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Passivation of Spacecraft Pressure Vessels: Some Comments on Requirements, Principles, and Practices

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Preface

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. 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 general, these requirements state that a spacecraft's stored energy devices are to be passivated at the end of a spacecraft's mission or useful life. For pressure vessels such as propulsion tanks, passivation equates to depletion of all pressure at the end of the mission. Programs whose spacecraft designs are not be able to comply with some aspects of those requirements employ an alternative, so-called "soft passivation" or "make safe", option.

This document presents the results of two studies performed with the aim of better understanding the state-of-the-art with regard to the passivation of spacecraft pressure vessels, such as fuel tanks. The chapters in this document contain the following articles that have appeared in the Journal of Spacecraft Safety Engineering.

(1) Hull, S., and Schonberg, W.P., "Spacecraft Passivation – An Overview of Requirements, Principles, and Practices," *Journal of Spacecraft Safety Engineering*, Vol. 9, No. 4, 2022, pp. 553-560.

In this paper, we review current spacecraft passivation philosophies and principles, as well as how those principles have been applied in practice, with specific emphasis on pressure vessel passivation. We then 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 pressure level targets that could allow the pressure vessel to be considered in a passivated state.

(2) Schonberg, W.P., "Meeting Passivation Requirements for Spacecraft Pressure Vessels and Fuel Tanks," *Journal of Space Safety Engineering*, Vol. 7, No. 3, 2020, pp. 222-229.

This paper provides a summary of a project performed with the intent of providing some guidelines and considerations that can be used by satellite programs to help satisfy passivation requirements using a "soft passivation" approach, that is, when not able to perform complete depletion of pressure, or "hard", passivation, with specific regard to mitigating the threat posed by on-orbit meteoroid or orbital debris particle impacts. A process was developed and demonstrated for two different types of pressurized fuel tanks that can be used to calculate the number of rupture-causing MMOD particles that a spacecraft might encounter in a so-called "soft passivated" state.

A strict interpretation of the absolute wording contained in the NASA passivation requirement that states that measures "cannot cause an explosion" effectively precludes being able to truly meet the requirement with soft passivation, and possibly hard passivation as well. Complete and full 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. However, effective soft passivation techniques may result in the reduction of risk for fragmentation events to an acceptable, but non-zero, level.

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1.0 Spacecraft Passivation – An Overview of Requirements, Principles, and Practices as Applied to Spacecraft Pressure Vessels

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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 then 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.

1.1 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., pyro-actuated valves 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, 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-8719.14C [1]. Specifically, Requirement 4.4-2 in this standard addresses the need to remove stored energy from spacecraft and LVs to prevent additional debris from being generated by either internal failure modes or external causes. This requirement states that passivation can be achieved in one of two ways:

1. *"…deplete all onboard sources of energy and dis-connect all energy generation sources..."*
2. *"…control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft."*

It is evident that the first option contains absolute language, that is, the requirement implies complete and absolute passivation, and not an acceptable level of probability that some other acceptable level of passivation has been achieved. If applied literally, this requirement 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. Even this option, though, contains an inherent ambiguity in the energy that might result in a spacecraft breakup or debris release.

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-8719.14C, this is not usually 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. Using this kind of language 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 robotic spacecraft 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.

1.2 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-8719.14C (which is invoked by NASA Procedural Requirements NPR 8715.6B [2]). In this standard, Requirement 4.4-2 addresses the need to remove stored energy from spacecraft and LVs at End-of-Mission (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.

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) [3] and United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) [4] and must comply with the U.S. Government Orbital Debris Mitigation Standard Practices [5].

In addition, there are international standards used by other space agencies and the International Organization for Standardization (ISO), which provide a reference for how other nations approach the question of passivation. For example, the European Space Agency (ESA) fully aligned its space debris mitigation policy with ISO Standard 24113 [6]. As such, ESA's space debris mitigation guidelines [7] include the same definitions of passivation as the ISO standard and make the same references to "deplete or make safe."

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 at the time of this work is Revision C.

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.

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.

It is important to note that 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. [8]). Table 1 illustrates the current gaps in the standard.

Table 1. Explicit Requirements in NASA-STD 8719.14C (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.

1.3 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 or pressurant 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 [9].

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 (e.g. a satellite launched to geosynchronous or geostationary orbit), 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 [10].

Soft passivation can be justified under certain conditions. For example, previous analyses [11-13] 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. Vapor arising from heating liquid residues on tank surfaces would cause the tank pressure to increase but at a rate where the leak-before-burst nature of space-rated propulsion tanks would prevent catastrophic rupture.

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 a rupture [14,15]. 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 [11-13] have been used to demonstrate that the resulting net system pressure is much 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 as well. Additional information and commentaries regarding passivation regulations and practices can be found in Refs. [16-18].

1.3.1 Pressurized Component Passivation

Requirements

The passivation requirement is presented in NASA-STD 8719.14C, 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 8719.14C refers to NASA-STD 8709.22 [19] 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) [20], 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" [21], SSP 30559, "Structural Design and Verification Requirements for International Space Station" [22], and JSC-65828, "Structural Design Requirements and Factors for Human Spaceflight Hardware" [23]).

As detailed in NASA-STD 8719.14C 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 8719.14C 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, when power will have been depleted. Since venting to completion could take weeks to months to occur (depending on how "completion" is defined), it is impractical to delay power system passivation until venting is finished. One alternative 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, largely because premature venting cannot not be corrected after such a single-use valve is triggered. 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 8719.14C 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 8719.14C 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 examining some of the passivation approaches used in several recent NASA programs.

1.4 Current Passivation Approaches For NASA Programs

1.4.1 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 post-mission 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. In these tables, BPR and FP refer to the burst pressure rating of and final pressure in a spacecraft propellant tank. Only three missions plan activities that approximate the requirement for hard passivation, though the practicality of at least 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 composite overwrapped pressure vessels (COPVs), and operate in pressure-regulated mode during orbit raising. Then the pressurant tanks are isolated (permanently trapping the pressurant) 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.

1.4.2 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 because the effectiveness of the commands cannot be confirmed.

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.

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
Van Allen Probes	Deplete 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
TDRS 1st Gen	Orbit raising, then opposing thrusters; pressurant trapped (0.9 MPa)	0.94	6.3	0.15	Soft	No	No waiver required

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
GOES N-Q	Deplete fuel after reaching disposal orbit	0	2.7	0	Hard	No	No waiver required
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 isolation valve	0.69	2.7	0.26	Soft	No	No waiver required
SDO	Orbit raising, then opposing thrusters; bypass valve to vent pressurant through thrusters	0	3.1	0	Hard	No	No waiver required

After a short relaxation time, the propellant migrates to the outlet for further short bursts of propellant. Final depletion of such tanks should use 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 for many years are eventually expected to execute 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 totally unmonitored for *centuries*, which must be considered in the EOM passivation approach.

1.4.3 Passivation Practices for Mono-propellant 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.

1.4.4 Passivation Practices for Bi-propellant 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 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.

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 [24]. 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) [25-27].

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.

1.5 Concluding Thoughts

A strict interpretation of the absolute wording contained in the NASA passivation requirement (NASA-STD 8719.14C, 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 demon-strated 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.

1.6 Acknowledgements

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2.0 Meeting Passivation Requirements for Spacecraft Pressure Vessels and Fuel Tanks

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Abstract

Most spacecraft have at least one pressurized vessel on board. In addition to a hole, it is possible that a pressure vessel may experience catastrophic failure (i.e. rupture) as a result of a hypervelocity impact. If a tank rupture were to occur on-orbit following a meteoroid or orbital debris particle impact, for example, not only could it lead to loss of life, but it would also generate a tremendous amount of debris that could compromise future space assets working in similar orbits. As a result, NASA and other space faring nations have put in place spacecraft design requirements to prevent additional sizable debris from being created in the event of pressure vessel rupture or catastrophic failure. In general, these requirements state that a spacecraft's stored energy devices are to be passivated at the end of a spacecraft's mission or useful life. Programs whose spacecraft designs are not be able to comply with some aspects of those requirements employ an alternative, so-called "soft passivation" or "make safe", option. This paper provides a summary of a project performed with the intent of providing some possible guidelines and considerations that can be used by satellite programs to help satisfy passivation requirements using a "soft passivation" approach, that is, when not able to perform complete, or "hard", passivation, with specific regard to mitigating the threat posed by on-orbit meteoroid or orbital debris particle impacts.

2.1 Introduction

Most spacecraft have at least one pressurized vessel on board. For robotic spacecraft, it is usually a liquid propellant tank. For human missions, these are usually the pressurized habitable modules of the spacecraft (such as the ISS, for example). If an orbital debris particle of sufficiently high kinetic energy were to strike a pressure vessel, in addition to a hole, it is possible that the pressure vessel may experience catastrophic failure (i.e. rupture) as a result of the hypervelocity impact. If such a tank rupture were to occur on-orbit following a meteoroid and/or orbital debris (MOD) particle impact, not only could it lead to loss of life, but it would also generate a tremendous amount of debris that could compromise the operation of either other current or future space assets working in similar or near-by orbits. As a result, NASA and other space faring nations have put in place spacecraft and satellite design requirements that are intended to totally avoid catastrophic failure. In general, these requirements state that a spacecraft's stored energy devices and/or containers, e.g., batteries and pressure vessels, respectively, for example, are to be passivated at the end of a spacecraft's mission or useful life. In this manner, these requirements are also intended to prevent additional sizable debris from being created in the event of, for example, pressure vessel rupture or catastrophic failure.

At the time of this study, for spacecraft designed and built to be launched in the United States, NASA-STD 8719.14 (Rev. A, Change Notice 1) [1] contained the technical requirements imposed upon the spacecraft design and operations, including but not limited to post-mission disposal and passivation. The specific requirement for passivation (applicable to all spacecraft remaining in Earth or lunar orbit) is found in Requirement 4.4-2. This requirement can be viewed as consisting of two parts. The first, the so-called "hard passivation" criterion, is very direct and calls for missions to, "… 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". Programs whose spacecraft designs are not be able to comply with some aspects of that requirement (for a variety of reasons) employ an alternative, so-called "soft passivation" option - "… 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 more practical "soft passivation" approach.

This paper presents the results of two tasks performed with the intent of providing some possible guidelines or considerations that can be used by US-based satellite programs and projects to help satisfy passivation requirements using the "soft passivation" approach, that is, when not performing or not being able to perform complete fuel depletion, or hard passivation. Although there are a number of possible causes of rupture, including material embrittlement or cracking due to age or thermal fatigue, tank over-pressurization due to environmental heating, upstream regulator failure, endothermic and reaction and tank wall corrosion from fuel decomposition, accidental fuel and oxidizer mixing, this study focused on the rupture threat posed by on-orbit meteoroid or orbital debris particle impacts of pressurized vessels, such as fuel, oxidizer, and pressurant tanks.

First, a comprehensive review of public domain literature regarding the passivation of spacecraft pressure vessels was conducted to assess the state-of-the-art in pressure vessel passivation design. This review yielded some interesting information regarding possibly acceptable pressure level thresholds below which pressure vessel rupture will likely not occur, even in the event of a high-speed impact by an MOD particle.

Second, a process was developed to calculate the number of rupture-causing MMOD particles that a spacecraft might expect to encounter in its so-called "soft passivated" state. This requires first calculating the size of a particle that might be expected to cause rupture of a "nearly empty" fuel tank of a given spacecraft, then determining the anticipated flux of particles of that size for that satellite, and then finally calculating the expected number of particles to be seen by that satellite over its passivated lifespan.

The results of both of these activities can be used by spacecraft designers and mission planners to help satisfy passivation requirements using the "soft passivation" approach.

2.1.1 Task 1 – Literature Review

A literature review was performed to assess how past and current spacecraft programs addressed the issue of pressure vessel passivation. The intent was to secure documented information regarding threshold internal pressures and/or fill levels that were deemed to be "safe enough," that is, they would result in a low enough remaining potential energy so that rupture would likely not occur during an end-of-life mission phase, regardless of pressure increase trigger. This information, if found, would prove to be useful to satellite project leaders, designers, and operators in meeting passivation requirements through soft passivation. If, for example, such programs designed their pressure vessels so that the internal pressure remaining at the end of the useful life of a satellite was no more than such a previously determined safe amount, then those projects could make the case that the pressure vessels in such satellites were sufficiently passivated. in an attempt to identify previous studies that had considered the effect of internal pressure and/or fill level on impact response for a specified set of impact conditions.

The results of the literature review are presented in the next two subsections. The first presents a discussion of general results and trends from published documents that discuss the passivation activities of a number of specific satellite programs. The second presents information specifically related to MOD particles and the threat they pose from impact on an orbiting satellite in the predisposal phase of its mission.

General Considerations

Much of the open literature on spacecraft passivation appears to be related to spacecraft missions funded by ESA. As such, the reported pressure vessel passivation designs, techniques, and methods reported all work towards satisfying ESA's "deplete or make safe" passivation requirement. Several ESA-funded programs and satellites have concluded that depletion of fuels, oxidizers, and pressurants is impractical, if simply not impossible (see, e.g. [1,2,3]). As such, nearly all, if not all, ESA-sponsored spacecraft designs opt for the "make safe" approach to satisfying ESA's end-of-mission passivation requirement.

Table 1 summarizes the main aspects of some recent spacecraft or satellite missions and their final, acceptably passivated, fuel levels.

Table 1. Summary of Passivated States of Recent Satellites

Satellite	Ref #	Altitude	Fuel	Fuel Pressures (psi)			Oxidizer	Oxidizer Pressures (psi)		
				Initial	Final	% Fin/Init		Initial	Final	% Fin/Init
Myriade*	3,4,5	LEO/MEO	Hydrazine	319	<80	~25%				
SPOT-1	6	LEO/MEO	Hydrazine	319	<80	~25%				
HELIOS 1A	7	LEO/MEO	Hydrazine	N/A	~40	-----				
				Avg	< ~73	< ~25%				
Eutelsat 2 FM4	8	GEO	MMH	N/A	< 14.5	-----	MON	N/A	43.5	-----
Eurosat	9	GEO	MMH	245-345	7.25	~2.5%	NTO/MON	245-345	43.5	~15%
E2000	10,11	GEO	MMH	290	0	~0	NTO	290	40.6	~14%
TDF2	12,13	GEO	MMH	N/A	8.7	-----	MON	N/A	29	-----
Telecom 2	14	GEO	MMH	319	0 - ~10	~1.6%	NTO	319	43.5	~13%
				Avg	< ~7	< ~2%		Avg	< ~40	< ~15%

*Myriade family of satellites, including DEMETER and ESSAIM

As can be seen from Table 1, the following passivation practices appear to be acceptable from the "make it safe" approach to fuel tank passivation:

- LEO/mono-prop satellites
    - Final fuel pressure remaining < ~73 psi[1] (or < ~25% of initial operating conditions)
    - Information regarding acceptable levels of pressurant pressure remaining was not available or found.
- GEO/Bipropellant satellites
    - Final fuel pressure remaining < ~7.3 psi (or < ~2% of initial operating conditions)
    - Final oxidizer pressure remaining < ~40 psi (or < ~15% of initial operating conditions)
    - Information regarding acceptable levels of pressurant pressure remaining that was found was not extensive enough to allow any reasonable conclusions to be made.

Additionally, a recent study performed by OHB of Sweden [15] proposed the following formal "safe" EOL pressure levels for LEO/MEO and GEO missions.

Table 2. OHB Recommendations for EOL Pressure Levels

	EOL Configuration	Fuel / Pressurant	Recommended Levels
GEO	Propellant Residuals	MON*, MNH**	1.8 – 2.6% of initial mass; P < 130 psi
	Pressurant Residuals	Helium	P ~ 725 psi
LEO / MEO	Propellant Residuals	Hydrazine	< 2% of initial mass; P ~ 80 psi
	Pressurant Residuals	Nitrogen	P ~ 80 psi

*Mixed oxides of nitrogen (oxidizer), **Monomethylhydrazine

The recommended EOL pressure and mass values were based on maximum achievable fuel and pressurant depletions in previous missions as well as minimum pressure levels required for thruster operation. It is not surprising, then, that the EOL pressure levels of the missions in Table 1 agree reasonably well with the respective recommended levels in Table 2.

The study by OHB also identified passivated tank rupture due to high-speed impact by MMOD particles as one of the main threats faced by passivated tanks until the time of their ultimate demise or other disposal. This issue was addressed in Task 2 as discussed later in this paper.

MOD Considerations

Recent studies have shown that the likelihood of pressure vessel rupture is directly linked to its internal pressure level when the impact occurs [16]. This aspect of the literature review focused on identifying studies that were performed to assess the effect of internal pressure and/or fill level on impact response. As before, the intention was to secure documented information regarding threshold internal pressures and/or fill levels above which rupture would likely occur and below which it most likely would not, but this time, following an on-orbit MOD particle impact. This information, if found, might then prove to be useful to satellite programs in helping

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[1] This is equivalent to 500 kilopascals (kPa).

them meet passivation requirements through soft passivation, especially as far as MOD impact-generated failures were concerned.

Ultimately, nineteen documents (mostly conference proceedings papers and journal publications) were found on test programs that addressed this goal. Salient features from these test programs and documents are listed in Table 3 below.

Table 3. Overview of Relevant Test Programs and Results

Ref #	LVI or HVI	Testing Overview	Results Overview
17	LVI	8 different fill levels; 5 different hammer impact locations for each fill level	At low fill levels, peak pressures due to sloshing effects; for high fill levels, peak pressures due to impact acceleration effects; no tank rupture in any test
18	LVI	8 different fill levels; 5 different hammer impact locations for each fill level	At low fill levels, peak pressures due to sloshing effects; for high fill levels, peak pressures due to impact acceleration effects; no tank rupture in any test
19	LVI	8 different fill levels; 5 different hammer impact locations for each fill level	Peak pressures occur at impact end, except for nearly full tanks in which case they occur at tank "tops"
20	LVI	Overview of results in [17-19]; no tank rupture in any test	Overview of results in [17-19]; no tank rupture in any test
21	LVI	Tubes were either completely empty or completely filled; $50 < V_{imp} < 200$ m/s	Perforation limit and crack limit impact velocities for empty tubes were approx. 10% higher than those for filled tubes
22	LVI	Three different fill levels considered; V_{imp} = 600, 900 m/s	Entry/exit walls flat for empty tubes, bulging for filled tubes; partially-filled tubes bulge until fill-level when impacted below fill-level
23	LVI	Three different fill levels considered; V_{imp} = 600, 900 m/s	Cracks and delaminations are longer / worse the more filled are the tubes
24	LVI	Two different partial-fill levels considered; V_{imp} = 600, 900 m/s	Numerical results follow experimental results
25	LVI	Three different fill elves - 0%, 50%, 100%; blast loading only	Empty -- steady decay from peak pressure; Full and Partially-Filled -- oscillatory dynamic response with much higher peak pressures occurring sometime after load applied
26	LVI	Two different partial-fill levels considered; V_{imp} = 600, 900 m/s	Development and validation of numerical models using previous experimental results
27	HVI	One high-speed shielded test of partially-filled tank; shotline below fill-level	Small holes in tank (which was behind two shields); slow leak rate
28	HVI	Cylindrical aluminum tanks 1/2 filled with water pressurized at various levels; impacts below water line	Burst threshold pressure for rupture ~ 22.5% of static burst pressure

29	HVI	Five high-speed shielded tests of partially-filled tanks; shotlines below fill-level in four tests based on observed failures	Unshielded tests (3) - petalling and cracking; shielded tests (2) - one with only holes, one with petalling and cracking
30	HVI	Pressurized spherical titanium tank impacted at 8.8 km/s by a 1 mm Al particle; no rupture	Burst threshold pressure for rupture ~ 20% of static burst pressure
31	HVI	19 tests with unshielded Al pressure vessels at varying impact energies and pressure levels	Lowest internal pressure causing rupture of aluminum tanks ~ 16.8% of static burst pressure
32	HVI	Same 19 tests with Al cylinders as in [31] + 10 tests with unshielded Ti pressure vessels at varying impact energies and pressure levels	Lowest internal pressure causing rupture of titanium tanks ~ 12.5% of static burst pressure
33	HVI	Same Al and Ti cylinder tests as in [32]; several shielded tests as well	Shielding is an effective way of reducing potential for pressure vessel rupture
34	HVI	V_{imp} ~ 3 km/s; six impact tests using pressurized partially-filled soda cans; fill levels not specified; impacts above and below fill level	When projectiles impacted above the water line, the damage was the same as if the entire can was filled with air (single front entry hole, several rear exit holes). When the projectiles impacted below the water line, the damage was the same as if the entire can was filled with water (significant petalling).
35	HVI	No new test results	Model developed replicated experimental results in [34]

There appear to be two “families” of impact studies performed with these objectives:

1. Low velocity tests on tanks that might simulate a tank drop – primarily of interest to the fuel/energy industry [17-26], and
2. High velocity tests that attempt to simulate MMOD impact conditions [27-35].

From the references that are concerned with high velocity impacts, it appears that the following main inferences can be drawn:

1. When projectiles impact the pressure vessel above a water fill line, the damage was the same as if the entire pressure vessel was filled with air (e.g. single front entry hole, several rear exit holes) [34,35].
2. When projectiles impact the pressure vessel below a water fill line, the damage was the same as if the entire pressure vessel was filled with water (e.g. significant petalling). [34,35].
3. While five [27,29,33,34,35] of the high velocity test programs fall into the “abuse testing” category (i.e., internal pressure was held constant at a high value while impact conditions – velocity, projectile size, etc – were varied), four [28,30,31,32] did not (i.e., impact conditions were held constant while internal pressure was steadily increased).
4. Those that held impact conditions constant while increasing (or decreasing) internal pressure found that once the pressure was decreased below 15-25% of the pressure vessel’s burst pressure, catastrophic failure or rupture no longer occurred [28,30,31,32].

5. Shielding is an effective means of reducing the potential for the rupture of a pressure vessel that is impacted by a high-speed particle [27,29,33].

The first two points can also perhaps apply to the case of a rubber diaphragm style propellant tank if, for example, either the pressurant side or the propellant side of the diaphragm, respectively, was struck. Of course, the relative sizes of these regions change throughout the mission as fuel is used up, with the pressurant side increasing with increasing mission elapsed time. However, no documentation was available for any tests conducted whose results might be applicable to propellant management device (PMD) tanks. In microgravity, the contents of such a tank might resemble a hollow bubble of vapor (ullage) in the center of a fluid layer that reduces in thickness as the mission progresses.

As a result of this literature review, it became evident that no comprehensive study has been performed to date that would be able to provide quantitative rationale for pressure thresholds that could be used to justify soft passivation techniques. At best, it was found that when a pressure vessel's internal pressure was at a level between 15% and 25% of its static burst pressure, catastrophic failure following a hypervelocity impact will mostly likely not occur.

2.1.2 Task 2 – Number of Rupture-Causing Particles

In this section, a calculation process is presented that can be performed to determine the number of rupture-causing MOD particles that a spacecraft might expect to encounter in a so-called "soft passivated" state (i.e. following all passivation activities, but prior to re-entry). This method could be used to help support compliance if the requirement was stated as, for example, a maximum allowed probability of causing a catastrophic event. This process requires first calculating the size of a particle that might be expected to cause rupture of a "nearly empty" fuel tank of a given still-orbiting satellite or spacecraft, then determining the anticipated flux of particles of that size for that satellite, and then finally calculating the expected number of particles that might be seen by that satellite over its remaining passivated lifespan. The results of such calculations can also be used by spacecraft designers and mission planners to help satisfy passivation requirements using a "soft passivation" approach.

As such, the following steps are following in this calculation process:

1. For a given satellite, estimate the most likely closing velocity and impact angle of an orbital debris particle in that satellite's orbit using an appropriate debris environment model
2. Using that information and the Rupture Limit Equation for the type of fuel tank in the given satellite, determine the diameter of a likely rupture-causing particle
3. Using the same model of the orbital debris environment, determine the anticipated flux of particles of that size for the given satellite's orbit
4. Calculate the expected number of particles to be seen by the given satellite in its orbit based on an assumed remaining orbital lifetime and exposed surface area.

The two satellites chosen to illustrate the calculations performed are the Aqua and EO-1 satellites. The Aqua satellite uses a PSI model 80263-1 tank, which has been designed into many satellite propulsion systems since the 1990s. It is contained within the propulsion module, near the rear of the spacecraft (i.e. it is not protruding). The tank is pressurized with nitrogen on one side of an internal diaphragm prior to launch, and operates in blowdown mode throughout the mission.

The baseline disposal plan for the Aqua satellite calls for depleting all hydrazine fuel by lowering the orbit, leaving approximately 100 psia of nitrogen pressurant in the tank trapped permanently behind the diaphragm during its remaining years of orbit decay until uncontrolled reentry. The operational orbit for Aqua is nominally 705 km circular, 98.2 degree inclination. Disposal orbit is decaying from 675 km x 697 km, same inclination.

The EO-1 satellite uses a PSI model 80389-1 tank. The tank is also pressurized with nitrogen on one side of an internal diaphragm prior to launch, and also operates in blowdown mode throughout the mission. Its baseline disposal plan also calls for depleting all fuel, leaving approx. 70 psia pressurant trapped behind a diaphragm during its remaining years in orbit decay until reentry. The disposal orbit is decaying from 673 km x 685 km at a 97.8 degree inclination.

Figures 1 and 2 below show illustrations of the Aqua and EO-1 fuel tanks, respectively. Table 4 below contains additional material properties and geometric parameters for these two tanks (see also [36,37]). As can be seen in Table 4, the EO-1 spacecraft is actually estimated to take about 40 years to reenter, while the anticipated passivated orbital lifetime of the Aqua satellite is 25 years. In Table 4, the diameter of each tank was calculated assuming a spherical tank equal in volume to the actual satellite tank. The rupture limit equation to be used subsequently requires a tank diameter as well as tank wall thickness; hence the need to calculate this quantity for each tank.

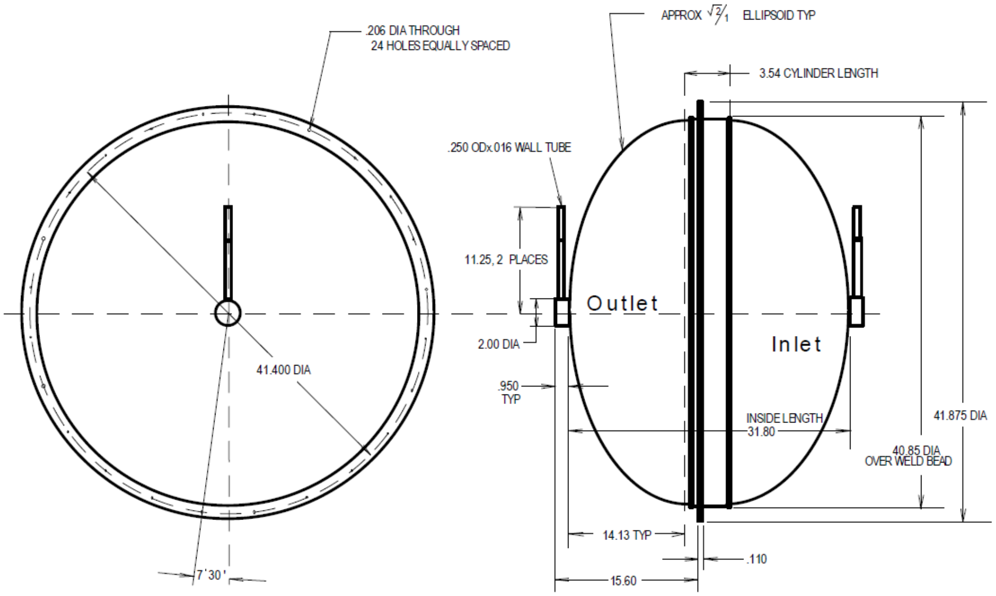

Figure 1. Sketch of Aqua Fuel Tank

(https://www.northropgrumman.com/Capabilities/DiaphragmTanks/Documents/DS263.pdf)

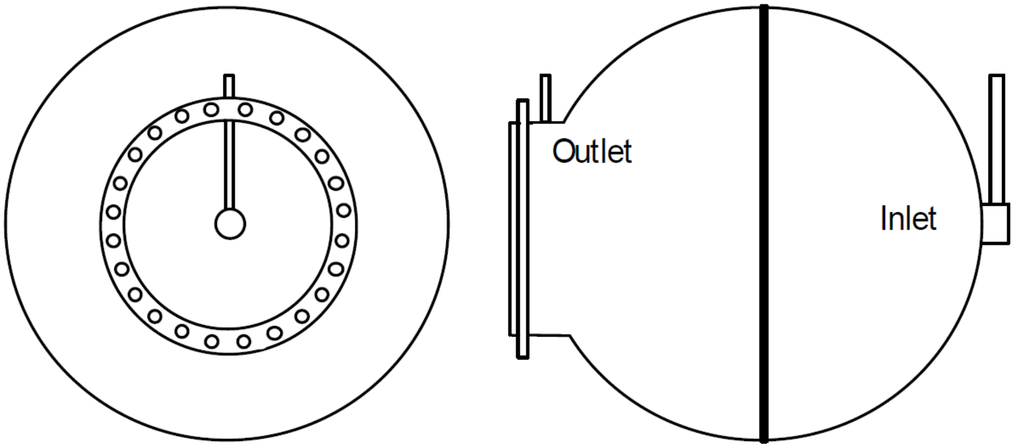

Figure 2. Sketch of EO-1 Fuel Tank

(https://www.northropgrumman.com/Capabilities/DiaphragmTanks/Documents/DS389.pdf)

Table 4. Material and Geometry Information for Aqua and EO-1 Tanks

Parameter	**Aqua**	**EO-1**	**Units**
Tank Material	6Al-4V-Ti	6Al-4V-Ti	-----
Tank Volume	28,144	1,865	in^3
Tank Diameter	96	39	cm
Wall Thickness	1.27	0.483	mm
Internal Press	100	70	psi
Anticipated Passivated Orbital Lifetime	25	40	yrs

The Rupture Limit Equation (RLE) for a pressurized spherical metallic tank was obtained using the rupture / no rupture data from a previous study that considered the high-speed impact of pressurized spherical aluminum and titanium tanks [38]. To render the equation as broadly applicable as possible, the operating conditions (x-axis) were parameterized as the hoop stress in the tank (non-dimensionalized by the ultimate tensile stress of the tank wall material), and the impact conditions (y-axis) were parameterized as impact energy (non-dimensionalized by a number of appropriate tank wall material properties).

Following on the successful application of this approach in several previous studies (see, e.g., [39]), the following simple power law form was chosen for the curve that separates the regions of rupture and non-rupture was chosen as follows:

$$\textit{Non-dimensional Projectile Energy} = A\left(\frac{\sigma_h}{\sigma_u}\right)^B \tag{1}$$

where σ_h and σ_u are the pressure vessel hoop stress and the tank wall material ultimate tensile stress, respectively. The non-dimensional form of projectile energy was taken as follows:

$$\textit{Non-dimensional Projectile Energy} = \frac{\frac{1}{2}m_p V_p^2}{(\rho_p t_w^3) C_w^2 (\frac{\rho_p}{\rho_w})^{-3\alpha} H_w^{3/4}} \tag{2}$$

In Eq. (2), ρ_p and ρ_w are the densities of the projectile and tank wall materials, respectively; t_w is the thickness of the tank wall, and H_w and $C_w = \sqrt{E_w/\rho_w}$ are the Brinell Hardness Number and the speed of sound, respectively, for the tank wall material. In addition, α has a value of 1/2 if $\rho_p/\rho_w < 1.5$ and 2/3 if $\rho_p/\rho_w > 1.5$. As such, the first term in the denominator in Eq. (2) has units of mass while the second has units of velocity squared, thereby rendering the right-hand-side of Eq. (2) unitless, or non-dimensional, so long as there is consistency in the units of mass and velocity used in its numerator and denominator.

Using the data in [38] and the procedure outlined in [39], the values of A and B were found to be $A = 1.606$, and $B = -0.8943$ (with a correlation coefficient of 68% for the regression that yielded the values of A and B). These values of A and B, together with Eqs. (1) and (2) complete the development of the RLE needed for this exercise. We are now ready to proceed with the four-step process outlined previously to determine the diameter of the most likely rupture-causing orbital debris particle for the two satellites considered in this effort and the number of such particles each satellite might be expected to encounter during its passivated lifetime.

STEP ONE: Estimate the most likely closing velocity and impact angle of an orbital debris particle in that satellite's orbit using an appropriate debris environment model

The most likely closing velocity and impact angle of an orbital debris particle in the disposal orbits of Aqua and EO-1 as stated above were found using ORDEM-3 [40]. Figures 3-6 show this information as obtained from ORDEM-3 for the Aqua and EO-1 disposal orbits, respectively.

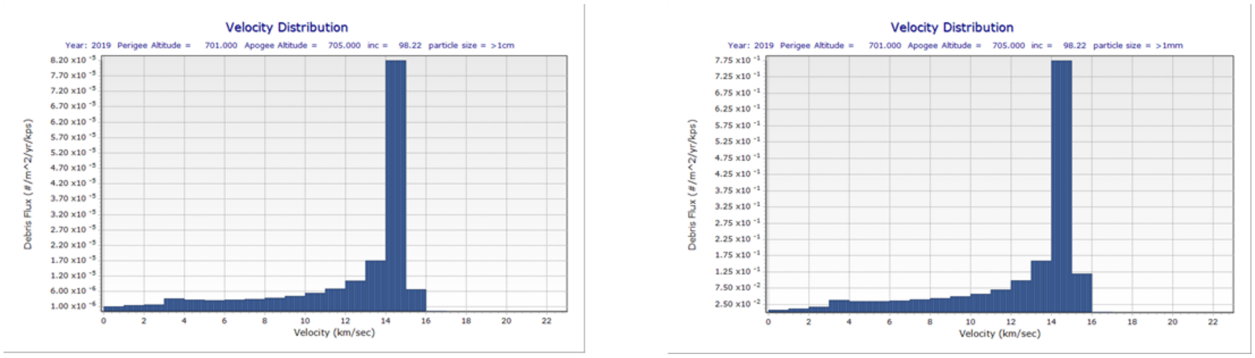

Figure 3. Debris Flux in Terms of Impact Velocity for the Aqua Satellite
(a) for 1 cm Particles, (b) for 1 mm Particles

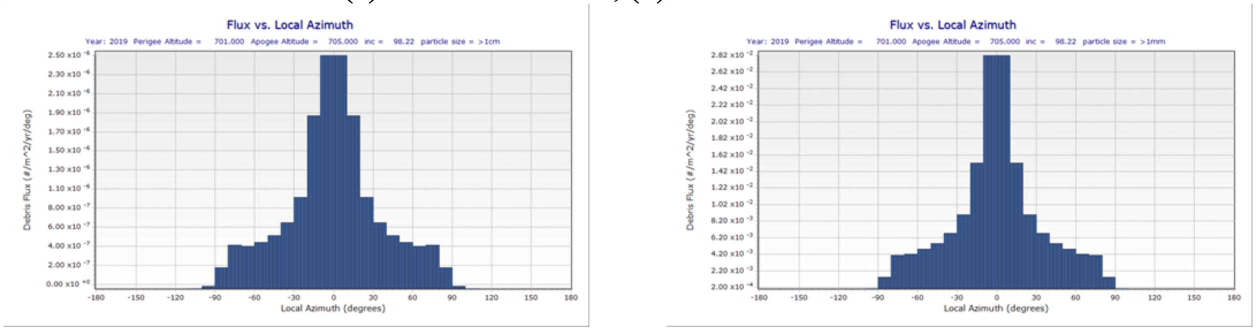

Figure 4. Debris Flux in Terms of Impact Angle for the Aqua Satellite

(a) for 1 cm Particles, (b) for 1 mm Particles

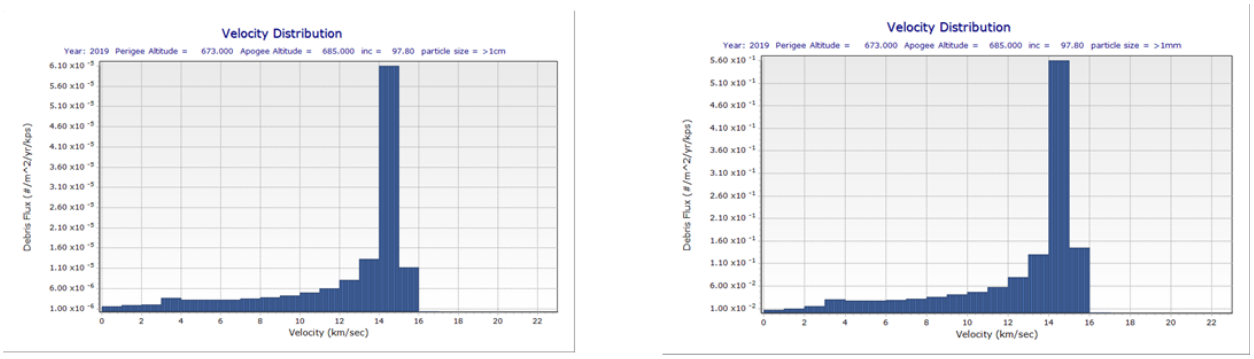

Figure 5. Debris Flux in Terms of Impact Velocity for the EO-1 Satellite

(a) for 1 cm Particles, (b) for 1 mm Particles

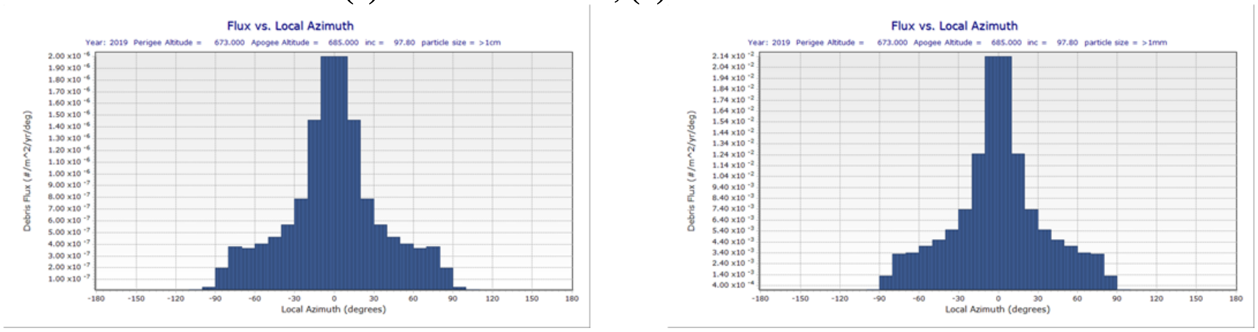

Figure 6. Debris Flux in Terms of Impact Angle for the EO-1 Satellite

(a) for 1 cm Particles, (b) for 1 mm Particles

As can be seen from Figures 3,4 and 5,6 the values of most likely orbital debris impact angle and velocity are not dependent on whether 1 mm or 1 cm size particles are assumed in the flux calculations. In both cases, and for both satellites, Figures 3,4 and 5,6 tell us that the most likely impact velocity and impact angle for both satellites is 14.5 km/s and 0-deg, respectively.

STEP TWO: Using the information from STEP ONE and the Rupture Limit Equation for the type of fuel tank in the each satellite, determine the diameters of the likely rupture-causing particles

Figure 7 shows a plot of the RLE developed for this task and the data from [38] that was used in its development. Also indicated in Figure 7 are the points on the RLE corresponding to the most likely impact angle and most likely impact velocity for the two satellites being considered.

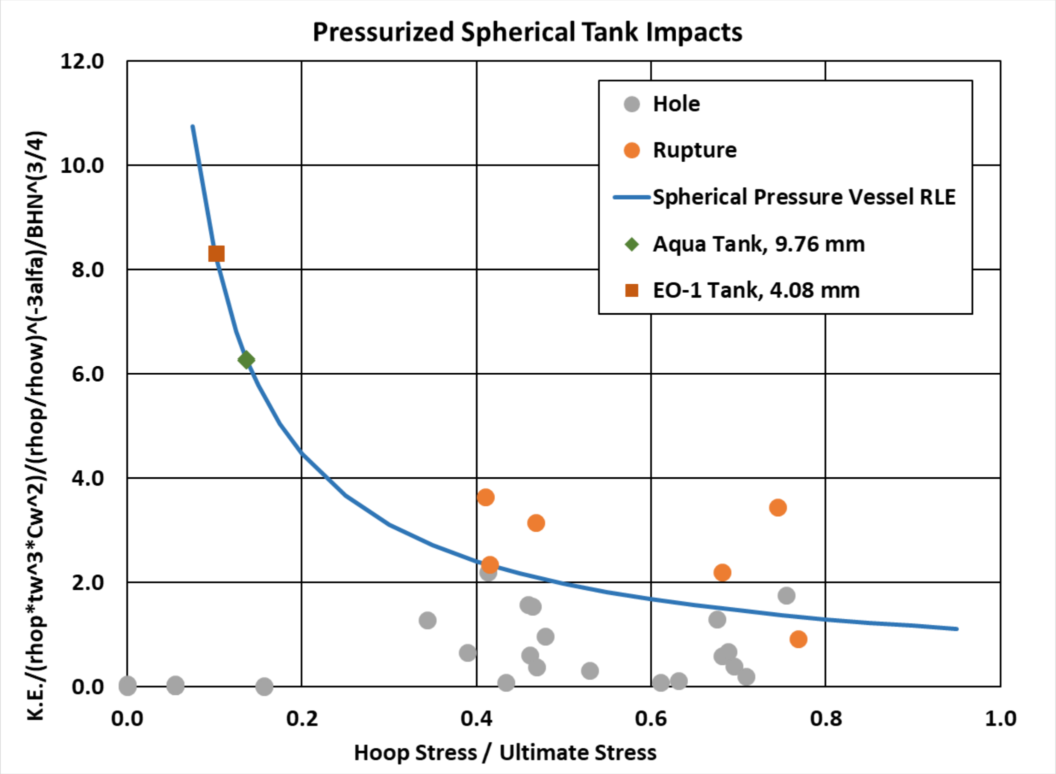

Figure 7. Plot of Spherical Metallic Tank RLE and Supporting Data

Based on the RLE developed herein, from Figure 7 we find that it would be reasonable to expect that the impact of a 4.08 mm aluminum particle would result in rupture of a soft-passivated EO-1 fuel tank (i.e. when it is in its disposal orbit), while a 9.76 mm aluminum particle would be required to rupture a soft-passivated Aqua fuel tank. The question now is, how many such rupture-causing particles might the Aqua and EO-1 satellites be expected to encounter during their disposal orbit lifetimes?

STEP THREE: Using the same model of the orbital debris environment, determine the anticipated flux of particles of those sizes for the given satellites' orbits

The anticipated flux of orbital debris particles of the size, closing velocity, and impact angle that can be expected to rupture passivated Aqua and EO-1 fuel tanks in their disposal orbits were again found using ORDEM-3. This information for each satellite is shown in the first row of Table 5 below.

STEP FOUR: Calculate the expected number of particles to be seen by the given satellites in their orbits based on assumed remaining orbital lifetimes and exposed surface areas

The number of rupture causing particles for each satellite was found by multiplying the flux value for each satellite found in STEP THREE by an assumed remaining orbital lifetime for each satellite (in years; see last row of Table 4) by the projected circular cross-sectional area of each (assumed spherical) tank; results are also shown in the second row of Table 5.

Table 5. Anticipated Flux and Number of Rupture Causing Particles for Each Satellite

Parameter	**Aqua**	**EO-1**	**Units**
Flux	0.00017	0.001	/m^2/yr
# particles	0.003067	0.002955	over the orbital lifetime

From the information in Table 5, it can be inferred then, that for the two satellites considered, the number of fuel tank rupture-causing particles that each satellite is likely to encounter is exceedingly low. Of additional interest is that the calculated numbers of possible rupture-causing particles shown in Table 5 agree reasonably well with the estimate of the number of explosion-causing particles obtained for another LEO satellite (Pleiades) having similar orbital parameters (695 km orbit, 98-deg inclination) using the Master 2009 model (i.e. 0.0025 over a 25 year time period) [41].

It is this kind of information that can then be used by satellite designers and mission planners to strength their case for soft passivation, if they would choose to do so. Of course, in order for this estimate to be useful, an acceptable risk threshold would need to be established.

The process presented herein has a number of assumptions including, for example, aluminum orbital debris particles in the ORDEM-3 calculations (and ignoring the existence of any higher density particles in the orbits), fully exposed tanks (and ignoring any shielding provided by other satellite components), etc. While the process can be readily modified to be more realistic and to provide more accurate assessments of the likelihood of encountering rupture-causing particles, it has at least shown to be fairly straightforward to implement to obtain the desired information.

2.2 Conclusions

This paper presents the results of a series of tasks that were performed with the intent of providing some possible guidelines and considerations that could be used by satellite programs and projects to help satisfy passivation requirements using the “soft passivation” approach, that is, when not performing complete fuel depletion, or hard passivation.

An in-depth review of available literature revealed that no comprehensive study has been performed to date that would be able to provide information regarding “safe” pressure levels. However, what was found was that when a pressure vessel’s internal pressure was at a level between 15% and 25% of its static burst pressure, catastrophic failure following a hypervelocity impact would probably not occur.

In addition, a process was developed that can be used to calculate the number of rupture-causing MMOD particles that a spacecraft might expect to encounter in a so-called “soft passivated” state. This process was applied to two typical pressurized fuel tanks that are frequently used in earth-orbiting satellites. In both cases, the number of rupture-causing particles was found to be exceedingly small. The results that can be obtained using this process can also be used by spacecraft designers and mission planners to help satisfy passivation requirements using a “soft passivation” approach.

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14. ABSTRACT

Many space-faring organizations have requirements to limit the growth of orbital debris by passivating spacecraft that remain in orbit after mission end. These requirements state that a stored energy devices are to be fully depleted at the end of a spacecraft’s useful life. Spacecraft designs not able to comply with those requirements use a so-called “soft passivation” option. This report presents the results of two studies aimed at better understanding spacecraft pressure vessel passivation state-of-the-art. They summarize current practices and principles of pressure vessel passivation and present an approach that can be used to show that spacecraft propulsion system passivation has been achieved.

15. SUBJECT TERMS

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