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1. INTRODUCTION

This document is the executive summary for the “System impact of Propulsion passivation” study under the European Space Agency contract 4000113039/11/NL/NR. The objective of the activity is the establishment of consolidated recommendations and processes to conduct passivation of propulsion systems for running and future ESA missions in a reliable way.

Space debris mitigation requirements specific to propulsion systems are scrutinized and compliance of OHB reference propulsion architectures is assessed. The risk of generating debris due to a failure in a propulsion system is assessed with a focus on the specific risk of a hypervelocity impact on a propulsion tank containing residuals.

The engineering activities, delta-qualifications or hardware development which can support the recommended propulsion passivation strategies are presented and prioritized.

The contract work is in collaboration with OHB System, the Swedish Defence Research Institute (FOI), Inmarsat, and Etamax.

2. COMPLIANCE TO SPACE DEBRIS MITIGATION RULES

2.1 SDM REQUIREMENTS

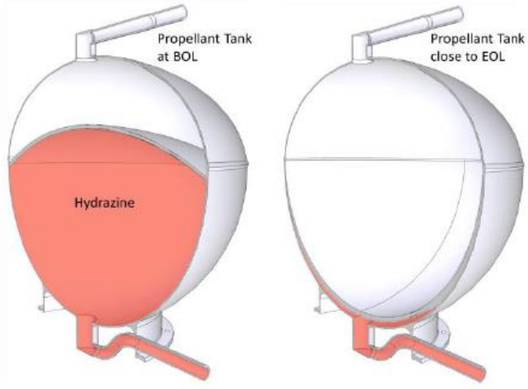
The European applicable requirements related to end of life decommissioning activities are defined in ISO 24113 “Space Debris Mitigations requirements”, which was adopted by the European Space Agency through the ECSS-U-AS-10 Rev. C.
ISO 24113 fails to identify what a “safe state” is and the handbook would therefore gain in being updated with tangible guidelines and quantitative targets to make the requirements clear and verifiable.
The ESSB-HB-U-002 “ESA Space Debris Mitigation Compliance Verification Guidelines” handbook released in February 2015 provides useful guidelines on verification methods and tools to facilitate the compliance assessment to the Space Debris Mitigation requirements.
It is recommended that the ESA handbook is updated and limits itself to ISO24113 requirements without adding new requirement.
Eventually, a European database registering safe End of Life conditions achieved by spacecrafts would facilitate the assessment of compliance by using similarity with other missions and platforms.

2.2 COMPLIANCE TO SDM REQUIREMENTS

The level of passivation achievable today on OHB reference missions is presented below. The tools and knowledge current limitations are too important to be able to claim that the propulsion systems are in a safe state at EoL. Way forwards are identified in §5.

❖ **Monopropellant propulsion systems for LEO / MEO missions**

Typical End of Life pressure in a diaphragm tank is ~6bar when the diaphragm hits its end position. At this point in time, the pressurant is trapped - by design - and the propellant can only be depleted down to thruster inlet qualified pressures. Also the tank expulsion efficiency is ~99.5% which translates in tiny amounts of hydrazine being trapped along the tank walls and also inside tubing and fluidic hardware due to the equipments internal pressure drop resistance. Full depletion of the tank and tubing cannot be performed but it is necessary to demonstrate that the propulsion system - with its residuals - is in a safe configuration.



❖ **Bi-propellant propulsion systems for GEO missions**

After isolating the pressurant following LEOP operations, the Helium tanks typically have a pressure of ~50bar. OHB System has experience in adding a passivation line to the propulsion system to lower this residual pressure to ~5bar. Residuals at EoL can be found in the following sections:

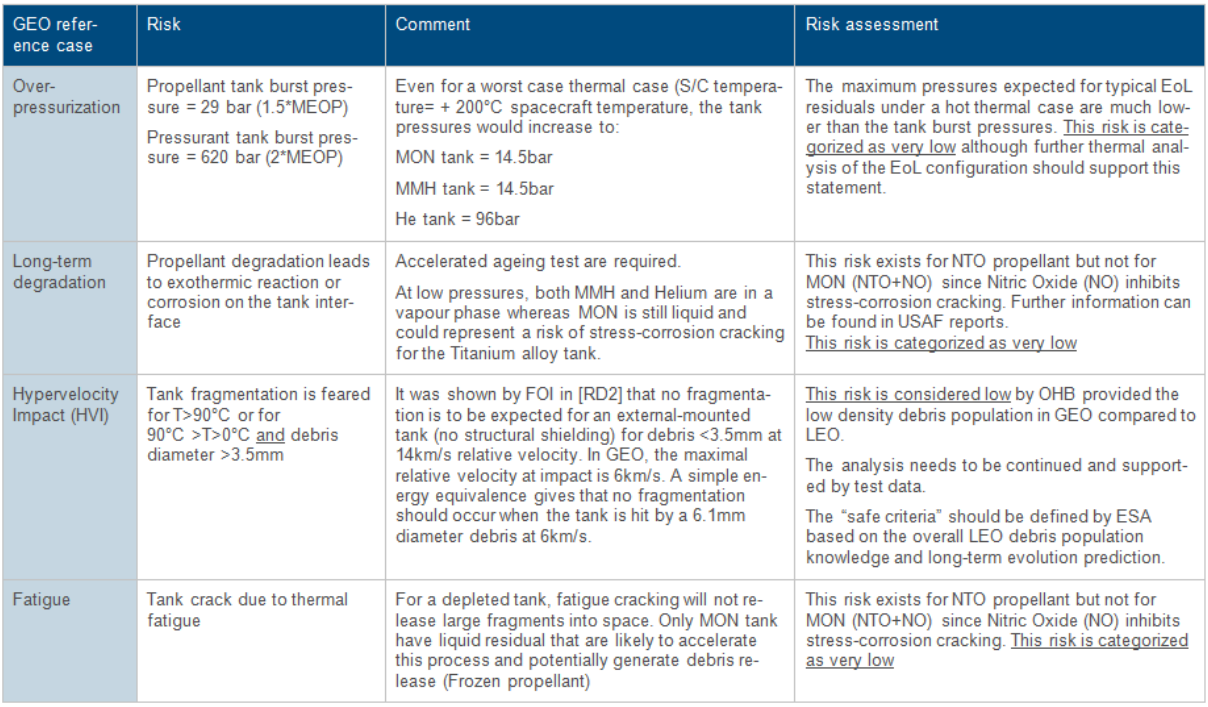
- Tank - Pressure regulator: ~5 bar GHe
- Check Valve - NO Pyrovalve: ~50bar GHe trapped in this small section
- Propellant tank - RCTs: ~4bar is achievable but limited in reality by the RCT qualification domain.
- Liquid Apogee Engine (LAE): Residual pressure ~ Propellant vapour pressure after isolation at BoL.

3. FRAGMENTATION RISK ASSESSMENT

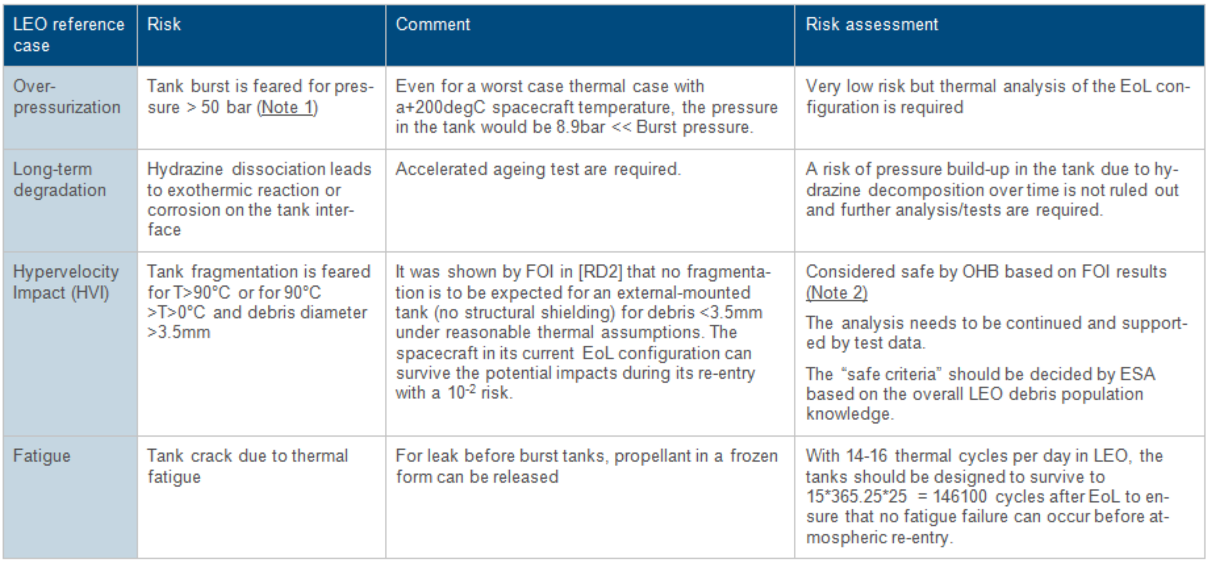
A Satellite break-up history review has shown that out of the 233 break-up events in orbit for satellites and launchers since 1958, 98 are accidental propulsion break-ups. Rocket Upper Stages failures represent 97 of these, and only one failure is attributed to a satellite that featured a solid rocket motor (USA-68). Although currently passivated propulsion systems are considered relatively safe, potential hazards are identified to further reduce risks.

3.1 RISKS IDENTIFICATION

The main risks identified during propulsion passivation are listed below.



GEO reference case	Risk	Comment	Risk assessment
Over-pressurization	Propellant tank burst pressure = 29 bar (1.5*MEOP) Pressurant tank burst pressure = 620 bar (2*MEOP)	Even for a worst case thermal case (S/C temperature= + 200°C spacecraft temperature, the tank pressures would increase to: MON tank = 14.5bar MMH tank = 14.5bar He tank = 96bar	The maximum pressures expected for typical EoL residuals under a hot thermal case are much lower than the tank burst pressures. This risk is categorized as very low although further thermal analysis of the EoL configuration should support this statement.
Long-term degradation	Propellant degradation leads to exothermic reaction or corrosion on the tank interface	Accelerated ageing test are required. At low pressures, both MMH and Helium are in a vapour phase whereas MON is still liquid and could represent a risk of stress-corrosion cracking for the Titanium alloy tank.	This risk exists for NTO propellant but not for MON (NTO+NO) since Nitric Oxide (NO) inhibits stress-corrosion cracking. Further information can be found in USAF reports. This risk is categorized as very low
Hypervelocity Impact (HVI)	Tank fragmentation is feared for T>90°C or for 90°C >T>0°C and debris diameter >3.5mm	It was shown by FOI in [RD2] that no fragmentation is to be expected for an external-mounted tank (no structural shielding) for debris <3.5mm at 14km/s relative velocity. In GEO, the maximal relative velocity at impact is 6km/s. A simple energy equivalence gives that no fragmentation should occur when the tank is hit by a 6.1mm diameter debris at 6km/s.	This risk is considered low by OHB provided the low density debris population in GEO compared to LEO. The analysis needs to be continued and supported by test data. The “safe criteria” should be defined by ESA based on the overall LEO debris population knowledge and long-term evolution prediction.
Fatigue	Tank crack due to thermal fatigue	For a depleted tank, fatigue cracking will not release large fragments into space. Only MON tank have liquid residual that are likely to accelerate this process and potentially generate debris release (Frozen propellant)	This risk exists for NTO propellant but not for MON (NTO+NO) since Nitric Oxide (NO) inhibits stress-corrosion cracking. This risk is categorized as very low



LEO reference case	Risk	Comment	Risk assessment
Over-pressurization	Tank burst is feared for pressure > 50 bar (Note 1)	Even for a worst case thermal case with a+200degC spacecraft temperature, the pressure in the tank would be 8.9bar << Burst pressure.	Very low risk but thermal analysis of the EoL configuration is required
Long-term degradation	Hydrazine dissociation leads to exothermic reaction or corrosion on the tank interface	Accelerated ageing test are required.	A risk of pressure build-up in the tank due to hydrazine decomposition over time is not ruled out and further analysis/tests are required.
Hypervelocity Impact (HVI)	Tank fragmentation is feared for T>90°C or for 90°C >T>0°C and debris diameter >3.5mm	It was shown by FOI in [RD2] that no fragmentation is to be expected for an external-mounted tank (no structural shielding) for debris <3.5mm under reasonable thermal assumptions. The spacecraft in its current EoL configuration can survive the potential impacts during its re-entry with a 10^{-2} risk.	Considered safe by OHB based on FOI results (Note 2) The analysis needs to be continued and supported by test data. The “safe criteria” should be decided by ESA based on the overall LEO debris population knowledge.
Fatigue	Tank crack due to thermal fatigue	For leak before burst tanks, propellant in a frozen form can be released	With 14-16 thermal cycles per day in LEO, the tanks should be designed to survive to 15*365.25*25 = 146100 cycles after EoL to ensure that no fatigue failure can occur before atmospheric re-entry.

3.2 HYPERVELOCITY IMPACT ON A HYDRAZINE TANK

The specific risk of tank fragmentation due to a hypervelocity impact with a debris is assessed in an attempt of defining a safe pressure threshold in the propellant tanks, as done for Ariane 5 Upper Stage in “Ariane 5 Attitude control system passivation: Theoretical and experimental determination of the explosion threshold pressure”. In this work, the penetration of vessels containing neutral gases was investigated with the conclusion that the tank shall be depleted to a pressure lower than 15bar at EoL to avoid an explosion in orbit. When transposing this work to hydrazine tanks on-board LEO spacecraft, not only the residual pressure inside the tank has been considered but also the contribution of the chemical energy contained inside the highly energetic hydrazine residuals has been accounted for.

A methodology is defined to assess the risk of tank rupture. The effect of temperature, pressure, and structural shielding are also presented. The analysis has been performed on a single case in LEO as the probability of collision is much greater than in GEO:

- Hydrazine tank: 65L - 1mm thickness - Ti 3AL2.5V - Externally mounted (no Spacecraft shielding effect!)
- Residuals: Hydrazine at 5bar and 20°C nominally.
- Spacecraft EoL temperature = [0 -170°C] (worst-case)
- A worst case orbit (high debris fluxes) is selected: altitude 800km, inclination 98.1°
    - Probability of impact with the tank over 25 years is <1e-3 →13mm Ø debris
    - Probability of impact with the tank over 25 years is <1e-2 →3.5mm Ø debris
    - Relative velocity = 14km/s (worst case)
    - Density of Aluminium is assumed for the debris

The following sequence of numerical models have been created and validated against available experimental data to simulate the hypervelocity impact:

1. **EXP:** Explicit Finite element codes (hydrocodes) using Eulerian description with a gridded mesh. The model is well suited to non-linear problems such as crash analysis or penetration models but material boundaries are difficult to track and the models do not permit to follow properly the plume propagation. This model allows calculating the shock pressure in the liquid hydrazine layer and is used as an input to the RMD simulation presented below.

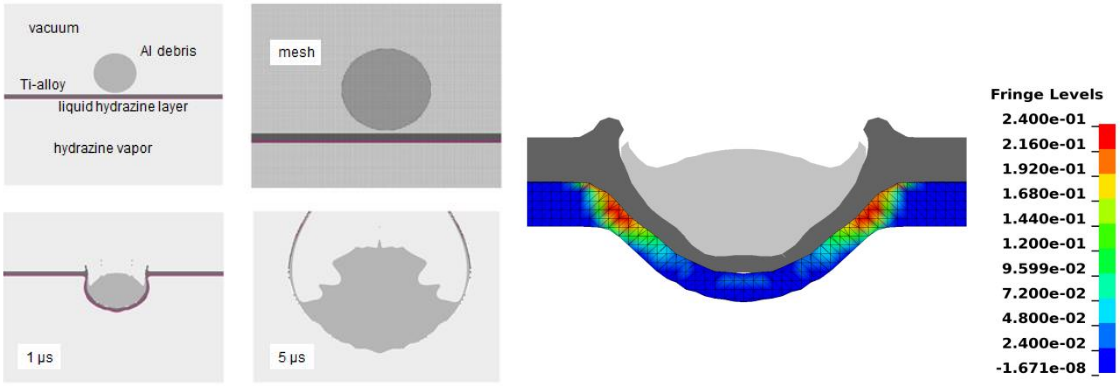


Figure 3-1 Left: Hydro code simulation 13mm debris Right: Interaction of 3.5mm debris with liquid hydrazine

2. **SPH:** Smoothed Particle Hydrodynamic is a mesh free particle method using Lagrangian formulations. It is used in a second step to analyse the formation and dynamics of the plume

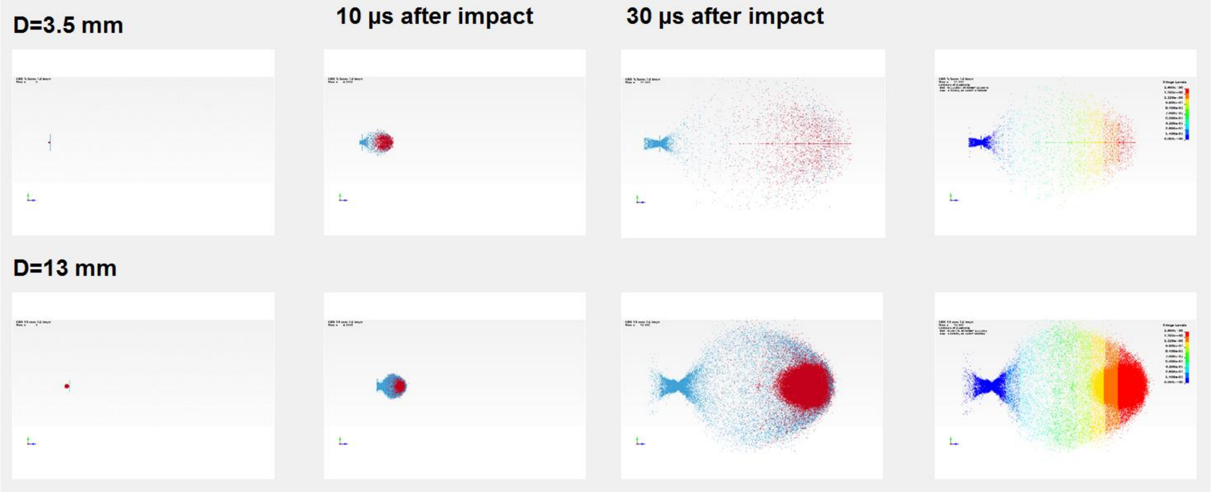


Figure 3-2 Plume dynamic using SPH.
The 3.5mm debris is totally dispersed whereas a rather dense core of debris material remains for the 13mm debris

Also the effect of adding a structural shield - a typical honeycomb panel in this case - is assessed. A protective structure would disperse the debris particle severely before impacting the propellant tank.

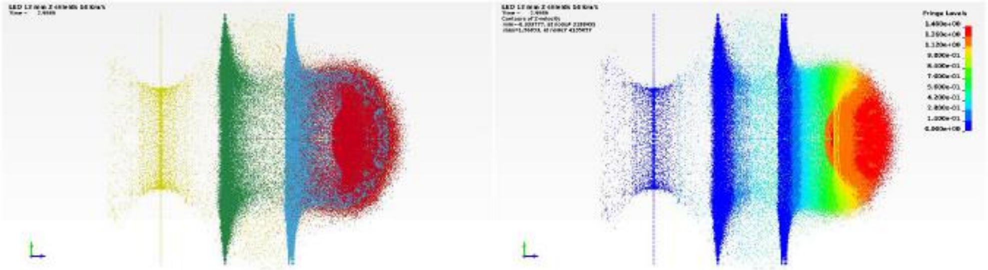


Figure 3-3 Simulation of a 13mm debris at 14km/s (relative velocity) hitting the S/C structure before impacting the tank wall (blue)

3. **RMD:** Reactive Molecular Dynamics. Chemistry at extreme temperature/pressures is difficult to describe and molecular dynamics methods describing the electrostatic interactions between and within molecules are used to simulate thousands of molecules over nanoseconds timescales. Breaking and formation of covalent bonds can be observed during a shock compression and decomposition of liquid hydrazine.
A shock pressure of about 30GPa (corresponding to an impact with a 3.5mm diameter, 14km/s debris, per Figure 3-1) is simulated and results in a limited decomposition of hydrazine, suggesting that prompt detonation is unlikely in that case (also supported by available test data).

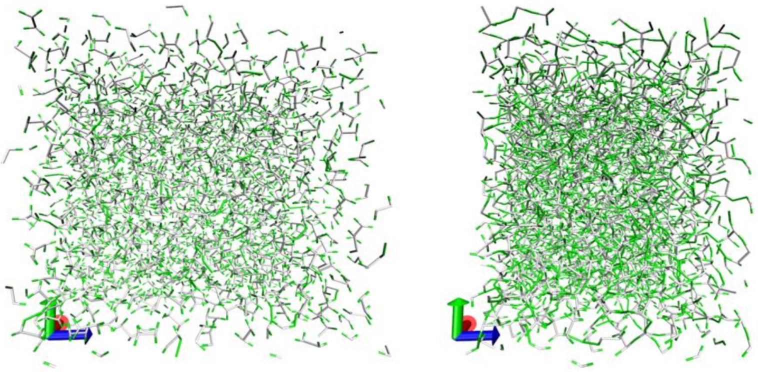
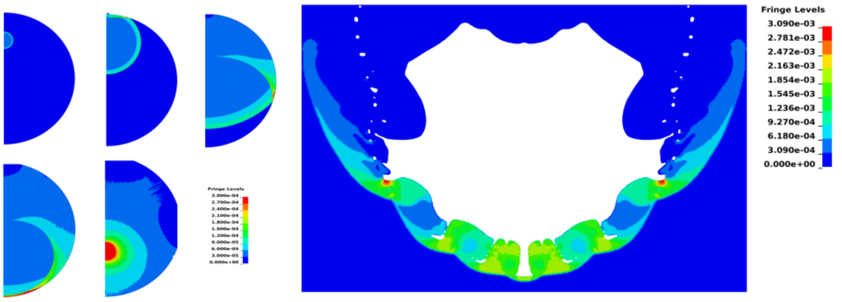


Figure 3-4 Reactive Molecular Dynamics simulation of hydrazine under a pressure shock of 40GPa

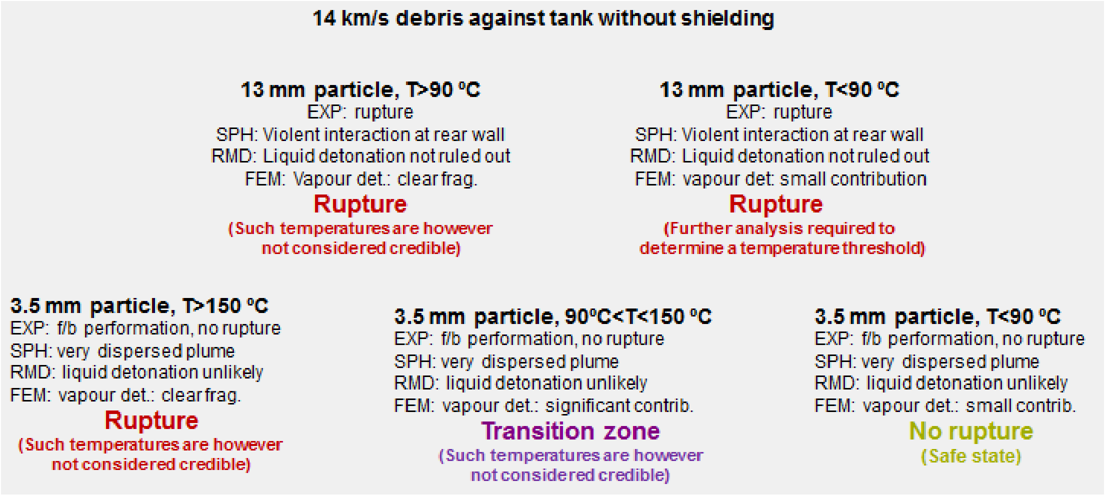
4. **FEM:** Finite Element Method using LS-Dyna is used to assess whether a detonation in the hydrazine vapour phase can occur.

Following the impact, the shock wave transmitted to the vapour phase of hydrazine can generate the decomposition of hydrazine and therefore a brutal fragmentation of the tank.

Under a worst case tank temperature of 443K, the impact with a 13mm debris leads to a detonation wave in the vapour phase where the pressure field is in the order of 30-90bar on a large surface area of the tank for tens of microseconds, which is sufficient for the tank to burst (may not be an issue for Leak-Before-Burst tanks).



The conclusive figure below shows how sensitive the results are to the final S/C EoL thermal configuration.



14 km/s debris against tank without shielding

13 mm particle, T>90 °C
EXP: rupture
SPH: Violent interaction at rear wall
RMD: Liquid detonation not ruled out
FEM: Vapour det.: clear frag.
Rupture
(Such temperatures are however not considered credible)

13 mm particle, T<90 °C
EXP: rupture
SPH: Violent interaction at rear wall
RMD: Liquid detonation not ruled out
FEM: vapour det: small contribution
Rupture
(Further analysis required to determine a temperature threshold)

3.5 mm particle, T>150 °C
EXP: f/b performation, no rupture
SPH: very dispersed plume
RMD: liquid detonation unlikely
FEM: vapour det.: clear frag.
Rupture
(Such temperatures are however not considered credible)

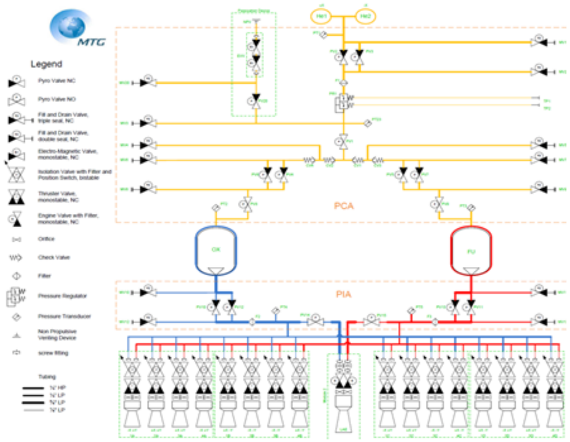
3.5 mm particle, 90°C<T<150 °C
EXP: f/b performation, no rupture
SPH: very dispersed plume
RMD: liquid detonation unlikely
FEM: vapour det.: significant contrib.
Transition zone
(Such temperatures are however not considered credible)

3.5 mm particle, T<90 °C
EXP: f/b performation, no rupture
SPH: very dispersed plume
RMD: liquid detonation unlikely
FEM: vapour det.: small contrib.
No rupture
(Safe state)

4. RECOMMENDATIONS FOR A SAFE AND RELIABLE PASSIVATION

Reference GEO mission

Passivation for GEO platform with Chemical Propulsion is limited by the pressurant Helium side than is isolated after LEOP (~50bar GHe at EoL) and by the minimum qualified thruster feed pressure (~9 bar).



EoL Configuration	Type	Value
Propellant residuals	MON MMH	1.8 – 2.6% initial mass T = 23±5 °C P < 9bar
Pressurant residuals	Helium	Mass unchanged T = 23±5 °C P ~ 50bar
Gauging accuracy at EoL	Book-keeping PVT TGPS	1-3% accuracy 2-4% accuracy 0.5-1% accuracy

The passivation strategy needs to be established also considering the others subsystems and the overall system impacts. For example, losing the satellite attitude during an uncontrolled passivation manoeuver could lead to a situation where the telecommunication link necessary to perform the spacecraft electrical passivation is lost, which is a critical event considering the history of break-ups due e.g. battery explosion.

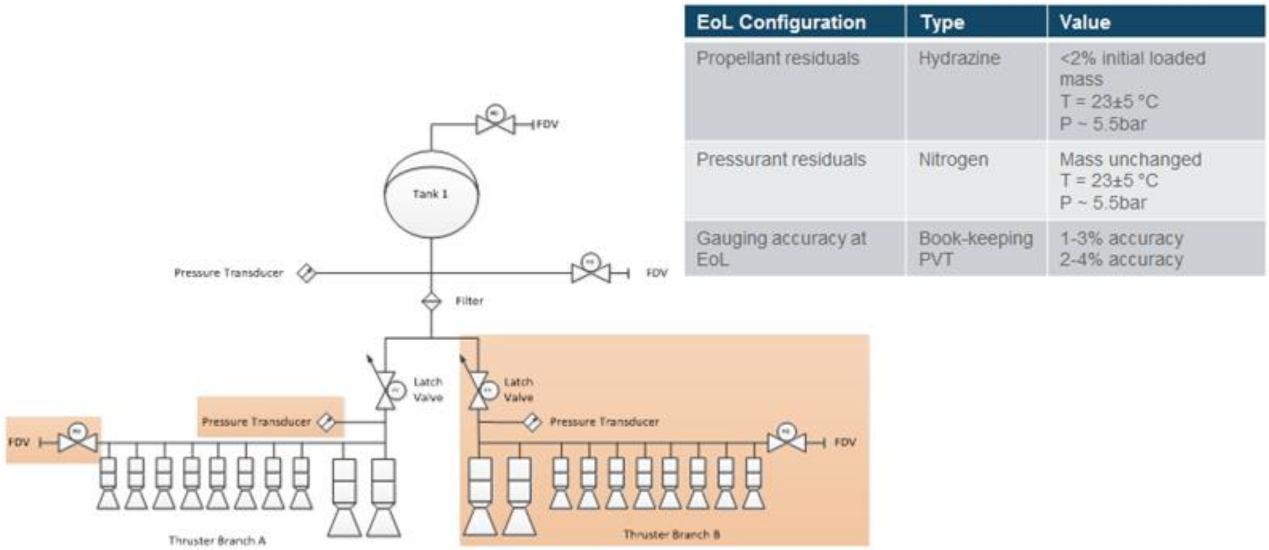
The actions performed for each step of the decommissioning are coupled. For example final stages of on-board propellant reduction and pressure reduction can have a significant negative impact on the already achieved long term final graveyard orbit. Other risks of propulsion system passivation, especially when operating outside equipment qualification domain, have to be very carefully managed not to put at risk the remaining spacecraft passivation tasks.

Based on OHB experience and a literature review, the main recommendations, controls, and monitoring reported below have been identified.

Type	Parameter	Comment
TM/TC	Telecommunication link	Link with ground station to detect anomalies (thermal drift, bubbles, assymetrical thrust)
	Acquisition rate	Typically 1Hz for PTs. Add-on channel typically permit ≥8Hz monitoring.
Attitude & Orbit	Collision probability	Maximizing the orbit altitude and minimize collision risk with passivated S/C
	Sun radiation pressure	Reduces the perigee to altitude - ~50km once per year.
	AOCS mode	Safest: Sun Pointing Mode (large field of view, stable mode). Recommended when bubbles are no longer manageable Best TM/TC conf: Earth Pointing mode ΔV optimization: Earth Pointing Mode (non-inertial forces in SAM hard to predict)
	Propellant venting torque	Plume impingement calculation is needed. Venting can generate a few m/s
Propulsion	Propellant gauging	TGPS + Book-keeping is recommended at EoL when possible
	Tank pressure	Show that the final pressure is safe wrt over-pressurization in the worst hot case
	Thruster duty cycles	Nominal duty cycles at beginning of passivation operations, then reduced (safer) duty cycle Thrusters are limited in #cycles
	Thruster / Filter temperature	1) Detection of potential freezing event. Special care should apply on MON lines and shadowed thrusters. RCTs can be heated during the final stages of evacuation. 2) Filter/Thruster valve temperature increases when gas passes as it is no longer cooled by "fresh" propellanrt.,
	Thruster actuation	The thrusters closest to the propellant tank should be fired first to avoid a "bubble contamination"
	Bubble ingestion	The thruster combustion chamber , the PTs noise, and the angular rates shall be monitored to detect a bubble passage
TCS	Thruster feed pressure	Tank temperature can be controlled to keep a thruster feed pressure within the qualified domain.

Reference LEO -MEO mission

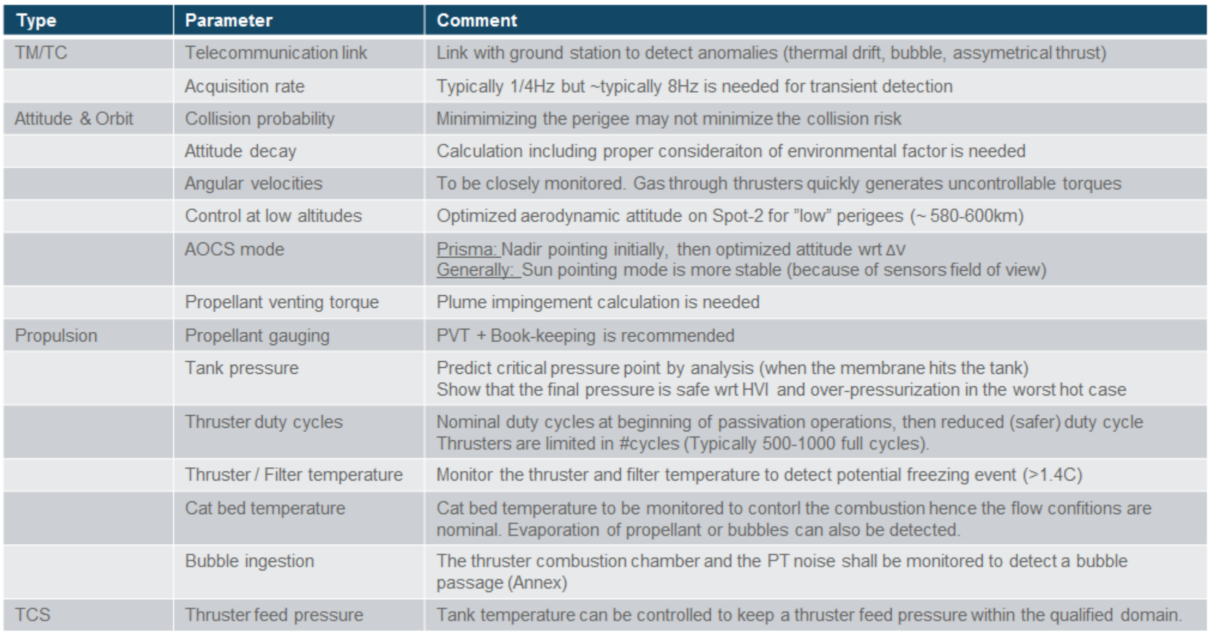
Passivation for LEO/MEO platform with Chemical Propulsion is limited by the minimum qualified thruster feed pressure and by design due to the presence of a diaphragm in the tank that separates the pressurant and the propellant sides. The propulsion passivation experience both of the hydrazine and LMP-103S systems of PRISMA, built and operated by OHB Sweden is used as a reference case to issue recommendations.



EoL Configuration	Type	Value
Propellant residuals	Hydrazine	<2% initial loaded mass T = 23±5 °C P ~ 5.5bar
Pressurant residuals	Nitrogen	Mass unchanged T = 23±5 °C P ~ 5.5bar
Gauging accuracy at EoL	Book-keeping PVT	1-3% accuracy 2-4% accuracy

As for GEO missions, the passivation strategy needs to be established considering potential system and mission impacts to not compromise the remaining passivation tasks.

Based on OHB experience and a literature review, the main recommendations, controls, and monitoring reported below were identified.



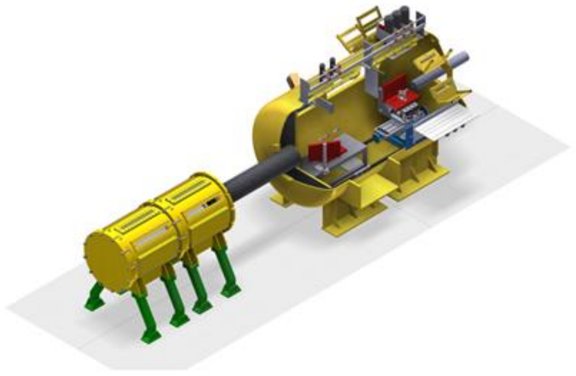
Type	Parameter	Comment
TM/TC	Telecommunication link	Link with ground station to detect anomalies (thermal drift, bubble, assymetrical thrust)
	Acquisition rate	Typically 1/4Hz but ~typically 8Hz is needed for transient detection
Attitude & Orbit	Collision probability	Minimimizing the perigee may not minimize the collision risk
	Attitude decay	Calculation including proper consideraiton of environmental factor is needed
	Angular velocities	To be closely monitored. Gas through thrusters quickly generates uncontrollable torques
	Control at low altitudes	Optimized aerodynamic attitude on Spot-2 for "low" perigees (~ 580-600km)
	AOCS mode	Prisma: Nadir pointing initially, then optimized attitude wrt ΔV Generally: Sun pointing mode is more stable (because of sensors field of view)
	Propellant venting torque	Plume impingement calculation is needed
Propulsion	Propellant gauging	PVT + Book-keeping is recommended
	Tank pressure	Predict critical pressure point by analysis (when the membrane hits the tank) Show that the final pressure is safe wrt HVI and over-pressurization in the worst hot case
	Thruster duty cycles	Nominal duty cycles at beginning of passivation operations, then reduced (safer) duty cycle Thrusters are limited in #cycles (Typically 500-1000 full cycles).
	Thruster / Filter temperature	Monitor the thruster and filter temperature to detect potential freezing event (>1.4C)
	Cat bed temperature	Cat bed temperature to be monitored to contorl the combustion hence the flow confitions are nominal. Evaporation of propellant or bubbles can also be detected.
	Bubble ingestion	The thruster combustion chamber and the PT noise shall be monitored to detect a bubble passage (Annex)
TCS	Thruster feed pressure	Tank temperature can be controlled to keep a thruster feed pressure within the qualified domain.

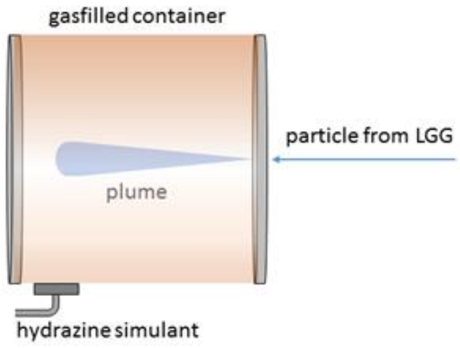
5. ACTIVITIES TO SUPPORT THE SELECTED PASSIVATION STRATEGIES

The engineering activities, delta-qualification, and hardware development in the table below are identified to support the improved passivation strategies recommended. The activities to be prioritised are then presented in further details.

	Task
1	Perform a study to assess the safe tank pressure threshold under the worst case hot temperature and Hypervelocity debris impact and study fragmentations process when impacted by HVI
2	Delta-qualification of thruster at low inlet pressures and characterization of Catalyst bed performance
3	Delta-qualification of thruster at low inlet pressures
4	Development of an Electronic Helium Pressure Regulator
5	Investigate and determine what a spacecraft propulsion subsystem “Safe State” is.
6	Develop and verify an operational sequence to perform depletion through thrusters and/or gas passivation valve
7	Assess the thermal configuration of LEO/GEO satellites beyond EOL, in particular propulsion system temperatures
8	Investigate the potential pressure build-up in hydrazine tanks resulting from hydrazine decomposition over time
9	Delta-qualification of regulator at low inlet pressures, characterization of regulation performance and reliability figure
10	Develop performant gauging methods or high accuracy gauging hardware
11	Leakage test of Diaphragm tank to assess the possibility to vent the pressurant thanks to the membrane permeation when a differential pressure appears across the membrane (at EoL).
12	Perform study to determine destruction potential of non-fired squibs, or simply perform tests. (Low priority as we prefer firing all PV at EoL)

- Item 1+2: An interesting activity to support the definition of a safe pressure threshold is the continuation of the **modelling activities of hypervelocity impacts**. The models could be refined and parametric studies could be done for different tank configurations, debris types, and residuals. **Experimental verification** with destructive tests using the FOI light-gas gun facility shown below is also suggested.





- Item 2+3: For LEO and GEO missions, trade-off have been performed between future propulsion architectures optimized for passivation. The **Delta-qualification of Reaction Control Thrusters** activity is considered the most beneficial to improve propulsion passivation as it permits reaching low levels of residuals in the spacecraft without modifying the propulsion architecture.

- Item 4: Also the **development of a Helium Electronic Pressure Regulator**, as shown below, would permit a full propellant and pressurant depletion on GEO platforms while being very beneficial to the missions since the thrusters performances are increased with the fuel and oxidizer tank pressures being controlled all along the mission, optimizing mixing ratio and thrust. The apparent added complexity and mass of the fluidic and electronics parts is counter balanced by the removal of many pyrovalves (isolation is provided by the bang-bang valves).

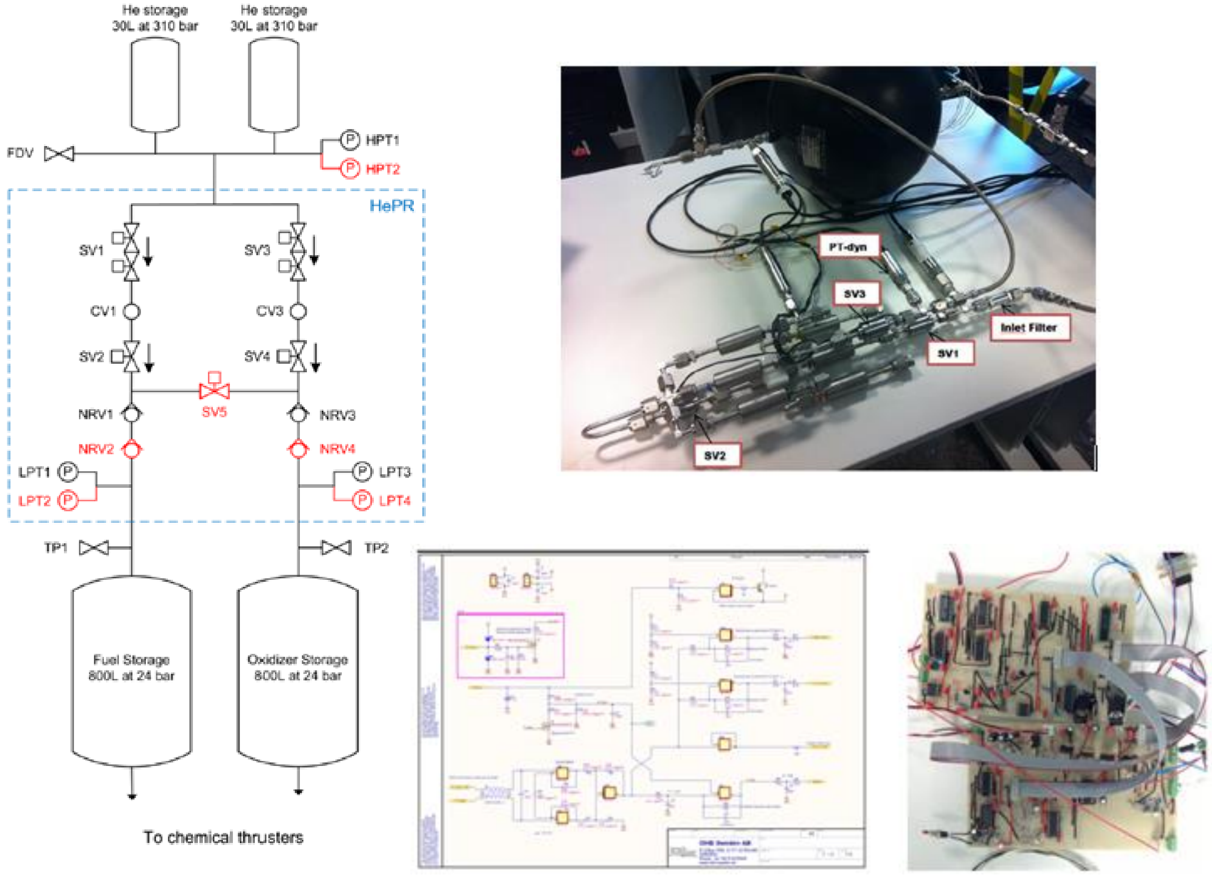


Figure 5-1 Left: GEO propulsion system with electronic Helium pressure regulation Right: OHB Sweden Helium EPR breadboard development (2014)

6. CONCLUSION

Applicable Space Debris Mitigation requirements are defined in ISO 24113 with the main objective of “making safe” the propulsion system at EoL. As of today, both knowledge and technological gaps prevent from stating with certainty that current spacecraft are in a safe state at EoL. However, no break-up due to propulsion subsystem failure was ever reported for satellites and after a first iteration, the main risks (over-pressurisation, thermal drift, debris impact with a tank containing residuals) are considered low both for LEO and GEO platforms.

Best practices for optimized propulsion passivation operations were gathered based on operators’ experience for LEO, MEO and GEO missions.

Future activities supporting the definition of an EoL safe state for a propulsion subsystem were presented (Hypervelocity models, Thermal analysis at EoL, Optimized passivation sequences). The definition of a safe state and acceptable risk for a propulsion system should be defined while also considering the acceptable risk for the overall spacecraft population. A trade-off has shown that the most promising future concepts to enhance propulsion passivation were the delta-qualification of mono and bi propellant RCTs to low pressures and the development of a Helium Electronic Pressure Regulator for GEO platforms.