# Controlled Reentry Analysis of LEO Satellites at EOL

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# Summary

Introduction to controlled re-entry

I) **Mission design**

   a. Orbit and spacecraft

   b. Mission overview

II) **Propulsion systems** (HET, Arcjet, Monopropellant)

   a. Main features

   b. Assumptions

III) **Trade-off**

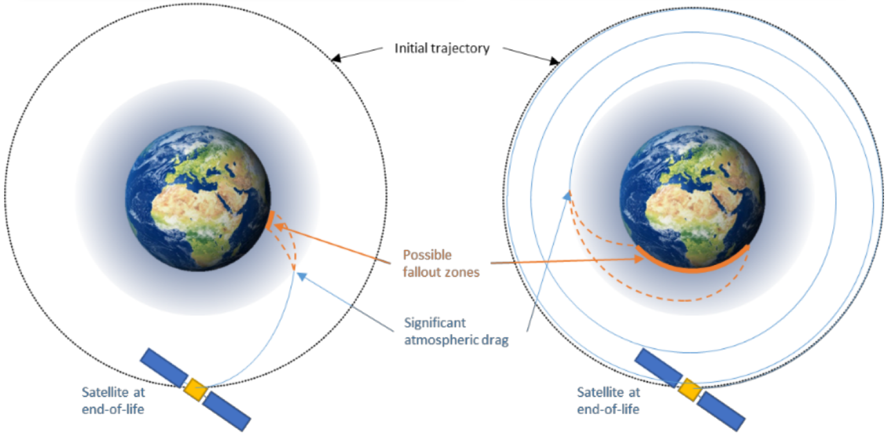
   a. Constraints and ranking criteria

   b. Results

Conclusions

# Introduction

- **Space Debris** is a growing concern
- One objective of **CleanSat** aims to ensure satellites to leave protected regions at End-of-Life
- **Possible hazard of parts surviving re-entry => must ensure low casualty risk (<1/10 000)**
    - Uncontrolled re-entry: no control
    - Semi-controlled re-entry: fallout within one orbital period
    - Controlled re-entry: greater control over fallout zone
- **Controlled re-entry conditions**
    - Medium/big satellites
    - Steeper re-entry into the atmosphere => high thrust for 1 single final burn
    - Heavier, more complex systems



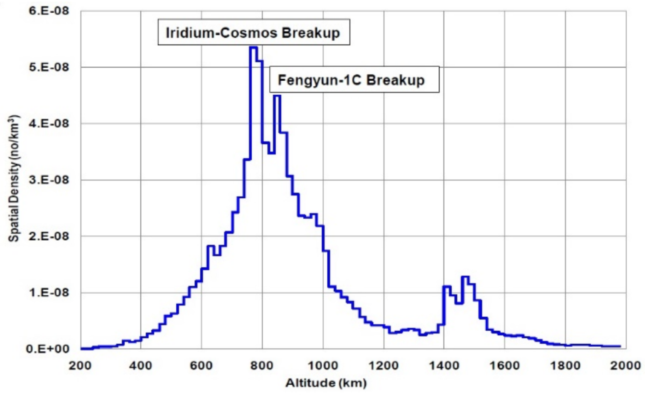

*Trajectories and fallout zones in case of a controlled (left) or semi-controlled (right) re-entry*

# I) Mission Design: a) Orbit and spacecraft

- **Orbit**

Target crowed regions with high probability collision

**=> SSO, ~800km**




*NASA report on Debris (2011)*

- **Spacecraft**

Wide range of spacecraft

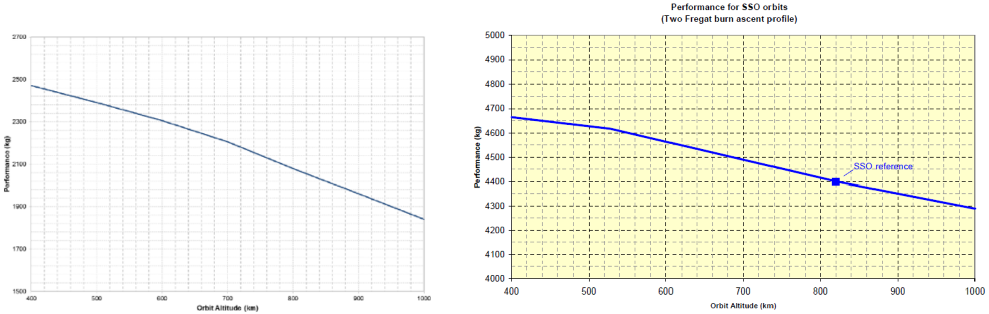
**=> Small (750kg), medium (1500kg), heavy (4000kg)**

**Focus on satellites** posing bigger hazard with **higher casualty risks** (with optical instruments, Ti-alloy tanks, heavy reaction wheels, …)

# I) Mission Design: b) Mission overview

## Launchers’ capacity

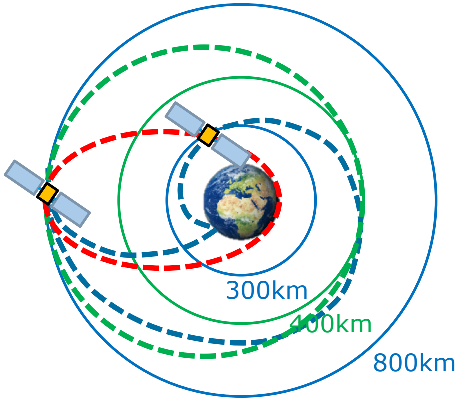
| Altitude | Vega C | Soyuz ST |
|---|---|---|
| 800 km | 2080 kg | 4430 kg |
| 300 km | 2550 kg | 4710 kg |




*Performances of Vega C (left) and Soyuz ST (right) for SSO as written in the launcher’s manual*

## Mission

- **Injection of S/C** in orbit with Vega C/Soyuz ST
  - **800km**
  - **300km**
- **Main propulsion system (MPS)**
  - (Orbit raising if injection at 300km: $\Delta v_{0'} = 274$ m/s)
  - **Operational lifetime**: $\Delta v_0 = 100$ m/s
  - **Lowering perigee** down to 430 km: $\Delta v_{12} = 99$ m/s
- **Deorbiting propulsion system (DPS)**
  - **Final burn (FB)** down to 30 km: $\Delta v_{23} = 124$ m/s

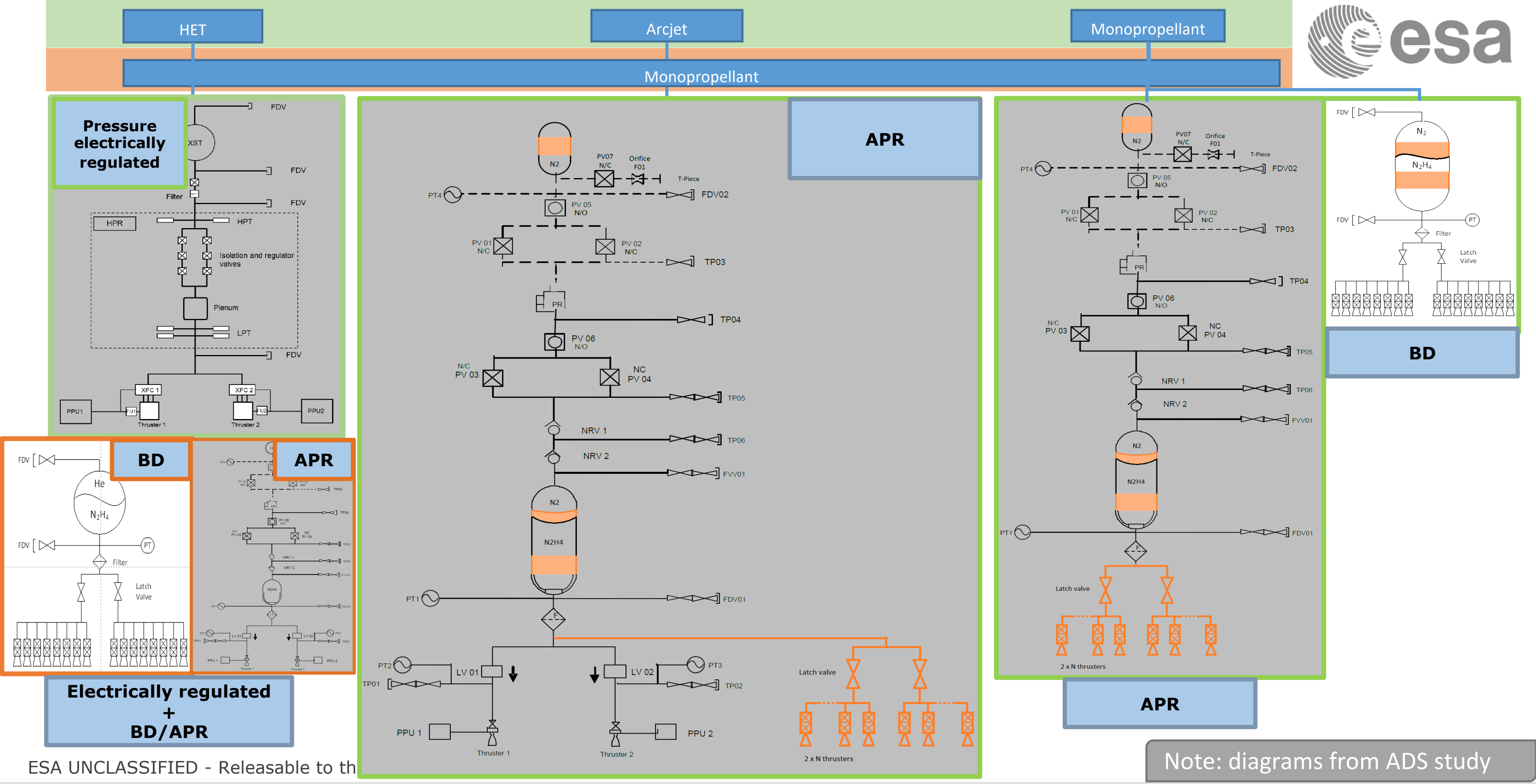



*Typical controlled re-entry mission*

# II) Propulsion Systems: a) Main features

| | HET | Arcjet | Monopropellant | | |
|---|---|---|---|---|---|
| Model | SAFRAN: PPS-1350-G | Lockheed Martin: Aerojet MR-510 | ArianeGroup | | |
| | | | 1N | 20N | 400N |
| Propellant | Xenon | Hydrazine | Hydrazine | | |
| Pressuring gas | - | Nitrogen | Nitrogen | | |
| Pressurization | Electrically regulated | APR | BD/APR | | |
| Power | ≤ 2 kW | ≤ 2 kW | Neglected | | |
| Thrust | ≤ 0.120 N | ≤ 0.25 N | [0.320; 1.1] N | [7.9; 24.6] N | [120; 420] N |
| $I_{sp}$ | 1660 s | 600 s | [200; 223] s | [222; 230] s | [212; 220] s |
| Cycle life | 7300 | 1950 | 59000 | 93130 | 3900 |
| Max single burn | | 3 h | 12 h | 1.5 h | 450 s |
| Max total burn | > 6700 h | > 1730 h | 50 h | 10.5 h | > 850 s |
| Propellant throughput | - | - | 67 kg | 290 kg | 300 kg |

**Notes:** - FB must have high thrust => **at least 1 monopropellant system** (MPS or DPS)






Note: diagrams from ADS study

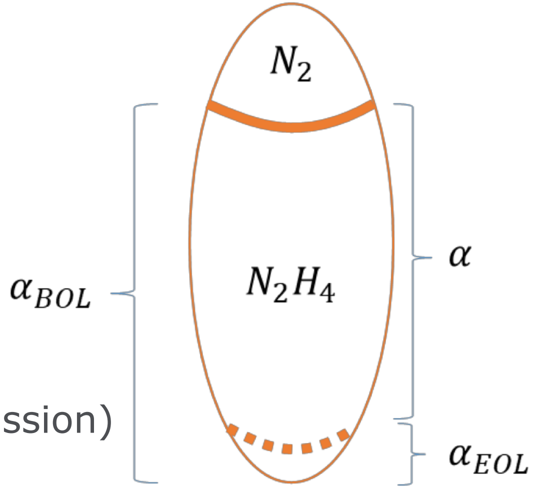
# II) Propulsion Systems: b) Assumptions

- **Blowdown mode (BD):**
  - Ideal gas
  - Main operations: constant temperature
  - Final burn: isentropic adiabatic
  - Isp and thrust linear wrt inlet thruster pressure
- **Active Pressure Regulation (APR):**
  - Constant pressure
  - Isp and thrust linear wrt inlet thruster pressure
- **Performance** does not deteriorate over time
- **Redundancy 2** with thrusters
- **Negligible drag** during manoeuvres

# III) Trade-off: a) Constraints and ranking criteria

**Constraints**

- **Filling ratio $\alpha$ for blowdown**
  - Pressure at thrusters' inlet: [5.5 ; 24] bar
  - Temperature of hydrazine (avoid freezing): > 2°C
  - **2 propulsion systems (P/S) concerned:**
    - HET + Monoprop. => Monoprop. only for FB
      => isentropic adiabatic
      => $\boldsymbol{\alpha = \alpha_{BOL} - \alpha_{EOL} < 32\%}$
    - Full Monoprop. => constant temperature (main mission) then isentropic adiabatic (final burn)
      => $\boldsymbol{\alpha = \alpha_{BOL} - \alpha_{EOL} < 72\%}$
- **Filling ratio $\alpha$ for APR:** $\alpha = \alpha_{BOL} - \alpha_{EOL} = 95\%$



# III) Trade-off: a) Constraints and ranking criteria

## Constraints

- **Maximum acceleration**
  - $< 0.04\,g$
  - (tolerance up to 1 g for small satellites)
- **FB duration**
  - $< 20\%$ of orbital period
- **Other thrusters constraints**
  - Number of cycles
  - Max single burn duration
  - Max total burn duration

# III) Trade-off: a) Constraints and ranking criteria

## To sum up

| Constraints |
| --- |
| **Filling ratio $\alpha$ for BD < 32% (HET + Monop.) < 72% (full Monop.)** |
| **Acceleration < 0.04 g** |
| **FB (% of orbital period) < 20%** |
| **Thrusters burn constraints** |

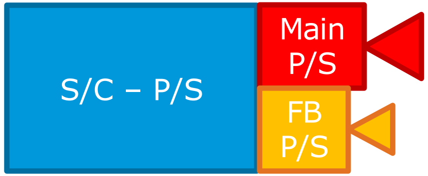
| Ranking |
| --- |
| **1) P/S wet mass** |
| **2) Reliability** |
| **3) Complexity** |
| **4) FB duration** |

To be investigated

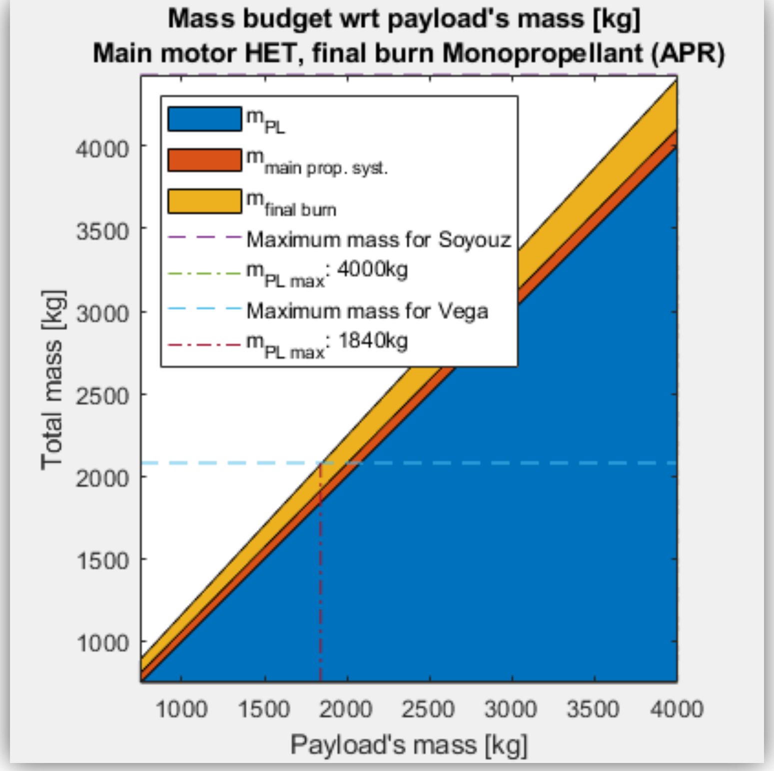
# III) Trade-off: b) Results

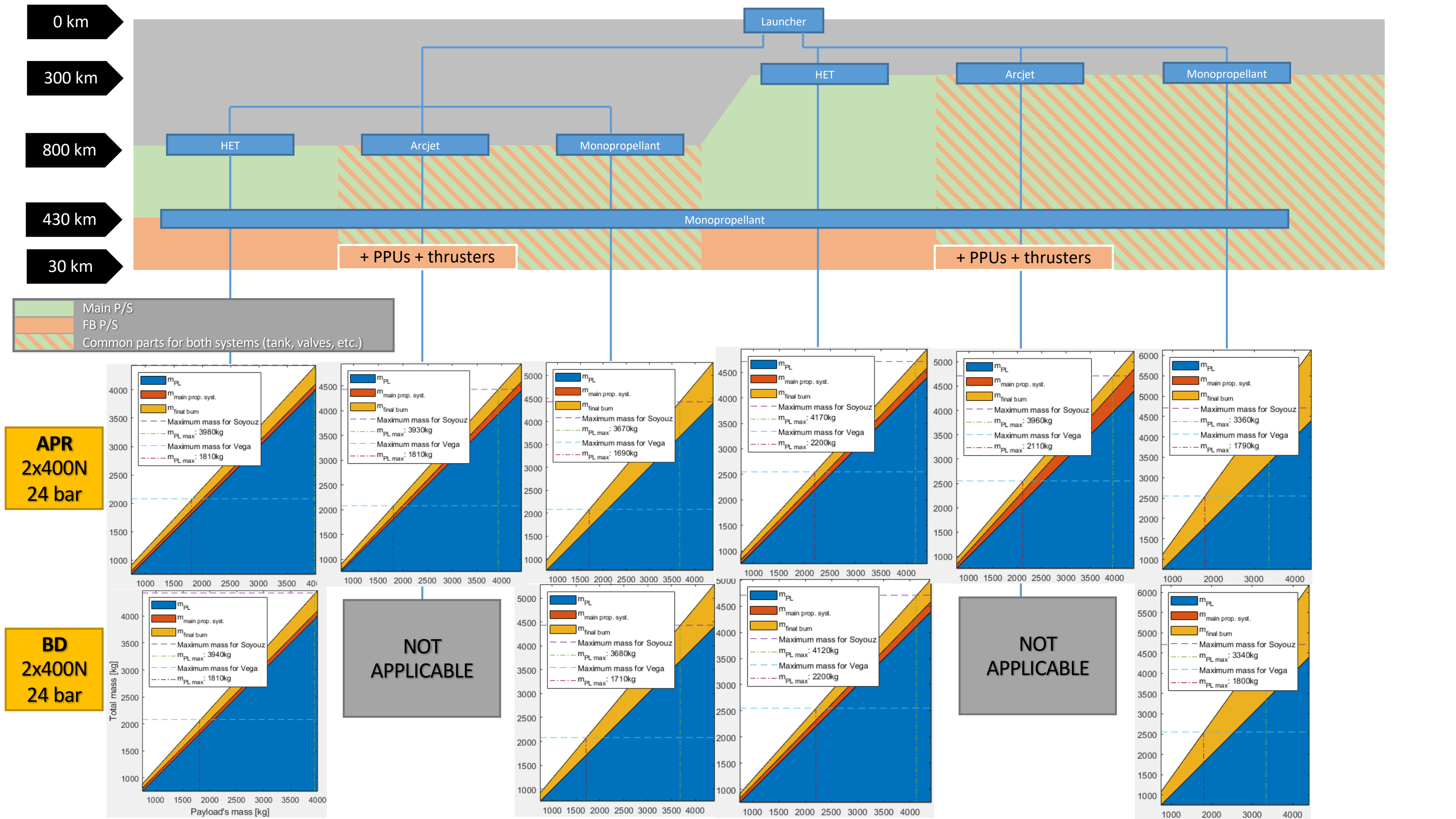
**1. General mass comparison with different:**

- Altitudes insertion
- Propulsion systems
- Pressurization systems
- Mass range [750 ; 4500] kg

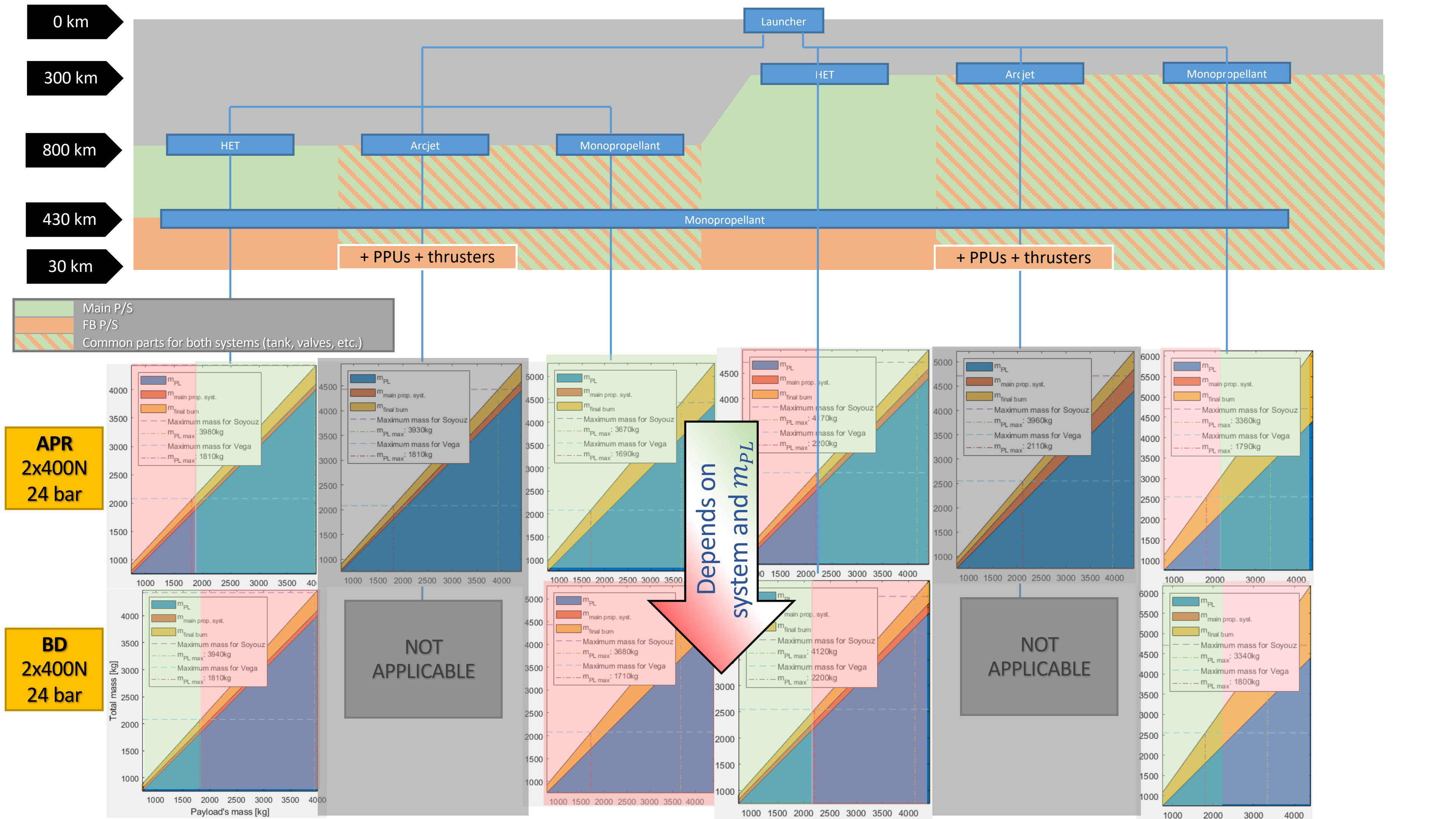



**2. Then, focus on 750 kg, 1500 kg, 4000 kg**





0 km
300 km
800 km
430 km
30 km
Launcher
HET
Arcjet
Monopropellant
HET
Arcjet
Monopropellant
Monopropellant
+ PPUs + thrusters
+ PPUs + thrusters
Main P/S
FB P/S
Common parts for both systems (tank, valves, etc.)
APR 2x400N 24 bar
BD 2x400N 24 bar
Maximum mass for Soyouz
Maximum mass for Vega
mPL max: 3980kg
mPL max: 1810kg
mPL max: 3930kg
mPL max: 1810kg
mPL max: 3670kg
mPL max: 1690kg
mPL max: 4170kg
mPL max: 2200kg
mPL max: 3960kg
mPL max: 2110kg
mPL max: 3360kg
mPL max: 1790kg
mPL max: 3940kg
mPL max: 1810kg
NOT APPLICABLE
mPL max: 3680kg
mPL max: 1710kg
mPL max: 4120kg
mPL max: 2200kg
NOT APPLICABLE
mPL max: 3340kg
mPL max: 1800kg
Total mass [kg]
Payload's mass [kg]


0 km
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Launcher
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$m_{main\ prop.\ syst.}$
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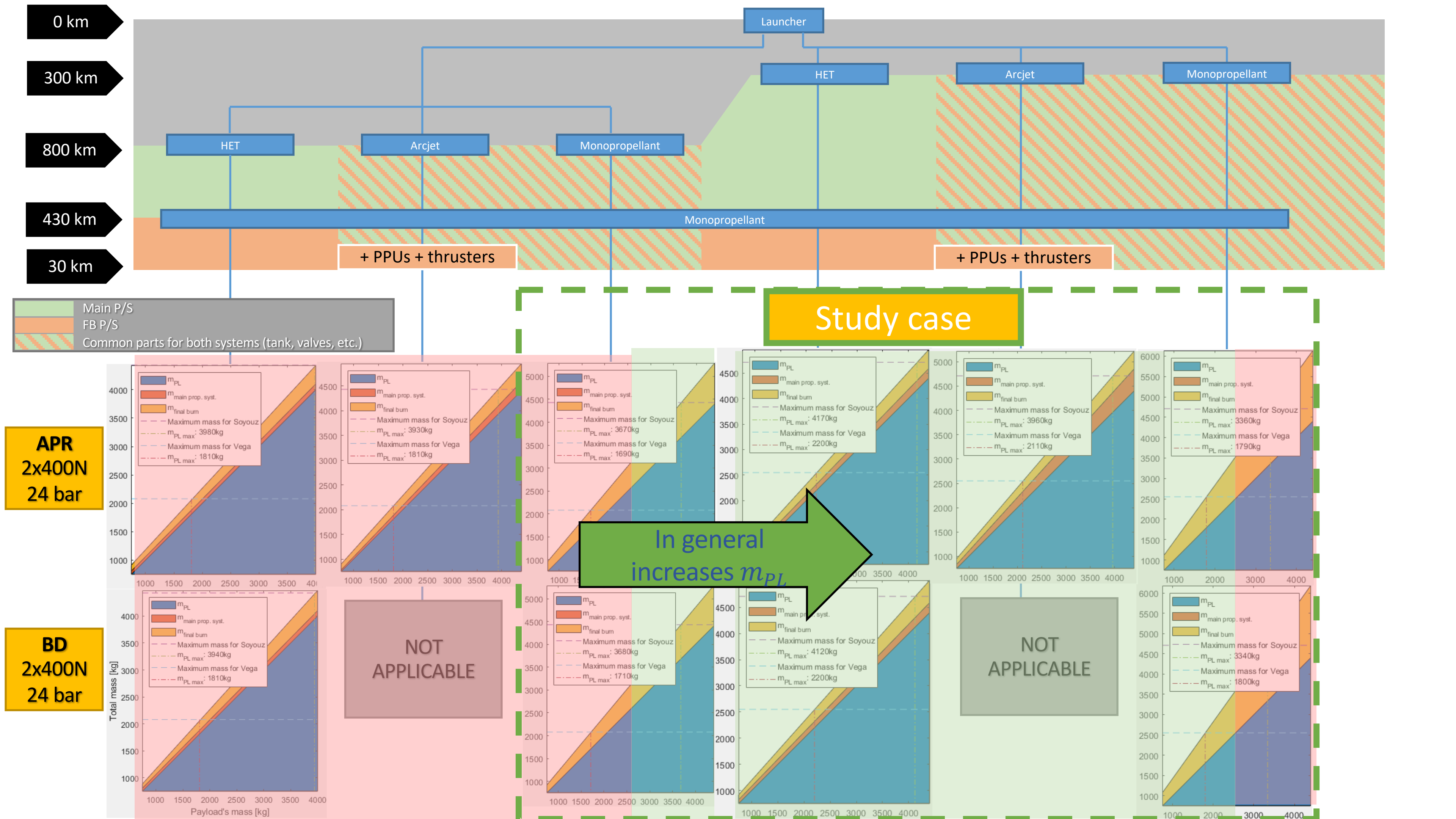
NOT APPLICABLE
$m_{PL\ max}$: 3340kg
$m_{PL\ max}$: 1800kg
Depends on system and $m_{PL}$
Total mass [kg]
Payload's mass [kg]



0 km
300 km
800 km
430 km
30 km
Launcher
HET
Arcjet
Monopropellant
HET
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Monopropellant
+ PPUs + thrusters
+ PPUs + thrusters
Main P/S
FB P/S
Common parts for both systems (tank, valves, etc.)
Study case
APR 2x400N 24 bar
BD 2x400N 24 bar
In general increases $m_{PL}$
NOT APPLICABLE
NOT APPLICABLE
Total mass [kg]
Payload's mass [kg]
$m_{PL}$
$m_{main\ prop.\ syst.}$
$m_{final\ burn}$
Maximum mass for Soyouz
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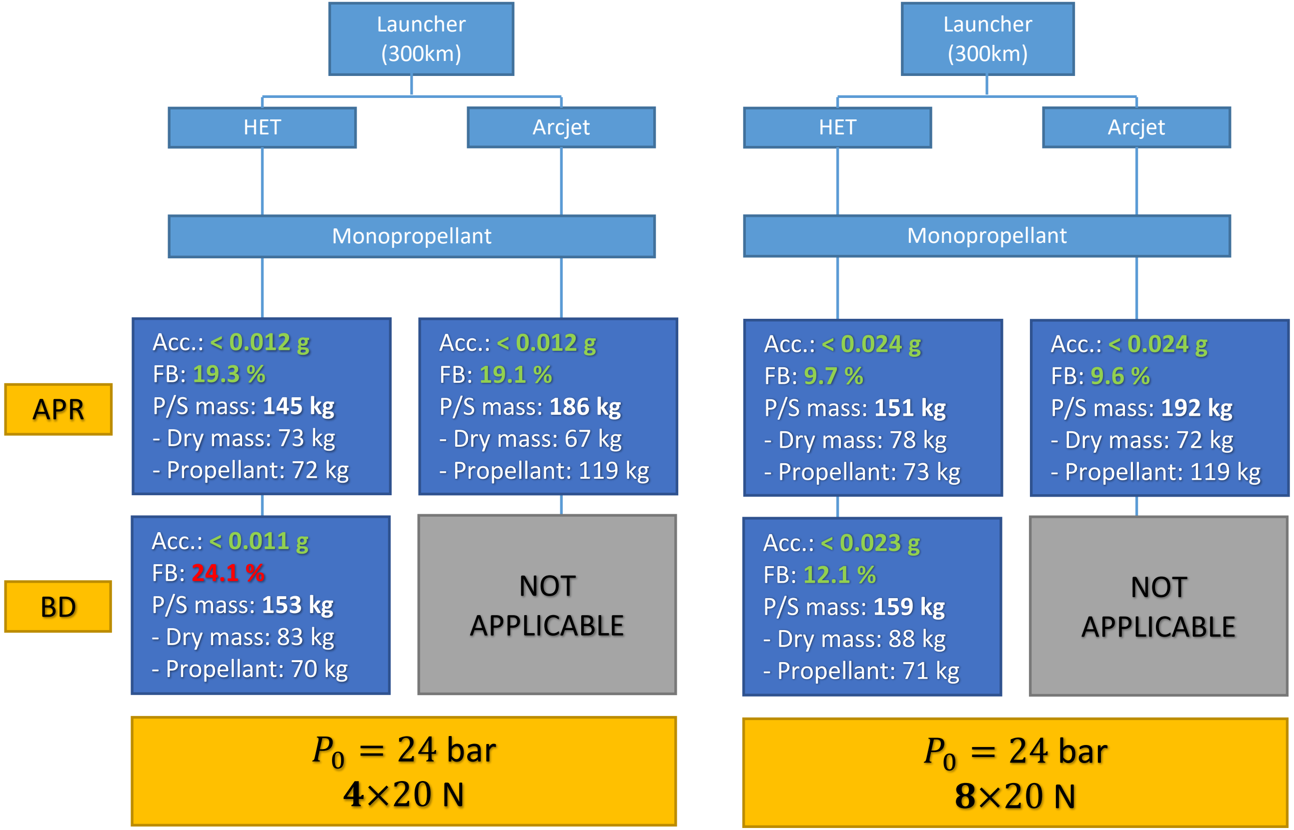
# III) Trade-off: b) Results: example

$m_{S/C} = 750$ kg




## Notes

- We considered 4, 8 and 12 thrusters as a common reliable configuration, but others could be investigated
- Configuration chosen to comply with all constraints

# III) Trade-off: b) Results: summing up

| | $m_{S/C} = 750$ kg | | | $m_{S/C} = 1500$ kg | | | $m_{S/C} = 4000$ kg | | |
|---|---|---|---|---|---|---|---|---|---|
| | HET | Arcjet | Monop. | HET | Arcjet | Monop. | HET | Arcjet | Monop. |
| Altitude | 300km | 300km | 300km | 300km | 300km | 300km | 300k | 300km | 800km |
| Mode | APR | APR | BD | APR | APR | APR | APR | APR | APR |
| Thrusters | 8x20N | 4x20N | 12x20N | 8x20N | 8x20N | 8x20N | 1x400N + 4x20N | 1x400N + 4x20N | 1x400N + 4x20N |
| | P/S wet mass: **145 kg**<br>- Dry mass: 73 kg<br>- Propellant: 72 kg | P/S wet mass: **186 kg**<br>- Dry mass: 67 kg<br>- Propellant: 119 kg | P/S wet mass: **286 kg**<br>- Dry mass: 59 kg<br>- Propellant: 227 kg | P/S wet mass: **224 kg**<br>- Dry mass: 85 kg<br>- Propellant: 139 kg | Added mass: **316 kg**<br>- Dry mass: 86 kg<br>- Propellant: 230 kg | P/S wet mass: **562 kg**<br>- Dry mass: 82 kg<br>- Propellant: 480 kg | P/S wet mass: **485 kg**<br>- Dry mass: 113 kg<br>- Propellant: 372 kg | P/S wet mass: **748 kg**<br>- Dry mass: 136 kg<br>- Propellant: 612 kg | P/S wet mass: **772 kg**<br>- Dry mass: 107 kg<br>- Propellant: 665 kg |

## Conclusion:

- **Best option mass-wise is with HET, however**:
  - HET low thrust => **higher collision risks (long transfer time) and operational complexity**
  - Two independent system => **more complex**
  - If Monopropellant system for deorbit is unused for decades => **uncertain behaviour**
- **Arcjet is a good option:**
  - Good compromise between $I_{sp}$ and thrust => **high efficiency and reduced time, thus hazard, in space**
  - One shared system => **limit complexity**
- **Next steps:** consider and weight the other criteria (reliability, complexity, etc.) to complete the trade-off