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Title : Propulsion Passivation (PPAS) Study Executive summary Report

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Summary

This technical note presents a summary of the analyses and assessments performed during the propulsion passivation study:

- Review of Propulsion passivation requirements and impacts (TN1.1)
- Review of current Propulsion passivation strategies (TN1.2)
- Analysis of partial Propulsion passivation (TN1.3)
- Propulsion passivation strategies for running missions (TN2.1)
- Potential propulsion passivation strategies for future missions (TN2.2)
- Propulsion passivation roadmap (summary report and final roadmap)

Document change log

ISSUE	DATE	MODIFICATION NB	MODIFIED PAGES	OBSERVATIONS
01/00	30/11/2016		All	First issue of the document

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1 INTRODUCTION

This technical note summarise all activity done as part of PPAS study

2 DOCUMENTATION

2.1 Reference documents

In this section are defined the documents which have been used to write the present document and which contain information that may be useful for the understanding of the present document.

If the document issue is not listed, the last issue is applicable.

If the document issue is listed only this issue is applicable.

RD No.	Document reference	Iss./rev., date	Document title
[RD 01]	ESYS.TCN.PPAS.ADST.00022	Issue 2 2/2/2016	TN1.1 Review of propulsion passivation requirements and impacts Restricted diffusion
[RD 02]	ESYS.TCN.PPAS.ADST.00023	Issue 2 2/2/2016	TN1.2 Review of current propulsion passivation strategies Restricted diffusion
[RD 03]	ESYS.TCN.PPAS.ADST.00024	Issue 1 28/7/2016	TN1.3 Analysis of partial propulsion passivation Restricted diffusion
[RD 04]	ESYS.TCN.PPAS.ADST.00044	Issue 2 13/7/2016	TN2.1 Propulsion passivation strategies for running missions Restricted diffusion
[RD 05]	ESYS.TCN.PPAS.ADST.00045	Issue 1 14/6/2016	TN2.2 Potential propulsion passivation strategies for future missions Restricted diffusion
[RD 06]	ESYS.TCN.PPAS.ADST.00051	Issue2 25/11/2016	Summary Report and final roadmap

2.2 Acronyms list

AOCS	Attitude and Orbit Control Subsystem
ATOX	Atomic Oxygen
DHS	Data Handling Subsystem
ECSS	European Cooperation for Space Standardization
EOL	End Of Life
FCV	Flow Control Valve
FDIR	Fault detection, isolation and recovery
GEO	Geostationary
IADC	Inter-Agency Space Debris Coordination
ISO	International Organization for Standardization
ISP	Specific Impulse
ITT	Invitation To Tender
LEO	Low Earth Orbit
MEO	Middle Earth Orbit
MMH	Monomethylhydrazine
NTO	Dinitrogen tetroxide
PV	Pyrotechnic Valve
PVT	Pressure, Volume, Temperature
RF	Radio Frequency
RFD/W	Request for Deviation/Waiver
SMA	Shape Memory Alloy
TBC	To Be Confirmed
TBD	To Be Defined
TC	Telecommand
TM	Telemetry
TN	Technical Note
TPGT	Thermal Propellant Gauging Technique

3 EXECUTIVE SUMMARY

3.1 TN 1.1: Review of propulsion passivation requirements and Impacts

Technical note **RD 01** gives generic requirements for propulsion passivation. The main driver for these requirements is the risk of self-explosion of tanks or explosion due to collision with debris or micro-meteorites after the end of mission in order to avoid generation of new debris.

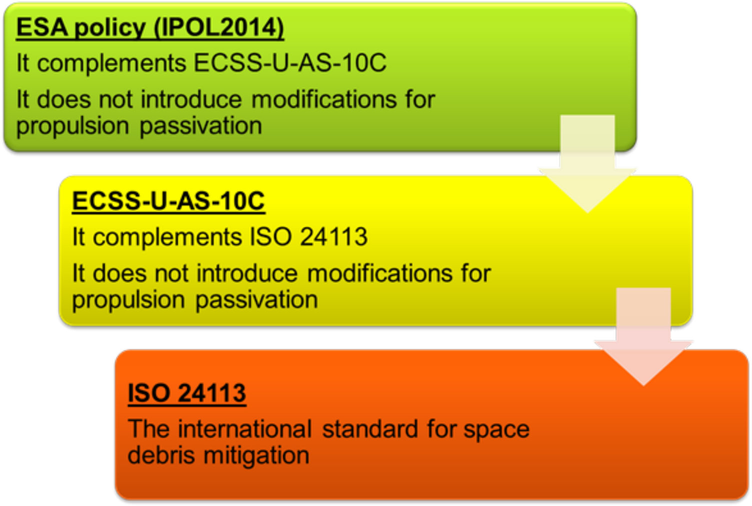

Figure 3-1: Applicable documents for the space debris mitigation

3.1.1 Requirements for new programs

New requirements were defined at propulsion level and also for AOCS, FDIR, DHS and satellite level. They let open the choice of the propulsion passivation: via thrusters (like the past propulsion passivation) or via a dedicated passivation device.

For the propulsion passivation via thrusters, requirements are introduced in order to have:

- Robust attitude control (to master the delta-V induced by the passivation),
- Sufficient telemetries for real time or a posteriori diagnostic of the propulsion passivation,
- Limitation of thruster freezing risk.

For propulsion passivation via new propulsion passivation device, requirements were defined for this new hardware. Very important issue for this device is the potential impact on the nominal mission: the addition of the new device on the propulsion architecture must not decrease the reliability of the nominal mission. The reliability requirements for the propulsion passivation device

- The probability of non-intentional passivation device commanding shall be lower than 1E-6 (TBC) over the operation lifetime .
- No single failure within the propulsion passivation device shall lead to unwanted passivation of any tank in operational mode.
- The propulsion passivation device reliability for ensuring the propulsion passivation at the end of the satellite operation lifetime shall be greater than 0.9 (TBC).
- (GOAL) The propulsion passivation device should be reversible during the nominal lifetime, so that it shall be possible to stop the propulsion passivation in case of unexpected commanding of the propulsion passivation device

3.1.2 Recommendations for on-going programs

Recommendation for ongoing programs is to achieve passivation through the thrusters as usually no specific device is part of the propulsion design. Defining the right passivation strategy requires analyses to choose the best option:

- At AOCS level: to identify AOCS limitations and capability for passivation with thrusters;
- At FDIR level: to identify which on-board surveillances are necessary or not;
- At system and operation level, to define propulsion passivation sequence via thrusters with autonomous mechanisms (time tagged TC for example) or through operations commanded by ground, taking into account that electrical passivation is done after propulsion passivation.

3.2 TN 1.2: Review of current passivation strategies

Propulsion passivation is most of the time feasible for running missions, using thrusters and existing AOCS modes, whatever the number of tanks and for both monopropellant and bipropellant systems.

- For monopropellant systems the propulsion passivation may be:
  - Partial for tank(s) with membrane. All the hydrazine under the membrane may be depleted but the pressurant gas above the membrane cannot be depleted. The final tank pressure is close to typically 5 bars at the end of mission.
  - Almost complete for tank(s) with PMD. All the hydrazine and the pressurant gas can be depleted. The minimum achieved final tank pressure was typically close to 2 bars.
- For bipropellant systems with PMD tank, the propulsion passivation can be almost complete. Typical tank pressures at end of the propulsion passivation are less than 1 bar for oxidizer (NTO) and close to 0 for fuel (MMH). For propulsion systems with several pairs of oxidizer and fuel tanks, tank swap strategy is necessary to deplete as much as possible every tank. Asymmetry in the oxidizer and fuel quantities induces firing with monopropellant phase before reaching pressurant phase. Operation usually has to face thruster blockage due to propellant icing.

The propulsion passivation via thrusters has successive phases:

- First phase with nominal behaviour of thrusters (named 'deterministic phase'). It corresponds to depletion of propellant(s). All the thrusters are still used inside their qualification domain and have nominal performances.
- Transient phase with possible transient behaviours of thrusters, with degraded performances. This phase corresponding at thruster inlet to mixture of pressurant gas with propellant and monopropellant for bipropellant systems.
- Last phase with pressuring gas depletion (named 'random phase'). The thrusters are used outside their qualification domain and have degraded performances.

For the deterministic phase, the strategy is to deplete propellant(s) with successive orbit corrections as the ones performed for the station keeping during the operational life. Commanding in-plane orbit corrections allow continuing to release the LEO/GEO protected orbital zone. For monopropellant systems all the tanks are in communication. For bipropellant systems the tank swap strategy based on ground monitoring of the time evolution of tank pressures (patented water hammer technique) allow depleting propellant as much as possible in all tanks. First phase ends when there is no more propellant(s) in all tank(s).

Ground is in charge of deciding when the deterministic phase ends to command the second phase. The objective is to detect imminent end of propellant. It can be achieved during the propulsion passivation through following symptoms on the telemetry during thrust:

- Sudden change of the slope of the tank pressure,
- More important variations of the angular rates and angular depointings,
- Decrease of the thruster temperatures,
- FCV soak-back,
- Water hammer technique (sharp reduction in pressure oscillations observed on the PT).

The strategies for propulsion passivation in transient phase and random phases are different. For these two phases, the thrusters are still used, but outside their qualification domain. As a consequence thrusters have degraded performances, with possible freeze for bipropellant systems for example. Thus additional precautions are required to have attitude control and FDIR robust to the degraded performances of thrusters (new tuning of control laws, increase of thresholds for on-board surveillances for example). Existing strategies for these phases are:

- Command small in-plane orbit corrections (ERS-2 case),
- Command never ending in-plane orbit corrections with automatic electric passivation at programmed epoch (SPOT-4 case),
- Command thruster firings in safe mode (GEO satellites Eurostar E2000+).

Typical duration of propulsion passivation for spacecrafts is seven day. An accurate propellant gauging is required for lifetime optimization and good planning for successful passivation. Moreover an extended ground station network is recommended in order to have more TM/TC visibility slots.

For Ariane 5, propulsion passivation of the main propulsion system is performed with dedicated hardware in order to flush the oxygen and hydrogen tanks after the end of the mission. T shaped doubled of nozzles at end of additional line are used. They are commanded thanks to pyrotechnical valves (redounded). This apparent simple solution (adding hardware to do “holes” in the propellant and pressurant tanks at end of mission), has faced several issues, that have been carefully analysed and solved.

The use of additional device for future satellite must be considered. It could be the solution for the propulsion passivation of pressurant tank for bipropellant system to be passivated at beginning of life just after the pressurant tank isolation. For propellant tank(s) there is an issue of commanding pyrotechnical about 10 to 15 years after the start of the mission. There points are analysed in [RD 05].

3.3 TN 1.3: Analysis of partial propulsion passivation

3.3.1 Objectives of the analyses

With current propulsion subsystem design (without dedicated passivation device), the propulsion passivation is not fully complete: there are some trapped propellants that cannot be expelled.

The objective of the analysis is to assess precisely the partial passivation efficiency and the associated remaining risk (of self-explosion under overpressure or explosion under collision with a debris or a micrometeorite), in order finally to be able to answer to the following question:

“Do we really need an additional passivation device to fulfil the Space Debris mitigation guidelines, that say that we shall « permanently deplete or make safe » the S/C for the disposal phase”.

The analysis logic and the main results are the following:

- Assessment of the minimal residual propellants with the best achievable passivation with current designs (no passivation devices) ð about 1% residuals for LEO S/C, a little less for GEO S/C (the larger the tank, the smaller the percentage of trapped propellants)
- Assessment of the risk of thermal runaway of propellants : MMH and NTO products not sensible to thermal runaway in the range of expected T° during the disposal phases. Hydrazine seems critical if tank T° is above 150°C
- Assessment of the worst tank T° during the disposal phase:
  - The S/C is definitely OFF so the orbit is uncontrolled: the Local Solar Time will drift slowly and will go through the 6h-18h orbits (without eclipse). The S/C attitude is also uncontrolled: so the propulsion module can face the sun during long periods
  - MLI thermal blankets in kapton will degrade (disappear?) due to ATOX at low altitude
  - With these pessimistic attitude/MLI assumptions, a T° of the tank of up to 100°C can probably be reached (to be confirmed by more accurate thermal analyses)
- Analysis of the decomposition process of the propellants: there is a decomposition of heavy molecules in lighter ones that create overpressure factor: selected values for decomposition ratio (for T° lower than 200°C) are all < 2 for N2H4, MMH and NTO
- Assessment of the max possible pressure with the previous assumptions (quantity of residuals, decomposition ratio and T° of 100°C) gives around 25 bars in LEO tanks, 5 bars for GEO (both below the respective bursts pressure of the tanks)
- Analysis of the risk of explosion of the tank under hypervelocity impacts
  - Done only for a LEO typical S/C (AS250 product), with simplified methods and models
  - Use of the MASTER 2009 model for micrometeorite and debris environment
  - Calculation of the probability of explosion for a tank without pressure: negligible
  - Calculation of the probability of explosion for a tank with 25 bars pressure and pessimistic assumption that all penetration will provoke explosion (whatever the impact energy): risk is about a few 10-3 per month at 25 bars.

3.3.2 Conclusion of this preliminary study

- **No risk of self-explosion under overpressure**
  - Even with pessimistic decomposition assumptions, and a T° of 100°C on the tank during the disposal phase, max pressure are far below burst pressure of the tanks (a few bars for GEO S/C, up to 25 bars for LEO S/C)
- **Risk of explosion under hypervelocity impact**
  - Risk is considered negligible for GEO tanks due to their very low remaining pressure
  - For LEO S/C, the risk is low but can exist and will depend on the max T° during the disposal phase, and the duration of such high T° phase (days, weeks, months?): more accurate analyses are necessary to refine the simplified assumptions used in this PPAS study.

3.4 TN 2.1: Propulsion passivation strategies for running missions

End of life condition conditions before the propulsion passivation are generic. The propulsion passivation starts as soon as at least one of the following conditions becomes true:

- Ø The targeted orbit for the release of the LEO/GEO protected orbit zone is reached;
- Ø The remaining propellants, assessed by ground, reaches EoL threshold;
- Ø The spacecraft goes out its flight domain (for e.g. LEO spacecraft reaches the smallest perigee altitude compatible with its AOCS).

The propellant gauging accuracy, the residuals (the propellants trapped in tank(s)) and additional margin (if needed) are used to define the EoL threshold for remaining propellants. They are used to define the different phases of the propulsion passivation (see Figure 3-4).

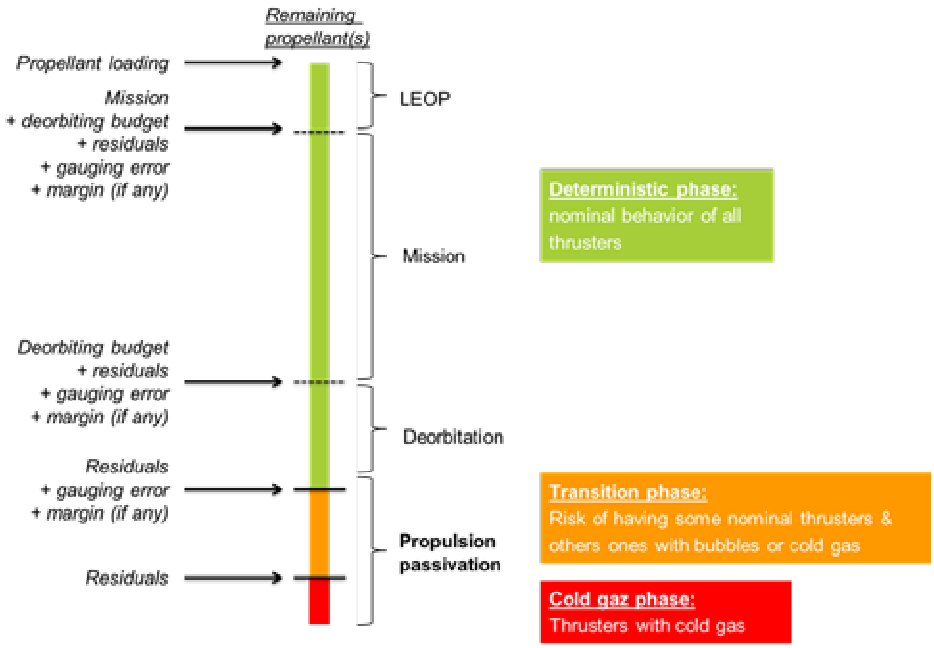

Figure 3-2: Different phases, function of the remaining propellant

The passivation strategy may be different for the three different phases of the propulsion passivation. There is no unique propulsion strategy because it depends on the propulsion system and on the AOCS design mainly, but also on operational constraints.

- Ø The recommended and generic strategy for the deterministic phase of the propulsion passivation is to continue to command long in plane orbit manoeuvres with same operations as the ones used for the release of the protected orbital area. It allows depleting the propellant and continuing to release the protected zone. The deterministic phase ends when there is risk of bubble. This risk may be detected by in-orbit telemetry and/or by the assessment of remaining propellant(s) in tank(s).
- Ø During the transition phase some thrusters may have transient unexpected behaviours while other ones have nominal performances. It is recommended to command short orbit control manoeuvres with durations. In case of several tanks, ground commands tank swap if imminent bubble is expected at thruster level (and propulsion branch swapping if any). The transition phase ends when there are bubbles from all tanks and both propulsion branches.

- Ø The random phase is more complex because thrusters are used outside their qualification range (in helium for monopropellant systems, or monopropellant first and helium then for bipropellant systems).

Technical note TN2.1 [RD 04] gives also recommended ground surveillances for each phase of the propulsion passivation. It concludes with generic recommendations to ease the building of the propulsion passivation strategy for given mission.

3.5 TN 2.2: Potential propulsion passivation strategies for future missions

Different passivation methods for future missions were studied taking into account general propulsion design concepts (mono-prop, bi-prop, multi tank, etc.) and the required passivation hardware (qualified and under qualification). These trade-off studies have shown it is best to passivate the remaining propellant via thrusters with the experience and knowledge available. This partial passivation is proven to be acceptable if it can be justified by analysis/test, the trapped propellant in the system does not pose a risk of explosion during the disposal phase (see task1 of the road map).

For more complex propulsion design concepts, where propellant passivation via thrusters is difficult to achieve, a dedicated propellant passivation line should be implemented. Its location should be selected to achieve full passivation of all propellant tanks and thruster branches in the system. Additionally, taking into account different failure modes, propellant tank design configuration (PMD Vs Diaphragm) and arrangement of thruster branching, the optimum locations for passivation line are discussed in this study. For propulsion systems with separate pressurant system, a dedicated passivation line with associated components to remove the pressurant gas is recommended.

Based on Airbus DS Eurostar experience, propellant tank passivation via thrusters is recommended. The propellant depletion rates can be improved by allowing tank heaters to increase the pressure. These off-nominal thruster operations are addressed in the study.

- Ø For mono-propellant thrusters with low risk of freezing, the recommendation is to extend the thruster qualification to cover passivation duty cycles with EoL conditions
- Ø For bi-propellant thrusters it is recommended to define passivation duty cycle or H/W improvement at thruster level (see task 2 of the roadmap)

The main findings of the study can be summarises as follows:

- Ø Perform passivation in robust AOCS mode;
- Ø Passivation of redundant thruster branch is recommended and feasible but it can be waived in case of anomalies as possible explosion risk is minimal for feed-lines;
- Ø For regulated or external pressurisation systems it is advantageous to passivate the pressurant gas by locating the passivation line downstream of regulator;
- Ø For bi-propellant systems propellant freezing should take into account when performing passivation via thrusters;
- Ø For propulsion systems that use permeable membrane propellant tanks, pressure reduction is achieved preferably from the pressurant side to limit propellant compatibility issues and propellant icing during depletion and to limit the number of safety barriers. It is recommended to carry out a proper permeability assessment in conjunction with the tank manufacturer in order to justify the passivation success through membrane (see task3 of the road map);
- Ø For metallic impermeable membranes tanks, both liquid depletion and gas venting subsystems shall be envisaged to achieve full passivation;

- Ø Propulsion systems with hydrazine as the propellant should take precautions when applying pyrotechnic valves in the passivation lines due to hydrazine vapour detonation risk;
- Ø Passivation lines should meet the required safety barriers from the launch authority. While designing the passivation subsystem, its relevance to the overall reliability figure for the mission shall be considered;
- Ø In-order to achieve safe and complete passivation for future missions, it is required to improve existing hardware and develop new hardware that have a longer lifetime, higher reliability and safe operation in a wide range of propellant types (hydrazine, Green propellants, MMH, MON, etc.);
- Ø As encountered in orbit during passivation via thruster, passivation device could be affected by propellant icing especially if they are located on the propellant lines. In such case passivation to zero pressure would potentially not be entire and complete. This risk of icing should be analysed through a dedicated depletion and passivation maximum duration requirement. This requirement can be part verified by analysis or test in the frame of the device qualification campaign (see task4 of the roadmap)

3.6 DEVELOPMENT ROADMAP

Based upon the passivation studies performed and summarised in this note, detailed decision-making roadmaps have been established for the improved operational measures and architecture options that may be introduced for :

- Ø Existing or in-flight propulsion systems
- Ø Future propulsion systems
- Ø Passivation device selection

The purpose of these roadmaps is to clearly identify the logical sequence of events and decisions that are required to achieve a satisfactory passivation of either chemical or electric propulsion systems as the passivation approach has been found to be highly dependent upon the specific system architecture. In each case, the roadmap highlights the necessary inputs from the system architect and also identifies the associated development tasks that are required to consolidate the selection.

The fundamental development tasks identified for further work are:

- Ø Task 1 : Consolidate the extent of propellant decomposition at elevated temperature

A test program to verify the study conclusions regarding the potential for propellant decomposition, and consequent gas generation, at the elevated temperatures that may exist during the de-orbit phase when the satellite protective MLI has been lost. Particular emphasis shall be place upon the characterisation of monopropellant hydrazine in particular regarding decomposition and thermal runaway.

- Ø Task 2 : Characterization of propellant and pressurant depletion via thruster

A test program to identify the generalised safe operating modes, and consequent robustness, of typical mono- and bi-propellant European thrusters when used to propellant and pressurant passivate a propulsion system under end-of-life conditions. This test would aim at defining the appropriate duty cycle and operating conditions for passivation or dedicated H/W change to avoid thruster blockage.

- Task 3 : Consolidate membrane/diaphragm material permeation rates

A test programme to characterise the varying elastomeric membrane/diaphragm materials currently in use for their permeability with regard to pressurant gases (helium and nitrogen typically) and also propellant vapours (hydrazine or LMP103S).

- Task 4 : Qualification of passivation device

A general task to ensure that a suitable propulsion passivation device is available for flight application in the event that the current or improved operational procedures for partial passivation do not allow the satellite to be 'made safe' or achieve the specified de-orbit probability of success.

The potential European passivation devices to be considered are divided into three distinct types :

  - Pyrotechnic venting devices (such as microperforator)
  - Pyrotechnically activated (normally closed) valves
  - Shape Memory Alloy (SMA) actuators

To further support the selection process for a passivation device, the available European options are presented, with their current status and approach for qualification.

Distribution list	OVERALL DOCUMENT		SUMMARY
	ACTION	INFORMATION	
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