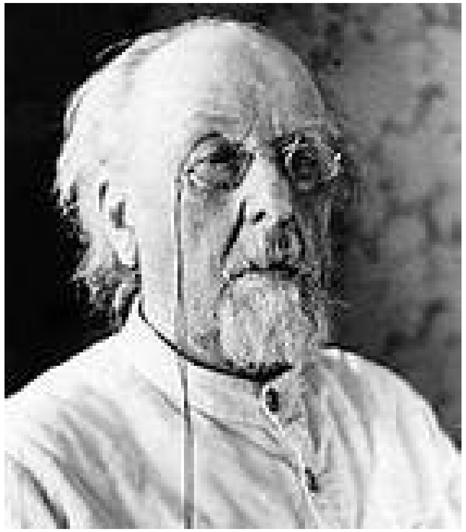
What is the principle of Space Propulsion?

Basic Working Principle for Propulsion:

- Basic rocket equation (Tsiolkovsky rocket equation)

$$\Delta v = v_e ln \frac{m_0}{m_1}$$





Konstantin Tsiolkovsky

What is the principle of Space Propulsion?

Basic Working Principle for Propulsion:

- Basic rocket equation (Tsiolkovsky rocket equation)

$$\Delta v = v_e ln \frac{m_0}{m_1}$$

Δv...Delta v - maximal change of velocity of the vehicle (with no external forces acting like gravitational forces or drag) [m / s]

v_e…Exhaust velocity [m / s]

m_0…Mass @ t_0 [kg]

m_1… Mass @ t_1 [kg]

What is the principle of Space Propulsion?

Basic Working Principle for Propulsion:

- Mass relations for different time steps:

$$m_1 = m_0 - \Delta m$$

Δm...Ejected mass [kg]

$$m_w = m_d + m_p$$

m_w…Initial total mass (including propellant – i.e. wet mass) [kg]

m_d…Final total mass (without propellant – i.e. dry mass) [kg]

m_p...Propellant mass [kg]

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What is the principle of Space Propulsion?

Basic Working Principle for Propulsion:

- Basic rocket equation (Tsiolkovsky rocket equation)

$$\frac{m_w}{m_d} = e^{\frac{\Delta v}{v_e}}$$

$$\frac{m_d + m_p}{m_d} = e^{\frac{\Delta v}{v_e}}$$

$$m_d + m_p = m_d e^{\frac{\Delta v}{v_e}}$$

$$m_p = m_d e^{\frac{\Delta v}{v_e}} - m_d$$

What is the principle of Space Propulsion?

Basic Working Principle for Propulsion:

- Basic rocket equation (Tsiolkovsky rocket equation)

$$m_p = m_d(e^{\frac{\Delta v}{v_e}} - 1)$$

Exhaust velocity describes the magnitude for the performance of the propulsion system in relation with complexity, risk, cost, …

$$MR = \frac{m_w}{m_d} = \frac{m_d + m_p}{m_d} \Rightarrow \Delta v = v_e lnMR$$

MR…Mass ratio between initial mass and final mass [-]

What is the principle of Space Propulsion?

Basic Working Principle for Propulsion:

- Performance of orbital maneuvers (small changes of orbit trajectory)
- Compensation of perturbations (orbit raising to compensate drag losses)
- Long duration burns (for significant Δv increases)
- Attitude control (with short, directed thrust (impulse, force push) linked to 3-axis control)
- Landing burns (for landing on the Moon)
- Lift-off burns requiring high thrust levels

What is the principle of Space Propulsion?

Basic Working Principle for Propulsion:

- Example: How can we maximize the speed of the row boat on the Water?
- Example: What was the problem with the Water rocket failing to reach an orbit respectively the targeted altitude of 100 m?

What is important on Δv?

Objective: To understand some specific points on Δv

- First one must differ between v and Δv
- v is the current velocity of a Spacecraft on his trajectory
- v could be constant on a circular orbit or changing permanently on an elliptical orbit (w/o any propulsion)
- Δv is the impulse which must be given to a Spacecraft to change the trajectory (e.g. change from elliptical to circular orbit or vice-versa)

What is important on Δv?

Objective: To understand some specific points on Δv

- Δv is not only resulting from space propulsion systems
- Δv is not only velocity change but also orbit change
- Δv is not only linked to start point and end point only but also on the way between the two points (orbital trajectory)
- Δv is not equal to velocity change
- Δv is the same for deceleration and acceleration

What is important on Δv?

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What is important on Δv?

Objective: To understand some specific points on Δv

- Δv is not only resulting from space propulsion systems
- Δv changes are also given due to drag forces, gravitational forces, … and similar
- Example: ISS is altitude is reduced every day by about 50 to 150 m linked to residual drag forces

What is important on Δv?

Objective: To understand some specific points on Δv

- Δv is not only resulting from space propulsion systems
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What is important on Δv?

Objective: To understand some specific points on Δv

- Δv is not only a velocity change but also directly an orbit change (which makes rendezvous maneuver is space very tricky…)
- Δv could be called as index / key increment of a space journey
- Changing the Δv is changing the orbit and also changing the energy of the spacecraft

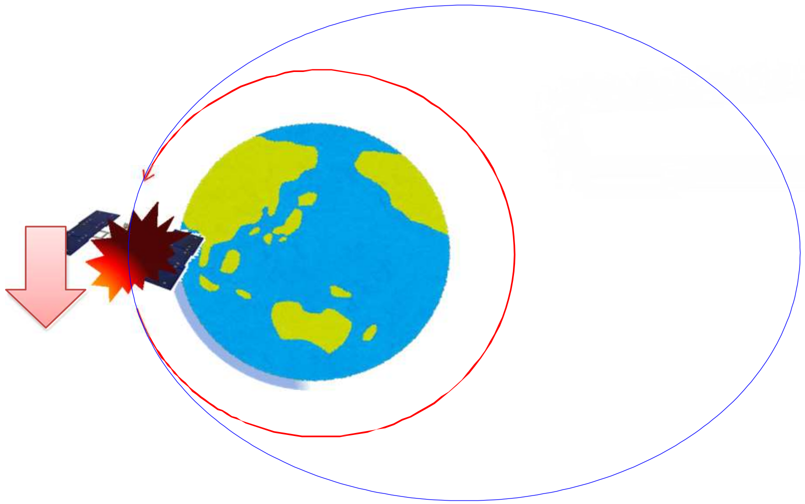
$$E = \frac{1}{2} m v^2 - m \frac{\mu}{r}$$

μ…Standard gravitational parameter [m^3 / s^2] (Earth 3.986E14 m^3/s^2)

What is important on Δv?

Objective: To understand some specific points on Δv

- Important Δv impulse on circular orbit changes the trajectory to an elliptical orbit (assuming escape velocity is not reached) and increasing the energy



What is important on Δv?

Objective: To understand some specific points on Δv

- On the elliptical orbit the real velocity is permanently changing (as well as radius of flight trajectory) considering the Energy conservation
- This velocity change is occurring without any further space propulsion impulse, just linked to the orbital trajectory and the Energy conservation which is described by the vis-viva equation

What is important on Δv?

Objective: To understand some specific points on Δv

- Vis-viva equation in astrodynamics the orbital-energy-invariance law:

$$v^2 = \mu\left(\frac{2}{r} - \frac{1}{a}\right)$$

v…Speed of an orbiting body [m / s]
μ…Standard gravitational parameter [m³ / s²] (Earth 3.986E14 m³/s²)
r…Distance of the orbiting body from the primary focus / body [m]
a…Semi-major axis of the body's orbit [m]

What is important on Δv?

Objective: To understand some specific points on Δv

- Δv is not (really) time dependent following the basic rocket equation

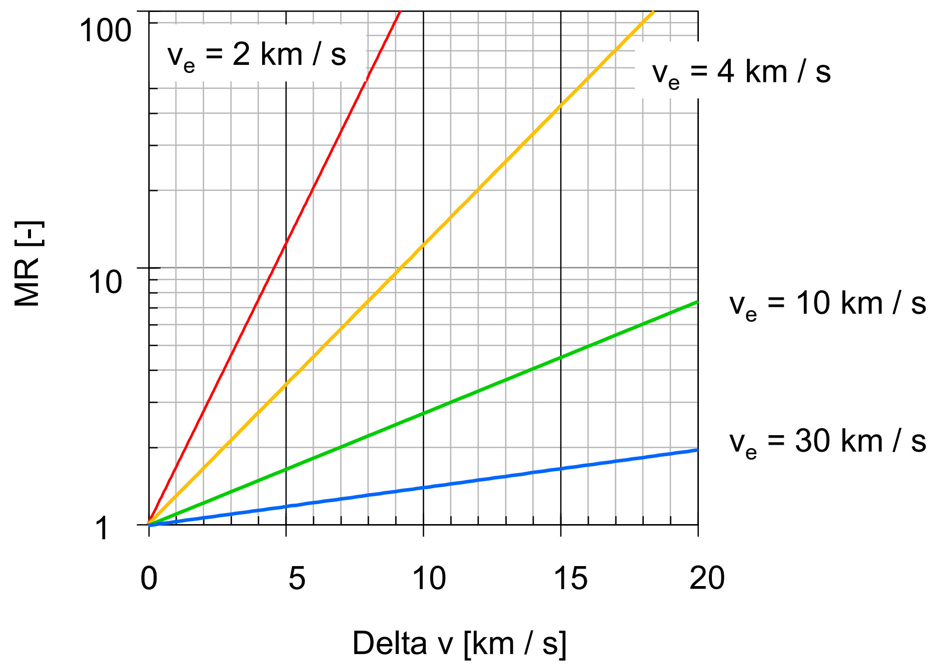
$$\Delta v = v_e ln \frac{m_0}{m_1}$$

- In other words, the efficiency of orbit changes is increased in case the impulse is given in a very short time span
- In that sense it is helpful to consider multiple engines for increasing mass exhaust but on the other hand mass ratio MR is also changed
- Trade-off needs to be performed between efficiency gain versus mass penalty

What is important on Δv?

Objective: To understand some specific points on Δv

- For same Δv need, the mass ratio (MR) between initial mass (dry mass + propellant mass) to final mass (dry mass) is smaller for higher exhaust velocity (v_e), i.e. efficiency is higher



What is important on Δv?

Objective: To understand some specific points on Δv

- Exhaust velocity is often referred to as specific impulse

$$I_{sp} = \frac{v_e}{g_0}$$

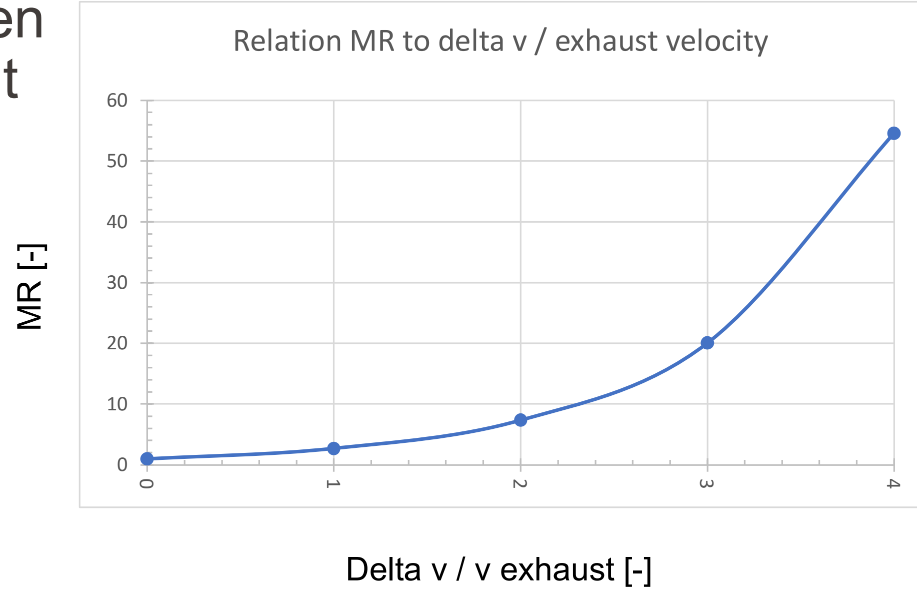
I_{sp}…Specific impulse [s]

g_0…Earth gravitational acceleration [m / s²] (9.807 m/s²)

What is important on Δv?

Objective: To understand some specific points on Δv

- For given mass ratio (MR) between initial mass (dry mass + propellant mass) to final mass (dry mass), maximal achievable Δv is depending on the effective exhaust velocity (v_e)
- Necessary wet mass grows exponentially with the desired Δv



What is important on Δv?

Objective: To understand some specific points on Δv

- Example 1: Assume an exhaust velocity of 4500 meters per second and a delta v target of 9700 meters per second (corresponding to the needed delta v for a Low Earth Orbit (LEO) including delta v need to overcome gravitational and drag forces) for a single-stage-to-orbit

$$e^{\frac{9.7}{4.5}} = 8{,}6 \Rightarrow MR = \frac{m_w}{m_d} = \frac{m_d + m_p}{m_d} = 8{,}6 \Rightarrow \frac{m_p}{m_d} = 0{,}884$$

So 88.4 % is the required mass fraction, i.e. 88.4 % of the initial mass must be propellant. The remaining 11.6 % is dry mass, which could be difficult to achieve without special measures (e.g. staging of launchers)

What is important on Δv?

Objective: To understand some specific points on Δv

- Example 2: To achieve a delta v of 10 000 meters per second with an exhaust velocity of 2 000 meters per second a mass ratio of 147 is needed and so a required mass fraction of 99,3 %

What is important on Δv?

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What is important on Δv?

Objective: To understand some specific points on Δv

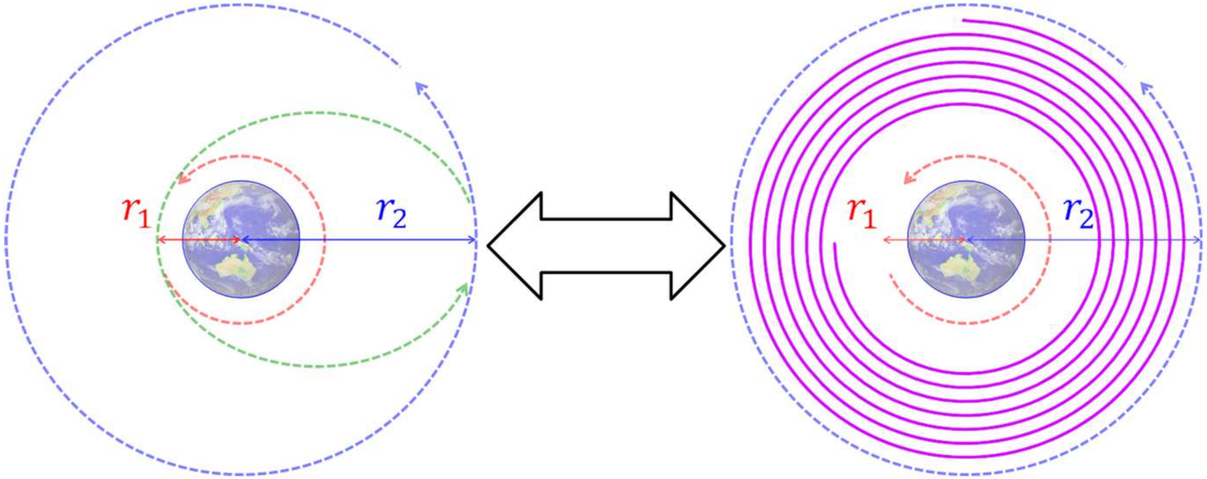
- Δv is not only linked to start point and end point only but also on the way between the two points (orbital trajectory)
- Two main different trajectories are discussed hereafter (not considering any change of inclination for simplification [inclination is the angular distance of the orbital plane from the plane of the planet's equator, stated in degrees])

What is important on Δv?

Objective: To understand some specific points on Δv

- Two classical orbital changes must be known
  - Hohmann transfer (impulsive maneuver – two short impulses)
  - Edelbaum transfer (long duration maneuver with low thrust – spiral orbit raising)

Hohmann Transfer Edelbaum Transfer



What is important on Δv?

Objective: To understand some specific points on Δv

- Hohmann transfer is a two-impulse orbit transfer
  - Acceleration in a period sufficiently smaller than the orbital period
  - Basic maneuver in chemical propulsion
  - Transfer from perigee (point close to Earth) to apogee (point far from Earth) on an elliptical trajectory

What is important on Δv?

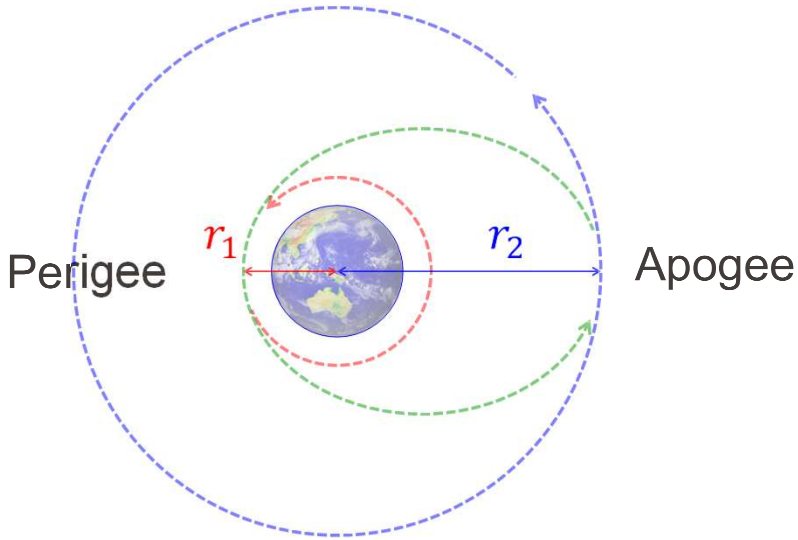
Objective: To understand some specific points on Δv

- Δv need for a Hohmann transfer is determined by (as derived from the vis-viva-equation considering instantaneous impulses):

$$\Delta v_1 = \sqrt{\frac{\mu}{r_1}}\left(\sqrt{\frac{2r_2}{r_1+r_2}} - 1\right)$$

$$\Delta v_2 = \sqrt{\frac{\mu}{r_2}}\left(1 - \sqrt{\frac{2r_1}{r_1+r_2}}\right)$$

$$\Delta v_{tot} = \Delta v_1 + \Delta v_2$$



What is important on Δv?

Objective: To understand some specific points on Δv

- Example: Δv need for a geostationary transfer considering the Hohmann transfer beginning at r_1 = 6 678 km (altitude 300 km) and ending in a geostationary Earth orbit with r_2 = 42 164 km (altitude 35 786 km)
- In the smaller circular orbit, the speed is 7.73 km / s; in the larger one, 3.07 km / s. In the elliptical orbit in between the speed varies from 10.15 km / s at the perigee to 1.61 km / s at the apogee
- Therefore, the Δv for the first burn is 10.15 − 7.73 = 2.42 km / s, for the second burn 3.07 − 1.61 = 1.46 km / s, and for both together the total Δv is 3.88 km / s

What is important on Δv?

Objective: To understand some specific points on Δv

- Spiral orbit raising is a continuous thrust orbit transfer
  - Basic maneuvers in electric propulsion (Assumptions: tangential thrust, constant thrust and velocity = circular orbit velocity at its radius

What is important on Δv?

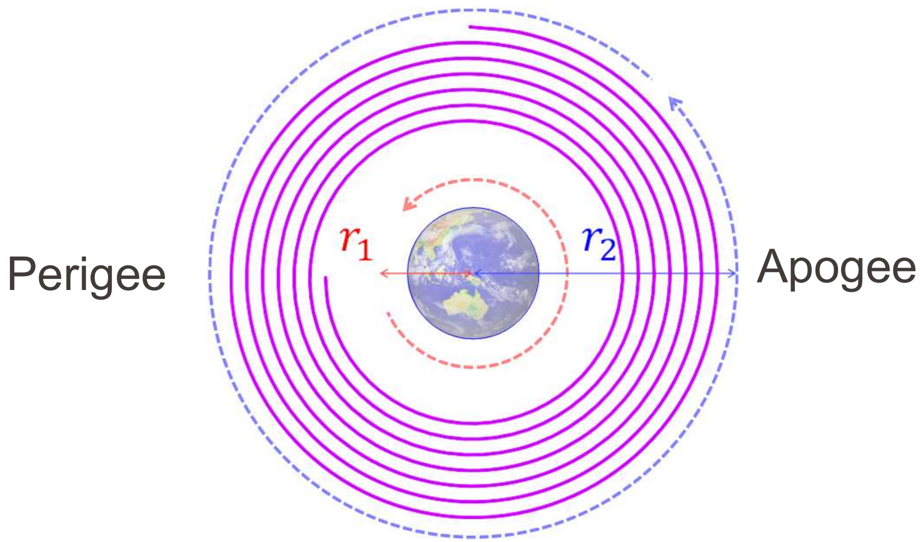
Objective: To understand some specific points on Δv

- Δv need for an Edelbaum transfer (spiral orbit raising) is determined by the following equations:

$$\Delta v_1 = \sqrt{\frac{\mu}{r_1}}$$

$$\Delta v_2 = \sqrt{\frac{\mu}{r_2}}$$

$$\Delta v_{tot} = \Delta v_1 - \Delta v_2$$



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- Example: Δv need for a geostationary transfer considering the Edelbaum transfer beginning at r_1 = 6 678 km (altitude 300 km) and ending in a geostationary Earth orbit with r_2 = 42 164 km (altitude 35 786 km)
- In the smaller circular orbit the speed is 7.73 km / s; in the larger one, 3.07 km / s
- Therefore the total Δv need for an Edelbaum transfer is 7.73 − 3.07 = 4.66 km / s, so higher compared to a Hohmann transfer requiring a total Δv of 3.88 km / s

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What is important on Δv?

Objective: To understand some specific points on Δv

- Hohmann transfer versus spiral orbit raising
  - Hohmann transfer is much faster
  - Hohmann transfer requires high thrust
  - Δv increase is higher for spiral orbit raising

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What is important on Δv?

Objective: To understand some specific points on Δv

- Δv is not equal to velocity change
- Δv and actual velocity depend on the orbit like for LEO (h = 420 km, v = 7.66 km/s)
- Assuming continuous thrust in the direction of acceleration
- Altitude will increase, but “velocity” will decrease in this circular orbit raise (h = 620 km, v = 7.55 km/s)
- Also as stated before, Energy will increase

What is important on Δv?

Objective: To understand some specific points on Δv

- Changing the energy of the spacecraft during spiral transfer in circular orbit

$$\frac{E}{m} = \frac{1}{2} v^2 - \frac{\mu}{r}$$

- Energy level # 1 for initial orbit (h = 420 km, v = 7.66 km/s)

$$\frac{E}{m} = \frac{1}{2} 7.66^2 - \frac{\mu}{6.800} = -29.3 \frac{MJ}{kg}$$

What is important on Δv?

Objective: To understand some specific points on Δv

- Energy level # 2 for final orbit raise (h = 620 km, v = 7.55 km/s)

$$\frac{E}{m} = \frac{1}{2}7.55^2 - \frac{\mu}{7.000} = -28.4\frac{MJ}{kg}$$

- Example: Hohmann transfer / Edelbaum transfer from Low Earth Orbit to Geostationary Earth Orbit compared to escape orbit
- Δv required for an escape obit is 10.93 − 7.73 = 3.20 km / s

What is important on Δv?

Objective: To understand some specific points on Δv

- Applying a Δv at LEO of only 0.78 km / s more (3.20 − 2.42) would give the rocket the escape velocity, which is less than the Δv of 1.46 km / s required to circularize the geosynchronous orbit
- This illustrates the Oberth effect, that at large speeds the same Δv provides more specific orbital energy, and energy increase is maximized if one spends the Δv as quickly as possible, rather than spending some, being decelerated by gravity, and then spending some more to overcome the deceleration

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- **Δv is the same for deceleration and acceleration**

What is important on Δv?

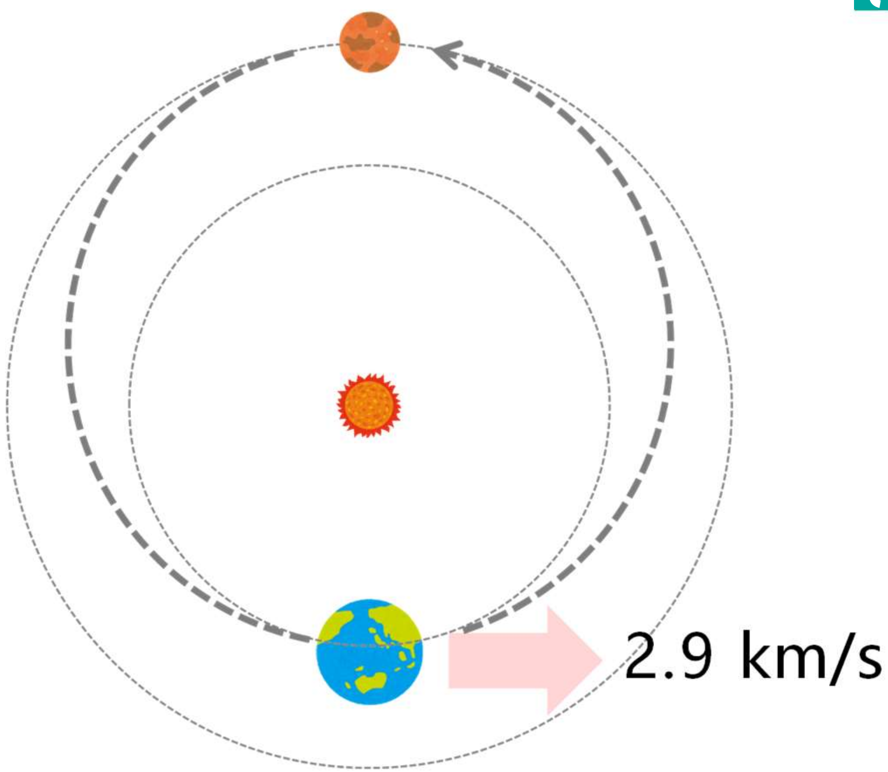
Objective: To understand some specific points on Δv

- Δv is the same for deceleration and acceleration
- Δv is the same going from LEO to GEO or from GEO to LEO
- One transfer is only supported by acceleration whereas the other one is referring to deceleration

What is important on Δv?

Objective: To understand some specific points on Δv

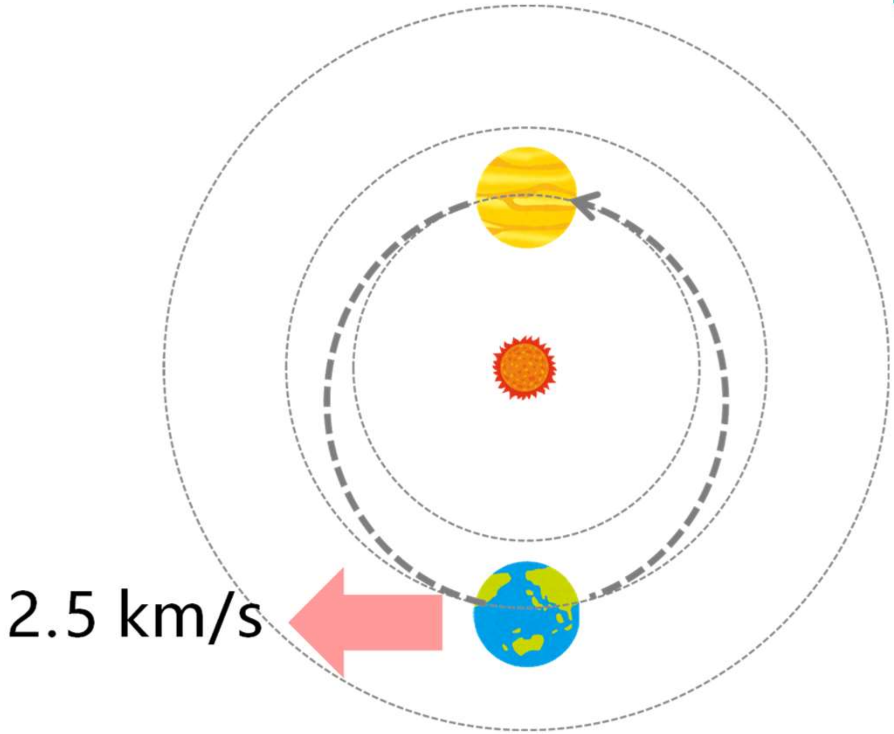
- Δv is the same for deceleration and acceleration
- One can reach Mars by escaping the Earth with Δv of + 2.9 km / s



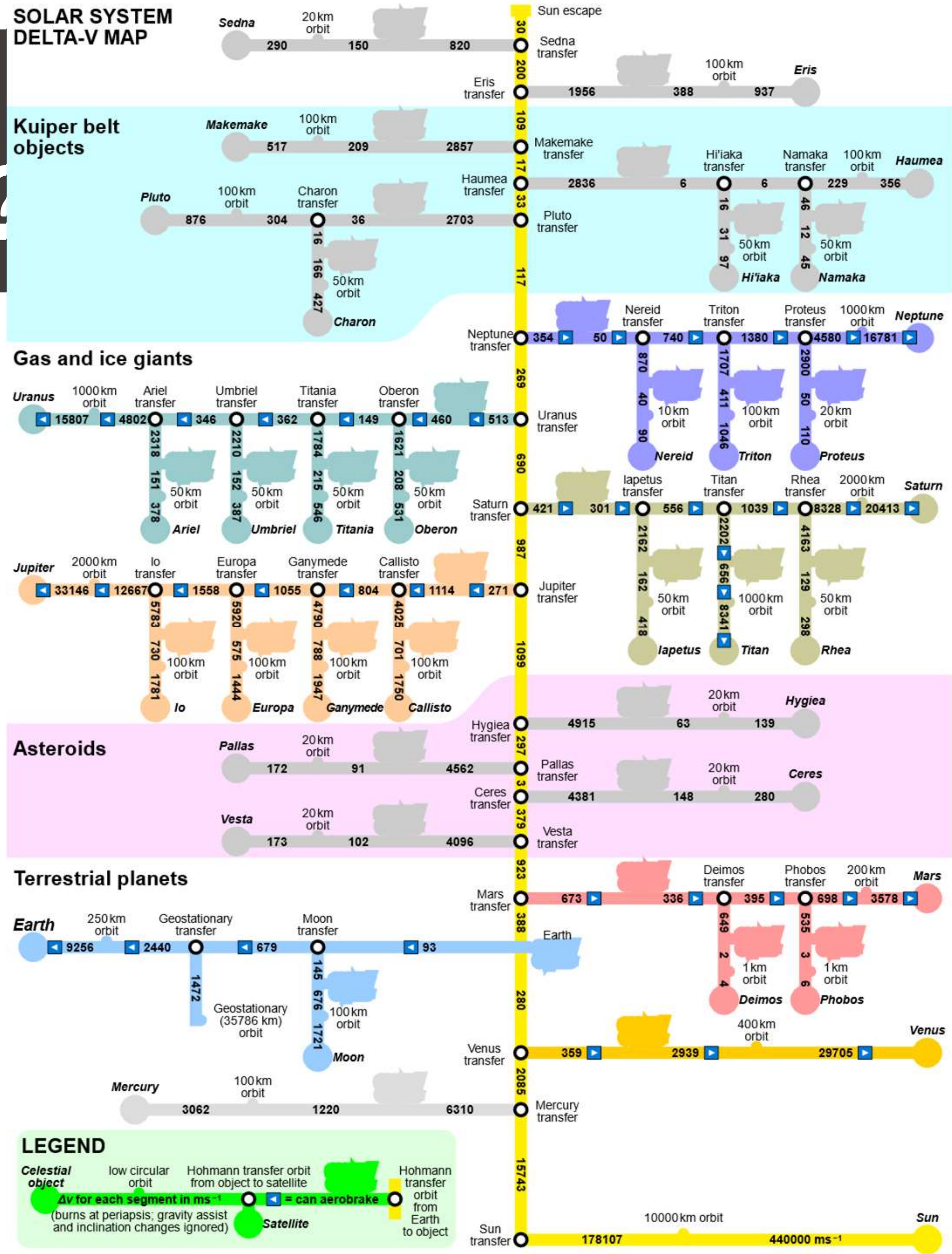
What is important on Δv?

Objective: To understand some specific points on Δv

- One can reach Venus by escaping the Earth with Δv of - 2.5 km / s as a deceleration maneuver
- Deceleration is not easy at all, but completely same effort is needed as for acceleration (while traveling on the Earth we do have already a certain velocity…)



What on Δv?



SOLAR SYSTEM DELTA-V MAP
Sun escape
Sedna
20 km orbit
290
150
820
Sedna transfer
30
200
Eris transfer
1956
388
937
100 km orbit
Eris
Kuiper belt objects
Makemake
100 km orbit
517
209
2857
109
Makemake transfer
Haumea transfer
2836
6
6
229
356
Hi'iaka transfer
Namaka transfer
100 km orbit
Haumea
Pluto
100 km orbit
Charon transfer
876
304
36
2703
Pluto transfer
17
33
16
166
427
50 km orbit
Charon
16
31
97
50 km orbit
Hi'iaka
46
12
45
50 km orbit
Namaka
117
Gas and ice giants
Neptune transfer
354
50
740
1380
4580
16781
Nereid transfer
Triton transfer
Proteus transfer
1000 km orbit
Neptune
870
40
90
10 km orbit
Nereid
1707
411
1046
100 km orbit
Triton
2900
50
110
20 km orbit
Proteus
269
Uranus
1000 km orbit
Ariel transfer
Umbriel transfer
Titania transfer
Oberon transfer
15807
4802
346
362
149
460
513
Uranus transfer
2318
151
378
50 km orbit
Ariel
2210
152
387
50 km orbit
Umbriel
1784
215
546
50 km orbit
Titania
1621
208
531
50 km orbit
Oberon
690
Saturn transfer
421
301
556
1039
8328
20413
Iapetus transfer
Titan transfer
Rhea transfer
2000 km orbit
Saturn
2162
162
418
50 km orbit
Iapetus
2202
656
8341
1000 km orbit
Titan
4163
129
298
50 km orbit
Rhea
987
Jupiter
2000 km orbit
Io transfer
Europa transfer
Ganymede transfer
Callisto transfer
33146
12667
1558
1055
804
1114
271
Jupiter transfer
5783
730
1781
100 km orbit
Io
5920
575
1444
100 km orbit
Europa
4790
788
1947
100 km orbit
Ganymede
4025
701
1750
100 km orbit
Callisto
1099
Asteroids
Hygiea transfer
4915
63
139
20 km orbit
Hygiea
297
Pallas
20 km orbit
172
91
4562
Pallas transfer
3
Ceres transfer
4381
148
280
20 km orbit
Ceres
379
Vesta
20 km orbit
173
102
4096
Vesta transfer
Terrestrial planets
923
Mars transfer
673
336
395
698
3578
Deimos transfer
Phobos transfer
200 km orbit
Mars
649
2
4
1 km orbit
Deimos
535
3
6
1 km orbit
Phobos
388
Earth
250 km orbit
Geostationary transfer
Moon transfer
9256
2440
679
93
Earth
1472
Geostationary (35786 km) orbit
145
676
1721
100 km orbit
Moon
280
Venus transfer
359
2939
29705
400 km orbit
Venus
2085
Mercury
100 km orbit
3062
1220
6310
Mercury transfer
15743
LEGEND
Celestial object
low circular orbit
Hohmann transfer orbit from object to satellite
Hohmann transfer orbit from Earth to object
Δv for each segment in ms⁻¹
= can aerobrake
(burns at periapsis; gravity assist and inclination changes ignored)
Satellite
Sun transfer
178107
10000 km orbit
440000 ms⁻¹
Sun

What is important on Δv?

Objective: To understand some specific points on Δv

- Δv is key parameter for understanding of space journeys, but
- Δv is not the only parameter…

What is the importance of thrust?

Objective: To discuss thrust + relation to Isp

- How thrust is produced?
- How efficiently thrust can be produced?
- How thrust and thrust efficiency affect the vehicle mass in terms of:
  - Propellant mass?
  - Inert mass required to hold the propellant and provide the thrust?
- Some key topics related to thrust:
  - Launcher versus Satellite propulsion
  - Thrust level on ground
  - Minimization of propellant mass and therefore maximizing of c (efficiency)

What is the importance of thrust?

Objective: To discuss thrust + relation to Isp

- Thrust equation

$$F_m = \frac{dP_{mom}}{dt} = \frac{dm}{dt} v_e = \dot{m} v_e$$

F_m...Momentum thrust magnitude [N]

$\dot{m}$ ...Mass flow rate of the propellant [kg/s]

v_e...Exhaust velocity [m/s]

What is the importance of thrust?

Objective: To discuss thrust + relation to Isp

- Thrust equation linked to pressure

$$F_p = \lambda(\dot{m}v_e + (p_e - p_a)A_e)$$

F_p...Pressure thrust magnitude [N]

p_e…Nozzle exit pressure [N/m²]

p_a…Ambient pressure [N/m²]

A_e…Nozzle exit cross-sectional area [m²]

λ…Nozzle efficiency [-] (typical range between 0.85 – 0.98)

What is the importance of thrust?

Objective: To discuss thrust + relation to Isp

- Relation thrust to specific impulse

$$I_{sp} = \frac{F}{\dot{m} g_0}$$

I_{sp}...Specific impulse [s]
F ... Thrust magnitude [N]

$\dot{m}$ ...Mass flow rate of the propellant [kg/s]

g_0...Earth gravitational acceleration [m/s²] (9.807 m/s²)

What is the importance of thrust?

Objective: To discuss thrust + relation to Isp

- Effective exhaust velocity

$$c = v_e + \frac{(p_e - p_a)A_e}{\dot{m}}$$

c…Effective exhaust velocity [m/s]

$$F_m = \dot{m}c$$

$$c = I_{sp} g_0$$

What is the importance of thrust?

Objective: To discuss thrust + relation to Isp

- Needed propellant mass

$$m_{prop} = \frac{m_{PL}\left(e^{\left(\frac{\Delta v}{I_{sp} g_0}\right)} - 1\right)(1 - f_{inert})}{1 - f_{inert} e^{\left(\frac{\Delta v}{I_{sp} g_0}\right)}}$$

Notice that this equation gives a fundamental limit on vehicle performance. If the denominator is less than or equal to zero, it is impossible to build the vehicle as designed

What is the importance of thrust?

Objective: To discuss thrust + relation to Isp

- Inert mass fraction

$$f_{inert} = \frac{m_{inert}}{m_{prop} + m_{inert}}$$

  f_{inert}...Inert mass fraction [-] (typical range 0.08 to 0.7)
  m_{inert}...Inert mass excluding P/L mass and propellant mass [kg]
  m_{prop}...Propellant mass [kg]

- Inert mass fraction is a performance parameter showing how well the structure is engineered. A small number indicates a high-performance structure whereas a higher number indicates lower performance

What is the importance of thrust?

Objective: To discuss thrust + relation to Isp

- Mission feasibility limit related to specific impulse

$$I_{sp} \geq \frac{\Delta v}{\ln(\frac{1}{f_{inert}})\, g_0}$$

Notice that this equation states that for a given mission (Δv) and a given technology (f_{inert}) the specific impulse must be above a certain value for the system to work

What is the importance of thrust?

Objective: To discuss thrust + relation to Isp

- Total impulse

$$I = \int_0^{t_b} F dt$$

For a system with constant thrust magnitude it follows

$$I = F t_b$$

Total impulse and Δv are related to each other

$$I_{sp} = \frac{I}{m_{prop} g_0}$$

What is the importance of thrust?

Objective: To discuss thrust + relation to Isp

- Thrust-to-Weight ratio

$$\frac{F}{W} = \frac{F}{m g_0}$$

F/W …Thrust-to-weight ratio [-]

- Launch vehicles must have an initial thrust-to-weight ration greater than 1.0 or the vehicle cannot get off the ground
- Thrust-to-weight ratios for upper stage engines can range from 10^{-4} for electric systems to 0 for solid rockets at burn-out

What is the importance of thrust?

Engine	Launcher	Propellant	Exhaust Velocity	Thrust
F1	Saturn V	LOx / RP-1	3.0 km / s	7.7 MN
RD-107	Soyuz	LOx / RP-1	3.1 km / s	1.0 MN
RD-264	Dnepr	NTO / UDMH	3.2 km / s	4.5 MN
SSME	Shuttle	LOx / LH2	4.5 km / s	2.2 MN
LE7A	H2A	LOx / LH2	4.3 km / s	1.1 MN
Vulcain 2	Ariane 5	LOx / LH2	4.3 km / s	1.3 MN
SSRB	Shuttle	Composite	2.7 km / s	13.8 MN
SRB-A	H2A	Composite	2.8 km / s	2.3 MN
M-V-1	M-V	Composite	2.8 km / s	2.4 MN

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Key equations are given in this section for launcher performance analysis

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Example: Assume an exhaust velocity of 4500 meters per second and a delta v target of 9700 meters per second (corresponding to the needed delta v for a Low Earth Orbit (LEO) including delta v need to overcome gravitational and drag forces) for a single-stage-to-orbit

$$e^{\frac{9.7}{4.5}} = 8{,}6 \Rightarrow MR = \frac{m_w}{m_d} = \frac{m_d + m_p}{m_d} = 8{,}6 \Rightarrow \frac{m_p}{m_d} = 0{,}884$$

So 88.4 % is the required mass fraction, i.e. 88.4 % of the initial mass must be propellant. The remaining 11.6 % is dry mass, which could be difficult to achieve without special measures (e.g. staging of launchers)

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- First part is linked to launcher staging
- A multistage rocket or step rocket is a launch vehicle that uses two or more rocket stages, each of which contains its own engines and propellant
- A tandem or serial stage is mounted on top of another stage; a parallel stage is attached alongside another stage
- The result is effectively two or more rockets stacked on top of or attached next to each other

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Two-stage rockets are quite common, but rockets with as many as five separate stages have been successfully launched
- By jettisoning stages when they run out of propellant, the mass of the remaining rocket is decreased
- Each successive stage can also be optimized for its specific operating conditions, such as decreased atmospheric pressure at higher altitudes
- Staging allows the thrust of the remaining stages to more easily accelerate the rocket to its final orbit

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- For multistage rockets standard performance equations are still valid
- Basic rocket equation (Tsiolkovsky rocket equation)

$$\Delta v = v_e ln \frac{m_0}{m_1}$$

- Exhaust velocity is often referred to as specific impulse

$$I_{sp} = \frac{v_e}{g_0}$$

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Thrust equation

$$F_m = \dot{m} v_e$$

- On top of the classical performance equations, dimensionless ratio are interesting in order to optimize launcher staging
- Initial to final mass ratio

$$\eta = \frac{m_d + m_p + m_{PL}}{m_d + m_{PL}}$$

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Structural ratio, which is the ratio between the empty mass of the stage, and the combined empty mass and propellant mass

$$\varepsilon = \frac{m_d}{m_d + m_p}$$

- Payload ratio, which is the ratio between the payload mass and the combined mass of the empty rocket stage and the propellant mass

$$\lambda = \frac{m_{\mathrm{PL}}}{m_d + m_{\mathrm{p}}}$$

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- After comparing the three equations for the dimensionless quantities, it is easy to see that they are not independent of each other, and in fact, the initial to final mass ratio can be rewritten in terms of structural ratio and payload ratio

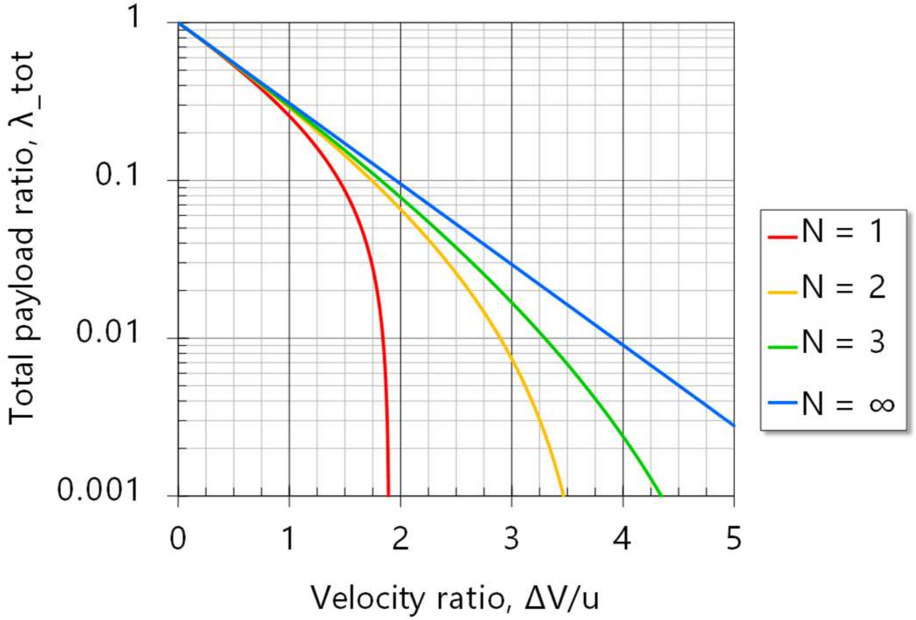
$$\eta = \frac{1 + \lambda}{\varepsilon + \lambda}$$

- The dimensionless ratio can be established for single stage launchers as well as multiple stage launchers

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

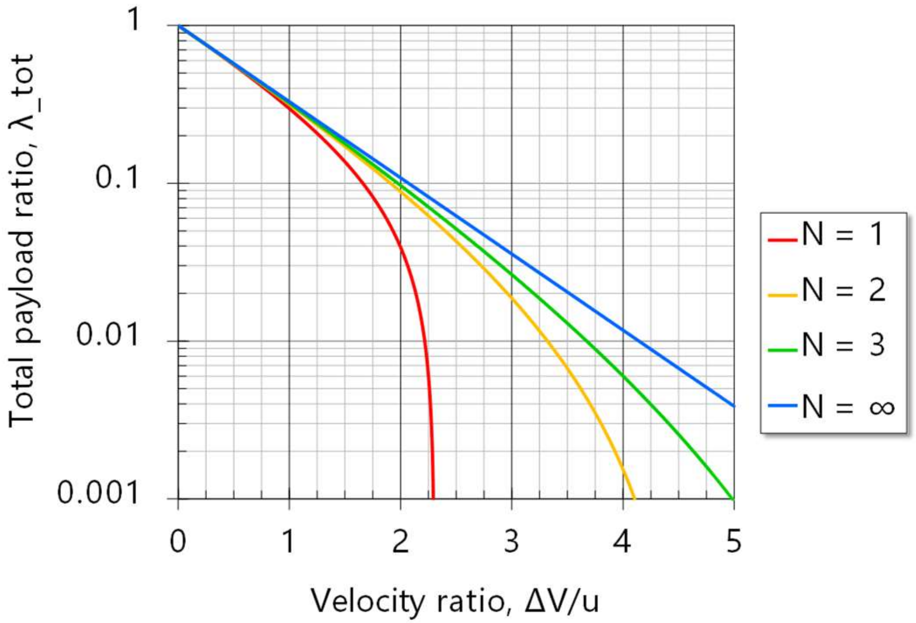
- Example: Multi-stage launcher with ε = 0.15



Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Example: Multi-stage launcher with ε = 0.10



Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

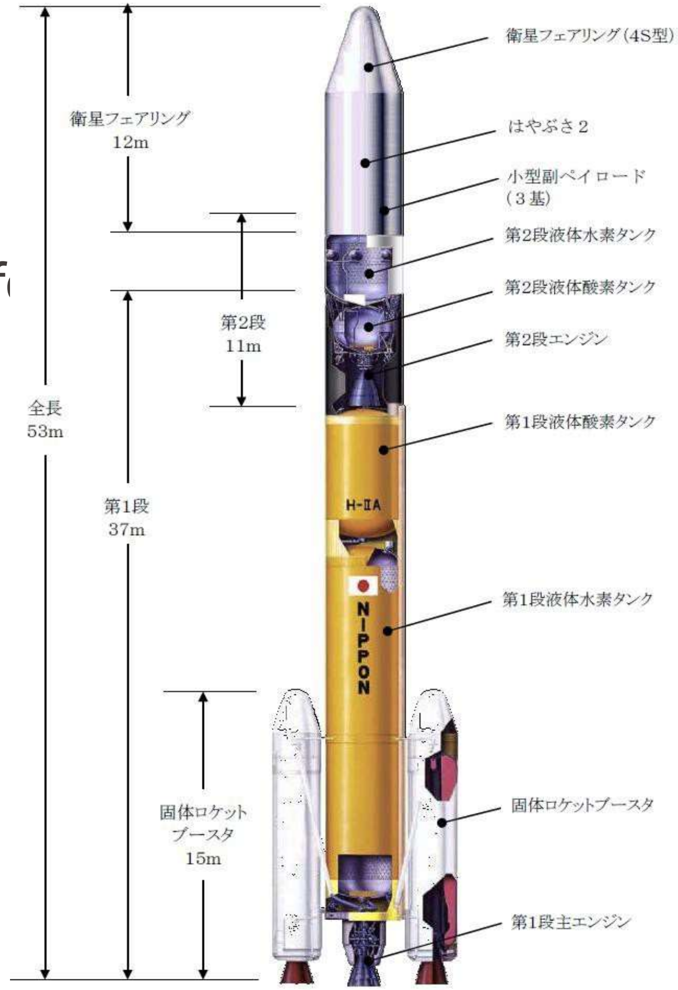
- Performance analysis for a tandem or serial stage is very simple as only one propulsion system is acting at a certain time with clear performance parameter like thrust, specific impulse
- It must only be determined when stages are jettisoned
- The result is effectively two or more rockets stacked on top of or attached next to each other
- Performance analysis for a parallel stage is more tricky

EPFL

Which general Performance Equations are given?

Objective: To analyze propulsion systems perf

- Example: H2A launch vehicle with liquid main engine LE7A with exhaust velocity of 4.31 km / s and two solid rocket booster SRB with exhaust velocity of 2.78 km / s



図－６　ロケットの形状（Ｈ２Ａ２０２型）

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Performance of a launch vehicle using different parallel stages can be assessed by using the effective exhaust velocity
- Effective exhaust velocity

$$c = \frac{F_{tot}}{\dot{m}_{tot}}$$

with F_{tot} as sum of all thrust levels

- Example: H2A launch vehicle with one main liquid engine (1100 kN and 260 kg / s) and two solid rocket boosters (2500 kN and 900 kg / s)

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

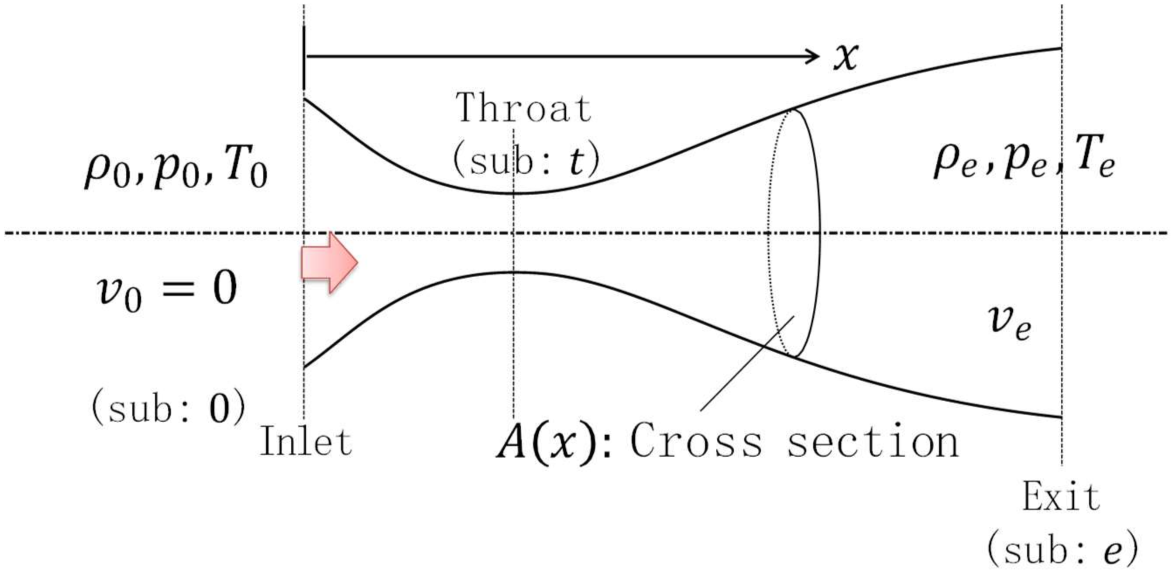
- Example: H2A launch vehicle performance
- Effective exhaust velocity

$$c = \frac{(1100 + 2500 + 2500)}{(260 + 900 + 900)} = 2.96\ \frac{km}{s}$$

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Second part is linked to engine / throat / nozzle performance with flow parameter ρ…density, p…pressure, T…temperature and v…velocity



Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Basic considerations are:
  - Steady flow: All flow variables are independent on the time
  - Quasi-1D flow: All flow variables are function of the axial coordinate
  - Adiabatic flow: No heat transfer to the flow
  - Ideal gas relation is given
  - No viscosity: No momentum loss to the wall

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Recap: Thrust is linked to mass flow rate, exhaust velocity and engine nozzle parameter

$$F_p = \lambda(\dot{m}v_e + (p_e - p_a)A_e)$$

F_p...Pressure thrust magnitude [N]

p_e...Nozzle exit pressure [N/m²]

p_a...Ambient pressure [N/m²]

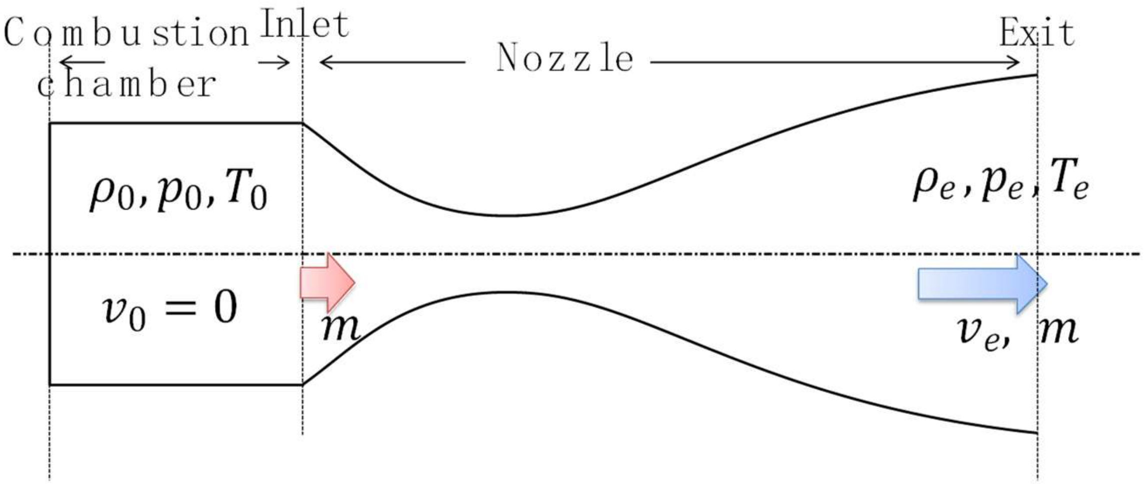
A_e...Nozzle exit cross-sectional area [m²]

λ...Nozzle efficiency [-] (typical range between 0.85 – 0.98)

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Recap: Thrust is linked to mass flow rate, exhaust velocity and engine nozzle parameter

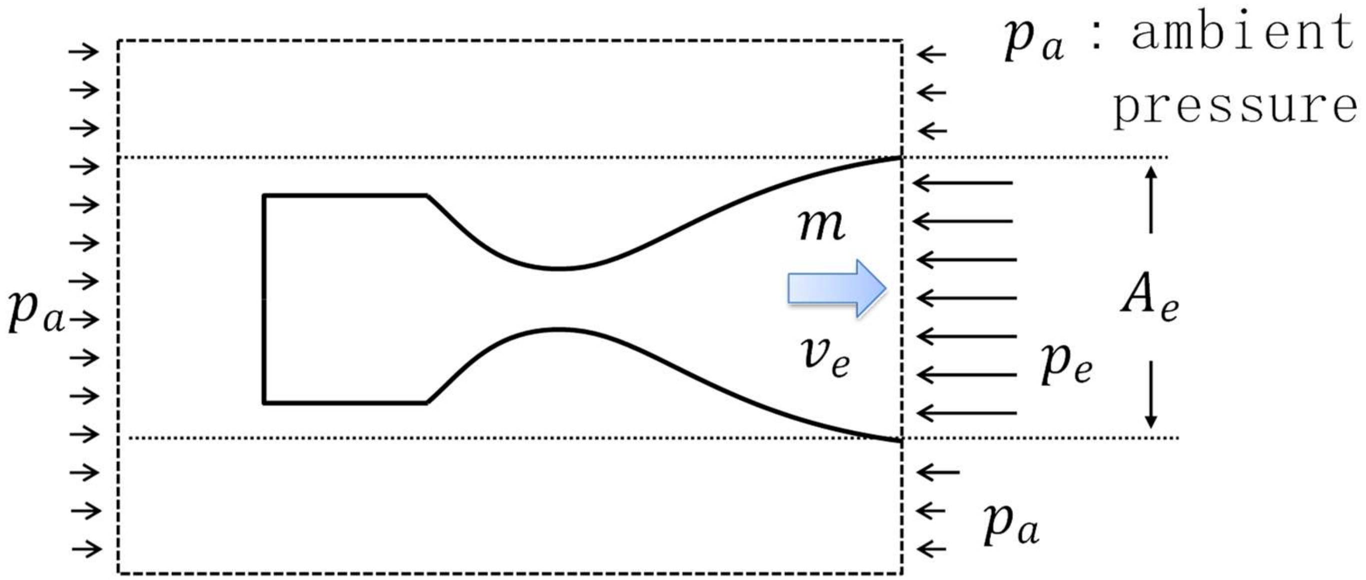


Impulse = Change of momentum

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Recap: Thrust is linked to mass flow rate, exhaust velocity and engine nozzle parameter

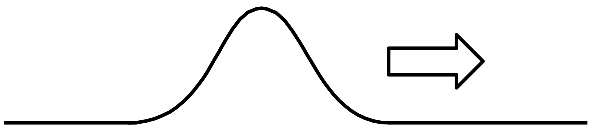


Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Important parameter are also speed of sound (propagation velocity of small disturbances) and the Mach number M (ratio of the flow velocity to the local speed of sound)
- Speed of sound

$$a = \sqrt{\gamma R T}$$



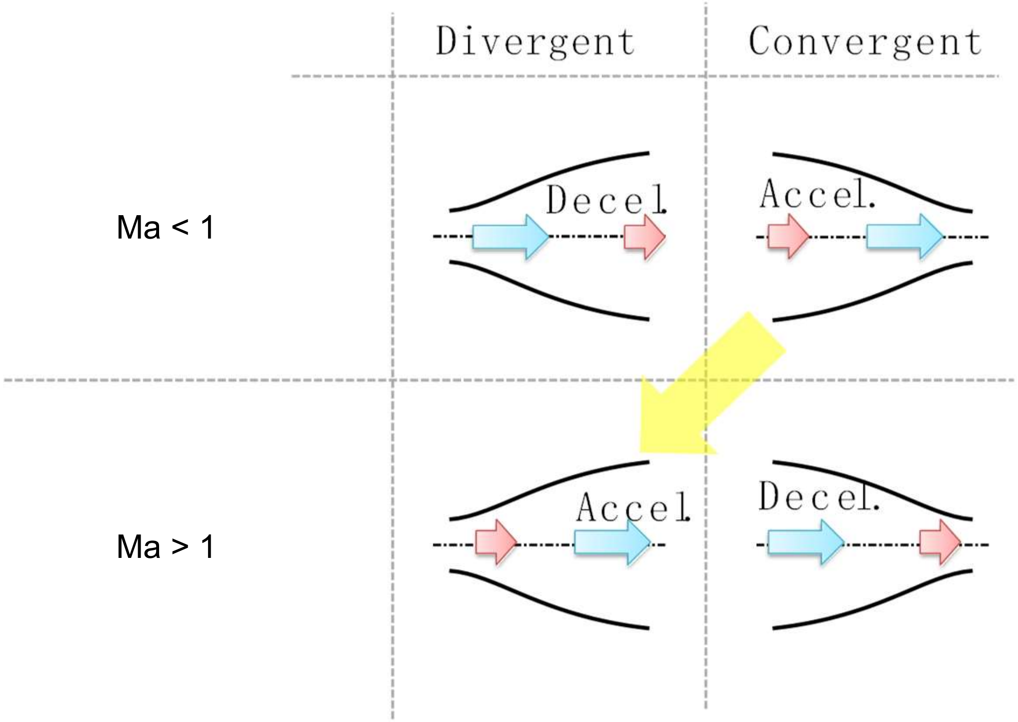
- Mach number

$$Ma = \frac{v}{a}$$

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

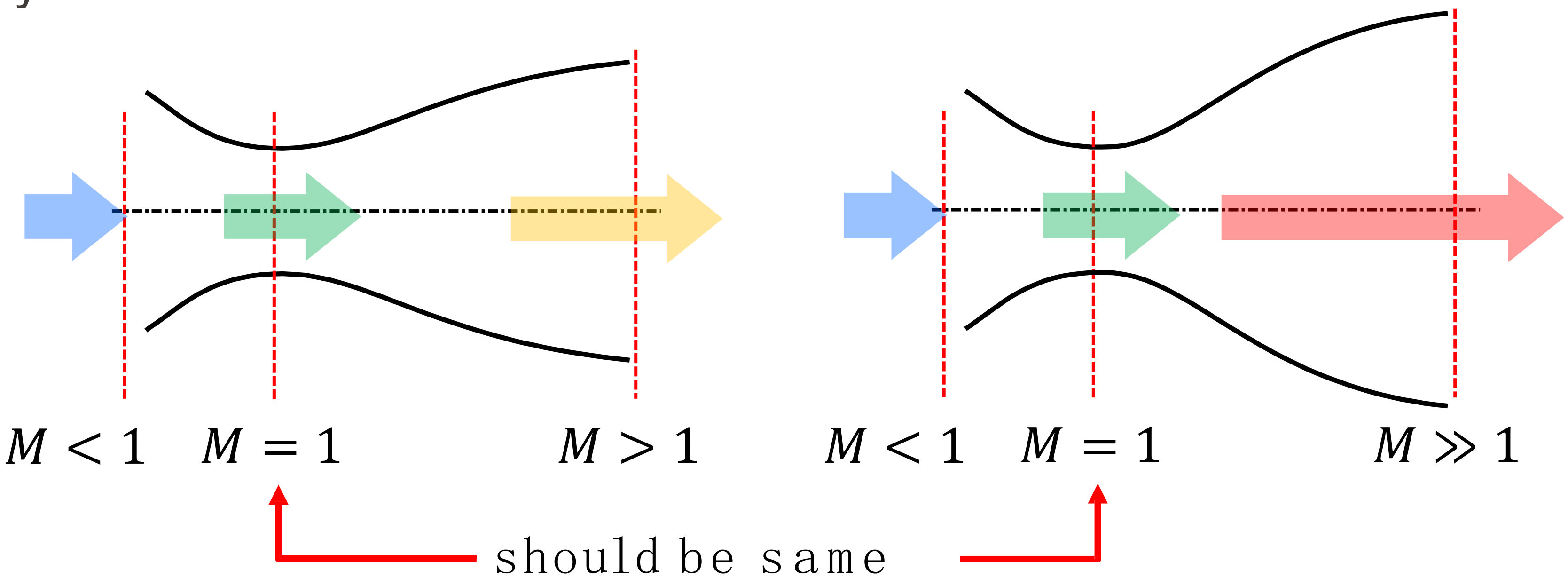
- Ma number is important in terms of flow acceleration / deceleration for different nozzle types



Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Once the flow reaches to Ma = 1 at the throat (= choked conditions), only downstream conditions determine the flow rate



Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

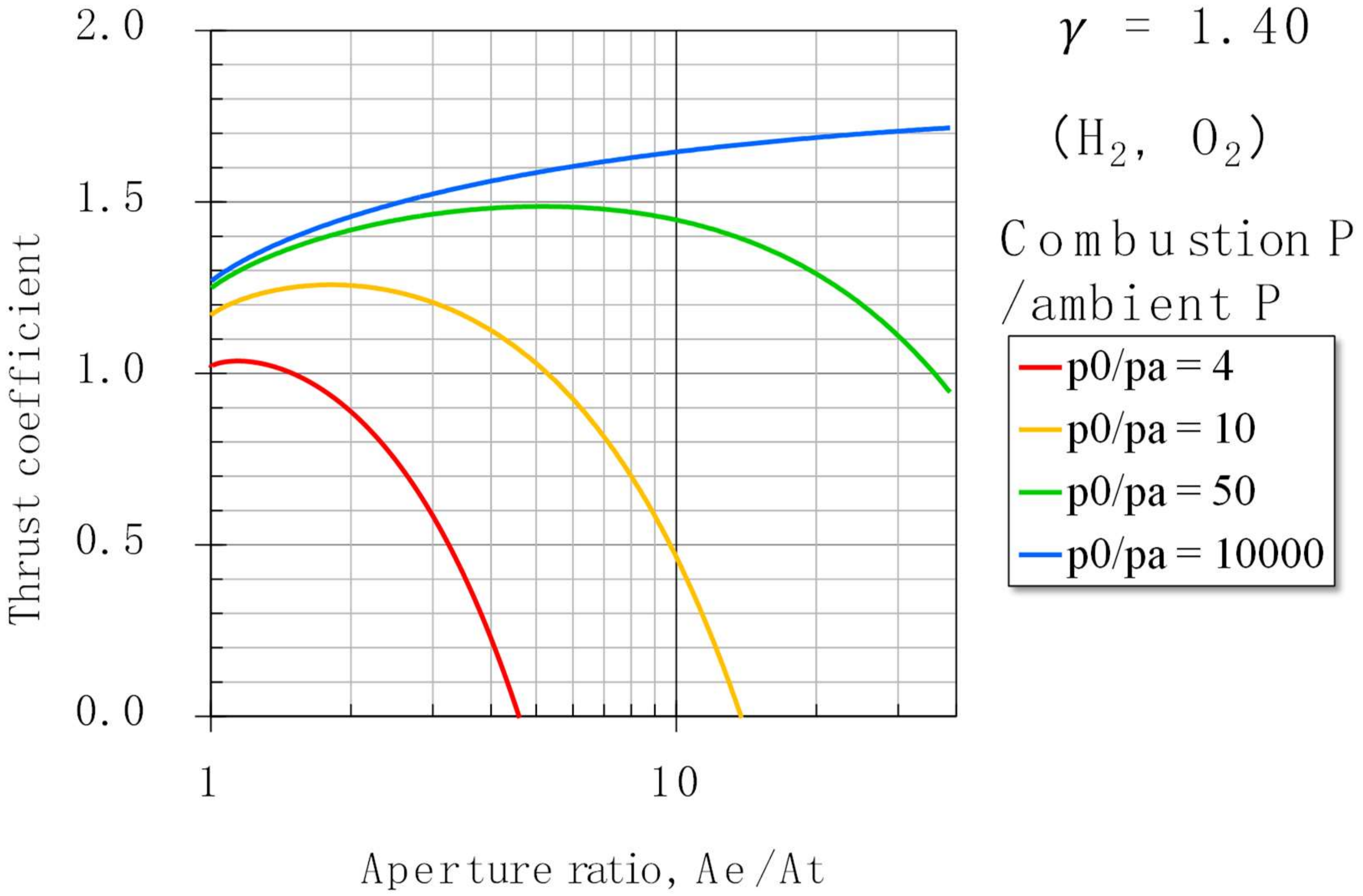
- Thrust equation using the thrust coefficient (thrust coefficient is depending on the aperture ratio and the gas type and is expressing the acceleration of the gas by the nozzle)

$$F = A_t p_C \gamma \sqrt{\left(\frac{2}{\gamma-1}\right)\left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}\left(1-\left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right)} + (p_e - p_a)A_e$$

$$F = A_t p_C c_F$$

c_F ...Thrust coefficient

Which general Performance Equations are given?



Which general Performance Equations are given?

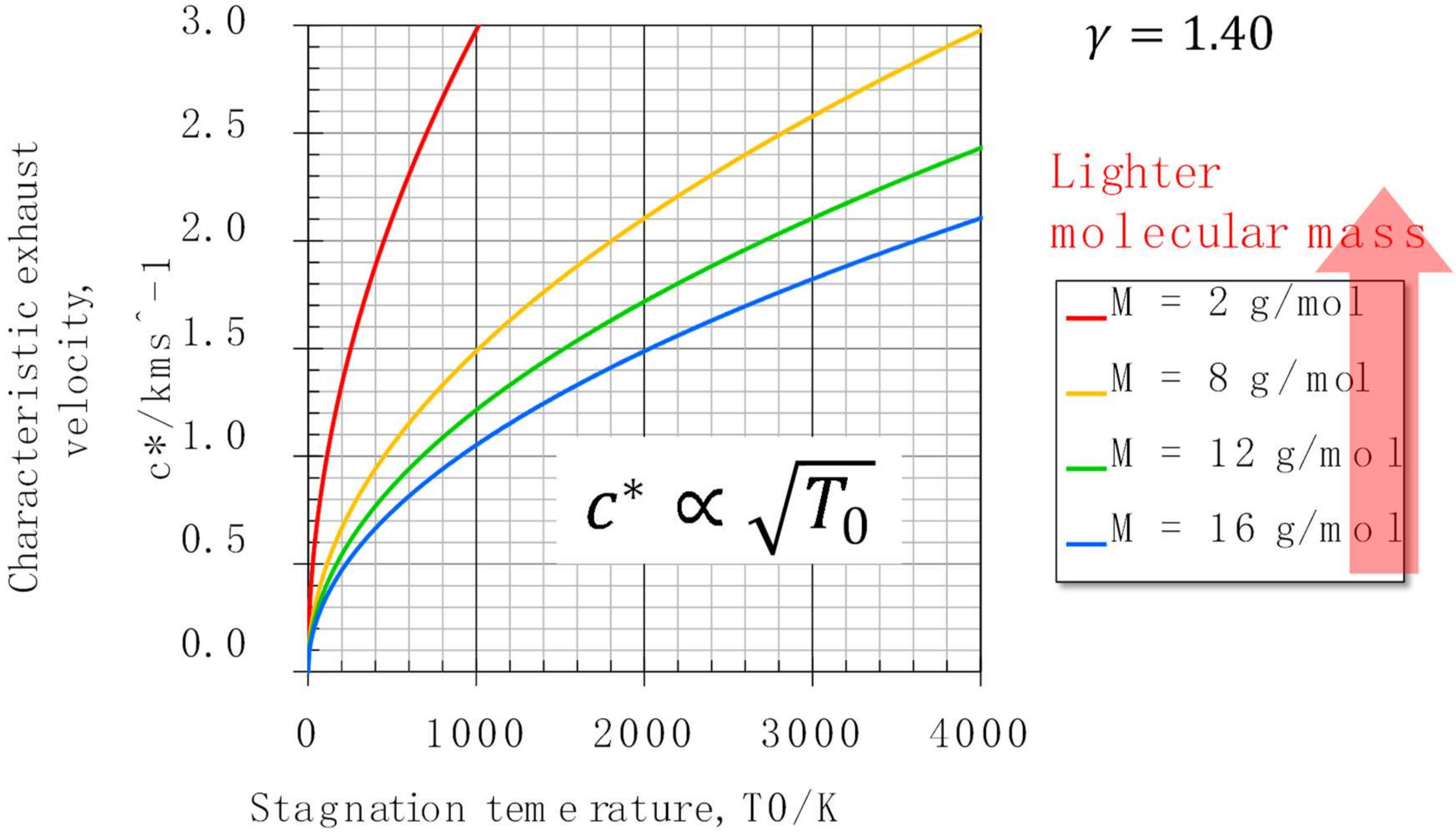
Objective: To analyze propulsion systems performance

- Final important parameter is c* (is depending on the temperature and gas type and is expressing the performance of combustion chamber)

$$c^* = \frac{A_t p_0}{\dot{m}}$$

c^* … Characteristic velocity

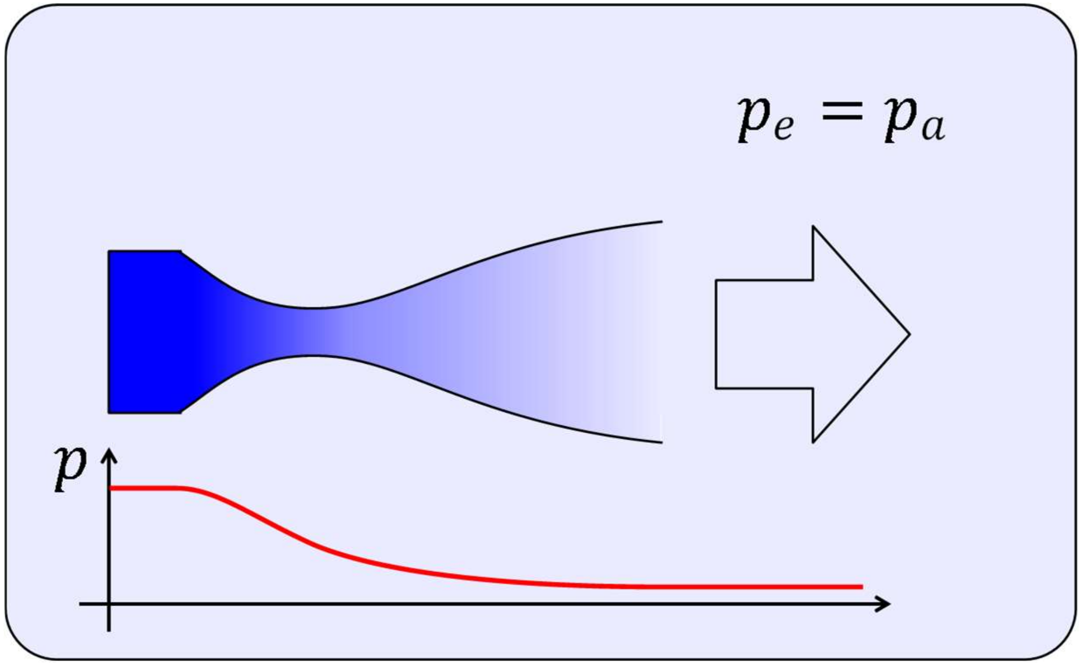
Which general Performance Equations are given?



Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Nozzle layout considerations



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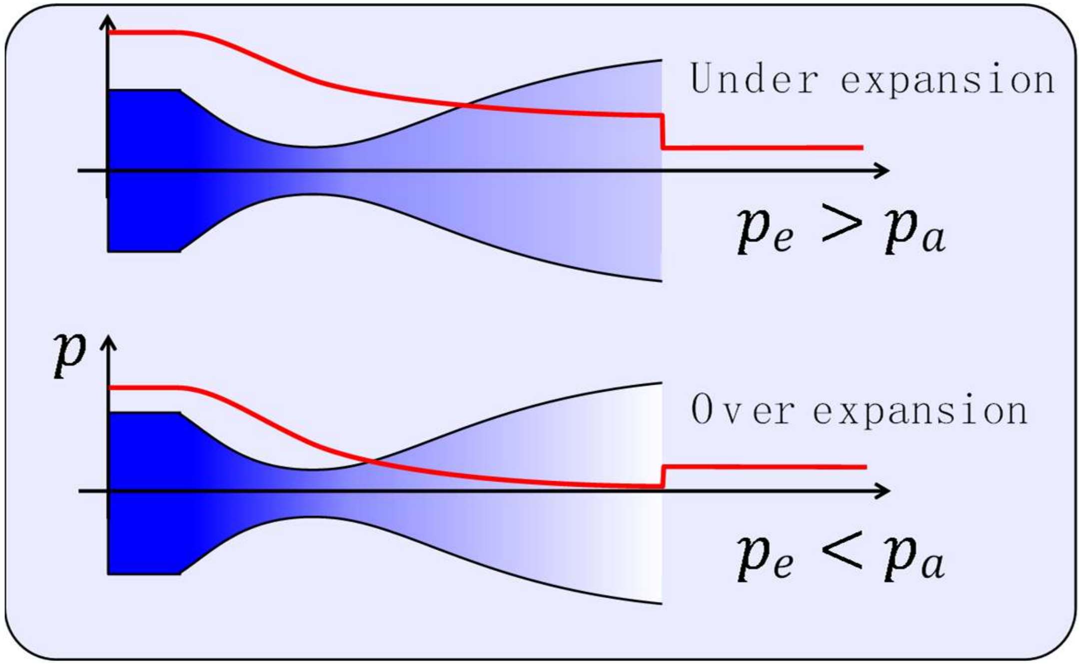

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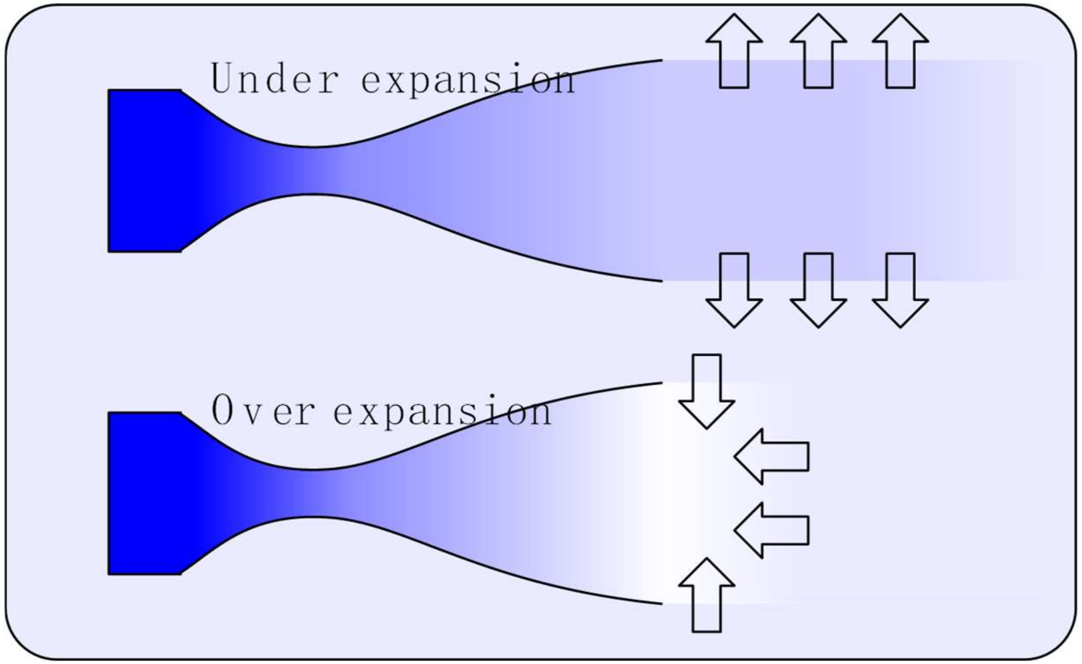
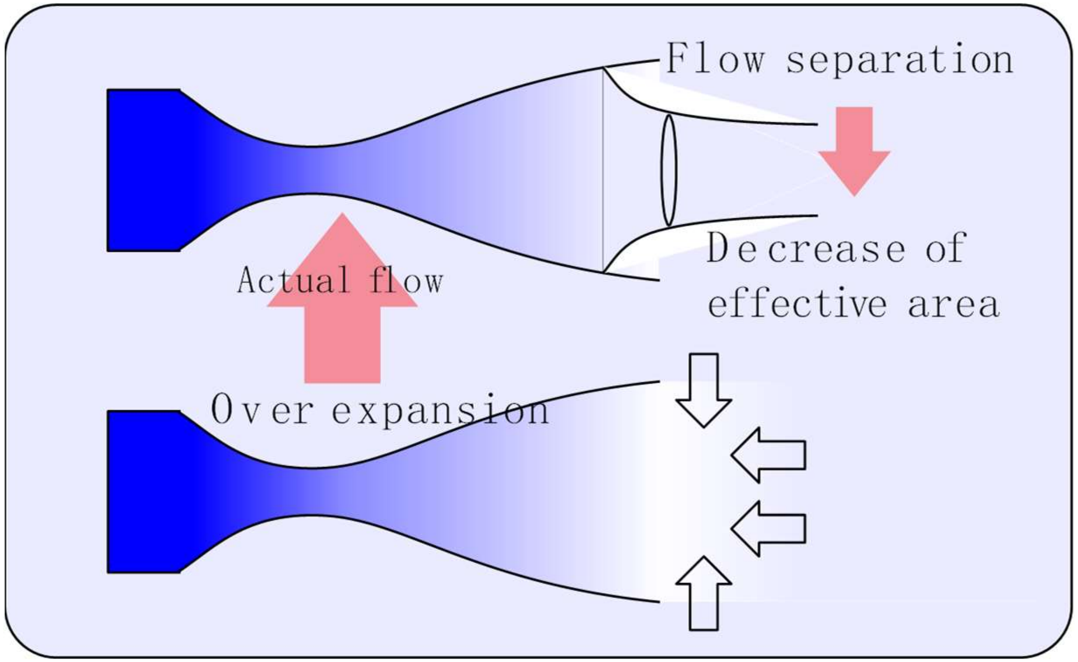


Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Nozzle layout considerations



Which general Performance Equations are given?

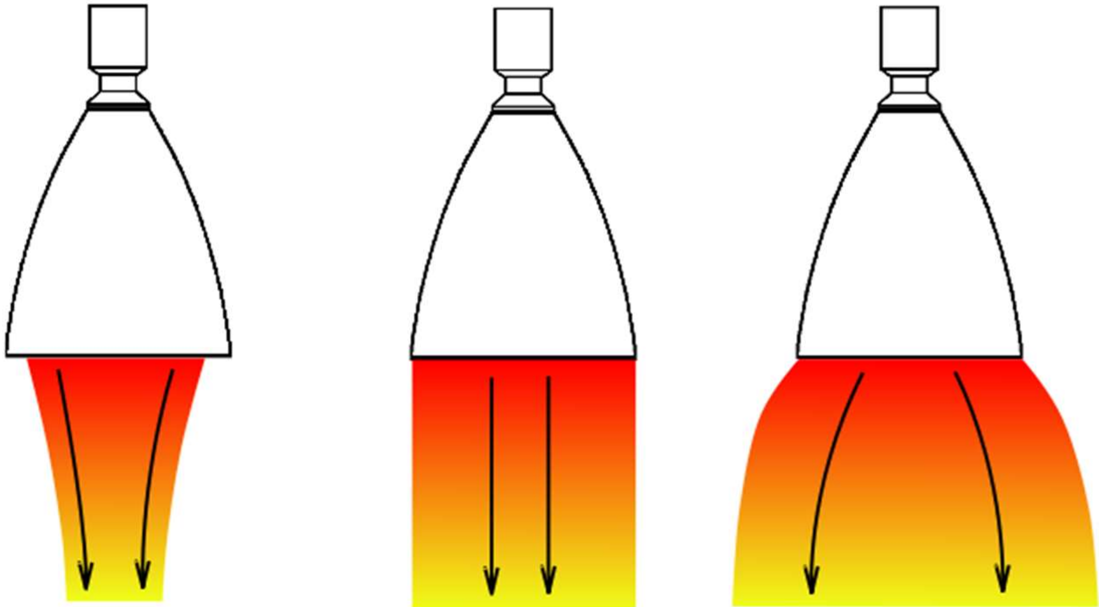
Objective: To analyze propulsion systems performance

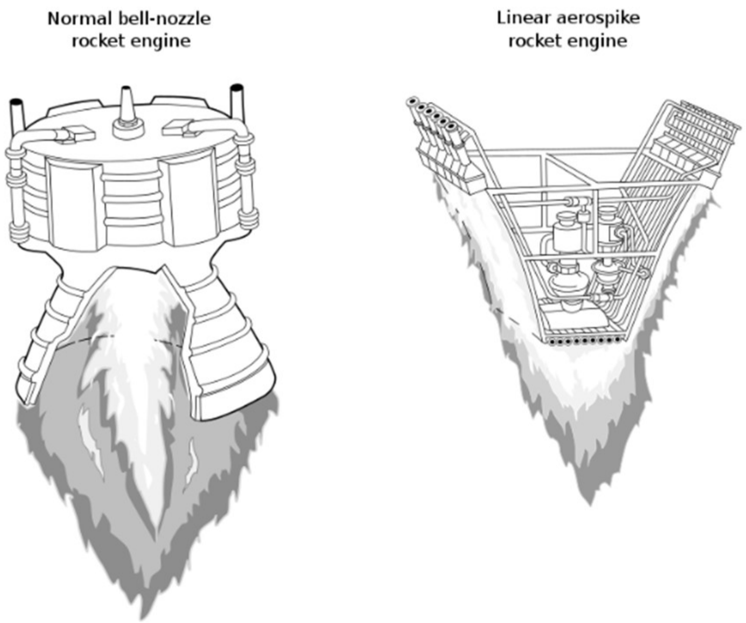
- Test as you fly and fly as you test…
- Example: Sea-level testing of large engines instead of altitude (vacuum) testing

Which general Performance Equations are given?

Objective: To analyze propulsion systems performance

- Bell-shaped nozzle extensions compared to aerospike engines

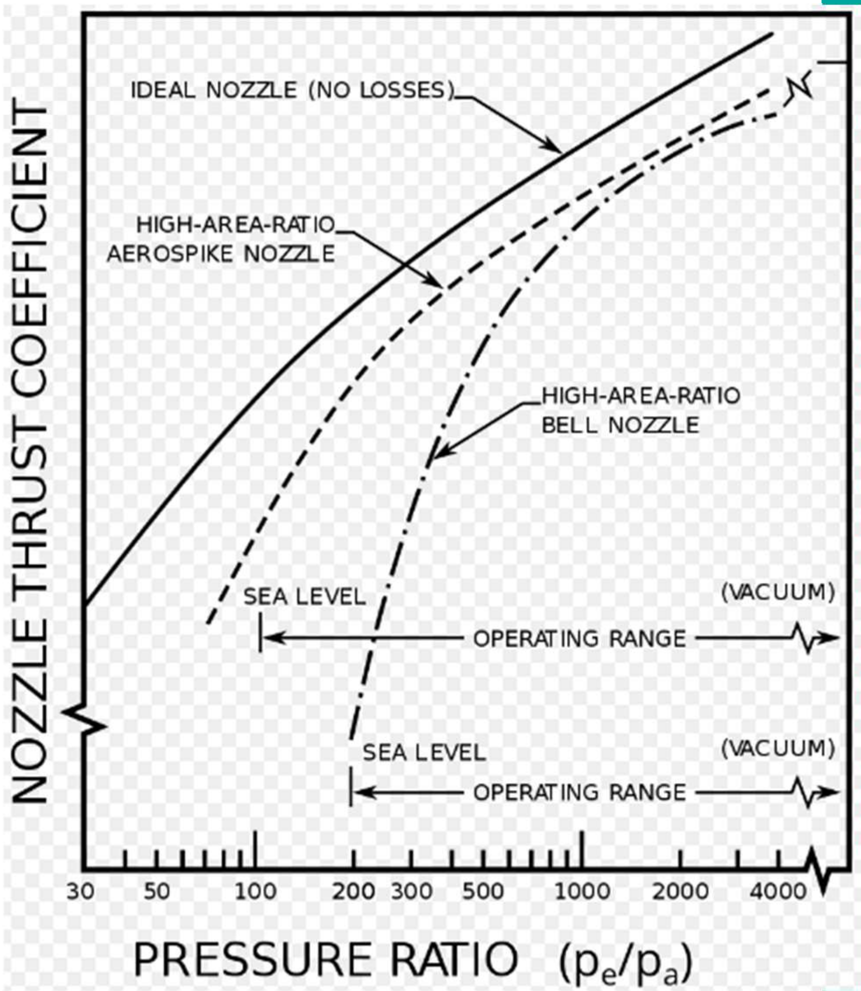




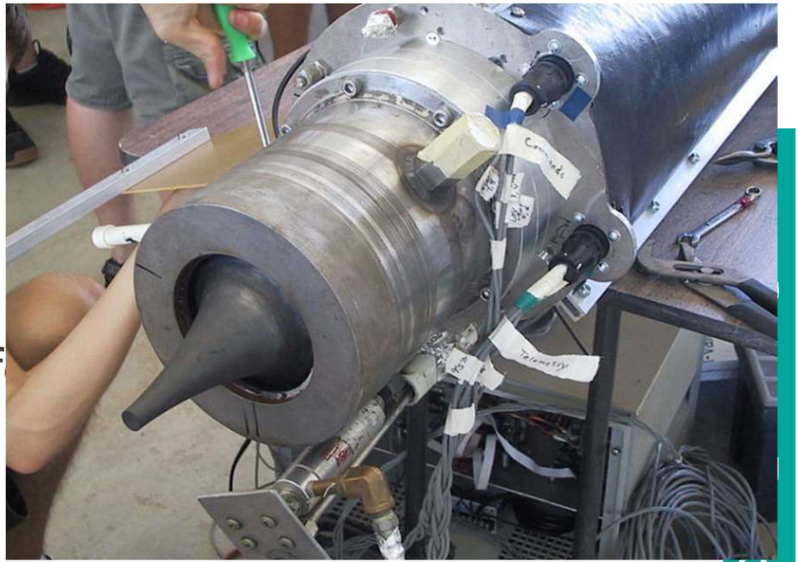
Which general Performance Equations are given?

Objective: To analyze propulsion systems

- Aerospike engines allow:
  - Optimal performance over wider external pressure range (wider altitude range)
  - Spike and surrounding air flow form a virtual bell
- Aerospike engines lead:
  - Increased thermal loads on spike

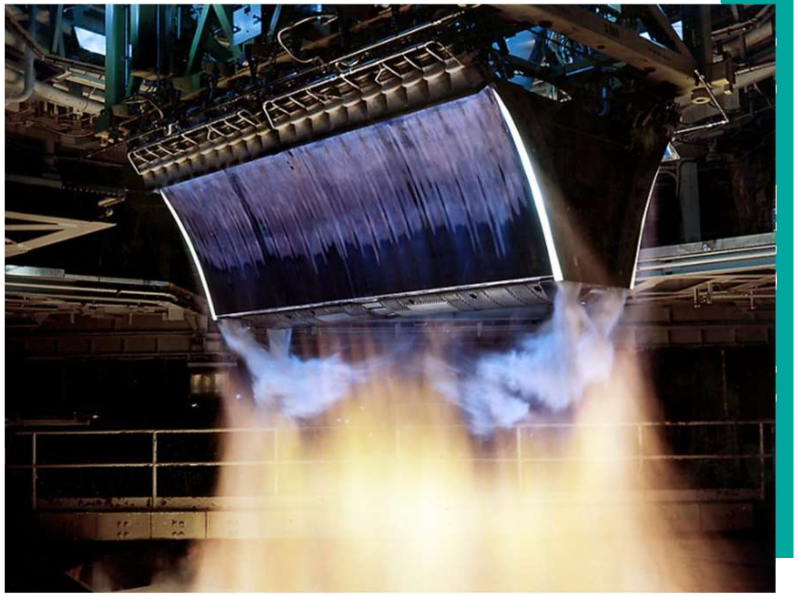


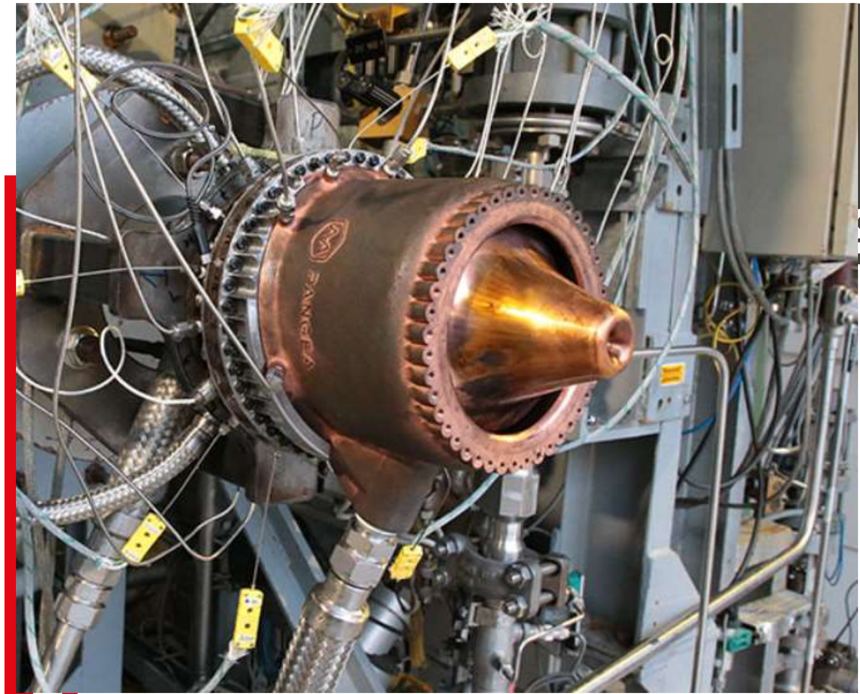
Which general Performance Equations are given?



Objective: To analyze propulsion systems perf

- Aerospike engines exist as:
  - Toroidal aerospike
  - Linear aerospike
- But no commercial application is given today





EPFL Space
Center

Which Propulsion Systems do we know?

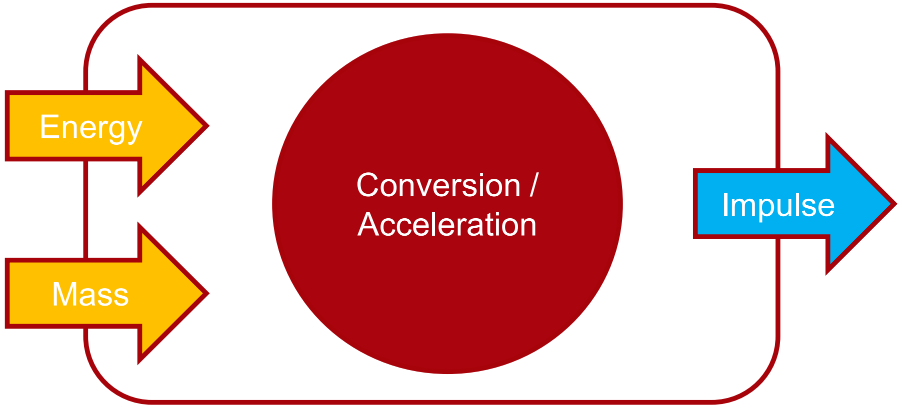
Objective: To categorize different space propulsion systems

- Space propulsion / in-space propulsion / towards space propulsion - Everything that accelerates a vehicle (launcher, rocket, satellite, orbital vehicle) by ejection of material

Which Propulsion Systems do we know?

Objective: To categorize different space propulsion systems

- Energy and Propellant:
  - Energy is needed to throw out the propellant / mass to get the push
  - Some energy must be converted to kinetic energy
- A propulsion system is an energy converter / accelerator



Which Propulsion Systems do we know?

Objective: To categorize different space propulsion systems

- Useable Energy:
  - Nuclear fusion
  - Nuclear fission
  - Chemical reaction
  - Pressure release
  - Electrical battery
  - Solar power
  - Muscle power
  - Mechanical acceleration
  - Others…

EPFL

Which Propulsion Systems do we know?

Objective: To categorize different space propulsion systems

- Transferring into space propulsion systems:
  - Nuclear fusion -> Not existing today
  - Nuclear fission -> Nuclear reactor is coming back again
  - Chemical reaction -> In use
  - Pressure release -> In use
  - Electrical battery -> In use
  - Solar power -> In use
  - Muscle power -> Not sufficient
  - Mechanical acceleration -> Under investigation (centrifuge)
  - Others… -> To be discussed

Which Propulsion Systems do we know?

Objective: To categorize different space propulsion systems

- Energy type and propulsion systems:
  - Nuclear fusion -> Not applicable
  - Nuclear fission -> Nuclear thermal propulsion and nuclear electric propulsion
  - Chemical reaction -> Chemical propulsion
  - Pressure release -> Pneumatic propulsion
  - Electrical battery -> Electric propulsion
  - Solar power -> Solar (radiant) electric propulsion
  - Muscle power
  - Mechanical acceleration -> Mechanical propulsion
  - Others… -> To be discussed

Which Propulsion Systems do we know?

Objective: To categorize different space propulsion systems

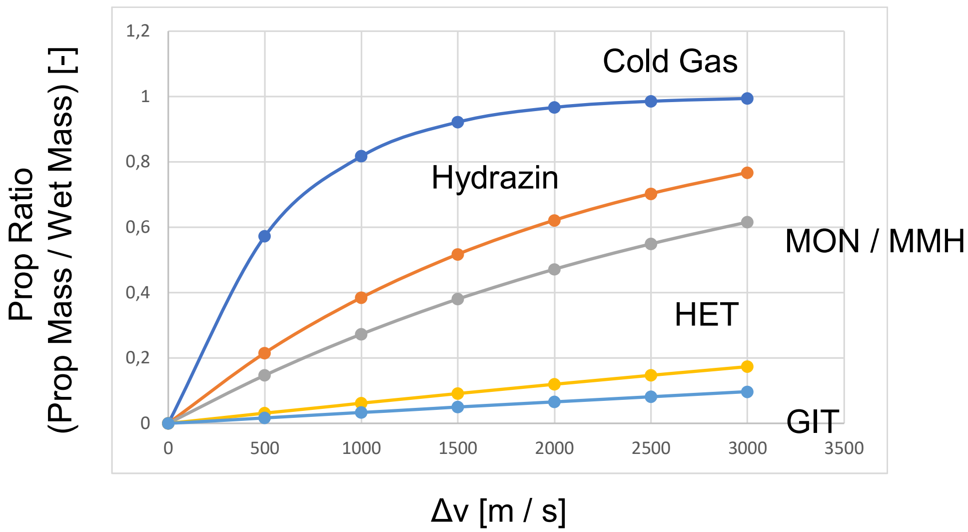
- Propulsion System categorization linked to energy conversion type:
  - Thermal Propulsion Systems (e.g. cold gas systems but also including electrothermal + solar thermal + nuclear thermal propulsion)
  - Chemical (Combustion) Propulsion Systems
  - Electrical Propulsion Systems (including nuclear electric propulsion)
  - Mechanical Propulsion Systems (e.g. gun, centrifuge, …)
  - Others…like radiant energy / solar wind / lasers

Which Propulsion Systems do we know?

Objective: To categorize different space propulsion systems

- Comparison of different Propulsion Systems:
  - Thermal Propulsion Systems
  - Chemical (Combustion) Propulsion Systems
  - Electrical Propulsion Systems
  - Mechanical Propulsion Systems
  - Others…

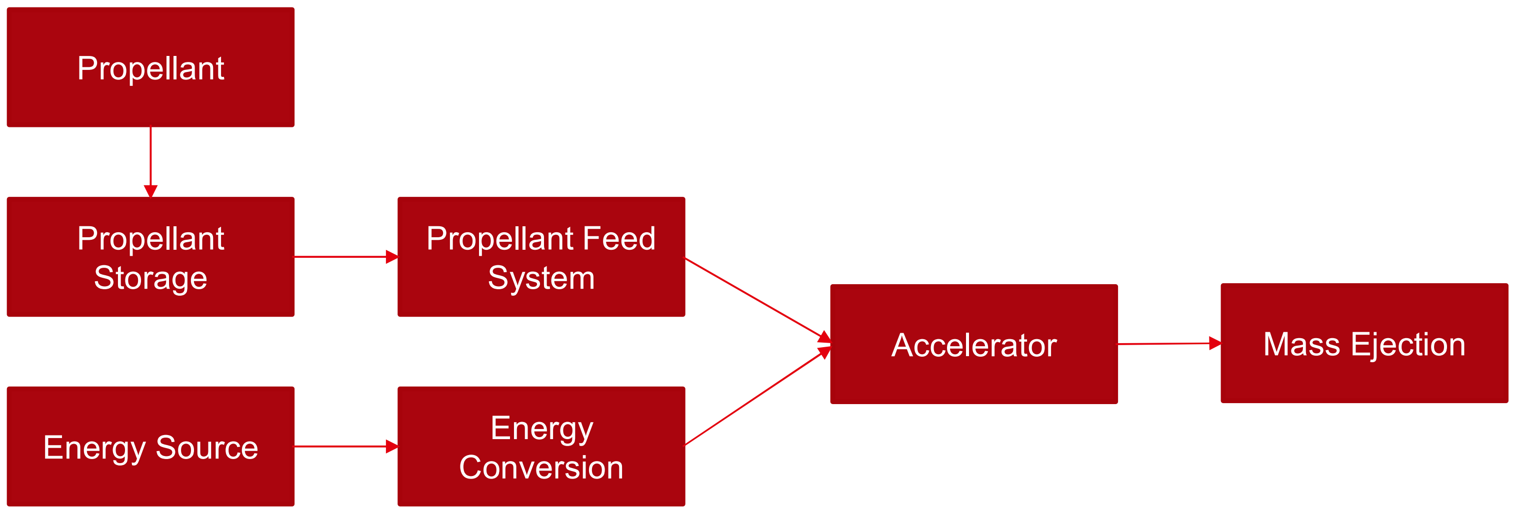
Possible Performance as Function of Propulsion Technology



Which Propulsion Systems do we know?

Objective: To categorize different space propulsion systems

- Generic block diagram for propulsion systems:



Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion

- Thermal Propulsion Systems
  - Cold gas propulsion systems
  - Cold gas / liquid propulsion systems (e.g. Water rocket…)
  - Solid powder / cold gas propulsion systems
  - Cryogenic boil-off propulsion systems
  - Liquefied gas propulsion systems
  - Electrothermal propulsion systems
  - Solar thermal propulsion systems
  - Nuclear thermal propulsion systems

Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion

- Thermal Propulsion Systems – Group 1
  - Cold gas propulsion systems
  - Cold gas / liquid propulsion systems (e.g. Water rocket…)
  - Solid powder / cold gas propulsion systems
  - Cryogenic boil-off propulsion systems
  - Liquefied gas propulsion systems

Which Thermal Propulsion Systems exist?

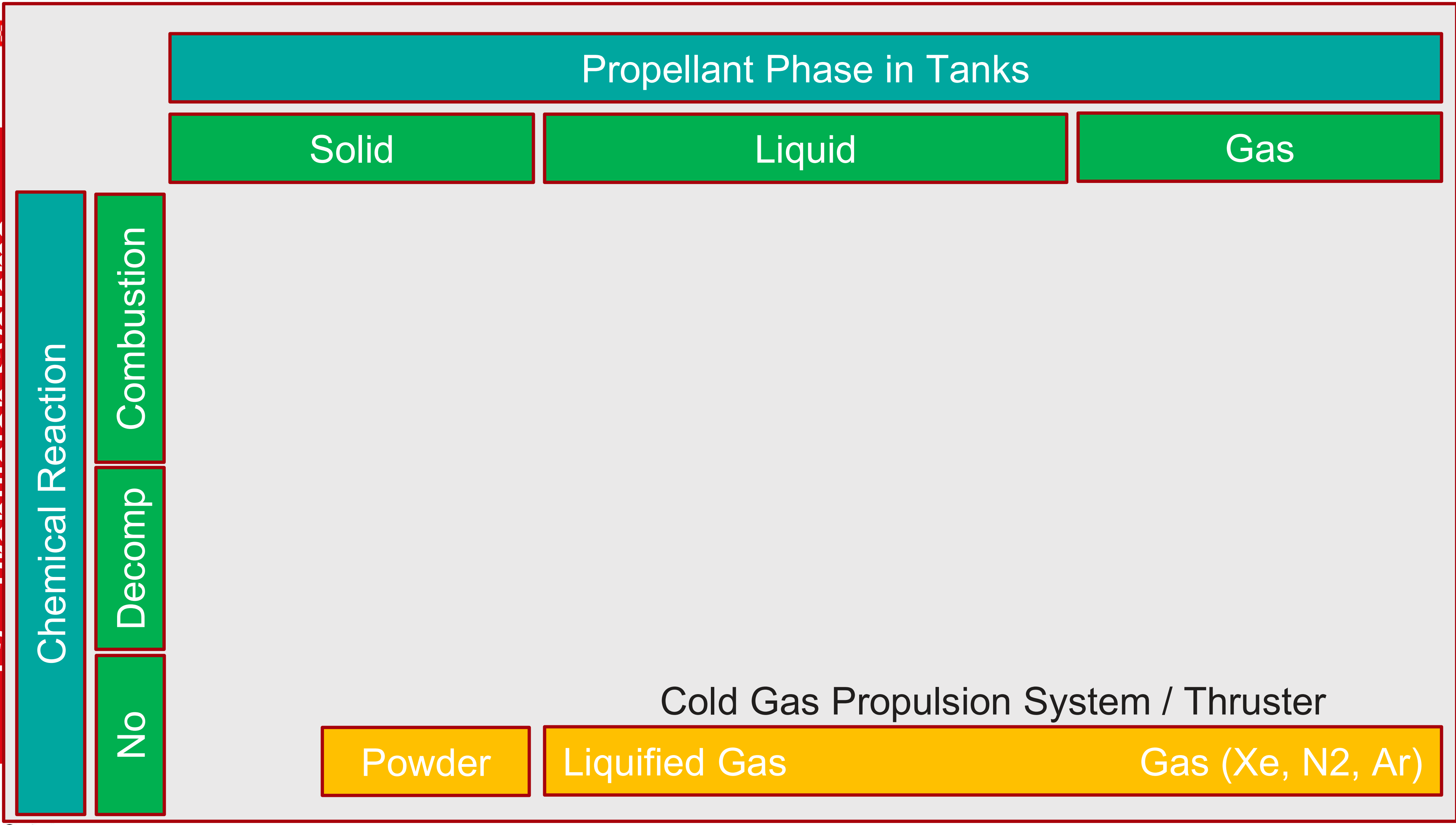
Objective: To develop the basics of thermal propulsion

- Thermal Propulsion Systems – Group 2
  - Electrothermal propulsion systems
- Thermal Propulsion Systems – Group 3
  - Solar thermal propulsion systems
  - Nuclear thermal propulsion systems

Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Application
  - Small Δv missions (e.g. only attitude control)
  - Small spacecrafts (e.g. cubesats)
- Architecture
  - Blow-down systems

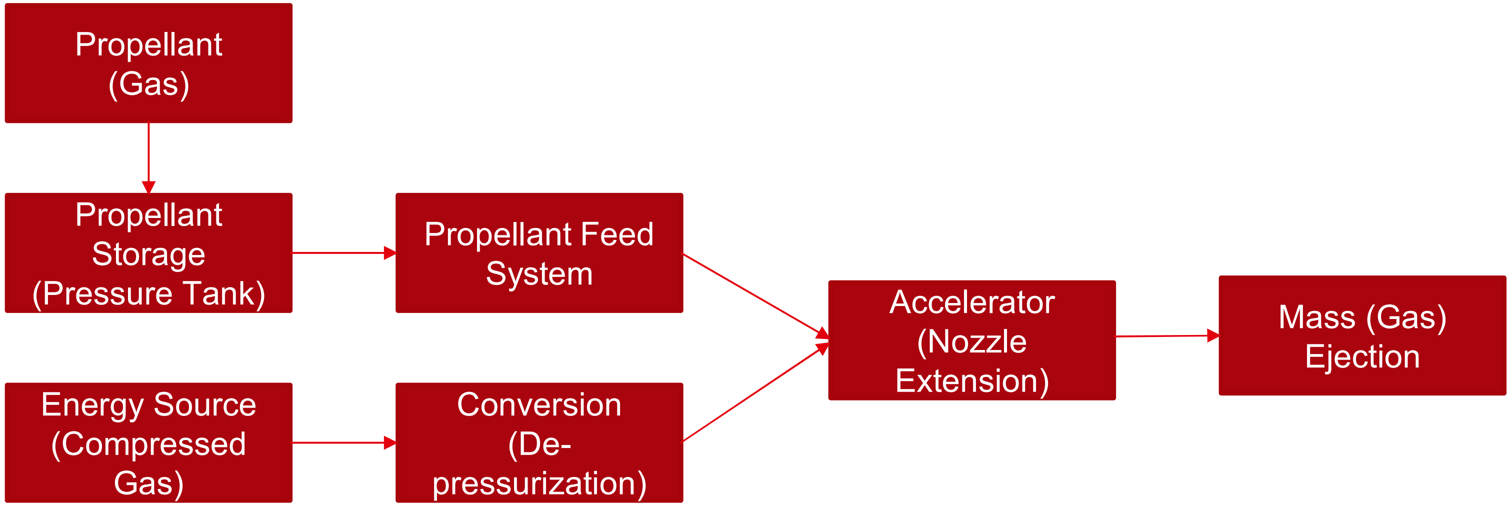


Propellant Phase in Tanks
Solid
Liquid
Gas
Chemical Reaction
Combustion
Decomp
No
Cold Gas Propulsion System / Thruster
Powder
Liquified Gas
Gas (Xe, N2, Ar)

Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Block diagram for Thermal Cold Gas Propulsion Systems:



Which Thermal Propulsion Systems exist?

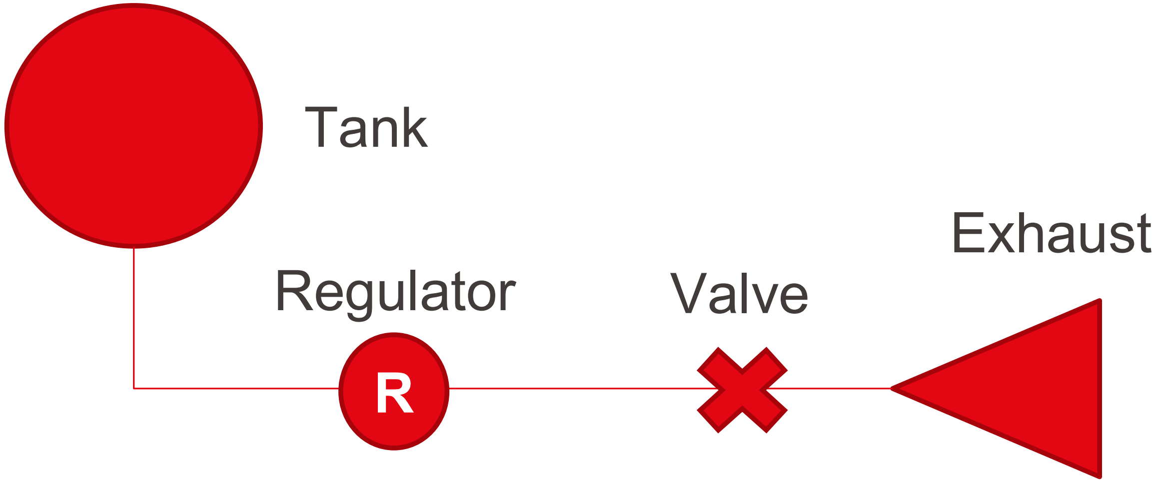
Objective: To develop the basics of thermal propulsion – Group 1

- Characteristics of Thermal Cold Gas Propulsion Systems:
  - High degree of reliability
  - Low system complexity (no combustion involved)
  - Low Δv
  - Extremely safe operation
  - No contamination from exhaust (combustion) gases
  - Low thrust
  - High pressure on ground

Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Architecture of Thermal Cold Gas Propulsion Systems (as a cold gas reaction control system):



Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Architecture of Thermal Cold Gas Propulsion Systems:
  - Consideration of a pressure regulator is not mandatory, but
  - It allows to operate all Equipment below the regulator at lower pressure and therefore has lower strength requirements
  - It allows to operate the thruster at constant inlet pressure until the storage tank pressure drops below the regulator pressure and therefore ensures consistent level of thrust

Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Thermal Cold Gas propulsion characteristics (needed propellant mass @ T = 298 K for different gases with same Δv requirement)

Gas	a_0 [m/s]	C^* [m/s]	m [kg/s]	Isp [s]	M [kg]
Air	346.1	427.2	0.051	78.9	51.6
Argon	320.7	343.6	0.071	57.0	71.5
CO2	269.3	356.8	0.056	72.3	56.3
He	1013.8	1085.6	0.022	180.1	22.6
H2	1314.4	1617.4	0.013	297.8	13.7
N2	351.9	434.4	0.050	80.2	50.8
O2	328.7	406.9	0.054	75.4	54.0

Which Thermal Propulsion Systems exist?

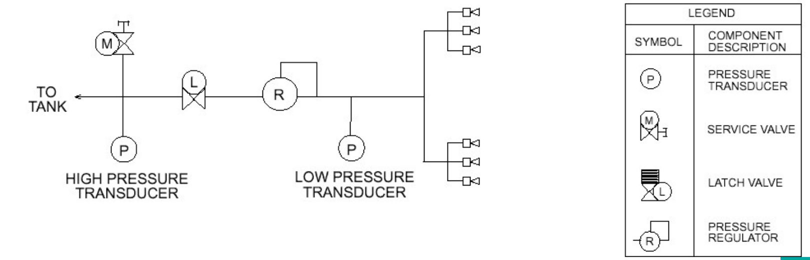
Objective: To develop the basics of therma

- Example: Cold Gas propulsion system

Thrusters

Inlet Pressure: .... 0 to 1.4 MPa, 0 to 200 psia (0 to 13.8 bar)
Thrust @ 50 psig: .... 0.44N for SAFER type valves; 55mN for Pluto Fast-Fly-By valves
Response: .... Less than 3.0 ms @ 28 Vdc, both opening and closing
Internal Leakage: .... Less than 5 scc/hr GN_2 at MEOP
External Leakage: .... Less than $1x10^{-5}$ scc/s GHe at MEOP
Duty Cycle: .... 10,000 cycles minimum
Weight: .... Less than 30 grams per thruster

Schematic



Typical System Performance Specifications

Operating Media: .... GHe or GN_2
Tank Storage Pressure: ..... 4000 psi MEOP (275.9 bar)
Regulated Pressure: .... 50 ± 10 psi (3.4 ± 0.6 bar)
Proof Pressure (Low): .... 200 psi (13.8 bar)
Burst Pressure (Low): .... 400 psia (27.6 bar)
Proof Pressure (High): .... 6500 psia (448 bar)
Burst Pressure (High): .... 8000 psia (552 bar)

Thrust per Axis @ 50 psi (3.4 bar) reg. outlet: 0.44N or 55mN
Tubing Material: .... 1/4 and 1/8 in. CRES Electropolished Inner Diam.
Overall Dimensions: .... 10 x 10 x 5 in. (25 x 25 x 13 cm)
Dry System Weight: .... 7.25 lb (16 kg) estimated

Configuration can be modified to meet individual customer requirements.

Worst Case Flow Conditions (two 0.44N thrusters and two 55mN thrusters)
Flow rate of 0.003 lb/sec GN_2 (0.0014 kg/sec)

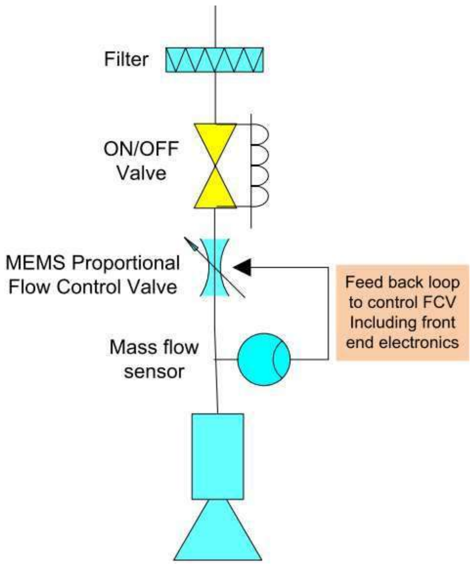
Minimum inlet pressure to regulator for full flow condition is 330 psi (22.7 bar). Minimum inlet pressure to latch valve inlet to support the downstream regulator is 350 psi (24.1 bar). System pressure budget for worst case flow demand is as follows: Tank (Inlet to latch valve): 350 psi (24.1 bar). Inlet to regulator: 330 psi (22.7 bar) for a regulated pressure of 50 psi (3.4 bar).

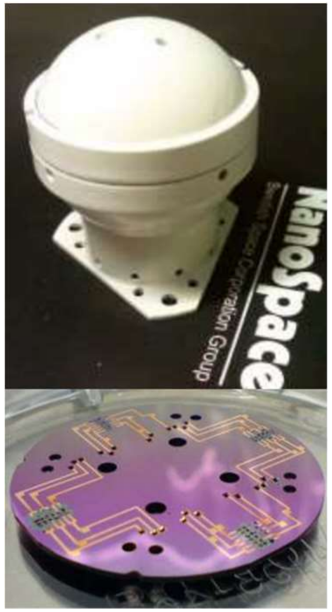
Which Thermal Propulsion Systems exist?

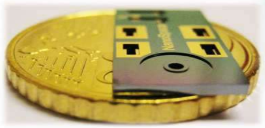
Objective: To develop the basics of thermal propulsion – Group 1

- Example: Cube Sat propulsion system

General specification:
- Four 1mN thrusters with closed loop thrust control
- Thrust resolution: <10µN
- Propellant: Butane
- Total impulse: 40Ns
- Size: 10*10*3cm
- Mass: 250g
- Operating pressure: 2-5 bar
- Power consumption: 2 W







Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Basic performance equations:
  - Sonic velocity

$$a_0 = \sqrt{\gamma R T_0}$$

  - Characteristic velocity

$$c^* = \frac{a_0}{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2\gamma-2}}}$$

EPFL

Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Basic performance equations:
  - Thrust

$$F = A_t p_C \gamma \sqrt{(\frac{2}{\gamma - 1})(\frac{2}{\gamma + 1})^{\left(\frac{\gamma+1}{\gamma-1}\right)}(1 - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}})} + (p_e - p_a)A_e$$

  - Mass flow

$$\dot{m} = \frac{A_t p_C}{c^*}$$

Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

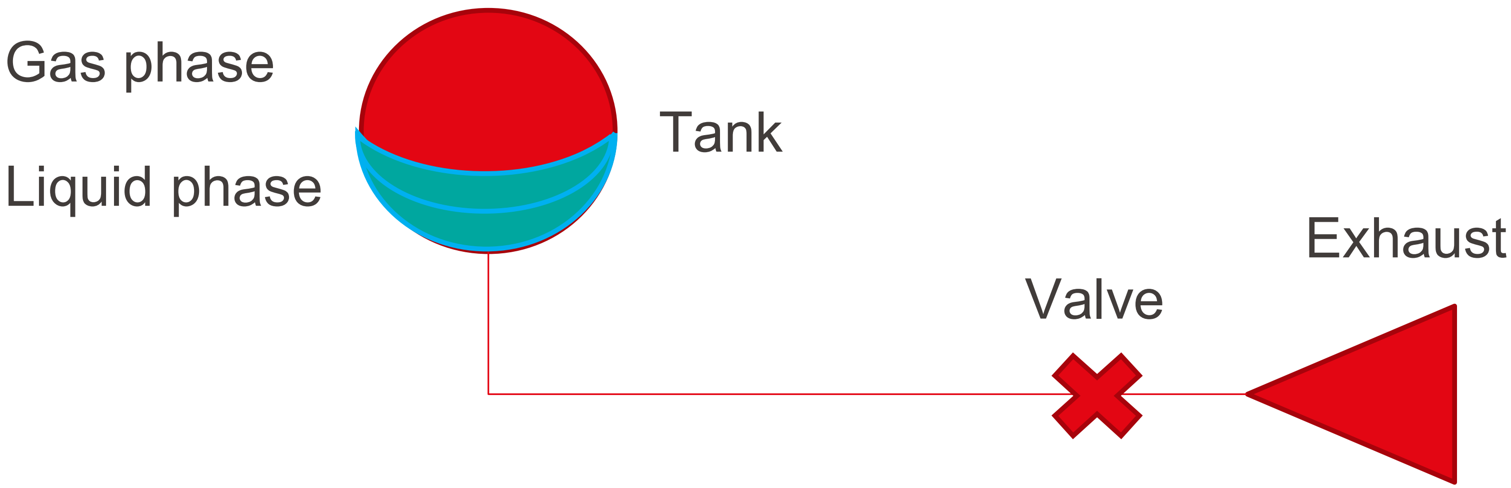
- Basic performance equations:
  - Isp

$$I_{sp} = \frac{F}{\dot{m} g_0}$$

Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

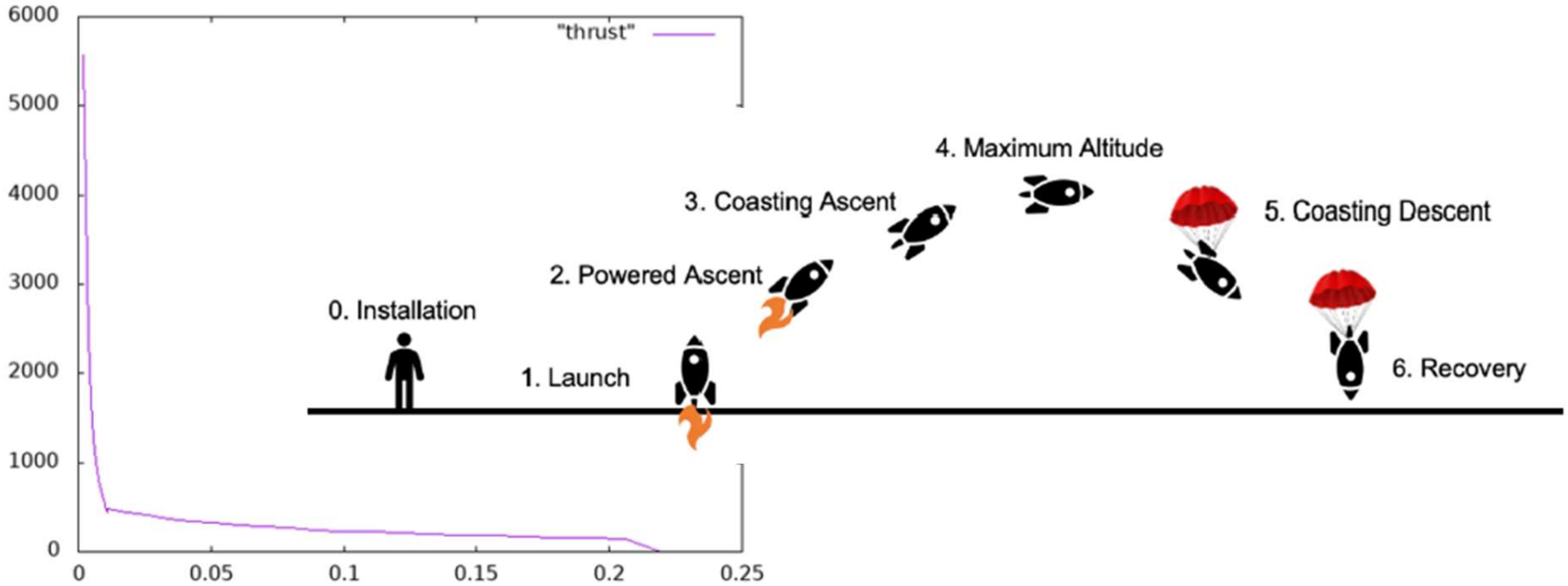
- Architecture of Thermal Cold Gas / Liquid Propulsion Systems (as student project):



Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – C

- Example: Plasti Blast and others

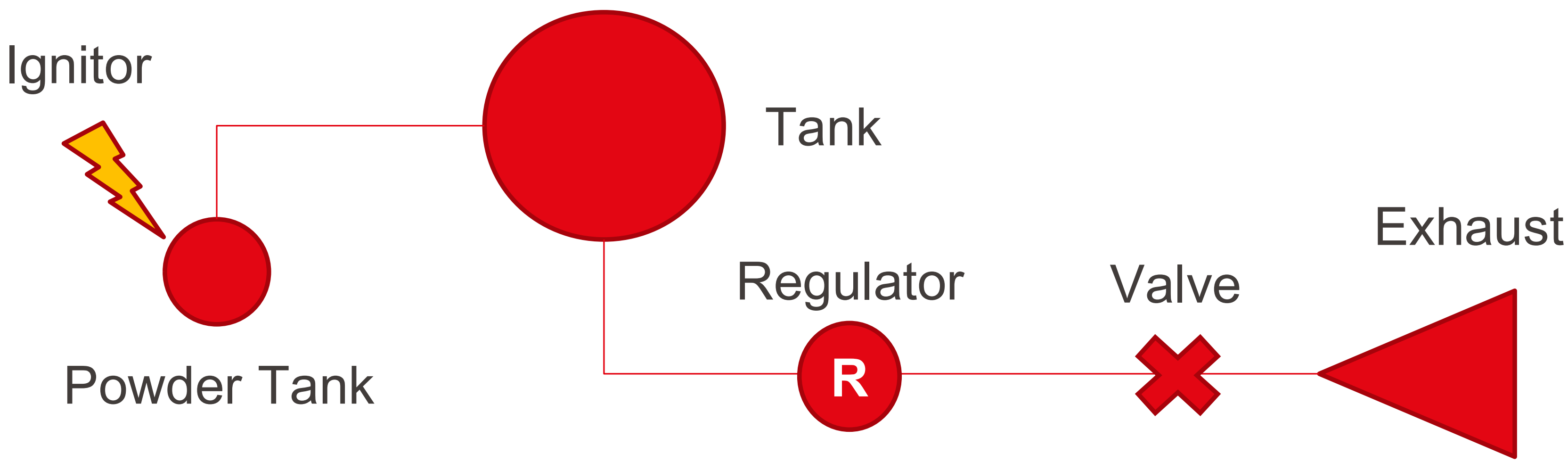


EPFL

Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Architecture of Thermal Gas Propulsion Systems solid powder on ground for storage:



Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Characteristics of Thermal Gas Propulsion Systems:
  - High degree of reliability
  - Medium ~~low~~ system complexity (~~no~~ combustion involved)
  - Low Δv
  - ~~Extremely~~ safe operation
  - No contamination from exhaust (combustion) gases
  - Low thrust
  - ~~High pressure on ground~~

Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Architecture of Cryogenic Boil-off:

Which Thermal Propulsion Systems exist?

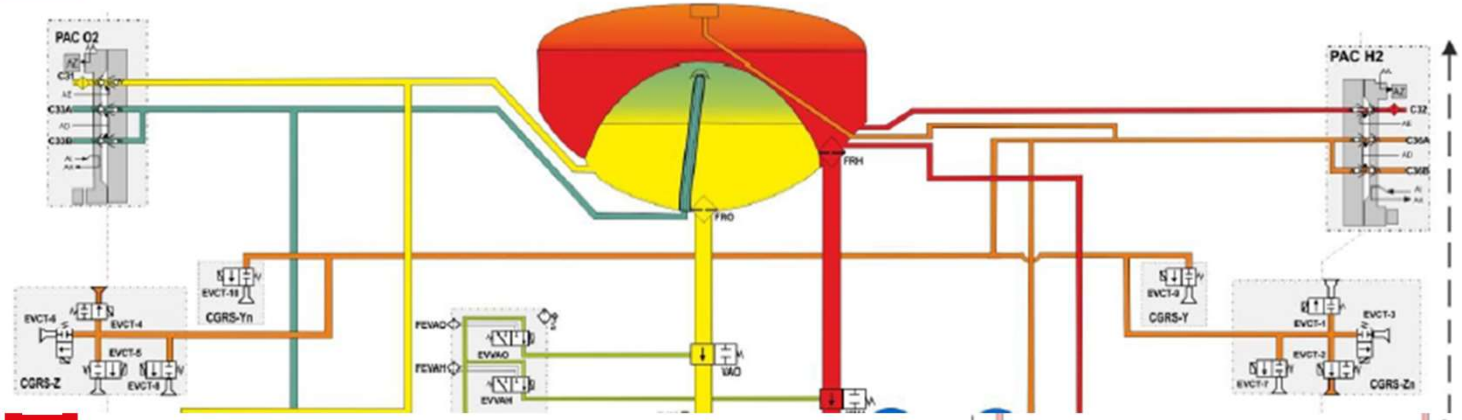
Objective: To develop the basics of thermal propulsion – Group 1

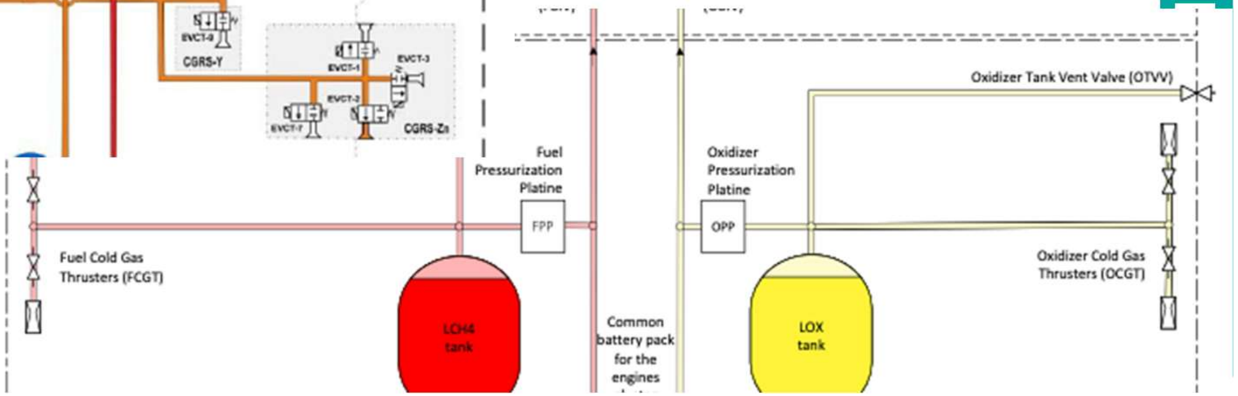
- Example: LH2 boil-off in cryogenic upper stages
  - Permanent LH2 boil-off is given as propellant temperature is @ 20 K
  - Tank pressure is important parameter to control liquid temperature
  - Also de-pressurization is performed to cool-down the propellant
  - Available gas pressure can be used for propellant settling, as attitude control system…but might also be just vented (not providing any impulse to the upper stage)
  - No pressure regulator is needed as tank pressure is already very low

Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Example: A5ME / A6 launch vehicles and TEC Nyx Moon capsule

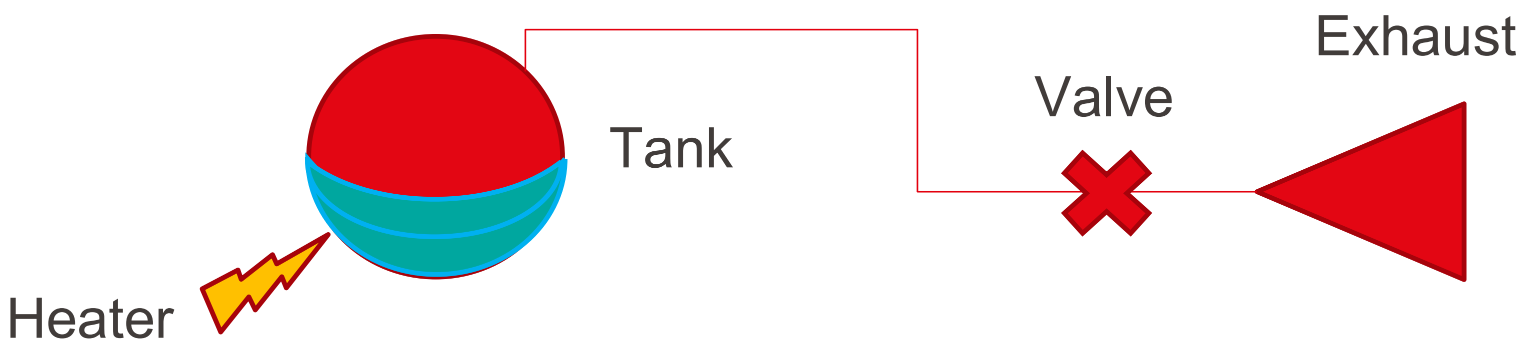




Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Architecture of Storable Propellant Boil-off @ ambient temperatures considering high vapor pressures:



Which Thermal Propulsion Systems exist?

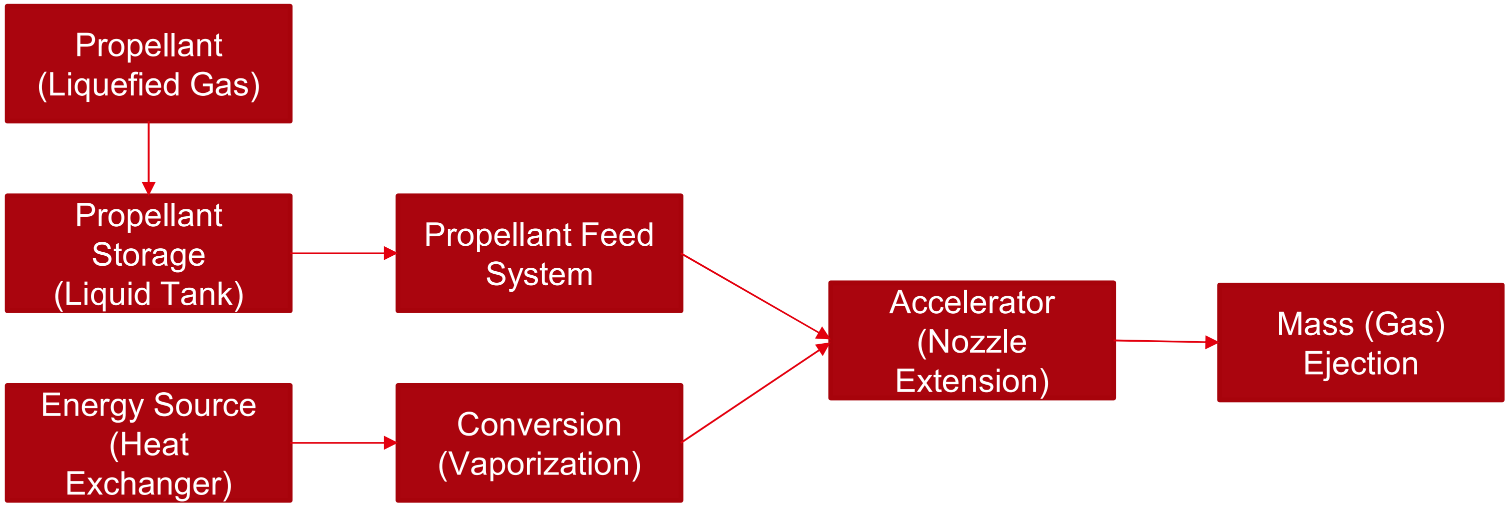
Objective: To develop the basics of thermal propulsion – Group 1

- Example: N_2O boil-off in
  - Forced N_2O boil-off due to high vapor pressure and correlation between liquid temperature and gas pressure
  - is important parameter to control liquid temperature
  - But also other way round liquid temperature is important parameter to control tank pressure
  - Available gas pressure can be used for propellant settling, as attitude control system…but might also be just vented (not providing any impulse to the upper stage)
  - Pressure regulator might be needed in order to get constant thrust (but could also controlled by effective temperature control of liquid N_2O)

Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

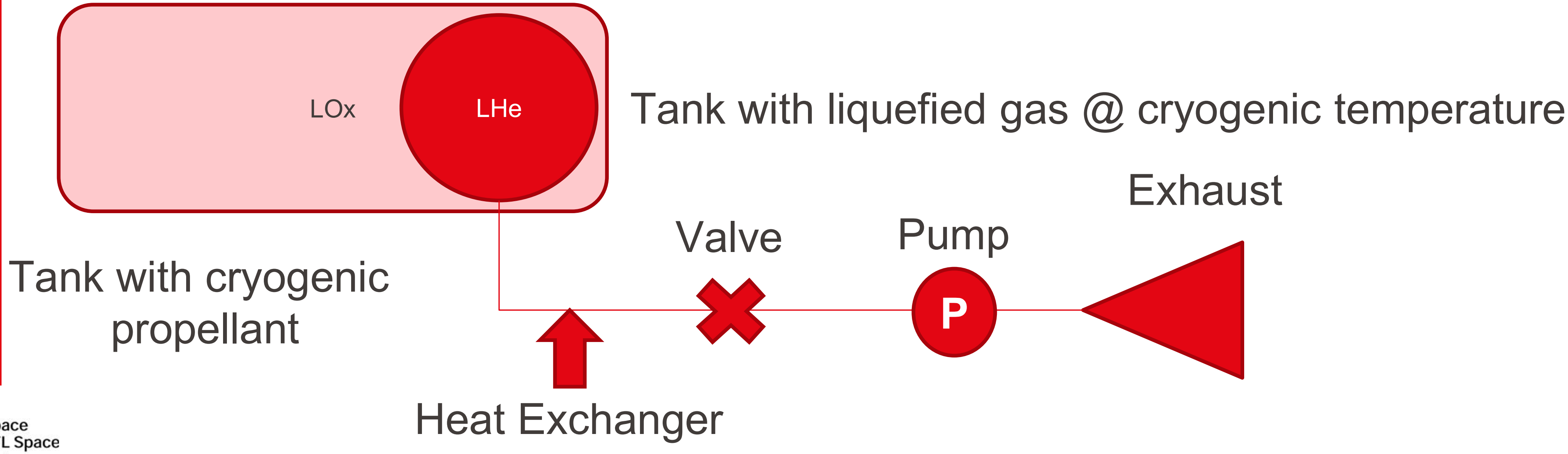
- Block diagram for Thermal Liquefied Gas Propulsion Systems:



Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Architecture of Thermal Liquefied Gas Propulsion Systems (as a cold gas reaction control system):



Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Architecture of Thermal Liquefied Gas Propulsion Systems:
  - Means must be provided for storage of liquefied gas (e.g. by storage of gas inside cryogenic propellant tank)
  - Heat Exchanger must be used in order to ensure sufficient vaporization rate
  - Most probably pump is needed to increased pressure of vaporized gas @ thruster (nozzle extension) inlet

Which Thermal Propulsion Systems exist?

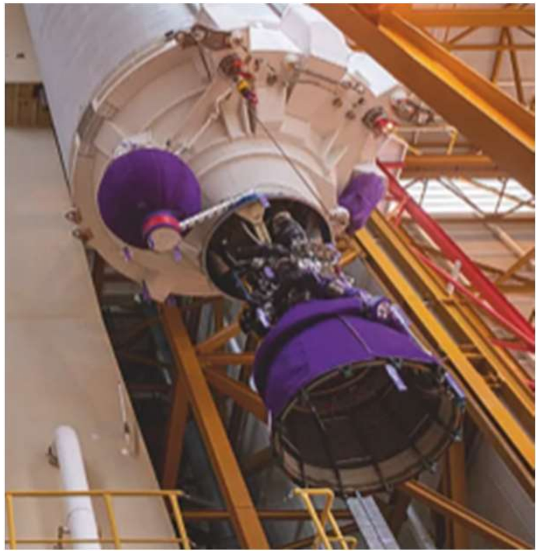
Objective: To develop the basics of thermal propulsion – Group 1

- Characteristics of Thermal Liquefied Gas Propulsion Systems:
  - High degree of reliability
  - High system complexity (no combustion involved but storage of liquefied gas)
  - Low Δv
  - Extremely safe operation
  - No contamination from exhaust (combustion) gases
  - Low thrust
  - Additional equipment (Heat Exchanger and potentially pump)
  - Gas tank in liquid tank

Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Example: SSHEL of ARIANE 5



Which Thermal Propulsion Systems exist?

Objective: To develop the basics of thermal propulsion – Group 1

- Performance comparison of different pneumatical propulsion systems

	Cold Gas	Solid Powder	Cryogenic Boil-off	Liquefied Gas	Water Rocket
Medium	GN2	GN2	GH2	GHe	Air
Temperature	293 K	1300 K	20 K	4 K up	293 K
Use case	Cubesat propulsion Attitude control	Pressurant gas De-orbit burn	Attitude control	Attitude control Pressurant gas	Fun