

Spacecraft Passivation – An Overview of Requirements, Principles, and Practices

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Abstract

Explosions, collisions, and other catastrophic breakups of launch vehicle orbital stages and satellites continue to be major contributors to the generation of orbital debris. Both launch vehicles and payload satellites typically have several types of stored energy sources on board, any of which might result in energetic breakups and the creation of debris after their mission has ended. These energy sources include propulsion systems, pressure vessels, reaction wheels, control moment gyros, heat pipes, and power systems. NASA, ESA, JAXA and other space-faring organizations have requirements in place to limit the growth of the orbital debris population by passivating space vehicles that remain in orbit after their missions have ended. In this paper, we review current spacecraft passivation philosophies and principles, as well as how those principles have been applied in practice. In particular, we focus on how NASA programs have addressed spacecraft passivation. We begin by considering and reviewing general passivation requirements, with specific emphasis on pressure vessel passivation. We discuss passivation approaches used in several recent NASA missions as well as some practical considerations in spacecraft passivation, and conclude by providing some summary guidelines regarding what may be considered acceptable (reduced) pressure level targets (depending on the tank commodity and the type of propulsion system) that could allow the pressure vessel to be considered in a passivated state.

Introduction

Since the beginning of the space age, explosions, collisions, and other catastrophic breakups of launch vehicle (LV) orbital stages (i.e., rocket bodies) and satellites have been major contributors to the generation of orbital debris. Both LVs and satellites typically have several types of stored energy sources on board, any of which might result in energetic breakups and the creation of debris. These energy sources can include propulsion systems, electrical power systems, reaction wheels, control moment gyros (CMGs), heat pipes, and energetic materials (e.g., pyros and flight termination systems). The term “passivation” refers to the process of removing stored energy from a space vehicle to reduce the risk of high-energy releases (e.g., explosions, fragmentations) that could produce orbital debris after the end of mission (EOM). NASA, ESA, JAXA and other space-faring organizations have requirements in place to limit the growth of the orbital debris population by passivating space vehicles (e.g., satellites, launch vehicle stages, etc.) that will be remaining in orbit after their missions have ended.

For example, the NASA standard that defines technical requirements to minimize the growth of

orbital debris is NASA-STD-8719.14B. Requirement 4.4-2 in this standard addresses the need to remove stored energy from spacecraft and LVs to prevent debris-producing explosions and deflagrations due to either internal failure modes or external causes. This requirement states that passivation can be achieved in one of two ways. However, the first option contains absolute language that, if applied literally, cannot be met by many satellite projects. Of note then is that there is allowance in the second option for reducing the risk to whatever may be defined as an acceptable level. This second option of the requirement, then, refocuses spacecraft design on the orbital debris generation events that must be prevented in order to sustain the orbital environment.

For the purposes of this assessment, the first option above is referred to as, “hard passivation”, while the second is referred to as “soft passivation”. While hard passivation provides an unambiguous method to meet the passivation requirement in NASA-STD-8719.14B, this is not always achievable. Even the soft passivation option, though, when interpreted literally would involve extensive assessment to ensure that the spacecraft under review *cannot* undergo a fragmentation event. Absolute language like this in the requirement invites waivers or inconsistent interpretation of the requirement.

Typically, if satellite operators cannot meet the standard using hard passivation, they have the option of requesting a waiver. There are several possible reasons for not performing complete hard passivation. Experience has shown that, for example, many satellite operators are reluctant to create single points of failure for the mission. These may include switches that could open the circuit between solar arrays and batteries or the capability to vent the propellant or pressurant via a single command, actions that would prematurely terminate the mission if performed during the operational phase. It is also important to recognize that it may not be possible to completely vent tanks to ambient pressure due to their design and the well-known reality that hydrazine adheres to tank walls and plumbing lines.

Most spacecraft are also designed with autonomous fault detection and correction capabilities, which respond to abnormal spacecraft conditions in ways that keep the spacecraft operating or autonomously recover after a shutdown. Such capabilities may work to counteract any passivation procedures. Passivation is an anomalous condition from the perspective of successful mission operations, so autonomous recovery systems need to be disabled before engaging in post-mission passivation. In some cases, though, these fault corrections cannot be fully disabled, preventing hard passivation.

The process of requesting a passivation waiver is typically available as a programmatic route, but the practice is generally discouraged since it represents a departure from the standard requirements. While soft passivation is increasingly pursued as an alternative approach, few accepted standards are currently defined for what constitutes sufficient passivation.

In this paper, we review current spacecraft passivation philosophies and principles, as well as how those principles have been applied in practice. In particular, we focus on how NASA programs have addressed spacecraft passivation. We begin by considering and reviewing general passivation requirements, with specific emphasis on pressure vessel passivation. We discuss passivation approaches used in several recent NASA missions as well as some practical

considerations in spacecraft passivation, and conclude by providing some summary guidelines regarding what may be considered acceptable (reduced) pressure level targets (depending on the tank commodity and the type of propulsion system) that could allow a pressure vessel to be considered in a soft passivated state.

Review of NASA Passivation Requirements

The majority of orbital debris is generated from breakups of spacecraft and other large objects in orbit. The NASA standard that defines requirements to minimize the growth of orbital debris is NASA-STD-8719.14B, which is invoked by NASA Procedural Requirements NPR 8715.6B. Requirement 4.4-2 in this standard addresses the need to remove stored energy from spacecraft and LVs at EOM to prevent debris-producing fragmentation after decommissioning, due to either internal failure modes (e.g., battery overcharging, tank over-pressurization) or external causes (e.g., meteoroids and orbital debris, or MOD, impact, solar heating, etc). The text of this requirement is:

Requirement 4.4-2: Design for passivation after completion of mission operations while in orbit about Earth, or the Moon: Design of all spacecraft and launch vehicle orbital stages shall include the ability and a plan to either 1) deplete all onboard sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or postmission disposal or 2) control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft. The design of depletion burns and ventings should minimize the probability of accidental collision with tracked objects in space.

The standard specifies two general options to achieve a passivated state:

1. “...deplete all onboard sources of energy and disconnect all energy generation sources...” (aka the “hard passivation” option)
2. “...control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft.” (the so-called “soft passivation” alternative)

This passivation requirement applies to systems that contain stored energy. Spacecraft that are disposed of by controlled reentry do not need to meet the passivation requirement, since the systems must remain active in order to target the reentry location. Similarly, crewed vehicles, not including the orbital stage LVs, are not passivated since a spacecraft would never be decommissioned while carrying crew. LV orbital stages left in Earth or lunar orbit, though, must be passivated.

These requirements are binding on most NASA missions that do not use controlled reentry, since the majority of them operate either in Earth or lunar orbit. NASA requirements reflect the intent of guidelines published by the Inter-Agency Space Debris Coordination Committee (IADC) and United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) and must comply with the U.S. Government Orbital Debris Mitigation Standard Practices. In addition,

there are international standards used by other space agencies and ISO, which provide a reference for how other nations approach the question of passivation. All of these sources were considered throughout this study, but NASA-STD 8719.14 contains the specific requirement addressed by this assessment. The latest revision to NASA-STD 8719.14 is Revision B, issued on April 25, 2019.

In this assessment, this requirement has been noted as having two parts. In the first, i.e., “hard passivation”, the criteria are explicit and absolute: “deplete all onboard sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or post- mission disposal.” Such steps should leave the vehicle essentially inert and not susceptible to self-initiated explosion mechanism and less susceptible to fragmentations caused by MOD impact.

As mentioned previously, in reality, most existing spacecraft and LV designs cannot comply with some aspects of hard passivation for a variety of reasons (e.g., mission success risks, mechanical limitations, mass penalties). As a result, an alternative soft passivation option was added: “control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft.”

If the release of debris can be prevented without hard passivation, then the intent of the requirement could be met by the soft passivation approach. However, even the soft passivation requirement is direct and explicit: any remaining onboard energy sources are to be controlled to a level that *cannot* cause a fragmentation. This implies *any* probability that a fragmentation event could occur shall be eliminated. This interpretation would severely limit soft passivation methodology, as it is unrealistic to completely eliminate risk.

In contrast, Requirement 4.4-1, the requirement preceding the passivation requirement, states:

“...the program or project shall demonstrate, via failure mode and effects analyses, probabilistic risk assessments, or other appropriate analyses, that the integrated probability of explosion for all credible failure modes of each spacecraft and launch vehicle does not exceed 0.001 (excluding small particle impacts).”

This requirement applies to the deployment and operational phases of the mission. Requirement 4.4-2 applies to the post-mission period, but does not specify probability-based compliance like Requirement 4.4-1 does.

Requirement 4.4-1 specifically excludes explosions due to small particle impacts (i.e., MOD). Section 4.5 of the standard addresses debris generated by on-orbit collisions. The only small particle impact requirement given in Section 4.5 is Requirement 4.5-2, which is targeted to prevent damage that would preclude post-mission disposal activities (the probability must not exceed 0.01). There is no requirement for limiting small particle impacts that would produce break-up for a passivated vehicle. This appears to be a gap in the requirements, the closing of which would allow a probability-based path for compliance using soft passivation. A requirement stated quantitatively as an MOD penetration risk could also take advantage of MOD shielding and shadowing provided by other elements of the spacecraft (see, e.g. [1]). Table 1 illustrates the

current gaps in the standard.

Table 1. Explicit Requirements in NASA-STD 8719.14B (in green) and Gaps (in red)

Debris-producing Failure Due to:	During the Mission	Post-mission
Explosions (non-MOD)	Req. 4.4-1, 0.001 probability	Req. 4.4-2, “0” probability
Large MOD Collisions	Req. 4.5-1, 0.001 probability during orbital lifetime	
Small MOD Impacts	Req. 4.5-2, 0.01	None explicitly – relies on Req. 4.4-2

In the next section, we discuss how these requirements are applied to pressurized spacecraft components. The application of soft passivation approaches for other components (batteries and reaction wheels, for example) are beyond the scope of this assessment.

Pressurized Spacecraft Systems and Components

Most spacecraft have at least one pressurized component on board. For robotic spacecraft, it is usually part of the propulsion system. The stored energy in a pressurized component represents a risk of rupture to the pressure vessel, which might create orbital debris. Possible causes of rupture include:

- Impact by an MOD particle;
- Material embrittlement or cracking due to age, thermal fatigue, stress rupture, or exposure (e.g., atomic oxygen (AO), ultraviolet radiation (UV), and ionizing radiation);
- Tank over-pressurization due to environmental heating, upstream regulator failure, exothermic reaction or tank wall corrosion from propellant decomposition; and
- Accidental fuel and oxidizer mixing (most likely due to a valve or regulator failure).

It is possible to design propulsion hardware to fully passivate spacecraft pressure vessels. However, there are a number of hurdles to the implementation of such designs, including:

- Existing commercial bus designs may need to be modified and requalified (e.g., additional valves may be necessary to completely drain or vent),
- Sensor accuracy may diminish with age, making it difficult to determine remnant propellant level depletion,
- Propellant exhausted through thrusters can destabilize or otherwise alter spacecraft orbits undesirably, and
- Propulsion systems have been observed to perform differently due to low propellant levels as well as wear and aging of components [2].

Creative problem solving may be required to perform passivation in cases where it was not considered early in the design. An example of a unique challenge was the passivation of TDRS-1 after a 26-year mission. Due to a modification in its mission, when the mission ended there remained a large excess of fuel on-board, which needed to be expended. Since lowering perigee

to reentry was not an option for a GEO mission, and using all remaining fuel to increase the altitude would cause the spacecraft to drift out of communications range during the maneuvers, an alternative solution was developed. The spacecraft was first raised to the disposal orbit, and then essentially a flat spin was induced to exhaust the remaining fuel, while not disturbing the orbit or exceeding the spacecraft mechanical design. In this way, the fuel was expended and the spacecraft was passivated before it drifted out of communications range.

Soft passivation can be justified under certain conditions. For example, previous analyses in support of the End of Mission Plan (EOMP) updates on missions using metallic tanks containing only pressurant gas have demonstrated that the temperature required for runaway heaters or solar radiation to raise tank pressures to the design burst pressure (per the Ideal Gas Law) are often higher than the melting point of the tank material. The most likely failure mode for the tank wall melting is a leak rather than an energetic fragmentation. In addition, heat sources that could raise the tank temperature to these levels would likely result in other system failures. In such situations, clearly the pressure vessels are immune from over-pressurization by overheating.

Although an infrequent occurrence now, regulator failures can present a risk of rupturing a downstream pressure vessel under some conditions, typically early in the mission. The most likely cause identified for the STEP-2 LV breakup is that it experienced a failed regulator, which over-pressurized the downstream propellant tank and caused an explosion. Since that breakup event, NASA has used redundant regulators to prevent this failure mechanism from occurring. Generally, although a pressurant tank is at higher pressure than the propellant tank, it also has much smaller volume. Calculations in support of the EOMP updates for some propellant systems have been used to demonstrate that the resulting net system pressure is less than the propellant tank's burst pressure rating, even if the regulator were to fail. Late in the mission, there is a larger empty volume in the propellant tank that may be able to contain the pressurant gas more effectively.

Fuel venting or draining so that as little as possible propellant remains, leak-before-burst (LBB) design approaches, and shielding all undoubtedly lessen the likelihood of a pressure vessel rupture at EOM.

Pressurized Component Passivation Requirements

The passivation requirement is presented in NASA-STD 8719.14B Requirement 4.4-2 to deplete all onboard stored energy (i.e., hard passivation) or control to an extent where debris would not be generated (i.e., soft passivation). The concept of passivation is addressed in greater detail in the Methods to Assess Compliance section of the standard, that is, section 4.4.4.1.2, which expands on the intent of the general requirement.

NASA-STD 8719.14B refers to NASA-STD 8709.22 for the definition of a "pressure vessel." This definition is not quantitative, though, and includes even minimally pressurized components with no realistic risk of generating debris, and is given as follows:

Any vessel used for the storage or handling of a gas or fluid under positive pressure.

There is a more detailed definition of pressure vessels provided in NASA-STD-5001, Section 3.9

(Structural Design and Test Factors of Safety for Spaceflight Hardware), which is given as follows:

Pressure vessel. A container designed primarily for storing pressurized gases or liquids and

(1) contains stored energy of 14,240 foot-pounds (19,309 Joules) or greater, based on adiabatic expansion of a perfect gas; or

(2) experiences a limit pressure greater than 100 pounds per square inch absolute (psia) (689.5 kilopascal [kPa] absolute); or

(3) contains a pressurized fluid in excess of 15 psia (103.4 kPa absolute), which will create a safety hazard if released.

This same definition is found in other NASA standards and requirement documents (e.g., NASA-STD-5019, “Fracture Control Requirements for Spaceflight Hardware, SSP 30559 Structural Design and Verification Requirements for International Space Station”, and JSC-65828, “Structural Design Requirements and Factors for Human Spaceflight Hardware”).

As detailed in NASA-STD 8719.14B Section 4.4.4.1.2, stored energy within pressure vessels can take two forms: chemical energy from propellants, and stored mechanical energy in the form of pressure. The main paragraph in NASA-STD 8719.14B applicable to propulsion system pressure vessels is 4.4.4.2.2.2, which reads as follows:

Residual propellants and other fluids, such as pressurants, should be depleted as thoroughly as possible, by either depletion burns or venting, to prevent accidental breakups by over pressurization or chemical reaction. Opening fluid vessels and lines to the space environment directly or indirectly at the conclusion of EOM passivation, is one way to reduce the possibility of a later explosion.

This instruction, written before the soft passivation option was added to the general requirement, would result in complete passivation if accomplished. However, there are cases where this cannot be accomplished. For example, opening pressurized vessels and lines to space permanently is problematic for most existing designs. Most propulsion system venting uses thrusters, controlled by valves that are held open during firings and would consequently be closed following power system passivation, since they cannot be maintained open when power will have been depleted. One exception to this is the case of pyrotechnic valves, which are actuated once; a normally closed valve would remain open after being actuated and could be used to permanently vent pressurant or propellant. However, few propulsion system designs have incorporated pyrotechnic valves for passivation. In either case, venting of liquid propellants would be expected to take a long time to reach completion, even when venting to space (and possibly much longer if liquid propellant freezes in the lines).

It is important to note that the statement that propellants should be depleted “as thoroughly as possible” may not be the same as stating that they should be depleted “as thoroughly as

practical” since the movement of fluid through the associated plumbing can take time, and may be prevented by complex mechanisms. For example, final depletion of a propellant tank that uses a rubber diaphragm may be complicated by the fact that the flow rate decreases significantly before all propellant has been expelled. With time, the diaphragm relaxes, so that additional propellant ideally could be removed. While it may be “possible” to deplete additional propellant with propellant usage (i.e. thruster firings), the low flow rates make thruster operation erratic. In addition, it is generally not practical to perform more than a few such operations as they are time consuming and require additional support (such as communication passes).

The practicality of complete depletion is addressed by NASA-STD 8719.14B Section 4.4.4.2.2.5 and reads as follows:

Small amounts of trapped fluids could remain in tanks or lines after venting or depletion burning. Design and operational procedures should minimize the amount of these trapped fluids.

The lack of a definition of “small amounts” leaves this section open to interpretation. There are additional clarifications regarding pressure vessel design in Section 4.4.4.2.2.4:

Leak-before-burst tank designs are beneficial but are not sufficient to prevent explosions in all scenarios. Therefore, such tanks should still be depressurized at the end of use. However, pressure vessels with pressure-relief mechanisms do not need to be depressurized if it can be shown that no plausible scenario exists in which the pressure-relief mechanism would be insufficient.

The lack of a definition of “plausible scenario” leaves the paragraph from Section 4.4.4.2.2.5 open to interpretation, and the user is asked to prove a negative, so the application of this exception is subjective.

Thus, while NASA-STD 8719.14B provides for both hard and soft passivation options for pressure vessels, with the exception of relief for sealed volumes in heat pipes, batteries, and nutation dampers, there is no specific objective guidance for evaluating whether a proposed soft passivation approach complies with the terms of the general requirement.

We conclude this discussion of passivation philosophies and practices by discussing in the next section some of the passivation approaches used in several recent NASA programs.

Current Passivation Approaches for NASA Programs

Survey of Robotic Spacecraft Missions

Information was collected for various missions operated by NASA’s Goddard Space Flight Center. Most are active robotic spacecraft; no LVs are included in this list. Information was drawn from Orbital Debris Assessment Reports (ODARs) and EOMPs, which include both a detailed hardware description and any post-mission passivation plans. A total of 32 missions were examined.

Seven of the missions have no propulsion system, six have baselined controlled reentry, and five are beyond Earth orbit (e.g., interplanetary missions). Therefore, none of these 18 missions requires pressure vessel passivation. The remaining 14 missions (representing 30 individual spacecraft) require postmission passivation. According to the ODARs and EOMPs, each of these missions plans to perform at least some degree of passivation.

Tables 2a,b summarize the details for the 14 missions that require pressure system passivation. Only three missions plan activities that approximate the requirement for hard passivation, though the practicality of one of these plans is questionable. Note that detailed information is not uniformly shared in the reports, largely due to proprietary design considerations.

Of the 14 missions planning some degree of pressure system passivation, there is considerable diversity. Nine missions (which in total comprise 16 spacecraft) use monopropellant designs, four missions (a total of 13 spacecraft) use bipropellant, and one spacecraft uses gaseous nitrogen (GN₂) cold gas thrust. The four missions that include separate pressurant tanks operate in GEO, use COPV designs, and operate in pressure-regulated mode during orbit raising. Then the pressurant tanks are isolated at nominally 6.9 MPa (1000 psia), and the remainder of the propulsion system operates in blowdown mode until EOM.

Propellant tank materials vary between titanium alloy (11 missions/24 spacecraft), Inconel (2 missions/3 spacecraft), and COPV with a titanium liner (1 mission/3 spacecraft). Six of the nine monopropellant missions (12 spacecraft) use diaphragms inside the tanks, resulting in pressurant that is trapped inside the tank at EOM. None of these six missions incorporates valves that would enable the pressurant to be vented.

Practical Considerations during Passivation

While planning the passivation process, it is necessary to consider the entire spacecraft, and not just the propulsion system. Despite passivation being performed at the end of the operational mission, additional commands will still need to be sent, for example to passivate the EPS, reaction wheels, and other hardware. The spacecraft attitude must remain stable throughout the passivation process so that communications can be maintained for reliable command uplinks and telemetry downlinks to confirm the effectiveness of the passivation tasks. Simply opening valves to exhaust all propellant and pressurant indiscriminately would result in inconsistent and unbalanced thrust, disrupting the spacecraft attitude and communications. It may be practical to send such venting commands within the final upload sequence, but this is not typically done.

Another way in which propellant passivation can affect spacecraft communications is by moving a GEO spacecraft out of the stable communications region. When propellant is depleted by raising the orbit altitude to the assigned graveyard orbit, the spacecraft eventually drifts out of continuous communication, and can take days or weeks to again be accessible to ground station commands. One way to address this is by planning inefficient maneuvers that use up excess propellants but do not appreciably change the orbit altitude. However, sufficient reserve propellant must be maintained to achieve the EOM disposal orbit after such depletion maneuvers.

Another consideration when depleting propellant involves tanks that use an internal diaphragm to

separate the pressurant and propellant. As the tank nears empty, the diaphragm contacts the tank wall and covers the outlet, which significantly reduces the propellant flow before the tank is completely emptied of propellant. After a short relaxation time, the propellant migrates to the outlet for further short bursts of propellant. Such tanks should be depleted with several short burns, instead of a few long burns.

Regardless of the passivation approach, it is important to consider that the decommissioning process requires a different perspective than the operations mindset of preserving functionality. Often the same operators who have been tasked with preventing the demise of a spacecraft are eventually expected to cause a permanent decommissioning shutdown. Similarly, designers whose objective is to incorporate robustness must also incorporate mechanisms for intentionally disabling spacecraft systems and making the craft inert at the end of the mission. It is also important to remember that spacecraft disposed from GEO will remain in the graveyard orbit unmonitored for centuries, which must be considered in the EOM passivation approach.

Passivation Practices for Monopropellant Missions

Of the nine missions listed that use monopropellant propulsion and need to be passivated, five have perigee in LEO, so they plan to expend as much propellant as practical reducing perigee to minimize the orbit decay period. One mission is in GEO, so it will be raised to the graveyard orbit, and the remaining propellant will be exhausted by firing opposing thrusters. The remaining three missions are in high eccentricity orbits outside LEO and will deplete their propellant in place as much as practical. In all cases but two, approximately 0.7 MPa pressurant will be permanently retained, providing examples of missions that can not strictly meet hard passivation. Bypass valves and plumbing around the tanks could have been incorporated into these designs to enable this pressurant to be vented through the thrusters.

Passivation Practices for Bipropellant Missions

Depleting the propellants in a single pressurant manifold bipropellant propulsion system brings the added concern of preventing unintentional mixing of the fuel and oxidizer vapors, which could result in fragmentation. This is a greater concern at low pressures, so most missions with bipropellants cease depletion burns when the system pressure begins to drop off more rapidly than usual, signaling that the liquid in at least one tank is nearly depleted. This is sometimes referred to as the “knee” in the pressure curve. Stopping at that point, as recommended by at least one spacecraft supplier, leaves some amount of fuel, oxidizer, and pressurant in the propellant tanks permanently. This has been a standard industry practice for many GEO spacecraft. Of the four bipropellant spacecraft studied, only one (Solar Dynamics Observatory, or SDO) has incorporated additional valves to allow the fuel and oxidizer to be depleted individually through the thrusters, using the previously isolated pressurant to flush the propellant tanks and lines.

Table 2a. Summary of Passivated States of Fourteen GSFC Missions – Cold Gas and Monopropellant Systems

Mission	Reported Propellant Passivation	Propellant Tank Final Pressure (FP) (MPa)	Propellant Tank Burst Pressure Rating (BPR) (MPa)	Ratio FP/BPR	Passivation Type	Waiver Granted	Reason For Granting Waiver
NOAA 19	Vented through opposing Cold Gas Thrusters	0	62	0	Hard	No	No waiver required
Aqua	Orbit lowering; pressurant trapped behind rubber diaphragm	0.69	4.7	0.15	Soft	Yes	Heritage design with no vent valve already on-orbit when req. issued; passivation as complete as hardware allows, LBB design; low % of BPR
Aura	Orbit lowering; pressurant trapped behind rubber diaphragm	0.69	4.7	0.15	Soft	Yes	Heritage design with no vent valve already on-orbit when req. issued; passivation as complete as hardware allows, LBB design; low % of BPR
Terra	Orbit lowering; pressurant trapped behind rubber diaphragm	0.62	5.5	0.11	Soft	Yes	Heritage design with no vent valve already on-orbit when req. issued; passivation as complete as hardware allows, LBB design; low % of BPR; no record of waiver being granted
Van Allen Probes	Depleted fuel and GN2 as much as possible; 2 or 3 tanks may retain some	0	5.5	0	Hard	No	No waiver required
MMS	Deplete fuel	0.90	5.0	0.18	Soft	No	OSMA judged that the design meets the intent of the requirement
IBEX	Spin up / down to exhaust fuel; stop when pressurant is detected (0.7 MPa)	0.69	4.1	0.17	Soft	No	Waiver request was not submitted; OSMA accepted pressurant passivation as meeting the intent
Polar	Propellant already nearly exhausted; He to be vented through thrusters	0	Unknown	N/A	Hard	No	No waiver needed; BPR would require extensive research; launched in 1996
TDRS 1st Gen	Orbit raising, then opposing thrusters; pressurant trapped (0.9 MPa)	0.94	6.3	0.15	Soft	No	Waiver request was written, but not submitted

Table 2b. Summary of Passivated States of Fourteen GSFC Missions – Bipropellant Systems

Mission	Reported Propellant Passivation	Propellant Tank Final Pressure (FP) (MPa)	Propellant Tank Burst Pressure Rating (BPR) (MPa)	Ratio FP/BPR	Passivation Type	Waiver Granted	Reason For Granting Waiver
TESS	Fuel depleted; pressurant trapped (90 psia)	0.62	5.2	0.12	Soft	Yes	Sufficient FP/BPR margin; extremely high orbit probably contributed
GOES N-Q	Deplete fuel after reaching disposal orbit	0	2.7	0	Hard	No	Waiver request was written, but not submitted
GOES R-T	Depletion of fuel, oxidizer, and helium through thrusters	0	3.1	0	Hard	No	No waiver required
TDRS 2nd / 3rd Gen	Propellants depleted as much as safe; pressurant trapped behind an isolation valve	0.69	2.7	0.26	Soft	No	Waiver request was written, but not submitted;
SDO	Orbit raising, then opposing thrusters; bypass valve to vent pressurant through thrusters	0	3.1	0	Hard	No	No waiver required

The following inferences can be drawn from the information in Tables 2a,b.

- (1) The average pressure remaining in the partially depleted monopropellant tanks is approximately 15% of their burst pressure ratings; for bi-propellant tanks this is approximately 19%, although only two such instances were found.
- (2) For bi-propellant systems, the highest acceptable pressure without a waiver as a percentage of burst pressure was 0.69 MPa, which was 26% of the tank burst pressure rating; for monopropellant systems, the highest remaining pressure acceptable without a waiver was 0.9 MPa, or 15% of tank burst pressure rating.
- (3) The average remaining pressure amount of 15% is consistent with the lower end of the pressure range where, in a previous study, hypervelocity impact testing did not result in pressure vessel rupture [3]. And, as a side note, this average remaining pressure amount of 15% is also consistent with the average pressure amounts remaining in several ESA satellites, where the monopropellant tank burst pressure ratings were twice the Maximum Expected Operating Pressure (MEOP) [3-6].

Finally, it is important to note that only four missions were granted waivers. Three of these missions were on-orbit and were essentially granted retroactive waivers to document the existing non-compliance. The main commonality for the granted waivers was programmatic (i.e., cost-effectiveness of using a heritage design) versus risk-based determination.

Concluding Thoughts

A strict interpretation of the absolute wording contained in the NASA passivation requirement (NASA-STD 8719.14A, Req. 4.4-2) that states that the measures “cannot cause an explosion” precludes truly meeting the requirement with soft passivation (and possibly hard passivation as well). However, effective soft passivation techniques may result in the reduction of risk for fragmentation events to an acceptable, but non-zero, level. While some failure mechanisms can be effectively eliminated using practical approaches, other very unlikely failure mechanisms may be unavoidable.

For example, shielding may be sufficient to protect components such as pressurized vessels from an MOD penetration, which would reduce the risk of debris generation, but very rare large object collisions could still cause breakup. Defining an acceptable post-mission risk level could enable soft passivation to be used effectively. Previous NASA approvals have demonstrated a range of approximately 10-25% of burst pressure as acceptable passivation levels for propellant pressure in monopropellant and bi-propellant propulsion systems.

Space vehicle propulsion system passivation can be technically difficult in new designs, and may be impractical in existing designs for a number of reasons, including the fact that thrust may be unreliable and inconsistent when the propellant is nearly exhausted. Because of this, propellant depletion by thrusting is commonly terminated before the pressure vessel is completely empty in order to prevent communications from becoming unreliable during passivation. Furthermore, pressurant in a diaphragm tank is often isolated from the propellant and must be vented separately, surfaces can remain wetted after venting, and liquids may freeze in the lines.

Propulsion system design should ensure that pressurant tanks are either isolated from propellant tanks or sufficiently depressurized to prevent over-pressurization in the case of a regulator failure. Also, bipropellant designs should isolate the oxidizer from the fuel during passivation to reduce the possibility of mixing of the two commodities when pressures are reduced at EOM. Finally, after passivation has been executed, no further telemetry monitoring or commanding potential is possible during the orbit decay or storage period. Hardware designs must therefore be inherently robust in the long term against debris generation without ground intervention.

Acknowledgements

The authors are grateful for the support provided by the NASA Engineering Safety Center that made this assessment possible.

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