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Revision A
June 22, 2026

STANDARD FOR THE CONTROL OF CATASTROPHIC HAZARDS IN HUMAN-RATED SPACECRAFT PROPULSION SYSTEMS

Abstract: Building safe, reliable, high performance, and successful spacecraft propulsion systems for human spaceflight by appropriate application of the necessary standards, practices, and hazard mitigations early in the design and test phase.

Engineering Directorate
Office of Primary Responsibility: EP / Propulsion and Power Division

Compliance is Mandatory

National Aeronautics and Space Administration

Change Record

Revision /DCN	Date	Originator	Approvals	Description
Basic	27 April 2025	Eric Hurlbert / EP4	Per EA MRCB CR/D EA-0296	Initial Release.
A	22 June 2026	Eric Hurlbert / EP4	Per EA MRCB CR/D EA-C0002	Rev A release to incorporate comments from additional internal NASA review and external industry review following the Prop Standard TIM in June 2025. Numerous modifications were made throughout the entire document.

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Foreword and Acknowledgements

This document was prepared with the review and inputs from many engineers within NASA and private industry representing technical disciplines such as propulsion; structures; guidance, navigation, and control (GN&C); thermal control; systems engineering; materials and processes (M&P), etc. over a period of several years. The requirements and information were gathered from as many different sources as possible. Without these inputs the document could not have been prepared up to this point.

1 INTRODUCTION

1.1 PURPOSE AND SCOPE

The gaps in requirements that control spacecraft propulsion systems hazards are a particular emphasis of this document with a strong belief that up-front communication and clarity in the standards, which consider the many costly lessons learned over time, will reduce technical, cost, and schedule issues and improve overall safety. The National Aeronautics and Space Administration (NASA) Procedural Requirements (NPR) document NPR 8705.2C, Human-Rating Requirements for Space Systems, defines requirements for the control of catastrophic hazards in human-rated space systems. The NASA Technical Authority (TA) and the NASA Design and Construction (D&C) standards are the foundation of the process. Some of the applicable standards are owned by NASA, some are owned by other United States (U.S.) Government agencies, and some are owned by private industry. Collectively, these TA standards provide a structured and repeatable means of designing, analyzing, manufacturing, assembling/integrating, testing, servicing/maintaining, and operating a human-rated spacecraft successfully.

Despite the existence of these TA standards, they are not always applied in a consistent manner by the various NASA projects/programs, and there are still some significant gaps in the content, understanding, and application of requirements that are relevant to the control of catastrophic hazards associated with human-rated spacecraft propulsion systems. This document was created to address both of those issues by ensuring that existing standards, in whole or in part, are invoked consistently and known gaps in existing standards are addressed through clarifications and/or new requirements, thus enabling effective control of propulsion system hazards.

Spaceflight history is full of lessons learned related to failure modes and hazards of propulsion systems which have been codified into the many technical standards and guidelines publications that are in use today, whether owned by NASA, the U.S. military, or the aerospace industry. Incorporating lessons learned into a project upfront has been shown to have significant benefit to its success. This document, which is specific to human-rated spacecraft propulsion systems, identifies failure scenarios, hazards, specific standards/requirements, and the source of one or more driving lesson(s) learned. The sources for lessons learned include publicly available reports from the cognizant engineers and the NASA Lessons Learned Information System (LLIS), with topics such as LLIS 21501. "Projects Benefit from Lessons Learned on Previous Spaceflight Projects" (LLIS-21501, 2017)

In summary, this document is intended to define the key requirements and address known requirement gaps needed to control catastrophic hazards associated with onboard chemical propulsion systems of any type on a human-rated spacecraft, including liquid abort systems. Note that the scope does include all orbital, transit, and lander vehicles but not boosters or upper stages. The goal is to ensure that the collective body of knowledge reflected by the existing TA standards, in addition to the supplemental requirements contained herein which have been gathered over a period of many years of spacecraft propulsion systems engineering, are applied efficiently and effectively without resulting in the catastrophic events and costly technical issues needing rework that can occur late in a project/program.

The scope covers gaseous, earth storable liquid, and cryogenic liquid and gaseous propellants and propulsion systems. It does not cover solid propellants or electric propulsion systems, though the fluid systems that deliver oxidizer for hybrid propulsion systems and gaseous propellants to electric thrusters would need to meet the requirements contained herein. Some additional requirements may apply to supporting subsystems, such as active refrigeration for long duration spacecraft, specific Xenon (Xe) propellant procurement and use specification, or electric propulsion system thrusters and their interfacing power systems. However, it is expected that those types of systems would still need to meet many of same hazard control requirements contained herein, such as service life, maximum design pressures, material compatibility, ignition hazards, etc., while noting that there may be additional hazard control requirements imposed on hybrid and electric propulsion systems.

Implementation of this propulsion standard for a given project/program as a Type 2 (i.e. meets or exceeds) or Type 3 (i.e. reference only) document will be determined by the NASA Project/Program Manager in conjunction with the NASA TA. Note that any requirements or standards proposed as an alternate to a Type 2 document would be subject to an evaluation of technical equivalence by the NASA TA and approval by the NASA Project/Program Manager.

1.2 BACKGROUND

The propulsion technical discipline at NASA, shared across multiple centers, has been heavily involved in the design, development, testing, and evaluation (DDT&E); failure modes and hazards analyses; assembly, integration, and testing (AI&T); ground checkout and servicing; launch preparations; flight operations; and sustaining engineering and maintenance for chemical propulsion systems on human-rated spacecraft and importantly on other non-human rated vehicles spanning multiple projects/programs over the last six decades. A list of the human rated propulsion systems, dating back to the beginning of the US human spaceflight program, is shown in Table 1. This document represents a set of knowledge and lessons learned from the propulsion engineering and flight/ground operations teams, who have provided technical support for propulsion systems of the past, to inform similar propulsion systems of the future. NASA programs and projects should assess their compliance with NASA lessons learned at each major program or project milestone. Reference Each NASA Project Should Assess Its Compliance with NASA Lessons Learned. (LLIS-2042, 2009)

TABLE 1 HUMAN SPACECRAFT ONBOARD CHEMICAL PROPULSION SYSTEMS WORKED BY THE PROPULSION TECHNICAL DISCIPLINE AT NASA

PROJECT/PROGRAM	ELEMENT/VEHICLE/PAYLOAD	PROPULSION SYSTEM DETAILS		STATUS
		PROPELLANT(S)	VACCUM THRUST LEVEL(S)	
MERCURY	SPACECRAFT CAPSULE	90% H2O2	1 LBF, 6 LBF, 24 LBF (REF) (NASA, 1963, pp. 54,283)	FLOWN
GEMINI	CAPSULE ORBIT ATTITUDE AND MANEUVERING SYSTEM (OAMS) AND REACTION CONTROL SYSTEM (RCS)	MMH / NTO	8 X 25 LBF OAMS 8 X 100 LBF OAMS 16 X 25 LBF RCS (REF) (Blatz, 1964, pp. 14, fig 13)	FLOWN
APOLLO	LUNAR MODULE (LM)	A50 / NTO	10500 LBF (DME) (REF) (Hammock, 1973, p. 7)	FLOWN
APOLLO	LUNAR MODULE (LM)	A50 / NTO	1 X3500 LBF (AME) (REF) (Humphries, 1973, p. 2) 16 X 100 LBF (RCS) (REF) (Vaughan, 1972, p. 2)	FLOWN
APOLLO	SERVICE MODULE RCS	MMH / NTO	SM: 16X 100 LBF (REF) (Taeuber, 1973, pp. 6, para. 4)	FLOWN
APOLLO	COMMAND MODULE (CM) RCS	MMH / NTO	CM: 12 X 100 LBF (REF) (Taeuber, 1973, pp. 9,39, fig. 18)	FLOWN
APOLLO	SERVICE MODULE (SM) MAIN ENGINE	A50 / NTO	21,500 LBF (SME) (REF) (Gibson C. R., 1973, pp. 5, para 3)	FLOWN
SSP	ORBITER MAIN PROPULSION SYSTEM (MPS)	LH2 / LO2	3 X 512,000 LBF (REF) (Martinez, 2011, p. 2), SSME RS25	FLOWN
SSP	ORBITER ORBITAL MANEUVERING SYSTEM (OMS)	MMH / MON3	2 X 6000 LBF (REF) (Gibson C. , 1985, pp. 13, fig 10)	FLOWN
SSP	ORBITER REACTION CONTROL SYSTEM (RCS)	MMH / MON3	38 X 870 LBF, 6 X 25 LBF (VERNIER) (PRIMARY) (REF) (Hernandez, 2011, pp. 23, para 2)	FLOWN
GEMINI, APOLLO, SSP	LO2/LH2 POWER REACTANT STORAGE AND DISTRIBUTION (PRSD) SYSTEM	LOX/LH2 (SUPERCRITICAL)	UP TO 3 X UP TO 16 KW (REF) (Hernandez, 2011, p. 28), (REF) (Davis, 1970), (REF) (Simon, 1985, pp. 15, table 3),	FLOWN
ORION MPCV	CREW MODULE (CM)	HYDRAZINE	12 X 160 LBF (REF)	FLOWN
ORION MPCV	SERVICE MODULE (SM)	MMH / MON3	1 X 6225 LBF (27.7 KN) (OMS-E) 8 X 110 LBF (490N) (AUX) 24 X 50 LBF (220N) (RCS) (REF) (Philippe Berthe, 2017, pp.	FLOWN

			4-5)	
ISS	SOYUZ ON-ORBIT	UDMH / N2O4	28 X 30 LBF (REF) (Bowman, 2016, p. 6:07)	FLOWN
ISS	SOYUZ DESCENT MODULE (DM)	H2O2	8 SMALL THRUSTERS (REF) (NASA PRESS KIT, 2004, p. para 6)	FLOWN
ISS CRS	H-II TRANSFER VEHICLE (HTV)	MMH / MON3	4 X 110 LBF MAIN 28 X 25 LBF ACS (REF) (Matsuo, 2012, pp. 1-2)	FLOWN
ISS CRS	AUTOMATED TRANSFER VEHICLE (ATV)	MMH / MON3	4 X 110 LBF MAIN 28 X 50 LBF ACS (REF) (European Space Agency, n.d.)	FLOWN
ISS CRS	CYGNUS	HYDRAZINE (N2H4) / MON3	DUAL MODE N2H4 AND MON3 OR N2H4 (REF) (Grumman, n.d.)	FLOWN
ISS CCP / CRS	DRAGON	MMH / MON3	8 X 16K LBF LIQUID ABORT 16 X 90 LBF DRACO (REF) (SpaceX, n.d.)	FLOWN
ISS CCP	CST-100 STARLINER	MMH / MON3	4X 40K LBF LIQUID ABORT, 20 X 1500 LBF ORBITAL, 28 X 85 LBF RCS (REF) (L3Harris, n.d.)	FLOWN

As evident in this table, the bulk of historical experience with onboard chemical propulsion systems in human-rated spacecraft involves pressure-fed, earth storable hypergolic propellant systems, which are the primary source of content appearing in this document. However, other propellant combinations have also been the subject of significant development, test, certification, and flight operations over the course of time. While there are many commonalities among propulsion systems in terms of design, construction, testing/checkout, ground/flight operations, and hazard analyses, there are also some unique attributes associated with certain propellants that must be considered in that context. The recent advent of high thrust (128,000 lbf+ total) pressure-fed liquid abort systems integrated with orbital maneuvering systems is also evident.

The body of work outlined above represents a high level of practical experience and subject matter expertise needed to effectively identify, document, and control the catastrophic hazards associated with spacecraft propulsion systems.

1.3 PROPULSION SYSTEM FAILURE MODES AND HAZARDS

The hazards are typically grouped into four major categories associated with a spacecraft propulsion system that could result in loss of mission (LOM), loss of vehicle (LOV), and/or loss of crew (LOC), as listed below:

- Rupture

- Leakage – external, internal
- Fire/explosion
- Loss of Control – translation and/or attitude

Of course, there are many possible causes for each of these catastrophic hazards and the controls are typically rooted in the use of appropriate design and construction standards; rigorous qualification, acceptance, and integrated system testing; and functional redundancy built into the system. For spacecraft propulsion systems, the failure modes associated with these hazards include leakage/release of fluid commodities from weld flaw or mechanical fittings, pressure vessel rupture, engine burn through, flammable environments, over-pressurization of the system or surrounding compartments/volumes, structural failure of the interfacing primary or secondary structure, fracture of thin wall membranes, thruster inadvertent firings due to avionics or wiring fault, loss of thrust vector control (TVC), thruster failure to fire or shut down due to valve sticking, etc. A table of requirements, applicability, and catastrophic failure modes/hazards, and lessons learned references is contained in Appendix A.

1.4 SPACECRAFT AND PROPULSION SYSTEM RELIABILITY

Reliability of the propulsion system, inclusive of the associated hardware and software, is established through the various design, analysis, assembly/integration, and test requirements contained in these standards. The goal is to keep it 'Safe, Simple, Lightweight, Reliable, and Robust.' Of course, that is a very challenging task full of critical design decisions and process optimization to meet the mission requirements with minimum practical risk and adequately controlled hazards, within the physics prescribed by the rocket equation. Extra mass and extra margin above that required are not extra good. For example, added mass in the propulsion system might be better spent to improve safety or performance in some other system within the spacecraft. A probabilistic risk assessment (PRA) that assigns a probability to LOM, LOV, and/or LOC requires test data on failure modes, anomalies, how often it occurs, and consequences etc. that is specific to the hardware being used and considers the details of its application (ref NASA/SP-2011-3421 Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners). The requirements included herein provide that test data, however the PRA is beyond the scope of this document. Capture of Apollo Lunar Module Reliability Lessons Learned: Reliability Engineering) (LLIS 1835, 2008)

2 HUMAN RATED SPACECRAFT PROPULSION SYSTEMS

This propulsion system standard, and other standards, derives from NASA Procedural Requirements (NPR) 8705.2C, Human-Rating Requirements for Space Systems and NASA-STD-8719.29 NASA Technical Requirements for Human-Rating, specifically:

- NPR 8705.2C, paragraph 2.2.3 requires a process to be defined for identifying, assessing, and mitigating failure scenarios and hazards through a formal safety analysis process.

- NPR 8705.2C, paragraphs 2.4.3 and 2.4.4 require a definition of how critical system level performance characteristics and critical system level interactions will be verified/validated, respectively, to avoid catastrophic hazards.
- NASA-STD-8719.29, paragraph 4.3.1 provides general requirements for the control of catastrophic hazards.
- NPR 8705.2C also describes the process for a project/program to define the standards to be implemented for the activity.

NASA-STD-8719.29 paragraph 4.3.1 states that the space system shall provide at least single failure tolerance to catastrophic events, with specific levels of failure tolerance and implementation (similar or dissimilar redundancy, alternately referred to as like or unlike redundancy, with dissimilar/unlike redundancy ensuring no common cause failure modes) derived via an integration of the design and safety analysis (required by NPR 8705.2). Notable exceptions include pressure vessels and primary structure, where redundancy of a structural nature is not practically achievable. In some cases, mission architecture may provide a form of dissimilar redundancy, but its use as a hazard control must be formally established by a given project/program and it does not provide effective control of certain catastrophic hazards associated with a propulsion system that are characterized by a short 'time to effect' due to rapid progression.

2.1 APPLICABLE TECHNICAL STANDARDS FOR SPACECRAFT PROPULSION SYSTEMS

The technical standards shown in Table 2 each play a role in addressing the catastrophic failure modes associated with human rated spacecraft propulsion systems, and all have been cited in one or more requirement statements appearing in subsequent sections of this document. Therefore, they are considered as 'applicable' Type 2 (i.e. meets or exceeds) standards to the extent specified herein, for use by all projects/programs charged with developing such systems. Tailoring and/or substitution are considered possible via an adjudication process to be defined by the NASA Project/Program and supporting NASA Technical Authorities.

The technical standards and other documents shown in Table 3 also play a role in hazard control for human rated spacecraft propulsion systems but have only been cited in the text and/or rationale paragraphs that accompany the requirement statements in this document. The intent is to provide a source of additional clarification/information on a given topic. Therefore, they are considered as Type 3 (i.e. reference only) standards for use by all projects/programs charged with developing such systems.

Note that all entries in both tables are listed in alphabetical/numerical order by document number. Also note that the philosophy here is to provide a pointer to the appropriate technical standards, in whole or in part, and avoid repeating the detailed requirements language of those standards herein, unless there is a specific need to clarify, modify, or expand the content to address common misconceptions or identified gaps in the implementation for the control of specific hazards. Any documents listed in Tables 2 and 3 which cannot be found online (e.g. NASA standards at https://standards.nasa.gov/, NESC engineering reports at https://ntrs.nasa.gov/, NESC technical bulletins at https://www.nasa.gov/nesc/knowledge-products/nesc-technical-bulletins/, industry standards at the issuing organization's web site, etc.) will be made available to an industry partner upon request for any NASA project/program that levies this propulsion standard as a Type 2 (meets or exceeds) or Type 3 (reference only) document.

Despite the existence of these standards, there are still some significant gaps in the requirements relevant to the control of catastrophic hazards for spacecraft propulsion systems. This statement is based on the many past and recent technical issues experienced during propulsion system development and operations. These gaps, along with necessary clarifications or augmentations to existing standards, are the main source of requirements included in this document. To reflect those distinctions, each requirement number is annotated with a suffix letter, as described below:

S = Standard Exists but needs to be Type 2 in whole or in part
SC = Standard Exists but needs Clarification or Augmentation
G = Gaps in the Standard or Requirement

The applicable revisions of each standard which have been used for the clarification and gap assessments herein are shown in Table 2, and that information has purposely been omitted from the remainder of this document to avoid a potential inconsistency. A conflict with a more recent version of a given standard, or the substitution of another standard altogether, would be subject to an adjudication process and could be influenced by other project/program considerations. Per the definition above, requirement numbers containing SC involve clarifications and/or augmentations to an existing standard for the purpose of addressing known limitations and past points of confusion/contention specific to propulsion system applications. Accordingly, any scope/content added by this propulsion standard takes precedence over the original standard being cited in those instances, subject to specific program requirements, with no applicability to other vehicle subsystems.

Requirement numbers containing S, which impose other existing standards as written, in whole or in part, do not need separate verifications as part of this propulsion standard if that verification is already being developed separately for the project/program. Instead, the verifications used for any duplicate requirements imposed by the project/program can be leveraged for this purpose. Requirement numbers containing SC or G will require separate verifications as part of this propulsion standard because those requirements don't exist elsewhere.

This document uses the word 'shall' for requirements that must be implemented and verified to control catastrophic hazards, ‘should’ for items that represent a recommended best practice but are not mandatory, ‘will’ for items that represent an expected outcome or statement of fact but are not verified, and ‘are’ or ‘is’ for items that represent informative/descriptive material.

Tailoring of the requirements in this standard for application to a specific project/program is acceptable when formally documented and approved by the delegated NASA Technical Authority in accordance with NPR 7120.5, NASA Space Flight Program and Project Management Requirements.

TABLE 2: LIST OF TYPE 2 STANDARDS FOR THE CONTROL OF CATASTROPHIC HAZARDS IN HUMAN-RATED SPACECRAFT PROPULSION SYSTEMS

Document #	Document Title	Rev	TA	Type	Public
A-A-59150	Cleaning Compound, Solvent, Hydrofluoroether (HFE)	A, 02/14/2003	Eng	2	Y
AFRPL-TR-69-149	USAF Propellant Handbooks, Hydrazine Fuels, Vol I	March 1970	Eng	2	Y
AFRPL-TR-76-76	USAF Propellant Handbook, Nitric Acid/Nitrogen Tetroxide Oxidizers, Vol II	February 1977	Eng	2	Y
AIAA G-082	Guide: Space Systems – Composite Overwrapped Pressure Vessels with a Plastic Liner	2022	Eng	2	Y
AIAA SP-084-1999	Fire, Explosion, Compatibility, and Safety Hazards of Hypergols – Hydrazine	1999 w/ 12/05/2001 Correction	Eng	2	Y
AIAA SP-085-1999	Fire, Explosion, Compatibility, and Safety Hazards of Hypergols – Monomethylhydrazine	1999	Eng	2	Y
AIAA SP-086-2001	Fire, Explosion, Compatibility, and Safety Hazards of Nitrogen Tetroxide	Jan 2001	Eng	2	Y
ANSI/AIAA G-095	Guide to Safety of Hydrogen and Hydrogen Systems	A-2017	Eng	2	Y
ANSI/AIAA S-080	Space Systems - Metallic Pressure Vessels, Pressurized Structures and Pressurized Components	A-2018	Eng	2	Y
ANSI/AIAA S-081	Space Systems - Composite Overwrapped Pressure Vessels	B-2018	Eng	2	Y
ANSI/AIAA S-157	In Space Storable Fluid Transfer for Prepared Spacecraft	2025	Eng	2	Y
ASTM D1193-24	Standard Specification for Reagent Water	11/01/2024	Eng	2	Y
ASTM G88-21	Standard Guide for Designing Systems for Oxygen Service	Nov 2021	Eng	2	Y

Document #	Document Title	Rev	TA	Type	Public
ASTM MNL 36	Safe Use of Oxygen and Oxygen Systems: Guidelines for Oxygen System Design, Materials Selection, Operations, Storage, and Transportation	Second Edition	Eng	2	Y
CGA G-8.2	Commodity Specification for Nitrous Oxide	Seventh Edition	Eng	2	Y
CGA G-11.1	Commodity Specification for Argon	Eighth Edition	Eng	2	Y
IEST-STD-CC1246	Product Cleanliness Levels – Applications, Requirements, and Determination	E, Feb 2013	Eng	2	Y
ISO 14644-1	Cleanrooms and Associated Controlled Environments – Part 1: Classification of Air Cleanliness by Particle Concentration	Second Edition, 12/15/2015	Eng	2	Y
JANNAF-GL-2022-0001 (Note: Formerly CPIA 655)	Guidelines for Combustion Stability Specifications and Verification Procedures for Liquid Propellant Rocket Engines	Jan 1997	Eng	2	N
JPD 1720.14	Spaceflight Hardware Classification and Control	BL w/ Adm Chg 1, 04/27/2023	Eng	2	Y
JSC-08080-2	JSC Design and Procedural Standards	B w/ DCN 001, 08/04/2020	Eng	2	Y
JSC 28596	NASA Standard Initiator User's Guide	A, 02/29/2000	Eng	2	N
JSC 62809	Human Rated Spacecraft Pyrotechnic Specification	G, 11/08/2024	Eng	2	N
JSC 65828	Structural Design and Factors of Safety for Spaceflight Hardware	B w/ Chg 1, 07/15/2014	Eng	2	Y
JSC 65829	Loads and Structural Dynamics Requirements for Spaceflight Hardware	B, 03/20/2024	Eng	2	Y
JSC 67035	Best Practices and Guidelines (BP&G) for Thin Wall Pressure Boundaries (TWPB) for Human Spaceflight Applications	A, Aug 2017	Eng	2	Y
JSC ES 151001-1	Use of ASME Code or Code of Federal Regulations (CFR) Title 49 Department of Transportation (DOT) Pressure Vessels for Space Applications	01/19/2016	Eng	2	N
MIL-DTL-25576	Detail Specification, Propellant, Rocket Grade Kerosene	F w/ Amd 1, 05/24/2023	Eng	2	Y
MIL-PRF-16005	Performance Specification, Propellant, Hydrogen Peroxide	F, 08/01/2023	Eng	2	Y
MIL-PRF-25508	Performance Specification, Propellant, Oxygen	J, 03/02/2020	Eng	2	Y

Document #	Document Title	Rev	TA	Type	Public
MIL-PRF-25567	Leak Detection Compound, Oxygen Systems	E, 07/10/2015	Eng	2	Y
MIL-PRF-26536	Performance Specification, Propellant, Hydrazine	H, 06/17/2025	Eng	2	Y
MIL-PRF-26539	Performance Specification, Propellant, Dinitrogen Tetroxide	G w/ Amd 1, 04/19/2017	Eng	2	Y
MIL-PRF-27201	Performance Specification, Propellant, Hydrogen	F, 08/26/2022	Eng	2	Y
MIL-PRF-27401	Performance Specification, Propellant Pressurizing Agent, Nitrogen	H w/ Amd 2, 01/09/2024	Eng	2	Y
MIL-PRF-27404	Performance Specification, Propellant, Monomethylhydrazine	D, 04/20/2012	Eng	2	Y
MIL-PRF-27407	Performance Specification, Propellant Pressurizing Agent, Helium	E, 04/23/2024	Eng	2	Y
MIL-PRF-27415	Propellant Pressurizing Agent, Argon	D, 02/28/2023	Eng	2	Y
MIL-PRF-32207	Performance Specification, Propellant, Methane	BL, 10/10/2006	Eng	2	Y
MIL-STD-461	Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment	G, 12/11/2015	Eng	2	Y
MSFC-SPEC-3746	Flow-Induced Vibration Assessment Requirements for Metal Bellows and Flex hoses	BL, 04/16/2020	Eng	2	Y
N/A	NASA Hydrogen Peroxide Propellant Hazards Technical Manual	June 2005	Eng	2	Y
NASA-SPEC-5022	NASA Manufacturing and Test Requirements for Normally Closed Pyrovalves for Hazardous Flight Systems Applications	BL w/ Chg 2, 06/24/2015	Eng	2	Y
NASA-STD-1008	Classifications and Requirements for Testing Systems and Hardware to be Exposed to Dust in Planetary Environments	BL, 09/21/2021	Eng	2	Y
NASA-STD-4003	Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment	A w/ Chg 1, 01/16/2019	Eng	2	Y
NASA-STD-5009	Nondestructive Evaluation (NDE) Requirements for Fracture Critical Metallic Components	C, 08/03/2023	Eng	2	Y
NASA-STD-5012	Strength and Life Assessment for Liquid Rocket Engines	C, 06/16/2016	Eng	2	Y
NASA-STD-5017	Design and Development Requirements for Mechanisms	B, 12/06/2022	Eng	2	Y

Document #	Document Title	Rev	TA	Type	Public
NASA-STD-5019	Fracture Control Requirements for Spaceflight Hardware	A w/ Chg 4, 02/01/2016	Eng	2	Y
NASA-STD-5020	Requirements for Threaded Fastening Systems in Spaceflight Hardware	B, 08/06/2021	Eng	2	Y
NASA-STD-6016	Standard Materials and Processes Requirements for Spacecraft	C w/ Chg 1, 11/15/2023	Eng	2	Y
NASA-STD-7009	Standard for Models and Simulations	A, 05/08/2019	Eng	2	Y
NASA-STD-7012	Leak Test Requirements	A, 02/22/2023	Eng	2	Y
NASA-STD-8719.12	Safety Standard for Explosives, Propellants, and Pyrotechnics	A w/ Chg 2, 03/18/2021	Eng	2	Y
NASA-STD-8719.24 and Annex to NASA-STD-8719.24	NASA Payload Safety Requirements Annex to NASA-STD-8719.24, NASA Payload Safety Requirements: Requirements Table	A, 03/30/2022 B, 03/30/2022	S&MA	2,	Y
NASA-STD-8719.29	NASA Technical Requirements for Human Rating	BL, 12/11/2023	S&MA	2	Y
NASA-STD-8739.10	Electrical, Electronic, and Electromechanical (EEE) Parts Assurance Standard	BL, 06/17/2013	S&MA	2	Y
NASA/TM-20210022275	Treatment of Transient Pressure Events in Space Flight Pressurized Systems	09/02/2021	Eng	2	Y
NESC-RP-19-01498	Filtration of Spaceflight Propulsion and Pressurant Systems	April 2022	Eng	2	Y
NESC Technical Bulletin No. 22-02	Revisiting Filtration Standards and Definitions for Spaceflight Propulsion and Pressurant Systems	03/09/2022	Eng	2	Y
NPR 6000.1	Requirements for Packaging, Handling, and Transportation for Aeronautical and Space Systems, Equipment, and Associated Components	H, 11/10/2010	Eng	2	Y
NPR 8705.2	Human-Rating Requirements for Space Systems	C w/ Chg 2, 07/10/2017	N/A	N/A	Y
SAE ARP 599	Dynamic Test Method for Determining the Relative Degree of Cleanliness of the Downstream Side of Filter Elements	D, 05/05/2020	Eng	2	Y
SAE ARP 901	Bubble-Point Test Method	B, 09/30/2022	Eng	2	Y
SLS-SPEC-159	SLS-SPEC-159, Cross-Program Design Specification for Natural Environments (DSNE)	I, 10/27/2021	Eng	2	Y

Document #	Document Title	Rev	TA	Type	Public
SMC-S-016	Test Requirements for Launch, Upper-Stage, and Space Vehicles	09/05/2014	Eng	2	Y
SMC-S-025	Evaluation and Test Requirements for Liquid Rocket Engines	07/26/2017	Eng	2	Y
TOR-2013(3909)-1	Objective Reuse of Heritage Products	04/30/2012	Eng	2	Y
TT-I-735	Isopropyl Alcohol	A w/ Notice 3, 06/06/2007	Eng	2	Y

TABLE 3: LIST OF TYPE 3 REFERENCE DOCUMENTS FOR THE CONTROL OF CATASTROPHIC HAZARDS IN HUMAN-RATED SPACECRAFT PROPULSION SYSTEMS

Document #	Document Title	Rev	TA	Type	Public
AIA NAS412	Foreign Object Debris (FOD) Prevention Guidance Document	3, 08/31/2023	Eng	3	Y
AIAA 90-2749	Methods Used to Investigate and Resolve the Space Shuttle Helium Pressure Regulator Instability	1990	Eng	3	Y
AIAA 91-2172	Propellant Management Device Conceptual Design and Analysis: Vanes	1991	Eng	3	Y
AIAA 93-1970	Propellant Management Device Conceptual Design and Analysis: Sponges	1993	Eng	3	Y
AIAA 97-2811	Propellant Management Device Conceptual Design and Analysis: Galleries	1997	Eng	3	Y
AIAA 98-1055	Forced Convection Boiling and Critical Heat Flux of Ethanol in Electrically Heated Tube Tests	1998	Eng	3	Y
AIAA 2001-3631	Compton Gamma Ray Observatory: Lessons Learned in Propulsion	2001	Eng	3	Y
AIAA 2011-5838	Lessons Learned from the Design, Certification, and Operation of the Space Shuttle Integrated Main Propulsion System (IMPS)	2011	Eng	3	Y
AIAA 2015-4158	Density Fit for MON Oxidizer Blends Including Accuracy	2015	Eng	3	Y
AIAA 2015-4159	Vapor Pressure Fit for MON Oxidizer Blends Including Accuracy	2015	Eng	3	Y
AIAA Journal of Propulsion and Power, Vol 31, No 4, July-August 2015	Solubility of Pressurant Gases in Liquid Hydrazine at Elevated Temperature	2015	Eng	3	Y
AFRL-RZ-ED-TP-2008-184	Nitrous Oxide Explosive Hazards	05/19/2008	Eng	3	Y
AFRPL-TR-67-256	Propellant Specifications Preparation and Use	Oct 1967	Eng	3	Y

Document #	Document Title	Rev	TA	Type	Public
ANSI/AIAA S-120	Mass Properties Control for Space Systems	A-2015	Eng	3	Y
ARAED CR-90002	Hazard Classification Testing of Liquid Propellants	May 1990	Eng	3	Y
CGA G-5.3	Commodity Specification for Hydrogen	8th Edition, 2024	Eng	3	Y
FED-STD-209	Airborne Particulate Cleanliness Classes in Cleanrooms and Clean Zones	E, 09/11/1992 (cancelled 11/29/2001)	Eng	3	Y
JANNAF CPIA Publication 246	Rocket Engine Performance Prediction and Evaluation Manual	April 1975	Eng	3	Y
JS-2018-009, NNJ13RA01B	Gary Johnson, Lessons Learned from 50+ Years in Human Spaceflight and Safety	04/30/2018	E	3	Y
KSC-STD-Z-0006	Design of Hypergolic Propellants Ground Support Equipment, Standard For	C	Eng	3	Y
MIL-STD-1252	Inertia Friction Welding Process, Procedure and Performance Qualification	06/30/1975	Eng	3	Y
MSC-03466	Apollo 11 Mission, Anomaly Report No. 3, Service Module Entry	November 1970	Eng	3	Y
MSFC-DWG-20M02540	Assessment of Flexible Lines for Flow Induced Vibration	A, 12/19/1991	Eng	3	Y
MSFC-SPEC-626	Test Control Document for Assessment of Flexible Lines for Flow Induced Vibration	BL, 02/28/1990	Eng	3	Y
MSFC-STD-531	High Voltage Design Criteria	September 1978	Eng	3	Y
N/A	Scaled Composites Safety Guidelines for N2O	06/17/2009	Eng	3	Y
NASA-HDBK-4007	Spacecraft High Voltage Paschen and Corona Design Handbook.	Change 3, 2020-12-29	Eng	3	Y
NASA-HDBK-5010	Fracture Control Implementation Handbook for Payloads, Experiments, and Similar Hardware, Vol I and II	Vol I: A, 12/15/2023 Vol II: A, 01/09/2024	Eng	3	Y
NASA-HDBK-5013	Pyrovalve Applications and Performance Handbook	A w/ Chg 2, 12/27/2021	Eng	3	N
NASA-HDBK-7009	NASA Handbook for Models and Simulations: An Implementation Guide for NASA-STD-7009	A, 05/08/2019	Eng	3	Y
NASA-HDBK-8739.19-2	Measuring and Test Equipment Specifications, NASA Measurement Quality Assurance Handbook - ANNEX 2	2010-07-13 Baseline	S&MA	3	Y
NASA-HDBK-8739.19-3	Measurement Uncertainty Analysis Principles and Methods, NASA Measurement Quality Assurance Handbook - ANNEX 3	2010-07-13 Baseline	S&MA	3	Y
NASA SP-8055	Prevention of Coupled Structure-Propulsion Instability (POGO)	October 1970	Eng	3	Y

Document #	Document Title	Rev	TA	Type	Public
NASA SP-4203	On the Shoulders of Titans: A History of Project Gemini				
NASA SP-2016-6105	NASA Systems Engineering Handbook	2	Eng	3	Y
NASA-STD-5005	Standard for The Design and Fabrication of Ground Support Equipment	D w/ Chg 2	Eng	3	Y
NASA-STD-6001	Flammability, Offgassing, and Compatibility Requirements and Test Procedures.	B w/ Chg 2, 04/21/2016	Eng	3	Y
NASA/TM-20210022275	Treatment of Transient Pressure Events in Space Flight Pressurized Systems	October 2021	Eng	3	Y
NASA TM X-2362	Investigation of Slosh Anomaly in Apollo Lunar Module Propellant Gage	October 1971	Eng	3	Y
NASA TN D-6349	Fundamental Techniques of Weight Estimating and Forecasting for Advanced Manned Spacecraft and Space Stations	May 1971	Eng	3	Y
NASA TN D-6795	Apollo Experience Report: Pressure Vessels	September 1972	Eng	3	Y
NASA TN D-7151	Apollo Experience Report – Command and Service Module Reaction Control Systems	June 1973	Eng	3	Y
NESC Technical Bulletin 19-02	90/95 POD Radiography Concern for COPVs and Metal Tank Welds	N/A	Eng	3	Y
NESC Technical Bulletin 20-06	Material Compatibility Assessment of Spacecraft Oxidizer Systems	N/A	Eng	3	Y
NESC Technical Bulletin 20-07	Evaluating and Mitigating Liner Strain Spikes in COPVs	N/A	Eng	3	Y
NESC Technical Bulletin 21-01	Experimental and Computational Study of Cavitation in Hydrogen Peroxide	N/A	Eng	3	Y
NESC Technical Bulletin 22-03	Treatment of Transient Pressure Events in Space Flight Pressurized Systems	N/A	Eng	3	Y
NESC Technical Bulletin 22-07	Helium Solubility in MMH and NTO	N/A	Eng	3	Y
NESC Technical Bulletin 22-08	Contamination Reduction in High Purity Hydrazine	N/A	Eng	3	Y
NESC Technical Bulletin 23-01	Including Key Design Features in Safety-Critical Pyrotechnic Firing Circuits	N/A	Eng	3	Y
NPR 7123.1	NASA Systems Engineering Processes and Requirements	D w/ Chg 2, 07/05/23	Eng	3	Y

Document #	Document Title	Rev	TA	Type	Public
SAE AS1424	Hose Assemblies, Metal, Medium Pressure, High Temperature	H, April 2020	Eng	3	Y
SAE AS85421	Fittings, Tube, Fluid Systems, Separable, Beam Seal, 3000-4000 psi, General Specification for	C, May 2021	Eng	3	Y
SAND2012-7321	Technical Reference on Hydrogen Compatibility of Materials	September 2012	Eng	3	Y
SSCMAN 91-710, Volume 3	Range Safety User Requirements Manual - Launch Vehicles, Payloads, and Ground Support Systems Requirements	12/27/2022	Eng	3	Y

3 HUMAN RATED PROPULSION SYSTEM STANDARDS AND REQUIREMENTS

The following sections call out the existing technical standards and additional requirements aimed at filling gaps to address the failure modes and controlling the associated catastrophic hazards of a human-rated spacecraft propulsion system. These requirements are broadly applicable to many types of liquid and gaseous spacecraft propulsion systems and can be tailored accordingly.

This section is structured as follows, from the vehicle and system level down to the components of the system as shown in Figure 1. Many of the most significant propulsion system failures can be traced back to the vehicle or propulsion system initial sizing or conceptual design selections or can be related to vehicle level interactions with avionics, Guidance, Navigation, and Control (GN&C), flight software (FSW), structures, thermal control, and other interfacing systems on the spacecraft, or can be traced to the application of 'heritage' components in manner for which it was not capable.

Detrimental interactions within the propulsion system itself can also lead to hardware failures and associated hazards. Recent examples include, but are not limited to, the following: (1) the operation of components, in series and/or in parallel, causing transient pressures that result in leakage or uncommanded state changes of other valves, (2) the combined effects of external ground environment exposure (e.g. moist air) and internal propellant exposure (e.g. MON propellant) resulting in permeation through seals that drives unexpected corrosion of 'non-wetted' component parts, (3) MON propellant exposure in combination with elevated pressure and temperature conditions resulting in Teflon seal swell that adversely affects component flow area/delta P and leakage performance, and (4) transient liquid propellant flow during water-hammer events caused by propulsion system activation sequences, line/manifold priming steps, thruster firings, etc. which damages components exposed to the excessive surge pressures. These types of interactions may occur for nominal, dispersed, and/or fault cases and conditions, necessitating a methodical and thorough assessment of all relevant scenarios.

In many cases, these types of issues are discovered late in the program and drive a complex and costly redesign, additional analysis and/or testing, operating procedure workarounds, or an increased level of risk acceptance for the technical authority (TA) and project/program. The goal is the early detection of any issues during pre-preliminary design review (PDR) tests, and successful completion of the component level qualification tests and propulsion system level qualification tests with those components included. Ultimately, a series of development, acceptance, and qualification tests will be necessary to verify the requirements.

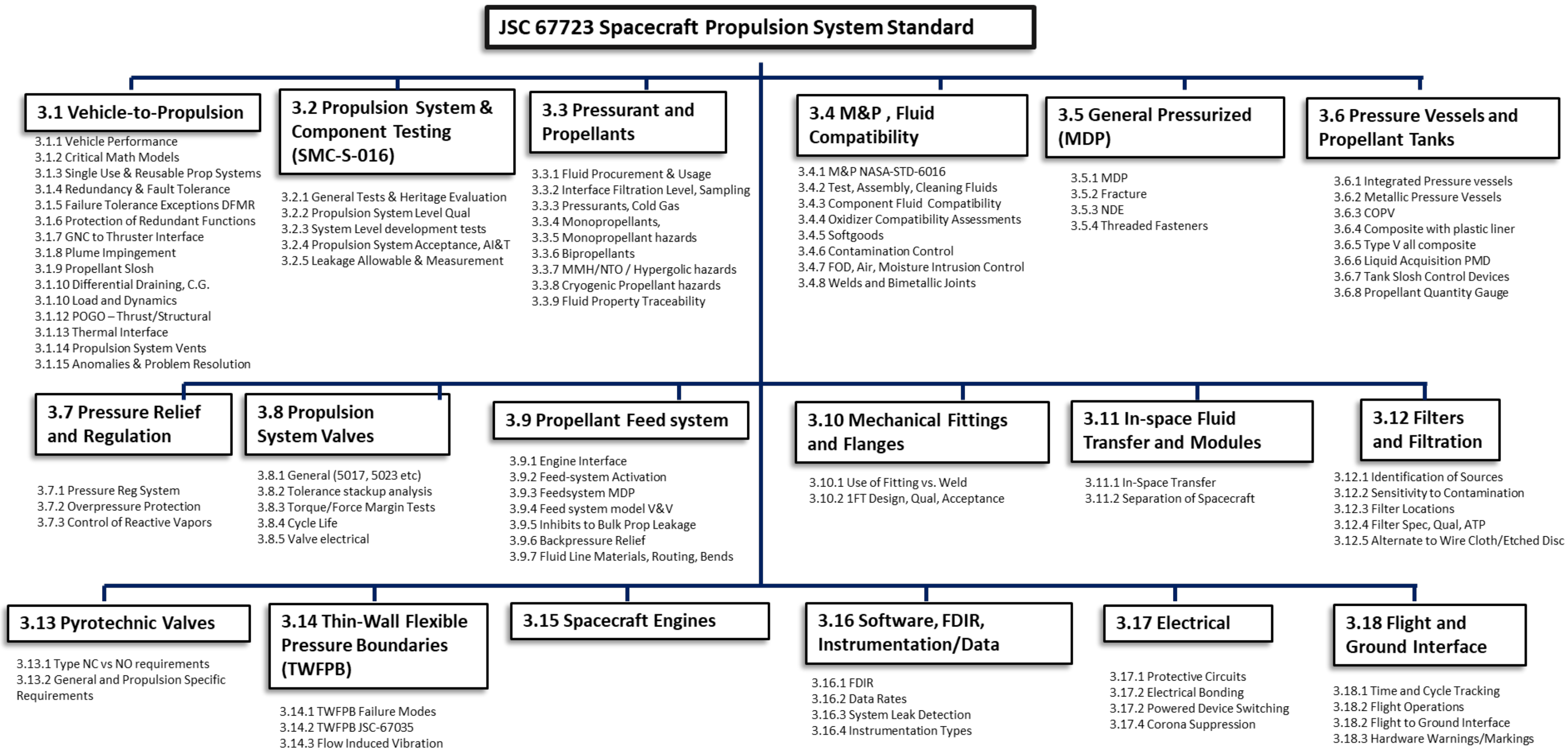

FIGURE 1: ORGANIZATION OF JSC-67723 SPACECRAFT PROPULSION SYSTEM STANDARD CONTENT

3.1 VEHICLE AND PROPULSION SYSTEM REQUIREMENTS

3.1.1 Vehicle and Propulsion System Performance

3.1.1.1 The critical propulsion system performance parameters, including delta-V, engine specific impulse (Isp), propellant load, propellant mass fraction of the total propulsion system mass, and mission duration including nominal values, tolerances, and margins shall be specified at the conceptual design phase for the design option(s) being pursued, with confirmation at the system definition review (SDR) and continued tracking throughout the remainder of the project to ensure that the vehicle and propulsion system with the required fault tolerance closes. ***[PSR-01G]***

Rationale: For a new project/program, a new/different application of heritage hardware, or an existing project/program that is within the initial conceptual definition phase of development, improper upfront definition and subsequent tracking of these key propulsion system performance requirements for which it is being qualified, such as the total amount of propellant or thrust levels, may later stress the propulsion system resulting in catastrophic failures of the pressure vessels, valves, and/or engines/thrusters as more performance is required and margins are reduced. Mission planners, vehicle designers, propulsion engineers, and GN&C engineers are collectively responsible for these inputs for the design option(s) being pursued, which need to be in place exiting SDR and entering the PDR phase of propulsion system development. Guidelines for engine/thruster specific impulse (Isp) estimation is to follow JANNAF CPIA Publication 246, Rocket Engine Performance Prediction and Evaluation Manual. Note that engine performance parameters, including thrust and Isp, are dependent on propellant inlet pressure and temperature. Guidelines for propulsion system mass estimation is to follow ANSI/AIAA S-120, Mass Properties Control for Space Systems, which recommends a 10-20% mass growth allowance (MGA) at the 'E2' level of design maturity (i.e. conceptual designs (equivalent to layout drawings or models) prior to initial sizing), a 5-15% MGA at the 'C3' level of design maturity (i.e. preliminary designs based on calculations that occur after initial sizing but prior to final structural/thermal/manufacturing analyses, assumes minor modifications to existing hardware, generally equivalent to PDR), and a 2-7% MGA at the 'C4' level of design maturity (i.e. released production drawings, assumes very minor modifications to existing hardware, generally equivalent to critical design review (CDR)). Note that applying a (MGA) plus dry mass margin (DMM) totaling >20% or more to the propulsion system and structure early in a project will cause excessive growth in the size/mass of the propulsion stage due to the mathematical nature of the rocket equation. Guidelines for propellant load estimation is to use historical spacecraft, propulsion system, and propellant mass fraction performance data using techniques described in NASA TN D-6349, Fundamental Techniques of Estimating and Forecasting for Advanced Manned Spacecraft and Space Stations, or actual heritage component masses with appropriate mass growth allowance.

3.1.1.2 Spacecraft propulsion systems shall be designed to accommodate the applicable natural environments defined in SLS-SPEC-159, Cross-Program Design Specification for Natural Environments (DSNE). ***[PSR-02S]***

Rationale: The cited standard defines critical natural environments which can greatly affect the performance and life of propulsion system hardware on a human rated spacecraft.

3.1.2 Critical Math Models

3.1.2.1 The critical math models and analysis products for a human rated spacecraft Propulsion System listed in section 3.1.2.2 [PSR-04G] that are used as a control for a catastrophic hazard, shall meet the requirements of NASA-STD-7009, including documentation (data book) that is maintained under configuration control at the project/program level. ***[PSR-03S]***

Rationale: The cited NASA standard, along with the accompanying NASA-HDBK-7009, NASA Handbook for Models and Simulation: An Implementation Guide for NASA-STD-7009, provides a comprehensive set of requirements governing the creation, verification, and configuration management of critical math models and analysis products. This content is especially relevant for math models and analysis products that are used as a control for a catastrophic hazard. Specific requirements are in applicable sections. This documentation and the associated data books must be maintained and updated as changes affecting hazard control are made.

3.1.2.2 For a human rated spacecraft propulsion system, the following critical math models and simulations, only as required to determine performance and control hazards, inclusive of all nominal and contingency in-flight operating scenarios and worst-case single failure cases, as a minimum, shall be generated, updated as changes to system design and operating conditions occur, and maintained under configuration control over the life of the project/program ***[PSR-04G]****:*

a) Performance Model

b) Maximum Design Pressure (MDP) Models

c) Thermal Model

d) GNC and Thruster Math Models with thruster limits and faults (Monte Carlo)

e) Structural Dynamic Math Models including, but not limited to, slosh, vibration, and pogo.

f) Controls Math Models, including the effects of slosh, pogo, and vibration.

g) Electrical power models for motor-driven components including, but not limited to, pumps, valves, and TVC actuators.

Rationale: A spacecraft propulsion system that meets the mission requirements from a performance standpoint, while avoiding the realization of catastrophic hazards during in-flight operation, begins with a comprehensive set of critical models and simulations, sometimes referred to as 'critical math models.' These items are intended to ensure that key performance requirements are met while the propulsion system hardware is maintained within its qualified operating bounds for pressure, temperature, cycle count, duty cycle, etc. This is especially important for avoiding catastrophic failures involving the engines/thrusters, which can progress rapidly, be highly energetic, and have severe consequences. Examples include steady state and transient feed system models used to establish internal fluid flow velocities, pressure drops, and maximum design pressure (MDP) values; steady state and transient thermal models to evaluate minimum/maximum temperatures and ensure the required thermal margins are maintained in service; dynamic structural models to verify the required structural factors/margins are maintained; duty cycle/electrical pulse width (EPW)/duration engine/thrust response; etc. Of course, all of these models and analysis products must continue to evolve as changes to propulsion system design and operating conditions occur and be maintained under configuration control over the life of the project/program.

3.1.3 Single Use and Reusable Vehicle Propulsion Systems

3.1.3.1 For a reusable spacecraft, the design and qualification (which includes the service life factors required herein) of the propulsion systems and associated components shall account for the effects of repeated exposure to all relevant environments and operating cycles/conditions, associated with in-flight usage, including landing environment, and ground turnaround testing, checkout, inspection, and maintenance tasks/activities across the designated number of missions to be certified. ***[PSR-05SC]***

Rationale: A properly designed and qualified propulsion system on a reusable spacecraft must account for the worst case cumulative effects, with service life margins as defined herein and NASA D&C standards, of repeated exposure to all relevant environments (e.g. vibration, shock, thermal (especially cryogenic temperatures), depressurization/repressurization, radiation, propellant exposure (especially at sealing interfaces involving humid air and cryogenic or hypergolic propellants) and operating cycles/conditions (e.g. tank pressure cycles, valve actuation cycles, pressurant regulator slam-start cycles, propellant manifold priming cycles, propellant drain/decontamination cycles, etc.) that are associated with in-flight usage, including landing environment, and the ground environment exposure and turnaround testing, checkout, inspection, and maintenance tasks/activities across the designated number of missions to be certified. That broad scope is consistent with the discussion of reusable flight hardware in section 9.5.3 of SMC-S-016, Test Requirements for Launch, Upper Stage, and Space Vehicles and the definition of 'service life' in section 3.44 of that same document. This topic is also treated in the definition of 'service life' in section 3.2 of NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware. However, that level of specificity is not always present in other existing standards cited herein. As a result, this requirement is needed to provide clarity and consistency of approach across the board. Additional factors to consider that can adversely affect hardware life include cryogenic pumping and condensation/freezing of water vapor from the surrounding ambient air, torque relaxation of fasteners due to cold-flow/compression-set of soft goods and/or thermal cycles to cryogenic temperatures, general wear and tear of fasteners caused by reuse, etc. Experience has shown that these considerations, particularly those involving ground turnaround activities, have sometimes been under-represented or completely neglected during hardware qualification for multiple flights, which can lead to premature failure of the hardware and the realization of catastrophic hazards in service.

3.1.3.2 For a reusable spacecraft, the design of propulsion systems and components shall comply with the requirements of the following additional paragraphs from JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-06S]***

a) G-1, Equipment Accessibility for Maintenance

b) G-52, Reuse of Flight Equipment

Rationale: The requirements of paragraphs G-1 and G-52 are considered critical to the successful planning and execution of the typical ground turnaround testing, checkout, inspection, and maintenance tasks/activities needed to address safety-of-flight risks and ensure flight readiness for the propulsion system across multiple flights on a reusable spacecraft. Past examples of collateral damage and other unintended consequences that could have led, or did lead, to hazardous hardware failures in service include damage to flex hoses and wire bundles, scratching of sealing surfaces and cold plates, compression of MLI layers, etc. With that said, it is understood some hardware may need to be disturbed or removed altogether in the course of propulsion system maintenance activities (e.g. loosening wire bundle tie-downs to provide enough slack to support removal of a motor driven valve or pump, removing a heat shield to provide access to electrical and fluid line connections for removal an engine/thruster, etc.). Note that these paragraphs may also have applicability to single use vehicles. Also note that other paragraphs, including G-3 (Electrical and Fluid Systems Checkout Provisions), G-5 (Prevention of Debris – Electrical & Mechanical Systems), G-8 (Design for Redundancy Verification), G-10 (Time/Cycle Critical Part Control), and F-12 (Protection of Pressurized Systems from Damage Due to Pressurant Depletion – Support Equipment) are considered relevant to this requirement but they were excluded here due to being levied elsewhere in this document.

3.1.3.3 An Operations and Maintenance Requirements and Specifications Document (OMRSD), or equivalent, shall define all initial and recurring ground tests, checkouts, inspections, and maintenance tasks/activities, each with qualified pass/fail criteria, to be performed on the propulsion system prior to the first flight, post flight, and prior to the next flight if reusable. ***[PSR-07G]***

Rationale: The ability to perform initial and recurring tests, checkouts, inspections, and maintenance tasks/activities, each with qualified pass/fail criteria, is considered critical to controlling hazards and ensuring flight readiness of a spacecraft propulsion system on a single-use vehicle or across multiple missions on a reusable vehicle. The content of the OMRSD is limited to ground operations only and typically includes a list of all necessary tasks/activities along with their associated pass/fail criteria, time intervals, hardware items involved, constraints/limitations for the task, failure modes being addressed, and flight effectivities for multiple missions on a given vehicle. Exercising of redundant functions to ensure continued operability over time and tracking of limited-life hardware items to ensure no exceedances occur are also within scope of the OMRSD.

3.1.4 Redundancy and Fault Tolerance

3.1.4.1 The propulsion system in a human rated spacecraft shall provide the level of failure tolerance for each and all catastrophic hazards as determined from an integrated design and safety analysis, which results in no less than single failure tolerance (1FT) for each catastrophic hazard in accordance with section 4.3 of NASA-STD-8719.29, NASA Technical Requirements for Human Rating. ***[PSR-08S]***

Rationale: The project/program will specify the level of failure tolerance and implementation approach (similar or dissimilar redundancy, backup systems), for each and all catastrophic hazards, from an integrated design and safety analysis. Single failure tolerance (1FT) is the minimum level required for a human rated spacecraft per NASA-STD-8719.29, though that may not be adequate in all instances to control catastrophic hazards. As such, the level of failure tolerance needed is to be commensurate with the severity of the hazard and the likelihood of occurrence. In some cases, specific catastrophic hazards or failure modes must be controlled by detection (e.g. engine burn-through, overheating) before they become catastrophic, thus allowing switching to redundant system. Those situations warrant additional review to ensure the instrumentation, avionics, and software are adequate. Individual programs may require additional fault tolerance requirements that take precedence. Note that JSC-65828 paragraph 3.2.8 requires pressure regulators, relief devices, and thermal control systems (e.g. heaters) be collectively two-fault tolerant (2FT) from causing the pressure to exceed the Maximum Design Pressure (MDP) of the system. Also note that the only failures considered non-credible from a propulsion system perspective include a Micrometeoroid and Orbital Debris (MMOD) strike given the MMOD shielding provided by the vehicle, and a structural failure of pressurized tanks, lines, and component housings that meet the defined criteria for a failure tolerance exception.

3.1.4.2 All scenarios involving a second failure in the spacecraft propulsion system that would result in a catastrophic hazard shall be identified to support a project/program decision on declaring Loss of Mission (LOM) following the first failure or levying a 2FT requirement. ***[PSR-09G]***

Rationale: The fault tolerance requirements for a given project/program, along with any supporting flight rules that govern contingency plans/actions in response to a failure, are important to establish early in the spacecraft design process. This will drive the need for a 1FT or 2FT propulsion system design configuration and inform the flight ops actions to be taken under different failure scenarios. Traditionally, flight rules for a crewed mission are written to declare Loss of Mission (LOM) following a single failure that results in 0FT condition. The goal of LOM is to get the crew to a 'safe haven' destination or back to earth as soon as possible to reduce the likelihood of a second failure resulting in catastrophic loss of crew. A 2FT design configuration for the propulsion system would avoid a LOM scenario following a single failure, but with an impact to vehicle development and operations from a technical, cost, and schedule perspective. This requirement is intended to ensure that a methodical process is used to identify all scenarios where a second failure in the propulsion system would result in a catastrophic hazard, thus driving a project/program assessment of the need to declare LOM following the first failure.

3.1.4.3 The spacecraft propulsion system shall comply with the 'design for redundancy verification' requirements of paragraph G-8 in JSC-08080-2, JSC Design and Procedural Requirements. ***[PSR-10S]***

Rationale: The requirements of paragraph G-8 (Design for Redundancy Verification) are critical to ensure that key design features are included in the propulsion system which enable all redundant functions and operational modes of the hardware to be verified during ground testing and/or while in-flight during a mission. These capabilities are considered a critical aspect of hazard control.

3.1.5 Failure Tolerance Exceptions in Propulsion Systems

3.1.5.1 For a human rated spacecraft propulsion system, the use of a Failure Tolerance Exception (also called Design for Minimum Risk (DFMR)), in lieu of fault tolerance, to control catastrophic hazards involving pressure-related structural failure of propulsion system hardware items shall meet all the requirements of this standard and comply with paragraphs 4.3.1.1 and 4.3.1.2 of NASA-STD-8719.29, NASA Technical Requirements for Space Systems, with the following clarifications: ***[PSR-011SC]***

a) The term 'structural failure' encompasses rupture, collapse, excessive deformation, and fracture of an affected hardware item.

b) The term 'primary structure' encompasses primary structural members that directly interface with propulsion system hardware and support propulsion system induced loads.

c) The term 'pressurized lines' encompasses rigid metallic tubing and ducts, in addition to component bodies/housings (e.g. valves, regulators, orifices, venturis, flow meters, pumps/compressors, pressure transducers (excluding diaphragms), heat exchangers, etc.), mechanical fitting bodies (e.g. threaded, swaged, cryo-fit, etc.), bolted flange joints, threaded ports, and fusion joints (e.g. weld joints, braze joints, bimetallic joints, etc.).

d) Engine/thruster injectors, combustion chambers, nozzles, nozzle extensions, and component bodies/housings are considered as valid candidates for a DFMR approach since they are rigid, pressurized structural elements with no moving parts.

e) Thin-walled flexible pressure boundary (TWFPB) hardware items (e.g. bellows, flex hoses, *diaphragms, etc.) are **not** considered as valid candidates for a DFMR approach due to an inability to apply conventional fracture control methods and a notable history of failure in service. Note that TWFPBs are governed by the requirements in JSC-67035 and herein.*

f) *Mechanical and electrical functional failure modes of the propulsion system, including those involving engines/thrusters, are **not** considered as valid candidates for a DFMR approach. Examples include, but are not limited to, the following: flow blockage due to propellant freezing, particulate contamination, valve fail-closed, etc.; over-pressurization caused by the functional failure of fluid system components (e.g. pressure regulators, flow control valves, relief valves, etc.); leakage through seals and mechanical joints (e.g. threaded fittings, threaded ports, flange joints, etc.); leakage through TWFPBs (e.g. bellows, diaphragms, flex hoses, etc. – see part (e) above); degradation or failure caused by a MMOD strike; components failing open or closed due to internal mechanical failures, accumulated cyclic wear, or system-induced pressure transients; etc.*

Rationale: This requirement originates from section 4.3.1 of NASA-STD-8719.29, NASA Technical Requirements for Human Rating. The use of a DFMR approach, in lieu of fault tolerance, to control catastrophic hazards involving pressure-related structural failure (i.e. rupture, collapse, excessive deformation, or fracture) of propulsion system hardware relies on a highly controlled and rigorous process for design, build, inspection, and test where established technical standards, increased margins, and added measures of quality assurance are used to ensure safety/reliability in situations where design redundancy is considered impractical. Examples include redundant primary structure interfacing with engines/thrusters, redundant structure in pressure vessels and pressurized lines, and redundant structure in combustion chambers and injectors, all of which can contribute to an excessive increase in vehicle mass, technical complexity, and overall mission risk. The Apollo Lunar Module (LM) Ascent Propulsion System (APS) serves as a past example of DFMR implementation. In that case, the ascent engine employed a single combustion chamber, with series-parallel valves and redundant mechanisms, in addition to extensive testing and inspections of the flight hardware, to minimize the overall risk for the mission. Levels of redundancy for particulate filtration, a test-demonstrated ability to withstand injector element plugging, and other controls were employed within the injector. It is important to note that TWFPBs (e.g. bellows, diaphragms, flex hoses, etc.) and functional failures of the propulsion system (e.g. flow blockage, leakage past seals, etc.) are not considered as valid candidates for failure tolerance exceptions. Reference Ambiguous Fault Tolerance Requirements. (LLIS 1493, 2004)

3.1.6 Separation or Protection of Redundant Functions

3.1.6.1 Human rated spacecraft propulsion systems shall comply with the 'separation of redundant systems' requirements of paragraph G-2 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-12S]***

Rationale: The requirements of paragraph G-2 (Separation of Redundant Systems), which addresses physical separation or protection of redundant functions (i.e. redundant systems, subsystems, and major elements of subsystems (e.g. assemblies, panels, power supplies, tanks, controls, etc. and any associated fluid lines or electrical wiring), is considered a critical means of ensuring overall reliability and controlling catastrophic hazards for a spacecraft. This key concept can have major implications for the design and assembly/integration of a propulsion system, and insufficiency in this regard can allow a single failure or event to compromise all redundant functions simultaneously, resulting in a variety of catastrophic consequences. Examples include pressurant and propellant tank location and configuration; pressurant and propellant line routing; thruster configuration and placement; electrical connector configuration and wire harness routing; avionics configuration for command, control, and health monitoring of powered components; etc. It is important that this requirement be accounted for in both the design and assembly/integration phases of spacecraft development. In the past, there have been instances where the design failed to meet the intent of this requirement from the start, and other instances where the as-built hardware violated the intent of this requirement due to inadequate specificity in the design (e.g. exact wire routings were delegated to the assembly technicians and redundant wire harnesses ended-up being bundled together for simplicity).

3.1.7 GN&C and Thrusters/Engine Performance and Service Life ICD

3.1.7.1 As required for attitude hold, docking, aborts, and entry, the joint Propulsion and GN&C engineering team shall define the following as a minimum: mission event durations, thruster minimum impulse bit and associated variability, range of duty cycles and minimum commanded on/off times, total impulse, cycle life requirements, thrust vs. time profile during engine/thruster startup (including overshoot, if any) and shutdown, minimum thrust requirements, and thruster locations. ***[PSR-13G]***

Rationale: Instead of minimum thrust and thruster locations, GNC may elect to define minimum and maximum moments/torques and vehicle rate increments which are considered to meet the intent of this requirement. The minimum impulse bit is a function of the engine thrust profile during a firing and the minimum commandable electrical pulse width (EPW). This parameter, sometimes approximated from hot fire test data (e.g. rise time to 90% thrust, transient overshoot, steady state thrust, decay time to 10% thrust), is important for docking and other mission phases to maximize vehicle control and minimize propellant consumption. Note that pulse mode impulse bit can/will vary based on the system configuration and number of engines fired simultaneously. Note that duty cycle is typically expressed as a percentage of thruster on-time over the total duration of the GNC-commanded pulse train, where on-time is electrical pulse width, and this can serve as a driver for certain thermally related catastrophic failure modes of the engine. Catastrophic failures driven by the accumulation of propellants or detonable fuel-oxidizer reaction products (FORP) in the engine is a consideration when operating in pulse-mode with short EPWs or at certain duty cycles, in particular with large residuals. The intent is to avoid oversizing the thrust level of RCS thrusters that would force a short EPW to meet minimum impulse bit requirements, which can result in significant accumulation of propellants within the engine. Hazards associated with the duty cycle and pulse profile duration include operation of a thruster in a known region of thermal ratcheting, which can result in a rapid incremental increase in engine component temperatures after each pulse due to heat soak back which, if it continues, could result in burn-through or valve damage if this heat soak back is not controlled. These effects can lead to multiple common cause engine/thruster failures in flight, as experienced on past projects/programs. To address these hazards, a thorough definition of engine/thruster performance requirements at the Prop-to-GNC interface, rooted in realistic vehicle controllability analysis, is needed, thus enabling proper selection, design, and qualification of the engines/thrusters and the propulsion system as a whole.

3.1.7.2 For vehicle translational maneuvers using the main engine(s) and/or a combination of Auxiliary and Reaction Control System (RCS) engines/thrusters, which include minor translational maneuvers (such as final approach to station) or larger delta-V burns (such as orbital insertions, deorbits, plane changes, etc.), the joint Propulsion and GN&C engineering team shall define the total impulse, minimum thrust level, thrust vs. time profile during engine/thruster startup (including overshoot, if any) and shutdown, gimbaling, and/or off-pulsing requirements (with tolerance, as applicable) associated with each individual maneuver. ***[PSR-14G]***

Rationale: While off-pulsing a thruster or having a multitude of high thrust RCS thrusters controlling the vehicle avoids gimbals, the engine or thruster design can be extremely sensitive to duty cycle and may not be capable of the specific set of off-pulsing commands for the duration required without catastrophic failure. Gimbal functionality, which adds to vehicle complexity in terms of actuators and controllers, can reduce the RCS thrust level and number of engines needed for the application, and simultaneously address the risk of catastrophic engine failure during pulse mode operation. Throttling main or abort engines can also reduce RCS requirements. The intent of this paragraph is to ensure the propulsion and GNC engineering teams trade the use of gimbaling or throttling vs. RCS off-pulsing for applications needing main engine, auxiliary engine, descent engine, or abort engine maneuvers.

3.1.7.3 By System Design Review (SDR), the propulsion engineering team shall identify the key driving requirements for the project/program and the engines/thrusters chosen to meet those requirements, which may include multiple options, whether new build or heritage, along with any capability, development, and/or test gaps if a heritage engine is proposed. ***[PSR-15G]***

Rationale: This requirement expects that a propulsion system SDR follows the vehicle level SDR, with the scope, entrance/exit criteria, and review products in accordance with NPR 7123.1 (NASA Systems Engineering Processes and Requirements) and the companion NASA SP-2016-6105 (NASA Systems Engineering Handbook). Many lessons have been learned about attitude control or reaction control thrusters that: 1) are too large for effective vehicle control and therefore require very short pulses which can introduce serious combustion issues, or 2) require operation outside of their qualified design and experience base which drive the need for delta qualification testing and can introduce significant technical and programmatic complexities. Given these recurring issues, early definition of the key driving requirements and engine/thruster selections are expected by the SDR major milestone for all human rated spacecraft projects/programs.

3.1.8 Plume Impingement Loads, Dynamics, Heating, and Contamination

3.1.8.1 In accordance with the requirements of JSC-65829, including the content in Appendix B, the locations, orientations, and nozzle scarf configurations of all propulsion system engines/thrusters, along with any plume impingement effects from firing those engines/thrusters, shall be assessed for thrust vector changes (performance impact to propulsion) and heating of the vehicle, including the propulsion system itself, caused by recirculation of plume flow, across the entire concept of operations for the vehicle configurations and missions being considered using validated analytical models. ***[PSR-16SC]***

Rationale: Multiple paragraphs and requirements in JSC-65829, Loads and Structural Dynamics Requirements for Spaceflight Hardware, explicitly cite the need to assess and quantify the plume impingement effects from firing engines/thrusters on a spacecraft propulsion system. The scope of this assessment includes thrust vector changes that may be introduced from plume impingement on adjacent hardware, in addition to ignition overpressure; thrust build-up, steady burn, and tail-off; thruster plume flow field pressure and heating; and contamination, acoustics, random vibration, sine vibration, shock, thermal, and pressure. All of these are relevant induced environments associated with the firing of engines/thrusters on a spacecraft. Reference Performance Decrease due to Propulsion Thruster Plume Impingement on the Voyager Spacecraft (LLIS-377, 1995); LLIS-424, Performance Decrease due to Propulsion Thruster Plume Impingement on the Voyager Spacecraft (LLIS-424, 1977), and Mariner Spacecraft Structure Dynamical Interaction with Attitude Control (LLIS-400, 1995).

3.1.8.2 The spacecraft propulsion system shall be designed, analyzed using plume contamination models anchored with test data, and operated to ensure that project/program-defined limits for the deposition of residue and/or contamination on sensitive surfaces from propellant leakage/release and engine/thruster combustion plumes are respected. ***[PSR-17G]***

Rationale: Exposure of sensitive spacecraft surfaces to the residue and contamination from propellant leakage/release and engine/thruster plumes, with field of view effects considered, can present a toxicity hazard for ground or flight crews (EVA) and induce malfunctions/failures for critical hardware items such as solar arrays, antennas, windows, star trackers, etc. The specifications, designs, and flight operations of the propulsion system must consider those relevant factors when selecting the propellants; engine/thruster types, thrust levels, and mounting configurations; propellant vent locations and features; and engine/thruster minimum pulse widths, duty cycles, and other operating parameters. All those items can influence the generation of potentially harmful residue and contamination interacting with sensitive spacecraft surfaces. The analysis of plume impingement may require additional tool development and test data to properly predict effects on nearby sensitive equipment (e.g. solar arrays, star trackers, windows, etc.), especially for new propellants and engines.

3.1.8.3 The spacecraft propulsion system shall be analyzed, designed, tested, and operated to ensure that project/program-defined limits for thermal heating of sensitive surfaces from engine/thruster combustion plumes are met. ***[PSR-18G]***

Rationale: Exposure of sensitive spacecraft surfaces and equipment to engine/thruster plumes can induce hazards associated with malfunctions/failures of critical hardware items such as solar arrays, antennas, windows, star trackers, etc. The specifications, designs, and flight operations of the propulsion system must consider those relevant factors when selecting the propellants; engine/thruster types, thrust levels, and mounting configurations; propellant vent locations and features; and engine/thruster minimum pulse widths, duty cycles, and other operating parameters. All those items can influence the generation of potentially harmful structural and thermal loads driven by engine/thruster firings. Typical mitigations for plume impingement include optimal engine/thruster mounting locations, orientations, and firing constraints; engine/thruster nozzle exit plane scarfing; reorienting of movable appendages (e.g. solar arrays, antennas, etc.) for planned vehicle maneuvers; shielding of sensitive hardware to prevent direct exposure to thruster plumes, etc.

3.1.8.4 The engine/thruster combustion plumes shall be evaluated for ingestion into the crew cabin and other sensitive areas on the spacecraft, such as parachute cavities, etc. ***[PSR-19G]***

Rationale: Pulse mode operation of engines/thrusters could result in unburned propellant in frozen, liquid, and/or vapor forms being expelled. During Apollo-Soyuz capsule return, cabin pressure relief valves ingested N_2O_4 venting out of the thrusters due to manually closed propellant isolation valves and GNC continuing to command thruster firings, which were caused by out of sequence steps during reentry. One crew member became unconscious due to high concentration of N_2O_4 in the cabin. (ref), (Nufer, 2010, pp. 8-10)

3.1.9 Propellant Slosh Coupling with GN&C & Structure

3.1.9.1 In accordance with the requirements of JSC-65829, section 6.6, LDR-043 and LDR-044, the need for slosh suppression features in the liquid propellant tanks shall be established based on dynamic analysis that evaluates the impact on overall vehicle loads, propellant tank local loads, control system effectiveness, and overall vehicle stability, with the additional impacts to propellant acquisition and propellant gauging also considered. ***[PSR-20SC]***

3.1.9.2 Based on a vehicle controllability analysis, the required slosh characteristic, such as *maximum level of angular momentum transfer and/or minimum level of slosh damping, in the liquid propellant tanks as a function of fill level shall be defined to ensure that propulsive attitude control and translation maneuvers can be executed successfully throughout the mission.* ***[PSR-21G]***

3.1.9.3 *The models used for vehicle control analysis with respect to the required propellant slosh characteristics shall include validation testing with test data for a similar (actual propellant tank) system.* ***[PSR-22G]***

Rationale (for 3.1.9.1 – 3.1.9.3): The hazards due to excessive slosh are loss of control, excessive RCS propellant consumption, inaccurate propellant gauging, and ullage gas ingestion causing engine failure. Slosh must be evaluated for single and multiple spacecraft elements that docked together for situations such as refueling or reboost. Note there have been numerous instances of loss of propellant acquisition or loss of vehicle control caused by liquid slosh in the past, including Apollo 11 where the LEM descent stage slosh caused fuel gauge issues (ref), Slosh Anomaly in Apollo Lunar Module Propellant Gage (Scholl, 1971), Apollo 11 SM slosh caused it to retrograde back into view of the CM upon separation (ref), Apollo 11 Mission Anomaly Report No. 3 Service Module Entry (McDivitt, 1970), and the Pixel lander four propellant tank coupled swirl mode necessitating vertical baffles (ref). Slosh Baffle Design and Test for Spherical Liquid Oxygen and Liquid Methane Propellant Tank for a Lander (Strahan, 2011). Similar issues can be avoided in the future by incorporating the appropriate type and level of slosh suppression in the liquid propellant tanks at the outset of a project/program. The typical approach is currently to initially size using >2.5% over the entire range of liquid fill levels for the propellant tanks. Note that analysis-based slosh suppression design should be anchored to applicable existing test data to ensure accuracy. A new update to NASA SP-106 content is 'The New "Dynamic Behavior of Liquids in Moving Containers", (Dodge, 2000) has been published by Southwest Research Institute (SWRI).

3.1.10 Differential Draining Impact on Vehicle Center of Gravity

3.1.10.1 *The shift in spacecraft center of gravity caused by differential draining of liquid from multiple propellant tanks in the propulsion system, whether those tanks are plumbed in a series or parallel configuration, shall be quantified by analysis for nominal and off-nominal operating conditions and then evaluated by test to ensure that the required vehicle attitude control and translational propulsive capability can be maintained throughout the mission.* ***[PSR-23G]***

Rationale: Differential draining of liquid from multiple propellant tanks in a spacecraft propulsion system could potentially induce a large shift in spacecraft center of gravity resulting in a loss of vehicle attitude control and translational maneuvering capability needed to complete the mission successfully. This can be a factor in bipropellant systems or monopropellant systems, regardless of the specific propellants involved and whether the tanks are plumbed in series or parallel. Many factors can affect this phenomenon, such as differences in pressure drop tied to variations in tank expulsion performance, propellant line routings, valve flow characteristics, thruster hot-fire performance, accumulation of particulate contamination in system filters, unexpected internal or external leakage of propellant, etc. The Apollo LM design provides a successful approach for parallel propellant tanks. The Apollo SM and Orion SM provide case studies for series propellant tanks. All those factors should be considered when quantifying and evaluating this differential draining phenomenon. Reference Migration and Differential Draw Between Multiple Propellant Tanks (LLIS-558, 1997).

3.1.11 Loads and Structural Dynamics Requirements

3.1.11.1 Spacecraft propulsion systems and components shall comply with JSC 65829, Loads and Structural Dynamics Requirements for Spaceflight Hardware. ***[PSR-24S]***

Rationale: The standard cited here provides a complete and comprehensive set of requirements governing the development of structural design loads for a given spacecraft; the approaches and criteria to be used for structural dynamic analyses; the interaction of vehicle structural dynamics with key environments and the operation of vehicle subsystems including propulsion; the verification approach for mathematical models used for loads development; and the transfer of structural design models, forcing functions, and analytical results among stakeholders. These requirements represent the minimum set of conditions necessary to ensure proper identification of bounding loads and loading conditions and, in turn, contribute to a structural design solution which is adequate to maintain structural integrity and the required degree of functionality during all phases of the expected life cycle. In other words, the requirements are focused on the analyses needed to accomplish structural verification of the integrated spacecraft for the design life of the hardware.

3.1.11.2 Transient thrust overshoot during start-up of an engine/thruster shall be quantified during ground hot fire qualification testing, inclusive of all worst-case faults as defined by programs fault tolerance requirements and other driving conditions (e.g. temperature, pressure, gas saturation, valve voltage, etc.) that can increase the magnitude and duration of the overshoot, with the associated peak chamber pressure enveloped by the Maximum Design Pressure (MDP) value of the engine/thruster combustion chamber. ***[PSR-25G]***

Rationale: The transient overshoot in combustion chamber pressure and thrust during thruster/engine start-up can impart significant transient loads to the thruster/engine itself, other parts of the propulsion system, and the interfacing primary/secondary support structure. These loads must be well understood and quantified for inclusion in a comprehensive structural dynamic analysis of the vehicle. Note that the thrust overshoot can also impact vehicle controllability during certain phases of flight where fine maneuvers are necessary, such as rendezvous, proximity operations, and docking (RPOD) and entry, descent, and landing (EDL). As a result, the thrust overshoot phenomenon must be well characterized during ground hot fire testing of the engine/thruster, inclusive of all worst-case single failure(s) and other conditions that can increase the magnitude and duration of the overshoot, with the associated peak transient chamber pressure enveloped by the MDP of the engine/thruster combustion chamber (per JSC 65828, paragraph 3.2.8.2 and requirements herein). Failures and other conditions to be considered include, but are not limited to, those that influence the pressure, temperature, saturation level, and/or entrained gas fraction of the propellant at the engine/thruster inlet; voltage/current supply to the engine/thruster propellant valves; and other analogous items.

3.1.11.3 The vehicle structural loads and deflections imparted upon propulsion system tubing and interfacing support structure, including loads created by internal pressure transients, shall be quantified and included in the structural dynamic analysis of the hardware. ***[PSR-26G]***

Rationale: The associated reaction loads and deflections imparted on the propulsion system tubing and interfacing support structure as well as forces produced by internal transient pressures must be included in the structural dynamic analysis of the integrated vehicle to avoid unexpected catastrophic failures of the hardware, which have occurred on past projects/programs.

3.1.12 Unstable Dynamic Coupling of Engine/Thruster, Feed System, and Vehicle Structure

3.1.12.1 In accordance with the requirements of JSC-65829, section 6.5, LDR-041 and LDR-042, and section 4.1.3, LDR-024, unstable coupling of vehicle structure with the nominal and off-nominal steady state and pulse-mode operation of the engines/thrusters in the propulsion system shall be avoided for all concepts of operation and mission configurations of the spacecraft. ***[PSR-27SC]***

Rationale: This requirement applies to the various stages of a launch vehicle, to a high-thrust liquid abort engine/thruster, and to the spacecraft itself, including pump and pressure-fed engines/thrusters, and the unstable dynamic coupling phenomenon could lead to premature structural failure and loss of crew and vehicle. The cited sections in JSC-65829, Loads and Structural Dynamics Requirements for Spaceflight Hardware, address the topic of pogo design and analysis requirements. The term ‘pogo’ refers to an undesirable, oscillatory fluid-structural instability that can cause catastrophic loss of crew and vehicle from dynamic coupling of the vehicle structure with nominal and off-nominal steady state and pulse-mode operation of the engines/thrusters in a propulsion system. A reference on this topic is NASA Special Publication SP-8055, Prevention of Coupled Structure-Propulsion Instability (POGO). Reference Saturn SII Liquid Propulsion Systems; POGO, Instrumentation (LLIS-334, 1993); Mariner Spacecraft Structure Dynamical Interaction with Attitude Control (LLIS-400, 1995); and Space Shuttle Pogo Lessons Learned. (LLIS-6356, 2010)

3.1.12.2 To ensure no detrimental fluid-structural instability or engine/structure dynamic coupling in propulsion systems containing pump-fed engines/thrusters, the assessment methodology described in sections 6.4.4 and 7.3.7 of SMC-S-025, Evaluation and Test Requirements for Liquid Rocket Engines, shall be implemented. ***[PSR-28S]***.

Rationale: Multiple instances of engine/structural dynamic coupling in propulsion systems containing pump-fed engines/thrusters have been discovered on past programs, which resulted in a catastrophic failure. As a result, this phenomenon must be addressed to ensure there are no adverse effects. An assessment methodology already exists to evaluate this condition for propulsion systems containing pump-fed engines, consisting of analytical modeling supplemented by performance testing of flight-like pumps at component level plus hot-fire testing of flight-like engines/thrusters and feed lines at system level. (ref) (Coppolino, 1978)

3.1.12.3 To ensure no detrimental fluid-structural instability or engine/structure dynamic coupling in propulsion systems containing pressure-fed engines/thrusters, structural and propulsion system level testing and analysis shall be performed to characterize the structure, propulsion feed system, and engine compliance as described in sections 6.4.4 and 7.3.7 (with exception of a pump) of SMC-S-025, Evaluation and Test Requirements for Liquid Rocket Engines. ***[PSR-29S]***

Rationale: Multiple instances of engine/structural dynamic coupling in propulsion systems containing pressure-fed engines/thrusters have been discovered on past programs, which could have resulted in a catastrophic failure. Examples include the Delta II pressure-fed upper stage (ref) (Markowitz, 1977) and the Diamant-B stage (ref) NASA SP-8055. As a result, this phenomenon must be addressed to ensure there are no adverse effects. These structural-fluid-engine coupling can include chug instabilities.

3.1.13 Thermal Control of the Propulsion System

3.1.13.1 Thermal models for a human rated spacecraft propulsion system, anchored to thermal balance test data in accordance with paragraphs 8.2.6 and/or 8.3.7 in SMC-S-016, Test Requirements for Launch, Upper-Stage, and Space Vehicles, shall be developed to predict the minimum and maximum operating and survival (i.e. non-operating) temperatures for the hardware in the propulsion system and demonstrate that established temperature limits for that hardware are not violated on a given vehicle and mission, over the full range of ground and flight operating conditions. ***[PSR-30SC]***

Rationale: It is critically important to ensure that thermal models of the propulsion system, anchored to relevant thermal balance test data, be created and used to predict the upper and lower temperature values for operation and survival (i.e. non-operation) of the hardware for a given vehicle and mission, which includes environments seen during ground operations and transport. This information will enable an effective thermal control approach to be developed that will prevent temperature excursions caused by the driving thermal environments and/or hardware usage specifics for a given mission from exceeding the hardware's established design capability and acceptance test bounds, which could lead to anomalous operation and premature failure resulting in a hazard.

3.1.13.2 Thermal models for a spacecraft propulsion system shall meet the analytical modeling *and simulation requirements of NASA-STD-7009, Standard for Models and Simulations, anchored to test data, and be maintained in the critical math model database throughout the life of the project/program.* ***[PSR-31S]***

Rationale: Thermal analysis and modeling of the hardware and fluid commodities associated with a spacecraft propulsion system is a critical aspect of verifying design adequacy and controlling hazards. The content of the cited NASA standard provides uniform and rigorous engineering and technical requirements for processes, procedures, practices, and methods applied to critical math models and simulations developed for NASA projects/programs. Note that this requirement is an extension of paragraphs 3.1.2.1 [PSR-03S] and 3.1.2.2 [PSR-04G] relative to thermal models, with additional thermal-centric details captured in the rationale. (ref). Magellan (MGN) High Rocket Engine Module (REM) Temperatures (LLIS-349, 1994)

3.1.13.3 Thermal uncertainty margins shall be applied to the analysis of passive and active thermal control of spacecraft propulsion systems per sections 3.62 and 4.4.2 of SMC-S-016, Test Requirements for Launch, Upper-Stage, and Space Vehicles. ***[PSR-32S]***

Rationale: The cited sections of this SMC-S-016 document provide a rigorous and standardized approach for the use of thermal uncertainty margins in the analysis of passive and active thermal control systems on spacecraft. Those sections also describe the purpose and define the magnitude of the necessary thermal uncertainty margins applied to the spacecraft, including the integrated propulsion system. Note that higher uncertainty margins are specified for situations involving passive thermal control approaches which have not been anchored to thermal balance testing of the integrated propulsion system.

3.1.13.4 All hardware and fluids in a spacecraft propulsion system shall be thermally controlled to remain within the acceptance upper and lower operating and survival (i.e. non-operating) temperature limits for the design while in service. ***[PSR-33G]***

Rationale: Inadequate thermal control of a spacecraft propulsion system can allow hardware or fluid temperatures to exceed acceptance limits, thus resulting in anomalous performance, premature failure, and catastrophic hazards, such as valve leakage or engine/thruster combustion pressure spikes and instability. The operating and survival temperature limits of the design for all of the propulsion system hardware should be clearly documented in the specifications, qualification test reports, and hardware certification packages.

3.1.13.5 All hardware in a spacecraft propulsion system, including the associated active and passive thermal control equipment, shall undergo thermal testing at unit level per Tables 6.3-1 and 6.3-2 and sections 6.3.8 and 6.3.9; subsystem level per Tables 7.3-1 and 7.3-2 and section 7.3.7; vehicle level per Tables 8.3-1 and 8.3-2 and sections 8.3.7 and 8.3.8; and per Appendix A of SMC-S-016, Test Requirements for Launch, Upper-Stage, and Space Vehicle. ***[PSR-34SC]***

Rationale: The cited sections of this SMC-S-016 document provide a rigorous and standardized approach for the content and execution (including necessary temperature margins) of unit, subsystem, and vehicle level thermal qualification and acceptance testing for a spacecraft propulsion system and its associated active and passive thermal control system elements.. Ideally, the propulsion system hardware and its interfacing thermal control elements should be integrated together for such testing (e.g. heaters installed on a propellant tank, MLI blanket installed on a pressurization system valve panel, low emissivity coating applied to a thruster nozzle, etc.), though it may be considered acceptable to execute the tests separately based on close coordination with the NASA Propulsion and Thermal Control teams. Following this approach serves as a key control for the potentially catastrophic hazards associated with thermal excursions beyond the certification and safety limits for the propulsion system hardware and fluids.

3.1.13.6 All hardware in the liquid propellant section of a spacecraft propulsion system shall be thermally controlled and operated to maintain a margin of least 3 °C (5 °F) above the propellant freezing point at all times when in contact with propellant, which is in addition to the thermal uncertainty margin for passive thermal control or the power margin for active thermal control imposed by section 4.4.2 of SMC-S-016, Test Requirements for Launch, Upper-Stage, and Space Vehicles. ***[PSR-35SC]***

Rationale: This is a missing requirement to protect against the liquid propellant freeze/thaw phenomenon. The intent is to ensure that the freezing point of the chosen propellant, which is a known physical property value, is not on the edge of the thermal uncertainty margin. Inadequate thermal control of the liquid propellant section of a spacecraft propulsion system can result in freezing of the propellant in flight, thus producing a detrimental flow restriction/blockage upstream of the engines/thrusters and setting the stage for excessively high pressures within the system during the subsequent thaw cycle, resulting in possible hardware functional failure or rupture. The risk associated with this phenomenon is particularly acute with hydrazine, which has a relatively high freezing point, contracts when freezing, and expands upon thawing. Note that the value specified in this paragraph is intended to be applied on top of the thermal uncertainty margin discussed in SMC-S-016 to address shortcomings/uncertainties in the thermal analysis. Note that SMC-S-016 Section 4.4.2 requires a higher thermal uncertainty margin for any unit or subsystem that is not thermal balance tested. That uncertainty value can be reduced to 11°C/18 °F, or possibly lower through model correlation with thermal-vacuum test data or eliminated altogether through the use of active thermal control for the hardware.

3.1.13.7 All hardware in the liquid propellant section of a spacecraft propulsion system shall be thermally controlled and operated such that the Maximum Predicted Temperature (MPT), as defined in section 3.23 of SMC-S-016, Test Requirements for Launch, Upper-Stage, and Space Vehicles, remains at least 28 °C (50 °F) below the demonstrated safe temperature *limit of the propellant(s) being used.* ***[PSR-36G]***

Rationale: Certain liquid propellants, such as hydrazine and hydrogen peroxide, are particularly sensitive to decomposition and have a relatively low auto-decomposition threshold temperature, which can be further reduced by the materials of construction and/or particulate contamination in the system that are wetted by the propellant. Unexpected decomposition can lead to an immediate catastrophic event, such as the destructive failure of a hydrazine auxiliary power unit (APU) during a ‘hot restart’ attempt during ground testing. Thermal soak back caused slow hydrazine decomposition in the fuel pump and gas generator valve module (GGVM) areas. The resulting gas bubble was adiabatically compressed during subsequent pulse operation of the APU, resulting in a temperature transient that caused detonation. As an outcome of that failure investigation, a maximum allowable operating temperature of 200 °F was required (ref) (Hernandez, 2011, p. 4) A water cooling system was added to fuel pump and GGVM to meet these targets. In a later failure on STS-9, a hydrazine leak and fire, combined with normal heat soak-back, caused the modulation valve and associated tubing to overheat to approximately 500 °F. The trapped hydrazine explosively decomposed, and the APU-1 modulation valve was damaged. (Nufer, 2010, pp. 25-28). The intent of this requirement is to ensure that the decomposition temperature for the propellant(s) in an as-built propulsion system is well understood and not on the edge of the thermal uncertainty margin, with additional margin against exceeding the temperature limit being maintained.

3.1.13.8 All propellant entering the engines/thrusters in a spacecraft propulsion system shall be thermally or operationally controlled to remain within the qualified start box temperature range (at startup) and run box temperature range (during firing) for the selected engines/thrusters with a minimum uncertainty of 11 °C (20 °F) for passively controlled systems or a power margin of 25% for actively controlled systems, consistent with section 4.4.2 of SMC-S-016, Test Requirements for Launch, Upper-Stage, and Space Vehicles. ***[PSR-37G]***

Rationale: Missing requirement for propellant temperatures at the engine/thruster inlet. In general, SMC-S-016 has typically been applied to the propulsion system hardware but not extended to the propellants themselves. The intent here is to ensure that the standard uncertainty of 11 °C (20 °F) for passively controlled systems or a power margin of 25% for actively controlled systems is applied to the propellants delivered to the engine/thruster interface. Inadequate thermal control of the liquid propellant entering the engines/thrusters can violate the qualified start box and run box temperature ranges for the hardware, thus resulting in engine/thruster performance anomalies and possible catastrophic failures. The qualified start and run box temperature ranges should be clearly established and documented in the engine/thruster specifications, qualification test reports, and hardware certification packages.

3.1.13.9 All hardware in the inert gas pressurization section of a spacecraft propulsion system shall be thermally controlled to maintain a minimum margin of 11 °C (20 °F) above the *condensation temperature (i.e. dew point) of any migrated propellant vapor while in quiescent flight, with the assumption that any temporary cold temperature excursions associated with a burn of the engines/thrusters are not conducive to condensation due to positive flow in the lines as well as subsequent pressurant gas thermal recovery as the thermal control system returns line temperatures to the target set point.* ***[PSR-38G]***

Rationale: Inadequate thermal control of the inert gas pressurization section of a spacecraft propulsion system can result in condensed liquid forming within the pressurant lines. Such condensation can adversely affect the performance of pressurant components (e.g. valves, regulators, etc.) that are not designed to have liquid within their internal parts. It may also coalesce into larger slugs of liquid which can produce excessive pressure transients pressurant flow leading to hardware functional failure or rupture. The presence of condensed propellant, either as a thin film on tube walls or as droplets entrained with the pressurant gas, also increases the risk of particle impact ignition events in propulsion systems with hardware featuring Titanium as a material of construction. It is understood that the pressurant gas temperature may drop below the dew point temporarily during or after a major burn of the engines/thrusters. Note that the value specified in this requirement is intended to be applied on top of the thermal uncertainty margin imposed by SMC-S-016 to address uncertainties in the thermal analysis. Also note that this paragraph does not apply to propulsion systems with propellant tanks featuring a metal diaphragm or bellows that provides a hermetic barrier that is impermeable to propellant vapor. It also doesn't apply to propulsion systems that feature autogenous pressurization (i.e. self-pressurization) using high vapor pressure propellants such as nitrous oxide. For monopropellants, there is a need to assess the risk with respect to heating of the pressurization lines and the specific monopropellant ignition hazard versus the risk of liquid propellant migration.

3.1.13.10 The active thermal control (e.g. cryocooler) or pressure control system shall prevent rupture of the propulsion system in the event of a degradation or failure of the passive thermal control system (e.g. loss of MLI, low-emissivity tape, foam insulation, vacuum annulus, etc.). ***[PSR-39G]***

Rationale: Passive thermal insulation systems have credible failure modes that are not considered as DFMR candidates. As a result, active thermal or pressure control systems need to protect against passive thermal control system failures. These active systems may be a thermodynamic vent, heaters, cryocoolers, etc. Potentially hazardous consequences include freezing/thawing of propellants; excessive leakage of components; reduced structural margins and cycle life of components; degraded performance and life of engines/thrusters; production and accumulation of explosive fuel oxidizer reaction products (FORP) in engines/thrusters; excess propellant vapor pressure effects; propellant vapor condensation in the pressurant system; etc.

3.1.13.11 Critical thermal model parameters used for design, such as effective emittance ε, conductance, and contact resistance, shall be based on values measured in a representative test.* ***[PSR-40G]***

Rationale: Thermal insulation systems can have a wide variability due to the installation and properties. This is for both cryogenic and storable liquid propulsion system for both heat leak in and out of the system.

3.1.13.12 Active cooling systems used with cryogenic liquid propellants shall have a heat load margin of 100% at initial design phase and 25% at final design, as measured in a high fidelity vehicle level ground test in a vacuum chamber with worst-case natural thermal environment or in a flight test involving an actual space environment, for a single string cryocooler operating as part of a fault tolerant active thermal control system. ***[PSR-41SC]***

Rationale: This is an augmentation of SMC-S-016, paragraph 4.4.2.2.1 that deals with thermal control design margins for cryogenic hardware used in spacecraft propulsion systems. In these instances, a catastrophic hazard could result from the loss of thermal control of the cryogenic liquid propellant, leading to rapid volumetric expansion via boil-off and subsequent overpressurization/rupture of the propulsion system hardware. This requirement is intended to establish a minimum design margin for fault-tolerant active thermal control systems that maintain cryogenic conditions of the propellants. Note that thermal conditioning of non-cryogenic liquid propellants, such as hydrogen peroxide which may benefit from active sub-cooling but does not require it for the purpose of hazard control, would be exempt from this requirement.

3.1.14 Propulsion System Vents and Unintended Leaks - External and Internal

3.1.14.1 Venting of fluid commodities from a spacecraft propulsion system into a surrounding secondary compartment shall meet the requirement of paragraph F-1 in JSC 08080-2, JSC Design and Procedural Standards, with the added provision that any flow restriction incorporated into the propulsion system to avoid exceeding the vent capacity of the secondary compartment does not result in over-pressurization/rupture of the propulsion system itself. ***[PSR-42S]***

Rationale: The intent of paragraph F-1 (Restriction Requirements – Pressurized Components) is to ensure that venting of gaseous fluid commodities from a spacecraft propulsion system into a secondary compartment (e.g. pressure regulator failure results in the release of pressurant gas through a relief valve on the propellant tank into a surrounding equipment bay, etc.) produces a peak mass flow rate that is enveloped by the venting capacity of the secondary compartment. The added provision is intended to ensure that any flow restriction incorporated into the propulsion system to respect the venting capacity of the secondary compartment does not result in hazardous over-pressurization/rupture of the propulsion system itself, thus trading one catastrophic hazard for another.

3.1.14.2 Intermittent, unplanned venting of fluids (liquid and/or gas) from a spacecraft propulsion system while in flight, such as through pressure relief devices or cryogenic pressure control systems, shall be non-propulsive or zero net torque, unless intended for the settling of propellants or purging/inerting/safing of the propulsion system, per paragraph F-9, Spacecraft Venting-Induced Perturbing Forces, in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-43G]***

Rationale: The intermittent, unplanned venting of fluids from a spacecraft propulsion system can create a thrust reaction leading to loss of vehicle control if not purposefully addressed with non-propulsive vent features in the vent line design. Note that the release of liquid propellants entrained with pressurant gas and propellant vapor could occur under these circumstances, which may lead to the realization of other hazards that need to be considered in the scope of risk assessment. Also note there is no intent to preclude planned venting for the purpose of propellant settling or purging/inerting/safing of the propulsion system. Reference LLIS-640, Inadequate Venting Analysis for the Wide Field Infrared Explorer (WIRE) Spacecraft (1999).

3.1.14.3 Propellant from vents, ullage pressurant gas vents, or leak sites that can be ingested by or come into contact with the spacecraft or launch vehicle shall be evaluated for hazards during ground and flight such as compatibility with materials in that area. ***[PSR-44G]***

Rationale: In the Shuttle program, hydrazine was vented through the OV-101 APU Cavity Seal drain and was ingested into the Orbiter aft fuselage where it damaged Kapton wire insulation, that is not compatible with hydrazine vapors (Nufer, 2010, p. 11). The gold foil of a multi-layer insulation (MLI) blanket caused ignition of the MMH fuel resulting in a fire in the Shuttle OMS pod during servicing. (Nufer, 2010, p. 18) An N2O4 spill caused damage to the tiles and later realized damage to electrical connectors. (ref). (Nufer, 2010, p. 18). During entry of Apollo 15 capsule, parachute failure was most likely attributed to the Command Module RCS propellant depletion firing and fuel expulsion that was in progress at the time of the failure, indicating the possibility of damage from propellants. Analysis and testing produced a flame front that existed up to 8 feet from the engine exit and unburned fuel was sprayed up to 10 feet from the engine and then ignited by burning droplets. (ref) (Donald D. Arabian, 1973, pp. 7-8)

3.1.14.4 The overboard venting of propulsion system fluids shall be evaluated by analysis, anchored to test data, for freezing of the vented commodity that may block the fluid lines or external vent path, and for other hazards. ***[PSR-45G]***

Rationale: Many fluids will freeze upon venting to vacuum with the potential to plug the vent path.

3.1.15 Anomaly, Issues, Problem Tracking and Resolution

3.1.15.1 All anomalies, issues, and/or problems related to performance or function, as defined in the specification, of propulsion system hardware during previous heritage use and present development, acceptance, qualification, ground operations, and flight operation shall be provided to NASA to determine if NASA needs to sign off on the disposition per the 'resolution of equipment failures/anomalies' requirement of paragraph G-15 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-46SC]***

Rationale: Paragraph G-15 (Resolution of Flight Equipment Failures/Anomalies Prior to Launch) is intended to ensure NASA awareness of all relevant anomalies, issues, or problems associated with the performance or function of heritage propulsion system hardware that is similar to a proposed use on an existing or future spacecraft. This level of understanding and insight is considered critical to the evaluation and control of hazards associated with the propulsion system, particularly when heritage data is being leveraged in lieu of partial or full qualification. Early prototype units would be exempt from this requirement, but flight-representative engineering development units (EDUs), formal qualification units, and actual flight units are considered in scope. Based on the specifics, NASA may elect not to elevate the reported issues for further NASA review.

3.2 PROPULSION SYSTEM, SUBASSEMBLY, AND COMPONENT TESTING

Due to the complexity and criticality of a human rated spacecraft propulsion system, rigorous qualification and acceptance testing of hardware at the component, subassembly, subsystem, and integrated spacecraft level is needed to demonstrate that the design is capable of meeting all applicable performance and life requirements; to screen individual units for workmanship defects that could compromise performance and/or life of the hardware while in service; and to ensure that the fully integrated propulsion system is operating as expected prior to flight. The paragraphs in this section provide requirements governing the test content for achieving those objectives. Note that qualification testing is needed for all new components/systems, and delta qualification testing may be needed for heritage components/systems used in new/different applications as discussed in requirements 3.2.1.3, Qualification by Similarity [PSR-49SC], 3.2.3.1, Development Tests for System Level Heritage Gaps [PSR-54SC], and 3.15.1.2, Operating Conditions and Heritage [PSR-281G]. Of course, it is acknowledged that certain gaps identified during the heritage hardware assessment process may not drive the need for a full system level development or qualification hot fire test campaign, in accordance with 3.2.2, Propulsion System Level Qualification Test [PSR-52G] and 3.2.3, Propulsion System Level Development Test [PSR-54SC]. As a simple example, a heritage propulsion system configuration with no change to the hardware configuration, operating conditions, or environments, but needing additional engine/thruster life to be demonstrated for a new application (e.g. more burn time, higher pulse count, longer duration single burn, etc.), could reasonably be addressed via engine/thruster level qualification hot fire testing alone.

3.2.1 General Testing Approach

3.2.1.1 The content, sequence, levels, durations, margins, tolerances, conditions, hardware configurations and fidelity, and post-test disassembly/inspection, associated with qualification and acceptance testing of components, subassemblies, and subsystems shall meet the requirements of SMC-S-016, Test Requirements for Launch, Upper Stage, and Space Vehicles. ***[PSR-47S]***

Rationale: The SMC-S-016 document provides a well-organized and comprehensive set of test requirements to ensure consistency and effectiveness in the area of development testing to generate engineering data that informs the design and reduces risk (ideally conducted to the point of failure in order to understand hardware failure modes and limitations), qualification testing to demonstrate design adequacy with margin, and acceptance testing to verify in-specification performance and screen workmanship defects for spaceflight hardware. Over time, this document has become widely accepted for use by government and private industry, with some degree of tailoring implemented on certain projects/programs. It also serves as the foundation for all propulsion-related test requirements contained in this document, with any clarifications and/or additions to the prescribed test content implemented in subsequent sections. In general, that testing can be classified as component testing (i.e. unit testing – tank, valve, regulator, feed line, etc.), subassembly testing (i.e. multi-unit-module testing – valve panel, service panel, thruster/engine, thruster/engine pod or cluster, etc. that each contain multiple components), subsystem testing (i.e. the integrated combination of all propulsion components and subassemblies), and vehicle level testing (i.e. the integrated combination of the propulsion subsystem combined with all other subsystems on the spacecraft). Note that propulsion system valves with any type of electrical/electronic features used for actuation and/or position sensing (e.g. solenoid valves, motor driven valves, etc.) are considered as both ‘pressure components’ and ‘electronic and electrical’ items, thus driving the most stressing combination of unit level qualification and acceptance tests to be performed, including T-vac, in accordance with section 6.3 of SMC-S-016. Also note that SMC-S-016 does not address hot fire testing of engines/thrusters (individually or arranged in pods/clusters) or the integrated propulsion system as a whole, so those topics are covered in other paragraphs of this document (refer to sections 3.2.2 and 3.18). Test equipment is covered in NASA-HDBK-8739.19-2 Measuring and Test Equipment Specifications. Measurement uncertainty is covered in NASA-HDBK-8739.19-3 Measurement Uncertainty Analysis Principles and Methods.

3.2.1.2 Component level qualification and acceptance vibration, shock, and thermal vacuum/thermal cycle tests shall include internal and external leakage measurement before and after each test, and monitoring for leakage during the test. ***[PSR-48G]***

Rationale: The content of SMC-S-016 provides a suggested (vs. required) qualification and acceptance test sequence and does not clearly address the topic of discrete leak tests being considered part of ‘performance’ or active leakage monitoring being performed during vibration, shock, and thermal vacuum/thermal cycle tests of individual pressurized components. This 'before, during, and after' leak test approach is considered critical to the design qualification and acceptance of propulsion system components in terms of performing within specification for leakage when exposed to enveloping environmental exposure conditions, inclusive of dynamic environments such as vibration/shock and temperature extremes associated with thermal vacuum/thermal cycle exposure. Examples of past design sensitivities identified by testing in this manner have include valve poppet chatter during vibration causing damage to seals, leak rate sensitivity of seals to high and low temperature extremes, and incremental ratcheting of seals out of their seal glands during thermal cycles, among other effects.

3.2.1.3 For a human rated spacecraft propulsion system, a Qualification by Similarity (QBS) approach shall comply with the conditions and requirements of section 4.10.1 in SMC-S-016, Test Requirements for Launch, Upper Stage, and Space Vehicles, and meet the definition of 'heritage hardware' in Aerospace Report TOR-2013(3909)-1, Objective Reuse of Heritage Products. ***[PSR-49SC]***

Rationale: The use of heritage hardware for a new/unique application can be highly desirable in a number of respects (e.g. cost, schedule, technical confidence, availability of existing components, etc.). However, a heritage certification approach without objective evidence that hardware having a prior qualification and flight history is truly representative and enveloping of a new application has resulted in numerous performance anomalies and in-flight failures, some of which have led to catastrophic hazards associated with the propulsion system. The intent of this requirement is to ensure that a heritage certification approach for any propulsion system hardware (i.e. components, subassemblies, and/or subsystems), inclusive of the critical processes associated with building that hardware (e.g. manufacturing, assembly/integration, contamination control, heat treating, welding, NDE/NDT, leak testing, etc.), is fully justified based on relevant data, in accordance with SMC-S-016 and Aerospace Report TOR-2013(3909)-1. Note that favorable results of this assessment relative to critical processes do not automatically provide relief from other requirements in this standard given numerous past instances of inadvertent process escapes that have occurred despite a positive track record on prior work. (ref). Inheritance Review of the Mars Phoenix Flight System. (LLIS-1807, 2007)

3.2.1.4 In the process of performing specification compliance evaluations of acceptance test results for all propulsion system components, a comparative review of the performance data shall be conducted to identify any units as outliers with parameters that statistically differ from the rest of the population. ***[PSR-50G]***

Rationale: The intent of this requirement is to purposefully assess 'in-family' vs. 'out-of-family' performance for any individual piece of hardware. Statistically differ means that a valid statistical approach is used to determine if a unit is an outlier based on a 3 sigma statistical method that considers the sample size. Some level of performance variability during acceptance testing can be expected across any population of similar units, but large deviations involving a single unit or group of units can indicate subtle process changes or tolerance stack up differences that could lead to premature failure at some point in the future. For units that are ‘out of family’ but still meet specification requirements, various strategies do exist to reduce the potential impact to an active flight project/program. Examples include placing the affected unit(s) in spares to be used as a last resort, using the affected unit(s) for secondary or tertiary functions only, etc. Lesson learned on acceptance data trend analysis is discussed in AIAA 2001-3631, “Compton Gamma Ray Observatory: Lessons Learned in Propulsion”. (Dressler, 2001, pp. 11,)

3.2.1.5 Spacecraft propulsion systems on lander vehicles shall be assessed and qualification tested for exposure to planetary surface dust environments in accordance with NASA-STD-1008, Classifications and Requirements for Testing Systems and Hardware to be Exposed to Dust in Planetary Environments. ***[PSR-51S]***

Rationale: The cited standard defines a rigorous methodology for assessing hardware exposure to planetary surface dust, along with the qualification test protocols needed to ensure the performance and life of lander propulsion systems is adequate and can be certified to complete the defined mission successfully.

3.2.2 Propulsion System Level Qualification Test

Propulsion system level testing for a human-rated spacecraft is required to demonstrate that the propulsion system controls the catastrophic hazards associated with the vehicle interfaces, such as avionics and GNC, and those associated with the propulsion system and its components, such as hazards related to maximum dynamic pressures and combustion stability. It is an important and broad topic that encompasses development testing (ideally run to the point of failure for understanding failure modes and limitations of the hardware), qualification testing, proto-qualification testing (not considered valid for crewed vehicles/missions), pre-launch validation testing, and post-launch validation testing. It is also important that this be flight-representative hardware, built with the same processes and procedures as the actual flight hardware, due to the fact that waiting to learn about issues on deliverable flight hardware has proven to be costly and failure prone. Maintaining a functionally identical, properly configured, test bed of spare spacecraft hardware and associated support equipment, enabling detailed analysis and ground testing of in-flight failure scenarios and candidate corrective actions, can also save a mission. Reference LLIS-284, In-Flight Spacecraft Fault Recovery. (LLIS-284, 1993)

The first four categories involve ground testing, while the fifth category involves in-flight testing. For a reusable spacecraft, post-flight checkouts conducted during the turnaround interval between flights should be added to the list of ground testing. In the past, in-flight testing has been combined with ground turnaround checkouts to collectively ensure continued reliability and performance of the propulsion system on a reusable vehicle.

3.2.2.1 For an integrated spacecraft propulsion system, the scope of qualification testing shall include subsystem level hot fire testing of engines/thrusters in a flight-representative integrated system configuration to ensure expected performance and no detrimental effects or interactions involving the integrated propulsion system during steady-state or pulse mode start-up, steady state, and shutdown operation of multiple engines, with the test article and test campaign possessing the following key attributes: ***[PSR-52G]***

a) Test scope in accordance with the requirements of section 8.0 in SMC-S-025, Evaluation and Test Requirements for Liquid Rocket Engines.[1]

b) Use of flight-representative fluid commodities.[2]

c) Use of flight-representative propulsion system components, including instrumentation.[3]

d) Use of flight-representative propulsion system lines.[4]

e) Use of flight-representative engines/thrusters, orientations, and pod/cluster configurations.[5]

f) Use of flight-representative thrust vector control (TVC) actuators and electronic controllers (if present in the design).

g) Use of flight-representative electrical power sources, connectors, and valve driver avionics, including software control logic and fault detection, isolation, and recovery (FDIR) functions.[6]

h) Use of equivalent passive and active thermal control elements for temperature conditioning of the engine/thruster hardware and the propellants entering the engines/thrusters to envelope the environment and full start and run box conditions that could be experienced prior to and during hot fire operations in flight.[7]

i) Use of flight-representative servicing/deservicing and ground turnaround interfaces and procedures for the liquid and gaseous fluid commodities used in the propulsion system, including interface filtration levels/ratings and all nominal and contingency fill/drain/decontamination cycles that encompass all specified flights of the vehicle.

j) Includes testing with liquid propellants that are saturated with pressurant gas at all pressure/temperature conditions included in the test matrix, thus demonstrating hot fire operation of the engines/thrusters in the propulsion system at conditions that are enveloping of the flight application.

k) Includes hot fire sequences performed at simulated space vacuum (i.e. equivalent high altitude > 100,000 ft for example) and, for entry vehicle applications, variable backpressure conditions ranging from high altitude to sea level, to demonstrate that each engine/thruster position of the integrated propulsion system provides in-specification performance for nominal and contingency modes of operation in flight, inclusive of single failures in the propulsion system that can influence engine/thruster *inlet pressure.*[8]

l) *Includes steady state and pulse mode operation of multiple engines in sequences with simultaneous and staggered firings representative of the mission design, with pulse mode electrical pulse widths, duty cycles (DCs), and full pulse train durations defined by Monte Carlo flight simulation runs provided by the GNC engineering team (if available), or using sweeps with an enveloping range of commandable electrical pulse widths, duty cycles, and full pulse train durations until thermal steady state has been established or hardware limitations have been identified based on temperature redlines being exceeded and/or hardware failures occurring. The pulses should reflect EPW/DC/durations that can be most stressing for the engine and its different parts (e.g., throat life at higher temperature in high DC pulses, injector thermal stability sensitivity at different DC points, etc.), for the purpose of detecting service life issues that need to be addressed for qualification.*[10]

m) *Includes content to demonstrate all nominal and contingency transient dynamic events in the pre-launch and in-flight concept of operations for the propulsion system, including but not limited to the firing of pyro valves, cycling of pressurant and propellant valves, slam-starting of pressure regulators, pressurization/venting of propellant tanks, priming/venting of propellant lines, backpressure relief of isolated propellant lines, soak-back heating of engines/thrusters, propellant and pressurant commodity transfer, and activation of pressure relief provisions on propellant tanks.*

n) *Includes exposure of the hardware to all relevant external environments that could drive adverse interactions with the loaded propellants within the system including, but not limited to, vacuum exposure and humid air, at conditions and durations that envelope all ground processing and flight operations over the full service-life of the vehicle. Note that external environments associated with ground processing can be simulated at the test site, thus avoiding the need for buildup and testing at the launch site. Also note that this objective can involve accelerated exposure test protocols (e.g. elevated temperatures to drive increased reaction rates, accounting for permeation and vapor migration time constants, etc.) and be split among multiple assets, including the system level hot fire qualification test article and any component or subassembly qualification test articles that use actual propellants (vs. water, inert gas, or another simulant fluid).*

o) *Includes content for structural coupling and thrust dynamics evaluation to verify no unstable coupling of the propulsion system mounting structure and the propulsion engines/thrusters and propellant feed system for all mission configurations.*

p) *Includes content for engine/thruster chug and combustion stability evaluation using a combination of analysis and test per the requirements of JANNAF-GL-2022-0001, Guidelines for Combustion Stability Specifications and Verification Procedures for Liquid*

Propellant Rocket Engines, at the minimum propellant tank pressure and maximum propellant feed system pressure drop to the engine/thruster inlet, and maximum gas saturation and entrained bubble levels, collectively accounting for the worst-case thermal environment and worst-case single failure condition.[9]

q) *Utilizes a development instrumentation system needed to provide qualification data and critical math model anchoring data, as a supplement to the onboard flight instruments, which includes, but is not limited to, pressure transducers, temperature sensors, position sensors, flow meters, accelerometers, strain gauges, leak detectors, etc., with a range, accuracy, frequency response, and sample rate capable of quantifying transient peak pressures (MDP), temperatures, flow rates, loads, deflections, stresses/strains, and commodity leakage during all phases of the test campaign.*

r) *Utilizes a structured test readiness review (TRR) process to finalize all test plans and test procedures that document the test hardware configuration and test operations scope, inclusive of any test like you fly (TLYF)/test as you operate (TAYO) exceptions*[1] *and any pre-existing conditions or anomalies involving the test hardware.*

Rationale: System level qualification hot fire testing with flight-representative fluids and hardware items, over the full range of potential engine/thruster operating modes, internal pressure and temperature conditions, propellant saturation levels, and external environmental exposure conditions, will ensure that survival and performance characteristics of the integrated propulsion system are as intended without introducing any unanticipated conditions or catastrophic hazards that could pose a threat to the vehicle and flight crew. Note that subsystem and vehicle level thermal vacuum test including the active and passive thermal control system are required per SMC-S-016. The use of actual flight software (FSW), including any Fault Detection, Isolation, and Recovery (FDIR) functionality, is also recommended to achieve a full end-to-end representation of the integrated flight system. Certification of a propulsion system that relies solely on qualification testing of individual components or single engines/thrusters can easily overlook integrated operating modes and interactions that detrimentally impact delivered performance caused by feed system transients or structural mode excitation when hot firing multiple engines within an integrated propulsion system. Vacuum conditions and flight feed system performance can adversely affect the engine startup and shutdown characteristics resulting in combustion instability, propellant detonations, or other catastrophic consequences. Exposure to challenging external environmental conditions while on the ground, including atmospheric moisture in the form of humid air, can drive corrosion on hypergolic propulsion systems that permeate oxidizer through non-metallic seals, and condensation/cryo-pumping on cryogenic propulsion systems that must be insulated. In addition, cryogenic thermal transitions can drive excessive torque relaxation of fasteners on mechanical joints. All of these phenomena can adversely affect cycle life, leakage, thermal management, and other key performance attributes and hazards associated with the hardware. Overall, the system level hot fire test is the most notable example of the critically important 'test like you fly (TLYF)' principle being applied to a complex spacecraft propulsion system. Reference LLIS 763, Systems Test Considerations for High Performance Liquid Propellant Rocket Engines (LLIS-763, 1999), and LLIS-1196, Test as You Fly, Fly as You Test, and Demonstrate Margin (LLIS-1196, 2002). Apollo Experience Report – Lunar Module Reaction Control System (Vaughan, 1972, pp. 10-13). (ref) NASA TN D-7151, Apollo Experience Report – Command and Service Module Reaction Control Systems.

Section Footnotes:

[1] The acceptability of any proposed deviations to this requirement, which is aimed at duplicating the key physical configurations and functional performance attributes of the flight vehicle propulsion system and its interfacing hardware/software, must be evaluated as part of the design review and test planning process for the system level hot fire test article, with the technical rationale for each instance, inclusive of any analyses performed to establish the adequacy of a given change/substitution, documented in a report as a Test Like You Fly (TLYF) exception and approved by the NASA Technical Authority and project/program management.

[2] The term 'flight-representative fluid commodities' refers to all liquid and gaseous propellants, pressurant gases, pad gases, purge gases, pneumatic gases, test gases, cleaning and flush liquids/gases, etc. as used for the flight vehicle propulsion system being represented in the system level hot fire test campaign. The intent is for the test fluids to meet the same specifications as the operational flight fluids in terms of chemical composition, physical properties, and particulate/non-volatile residue (NVR) levels, thus enabling an unambiguous assessment of system functionality and performance. For cryogenic propulsion systems that feature liquid hydrogen (LH2) as a fuel, it is considered acceptable to use liquid nitrogen (LN2) and/or liquid helium (LHe) for initial low temperature leak checks prior to introducing LH2 into the system for hot fire testing.

[3] The term 'flight-representative propulsion system components' refers to the propellant and pressurant tanks, valves (including pyro valves), regulators, accumulators, filters, orifices, bubble traps, heat exchangers, service valves/disconnects, instrumentation (including pressure, temperature, propellant gauging), valve pneumatic systems, etc. The intent is qualification fidelity hardware, featuring an exact duplication of the flight units in terms of design, build, inspection, testing, and installation into the system level hot fire test article. The end result will be verification of these components in an actual integrated PSS hot fire test environment (e.g., pressure oscillations, pressure regulation, vibration, thermal, etc.). Of course, this has been a point of debate and compromise for past projects/programs. In some cases, based on the specific objectives of the system level hot fire test campaign, select flight-representative components have been substituted with early development units and/or industrial equivalent items having similar performance

characteristics, depending on the circumstances. Examples have included propellant tanks (e.g. gravity feed with no diaphragm or PMD, higher structural safety factors, reduced levels of fracture control, limited redundancy configuration, etc.), pressure and temperature instrumentation, and increased response time manifold isolation valves, among other items. Situations of this nature warrant an evaluation of adequacy on a case-by-case basis. Reference LLIS-1487, Need for Flight Configuration Ground Test facility. (LLIS-1487, 2004)

[4] The term 'flight-representative fluid lines' refers to the propellant lines, pressurant lines, pneumatic lines, fill/drain lines, test port lines, high/low points, etc., including the mounting clamps, brackets, stanchions, and other items that interface with those lines as secondary structure. Collectively, these features contribute to the induced pressure transient environment within a flight vehicle propulsion system, so they need to be included in the system level hot fire test article too. The intent is qualification fidelity hardware, featuring an exact duplication of the flight units in terms of design, build, inspection, testing, and installation into the system level hot fire test article. In some cases, based on the specific objectives and/or unique constraints of the system level hot fire test campaign, a 'flat pack' configuration for the lines (i.e. two-dimensional representation of a three-dimensional flight configuration) or some other necessary alternate routing, may be considered adequate based on performance analysis to establish equivalence. Situations of this nature warrant an evaluation of adequacy on a case-by-case basis.

[5] The term 'flight-representative engines/thrusters' refers to firing engines/thrusters (vs. non-firing flow simulators), engine orientation, and pod/cluster configurations of all the different thrust levels and positions, inclusive of all structural mounting and thermal insulation provisions that could impact engine/thruster-to-structure dynamic coupling and engine/thruster thermal soak back characteristics. The intent is qualification fidelity hardware, featuring an exact duplication of the flight engines/thrusters and pod/cluster assemblies in terms of design, build, inspection, testing, and installation into the system level hot fire test article. Note that the pod/cluster package configurations (e.g. enclosures, heaters, blankets, etc.) are particularly important from a thermal interaction and performance perspective. Also note that engine/thruster orientation may be important for some applications, such as up-firing jets in an acceleration field, which can cause damage to the hardware (e.g. valve leakage from catalyst fines migration in monopropellant hydrazine thrusters, explosions (Zots) within the injector of bipropellant MMH/MON3 thrusters, etc.). Also note that reduced area ratio 'sea-level' nozzles may be considered adequate when hot-firing flight-configuration engines/thrusters at non-vacuum conditions would damage/degrade the flight configuration nozzles. Situations of this nature warrant an evaluation of adequacy on a case-by-case basis.

[6] The term 'flight-representative electrical power sources, connectors, and valve driver avionics' refers to the power source and valve driver avionics hardware, inclusive of the interconnecting electrical cables, that provide conditioned power to the various propulsion system hardware components (e.g.

solenoid valves, motor driven valves, pyro valves, TVC actuators, transducers, etc.) on the flight vehicle. Past experience with system level hot fire testing has shown that laboratory power supplies (vs. vehicle batteries, fuel cells, etc.), industrial switches, and simplified cabling may not provide the necessary power quality to ensure in-specification response times and other critical performance attributes for the propulsion system hardware. As a result, it is necessary to duplicate these key electrical features to the greatest extent practical, excluding the radiation hardening and extreme reliability ratings needed for EEE parts in a space environment, in order to ensure validity of the system level hot fire test campaign. Reference LLIS-6144, Shuttle External Tank Engine Cut Off Feed Through Connector Failure. (LLIS-6144, 2010)

[7] The term ‘equivalent thermal control elements’ refers to the heaters, cold plates, cooling jackets, heat pipes, temperature sensors and controllers, etc. that externally interface with the propulsion system and are used to maintain the hardware and fluid commodities within an allowable temperature range and/or achieve a specified pressure or temperature condition during ground testing to simulate pre-launch or in-flight scenarios. These items can be particularly important when they influence a launch commit criteria (LCC) or flight rule (FR), maintain an operational placard, or serve as a hazard control. However, it is recognized that the design, sizing, and installation of thermal control elements to be used in an ambient environment on the system level hot fire test article may differ from those to be used on the actual flight vehicle in a vacuum environment. This is considered acceptable, without the need for a dedicated TLYF exception, providing that the thermal conditions needed to meet the objectives of the system level hot fire test campaign can be achieved. Note that subsystem and vehicle level thermal vacuum test including the active and passive thermal control system are required per SMC-S-016. Reference LLIS-349, Magellan (MGN) High Rocket Engine Module (REM) Temperatures. (LLIS-349, 1994)

[8] For thermal vacuum and variable backpressure conditions that can’t be duplicated during system level hot fire testing on the ground, options to complete qualification successfully include: (1) a test setup that allows a subset of individual engines/thrusters to be fired into an evacuated enclosure (vs. all engines/thrusters firing into a much larger evacuated enclosure that contains the entire test article), combined with a separate thermal vacuum test that doesn’t involve firing engines/thrusters, or (2) an instrumented flight test of the propulsion system in an actual space vacuum and entry environment to demonstrate all modes of system operation in the most realistic manner possible.. Note that subsystem and vehicle level thermal vacuum tests of the integrated propulsion system, including the interfacing active and passive thermal control system elements, are required per SMC-S-016. Reference LLIS-6345, Space Shuttle Program Ground and Flight Data Measurements. (LLIS-6345, 2011)

[9] Spacecraft propulsion system engines/thrusters can be sensitive to chug and combustion instability phenomena at certain pressure and temperature conditions, and gas saturation and entrained bubble

levels, during steady-state and pulse mode hot-fire operation. These issues can result in life degradation and catastrophic failure of the affected engines/thrusters if allowed to develop and persist while in service. The intent of this requirement is to ensure that the worst-case engine/thruster inlet condition, which can serve as a trigger for combustion chug and instability, is identified, evaluated analytically, and verified by test to ensure there is no concern.

[10] The variables discussed in this sub-paragraph are critical to exercise during system level hot fire qualification testing. Those items, taken individually or collectively, can have a significant impact on engine/thruster performance and cycle life, in addition to driving certain hazardous failure modes of the hardware in service. As an example, water hammer magnitudes during engine/thruster firings can vary greatly based on propellant properties, propellant feedline designs, and engine/thruster pulse mode duty cycles. Significant amplification can occur when feedline natural frequencies coincide with engine/thruster pulsing frequencies. Adequate replication of the flight-representative conditions during ground testing is essential for characterizing these effects and to complete the safety assessment and flight certification of a human rated spacecraft propulsion system.

3.2.2.2 For a human rated spacecraft propulsion system, all propulsion-related qualification testing shall be completed prior to the final uncrewed test flight of the integrated vehicle, if such a test flight is performed. ***[PSR-53G]***

Rationale: The scope of propulsion system qualification testing encompasses component/unit level (e.g. valve, regulator, engine/thruster, etc.), sub-assembly/multi-unit module (MUM) level (e.g. service panel, regulator panel, valve panel, etc.), and subsystem level (e.g. integrated system hot fire test article). All of these elements of the qualification test program are expected to be complete and successful prior to the final uncrewed test flight, if that test flight is part of certification, or the first crewed flight if an uncrewed flight is not required by the program. System level hot fire qualification testing is intended to serve as the final verification of the end-to-end propulsion system and needs to be executed with very few failures or anomalies, though it may uncover unexpected behavior as seen in the past that warrants additional evaluation during the final flight test. Development flight instrumentation (DFI) may be used for additional data gathering and performance verification during a test flight in a space environment as part of the final certification of a human rated prop system. The majority of the technical risk is expected to be retired by either the early development testing per paragraph 3.2.3 or applicable heritage as assessed via Aerospace Report TOR-2013(3909)-1, Objective Reuse of Heritage Products.

3.2.3 Propulsion System Development System Level Test

3.2.3.1 If the propulsion system is determined to not have applicable heritage in accordance with Aerospace Report TOR-2013(3909)-1, Objective Reuse of Heritage Products, then a development propulsion system level hot fire test, featuring prototype, EDU, and/or spare heritage engines/thrusters arranged in a preliminary system configuration and operated in an *enveloping manner, shall be conducted prior to CDR to determine if any modifications are required to the system or engine/thruster design per section 4.2.1 of SMC-S-016, Test Requirements for Launch, Upper Stage, and Space Vehicles.* ***[PSR-54SC]***

Rationale: This type of early propulsion system development testing reduces risks to the program from a safety, technical, and schedule perspective. Engine/thruster testing alone may overlook detrimental interactions (e.g., chug instability, injector explosions (ZOTS), thermal runaway, etc.) with flight-like propellant feed systems (e.g., line lengths/diameters, manifolding, flow rates, response times, volumes, etc. that affect performance) and other mission variables (e.g., altitude, orientation, valve command lead/lag timing, temperatures, saturation levels, manifold priming conditions and operations, etc.), as well as added instrumentation necessary to detect anomalous behavior/failures (e.g., leaks). In addition, vacuum conditions and flight-like feed systems can affect the engine startup and shutdown characteristics manifesting in combustion instability, propellant detonations, or other catastrophic consequences. Given the pre-CDR stage of development, it is understood that the fidelity of the propulsion system hardware configuration, operational firing sequences, and driving environments will all be preliminary, and added ground test instrumentation may also be present to detect anomalous behavior/failures of the hardware. As a result, this testing is viewed as a 'best efforts' risk reduction activity and the verification burden is reduced relative to formal system level qualification hot fire testing, which would have clearly defined objectives and specific quantifiable pass/fail criteria defined prior to commencement of the test campaign.

3.2.4 Propulsion System Acceptance, Assembly, Integration, and Test (AI&T)

3.2.4.1 For unit performance/functional and leakage tests conducted during acceptance of propulsion system components in accordance with sections 6.3.2 and 6.3.3 in SMC-S-016, Test Requirements for Launch, Upper Stage, and Space Vehicles, the scope shall include testing with the hardware and test fluid at the maximum and minimum predicted temperature (MPT) extremes. ***[PSR-55SC]***

Rationale: The intent of this requirement is to codify the inclusion of unit performance/functional and leak tests during the acceptance of propulsion system components at MPT conditions associated with the application for both the hardware and fluid. Note that MPT is defined in paragraph 3.23 in SMC-S-016, Test Requirements for Launch, Upper Stage, and Space Vehicles to include model prediction and thermal uncertainty. The content of SMC-S-016 currently addresses this topic as a ‘consideration’ only rather than a firm requirement. To accomplish this objective with cryogenic propulsion systems using LH2, it will be necessary to use actual LH2 or colder liquid helium (LHe) rather than warmer liquid nitrogen (LN2), which would be less rigorous in terms of screening for workmanship defects in critical propulsion system hardware.

3.2.4.2 For individual engines/thrusters, the scope of acceptance testing shall include engine/thruster level hot fire tests, with all parts of the 'thruster' which could affect performance of the 'thruster' and measure that performance in flight, with flight-representative propellants and pressurant gas that demonstrates in-specification functional performance at nominal and 'corner of the box' operating conditions for the hardware including, but not limited to, propellant inlet pressures, inlet temperatures, valve voltage/current levels, steady state firing, and pulse mode firing with duty cycles defined in the thruster specification. ***[PSR-56G]***

Rationale: The purpose of acceptance testing for individual engines/thrusters is to verify in-specification performance and screen for workmanship flaws/defects in each unit prior to being used for qualification testing or integrated into the flight vehicle. The extreme thermal, pressure, and dynamic environments created during engine/thruster operation can cause failure if workmanship flaws exist. The content of SMC-S-016 does not explicitly address acceptance hot fire testing for engines/thrusters at the component or subassembly level, which has led to past conflicts on the scope and need for such testing. The content of PSR-290SC, NASA-STD-5012 (section 9.5.2, requirement PSER 32) and SMC-S-025 (section 7.1.3, requirement 7.1.3-1) drive the need for acceptance hot fire testing, but both describe 'nominal' operational levels and durations without further details. The intent here is to include a rigorous hot fire test at nominal and 'corner of the box' operating conditions that could be seen in service as part of acceptance testing on every qualification and deliverable flight unit, which has historically proven critical in controlling catastrophic hazards (instability and cooling related chamber burn-through, etc.), quantifying performance, screening for workmanship-related defects, and evaluating anomalies that may occur in flight. Note that additional requirements associated with engine/thruster acceptance hot fire testing are contained in the 'spacecraft engines and thrusters' section of this document.

3.2.4.3 For a fully assembled/integrated propulsion system on a human rated spacecraft, the subsystem and vehicle level performance tests conducted per sections 7.3 and 8.3, respectively, in SMC-S-016, Test Requirements for Launch, Upper Stage, and Space Vehicles, shall include an end-to-end inert gas flow test through each individual flow path, with the propulsion system in its final integrated/assembled configuration for flight, subsequent to any prior system break-ins or component replacements, to ensure no flow restrictions/blockages are present and assess that particulate contamination and other contaminates such as moisture, cleaning fluid vapors, or residual propellant vapors, are within specified limits, thus meeting the intent of paragraph F-20 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-57SC]***

Rationale: The content of paragraph F-20 (Fluid Systems – Cleanliness) drives flushing/purging of an assembled/integrated spacecraft propulsion system using filtered fluids that are compatible with the flight fluid commodities and hardware materials of construction. The intent of this requirement is to ensure that all propulsion system components are functioning as expected in terms of flow/delta P performance, thus ensuring that no significant particulate contamination and/or foreign object debris (FOD) was introduced into the system during the initial assembly/integration process or anytime a component in the flow path is replaced. There have been numerous past instances of particulate/FOD being generated and ending up in the propulsion system during assembly/integration or ground turnaround maintenance, creating flow restrictions/blockages that were discovered later during ground testing or in-flight anomaly (IFA) investigations. It is understood that normally closed (NC) pyro valves installed in a propulsion system may complicate this task. As a result, the end-to-end flow test may need to be conducted in separate steps for the lines/components upstream vs. downstream of the NC pyro valves.

3.2.4.4 The design of a human rated spacecraft propulsion system shall comply with the 'electrical and fluid system checkout' requirements of paragraph G-3 in JSC-08080-2, JSC Design and Procedural Requirements. ***[PSR-58S]***

Rationale: The requirements of paragraph G-3 (Electrical and Fluid Systems Checkout Provisions) are critical to ensuring that key design features needed to permit rigorous testing of the propulsion system, including internal/external leakage and functional checkouts of the hardware, are present in the propulsion system, thus enabling those activities to be conducted without disconnecting any tubing, mated flight couplings, or other mated flight electrical connectors. These capabilities are considered key aspects of hazard control.

3.2.4.5 For a fully assembled/integrated cryogenic propulsion system, the vehicle level performance tests conducted as part of section 8.3 in SMC-S-016, Test Requirements for Launch, Upper Stage, and Space Vehicles, shall include a vehicle tanking test in accordance with section 8.2.5 of SMC-S-025, Evaluation and Test Requirements for Liquid Rocket Engines, and a 'green run' of all installed engines/thrusters, with the propulsion system in its final integrated/assembled configuration for flight, subsequent to any prior system break-ins or component replacements, to evaluate system performance at cryogenic operating temperatures. ***[PSR-59SC]***

Rationale: The intent of this requirement is to ensure that cryogenic propulsion systems are confirmed, as part of initial acceptance testing, to perform as expected at the extreme low temperatures associated with cryogenic propellants. The scope includes a cryogenic tanking test, which exposes all propellant lines, components, sensors/transducers, mechanical joints, and insulation to the thermal stresses induced by chill-down, and a 'green run' (i.e. hot firing) of all engines/thrusters, which demonstrates acceptable performance of that complex hardware when integrated with the propellant feed system. As demonstrated on past projects/programs, this is a critical step in screening for workmanship defects and other conditions/issues exacerbated by the exposure of critical components to extreme cryogenic temperatures, including internal and external leakage of propellant; thermal insulation failure resulting in thermal excursions at the engine/thruster inlet, ice formation, and/or liquid air formation; sluggish valve response times and position indicator failures; excessive structural deflections; loss of electrical connector continuity due to thermal expansion/contraction effects; etc. Note that re-torque of fasteners on bolted joints following these tests with cryogenic fluids is also recommended based on past experience with torque relaxation driven by exposure to thermal extremes.

3.2.4.6 For a fully assembled/integrated propulsion system using hydrazine, hydrogen peroxide, or other monopropellants sensitive to decomposition, the vehicle level performance tests conducted as part of section 8 in SMC-S-016, Test Requirements for Launch, Upper Stage, and Space Vehicles, shall include monitoring of pressure and temperature to assess the decomposition rates are within specified limits during final system acceptance tests or final propellant loading. ***[PSR-60G]***

Rationale: The intent of this requirement is to provide a key hazard control for energetic propulsion systems featuring hydrazine, hydrogen peroxide, and other monopropellants that are sensitive to decomposition caused by contamination. The presence of particulate contamination and unintended reactive materials within a propulsion system can accelerate the decomposition rate for those types of propellants, resulting in gas formation, pressure buildup, and potential rupture of a propulsion system. Similar propellant wetting tests were included as part of the Mercury Spacecraft hydrogen peroxide system acceptance process, and they are used on other hydrazine and hydrogen peroxide propulsion systems too. Note that the results of this test may require that the propellants are off-loaded, and the system is inerted.

3.2.5 Propulsion System Allowable Leak Rate Assessment and Verification for Flight and Qualification articles

3.2.5.1 The performance specification for a human rated spacecraft propulsion system shall define a maximum allowable leak rate for each fluid commodity at the integrated system level, a maximum allowable leak rate for each individual component (e.g. tank, valve, etc.) in the system, and a maximum allowable leak rate for each individual mechanical and fusion joint in the system. ***[PSR-61G]***

Rationale: Excess leakage of fluid commodities from the propulsion system, whether distributed across the system or localized at a single leak site, can result in a variety of catastrophic hazards including inadvertent depletion of pressurant/pneumatic gases or propellants, flammable atmospheres, toxic atmospheres, corrosion, or other degradation of incompatible adjacent hardware, electrical shorting, and over-pressurization of secondary volumes/compartments.

3.2.5.2 Leak testing performed on a human rated spacecraft propulsion system and its associated components and subassemblies shall comply with the requirements of NASA-STD-7012, Leak Test Requirements, including all 'supplementary provisions' in sections 5.15 – 5.19 for flight and qualification test articles. ***[PSR-62SC]***

Rationale: The cited NASA-STD-7012 provides a complete and comprehensive treatment of system level and localized leak testing methodologies, procedural steps and constraints, and detection sensitivity levels for use on all NASA projects/programs. Having the maximum allowable leak rates documented and actual leak rates of the hardware verified to be acceptable by test using the methods outlined in NASA-STD-7012 serves as a key form of hazard control for the propulsion system. The content of this document captures many lessons learned accrued over decades of leak tests on spacecraft propulsion and fluid system hardware, sometimes resulting in inconsistent and questionable results, and it is expected to be followed on spacecraft propulsion systems and their associated qualification test articles due to the many catastrophic hazards associated with their design and operation.

3.2.5.3 Leak testing, using methods in NASA-STD-7012, of a human rated propulsion system shall be performed to accomplish 1) global internal-to-external leakage rate verification for the integrated system; 2) local internal-to-external leakage rate verification using a trace gas for each mechanical and fusion joint in the system; and 3) a 'sniff' check of all surrounding spaces/volumes and previously disturbed mechanical joints in the system for evidence of system leakage after final commodity loading. ***[PSR-63G]***

Rationale: NASA-STD-7012, paragraph 4.2.2 [LTR 9] specifies the use of one method. However, experience shows that both global system decay and local leak measurement methods are required to sufficiently screen for leaks in a propulsion system. There are many past examples of propulsion system leaks that have been detected via system level leak test methods (e.g. pressure decay, accumulation, vacuum chamber exposure, etc.), localized leak test methods (e.g. bubble soap leak check, GHe mass spectrometer or hazardous gas detector 'sniff' check, volumetric displacement, etc.), or a combination of the two. The Space Shuttle hypergolic systems utilized a hazardous vapor ("sniff") leak check, in addition to the GHe mass spectrometer leak check of individual fittings after being disconnected for any reason. Reference (ref), (Nufer, 2010, p. 40), and LLIS-3177, Shuttle Main Propulsion Helium Signature Test. (LLIS-3177, 2010)

3.2.5.4 Leak testing of individual mechanical and fusion joints in the pressurized fluid lines of a human rated spacecraft propulsion system shall be conducted using the quantitative 'Method II – Accumulation' [LTR15] technique described in section 5.2 of NASA-STD-7012, Leak Test Requirements. ***[PSR-64G]***

Rationale: The quantitative 'accumulation' method of leak testing for individual mechanical and fusion joints in the pressurized fluid lines of a propulsion system involves providing an enclosure around each joint (i.e. bagging, etc.) that will direct all leakage of the test commodity to the leak detection equipment, thus avoiding the complex procedural steps/controls and associated uncertainties of the alternate semi-quantitative ‘Method XI – Detector Probe’ technique described in section 5.11.a of NASA-STD-7012. For example, small pinhole leaks in a fusion joint may not be detected using a probe in Method XI due to air motion or lack of mixing or not getting the probe close enough the leak site due to restricted access. In this case, the individual mechanical or fusion joint is considered as the ‘test article’ and the leakage emanating from each joint is considered the ‘total’ leak rate, consistent with the terminology used in section 5.2 of NASA-STD-7012. Of course, the ‘accumulation’ method could also be used with similar success for a larger subassembly (e.g. valve panel containing multiple components connected with mechanical and/or fusion joints), or the fully integrated propulsion system.

3.2.5.5 Leak testing of bellows and flex hoses in the pressurized lines of a human rated spacecraft propulsion system shall be conducted using the quantitative ‘Method II – Accumulation’ [LTR15] technique described in section 5.2 of NASA-STD-7012, Leak Test Requirements, or, if they are too long to be fully enclosed, using the semi-quantitative ‘Method XI – Detector Probe’ [LTR24] technique described in section 5.11.b of NASA-STD-7012. ***[PSR-65SC]***

Rationale: The quantitative ‘accumulation’ method of leak testing for bellows and flex hoses in the pressurized lines of a propulsion system involves providing an enclosure around each item (i.e. bagging, etc.) that will direct all leakage of the test commodity to the leak detection equipment, thus avoiding the complex procedural steps/controls and associated uncertainties associated with the alternate semi-quantitative ‘Method XI – Detector Probe’ technique described in section 5.11.b of NASA-STD-7012. In cases where a flex hose is too long to be fully enclosed (e.g. radiator retract hoses on the Shuttle payload bay doors, etc.), the semi-quantitative technique of section 5.11.b of NASA-STD-7012 is considered an acceptable compromise despite the recognized limitations.

3.3 FLIGHT OPERATIONAL FLUIDS; PROPELLANT, PRESSURANTS, PNEUMATIC; PROCUREMENT AND USAGE SPECIFICATION

The propellants and other fluids selected for a new chemical propulsion system on a human-rated spacecraft are chosen by the design engineering team. The types used for a given system have a history and process of selection, and the use of heritage hardware necessitates that the fluid specifications, sources of supply, and manufacturing processes remain identical to legitimately leverage historical performance and material compatibility data for a new/different application.

It should be noted that the usage requirements for a given fluid can sometimes differ from those listed in the associated procurement specification. If so, additional requirements are levied to ensure that the fluid will provide the necessary performance capability without inducing other adverse effects for the hardware.

The following paragraphs define the requirements for the propellants, pressurant gases, pneumatic gases, and other operational flight and test fluids to be procured and used in the chemical propulsion systems on human-rated spacecraft. If a project/program has a 'fluid procurement and usage specification' as described above, then these requirements should be replicated in that document too. Of course, the intent is for all propulsion system fluids to be initially procured and then subsequently stored and used in accordance with the requirements of the specification (vs. compliance at initial procurement only).

3.3.1 General Fluid Procurement and Usage Requirements

3.3.1.1 *A specification for the procurement and usage of a propellant and other flight fluids shall be created (if not already in existence), controlled, and utilized for the propulsion system.* ***[PSR-66G]***

Rationale: This specification contains requirements aimed at controlling the critical characteristics of all fluids (i.e. liquids and gases) introduced into the flight hardware on a human-rated spacecraft. In some cases, that specification takes the form of a newly generated document, while in other cases it takes the form of a pointer to an existing document from a different project/program. Regardless, the scope typically covers the chemical composition/purity, physical properties, cleanliness levels (i.e. particulate and non-volatile residue (NVR)), and interface filtration needs for the fluids used with the fully integrated flight system (vs. individual components at their suppliers). For propulsion systems, this would include the propellants, pressurant gases, and pneumatic gases used in flight, along with any additional fluids used for cleaning, flushing, purging, and testing/checkout of the integrated system pre- and post-flight. Reference AFRPL-TR-67-256, Propellant Specifications Preparation and Use.

3.3.1.2 *In the event of a manufacturing process change that affects the production/synthesis of any propellant being used for a spacecraft propulsion system, the following steps shall be performed:* ***[PSR-67G]***

a) Sampling and testing of the fluid to verify continued compliance with the applicable fluid specification

b) Functional performance testing with a flight-representative engine/thruster to verify in-specification performance and life of the hardware.

Rationale: Manufacturing process changes affecting the production/synthesis of a propellant can have a major effect on the performance and life of engines/thrusters used in spacecraft propulsion systems. As a result, it is critical to verify that all propellants created with the updated manufacturing process comply with the applicable fluid specification and will allow the engines/thrusters to maintain in-specification performance and life of the hardware. Note that fluids used in a simple, inert 'cold gas' propulsion system are considered exempt from this requirement.

3.3.1.3 A specification for propellant storage systems shall be generated that defines requirements for items including, but not limited to, storage tank materials, soluble contamination, moisture, particulate, duration, and maintenance of pressure, propellant saturation levels with inert ullage gas, and temperature range. ***[PSR-68G]***

Rationale: Improper propellant storage can adversely affect the quality of propellant being used and result in common cause failure modes of the propulsion system. The intent is to ensure a comprehensive specification is developed for the propellant ground storage systems that controls key properties and other variables contributing to such failure modes.

3.3.1.4 Documentation of formal training for designers and operators in the use and hazards for all propellants and a formal process to identify and control the hazards shall be maintained. ***[PSR-69G]***

Rationale: Awareness of the propulsion system hazards for flight vehicle and ground systems designers and operators is a critical need relative to effective hazard control.

3.3.2 General Fluid Interface Filtration and Sampling Requirements

The requirements of this section are collectively intended to prevent fluid commodities that are incorrectly identified/labeled, contain excessive particulate contamination, and/or have out-of-specification chemical composition or physical properties from being introduced into the propulsion system of a human rated spacecraft. There have been numerous past instances of fluid sampling in the storage tanks, at test ports in the ground support equipment (GSE) or Test Support Equipment (TSE), and at the GSE or TSE interface to flight hardware (i.e. point of use), spread across multiple NASA projects/programs, that have identified fluid commodity non-conformances. Early detection of such issues via targeted sampling allows appropriate corrective actions to be taken prior to exposing the flight hardware and/or critical ground test articles to any adverse effects from discrepant fluids on performance, life, or hazard controls. Filtration of all fluids at the GSE or TSE interface to flight hardware has also proven critical to the prevention of excessive particulate from being introduced into sensitive equipment, which can cause a variety of anomalies/failures of the propulsion system.

3.3.2.1 Propellants, pressurant gases, and other fluids entering a spacecraft propulsion system shall be filtered by the Ground Support Equipment (GSE) prior to the propulsion system interface to prevent particulate larger than the minimum size associated with the specified precision cleanliness level from entering the integrated propulsion system. ***[PSR-70G]***

Rationale: Filtering of all propellants, pressurant gases, and other fluid commodities at the propulsion system interface serves as a critical means of particulate contamination control during ground testing and commodity servicing of the flight vehicle, thus reducing the likelihood of hazardous malfunctions involving the propulsion system and its components. The intent of the words "prior to" in this requirement is to allow options for meeting the objective, such as the use of a high capacity (large) filter before the final hose and a small (low capacity/fitting-size) filter right at the interface. This prevents potential side load damage to the flight half coupling from a heavy ground half coupling, and it also helps improve access to valves with Self-Contained Atmospheric Protective Ensemble (SCAPE) suit gloves on. The filtration level specified here will prevent particles in the GSE and/or fluid commodities from passing through the filter that would contribute to a particle count during a precision cleanliness verification of the hardware, and it has been used successfully for this purpose on past human spaceflight projects/programs. As one example, the particle counts for the most stringent precision cleanliness levels typically used for spacecraft propulsion systems begin at 5 microns, so the intent is to avoid adding particulate above that size to the propulsion system. Note that irregularly shaped particles up to 2.5x larger than a filter's absolute rating could pass through, which could affect the filter sizes chosen to meet this requirement (reference) (Bauer, 2000, p. 4)

3.3.2.2 Sampling of all ground supply tanks/vessels that contain operational flight fluids or flushing/testing/checkout fluids to be used with a human rated spacecraft propulsion system shall be conducted to verify proper labeling and compliance with the applicable fluid specification, in accordance with paragraph F-27 of JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-71S]***

Rationale: The requirements of paragraph F-27 (Verification of Liquid or Gas Properties) involve sampling of the liquids and gases in all tanks/vessels containing fluids that are intended for use with a spacecraft propulsion system. This is a critical means of verifying that the fluid actually matches the container labeling, and that the associated chemical composition/purity and other key fluid property requirements are met, prior to being introduced into the flight hardware. This step will reduce the likelihood of inducing hazardous chemical reactions and/or malfunctions of the propulsion system and its components.

3.3.2.3 Ground storage vessels that are used for multiple servicing events of spacecraft propulsion systems shall be sampled prior to each spacecraft loading event and prior to refilling the storage vessel to verify compliance with the requirements of the applicable fluid specification. ***[PSR-72G]***

Rationale: Sampling of the liquid propellant contained in a ground storage vessel used to service a spacecraft propulsion system provides a critical means of verifying that chemical composition/purity and other key fluid properties are maintained over time and over the fill level range. Vaporization of liquid into the tank ullage volume as propellant is consumed, especially when combined with repetitive venting of the tank ullage volume, can change the relative concentration of key chemical constituents in the remaining liquid, potentially affecting the structural integrity and performance of the propulsion system leading to a catastrophic hazard. One notable example involves the reduction of nitric oxide (NO) concentration in mixed oxides of nitrogen (MON) blends of nitrogen tetroxide oxidizer (NTO), which can result in stress corrosion cracking (SCC) and eventual rupture of Titanium propellant tanks on the spacecraft. Change in composition of a cryogenic hydrocarbon propellants can also lead to propulsion system failure. Reference LLIS-6056, STS-114 Liquid Oxygen (LO2) Purity Impacts Engine Performance. (LLIS-6056, 2010)

3.3.2.4 All liquids and gases entering a spacecraft propulsion system through the servicing GSE shall be sampled at the ground side interface to verify requirements of the applicable fluid specification are met, with the exposed surfaces of the mating ground and flight half couplings also visually inspected to verify cleanliness, prior to final mating of the coupling and fluid being introduced into the vehicle. ***[PSR-73G]***

Rationale: Sampling of all liquids and gases at the propulsion system interface serves as a critical means of verifying chemical composition/purity and other key fluid properties during ground testing and servicing of the flight vehicle, thus reducing the likelihood of hazardous malfunctions involving the propulsion system and its components. This supplements the sampling of fluids in the various tanks/vessels driven by other requirements in this section and serves as a final opportunity to identify an anomalous condition involving a fluid prior to entering the flight vehicle. Reference LLIS-6056, STS-114 Liquid Oxygen (LO2) Purity Impacts Engine Performance.

3.3.3 Operational Fluids: Pressurant, Pneumatic, Purge, and Cold Gas Propulsion Gases

3.3.3.1 Helium (He) used in chemical propulsion systems on human-rated spacecraft shall comply with the requirements for Type 1 helium per MIL-PRF-27407, Performance Specification, Propellant Pressurizing Agent, Helium. ***[PSR-74S]***

Rationale: This specification provides stringent controls on chemical composition/purity, physical properties, and sampling protocols, and it has been used successfully with propulsion systems on prior human-rated spacecraft. Note that this specification covers the liquid and gaseous forms of helium. Type 1, grade B helium has a slightly higher purity and lower levels of certain key impurities relative to grade A. Either grade is considered acceptable as a flight fluid, providing all acceptance and qualification are performed using the chosen grade. Note: Procurement as MIL-PRF-27407 Type II (liquid) and delivery to the interface as Type I (gaseous) Grade A is normal and acceptable.

3.3.3.2 Nitrogen (N2) used in chemical propulsion systems on human-rated spacecraft shall comply with the requirements for grades B or C per MIL-PRF-27401, Performance Specification, Propellant Pressurizing Agent, Nitrogen. ***[PSR-75S]***

Rationale: This specification provides stringent controls on chemical composition/purity, physical properties, and sampling protocols, and it has been used successfully with propulsion systems on prior human-rated spacecraft. The scope of that document covers the liquid and gaseous forms of nitrogen in grades A, B, and C. Grade C is the purest N2 and has the most stringent controls on impurities, particularly O2 and water content. All grades have been used in past propulsion system applications, but grade A contains significantly higher levels of moisture and O2 which can cause issues with condensation/freezing at low temperatures and concerns for use with various liquid/vapor fuels, respectively.

3.3.3.3 Pressurant, pneumatic, purge, and/or cold gas propulsion system functions shall be evaluated by analysis for hazards associated with asphyxiation from oxygen/air displacement, low temperatures during rapid expansion/pressure decay events, and over pressurization of surrounding compartments/volumes within the spacecraft. ***[PSR-76G]***

Rationale: Inert gases used for pressurant, pneumatic, purge, and/or cold gas propulsion system purposes can create potential hazards to flight and ground crew personnel in the form of asphyxiation from oxygen/air displacement, low temperatures during rapid expansion/pressure decay events (e.g. tank blowdown, etc.), and over pressurization of surrounding compartments/volumes. It is not uncommon for these types of applications to exist in human crew extravehicular activity (EVA), such as Simplified Aid for EVA Rescue (SAFER) and intravehicular activity (IVA) environments, such as use of the Gemini Astronaut Maneuvering Unit inside Skylab. (Williams, 1994, pp. 360-361) Accordingly, a thorough hazard analysis is warranted even when non-reactive gases are involved. As a recent example, the impacts of GHe pressurant gas flowing through a relocated burst disk/relief valve vent line into the spacecraft aft compartment had to be verified as non-hazardous.

3.3.4 Operational Fluids: Monopropellants (May Also Be Used in Bipropellant or Dual Mode Propulsion Systems)

3.3.4.1 Hydrazine (N2H4) used in chemical propulsion systems shall be High Purity Hydrazine (HPH) grade that complies with the requirements of MIL-PRF-26536, Performance Specification Propellant, Hydrazine. ***[PSR-77S]***

Rationale: This specification provides stringent controls on contaminants, physical properties, and sampling protocols, and it has been used successfully with propulsion systems on prior human-rated spacecraft. Note that HPH is the only form of this propellant considered adequate for a newly developed human-rated spacecraft due flow decay and performance issues with legacy monopropellant hydrazine (MPH). However, MPH from existing stocks may continue to be used in systems that were previously qualified using that grade. Ref. NASA Technical Bulletin 22-08 Contaminant Reduction in High Purity Hydrazine.

3.3.4.2 High Purity Hydrazine (HPH N2H4) used in chemical propulsion systems shall be assessed for chemical constituents not controlled in MIL-PRF-26536 for impacts to the systems and engines/thrusters. ***[PSR-78G]***

Rationale: Uncontrolled chemical constituents resulting from hydrazine production may impact engine/thruster life and performance, primarily via adverse impacts on the reactivity of catalyst materials contained in the catalyst bed. Reference NESC Technical Bulletin 22-08, Contaminant Reduction in High Purity Hydrazine, and LLIS-29801, Best Practices for the Elemental Profiling of High-Purity Hydrazine. (LLIS-29801, 2020)

3.3.4.3 Hydrogen peroxide (H2O2) used in chemical propulsion systems shall comply with the requirements of MIL-PRF-16005, Performance Specification, Propellant, Hydrogen Peroxide. ***[PSR-79S]***

Rationale: This specification provides stringent controls on chemical composition/purity, physical properties, and sampling protocols, and it has been used successfully with propulsion systems on prior human-rated spacecraft.

3.3.4.4 Nitrous Oxide (N2O) used in chemical propulsion systems shall be Quality Verification Level A (QVL-A) grade that complies with the requirements of CGA G-8.2, Commodity Specification for Nitrous Oxide. ***[PSR-80S]***

Rationale: This specification provides stringent controls on chemical composition/purity, physical properties, and sampling protocols, and it has been used successfully with propulsion systems on prior human-rated spacecraft.

3.3.5 Monopropellant Hazards

3.3.5.1 The worst-case fluid temperatures that could occur on propulsion system components due to environmental exposure and/or a single credible fault (e.g. command or electrical failure to a latch valve, pressure transducer, line heater, etc.) which results in the component being continuously energized shall be determined by test to establish acceptability. ***[PSR-81G]***

Rationale: This maximum fluid temperature is required in order to evaluate fluid decomposition or explosion hazards within the propulsion system, in particular for monopropellants.

3.3.5.2 Hydrazine thruster valves and other head-end engine/thruster components in contact with hydrazine shall be limited to a Maximum Predicted Temperature (MPT) of less than 160 °F under all conditions including faults. ***[PSR-82G]***

Rationale: The MPT includes the highest temperatures that an item can experience during its service life, including all test and operational modes including the uncertainty. The limit of 160 °F is based on all of the materials meeting test requirements in NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft, including Test 15 in NASA-STD-6001, Flammability, Offgassing, and Compatibility Requirements and Test Procedures.

3.3.5.3 Operation of hydrazine thruster valves and other head-end engine components in contact with hydrazine above the value of 160 °F shall require additional material compatibility tests per NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft, and configuration-specific qualification testing with flight-representative hardware, including hydrazine-wetted head-end engine components (e.g., valves, pressure transducers, temperature probes) to demonstrate safe operation. ***[PSR-83G]***

Rationale: Heat from soak back, valve coils, and environment may create temperatures above 160 °F where materials in the valve or system contaminates can cause decomposition. The shuttle APU experienced fuel decomposition, bubble formation, and an explosion, during dwelling at temperatures above 200 °F. (ref) (Hernandez, 2011, p. 4 para 3)

3.3.5.4 Chemical monopropellants (e.g., hydrazine, hydrogen peroxide, nitrous oxide) used in a spacecraft propulsion system shall be demonstrated by test in a flight-representative configuration to avoid catalytic decomposition and adiabatic compression detonation (ACD) events under worst-case pressure, temperature, contamination, and pressurant gas saturation/entrainment conditions. ***[PSR-84G]***

Rationale: Prior experience (e.g., Shuttle APU) informs that relevant variables must be identified to control the safe application of chemical monopropellants in spacecraft propulsion systems, including specifically quantifying the acceptable operating ranges of relevant variables. These variables include helium/nitrogen saturation levels, contamination, pressurization rates, temperature, and/or energy transfer rates. Protocol outlined in ARAED CR-90002, Hazard Classification Testing of Liquid Propellants may be used to guide testing.

3.3.5.5 Spacecraft propulsion systems that involve the storage and distribution of reactive (i.e. non-inert) fluid commodities shall comply with the 'temperature and pressure monitoring' requirements of paragraph F-6 in JSC-8080-2, JSC Design and Procedural Standards. ***[PSR-85S]***

Rationale: The content of paragraph F-6 (Temperature and Pressure Monitoring Requirements for Potentially Hazardous Reactive Fluids) drives the design of a propulsion system that contains reactive (i.e. non-inert) fluids to include sensors for monitoring system pressure and temperature conditions. Such measurements can be used to ensure that no gradual or abrupt increases in pressure and/or temperature are occurring, which could indicate a potentially hazardous reaction is underway within the system. This is an important form of hazard control.

3.3.5.6 Hydrazine (N2H4) application shall be evaluated for hazards observed in the past per AIAA SP-084-1999, Fire, Explosion, Compatibility, and Safety Hazards of Hypergols – Hydrazine. ***[PSR-86S]***

Rationale: The cited document is considered a comprehensive reference for the properties and hazards associated with hydrazine. It was originally published by the NASA White Sands Test Facility (WSTF) and later converted to a Special Project (SP) document by the AIAA.

3.3.5.7 Nitrous Oxide (N2O) application shall be evaluated for monopropellant ignition mechanisms (e.g. friction, spark, impact), adiabatic compression, material compatibility, catalytic decomposition or the gas and liquid phases, flow induced (e.g. cavitation) and contamination hazards, with adequacy of the hazard controls to be verified by test. ***[PSR-87G]***

Rationale: Recent serious safety incidents involving N2O indicates that addressing the hazards of N2O is required, as discussed in Scaled Composites N2O Safety Guidelines 6.17.09.doc

(Composites, 2009) and AFRL-RZ-ED-TP-2008-184, Nitrous Oxide Explosive Hazards (Merrill, 2008). It should be noted that additional testing will be required to show acceptability of the hazard controls, as indicated by the requirement statement itself.

3.3.5.8 Hydrogen Peroxide (H2O2) systems shall be evaluated for hazards per NASA HYDROGEN PEROXIDE PROPELLANT HAZARDS TECHNICAL MANUAL. ***[PSR-88S]***

Rationale: NASA HYDROGEN PEROXIDE PROPELLANT HAZARDS TECHNICAL MANUAL contains many additional references cited therein.

3.3.5.9 Hydrogen peroxide (H2O2) systems shall follow documented and validated contamination control and inspection processes to preclude catastrophic hazards due to decomposition and component failures driven by contamination related conditions (leakage, plugging, etc.). ***[PSR-89G]***

Rationale: Hydrogen peroxide, as well as other monopropellants, is sensitive to contamination causing decomposition so strict attention to contamination control practices is critical to ensure the associated hazards are adequately controlled.

3.3.5.10 The potential for cavitation and its associated hazards in hydrogen peroxide propulsion systems shall be evaluated by test as part of system design qualification . ***[PSR-90G]***

Rationale: The intent here is to assess the hazards associated with hydrodynamic cavitation of hydrogen peroxide by test as part of system design qualification. In the case of rapid valve actuation cycles, such as with pulsing engine/thruster systems, it may be possible for water-hammer effects to create cavitation and then the liquid column to collapse the vapor at the engine/thruster valve if closed rapidly. The resulting high amplitude pressure and rapid compression of the condensable vapor, including any influence of evolved non-condensable pressurant gases, needs to be evaluated for localized decomposition of hydrogen peroxide if cavitation is allowed to occur. There is also the potential for cavitation-induced erosion of the materials, performance degradation, and hardware failures in the prop system. Reference NESC Technical Bulletin 21-01, Experimental and Computational Study of Cavitation in Hydrogen Peroxide.

3.3.5.11 An evaluation of the catalytic effect of propulsion system materials of construction on decomposition of hydrazine, and other monopropellants, at maximum predicted temperatures shall be performed. ***[PSR-91G]***

Rationale: The materials of construction can have an increased catalytic effect of with increasing temperatures on decomposition of the monopropellant which can lead to an explosion and rupture of the hardware. Note that this type of evaluation for hydrazine specifically is also addressed in the broader context of hazard assessment in paragraph 3.3.4.9.

3.3.5.12 To control hazard for adiabatic / rapid compression detonation of monopropellants (N2H4, H2O2, N2O), the propulsion system and its components shall be evaluated for *thermal and pressure transient operation that could create gas bubbles via desaturation of pressurant gases, propellant vapors caused by heating, or auto decomposition product gases, and then subsequently rapidly compress the bubble thus creating an explosion hazard.* ***[PSR-92G]***

Rationale: The most likely mechanism of explosive failure of a Shuttle APU is that during post-Auxiliary Power Unit (APU) shutdown in the space environment, the thermal soak back caused a slow hydrazine decomposition in the fuel pump and Gas Generator Valve Module (GGVM) areas. The resultant gas bubble was adiabatically compressed during pulse-mode operation of the APU, resulting in a temperature transient that caused an explosion. Corrective action included allowing time to cool both the APU fuel pump and the GGVM after shutdown in space (vacuum) conditions. This historical failure involving the Shuttle APU is also relevant to spacecraft propulsion systems that feature pulsing thrusters consuming hydrazine propellant, which can have similar vulnerabilities. (ref) (Hernandez, 2011)

3.3.5.13 Throat plugs inserted into engines/thrusters using monopropellant hydrazine shall have a flow-through inert-gas purge that has been demonstrated by test to prevent carbon dioxide exposure at the air interface, and all associated corrosion of engine components, whenever the valves are wetted with propellant during ground operations. ***[PSR-93G]***

Rationale: The reaction between hydrazine leakage/permeation passing through the thruster valve seat and carbon dioxide from the ambient air has been observed to cause carbazic acid corrosion of valves and other sensitive parts of the engine/thruster, resulting in failures of the affected hardware in service. This effect is particularly concerning for reusable vehicles that experience multiple ground turnaround cycles with thruster valves remaining wetted with propellant.

3.3.6 Operational Fluids: Bipropellants

Note that any monopropellant used in bipropellant applications must also meet the requirements of Sections 3.3.4 and 3.3.5.

3.3.6.1 Oxygen (O2) used in chemical propulsion systems on human-rated spacecraft shall comply with the requirements of MIL-PRF-25508, Performance Specification, Propellant, Oxygen, with the exception of in-space generated propellant where engine/thruster and system level hot fire qualification testing has demonstrated that all performance and life requirements can be met with the worst-case commodity composition to be produced. ***[PSR-94S]***

Rationale: This specification provides stringent controls on chemical composition/purity, physical properties, and sampling protocols, and it has been used successfully with propulsion systems on prior human-rated spacecraft. Note that this specification covers the liquid and gaseous forms of oxygen. Also note that a higher purity of O2, such as Type II Grade A with a modified min purity level of 99.85% by volume, may save propellant mass on the spacecraft.

3.3.6.2 *Hydrogen (H2) used in chemical propulsion systems on human-rated spacecraft shall comply with the requirements of MIL-PRF-27201, Performance Specification, Propellant, Hydrogen, with the exception of in-space generated propellant where engine/thruster and system level hot fire qualification testing has demonstrated that all performance and life requirements can be met with the worst-case commodity composition to be produced.* ***[PSR-95S]***

Rationale: This specification provides stringent controls on chemical composition/purity, physical properties, and sampling protocols, and it has been used successfully with propulsion systems on prior human-rated spacecraft. Note that this specification covers the liquid and gaseous forms of hydrogen.

3.3.6.3 *Nitrogen Tetroxide (NTO) used in chemical propulsion systems on human-rated spacecraft shall comply with the requirements for mixed oxides of nitrogen (MON) blends of MON3 or higher per MIL-PRF-26539, Performance Specification Propellants, Dinitrogen Tetroxide, with the added provision that water content be below 0.05% by weight and iron content be below 0.1 mg/kg (ppmw).* ***[PSR-96SC]***

Rationale: This specification provides stringent controls on chemical composition/purity, physical properties, and sampling protocols, and it has been used successfully with propulsion systems on prior human-rated spacecraft to avoid the common cause failure of hardware. The use of a MON3 blend, with a nitric oxide (NO) content of 3%, has become common practice for propulsion systems in human-rated spacecraft, but other MON blends with a higher NO content are also considered acceptable. Note that the version of this MIL-PRF specification cited in Table 2 reflects a water content of <0.17% by weight and an iron content of <0.5 ppm by weight (ppmw), which are considered excessive for human rated prop system applications. This is based on significant past history involving accelerated corrosion and formation/accumulation of gelatinous and/or crystalline iron nitrate deposits (flow decay material) within the propulsion system (e.g. orifices, valves, filters, etc.) at higher levels of water and iron content, which can be especially severe in long-life systems with high propellant throughput, iron-bearing materials of construction (e.g. stainless steel, etc.), and external interfaces between the prop system and ambient moist air. Even Titanium propulsion systems may contain components with propellant-wetted, iron-bearing piece-parts which could experience corrosion in MON3, thus increasing the local concentration of iron available for nitrate precipitation in small flow orifices, tight-clearance mechanical interfaces between moving parts, and sealing interfaces. As a result, the added provision in this requirement drives those levels down to <0.05% and <0.1 ppmw, respectively, to aid in controlling the associated adverse effects . These low levels have been used successfully in recent human spacecraft, though they may drive the need for additional processing through a molecular sieve to achieve. Deviations to this requirement may be considered by the NASA Propulsion and M&P engineering teams based on specific circumstances (e.g. wetted materials, exposure durations, pressure/temperature ranges, corrosion behavior, orifice sizes and moving part clearances, seal configurations and materials, filter locations and ratings, qualification test approach and results, heritage usage experience, etc.). Also note that MON1 is prohibited due to its excessively low NO content, which can lead to stress corrosion cracking (SCC) and rupture of titanium alloy propellant tanks and weld joints, as observed in past spacecraft.

3.3.6.4 *For propulsion systems on human-rated spacecraft that use titanium alloy propellant tanks with nitrogen tetroxide propellant, a nitric oxide (NO) content of at least 1.0% shall be maintained at all times during ground and flight operations.* ***[PSR-97G]***

Rationale: Maintaining a minimum NO content of 1.0% in a MON blend of nitrogen tetroxide propellant is necessary to prevent stress corrosion cracking (SCC) and rupture of titanium alloy propellant tanks and weld joints, as observed in past spacecraft. During ground and flight operations, a concerted effort is needed to ensure that the NO content of the propellant remains above the 1.0% threshold at all times. For example, vacuum loading or venting of the propellant tank below the vapor pressure of the fluid at the prevailing temperature condition will serve to remove the NO content that is critical for preventing SCC. (Ref) NASA-TN-D-6795, Apollo Experience Report: Pressure Vessels . (Ecord, 1972, p. 17)

3.3.6.5 *Monomethylhydrazine (MMH) used in chemical propulsion systems on human-rated spacecraft shall comply with the requirements of MIL-PRF-27404, Performance Specification Propellant, Monomethylhydrazine.* ***[PSR-98S]***

Rationale: This specification provides stringent controls on chemical composition/purity, physical properties, and sampling protocols, and it has been used successfully with propulsion systems on prior human-rated spacecraft.

3.3.6.6 *Methane (CH4) used in chemical propulsion systems on human-rated spacecraft shall comply with the requirements of MIL-PRF-32207, Performance Specification, Propellant, Methane, with the exception of in-space generated propellant where engine/thruster and system level hot fire qualification testing has demonstrated that all performance and life requirements can be met with the worst-case commodity composition to be produced.* ***[PSR-99S]***

Rationale: This specification provides stringent controls on chemical composition/purity, physical properties, and sampling protocols, and it has been used successfully with propulsion systems on prior human-rated spacecraft. Note that this specification covers the liquid and gaseous forms of methane that may be procured as liquified natural gas.

3.3.6.7 Kerosene used in chemical propulsion systems on human-rated spacecraft shall comply with the requirements of MIL-DTL-25576, Detail Specification Propellant, Rocket Grade Kerosene. ***[PSR-100S]***

Rationale: This specification provides stringent controls on chemical composition/purity, physical properties, and sampling protocols, and it has been used successfully with propulsion systems on prior human-rated spacecraft.

3.3.7 Bipropellant MMH/NTO Hypergolic Systems Hazards

There are several sources of requirements, best practices, and hazards based on lessons learned for hypergolic systems.

3.3.7.1 The propulsion system design, operational procedures and associated ground support test equipment and facilities shall address hazards identified in AIAA SP-086-2001 (NTO), "Fire, Explosion, Compatibility, and Safety Hazards of Nitrogen Tetroxide." and AIAA SP-085-1999 "Fire, Explosion, Compatibility, and Safety Hazards of Hypergols – Monomethylhydrazine". ***[PSR-101S]***

Rationale: Numerous examples of injury, death, and close calls are identified in (Nufer, 2010) .

3.3.7.2 Hypergolic propulsion systems shall implement and maintain a dry, low dew point environment , that has been shown through component testing to prevent corrosion, at all dynamic and environmental seals and openings if the system is exposed to local atmospheric conditions while loaded with oxidizer. ***[PSR-102G]***

Rationale: Lessons learned on corrosion show that moisture and NTO will permeate and mix in the sealing surface creating corrosion causing leaks and/or sticking of the mechanism. NTO vapors will continue to offgas even after draining the liquid propellant and will mix with atmospheric water to create highly corrosive nitric acid during ground turnaround activities, thus damaging the exposed hardware. The primary means of meeting this requirement has typically involved an inert gas purge with dew point measurements to verify the specified level of dryness, but other solutions may also exist.

3.3.7.3 Throat plugs for engines/thrusters using hypergolic propellants shall have a flow through purge to prevent NTO/MON3 propellants from reacting at the fuel valve seat and to reduce moisture exposure at the air interface during ground operations whenever the valves are wetted with propellants. ***[PSR-103G]***

Rationale: The low-level chemical reaction between fuel and oxidizer due to thruster valve seat leakage/permeation has been observed to create energetic deposits of Fuel-Oxidizer Reaction Product (FORP) residue inside the injector and combustion chamber under certain circumstances. The heat energy created by the low-level oxidizer-fuel reaction can also cause fuel valve seat extrusion and result in leakage and valve response time changes (including engine/thruster fail-off in flight). The reaction of ambient moisture and NTO at the valve seat can also cause localized corrosion, resulting in additional leakage that makes the situation worse. This effect is particularly concerning for reusable vehicles that experience multiple ground turnaround cycles with thruster valves remaining wetted with oxidizing propellants.

3.3.7.4 The use of Teflon-lined flex hoses shall be prohibited in the design of human rated spacecraft propulsion systems featuring hypergolic monopropellants and bipropellants, or any other propellants that can permeate the Teflon and create a hazard. ***[PSR-104G]***

Rationale: Although Teflon-lined flex hoses are common in hypergolic propellant ground servicing systems and have also appeared sparingly on select hydrazine propulsion and auxiliary power unit (APU) applications for human rated spacecraft, that type of hardware is not an all-welded configuration (i.e., the Teflon liner is non-metallic and there's a mechanical joint at the interface between the Teflon and metallic end fittings). In addition, Teflon-lined flex hoses do not have a NASA-accepted design and construction standard and have experienced degradation over time with exposure to propellant (e.g., blistering) in ground applications, driving the need for additional periodic inspection, testing, and replacement efforts. Finally, the Teflon liner configuration presents a heightened risk of propellant absorption/permeation, GHe pressurant gas permeation (Hernandez, 2011, p. 9), hydrogen gas permeation (Sandia Report SAND2012-7321, Technical Reference on Hydrogen Compatibility of Materials, Section 8100), and premature failure in service, all of which can result in a hazardous external leakage/release of propulsion system fluid commodities. As such, the intent of this requirement is to prohibit the use of Teflon-lined flex hoses on human rated propulsion systems, with all-welded metal bellows flex hoses being considered as a reasonable substitute. Reference KSC-STD-Z-0006, Design of Hypergolic Propellants Ground Support Equipment, Standard For, and LLIS-8016, Residual Oxidizer in Flex Tubing High Visibility Close Call. (LLIS-8016, 2013)

3.3.8 Bipropellant Cryogenic Systems Hazards

Cryogenic propulsion systems and their associated test fluids and propellants (e.g. LN2, LHe, LCO2, LAr, LH2, LO2, LCH4, LNG, etc.) present unique challenges and hazards for personnel and equipment during ground operations and in-flight usage. Examples include, but are not limited to, skin damage from low touch temperatures, asphyxiation from inert gas displacement of air, explosions from rapid volumetric expansion at increasing temperatures, failure of hardware from exposure to low temperatures, localized formation of water ice and liquid air (a.k.a. oxygen enriched air), and various ignition mechanisms within oxidizer systems. The requirements and references in this section are intended to address such hazards. The section primarily assumes liquid oxygen as the oxidizer; however, these requirements may also extend to other cryogenic oxidizers. Other cryogenic fuels will need similar hazard control manuals.

3.3.8.1 Ground and flight hazards associated with the use of oxygen in a human rated spacecraft propulsion system shall be evaluated in accordance with ASTM G88-21, Standard Guide for Designing Systems for Oxygen Service and ASTM MNL 36, Safe Use of Oxygen and Oxygen Systems: Guidelines for Oxygen System Design, Materials Selection, Operations, Storage, and Transportation. ***[PSR-105S]***

Rationale: These standards and handbooks address many catastrophic hazards associated with oxygen systems that have a long history of lessons learned.

3.3.8.2 Ground and flight hazards associated with the use of hydrogen in a human rated spacecraft propulsion system shall be evaluated in accordance with ANSI/AIAA G-095, Guide to Safety of Hydrogen and Hydrogen Systems. ***[PSR-106S]***

Rationale: These standard addresses many catastrophic hazards associated with hydrogen systems that have a long history of lessons learned.

3.3.8.3 Cryogenic propellants (Oxygen, Liquified Natural Gas /Methane, etc.) use application and operations shall be evaluated for boil-off that will leave other hydrocarbons as residuals in the propellant tanks. ***[PSR-107G]***

Rationale: Residues, such as hydrocarbons in oxygen systems, can result in hazardous chemical reactions within spacecraft propulsion systems. A propellant such as liquified natural gas, which is mostly composed of methane initially, can change chemical composition and fluid properties as methane boils-off, thus resulting in off-nominal performance as the system is loaded, vented, and then reloaded. Use specification is critical to monitor this.

3.3.8.4 The system and its components, including pressure vessel and line insulation systems, shall be evaluated at cryogenic temperatures, including any additional sub-cooling below Normal Boiling Point (NBP), causing liquefaction of air or intrusion of moisture via cryopumping (i.e. into foam, etc.). ***[PSR-108G]***

Rationale: Liquefaction of air could cause enriched oxygen liquid to drip off surfaces. Intrusion of moisture could upon expansion cause failure of the insulation system and create debris.

3.3.8.5 The propulsion system and its operation shall be evaluated for boiling liquid expanding vapor explosion (BLEVE) as caused by external heating. ***[PSR-109G]***

Rationale: Adequate insulation from heat and relief device as required to insure 1 FT to this catastrophic hazard.

3.3.8.6 Moisture content of cryogenic propulsion systems shall be verified and maintained below a specified dewpoint or moisture content, shown by test and analysis to prevent plugging of critical components such as orifices, filters, and FOD screens. ***[PSR-110G]***

Rationale: Ice formation in the cryogenic propellant can plug filters and orifices. This includes moisture from the environment, pressurant gases, propellants, or autogenous pressurization systems.

3.3.9 Propellant and Pressurant Data Property Traceability

3.3.9.1 *For a human rated spacecraft propulsion system, the physical and/or thermodynamic properties of all fluids used for the purpose of propulsion system analyses/assessments shall be traceable to the National Institute of Standards and Technology (NIST) and applicable over the full range of system operating conditions in service, with an exception to use AFRPL-TR-69-149 and AFRPL-TR-76-76 for hydrazine based fuels and nitrogen tetroxide, respectively.* ***[PSR-111G]***

Rationale: The use of inaccurate/incorrect physical and/or thermodynamic properties of fluids when performing propulsion system analyses/assessments could lead to unexpected catastrophic failures of the hardware in service. Fluids that are commonly used in the propulsion system include liquid and vapor phase propellants and pressurant/pneumatic/purge gases. For Hydrazine and MMH, 1969 AFRPL-TR-69-149, USAF Handbooks, Hydrazine Fuels, Vol I, is a good source because it combines data from several sources and includes a wide range of properties. For Nitrogen Tetroxide Oxidizers, 1976 AFRPL-TR-76-76, USAF Propellant Handbooks, Nitric Acid/Nitrogen Tetroxide Oxidizers, Vol II, is a good source, with the following additional references; (ref) AIAA 2015-4158, Density Fit for MON Oxidizer Blends Including Accuracy (Mueller M. , 2015) and (ref) AIAA 2015-4159, Vapor Pressure Fit for MON Oxidizer Blends Including Accuracy (Mueller M. J., 2015). For helium solubility, reference AIAA Journal of Propulsion and Power, Vol 31, No 4, July-August 2015, Solubility of Pressurant Gases in Liquid Hydrazine at Elevated Temperature (Desain, 2015) and NASA-Tech Bulletin 22-07, Helium Solubility in MMH and NTO. Also reference LLIS-6146, Absence of Explicitly Defined Fluid Property/Composition at The Vehicle/Engine Interface. (LLIS-6146, 2010)

3.3.9.2 *If the physical and/or thermodynamic properties of a particular fluid used for the purpose of propulsion system analyses/assessments are not available from an existing NIST-traceable source, then a NIST-approved methodology shall be used for generating those properties.* ***[PSR-112G]***

Rationale: The NIST Chemistry WebBook and the NIST REFPROP program do not contain all properties for all fluids that may be needed for propulsion system analyses/assessments of critical importance to system performance and hazard control. In that case, it is important to develop the necessary fluid properties in a manner that is endorsed by NIST to ensure accuracy.

3.4 MATERIALS AND PROCESSES (M&P) AND FLUID COMPATIBILITY

3.4.1 Materials and Processes Standard

3.4.1.1 *Materials and processes used in the design, fabrication, assembly/integration, testing/checkout, and cleaning/contamination control of spacecraft propulsion systems, subassemblies, and components, including vendor-designed, commercial off-the-shelf, and vendor-furnished items, shall meet the requirements of NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft.* ***[PSR-113S]***

Rationale: This requirement is needed to ensure that sufficient attention to detail is provided in the technical discipline of materials and processes for spacecraft propulsion systems and components to avoid premature and unexpected failures of the hardware while in service. The concern includes common cause failures of multiple components stemming from material and/or process issues that could lead to rupture of the propulsion system. The standard being cited here is intended to provide a uniform and comprehensive set of requirements for governing the selection of materials, fabrication methods, and control of critical processes used in design, manufacturing, and assembly of spacecraft propulsion systems and components that can have a major influence on hardware performance and hazard control.

3.4.1.2 Materials and processes used in the design, fabrication, assembly/integration, testing/checkout, and cleaning/contamination control of Special Test Equipment (STE) and Ground Support Equipment (GSE) that interfaces with spacecraft propulsion systems and components shall meet the requirements of NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft. ***[PSR-114G]***

Rationale: This requirement is needed to ensure that sufficient attention to detail is provided in the area of materials and processes for interfacing STE and GSE to avoid damaging or contaminating spaceflight propulsion systems and/or components while in service. The standard being cited here is intended to provide a uniform and comprehensive set of requirements for governing the selection of materials and control of critical processes used in STE/GSE that can have a major influence on spacecraft propulsion system and component performance and hazard control. Any requirements contained in NASA-STD-6016 that relate to the space environment experienced by the spacecraft propulsion system itself (e.g. vacuum, radiation, etc.) would not apply to the interfacing STE/GSE.

3.4.2 Test and Assembly Fluids; Cleaning, Flushing, and Drying

The fluids specified in this section have commonly been used for assembly, integration, and testing (AI&T) activities associated with human rated spacecraft propulsion components and systems. Fluids not specified here may also be considered for use during AI&T, providing a thorough assessment of the effects on propulsion system materials of construction and operational propellants is conducted to ensure no performance/life impacts or hazards exist.

3.4.2.1 Deionized (DI) water used for cleaning, flushing, testing, and/or assembly of propulsion system hardware shall meet the requirements of ASTM D1193, Standard Specification for Reagent Water, Type I (any grade) or Type II (any grade), with the added provision that the 'monitoring' content of Appendix X1.3 be implemented. ***[PSR-115SC]***

Rationale: This specification provides stringent controls on chemical composition/purity, physical properties, and sampling protocols which have been used successfully with propulsion systems on prior human-rated spacecraft. There have been many past instances of issues involving water, including corrosion, other chemical reactions, and the introduction of non-volatile residue (NVR), which warrant strict control on the water being used for these purposes. A past example of this type of issue involves the common-cause failure of multiple engines/thrusters due to elevated chloride content found in the DI water. Note that Type III DI water is not considered acceptable due to the significant increase in allowable hydrocarbon, silica, chloride, and sodium content. Also note that the 'monitoring' content of Appendix X1.3 is currently written as a guideline but is viewed as especially important for ensuring a continuously acceptable level of DI water quality.

3.4.2.2 Isopropyl alcohol (IPA) used for cleaning, flushing, testing, and/or assembly of propulsion system hardware shall meet the requirements of TT-I-735, Isopropyl Alcohol, Grade A, with the final rinse and sampling using reagent grade or better. ***[PSR-116S]***

Rationale: This specification provides stringent controls on chemical composition/purity, physical properties, and sampling protocols which have been used successfully with propulsion systems on prior human-rated spacecraft, including MPCV and others.

3.4.2.3 Argon used for welding during assembly of a human rated spacecraft propulsion system shall meet the requirements of CGA G-11.1, Commodity Specification for Argon, Quality Verification Level (QVL) C, D, E, or F, or MIL-PRF-27415, Propellant Pressurizing Agent, Argon, Type I, Grade A or B. ***[PSR-117S]***

Rationale: These specifications provide stringent controls on chemical composition/purity, physical properties, and sampling protocols which have been used successfully for propulsion system assembly on prior human-rated spacecraft. Note that this specification covers the liquid and gaseous forms of argon.

3.4.2.4 Hydrofluoroether (HFE) solvent used for cleaning and/or flushing of propulsion system hardware shall meet the requirements of A-A-59150, Cleaning Compound, Solvent, Hydrofluoroether (HFE). ***[PSR-118S]***

Rationale: This specification provides stringent controls on chemical composition/purity, physical properties, and sampling protocols which have been used successfully with propulsion systems on prior human-rated spacecraft. Note: This fluid may not be available in the near future, though an equivalent replacement has yet to be identified and formally evaluated for acceptability for inclusion in this propulsion standard. Compatibility of HFE with hydrazine and monomethyl hydrazine fuels in a propulsion system has also been recently shown to be an issue and requires removal of residual fluorinated solvents to less than 10 ppm.

3.4.2.5 Leak detection fluid used for leak checks on external surfaces of a propulsion system hardware shall meet the requirements of MIL-PRF-25567, Leak Detection Compound, Oxygen Systems, Type I or Type II. ***[PSR-119S]***

Rationale: This specification provides stringent controls on chemical composition/purity, physical properties, and sampling protocols which have been used successfully with propulsion systems on prior human-rated spacecraft. This type of liquid leak detection fluid (a.k.a. bubble soap) would be used when performing leak checks in accordance with 'Method XII—Foam/Liquid Application' as described in paragraph 5.12 of NASA-STD-7012, Leak Test Requirements.

3.4.2.6 For any cleaning, flushing, testing, and/or assembly fluids not covered in the preceding paragraphs of this section, an assessment of compatibility for those fluids with the propulsion system materials of construction and operational propellants shall be performed to ensure no detrimental interactions or effects. ***[PSR-120G]***

Rationale: The possibility exists that process fluids not covered in the other paragraphs of this section may be proposed for use with the propulsion system hardware. In those cases, it is critical to ensure that any detrimental effects on the propulsion system materials of construction and the operational propellants be identified early in the development process to avoid potential hazards created by adverse interactions that may occur within the system. As an example, two NASA technical documents, NASA/TP-2015-218207 and NASA/TM-2017-219687, were generated in the assessment of various cleaning solvents proposed to replace HCFC-225, being discontinued due to Earth environmental impacts, for use with gaseous oxygen (GO2) and liquid oxygen (LO2) propulsion system hardware. Compatibility with hydrazine and monomethyl hydrazine fuels has also been recently shown to be an issue and requires removal of residual fluorinated solvents to less than 10 ppm. Reference LLIS-1334, Cleanliness of Diaphragm Propellant Tanks (2000). Close coordination with the NASA Propulsion and Materials & Processes (M&P) Engineering teams will be necessary for the review/approval of any new/unique fluids proposed for use in a human rated propulsion system.

3.4.2.7 Verification of dryness at component level during acceptance testing and at integrated propulsion system level after final assembly shall be performed to ensure that residual water and other solvents have been removed to the specified levels. ***[PSR-121G]***

Rationale: Part of the use of these materials on a propellant/purge system is also verification of removal of water and/or solvents to ensure a dry system. Verification of water removal is through a dew point and solvent removal is with a Draeger apparatus that is set to measure the specific solvent. Reference LLIS-2043, Understand What 'Cleaning' Means in The Context of The Flight Item. (LLIS-2043, 2009)

3.4.3 Component Fluid Compatibility and Corrosion Assessment Test

3.4.3.1 Qualification of spacecraft propulsion systems and components shall include performance testing of flight-representative hardware items, inclusive of any lubricants, before, during, and after exposure to all relevant propellants and other service fluids over an enveloping range of internal pressures/temperatures, ambient external environments (pressures/temperatures, humidity, etc.), and exposure durations, inclusive of ground and flight activities over the full vehicle service life, to assess fluid compatibility, corrosion characteristics, and functional performance degradation of the hardware. ***[PSR-122G]***

Rationale: Propulsion system components frequently contain precision moving parts and complex mechanisms that must function properly for mission success and crew safety under harsh internal and external conditions/environments. Selection of these components based solely on a list of ‘compatible’ propellant-exposed materials and performance/life testing with non-flight-like referee fluids only (e.g. inert gas, water, etc.) or actual propellants with a shortened exposure period and no interacting external environments (e.g. moist ambient air, ozone, etc.), has contributed to numerous hardware anomalies in the past. Therefore, component and/or system level testing with relevant flight fluids in combination with potentially interacting external environments is needed to ensure acceptable hardware performance over time. For example, internal exposure to MON3 with simultaneous external exposure to moist air can lead to the formation of nitric acid and corrosion of the hardware in the event of seal permeation or leakage. Common cause functional failures of multiple components or rupture of pressurized systems may result due to the effects of corrosion and/or material degradation. Where material compatibility assessments and enveloping test data or flight operations of the nature described above do not exist from heritage projects/programs to justify component selection, additional qualification testing of flight-representative hardware is necessary to avoid unexpected and premature failure while in service. This testing is intended to capture all relevant propellant exposure conditions (e.g. pure liquid, pure vapor, condensed vapor droplets/film, mixtures of vapor with inert gas and/or moist air, etc.) over the full range of operating environments (e.g. pressures, temperatures, etc.) and durations (e.g. physical time, actuation cycles, wet/dry cycles, etc.), inclusive of ground and flight activities. These test attributes, either individually or collectively, can influence hardware performance via the effects of corrosion, permeation, absorption/adsorption, chemical/physical/mechanical property degradation, and other possible mechanisms. Note that testing of this nature may be accomplished in a variety of different ways, spread across multiple test articles, accelerated with time by varying certain test parameters, using a ‘fleet leader’ test article approach, etc. As a result, early coordination of test plans with the Propulsion and M&P Engineering teams of the NASA Technical Authority is recommended. Reference LLIS-487, Long Term Materials Compatibility in Propulsion Systems (LLIS-487, 1997)and LLIS-1000, Leaking Reaction Control System (RCS) Thruster Valves. (LLIS-1000, 1997)

3.4.3.2 Fluid line material selection and manufacturing tool materials (dies, mandrels) that can leave residues within propellant wetted surfaces shall address hazards of catalytic propellant decomposition and gas generation within the propulsion system. ***[PSR-123G]***

Rationale: In recent past programs, precision cleaned tubing has been delivered with residual deposits from the manufacturing tooling on the internal propellant wetted surfaces of the hardware. Those deposits contained materials that were incompatible with the propellants to be used and were only discovered via borescope inspections of the hardware. The intent of this requirement is to prevent those types of incompatible deposits from occurring in the first place, rather than relying on precision cleaning and inspection processes to address such conditions prior to integration of the affected hardware into the propulsion system.

3.4.3.3 Fluid line and component selections that involve corrosion resistant steel (CRES) exposed to NTO in a human rated spacecraft propulsion system shall assess the flow passages and/or clearances where obstruction could occur due to corrosion products. ***[PSR-124G]***

Rationale: There have been numerous past instances of iron nitrate 'flow decay material' causing NTO propellant flow restrictions, particularly involving small/tight flow passages and clearances (e.g., clogging of orifices, valve flow passages, and filters) and other adverse performance effects (e.g., valve stiction and leakage) on propulsion system hardware. These effects can be mitigated by reducing the level of iron in the NTO (see requirement herein for verifying water and iron content at the interface to GSE supplying propellant), avoiding or limiting iron-bearing materials of construction in NTO wetted hardware, and ensuring that the system is dry, and addressed by performing an assessment of iron nitrate 'flow decay material' sensitivity in the propulsion system as a whole. Reference LLIS 305, Galileo Retro Propulsion Module (RPM) Flow Decay Problem. (LLIS-305, 1993)

3.4.3.4 Materials or fluids used in propulsion system components that may come into contact with other operating fluids and materials due to the leakage or structural failure of a seal or barrier (includes a TWFPB) shall be evaluated for compatibility. ***[PSR-125G]***

Rationale: Leakage or structural failure of seals, diaphragms, or bellows in components such as sensors, valves, pressure regulators, etc. may result in propulsion system operating fluids coming in contact with other incompatible fluids or materials. In addition to causing a functional failure of the affected component, additional potentially hazardous effects could also be realized (e.g. structural failure/rupture of a secondary compartment/volume, overboard release of propellant, decomposition of propellant, shorting of electrical circuits, fire/explosion or other chemical reaction within the secondary compartment/volume, etc.). Examples include corrosion of brass valve stem retainer nuts due to hydrazine decomposition to ammonia and leakage through the stem seals, resulting in failure of the valve and bulk propellant release, in addition to the degradation and reactivity of electrical circuit board EEE parts and conformal coating when exposed to propellant. As a result, a failure modes and effects analysis (FMEA) and hazard analysis (HA), inclusive of static/dynamic seals and TWFPBs, are considered necessary to identify and assess those risks. Reference LLIS-1380, Pressure Transducer, Failure. (LLIS-1380, 2002)

3.4.4 Propellant Oxidizer and Material Ignition and Combustion

3.4.4.1 A compatibility assessment related to ignition and sustained burning of the materials of construction in a spacecraft propulsion system containing any oxidizer propellant shall be completed in accordance with paragraphs 4.2.1.4 (Oxygen Compatibility) or 4.2.1.3 (Fluid Compatibility, Fluids Other Than Oxygen) of NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft. ***[PSR-126SC]***

Rationale: The catastrophic hazards associated with ignition/burning of propulsion system materials of construction when exposed to oxidizing propellants in a spacecraft propulsion system are well known and destructive events have been experienced in recent programs. Operation at high pressures, temperatures, and velocities, including transient dynamics are of particular concern as those conditions may support ignition and combustion of the propulsion system materials of construction by the oxidizer propellant. This is a particular concern when using Titanium alloys for tanks, lines, and components in contact with oxidizers. Assessments driven by this requirement are typically organized by ignition mechanism (e.g. mechanical impact ignition, frictional ignition, particle impact ignition, adiabatic heating/ignition), system segment (e.g. GHe press system, oxidizer propellant system), and mission phase/event (e.g., prop loading, pre-launch, in-flight ops, entry/landing, etc.), and the risk is assessed using a combination of analysis + testing that maps to a rating scale provided by the M&P subject matter experts as part of the Engineering Technical Authority. Reference NESC Technical Bulletin 20-06: Material Compatibility Assessment of Spacecraft Oxidizer Systems; NASA TM-2007-213740, Guide for Oxygen Compatibility Assessments on Oxygen Components and Systems. (Keisa Rosales, 2007)

3.4.5 Soft Goods Material Selection, Propellant and Cleaning Fluid Exposure

3.4.5.1 *Non-metallic materials (i.e. soft goods) used in propulsion systems and components shall be assessed per NASA-STD-6016, paragraph 4.2.1.3 [MPR 47 and 48] for the chemical, physical, and mechanical effects of exposure to relevant liquid and/or vapor phase propellants at min/max temperature and pressure range and cleaning fluids, with additional tests for electrical insulation impacts as necessary, over the service life of the hardware to ensure there are no detrimental impacts to hardware performance.* ***[PSR-127S]***

Rationale: History has shown that the selection of individual non-metallic materials considered ‘compatible’ with the liquid and/or vapor phase propellants for a given propulsion system application is not sufficient alone to ensure functionality and maintain in-specification performance of the hardware over time. Soft goods of concern include static and dynamic seals, guide rings, flexible diaphragms, low-friction surface coatings, actuation soft-stops, flex hose liners, electrical insulation, etc. Chemical, physical, and mechanical effects of concern include reactivity, swelling, softening, permeation, cold flow, embrittlement, bonding adherence, frictional properties, electrical resistance, etc. Despite being ‘compatible’ with the propellants, these types of non-metallic items can still experience subtle changes in key attributes/properties from exposure to propellant that can adversely affect the functional performance and cycle life of the hardware. Examples of effects that should be considered in this assessment include, but are not limited to, the following:

- Seal Swell – This effect can alter the stroke, response time, pressure drop, leakage characteristics, and cycle life of a valve. It can alter the stroke of a back-relief mechanism in a valve leading to rupture of a liquid-locked propellant line. It can alter the precision fit of guide rings in a pressure regulator thus affecting the damping characteristics, dynamic performance, and cycle life of the unit. It can contribute to the increased cold-flow of seals within a valve or flange joint leading to increased leakage. Other detrimental effects are also possible such as leading to obstructed flow past valve seat.

- Seal or Liner Permeation – This effect can lead to propellant migration through single or redundant seals into secondary volumes/compartments containing incompatible materials subject to chemical reaction with the propellant vapor (e.g. slow corrosion, rapid energetic reaction, etc.), thus leading to functional failure or rupture of the component. It can also lead to propellant migration into the local ambient environment where mixing with ambient moist air could produce a highly acidic byproduct that corrodes interfacing materials resulting in the failure of a valve or actuator to operate when commanded. Other detrimental effects are also possible.
- Leak caused by an electrostatic charge generated by the flow of the non-conductive oxidizer through the Teflon flex line, discharging to the wire mesh covering. Reference LLIS-217, Galileo Retro Propulsion Module Oxidizer Leak During Loading (LLIS-217, 1992). Reference NASA Lesson Learned "Long Term Compatibility in Propulsion System (1993). (LLIS-487, 1997)

3.4.5.2 Cleaning fluids for Oxidizer and Fuel designated components shall be specific to the propellant to preclude putting a fluid that is a fuel into an oxidizer component containing soft goods, or trapped cavities created by soft goods, that can cause a combustion hazard. ***[PSR-128G]***

Rationale: This is intended for an assembled component to prevent combustion hazards that could result, such as residual IPA in an oxidizer system.

3.4.5.3 Switching fluid components of a common design between the oxidizer and fuel systems in a human rated spacecraft propulsion system shall be prohibited if the hardware has previously been exposed to the opposite propellant or an incompatible flushing/cleaning fluid. ***[PSR-129G]***

Rationale: In some cases, common designs are used for propulsion components that can be installed in fuel or oxidizer systems. However, residual propellants and incompatible flushing/cleaning fluids can be left behind within these components after initial exposure, particularly in tight clearances, small volumes, and soft goods/seals that have become saturated with fluid via permeation, which can introduce a combustion or reaction hazard. If components in this situation are to be switched, then complete disassembly, recleaning with appropriate flushing/cleaning fluid, reassembly with new soft goods, and a reverification of internal precision cleanliness is required.

3.4.6 System and Component Contamination Control

Historically, there have been many performance anomalies and premature functional failures of propulsion systems and components driven by excess particulate contamination and/or non-volatile residue (NVR) in the hardware. Some of that contamination was non-native (i.e. originated from an external source) and introduced into the propulsion system inadvertently during manufacturing, assembly/integration, ground testing/checkout, final servicing of the fluids for flight, or post-flight maintenance of the system.

3.4.6.1 The contamination control approach used for spacecraft propulsion systems and components, including ground support equipment, shall comply with the requirements of sections 4.2.6.7 and 4.2.6.8 of NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft. ***[PSR-130S]***

Rationale: Historically, there have been many performance anomalies and premature functional failures of propulsion systems and components driven by excess particulate contamination and/or non-volatile residue (NVR) in the hardware. Contamination from a wide variety of potential sources, if not adequately anticipated and controlled, can result in propulsion system performance degradation, loss of mission objectives, and/or loss of crew and vehicle. The standard being cited here is intended to provide a uniform and comprehensive means of controlling contamination and foreign object debris (FOD) to avoid any detrimental effects in propulsion systems and components. Note that this requirement combined with others included herein capture the intent of paragraphs F-17 (Cleanliness of Flowing Fluid and Associated Systems) and F-19 (Cleanliness Protection for Fluid Systems) in JSC 08080-2, JSC Design and Procedural Requirements.

3.4.6.2 The precision cleanliness levels applied to spacecraft propulsion systems and components shall be selected from those defined in IEST-STD-CC1246, Product Cleanliness Levels – Applications, Requirements, and Determination, with the added provisions that no silting of particles below the minimum size defining the specified cleanliness level or any particles above the maximum size defining the specified cleanliness level are allowed in the final particle count. ***[PSR-131SC]***

Rationale: The cited IEST-STD provides key definitions and requirements applicable to the precision cleanliness of a spacecraft propulsion system and its components (e.g. particle size/quantity limits, NVR limits, etc. expressed on a normalized basis relative to hardware surface area, fluid volume, etc.). The bin sizes defined in 1246 are not necessarily aligned with the discrete cleanliness levels, and the 'added provisions' here are intended to prohibit silting of tiny particles below the minimum size defining the specified cleanliness level and any individual particles above the maximum size defining the specified cleanliness level (e.g. no particles >100 microns are allowed for level 100, no particles >200 microns are allowed for level 200, etc.). Regarding silting, a preponderance of tiny particulate can be an indicator of a cleanliness process escape, hinder the ability to perform a valid particle count, and adversely affect monopropellant decomposition characteristics due to a high level of exposed surface area.

3.4.6.3 For spacecraft propulsion valves that have a required precision cleanliness level and are intended for use in onboard liquid propellant systems or onboard inert gas systems (e.g. pressurization systems, pneumatic actuation systems, purge systems, gas generator systems, cold/warm gas propulsion systems, etc.), final verification of internal cleanliness shall be performed with a high volatility liquid solvent and the component vacuum dried at elevated temperature prior to integration with other spacecraft hardware. ***[PSR-132G]***

Rationale: Historically, there have been many performance anomalies and premature functional failures of propulsion systems and components driven by excess particulate contamination and/or non-volatile residue (NVR) in the hardware. It is well established that inert gas flow is a poor transport mechanism for particulate contamination, and incorrect cleanliness results for propulsion components have occurred using gas flow only in the past. A recent example of this issue was documented in a NASA Advisory on the topic of valve contamination following precision cleaning, and other instances have occurred before too. Furthermore, inert gas flow cannot be used for a non-volatile residue (NVR) measurement, which is typically required for valves that will be exposed to oxidizer (liquid or vapor phase) while in service. Therefore, the flow of a high volatility liquid solvent is needed for final cleanliness and NVR verification of propulsion system valves, followed by a demonstrated vacuum bake step to remove residual liquid solvent from the interior of the component. An exception is made for gas pressure regulators due to their extreme level of internal complexity where vacuum drying to remove residual liquids, even those with high volatility (e.g. IPA, HFE-7100, etc.) can be ineffective and small quantities of remaining liquid can have serious negative impacts on component functionality.

3.4.6.4 Assembly/integration operations for a spacecraft propulsion system with a required precision cleanliness level shall be conducted within a cleanroom environment rated at Class 8 or better per ISO 14644-1, Cleanrooms and Associated Controlled Environments – Part 1: Classification of Air Cleanliness by Particle Concentration. ***[PSR-133SC]***

Rationale: Historically, there have been many performance anomalies and premature functional failures of propulsion systems and components driven by excess particulate contamination and/or non-volatile residue (NVR) in the hardware. Based on past experience, a Class 8 cleanroom per ISO 14644-1 is considered the minimum acceptable rating for assembly/integration of precision clean spacecraft propulsion systems which have performance attributes and failure modes that can be highly sensitive to the effects of particulate contamination. It is also recommended that unrelated vehicle assembly/integration operations cease whenever the propulsion system is open to the cleanroom environment. This is intended to prevent those operations from generating additional particulate contamination which can end-up inside the open propulsion system, which has contributed to systemic contamination issues in the past. Note that a Class 8 clean room per ISO 14644-1 is equivalent to a Class 100,000 clean room per the previously cancelled FED-STD-209, Airborne Particulate Cleanliness Classes in Cleanrooms and Clean Zones.

3.4.6.5 Spacecraft propulsion systems that carry propellants, pressurant gases, purge gases, pneumatic actuation gases, etc. shall undergo a final verification of cleanliness outlined in the other paragraphs of this section after final assembly or subsequent to removal and replacement (R&R) of components. ***[PSR-134G]***

Rationale: Contamination introduced during initial propulsion system assembly/integration or subsequent repair/replacement of components can cause catastrophic failures of multiple components during spacecraft operation. Final verification of cleanliness may include liquid/gas flush to remove contamination and verify particulate and NVR requirements, borescope inspection to ensure no visible particulate or other anomalous conditions are present (e.g. corrosion, staining, etc.), and/or x-ray to examine weld joints and look for sizeable metallic particulate or evidence of weld drop-through or. Note that the process of satisfying this requirement may include incremental cleanliness verifications for sub-sections/segments of the fully integrated propulsion system, particularly for dead-ended lines that won't permit the flow-through of fluids in their final assembled configuration.

3.4.6.6 Individual tube segments and welded tube subassemblies for a human rated spacecraft propulsion system shall be removed and precision cleaned after any trim-to-fit tube facing, or other tube cutting operation at the next higher level of assembly, prior to final welding into the propulsion system. ***[PSR-135G]***

Rationale: Assembly/integration operations, including weld prep and welding of precision cleaned propulsion system hardware, are a recognized source of particulate contamination. Such debris can cause a variety of hardware anomalies/failures in the propulsion system, leading to a catastrophic hazard. As a result, design features, fixtures/tools, and assembly/integration sequences must be adopted for the purpose of contamination control. Any trim-to-fit, tube facing, or other tube cutting operation can generate additional metallic debris, so the affected hardware should be re-cleaned prior to final welding. Note that simple fit checks of previously cleaned tubing and final tube-end surface prep to remove oxidation from precision cleaned tubing immediately prior to welding do not require re-cleaning afterward, though a detailed visual inspection of the interfacing surfaces would be expected in those cases. Also note that paragraph 3.4.6.5 drives a subsequent verification of cleanliness for the entire integrated propulsion system, making use of the available mechanical joints/fittings, test ports, and/or fluid disconnects in the design.

3.4.6.7 All individual tube segments and welded tube subassemblies used in the propulsion system shall undergo a liquid flush cleaning process for the internal surfaces of the hardware, followed by sampling of the flush effluent to ensure particulate cleanliness and NVR requirements are met, and an internal borescope inspection, if accessible, followed by a final *flush, to ensure all visible particulate has been removed and no abnormal surface conditions (e.g. corrosion, stains, residue, etc.) are present. [**PSR-136G**]*

Rationale: Gross particulate and NVR contamination of the pressurized lines that handle gaseous and/or liquid phase fluid commodities in a spacecraft propulsion system can result in common cause performance degradation and failure of multiple components. In fact, poorly conceived or executed cleaning and verification processes for the internal surfaces of such fluid lines have contributed to numerous instances of anomalous performance and failure of other propulsion system components in the past (e.g. leakage, flow restriction, flow erosion, jamming, etc.). This points to the need for visual inspection of the internal surfaces of all tubing as a supplement to the typical sampling of flush fluid effluent to verify particulate contamination and NVR requirements are met. Note that this requirement applies to all tubing end items, whether cleaned in-house or by an outside supplier. Also note that orientation of the hardware (e.g. vertical vs. horizontal, etc.) during the liquid flush and drying steps may be an important consideration when developing the procedures for complex manifolds, flex hoses, and other unique hardware items.

*3.4.6.8 For individual tube segments and welded tubing subassemblies where internal surfaces are not readily accessible for borescope inspection due to small tube diameters and/or tight bend radii, surveillance of the cleaning process for the uninspectable hardware items shall be conducted via the borescope inspection results for other representative tubing specimens of all larger sizes and processed in an equivalent manner to infer the condition of the uninspectable items. **[PSR-137G]***

Rationale: In rare cases, certain tubing items may be too small in diameter and/or too tightly bent to permit borescope inspection of the internal surfaces after precision cleaning. In those situations, assuming a design change to enable the required borescope inspections has been considered but rejected, the intent is to conduct surveillance of the cleaning process for the small uninspectable items by leveraging borescope results from all of the larger inspectable items processed in an equivalent manner. In other words, the larger inspectable items are being used as ‘referee’ specimens to represent the smaller uninspectable items. This is considered a reasonable compromise to address such unique situations, though it is understood there is an elevated risk that must be evaluated for acceptability.

*3.4.6.9 When conducting internal borescope inspections of individual tube segments and welded tube subassemblies in accordance with requirements herein, the borescope shall be precision cleaned to a level that meets or exceeds the specified cleanliness level for the hardware item being inspected, and then maintained clean at that level throughout the entire inspection process. **[PSR-138G]***

Rationale: The intent of this requirement is to ensure that an inadequately cleaned borescope used for internal inspection of individual tube segments and welded tubing subassemblies does not, itself, invalidate the clean status of the hardware items being inspected.

3.4.6.10 For cutting out and replacing components that have been welded into an assembled propulsion system, a test-verified tube cutting process shall be used to avoid particle generation. ***[PSR-139G]***

Rationale: This is a critical requirement needed to prevent the contamination of an integrated propulsion system with metal particles from tube cutting associated with hardware replacements. Such particulate could generate common-cause failures of multiple components, thus resulting in a catastrophic hazard. Key process variables that contribute to meeting this requirement include the use of a sharp blade that is inspected for excess wear and changed on a regular basis, in addition to the use of minimal cutter pressure during the tube cutting operation. A verification of the process by test to demonstrate particulate prevention and the development of a plan for inspection and maintenance of the cutting tool itself are expected as part of this effort.

3.4.6.11 For hardware that cannot be subsequently precision-cleaned, a method for protecting against propulsion system contamination during tube preparation for welding shall be implemented through the use of physical orientations that discourage gravity-driven migration of particulate into the system, in addition to physical barriers that prevent migration of particulate into the system, such as plugs inserted in tube ends, with the following additional constraints: ***[PSR-140G]***

a. The installation and removal of plugs is tracked by a documented method and independently verified.

b. Prior to plug removal, the exposed internal surfaces of the tube are cleaned using a swab wetted with an approved solvent for the application, and positive backpressure within the tube using dry inert gas is maintained as the plug is removed.

Rationale: This is a critical requirement needed to prevent the contamination of a propulsion system with metal particles generated by tube preparation for welding, which could induce common-cause failures of multiple components. During such operations, the combination of physical orientations and plugs to control the migration of unwanted particulate into the system is considered critical. The tracking and removal of each plug, while maintaining a slight positive pressure in the propulsion system relative to the surrounding ambient environment, is also a key step as a plug could become FOD itself.

3.4.6.12 After completing a welding, rework, or repair and replacement (R&R) operation on the propulsion system, a cleanliness assessment shall be performed using one of the following methods: 1) inert gas purge at a minimum velocity that has been demonstrated, via process development involving a borescope, to displace particulate through an open port without downstream components or thrusters installed to prevent migration into other parts of the system, 2) an internal borescope inspection if accessible, or 3) an x-ray for closed systems. ***[PSR-141G]***

Rationale: The ability to do one of these inspections depends on the type of rework being performed and accessibility. Historically, there have been many performance anomalies and premature functional failures of propulsion systems and components driven by excess particulate contamination and/or non-volatile residue (NVR) in the hardware. The additional requirements defined here are intended to ensure that propulsion system lines and line segments that carry propellants, pressurant gases, purge gases, pneumatic actuation gases, etc. are precision cleaned effectively and verified to be in an acceptable condition at multiple points in the assembly/integration sequence to further reduce the likelihood of contamination/FOD getting into the propulsion system and causing hardware failures with potentially catastrophic consequences. It is understood that the final cleanliness check of an integrated propulsion system using inert gas flow has limitations in terms of particle transport effectiveness. However, a result that fails to meet the cleanliness level requirement would imply that a process escape occurred during the controlled assembly/integration effort, thus triggering a more thorough review to ensure adequacy of the system configuration prior to final loading of the flight commodities.

3.4.6.13 Cleaning of TWFPB piece parts and assemblies, such as bellows, diaphragms, and flex hoses, which have regions that can trap contamination or residual fluids, shall have specific processes that include cleaning in the vertical orientation, multiple reorientations during cleaning, and verification developed that includes visual examination of convolutes where possible. ***[PSR-142G]***

Rationale: Cleaning of any item with bellows or flexible thin wall pressure boundaries, particularly if lined, is difficult. Trapped contamination can cause thin-walled items to fail and leak or cause failure of components downstream. It is understood that visual inspection, although effective for identifying particulate contamination/FOD and other non-conforming conditions, may not be possible in all instances.

3.4.6.14 Convoluted flex hoses shall receive special attention to cleaning via the following elements: ***[PSR-143G]***

a) Verify all flex hoses as precision-clean in a vertical orientation.

b) For flex hose tube diameters equal to or greater than one inch, sample using a rinse fluid applied internally through use of a high-pressure nozzle to the entire length of the flex hose and visually inspect to verify cleanliness.

c) For flex hose tube diameters less than one inch, the use of a high-pressure nozzle is preferred, but verification may be performed by flushing a rinse fluid through the entire length of the flex hose with flex hose agitation.

d) Precision cleaning is considered successful when the verification rinse fluid indicates compliance with the flex hose engineering drawing cleanliness requirement.

e) Flex hoses for use with tube diameters of 3/8" and smaller are to be shaken while flowing cleaning fluid through the hose to liberate small particles from trapped volumes.

f) Prior to welding, metal bellows and interfacing fluid-wetted components are to be precision cleaned.

Rationale: Convolutes tend to trap contaminates. A full visual inspection may not be possible. Note that 'flex hose tube diameter' refers to the outer diameter (OD) of the hardline tubing that is part of the propulsion system in which the flex hose is installed (e.g. propellant feedline supplying the flex hose with fluid), or that is built into the flex hose itself (e.g. inlet/outlet tube stubs, bent hardline tube segment between two flex hoses segments, etc.).

3.4.7 External FOD, Water, or Ambient Air Intrusion Control

3.4.7.1 A Foreign Object Damage (FOD) prevention program shall be implemented for all ground operations involving the mechanical and electrical systems of a human rated spacecraft propulsion system, NASA-STD-6016, paragraph 4.2.6.7, requirement MPR 206. ***[PSR-144S]***

Rationale: This requirement from NASA-STD-6016 drives the implementation of a FOD prevention program that conforms to AIA NAS412, Foreign Object Damage (FOD) Prevention Guidance Document for all ground operations involving mechanical or electrical flight hardware systems. Significant hazards can be introduced by foreign object debris (FOD) being left in the system during all phases of the program. This includes the design, development, manufacturing, assembly, repair, processing, testing, maintenance, operation, and check out of flight equipment to ensure the highest practical level of preventing FOD.

3.4.7.2 The electrical and mechanical elements of a human rated spacecraft propulsion system shall comply with the 'protection from debris' requirements of paragraph G-4 in JSC-08080-2, JSC Design and Procedural Standards, with the exception of sub-part (4) on the topic of fluid filtration which is covered by other requirements in this standard. ***[PSR-145S]***

Rationale: The intent of paragraph G-4 (Protection from Debris – Electrical & Mechanical Systems) is to design and fabricate electrical circuitry to prevent the establishment of unwanted current paths from such debris by providing critical electrical items with debris-proof covers, suitable containers, housings, potting, or conformal coatings. Exposed electrical terminals inside a propellant tank were shorted by metal particulate thus requiring potting of the electrical feed through. The intent is to provide critical mechanical systems with debris-proof covers, shrouds, or containers that protect the entire system prior to use, or that prevent debris from entering into critical areas of the mechanism where the debris could cause binding, jamming, or seizing.

3.4.7.3 The design of Ground Support Equipment (GSE), Special Test Equipment (STE), and 'shop aid' equipment that interfaces with 'openings' in the flight propulsion system shall include features to prevent its use on the wrong size opening, avoid shedding particulate contamination/FOD into the opening, and preclude being inadvertently left in the opening upon completion of an operation. ***[PSR-146G]***

Rationale: This includes tethering of interfacing hardware. The use of tape to cover or plug an opening is an example of equipment that should not be used for FOD control because it can (and has) led to FOD (the tape itself) entering the flight hardware. An exception could involve an instance where the size of the tape is much larger than the size of the opening, thus precluding inadvertent ingestion. Plugs used for trimming tubing are expected to include features that prevent it from being left in the tubing or traveling down into the tubing.

3.4.7.4 Positive restraints to prevent back-off and separation shall be implemented on STE and GSE pressurized fluid connections that interface via threaded and torqued attachment to the flight propulsion system. ***[PSR-147G]***

Rationale: Requirement PSR-350SC in this document addresses positive locking features for quick disconnects (QDs) used in pressurized fluid connections that interface with the flight propulsion system. However, the term 'QD' is not typically interpreted to include threaded fluid connections, which can also appear in such applications. Examples include certain fill and drain valves, test port couplings, fluid fittings, etc. where threads are engaged, and torque is applied, for the purpose of attachment. In those cases, positive restraints (i.e. secondary means of retention) are needed to prevent back-off and separation of the connection while pressurized, over and above the torque-induced preload and associated thread friction. This topic is not addressed in NASA-STD-5020, which governs threaded fasteners used in spaceflight hardware and requires a minimum of one locking feature that doesn't depend on preload or friction to function. It's also not addressed in NASA-STD-

5005, which governs the design and fabrication of GSE but only requires lanyard-style tethering of fluid system QDs, caps/plugs, and flex hoses. Relying on torque alone for separable threaded fluid connections is not considered sufficient, whether between flight hardware items/elements or between STE/GSE and flight hardware items/elements, and this requirement is intended to ensure that a positive restraint in the form of a secondary thread locking feature is used in both cases where pressurized connections are involved.

3.4.7.5 Work procedures shall include steps to perform periodic inspections (e.g. prior to every installation step) that include closeout photographs such as to ensure no missing or loose parts on interfacing ground support hardware and that interfacing hardware has been removed. ***[PSR-148G]***

Rationale: The state of the closeout of the hardware is critical to flight rationale to provide verification data that FOD from a variety of sources has not entered the system. Failures of propulsion system are attributed to FOD in many cases.

3.4.7.6 Points of ambient moisture-laden air intrusion that could result in a propulsion system hardware failure, such as due to icing or corrosion, shall maintain a dry gas purge or have a verified seal to mitigate adverse effects. ***[PSR-149G]***

Rationale: The reliance on check valve or an unverified seal is not sufficient. Reference LLIS 467, Centaur RL10 Rocket Engine Check Valve - Atlas/Centaur Program. (LLIS-467, 1995)

3.4.7.7 The hazards associated with ingestion of water into the propulsion system, such as combustion chambers/injectors or insulation, shall be evaluated for the potential that the water will freeze during ascent and may cause blockage of propellant lines or cool engine combustion chambers below their capability to operate. ***[PSR-150G]***

Rationale: The Shuttle APU experienced blockage of the hydrazine fuel lines due to rainwater entering the aft fuselage and being ingested into the insulation. (ref) (Hernandez, 2011, p. 5). Similar issues occurred on Shuttle RCS thrusters due to condensation and rainwater entering the combustion chambers and injectors, resulting in cooling of the injectors, and plugging of the chamber pressure (Pc) sense tubes with ice during ascent. The onboard FDIR software misinterpreted those symptoms as propellant leakage and off-nominal thruster performance, respectively, causing invalid thruster deselections while in flight.

3.4.8 Welds and Bimetallic joints

Welds in propulsion systems can provide a highly reliable, leak free joint, that can be used in 0FT design for minimum risk (DFMR) situations, however this requires stringent design, process, and inspections to qualify for use. This section calls out NASA-STD-6016 and identifies some specific requirements that are needed to address a number of repeated lessons learned and catastrophic hazards.

3.4.8.1 Weld requirements shall be per NASA-STD-6016 and Class A for mission critical structural welds. ***[PSR-151S]***

Rationale: NASA-STD-6016 provides the overall standard and imposition of industry standards for welds, with pressurized joints in the propulsion system considered as mission critical structural welds. Hazards can be introduced throughout the weld process. An explosion of an auxiliary power unit (APU) on STS-9 OV-102, occurred due to sensitized microstructure and later stress corrosion cracking by carbazic acid, which caused the injector tube to leak (as indicated by cooling due to evaporation in a vacuum), then freeze the hydrazine, and then unfreeze and ignite after landing. (Ref). (Nufer, 2010, p. 25)

3.4.8.2 The process control for bi-metallic transition joints shall include lot acceptance microstructure evaluation of first and last samples of a lot for brittle intermetallics using Scanning Electron Microscope (SEM) or other NASA-approved alternate inspection technique. ***[PSR-152G]***

Rationale: NASA-STD-6016 and MIL-STD-1252, Inertia Friction Welding Process, Procedure and Performance Qualification, do not require metallographic examination unless specified in the contract. Lack of acceptance screening for brittle intermetallics has resulted in propellant leaks from bi-metallic joints which created potential catastrophic hazards. Lessons learned more recently on the Orion program include propellant leaks through welded parts, as well as issues with Mars Science Laboratory (MSL). Reference LLIS-14201, Fabrication of Propulsion Tubing. (LLIS-14201, 2014)

3.5 PROPULSION SYSTEM PRESSURIZED HARDWARE

This section describes the requirements for pressurized systems for human spacecraft. Design of lightweight, high performance, and safe systems requires minimizing structural margins which in turn requires increasing fracture control and inspection requirements.

3.5.1 Maximum Design Pressure (MDP) and Factors of Safety

This section describes the requirements for pressurized systems for human spacecraft. Design of lightweight, high performance, and safe systems require minimizing structural margins, which in turn requires well defined and verified maximum pressures in the propulsion system and structural verification standards. This includes additional requirements in Section 3.6 related to controlling catastrophic hazards for new construction and fabrication technologies for pressure vessels that are in development where current standards are not well specified.

The section also introduces requirements for Maximum Design Presssure (MDP) per JSC-65828, Structural Design and Factors of Safety for Spaceflight Hardware, that are further captured in sections related to the following parts of the system. Note that Maximum Expected Operating Pressure (MEOP) per SMC-S-016, Test Requirements for Launch, Upper-Stage, and Space Vehicles, and the MDP definition both include transient pressures and that proof pressure is a safety factor x MDP, with MDP defined to include the pressure after two faults. Pressure component specifications using MEOP terminology should ensure that the MEOP value is greater than or equal to the MDP for that component as determined by requirements in JSC-67723 and JSC-65828.

Pressurant or Pneumatic Pressure Vessel MDP: This value is driven by thermal environments and initial fluid loading conditions. Relief devices are typically not required on a pressurant tank, however, two-fault tolerance to over-pressurization above MDP must be maintained.

Pressurization or Pneumatic System Pressure Components (valves, regulators, tubing, etc.) MDP: The MDP value for pressurization and pneumatic system lines and component inlets are based on supply tank and transient pressures. Component outlet and line MDP values are based on faults and transients including such things as leakage, slam starts, and consideration for liquid accumulation in the lines driven by vehicle acceleration environments, vapor migration and condensation effects, cryopumping conditions, etc.

Propellant Pressure Vessel MDP: These are 2 FT to overpressurization exceeding MDP. MDP is driven by pressurization system including faults, leakage, relief device setpoints, existence of check valves, and thermal conditions in the tanks including thermal control system failures or degradation. MDP per JSC-67723 is set at the relief device setpoint not the 10% below setpoint. This was largely for tanks that may be proofed to 1.25 where this can significantly eat into the safety factors.

Propellant Feed System Pressure Component MDP This includes that it may be operating at fault condition pressures in the propellant tank. This includes flow transients from valve and engine operation. This also includes isolation of line segments, thermal effects, and back-relief settings.

Engine Inlet MDP. The MDP includes the feed system transients consistent with 2 FT pressures in the propellant tank. There may be other MDPs internal to the engine that include pumps and other transient effects. This is consistent with requirements in NASA-STD-5012, which also clarifies MEOP.

3.5.1.1 Spacecraft propulsion systems and interfacing secondary structure shall comply with the requirements of JSC 65828, Structural Design Requirements and Factors of Safety for Spaceflight Hardware. ***[PSR-153S]***

Rationale: The content of section 3.2.8 in JSC 65858 provides the necessary structural requirements for pressurized systems to correctly define the maximum design pressure (MDP) value(s) for the propulsion system, establish the minimum allowable factors of safety for all components in the propulsion system, and impose the appropriate technical standards for all components in the propulsion system. Per the definition of MDP in JSC 65828, the worst-case system two failure condition and all transient pressures (regardless of duration) associated with propulsion system activation, manifold priming, water hammer from engine/thruster firings, temperature range, minimum ullage volume, zero-g liquid propellant migration into the upstream gas pressurant lines, etc. must be accounted for when establishing the MDP values for propulsion system hardware. Note that water hammer magnitudes during engine/thruster firings can vary greatly based on propellant properties, propellant feedline designs, and engine/thruster pulse mode duty cycles. Significant amplification can occur when feedline natural frequencies coincide with engine/thruster pulsing frequencies. As a result, the MDP values must account for such amplification, or the feedline designs and/or engine/thruster duty cycles or pulse frequencies must be altered to avoid the effect.

3.5.1.2 Pressurized hardware in a spacecraft propulsion system shall meet the structural requirements of section 3.2.8 in JSC 65828, Structural Design Requirements and Factors of Safety for Spaceflight Hardware, with the exception of sub-section 3.2.8.3 [STR0021] which allows an undesired exceedance of MDP during venting in a failure scenario. ***[PSR-154SC]***

Rationale: The content of section 3.2.8 in JSC 65828 provides the necessary structural requirements for pressurized systems to correctly define the maximum design pressure (MDP) value(s) for the propulsion system, establish the minimum allowable factors of safety for all components in the propulsion system, and impose the appropriate technical standards for all components in the propulsion system (e.g. ANSI/AIAA S-080 for metallic pressurized hardware, ANSI/AIAA S-081 for COPVs, etc.). Per the definition of MDP in section B of JSC 65828, the worst-case two failure condition and all transient pressures associated with propulsion system activation, manifold priming, water hammer from engine/thruster firings, temperature range, minimum ullage volume, zero-g liquid propellant migration into the upstream gas pressurant lines, etc. must be accounted for when establishing MDP values for the propulsion system hardware. In addition, per section 3.2.8.2 in JSC-65828, the heritage expectation carried forward from Shuttle and ISS involves maintaining 2FT against exceeding MDP due to the exceptionally hazardous nature of over-pressurization/rupture of propulsion system hardware. The exception is intended to disallow the 10% exceedance of MDP at full flow for relief devices installed in a pressurized system. It is not considered acceptable exceed MDP at any time during propulsion system operation, given that proof and leak test levels for the components and integrated system have been established based on safety factors applied to MDP. As a result, any pressure excursions above the maximum set point of the relief device (including tolerance) during relief flow must be considered when establishing the MDP value.

3.5.1.3 As part of determining the MDP, a dynamic amplification factor for transient pressure events shall be applied that follows NASA/TM-20210022275, Treatment of Transient Pressure Events in Space Flight Pressurized Systems, for all transient pressures in tanks, lines, engines/thrusters, etc. ***[PSR-155G]***

Rationale: The dynamic amplification factor (DAF) for pressure transients is critical to determine for each application and pressure transient. As summarized in NASA TB 22-03, with details in NASA/TM-20210022275, MDP is equal to the steady pressure plus the effective pressure transient which is the DAF times the measured transient. In many cases, sharp transient pressures have caused rupture of lines. In some cases, a resonance may cause a higher structural load, and in other cases the structure may not be able to respond.

3.5.2 Fracture Control Requirements for Spaceflight Hardware.

3.5.2.1 Spacecraft propulsion systems and components shall comply with NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware for classification of and requirements for fracture critical elements. ***[PSR-156S]***

Rationale: High performance spacecraft propulsion systems operate at lower factors of safety to reduce mass. Material fracture can contribute to unexpected failures of spacecraft propulsion system hardware, resulting in a potentially catastrophic hazard. Note that NASA-HDBK-5010 provides additional guidance for implementing the fracture control requirements of NASA-STD-5019. Note that metallic thin walled flexible pressure boundaries (TWFPBs) in propulsion components, such as bellows, diaphragms, flex hose inner core, flexure sleeves, etc., which are classified as fracture critical but not amenable to standard fracture control approaches in NASA-STD-5019, are covered by the requirements of paragraph 3.14.2.1 [PSR-278S].

3.5.3 Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components

3.5.3.1 Spacecraft propulsion systems and components that are fracture critical shall comply with NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components. ***[PSR-157S]***

Rationale: Undetected material issues can contribute to unexpected failures of spacecraft propulsion systems. It is important to understand the capabilities of the NDE methods. The capabilities will dictate the sensitivity for detecting tight cracks and the initial crack size opening which is what will be used in the fracture analysis.

3.5.4 Threaded Fasteners

3.5.4.1 Threaded fasteners used in spacecraft propulsion systems and components shall comply with the requirements of NASA-STD-5020, Requirements for Threaded Fastening Systems in Spaceflight Hardware. ***[PSR-158S]***

Rationale: Errant threaded fastening hardware and implementation approaches can contribute to unexpected functional (i.e. mechanical and/or leakage) failures of spacecraft propulsion systems, and the requirements of NASA-STD-5020 are intended to mitigate those potential issues. Note that NASA-STD-5020 is also invoked by paragraph MS-5 (Threaded Fasteners) in JSC-08080-2, JSC Design and Procedural Standards.

3.6 PRESSURE VESSELS AND PROPELLANT TANKS

Pressure vessels include those used for: 1) pressurant gas storage and 2) liquid propellant storage containing internal propellant management features for liquid acquisition, slosh damping, and liquid migration control.

3.6.1 Integrated Propellant Tank Design and Analysis

3.6.1.1 All analysis and test requirements for structural integrity and material compatibility shall be applied at the full tank assembly level, inclusive of the pressure shell, all internal design features for propellant management (e.g. liquid acquisition, slosh damping, liquid migration control, etc.), and external features for tank mounting support and interfacing fluid lines. ***[PSR-159G]***

Rationale: ANSI/AIAA S-080 does not provide individual requirements that acknowledge the critical interactions of internal features within a propellant tank (e.g. liquid acquisition, slosh damping, liquid migration control, etc.), nor does it explicitly address other forms of mechanical loads that must also be considered when performing the structural assessment (e.g. tank structural supports, interfacing fluid lines, etc.). Note that this standard does not address the pressure vessel itself acting as an integral load bearing part of the vehicle.

3.6.2 Type I Metallic Pressure Vessels

3.6.2.1 The design, manufacture, inspection, test, qualification, and use of spacecraft propulsion systems, pressure vessels, and pressurized components shall comply with JSC 65828, Structural Design Requirements and Factors of Safety for Spaceflight Hardware, including paragraph 3.2.8.4 [STR0022] governing Metallic Pressurized Hardware. ***[PSR-160S]***

Rationale: The cited JSC 65828 standard provides a complete and comprehensive set of design, inspection, and test requirements for metallic pressure vessels used in spacecraft propulsion systems. This includes invoking the requirements of ANSI/AIAA S-080 governing metallic pressure vessels and pressurized components, inclusive of certain conservative exceptions for human spacecraft applications. This content is considered critical to the control of hazards associated with such pressure vessels.

3.6.2.2 A metallic pressure vessel design that is tested to a 1.25 x MDP proof and 1.5 x MDP burst, as an exception to JSC-65828, Structural Design Requirements and Factors of Safety for Spaceflight Hardware, Table 3.3.1.-6 and ANSI/AIAA S-080, Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components, Table 1, shall meet additional requirements for NDE (section 3.6.2.3) and fracture, where proof pressure is not the sole means of flaw screening. ***[PSR-161SC]***

Rationale: In some spacecraft propulsion system applications, with high propellant fractions, the minimum risk solution (i.e. reduced vehicle complexity and/or dry mass, etc.) or the use of heritage pressure vessels may drive the use of lower factors of safety on proof pressure (1.25xMDP vs. 1.5xMDP) and design burst pressures (1.5xMDP vs. 2.0xMDP). Following this path will require additional forms of risk mitigations, as outlined in this section.

3.6.2.3 NDE methods shall comply with NASA-STD-5009. ***[PSR-162S]***
Rationale: It is important to understand the capabilities of the NDE methods. The capabilities will dictate the sensitivity for detecting tight cracks and the initial crack seize opening which is what will be used in the fracture analysis.

3.6.2.4 The NDE method shall be approved by NASA and have a Probability of Detection (POD) of 90/95 that accounts for double-wall radiography of metallic pressure vessels. ***[PSR-163G]***
Rationale: X-ray processes developed for single wall crack detection do not guarantee detection with the same level of reliability when used for double wall, as is typical for shooting X-rays on pressure vessels. Reference NESC Technical Bulletin 19-02, 90/95 POD Radiography Concern for COPVs and Metal Tank Welds.

3.6.2.5 The aspect ratios of A/C=1.0 and A/C=0.2 shall each be evaluated, with fracture analysis or testing performed to determine the pass/fail threshold, if A/C=0.2 is not achievable. ***[PSR-164G]***
Rationale: This rationale is intended to be used to meet the alternative approach method in NASA-STD-5019 and the requirements of ANSI/AIAA-S-080.

3.6.3 Type II and III Composite Overwrapped Pressure Vessels (COPVs).

3.6.3.1 The design, manufacture, inspection, test, qualification, and use of spacecraft propulsion systems, pressure vessels, and pressurized components shall comply with JSC 65828, Structural Design Requirements and Factors of Safety for Spaceflight Hardware, including STR0023 governing Composite Overwrapped Pressure Vessels (COPVs). ***[PSR-165S]***
Rationale: JSC 65828 calls out, with critical exceptions, ANSI/AIAA-S-081, Standard for Space Systems - Composite Overwrapped Pressure Vessels (COPVs). The AIAA standard for COPVs is tailored to account for human spaceflight safety factor requirements and design loads.

3.6.3.2 Structural math models shall be correlated to the qualification tank per requirements STR0066, STR0067, STR0068, and STR0070 in JSC-65828, Structural Design Requirements and Factors of Safety for Spaceflight Hardware. ***[PSR-166SC]***
Rationale: ANSI/AIAA S-081, invoked for COPVs via paragraph 3.2.8.5 [STR0023] in JSC-65828, states this in section 10.5. However, the details on what would be required for this correlation are not clear. Thus, it is considered necessary to follow JSC-65828, requirements STR0066, STR0067, STR0068, and STR0070, as driven by this requirement.

3.6.3.3 Bond line sensitivity studies shall be performed for tanks that have a bond line and for tanks *that have no intended bond line.* ***[PSR-167G]***

Rationale: Partial bond lines are a concern. A partial bond line leads to non-uniform loading and higher strains in the liner causing fatigue cracks to begin. If the tank does not have a bond line, the methods of ensuring there is no bond occurring need to be examined. A sensitivity study of partial bonds can be broken down into two separate areas of concern. The first deals with weak process controls, liner preparation, and a reliable primer (BR-127 or an equivalent water-based primer (current primers on the market have shown a reliable bond)). A lack of in-process control can create a failure point in which a manufactured defect is present from the beginning. The second deals with adhesive yielding due to strain spikes. Follow the NESC Technical Bulletin 20-07, Evaluating and Mitigating Liner Strain Spikes in COPVs, to ensure these strain spikes are not present in the design.

3.6.3.4 The NDE method shall be approved by NASA and have a POD of 90/95 that accounts for double-wall radiography of metallic pressure vessels including COPV metallic liner tank welds. ***[PSR-168G]***

Rationale: The X-ray process as developed for single wall crack detection do not guarantee detection with the same level of reliability when used for double wall as typical for shooting X-rays on pressure vessels. Reference NESC Technical Bulletin 19-02, 90/95 POD Radiography Concern for COPVs and Metal Tank Welds.

3.6.3.5 The approved NDE methods in NASA-STD-5009 shall be followed. ***[PSR-169S]***

Rationale: It is important to understand the capabilities of the NDE methods. The capabilities will dictate the sensitivity for detecting tight cracks and the initial crack size opening which is what will be used in the fracture analysis.

3.6.3.6 The aspect ratios at A/C=1.0 and A/C=0.2 shall each be evaluated, with fracture analysis or testing performed to determine the pass/fail threshold if A/C=0.2 is not achievable. ***[PSR-170G]***

Rationale: This rationale is going to be used to meet the alternative approach method in NASA-STD-5019 and the requirements of ANSI/AIAA S-081.

3.6.4 Type IV. Composite Pressure Vessels with Plastic Liner

The standard for Type IV composite pressure vessel is currently in development. The use of this type of hardware in a human rated spacecraft propulsion system is subject to coordination and review by a NASA-appointed subject matter expert prior to being included in the design.

3.6.4.1 The use of Type IV pressure vessels procured as ASME Code or Code of Federal Regulations (CFR) Title 49 Department of Transportation (DOT) Pressure Vessels, shall meet the requirements of JSC ES 151001-1, Use of ASME Code or Code of Federal Regulations Title 49 Department of Transportation (DOT) Pressure Vessels for Space Applications.. ***[PSR-171G]***

Rationale: This ensures that the pressure vessel is safe to use for space applications.

3.6.4.2 The use of Type IV pressure vessels in accordance with AIAA G-082, Guide: Space Systems - Composite Overwrapped Pressure Vessels with A Plastic Liner, shall be subject to the following added provisions: ***[PSR-172SC]***

a. *Proposed design and qualification requirements are to be reviewed by a NASA appointed Subject Matter Expert (SME)*
b. *A test or tests of mission representative duration are to be performed if reactive media can penetrate the overwrap, either by permeation or submersion.*
c. *The composite is to be chemically compatible with all fluids contacting it, without detrimental deformation, leakage, or rupture relating to fluid compatibility, materials, unique operating environments, and permeability.*
d. *Controls are to be listed for the raw materials used to make the liner.*
   Rationale: Inherent in plastic manufacturing, manufacturers recycle all scrap materials by regrinding and then reusing in subsequent melts. This process introduces FOD and variables into the material properties, which might not be analyzed against.
e. *An assessment for damage tolerance is to incorporate, at each location, the stress, strain, thickness, initial flaw (crack) size, and material properties of the liner, boss, boss to liner interface and bonded interfaces.*
f. *A statistical basis for material properties is to be used for all tank materials, including the liner material.*
   Rationale: Although the liner does not load share, mechanical properties still need to be developed in order to show the coefficient of variation (COV) between material lots.
g. *External pressure conditions are to be examined for vacuum filling, purge, applied external pressure, and buckling since the liner is not bonded to the composite overwrap, which creates a susceptibility to failure at reduced internal pressure levels.*
h. *Manufacturing, transportation, integration, and operational environments are to be analyzed to determine credible sources of mechanical damage to the COPV, with results documented in the Damage Control Plan (DCP) which will be updated as changes to the credible threats occur.*
i. *The COPV is to be evaluated for exposure to and operation in the unique ascent and*

space operating environments (e.g. radiation, vacuum, atomic oxygen).
Rationale: Relative to the space environment, published works have only examined composites from a strength perspective and never from a fatigue standpoint. All published work agrees that the epoxy is degraded by either exposure to radiation, atomic oxygen, cross-linking or chain scission, etc.

j. *The COPV is to be designed to sustain the negative pressure differential without detrimental deformation, detrimental leakage, or rupture.*
Rationale: There may be instances where liner buckling is characterized as detrimental deformation and needs to be assessed.

k. *Examination of full saturation of the liner when assessing for permeation of the working fluid is to be performed.*

l. *Non-Destructive Testing (NDT) capabilities are to be based on a credible set of flaws/indications which are identified through an assessment of the credible range of sizes/shapes/depths.*
Rationale: Multiple types of flaws are inherent in the manufacture of plastic liners, which can cause a leak to occur. Examples of these flaws are FOD, partial melt, contamination from the molds or machines, flashing removal process, porosity, crevices from pinch lines (blow molding), etc.

3.6.5 Type V All Composite Pressure Vessel

3.6.5.1 The use of all-composite pressure vessels in human rated spacecraft propulsion systems shall require standards governing the design, analysis, fabrication, testing, installation, and operation of such hardware to be developed in coordination with NASA. ***[PSR-173G]***

Rationale: This type of all composite pressure vessel is currently in development. Sufficient technical standards for human rated spacecraft applications have not yet been developed and must be put in place for consideration in a human rated propulsion system application.

3.6.6 Liquid Propellant Acquisition

The requirements of this section apply to propulsion system designs where gas-free liquid is the desired state of the fluid commodity being discharged from the propellant tanks and consumed by the engines/thrusters. That objective is typically achieved through the use of a non-metallic bladder or diaphragm, a metallic diaphragm or bellows, or a metallic surface tension PMD located inside the propellant tanks. Other less common propulsion system designs that involve liquid-free gas or a liquid/gas two-phase mixture being discharged from the propellant tanks are not addressed here.

3.6.6.1 The PMD in a liquid propellant tank shall provide gas-free liquid to the propellant feed lines during engine/thruster operation under all operational acceleration environments as provided *by GN&C.* ***[PSR-174G]***

Rationale: Flowing pressurant gas through the propellant tank PMD and into the firing engines/thrusters of a spacecraft propulsion system, whether that gas is entrained with or displaces the intended liquid propellant, can cause catastrophic engine failure due to off-mixture ratio operation, disruption of fuel film or regenerative cooling, and loss of thrust needed for attitude control and/or translational maneuvers.

3.6.6.2 For the design and analysis of surface tension screen galleries in a liquid propellant tank, a minimum safety factor of 2.0 for bubble point to the total combination of hydrostatic, flow loss, including the effect of contamination build-up, and dynamic head to prevent gas break-through shall be maintained. ***[PSR-175G]***

Rationale: For surface tension devices, a low-g verification test is not always practical. Therefore, all individual inputs to the analysis of that hardware should be based on conservative values of parameters measured by test with conservative assumptions in terms of surface tension breakdown from liquid flow to gas flow (i.e. screen bubble point, etc.). These assumptions and parameter values/margins should be clearly stated and explained in the analysis documentation. In addition, the tank designer/supplier and propulsion system integrating contractor are jointly responsible for ensuring that the overall FoS requirement is met without excessive 'stacking' of individual margins, which can negatively impact size, weight, and complexity of the hardware. Reference Shuttle OMS and RCS tank retention safety factors (ref) Orbiter OMS and RCS technology (Boudreaux, 1983, p. 21) , (ref) Surface Tension Propellant Acquisition System Technology for Space Shuttle Reaction Control Tanks (Fester, 1975), and AIAA 97-2811, Propellant Management Device Conceptual Design and Analysis. (Jaekle, 1997, p. 12)

3.6.6.3 For the design and analysis of surface tension vanes in a liquid propellant tank, minimum safety factors of 3.0 on friction/flow losses and 2.0 on surface tension shall be maintained. ***[PSR-176G]***

Rationale: For surface tension devices, a low-g verification test is not always practical. Therefore, all individual inputs to the analysis of that hardware should be based on conservative values of parameters measured by test with conservative assumptions in terms of surface tension breakdown from liquid flow to gas flow (i.e. screen bubble point, etc.). These assumptions and parameter values/margins should be clearly stated and explained in the analysis documentation. In addition, the tank designer/supplier and propulsion system integrating contractor are jointly responsible for ensuring that the overall FoS requirement is met without excessive 'stacking' of individual margins, which can negatively impact size, weight, and complexity of the hardware. Reference AIAA 91-2172, Propellant Management Device Conceptual Design and Analysis: Vanes. (Jaekle, 1991, p. 4)

3.6.6.4 For the design and analysis of surface tension sponges in a liquid propellant tank, minimum safety factors of 2.0 for the deliverable volume vs. the demand volume shall be maintained.

[PSR-177G]

Rationale: For surface tension devices, a low-g verification test is not always practical. Therefore, all individual inputs to the analysis of that hardware should be based on conservative values of parameters measured by test with conservative assumptions in terms of surface tension breakdown from liquid flow to gas flow (i.e. screen bubble point, etc.). These assumptions and parameter values/margins should be clearly stated and explained in the analysis documentation. In addition, the tank designer/supplier and propulsion system integrating contractor are jointly responsible for ensuring that the overall FoS requirement is met without excessive 'stacking' of individual margins, which can negatively impact size, weight, and complexity of the hardware. Reference AIAA 93-1970, Propellant Management Device Conceptual Design and Analysis: Sponges. (Jaekel, 1993, pp. 9-12)

3.6.6.5 Positive expulsion thin wall flexible metallic bellows or diaphragms within liquid propellant tanks or liquid propellant feedline accumulators shall be classified as fracture critical and meet the fracture control requirements of NASA-STD-5019 or, as an alternate approach, a tailored set of requirements driven by the thin-walled flexible pressure boundary (TWFPB) content of JSC-67035, Best Practices and Guidelines (BP&G) for Thin Wall Pressure Boundaries (TWPB) for Human Spaceflight Applications. ***[PSR-178G]***

Rationale: Positive expulsion metallic tanks containing internal bellows or diaphragms can provide gas-free propellants, however there are welds and regions of potential yielding that could crack and allow pressurant gas to flow through or allow propellants to mix with pressurant on the ullage side. When classical fracture control methods in NASA-STD-5019 can't be applied to a thin-walled, flexible bellows/diaphragm used to separate pressurant gas and liquid in a propellant tank, the content of JSC-67035 must be applied for adequate reliability and safety of that hardware.

3.6.6.6 Positive expulsion elastomeric and flexible metallic diaphragms used in liquid propellant tanks shall include an assessment of the material compatibility, performance impacts, and hazards associated with permeation of propellant vapors into the upstream pressurization system and of the pressurant gases into the propellant. ***[PSR-179G]***

Rationale: Propellant vapors can diffuse/permeate through elastomeric barriers or leak through thin wall flexible metallic barriers (e.g. weld porosity, crack) therefore the gas pressurization side of the system needs to be evaluated for propellant compatibility to control hazards associated with pressurization system failure due to corrosion. Pressurant gas may become dissolved in the propellants.

3.6.6.7 For diaphragms, the delta pressure limits across the diaphragm shall be defined to prevent damage to the diaphragm material at full expulsion and full reversal cycles and verified as part of cycle life tests. ***[PSR-180G]***

Rationale: The typical approach is to define an acceptable maximum 'time of exposure at delta pressure' constraint to ensure no damage/degradation. The hazard is the extrusion of elastomer material into the tank inlet or outlet.

3.6.6.8 The propellant management device (PMD),while attached to the pressure vessel wall as part of the propellant tank assembly, shall be qualification tested for vibration, thrust accelerations, propellant slosh, and maximum specified fluid outflow rates, with margins, over the expected range of service fill levels, including full wet and completely dry as appropriate, based on the expected ground operations and in-flight usage conditions, as part of the unit level tank qualification test protocol in accordance with SMC-S-016, Test Requirements for Launch, Upper-Stage, and Space Vehicles. ***[PSR-181SC]***

Rationale: Wear, fatigue, structural damage, or failure of a propellant tank's PMD can occur in service allowing gas to flow to the engines/thrusters rather than propellants only as intended, if not adequately designed and qualified. Table 6.3-1 in SMC-S-016 contains a unit level qualification test protocol for tanks/pressure vessels, but it does not address the environments and conditions of most relevance to the life and performance of an internal PMD, thus necessitating this requirement. Shock, vibration, thrust accelerations, propellant slosh, and propellant flow demands can all impart cyclic mechanical loads on a PMD, which need to be accounted for during tank qualification. Wet vs dry tank testing in acoustic or vibration environments on the ground, especially for tanks with PMD's (e.g., reverberant acoustic/Direct Field Acoustic Test (DFAT) or vibration), can impart loads on the PMD that are different from flight, either an over- or under-test condition, creating the potential for damage to flight hardware. As a result, tank qualification testing must account for all such conditions to demonstrate design adequacy for the performance and life requirements.

3.6.6.9 Performance testing of the integrated propellant tank assembly as part of unit qualification and acceptance per SMC-S-016, after exposure to shock and vibration, shall include expulsion efficiency, bubble point of the PMD screens, effect of contamination, and flow/delta P of the PMD at maximum flow rate to ensure compliance with the requirements for these parameters in the propellant tank specification. ***[PSR-182G]***

Rationale: All of the performance parameters for a propellant tank cited in this requirement are critical controls for catastrophic hazards in a propulsion system relative to quantifying unusable propellant (i.e. premature depletion of propellant), delivering gas-free propellant to the feed system, and maintaining inlet conditions at the engine/thruster interface within certified limits.

3.6.7 Tank Slosh Control Devices

3.6.7.1 The slosh control devices within a propellant tank shall be designed and verified by test and analysis to control swirl motion (single and multi-tank), vortex motion, and lateral motion of the contained liquid as needed to achieve the required slosh damping performance characteristics defined by GNC in section 3.1.9.2 [PSR-21G] of this document, to meet pressurant gas bubble ingestion limits of the engines under the accelerations and rates provided by GNC, and to be compatible with propellant gauging accuracy requirements. ***[PSR-183G]***

Rationale: Control of slosh amplitudes are needed to prevent gas ingestion into engines, structural failure, and loss of control hazards. Individual propellant tank drains can induce a vortex that impacts tank expulsion efficiency. Also, multi-tank configurations can be susceptible to a coupled swirl motion induced by engine gimbaling and roll control. Apollo 11 experienced significant propellant slosh resulting in issues with controllability, potential for gas ingestion, and inaccuracy in propellant levels, thus driving design modifications to add slosh baffles to the propellant tanks for subsequent flights (ref) NASA TM X-2362, Investigation of Slosh Anomaly in Apollo Lunar Module Propellant Gage (Scholl, 1971) and (ref) Apollo 11 Mission, Anomaly Report No. 3, Service Module Entry. (McDivitt, 1970)

3.6.7.2 Performance of the slosh damping devices within a propellant tank shall be demonstrated through a combination of analysis and unit level qualification testing of the tank in accordance with SMC-S-016 to verify the required level of damping defined by GNC in section 3.1.9.2 of this document has been met. ***[PSR-184G]***

Rationale: There is a need to quantitatively demonstrate the performance of slosh features within a propellant tank through a combination of analysis and testing to ensure that the damping requirements established via GNC controllability analysis are being met, thus ensuring that propulsive attitude control and translational maneuvers can be executed successfully throughout the mission. Propellant slosh can also induce significant loads on the slosh features within the tank, which need to be considered in the structural analysis of the tank. Propellant slosh is a complex phenomenon so analytical predictions are expected to be anchored to relevant test data as part of verifying design adequacy.

3.6.7.2.1 If slosh suppression features are present, they shall be designed to provide positive structural margins of safety under all applicable externally applied and self-induced loads while maintaining the GNC-specified level of liquid damping. ***[PSR-185G]***

Rationale: Failure of the slosh suppression features can cause slosh levels to be excessive or cause loss of proper propellant acquisition by blocking or creating excessive delta-pressure.

3.6.8 Propellant Quantity Gauge

3.6.8.1 The design of a spacecraft propulsion system shall incorporate a method of propellant quantity gauging to address the catastrophic hazards associated with inadvertent depletion of propellant and improper refueling of propellant while in flight. ***[PSR-186G]***

Rationale: A reliable method of propellant quantity gauging is a key means of control for the catastrophic hazards associated with inadvertent depletion of propellant and improper refueling of propellant in a spacecraft. Causes of inadvertent depletion include external leakage from the propulsion system (e.g. sluggish or failed-open thruster valves, leakage past seals or through flaws/defects in the propulsion system hardware, structural failure of the propulsion system hardware, etc.) and/or off-nominal performance of the engines (e.g. mixture ratio variations, filter plugging, orifice or venturi throat erosion, injector plugging or structural failure, thruster valve malfunctions, etc.). Causes of improper refueling include external leakage at the refueling coupling interface, overpressurization of the propellant tanks, breakdown of the propellant tank acquisition screens, overheating of compressed pressurant gases, transient pressure surges in the propellant lines, overboard venting of propellants, and various other failure modes within the tanker/servicer vehicle. Quantity gauging methods on the spacecraft play a key role in controlling such hazards. Options include instruments that directly measure the quantity of propellant remaining in the system (e.g. capacitance probes, ultrasonic detectors, acoustic, shell modal response, radio frequency mass propellant gauges, etc.), along with analysis-only approaches that indirectly estimate the quantity of propellant remaining in the system (e.g. Pressure-Volume-Temperature (PVT), Burn-Time Integration (BTI), etc.). All those approaches, whether used individually or collectively, have a unique set of pros/cons and introduce an error band in the measurement that must be quantified and considered when developing an approach for a given vehicle and mission.

3.6.8.2 If an indirect (i.e. analysis only) means of propellant quantity gauging is pursued, a separate means of detecting external/overboard propellant leakage and off-nominal engine/thruster performance shall be implemented. ***[PSR-187G]***

Rationale: Indirect measurement approaches for propellant gauging. such as Pressure-Volume-Temperature (PVT) and burn time integration (BTI) that calculate propellant usage and quantity remaining based on analysis alone (vs. direct measurements such as integrating flow meters, capacitance probes, ultrasonic sensors, modal propellant gauges, etc.), are insensitive to external/overboard leakage and engine/thruster performance variations that can significantly alter the actual amount of propellant remaining. In addition, there is a notable history of overboard propellant leakage and engine/thruster performance anomalies, component and feed line restrictions, etc. in spacecraft propulsion systems while in service that led to errors in the propellant consumption calculations. As a result, additional hazard controls are needed in such instances.

3.6.8.3 Any uncertainty or error associated with the propellant quantity gauging method shall be *considered as unusable commodity in the propellant budget for the mission.* ***[PSR-188G]***

Rationale: The uncertainty or error for a given quantity gauging method implies a lack of certainty that the estimated amount of propellant remaining in the propulsion system is truly present. Such uncertainty occurs when estimating the quantity of propellant used/remaining onboard a spacecraft at any point during the mission, and also when transferring propellant to a spacecraft during a refueling operation. For conservatism, mission planning and flight operations of the spacecraft should be conducted under the assumption that the quantity associated with measurement uncertainty or error will not be available to produce useful thrust/impulse when needed, akin to the residual propellants remaining in a fully spent propulsion system. Reference LLIS-915, Propellant Management for Geosynchronous Satellite. (LLIS-915, 2000)

3.6.8.4 Performance verification of the propellant quantity gauging method shall be accomplished via testing and an error analysis. ***[PSR-189G]***

Rationale: It is critical that the gauging method provides the specified accuracy for propellant quantity remaining in the propulsion system of the spacecraft. Reliance on this method by the mission planners and flight operations teams to prevent propellant depletion necessitates a rigorous analytical and/or test-based approach to characterize quantity gauging performance and verify its advertised performance under nominal and off-nominal conditions.

3.6.8.5 Any uncertainty or error, such as vapor loss, propellant temperature/density, tank volume, liquid level height, etc. associated with the propellant loaded into the propulsion system during pre-launch ground operations shall be considered as unusable commodity in the propellant budget for the mission. ***[PSR-190G]***

Rationale: The uncertainty or error in the propellant loading process implies a lack of certainty that the estimated amount of propellant loaded into the propulsion system during pre-launch ground operations is truly present. Cryogenic propellants temperature measurements, including amount of subcooling, are critical to establishing density. For conservatism, mission planning and flight operations of the spacecraft should be conducted under the assumption that the quantity associated with measurement uncertainty or error will not be available to produce useful thrust/impulse when needed, akin to the residual propellants remaining in a fully spent propulsion system.

3.7 PRESSURIZATION SUBSYSTEM

The pressurization subsystem is intended to control propellant tank ullage pressure in order to supply the proper engine/thruster inlet pressure condition and avoid exceeding the MDP of the system. This typically consists of pressurant storage tanks, isolation valves, pressure regulation devices, and pressure relief devices that operate in conjunction with the thermal control systems (e.g. heaters, heat pipes, etc. that influence hardware and fluid temperature) to collectively provide two-fault tolerance (2FT) to exceeding the MDP of the system.

3.7.1 Pressure Regulation and Isolation

The pressure regulation 'device' in a spacecraft propulsion system may consist of a mechanical regulator, an electronically controlled "bang-bang" valve, an electronically controlled proportional valve, or an electronically controlled pilot on a mechanical regulator. Other configurations may also be possible and considered for a given application. The following requirements are intended to ensure that key design inputs, features, and performance attributes of the regulation device are addressed.

3.7.1.1 The regulated outlet pressure range shall be established and specified as a function of fluid flowrate and case-consistent pressure/temperature conditions at the regulation device inlet. ***[PSR-191G]***

Rationale: The performance specification for a pressure regulation device should establish a target regulated outlet pressure, with associated tolerances, based on the necessary fluid flow rates and case-consistent pressure/temperature conditions at the inlet corresponding to a given application. The words 'case-consistent' are intended to ensure that the extremes of fluid pressure, temperature, and flow rate are not combined in an unrealistic manner, thus driving an overdesign of the regulation device. For example, the maximum inlet pressure would likely not occur in combination with the minimum inlet temperature to produce the necessary outlet pressure and flow rate. As such, the regulation device specification must be clear on how those key parameters are to be used in the design process to ensure the hardware will meet the performance needs for ground testing and in-flight operation.

3.7.1.2 The device shall be dynamically stable with a return to stable operation, within a specified time duration, with no organized and sustained oscillations including at natural frequencies within the component over the full inlet pressure range, flow, and ullage volume range. ***[PSR-192G]***

Rationale: The pressure regulation system (controls, components, line diameters and lengths, ullage volumes, pressure drops etc.) needs an ability to experience a perturbation, such as with a sudden flow stoppage or flow rate change within the range of nominal and fault tolerant operation, and then return to stable operation, within a specified time duration. There should be no organized oscillations at specific frequencies that would wear internal mechanisms. An undamped instability of this nature, triggered by a discrete change in flow rate within the previously certified bounds of operation, contributed to the rapid premature fail-open of the regulator during ground testing. In response, the regulator was redesigned to control damping and avoid the potentially catastrophic fail-open condition observed during the original anomaly. ref AIAA 90-2749, "Methods Used to Investigate and Resolve the Space Shuttle Helium Pressure Regulator Instability" (Hurlbert, 1990).

3.7.1.3 The pressure regulation system and components shall be tested for slam start pressure transients when the system is activated and for pressure transients when the maximum change in flowrate occurs at maximum inlet pressures and minimum downstream volumes in series and parallel configurations. ***[PSR-193G]***

Rationale: Activation of pressure regulators and pressure regulation systems can result in excessive transients in downstream volumes, which can lead to inadvertent rupture of bust disks. The minimum volume can exist if parallel regulation systems are activated in sequence and downstream check valves are backed by pressure. See report entitled NASA TN D-7151, 'Apollo Experience Report - Command and Service Module Reaction Control Systems' (Taeuber, 1973, pp. 11,12,14) for examples where regulator overshoot during system activation unexpectedly ruptured the burst disks during development testing for both the CM RCS as well as the SM RCS. Also see AIAA 2011-5838, Lessons Learned from the Design, Certification, and Operation of the Space Shuttle Integrated Main Propulsion System (IMPS) (Martinez, 2011, p. 8) for a related reference on regulator slam start causing high system pressures that can lead to line/component rupture/breakage, such as the check valve.

3.7.1.4 *The overshoot pressure upon initiation or termination of flow shall remain below the hardware MDP or the activation pressure of the relief device if one is used.* ***[PSR-194G]***

Rationale: A relief device is not intended as a means to control the MDP by relieving pressure under nominal initiation or termination of flow. A relief device is intended for fault cases.

3.7.1.5 The peak overshoot pressure shall account for liquid propellant that, in zero-g, may have migrated into or condensed within the pressurization system feed lines. ***[PSR-195G]***

Rationale: The presence of liquid-phase propellant in the pressurization system feed lines represents a hazard that can cause pressure transients in those lines to be significantly higher than anticipated based on analysis or measured in test.

3.7.1.6 The fault tolerance of the pressure regulation function in a propulsion system shall include failures in the electronic control, such as pressure sensing and other electrical components. ***[PSR-196G]***

Rationale: Electronic control failures could lead to failure modes such as full open flow, full closed, or stability issues.

3.7.1.7 Each serial stage and/or parallel leg in a redundant pressure regulation system shall be functionally tested during qualification and acceptance, inclusive of the nominal and contingency failure configurations and conditions that could occur in flight (single failure cases for 1FT systems, two failure cases for 2FT systems). ***[PSR-197G]***

Rationale: This testing is required to verify that the redundant pressure regulation functions present by design will actually provide the specified performance levels in the as-built integrated propulsion system. It is especially important to ensure that static and/or dynamic conditions/events associated with operating the primary flow path under nominal and contingency conditions don't trigger an anomaly/failure in the redundant flow path prior to or during use, as seen on past projects/programs.

3.7.1.8 The sizing of the pressurant tanks shall account for the specified leakage rate through the 2-fault tolerant pressurization system (e.g. isolation valves and the regulation device) over the duration of the mission, which results in the loss of commodity over the duration of the mission either through the relief device which is a function of ullage volume at the start time of leakage, if there is one, or the loss of commodity through a bleed device. ***[PSR-198G]***

Rationale: This leakage always occurs at some rate and must be accounted for over the duration of the mission.

3.7.2 Overpressure Protection – Pressure Relief

The approach to overpressure protection in a spacecraft propulsion system can be active, involving the monitoring of pressures and modulation of valves to control pressure levels, or passive, involving the use of burst disks and/or relief valves that automatically activate when pressure reaches a certain level. The former requires a source of power to enable the operation of software, instrumentation, and valves on the spacecraft, while the latter does not. As a result, passive protection is considered necessary to avoid reliance on active monitoring and a timely response given the catastrophic nature of the hazards involved and the multitude of failure modes in a pressure control system that could produce such an event, either rapidly or slowly over time. Of course, cryogenic propulsion systems are especially sensitive to rapid increases in pressure due to changing thermal conditions, so a passive approach is routinely employed in those situations. If an active monitoring/control approach is desired instead of the design-based passive approach described herein, then a variance to the requirements of this section containing appropriate technical acceptance rationale would be needed for review/approval by the NASA Technical Authority (TA).

*3.7.2.1 A human rated spacecraft propulsion system shall contain passive pressure relief devices/features in the design to prevent all hardware located downstream of any pressure regulating equipment (e.g. regulators, valves, orifices, etc.) from exceeding its MDP under worst-case two-failure conditions, unless that hardware can withstand the full MDP of the upstream pressure source****. [PSR-360G]***

Rationale: This requirement captures the intent of paragraph F-30 (Pressure Relief for Pressure Vessels/Systems) in JSC-08080-2, JSC Design and Procedural Standards, and paragraphs 12.6.1.9.3 and 12.6.1.9.5 in SSCMAN 91-710, Volume 3, Range Safety User Requirements Manual - Launch Vehicles, Payloads, and Ground Support Systems Requirements. The consequences of inadvertent overpressurization and rupture of a pressure vessel within a spacecraft, whether the event develops slowly over time or occurs rapidly, could be catastrophic. Passive pressure relief features built into the pressurization system feeding the propellant tanks, combined with other flow control inhibits located further upstream (e.g. valves, regulators, etc.), provide an effective fault-tolerant design control for the rupture hazard without the need to rely on active monitoring and timely intervention in response to an unexpected condition. This approach addresses potential shortcomings and execution errors associated with procedural means of pressure monitoring/control; planned or unplanned periods of time when onboard flight software, thermal conditioning, and/or power may not be available for active pressure monitoring/control; and in-specification or out-of-specification internal leakage of fluid components being relied upon as inhibits to provide isolation from a higher-pressure source.

3.7.2.2 All pressure relief devices shall be designed to provide venting performance that maintains the pressure of all protected hardware items below their MDP, including the effects of mechanical and temperature-driven activation set-point tolerances of the relief device, all temperatures and phases (i.e. gas vs. liquid) of fluid flow, and all applicable sources of pressure drop in the vent system flow path. ***[PSR-199G]***

Rationale: This requirement is intended to ensure that overpressure of the hardware in a spacecraft propulsion system beyond MDP, which could lead to a catastrophic rupture event, does not occur and properly accounts for all key conditions affecting performance of the relief device itself and the associated vent system flow path. Note that this requirement is slightly more conservative than paragraph 3.2.8.3 [STR0021] in JSC-65828, which allows a 10% exceedance of MDP. Also note that internal leakage of the pressurization system, whether in-spec over a long period of time or out-of-spec over a shorter period of time driven by a failure condition, may cause regulated propellant system pressures to exceed MDP and reach the activation pressure of the relief device, which is not a desired mode of operation for the propulsion system.

3.7.2.3 The specification of performance parameters associated with testing of a pressure relief valve for a human rated spacecraft propulsion system shall comply with the ‘pressure relief valves’ requirements of paragraph F-18 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-200S]***

Rationale: The content of paragraph F-18 (Pressure Relief Valves – Standardization of Functional Testing) is intended to ensure that key performance parameters associated with testing of a pressure relief valve, including crack and reseat pressures, mass flow rates, full flow pressures, allowable leak rates, and retest intervals, are adequately specified with a target value and a tolerance by the hardware manufacturer/supplier.

3.7.2.4 The relief device, vent line location, and vent line sizing shall consider the migration of liquid propellant due to vapor condensation, zero-g/low-g wicking (surface tension), acceleration induced by propulsive maneuvers, and/or the pressure relief event into the vent lines. **[PSR-201G]**

Rationale: The migration of liquid into a relief device or pressure regulation system can provide additional pressure delta that causes an overshoot in pressure at the outlet of the pressure regulator/valve or in the system being protected by relief device.

3.7.2.5 For relief valves exposed to liquid or vapor phase propellant, a non-permeable vapor barrier (e.g., welded burst disk) located upstream shall be included in the design to prevent corrosion of the relief valve and/or a build-up of frozen fluids at the relief valve outlet, with a sealable test port located in between to allow leakage and functional checkout of both devices during ground testing. ***[PSR-202G]***

Rationale: Frozen propellant during vent flow, such as due to leakage/venting into a vacuum, or corrosion of the relief valve hardware from propellant vapor, especially from interaction with a humid air environment, may cause inability of the relief valve to relieve pressure as designed, thus resulting in a catastrophic over pressurization/rupture of the tanks being protected. The presence of an impermeable vapor barrier as part of the design will prevent those types of conditions from leading to relief valve performance issues. The sealable test port between the burst disk and relief valve is intended to enable leakage and functional checkout of both devices during ground testing. In some cases, a pressure transducer has also been installed on that test port for flight to allow continuous health monitoring of the burst disk's welded diaphragm, but that feature is not considered mandatory.

3.7.3 Control of Corrosive and Reactive Propellant Liquid and Vapors in the Pressurization System

3.7.3.1 The unintended mixing of liquid and/or vapor-phase hypergolic fuel and oxidizer in a human rated spacecraft propulsion system shall be controlled via compliance with the 'separation of hypergolic reactants' requirements of paragraph F-15 in JSC-08080-2, JSC Design and Procedural Requirements, with an exception for select common pressurization systems as discussed in section 3.7.3.4. ***[PSR-203S]***

Rationale: The content of paragraph F-15 (Separation of Hypergolic Reactants) drives the purposeful separation of liquid and/or vapor-phase hypergolic fuel and oxidizer using a positive, all-metal containment approach throughout a spacecraft propulsion system, except for the intentional mixing of those fluids in the combustion chamber of a firing engine/thruster.

3.7.3.2 Check valves, vapor isolation valves, tank elastomeric diaphragms/bladders, and tank liquid retention devices shall be prohibited from consideration as effective means of preventing propellant vapor migration upstream into the pressurization system, thereby requiring material compatibility and component exposure tests of pressurization system hardware per

NASA-STD-6016 and herein. ***[PSR-204SC]***

Rationale: Past experience has clearly demonstrated that propellant vapor can permeate through tank elastomeric diaphragms/bladders and non-metallic seals in passive check valves and commandable vapor isolation valves, resulting in significant quantities of propellant vapor accumulation within the upstream inert gas pressurization system. This vapor can participate in chemical reactions with incompatible materials (e.g. corrosion, catalytic decomposition, etc.), degrade incompatible soft goods (e.g. swelling, embrittlement, compression set, etc.), and condense/freeze on feed line and component internal surfaces or coalesce into slugs of liquid that increase pressure drop and cause transient pressure excursions exceeding MDP of the hardware. Therefore, a strategy of preventing vapor migration by design or by performing configuration specific qualification testing of flight-representative hardware to demonstrate insensitivity to the associated hazards must be pursued, etc. and migrate upstream into the pressurization system, resulting in corrosion or other reactions in the case of monopropellants that can result in catastrophic hazards.

3.7.3.3 The condensation of propellant vapors in the pressurization system and components shall be controlled to preclude material reactions, corrosion, clogging, and excessive transient pressures during system operation, leading to component failures which can create a catastrophic hazard. ***[PSR-205G]***

Rationale: Temperature gradients, thermal cycles, inadequate thermal control design, etc. can allow propellant vapor that has migrated into the upstream pressurization system to condense in the components and lines, resulting in reactions, corrosion, clogging, and/or excessive transient pressures above MDP during system operation, which can result in hardware failure leading to a catastrophic hazard.

3.7.3.4 The use of a common pressurization system in a spacecraft bipropellant propulsion system shall be limited to situations where the migration and mixing of fuel and oxidizer (liquid or vapor) is initially prevented by pyro valve separation or other means of inhibiting the propellant reaction, followed by short term use or engine burn and disposal, with the added stipulation that this other means has been verified by system level tests for 2x the maximum potential exposure duration. ***[PSR-206G]***

Rationale: Short duration (i.e. hours-days) mission vehicles have been successful, however catastrophic failure has been observed at longer durations possibly due to higher than expected permeation, leakage, or thermal conditions that allow the collection and condensation of propellant vapor, resulting in the possible mixing of fuel and oxidizer to create catastrophic hazard. This was most probable cause of failure for the Mars Observer spacecraft, reference (LLIS-485) Isolate the Propulsion Pressurization System from the Propellant Tanks (LLIS-485, 1996) , and involved with other in-flight anomalies such as the Juno Spacecraft, reference (LLIS-28105) High Oxidizer Vapor Content May Cause Vapor Reaction in Bi-Propellant Systems. (LLIS-28105, 2017)

3.7.3.5 A liquid retention device (LRD) shall be incorporated into the liquid propellant tank design to preclude the inadvertent migration of liquid upstream into the pressurization system if the tank pressurization and pressure relief functions could be adversely affected by the liquid. ***[PSR-207G]***

Rationale: The presence of liquid propellant in the upstream pressurization system lines, inclusive of the pressure relief line, can potentially cause material reactions, corrosion, clogging, and excessive transient pressures above MDP during system operation, which can drive hardware failure resulting in a catastrophic hazard.

3.8 PROPULSION SYSTEM VALVES

3.8.1 General Requirements

3.8.1.1 Valves shall meet all requirements in NASA-STD-5017, Design and Development Requirements for Mechanisms. ***[PSR-208S]***

Rationale: The cited NASA-STD provides a comprehensive set of requirements aimed at ensuring the safety and reliability of space mechanisms. Note that propulsion system valves, which can be operated with a variety of different mechanisms (e.g. stepper motor, solenoid, pneumatic, etc.), are considered to fall under the scope of this standard. However, there are some known limitations and necessary clarifications as related to fluid system valves, which are addressed by the requirements herein.

3.8.1.2 RESERVED ***[PSR-209G]***

Rationale: This is reserved for the future NASA-STD-5023, DESIGN AND VERIFICATION REQUIREMENTS FOR VALVES .

3.8.2 Dimensional Analysis and Clearances

3.8.2.1 Dimensional analysis in accordance with paragraph 4.1.2 [DDMR2] of NASA-STD-5017, Design and Development Requirements for Mechanisms, shall account for the effects of exposure to propellants, including but not limited to, swelling of non-metallic materials/soft-goods, corrosion of metallic materials, accumulation of allowable particulate contamination, etc. which can result in changes to as-designed tolerances and strokes leading to valve malfunction in service. ***[PSR-210G]***

Rationale: These effects are missing from this list. They can also significantly impact the dimensions and clearances.

3.8.3 Torque/Force Margin Analysis

3.8.3.1 Valve (engine and other) torque/force margin analysis per paragraph 4.3.3.1 [DDMR9] of NASA-STD-*5017*, *Design and Development Requirements for Mechanisms, shall account for startup and shutdown pressure transients from all operating engines in the integrated propulsion system, in conjunction with avionics box pull-in/hold-in current circuit designs and timing features, to assure proper functionality with required margins.* ***[PSR-211SC]***

Rationale: Large, distributed propulsion systems with many engines/thrusters have the potential for large magnitude shutdown and start-up pressure transients generated by firing certain engines/thrusters that can adversely affect planned operation of other engines/thrusters within the subsystem. Multiple occurrences on different vehicles of engine valves not opening when commanded due to water-hammer pressure levels being elevated and persisting through the pull-in/full current level of application and into the hold-in circuit operation.

3.8.3.2 The effects of exposure to liquid and/or vapor phase propellant, including in-specification leak rates and permeation through soft goods over the duration of ground processing and in-flight operation on propulsion system components, shall be quantified and included when applying the torque/force margin requirements of paragraph 4.3.1.1 [DDMR9] of NASA-STD-5017, *Design and Development Requirements for Mechanisms*. ***[PSR-212SC]***

Rationale: The functional performance of propulsion system components exposed to liquid and/or vapor phase propellant during ground processing and in-flight operations can be adversely affected and must be purposefully assessed. This requirement drives explicit consideration of any binding/stiction, stroke changes, trapped liquid, vapor pressure, corrosion, or other potential effects on the mechanism of a propulsion system component when determining the associated force margins. This is especially critical when 'like' redundancy is used in a propulsion system design, with all redundant components being exposed to a common environment.

3.8.4 Cycle Life

3.8.4.1 For all spacecraft propulsion system components that contain moving parts (e.g. valves, regulators, actuators, etc.), the estimation of 'ground cycles' in paragraph 4.19.3.2 [DDMR75] of NASA-STD-5017, Design and Development Requirements for Mechanisms, shall include all wet and dry cycles associated with flight fluid commodity servicing, deservicing, and decontamination operations, in addition to all 'test cycles, installation cycles, and maintenance cycles' as currently stated, for capture in the cycle life requirement of the component specification. ***[PSR-213SC]***

Rationale: The specified cycle life for a propulsion system component in a given spacecraft application must include the many actuation cycles that can accrue during ground processing of a spacecraft, whether in preparation for the first flight or between flights for a reusable vehicle (in addition to all estimated cycles in-flight). Neglecting this aspect of component operation and failing to include these cycles in the component specification and qualification test campaign, which has occurred in past projects/programs, can result in unexpected and premature failure of the hardware in service, thus leading to undesirable limited-life constraints, propulsion system malfunctions, and potentially catastrophic hazards.

3.8.4.2 For all spacecraft propulsion system valves, such as pressurant isolation, propellant isolation, or engine valves, the estimation of flight 'operational cycles' as mentioned in paragraph 4.19.3.2 [DDMR75] of NASA-STD-5017, Design and Development Requirements for Mechanisms, shall include the nominal and contingency operations, fault cases impacting propulsion system hardware usage, 3-sigma Monte Carlo simulation of engine/thruster burns, and number of reuse missions to be certified. ***[PSR-214SC]***

Rationale: The intent of this requirement is to clarify the expected method for determining the specified flight cycle life of valves and mechanisms used in the control of pressurant gas, pneumatic gas, and propellant flow to engines/thrusters. Examples include isolation valves; pneumatic, electromechanical, or hydraulic valves and actuators used to control propellant valves; etc. Engines/thrusters used for attitude control can be especially difficult to estimate, resulting in past instances where the cycle counts have been underestimated, thus driving the need for a rigorous approach that is rooted in Monte Carlo simulation analysis performed by the GNC engineering team which inherently accounts for sources of variability that affect hardware usage. Note that other cycles of the subject valves and mechanisms may also occur in flight which aren't directly associated with an engine/thruster firing. If so, those cycles should be included in the estimate too as appropriate.

3.8.4.3 For all spacecraft propulsion system components that contain moving parts (e.g. valves, regulators, actuators, etc.), the scope of qualification testing described in section 3.2.1.1 [PSR-47S] of this document shall include a factor of 4x on the specified cycle-life of the unit, spread across the full range of applicable operating conditions for the hardware. ***[PSR-215G]***

Rationale: In this case, the term 'cycle-life' refers to a combination of operational actuation cycles and pressure cycles, both of which consume life and degrade performance of a propulsion system component over time. A factor of 4x applied to the specified number of operational cycles throughout the full service life (e.g. actuation cycles, pressure cycles, etc.) for qualification testing of propulsion components that contain moving parts is rooted in the mechanisms test requirements of NASA-STD-5017 (paragraph 4.19.3.2 [DDMR75], life testing) and SMC-S-016 (paragraph 6.3.14.3, unit life test, and paragraph 6.3.12.3, unit pressure test). The intent is to ensure that sufficient margin is included in the qualification test campaigns at component level and engine/thruster level (or at a higher level of hardware assembly if desired) for valves and other components with moving parts to encompass unit-to-unit variability in terms of material strength and fatigue properties, piece-part dimensions and tolerances, surface tribology effects at moving part interfaces, etc. Spreading the required 4x cycle count across the full range of operating conditions (e.g. performing a fraction of the qual cycles at minimum, nominal, and maximum levels for pressure, temperature, voltage/current, liquid/gas exposure, etc.) acknowledges that not all cycles will occur under the same conditions and ensures that the qualification test campaign is comprehensive in accounting for those differences while in service. Note that ANSI/AIAA-S-080, section 10.4.8 also includes pressure cycles to 4 times service life.

3.8.5 Valve Electrical

3.8.5.1 The electrical, electronic, and electromechanical (EEE) parts used in propulsion system components shall comply with the requirements of NASA-STD-8739.10, Electrical, Electronic, And Electromechanical (EEE) Parts Assurance Standard. ***[PSR-216S]***

Rationale: Certain propulsion system components (e.g. valves, transducers, actuators, controllers, heaters, pyro devices, etc.), along with the interfacing electrical power and avionics hardware (e.g. valve drivers, electrical power and data transfer wiring, pyro firing circuits, signal conditioners, data recorders, etc.), contain EEE parts. The cited NASA-STD provides a clear and comprehensive set of requirements governing the selection, sizing, quality assurance measures, and other key aspects of EEE parts implementation. Following these requirements will avoid propulsion system component malfunctions that could lead to potentially catastrophic hazards.

3.8.5.2 Propulsion system valves, or other propulsion system devices, featuring electromechanical actuation and pyrotechnic firing mechanisms shall comply with the requirements of EMI/EMC for space systems per MIL-STD-461, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment for space systems. ***[PSR-217S]***

Rationale: The intent of this requirement is to address electrical drive mechanisms for propulsion valves (e.g. pyro devices/firing circuits, motor drives on valves, etc.) and their associated interfaces, which are not explicitly addressed in NASA-STD-5017. Although 5017 does provide some explanation and acknowledge risks associated with electromagnetic interference/electromechanical compatibility (EMI/EMC) effects on/from electric motor drives (brushed and brushless) used in aerospace mechanisms, there are no actual requirements imposed to evaluate these important sensitivities with the hardware. The content of the cited MIL-STD will ensure that electrically powered valves do not produce spurious electromagnetic fields that could interfere with other pyrotechnic devices, instrumentation, avionics, etc., and they are not susceptible themselves to malfunction (e.g. inadvertent actuation, instrumentation offsets, etc.) from electromagnetic fields produced by other adjacent equipment.

3.9 PROPELLANT FEED SYSTEM

The sizing, design, analysis, and test of the propellant feed system is critical step that ultimately impacts engine pulse performance, component MDPs, selection of components, etc. This is a driver for the selection of valves and components that are critical to avoiding potential catastrophic failure modes and lack of reliability. This process must start in early conceptual design/sizing/analysis, followed by early prototype testing, and verification and validation of this critical model. The primary events the create pressure transients are engine operation, feed system priming or activation, repriming, and thermal cycles of liquid locked systems. Meeting the engine interface condition requirements is the primary function of the feed system.

3.9.1 Propellant Feed System and Engine Interface Conditions

3.9.1.1 The propellant feed system shall be designed to meet engine/thruster interface condition limits during the start transient and steady state-run box, in terms of propellant pressure range, temperature range, flow rate range, fluid quality range, gas saturation range, and entrained pressurant or decomposition gas bubble volume range, over the duration of the mission duty cycles per GNC requirements governing the number of engines that are being fired simultaneously or staggered. ***[PSR-218G]***

Rationale: The engines/thrusters in a propulsion system are qualified to operate over a finite range of inlet conditions during transient start-up and steady state firing. These critical inlet conditions include propellant pressures, temperatures, fluid quality levels, pressurant saturation levels, and entrained non-condensable pressurant gas bubble volumes driven by gas evolution at pressure drops within the system. Operation of the engines/thrusters with any or all of these parameters outside of their allowable ranges can have adverse impacts on engine/thruster performance and result in catastrophic failure of the hardware. Example hazards include the accumulation and detonation of fuel-oxidizer reaction products (FORP) due to propellant temperature, combustion instability due to pressure transients or gas bubble ingestion, combustion chamber thermal issues such as rapid burn-through, etc. Given those risks, having an interface requirements document (IRD) or interface control document (ICD) that clearly defines the acceptable engine/thruster operating bounds is considered critical, thus enabling the feed system to be designed in a manner that will respect those bounds at the thruster engine/thruster inlet, thus avoiding any hazards associated with exceedance. It should be noted that during pulse transient, the engines/thrusters can spend much of the time outside of the steady state-run box, which is a particular concern that can be addressed via purposeful feed system design.

3.9.1.2 The propellant lines, components, and engines shall be collectively analyzed for water-hammer pressure transients produced by operation of the engines/thrusters to quantify the minimum and maximum pressure values, including creation of slumps and overpressure at the engine inlet, engine injector manifolds, and chamber pressure over the full range propellant inlet pressures and temperatures, gas saturation levels and gas bubble evolution, commanded electrical pulse widths and duty cycles, and number of engines fired simultaneously. ***[PSR-219G]***

Rationale: The firing of engines/thrusters on a spacecraft propulsion system will inevitably create pressure transients in the propellant feed lines and quantifying that pressure environment is a critical aspect of hazard control. The maximum pressures are of interest when establishing MDP values for the propulsion system and ensuring that positive structural margins are maintained for the hardware, and also when evaluating engine/thruster performance characteristics and confirming that the certified operating bounds for the engines/thrusters are being respected. The minimum pressures are of interest when assessing the margins against localized boiling of the propellants, and also when evaluating engine/thruster performance characteristics and confirming that the certified operating bounds for the engines/thrusters are being respected.

3.9.1.3 Local pressure slumps in the liquid propellant feed system relative to the steady pressure, caused by the opening and/or closing of valves (e.g. engine/thruster firing events), shall maintain a cavitation number K greater than 1.25, with the vapor pressure, P_vapor, of the fluid at the maximum temperature in order to avoid localized cavitation that can generate excessive pressure transients in the feed lines and damage propulsion system hardware. ***[PSR-220G]***

Rationale: K is defined as (P_steady-P_vapor)/(P_steady –P_minimum). The cycling of valves in a propulsion system will inevitably create local low pressures in the propellant feed system that, if below the vapor pressure, can cause cavitation or column separation of the liquid. The resulting in vapor bubbles can be ingested into the engines/thrusters causing a variety of adverse performance effects. They can also rapidly recondense (i.e. collapse) as feedline pressures recover to steady levels. This 'bubble collapse' phenomenon can generate extremely high peak pressures and fluid velocities within the feedlines that could lead to catastrophic hazards including structural failure of the hardware, ignition of the metallic and non-metallic materials of construction in a highly oxidizing environment, and serious performance anomalies of engines/thrusters in the system. As a result, a minimum margin for the transient pressures in the propellant feedlines to remain above the vapor pressure of the fluid is needed to avoid these potentially hazardous conditions. Note that this requirement is aimed at propellant feedlines located upstream of the engine/thruster interface and it does not apply to the intended use of cavitation devices for propellant flow control (e.g. cavitating venturis used in manifold priming, cavitating valves used in engine throttling, etc.); the cavitation that normally occurs within the propellant flow paths of an engine/thruster during start-up in a vacuum environment (e.g. injector passages, regenerative cooling channels, etc.); or to self-pressurized propulsion systems that are intentionally designed for engines/thrusters to operate at two-phase conditions. In those situations, the assessment of possible detrimental effects driven by cavitation would be accomplished as part of component, subassembly, and/or subsystem level qualification testing covered in other sections of this document. Reference (ref) Water hammer with column separation: A historical review (Bergant, 2006) and NESC Tech Bulletin 21-01, Experimental and Computational Study of Cavitation in Hydrogen Peroxide.

3.9.1.4 When performing pressure transient analysis, testing, and operation of the propellant tanks, *manifolds, and feed lines in a spacecraft propulsion system, all pressurant gas dissolved in a saturated liquid propellant commodity shall be assumed to evolve at the minimum pressure and maximum temperature (i.e. minimum solubility) conditions to which the propellant is exposed during fluid commodity loading and in-flight operation of the propulsion system.* ***[PSR-221G]***

Rationale: The intent of this requirement is to ensure that the evolution of non-condensable pressurant gas from a saturated liquid propellant, which varies as a function of pressure and temperature, is properly accounted for in the pressure transient analysis, testing, and operations of a spacecraft propulsion system. In general, gas bubbles typically reduce peak pressures associated with water hammer transients in a liquid propulsion system because gases are very compressible compared to liquids. Even a single bubble in the liquid makes the whole mixture more compressible, thus 'softening' the system and altering the peak pressures and natural frequencies in service. However, in certain cases, trapped gas bubbles can also create very high-pressure spikes depending on their quantity, location, distribution, and size. Locations closer to a flow demand source (thruster) can have higher amplitudes. A single large bubble (gas pocket) tends to be worse than multiple well-distributed small bubbles (entrained gas), and a medium-sized ("goldilocks") bubble can be worse yet. Careful treatment of pressurant gas solubility characteristics and evolution from the propellant at worst-case operating conditions is critical to determining MDP values for the propulsion system and avoiding exceedance of those values while in service. Reference NESC Tech Bulletin 22-07, Helium Solubility in MMH and NTO.

3.9.2 Propellant Feed System Activation; Priming and Repriming

The process of activating a spacecraft propulsion system during ascent, on-orbit, inbound/outbound transit, or entry, descent, and landing (EDL) phases of a mission may involve filling evacuated feed lines or bringing low pressure feed lines up to full tank pressure. The analysis of priming or repriming a feed line containing low pressure inert gas or at hard vacuum is a challenge that necessitates testing to anchor the mathematical models. In order to reduce the magnitude of surge pressures in evacuated lines, a bypass, low flow priming circuit, cavitating venturi, or rate controlled priming valve may be needed in the propulsion system design. The requirements of this section pertain to controlling hazards associated with propulsion system activation, priming, and repriming events.

3.9.2.1 A concept of operations for the propellant feed system activation approach shall be developed and evaluated at the propulsion SDR. ***[PSR-222G]***

Rationale: The is a critical step that is required to produce a schematic of the propulsion system, perform system feed system analysis, and develop a draft concept of operations document and component/subsystem specifications that are all critical products for PDR. The root cause of many issues with catastrophic hazards can be traced back to early formulation.

3.9.2.2 Redundant pressure measurements shall be provided for priming or repriming operations of a manifold at low pressure or vacuum with liquid propellant to ensure that the operation is not performed with the manifold pressure in an unknown state below the qualified limit to prevent a rupture or explosion hazard, such as MDP exceedance, auto decomposition of the propellant, ACD event, compression heating of component soft goods above the auto ignition temperature (AIT) in an oxidizing environment, etc. ***[PSR-223G]***

Rationale: This requirement is intended to verify that priming or repriming a low-pressure propellant line/manifold can be executed safely and successfully in the event that the output of a single pressure transducer becomes non-functional or erroneous. In that circumstance, there is a need for redundant measurement to ensure non-hazardous conditions exist in the line/manifold prior to executing a priming or repriming event. The alternative would be to verify with a combination of analysis and testing that priming or repriming of a line/manifold under the full range of potential pressure conditions, including hard vacuum caused by external leakage through threaded fittings, bolted flange joints, single or series-redundant thruster valve seals, etc., can occur safely even without knowledge of the actual pressure following a single transducer failure.

3.9.2.3 The fluid system transient analysis and test for the propellant manifolds/feedlines during priming/repriming events shall encompass the worst-case driving pressure, propellant quality, propellant vapor, propellant decomposition gases, and non-condensable gas bubble size/void fraction/distribution in the low pressure line/manifold being primed, etc. as dictated by the commodity loading procedures, equipment, pressure/temperature instrumentation monitoring capabilities, and flight environments and operations. ***[PSR-224G]***

Rationale: Thermal cycles may cause the pressure in an isolated liquid locked manifold to drop down to vapor pressure. Non-condensable gases, whether in solution or distributed as bubbles entrained with the propellant, can change the system level speed of sound thus impacting peak pressures. Due to the difficulty of modeling at zero pressure, some level of gas pressure is required as an initial condition. To validate models, a priming test is needed as part of early development, as covered in section 3.9.4. The report AIAA 2001-3631 Compton Gamma Ray Observatory Lessons Learned in Propulsion (Dressler, 2001, p. 10) discusses surge pressure damage to a pressure transducer and valves due to a larger than expected bubble.

3.9.3 Propellant Feed System Maximum Design Pressure Transients

3.9.3.1 The determination of MDP values for the hardware shall include all water-hammer or surge transient conditions and events of any duration in service, in addition to thermal effects of trapped/isolated volumes within the system and the effects of dissolved gases. ***[PSR-225G]***

Rationale: Per paragraph 4.2.10.1 and JSC-65828, the definition of MDP includes the effects of pressure transients, thermal conditions, and two credible hardware failures. Examples of conditions/events that produce pressure transients include tank pressurization, feed system priming/repriming, engine/thruster operation, valve open/close cycling, pressure relief following a regulator failure, stage separation effects, etc., and NESC Technical Bulletin 22-03, Treatment of Transient Pressure Events in Space Flight Pressurized Systems, demonstrates that short-lived dynamic events (i.e. <1 ms duration) can indeed cause stress-related damage to the hardware. Analytical and experimental evidence also shows that short-lived dynamic pressure fluctuations caused by valve actuation, fluid-system priming/repriming, fluid discharge, vibration, and flow disturbances can elicit adverse structural response and must be considered in the space flight pressure system design and verification process.

3.9.3.2 The determination of the dynamics amplification factor for transient pressure events shall follow NASA/TM-20210022275, Treatment of Transient Pressure Events in Space Flight Pressurized Systems. ***[PSR-226G]***

The dynamic amplification factor for pressure transients is critical to determine for each application. These values can be typically 2.0-2.5.

3.9.4 Feed System Model Verification and Validation

3.9.4.1 A breadboard/prototype system level test, with referee fluids and/or actual propellants, including the effects of dissolved gases, shall be conducted by propulsion system PDR to verify the minimum and maximum dynamic pressures (i.e. surge pressures, water-hammer pressures, etc.) resulting from tank pressurization events, line/manifold priming and repriming events, and thruster firing operations. ***[PSR-227G]***

Rationale: This type of testing provides early data needed to anchor feed system math models that are critical to establishing the MDP of the system, which will serve as a critical input to the procurement specifications for long-lead prop system hardware being reviewed at PDR. For the purpose of this test effort, it would be reasonable to use industrial equivalent (i.e. COTS) hardware with similar flow characteristics and open/close response timing, or to leverage test data from prior heritage test rigs having a similar configuration to the proposed flight prop system. *(ref)* (Vaughan, 1972, pp. 7-8)

3.9.4.2 A feed system priming and thruster operation analysis, that is anchored to test data using referee fluids and/or actual propellants including the effects of dissolved gases , shall be conducted by PDR and updated to include system level qualification test data to determine the enveloping MDP values for inclusion in the component and subsystem specifications. ***[PSR-228G]***

Rationale: A validated math model, anchored to test data, is needed to determine MDP for conditions or configurations that were not able to be tested as part of prototype tests.

3.9.4.3 The fluid transient models used to predict peak pressures during propellant tank pressurization, feed system priming, water-hammer from engine/thruster firings, and other *dynamic events in a spacecraft propulsion system shall meet the analytical modeling and simulation requirements of NASA-STD-7009, Standard for Models and Simulations, and be maintained/updated in the Critical Math Model (CMM) database for the life of the project/program.* ***[PSR-229G]***

Rationale: Analysis of the transient pressure environment associated with dynamic events in a spacecraft propulsion system, including propellant tank pressurization, feed system priming, water-hammer from engine/thruster firings, etc., is a critical aspect of verifying design adequacy, confirming peak pressures remain below MDP, and controlling hazards. The content of the cited NASA standard provides uniform and rigorous engineering and technical requirements for processes, procedures, practices, and methods applied to critical math models and simulations developed for NASA projects/programs. Based on past experience, minor design changes can significantly impact the magnitude of pressure transients and model accuracy. When performing this type of work, all assumptions and inputs should be documented, and strong rationale should be provided when adjusting the models based on test results. Following this approach has historically produced very good correlation with propulsion system test data relative to pressure transient magnitudes, frequency content, and damping rates. Note that the uncertainty in the analysis results should be quantified and sensitivity analysis covering a range of inputs is recommended, especially in critical applications or with marginally acceptable results. Also note that this requirement is an extension of requirements 3.1.2.1 [PSR-03S] and 3.1.2.2 [PSR-04G] relative to propulsion system transient pressure models, with additional prop-centric details captured in the rationale.

3.9.5 Propellant Isolation – Inhibits to Bulk Propellant Loss

The intent of this section is to govern the number of inhibits in the propulsion system design controlling the hazards associated with the overboard leakage or release of bulk propellant or other hazardous quantity, where bulk propellant is defined as the quantity stored in the propellant tanks. Note there are separate companion requirements for propellant gauging, leak detection/isolation, and associated leak detection sensitivity/error being bookkept as unusable commodity. Also, for pyro valves meeting the requirements specified herein, a NC pyro valve prior to activation and a NO pyro valve after activation are considered as non-credible leak site. Thin Wall Flexible Pressure Boundaries (TWFPB) that are directly connected (non-isolatable) to the bulk propellant supply are subject to requirements herein and are not recommended due to credible failure modes.

3.9.5.1 A human-rated spacecraft propulsion system shall provide a minimum of three (3) independently verifiable mechanical inhibits to the leakage/release of bulk propellant or other hazardous quantity through the intended propellant flow path(s) during nominal system operation, in the time interval between propellant loading and propulsion system activation. ***[PSR-230G]***

Rationale: A mechanical inhibit is an independent and verifiable device, whether reconfigurable (e.g. a propellant valve that can be commanded open or closed, etc.) or non-reconfigurable (e.g. a static seal in a flange joint, service valve, or fitting, etc.), that prevents the overboard leakage/release of bulk or a hazardous quantity of propellant from occurring. This paragraph is intended to address the reconfigurable inhibits located between the propellant tanks, the thrusters, and any propellant vent/dump lines that may be present in the system. Historically, three (3) inhibits have been considered the minimum quantity for adequate control of the catastrophic hazard associated with leakage/release of bulk propellant, and that is rooted in a combination of range safety requirements governing ground operations prior to launch and flight operations after launch.

3.9.5.2 A human-rated spacecraft propulsion system shall provide a minimum of two (2) inhibits to the leakage/release of bulk propellant or other hazardous quantity through the intended propellant flow path(s) during nominal system operation, after propulsion system activation while docked to a destination vehicle or landed on a planetary surface. ***[PSR-231G]***

Rationale: A mechanical inhibit is an independent and verifiable device, whether reconfigurable (e.g. a propellant valve that can be commanded open or closed, etc.) or non-reconfigurable (e.g. a static seal in a flange joint, service valve, or fitting, etc.), that prevents the overboard leakage/release of bulk propellant or other hazardous quantity from occurring. Based on historical precedent for flight operations of a spacecraft during the quiescent phases of a mission, it is considered acceptable to establish only 2 inhibits (of 3 total) while docked to a destination vehicle or after landing on a planetary surface. The intent is to balance the risk of external leakage/release of bulk propellant with the risks posed by additional thermally sensitive, liquid-locked volumes of propellant in the feed system and increased opportunities for a temporarily closed isolation valve to erroneously remain closed (i.e. fail to reopen upon command) later in the mission.

3.9.5.3 Mechanical joints in a human-rated spacecraft propulsion system shall provide a minimum of two (2) independently verifiable mechanical inhibits to the leakage/release of bulk or other hazardous quantity propellant through the static, non-reconfigurable seals, with all mechanical joints subject to the requirements herein. ***[PSR-232G]***

Rationale: A mechanical inhibit is an independent and verifiable device, whether reconfigurable (e.g. a propellant valve that can be commanded open or closed, etc.) or non-reconfigurable (e.g. a static seal in a flange joint, service valve) that prevents the overboard leakage/release of bulk propellant or other hazardous quantity from occurring. In general, mechanical joints are considered less reliable than welded joints from a leakage standpoint, which is supported by their notable leakage history in service. This can be especially concerning for mechanical joints in direct communication with the bulk propellant supply, creating a non-isolatable leakage vulnerability in the propulsion system. The intent of this requirement is to ensure that any such mechanical joints contain at least 2 independently verifiable inhibits (i.e. sealing features) in the design, and that all other design, qualification, and acceptance test requirements in section 3.10 of this document are met. Those items serve as a key aspect of the control for catastrophic hazards associated with the overboard leakage/release of propellant.

3.9.5.4 Propellant ground service valves in a human-rated spacecraft propulsion system shall provide a minimum of three (3) mechanical inhibits to the leakage/release of bulk propellant or other hazardous quantity through the static, non-reconfigurable seals, with a minimum of one (1) of those inhibits being independently verifiable. ***[PSR-233G]***

Rationale: A mechanical inhibit is an independent and verifiable device, whether reconfigurable (e.g. a propellant valve that can be commanded open or closed, etc.) or non-reconfigurable (e.g. a static seal in a flange joint, service valve, or fitting, etc.), that prevents the overboard leakage/release of bulk propellant or other hazardous quantity from occurring. In general, mechanical joints are considered less reliable than welded joints from a leakage standpoint, which is supported by their notable leakage history in service. This can be especially concerning for mechanical joints in direct communication with the bulk propellant supply, creating a non-isolatable leakage vulnerability in the propulsion system. Service valves are unique as they are in direct communication with the bulk propellant supply, the sealing features are reconfigurable during ground operations but not in flight, and not all of the sealing features can be independently verified via leak testing during final closeout after propellant loading. The intent of this requirement is to ensure that a service valve contains at least (3) mechanical inhibits (i.e. sealing features) in the design, and at least one (1) of those inhibits can be verified via leak testing during closeout. Those items serve as a key aspect of the control for catastrophic hazards associated with the overboard leakage/release of propellant.

3.9.6 Feed System Back Pressure Relief

3.9.6.1 Sections of tubing where propellants may be trapped (e.g. hydraulically locked) shall include redundant pressure relief provisions to ensure MDP is not exceeded under all nominal and off-nominal operating conditions including thermal excursions. ***[PSR-234G]***

Rationale: Trapped volumes of liquid (i.e. hydraulic lock) could be realized due to the planned or contingency closure of various isolation valves in the propellant manifolds/feedlines, the presence of passive check valves functioning properly within the system, etc. In these situations, upward thermal fluctuations of the trapped volumes can result in hydraulic pressures which are sufficiently high to exceed MDP and rupture the hardware, unless adequate provisions are designed into the system to relieve this pressure back upstream. Note that redundant features are needed to comply with the 1FT to a catastrophic hazard and collectively 2FT to exceeding MDP requirements. Monitoring the pressure in a liquid locked line segment can be used for checkout of this back pressure relief function during ground testing and in-flight and can also trigger a manual or automated response to increasing pressure when that condition is observed in flight.

3.9.7 Fluid Line Design, Routing, and Installation

3.9.7.1 Detailed drawings and Computer Aided Design (CAD) model images shall be provided for design routing and installation procedures of all fluid lines in the propulsion system, including pressure sensor and servicing lines. ***[PSR-235G]***

Rationale: This is critical data that allows analysis of MDPs, engine interface conditions, contamination levels, sources of installation-induced loads for inclusion in the structural analysis, separation of redundant functions with respect to line routing, etc. Reference LLIS-13801, Large Diameter Tubing in Propulsion Subsystems Poses Design Challenges. (LLIS-13801, 2015)

3.9.7.2 The fluid line design and analysis shall consider vacuum and gravitational effects, ranging from maximum acceleration to zero-g, on thermal behavior of the fluid line and possible heat and mass transport, such as from soak back of thrusters or attachments points, high points and low points in the system serving as traps for propellant vapor, non-condensable gas bubbles, and contamination. ***[PSR-236G]***

Rationale: 1-g behavior will be different than zero-g or low-g. This could result in different conditions for the engine at start-up.

3.9.7.3 Bent metallic tubing used as a pressurized component of a propulsion system in a human rated spacecraft shall meet the requirements of SAE AS33611, Tube Bend Radii. ***[PSR-362S]***

Rationale: The cited SAE standard defines the acceptable geometric shape features and surface conditions associated with bent metallic tubing made from aluminum, stainless steel, and Titanium. Excessively tight bend radii, flatness, wrinkling, and scratch depths can lead to premature structural failure of the tubing, resulting in leakage/release of the contained fluids in service. As such, meeting the requirements in that standard, identified as a gap in the typical design and construction process for a spacecraft, serves as an important aspect of hazard control for the propulsion system. Note that additional requirements governing tubing used in a pressure system, whether bent or straight, are contained in SMC-S-016, Test Requirements for Launch, Upper Stage, and Space Vehicles.

3.10 GENERAL REQUIREMENTS FOR MECHANICAL FITTINGS, JOINTS, AND FLANGES

3.10.1 Use of Mechanical Fittings/Joints vs. Brazing or Welding

3.10.1.1 For a human-rated spacecraft propulsion system, the use of separable mechanical fluid fittings/joints in lieu of brazed or welded joints at the interface between metallic components and line segments shall be limited to the situations outlined in paragraph MS-15 of JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-237G]***

Rationale: The content of paragraph MS-15 (Fluid Systems – Method of Joining Metallics) drives the use of fusion joints between metallic components (e.g. tanks, lines, valves, etc.) in a human rated spacecraft propulsion system, but it also allows 3 exceptions where the use of separable mechanical fittings/joints can be considered allowable. In general, brazed, or welded joints are considered superior to mechanical fittings/joints in terms of performance and reliability for the control of catastrophic hazards associated with external leakage/release of liquid and vapor-phase propellants. This statement is rooted in numerous past instances of external leakage occurring at mechanical fittings/joints during ground processing and in flight. However, there are certain situations where the use of mechanical fittings/joints can be considered justifiable, despite an elevated risk of leakage. The intent of this requirement is to ensure the judicious and targeted use of mechanical fittings/joints in a propulsion system as an important means of hazard control.

3.10.2 Mechanical Fitting, Joint, and Flange Design, Qualification, and Acceptance

3.10.2.1 Mechanical port seals or fittings, such as K-Port seals or Dynatube or other similar beam-seal fittings, joints, and flanges, shall meet all of the requirements defined below for design, qualification, and acceptance. ***[PSR-238G]***

3.10.2.1.1 Design: Mechanical fittings/interfaces/joints shall contain at least two seals or sealing surfaces in the design. ***[PSR-238a]***

3.10.2.1.2 Design: Each seal shall be verified capable of independently performing the intended sealing function, including structural capability. ***[PSR-238b]***

3.10.2.1.3 Design: The design shall have a verifiable positive restraint to preclude loss of seal load resulting in leakage of fitting. A positive restraint is one which mechanically precludes back-off of the fittings; thread friction is not considered an acceptable method. ***[PSR-238c]***

3.10.2.1.4 Certification data, when required, shall be summarized by the provider, and included in the submittal of safety data to NASA for all fluid systems having catastrophic hazard potential as a result of fluid leakage through a mechanical fitting. ***[PSR-238d]***

3.10.2.1.5 Qualification Test data (and analysis if appropriate) showing that each individual seal is capable of independently performing the intended sealing function under the conditions shall be provided. ***[PSR-238e]***

3.10.2.1.6 Qualification: Vibration qualification test data, subsequent leak tests, and supporting analysis to qualify the fitting/joint design for the predicted ground and flight vibration level and duration, without the use positive restraint, shall be provided. ***[PSR-238f]***

3.10.2.1.7 Qualification: Thermal cycle qualification test data, subsequent leak tests, and supporting analysis shall be used to qualify the fitting/joint design for the predicted thermal cycle magnitudes and life. ***[PSR-238g]***

3.10.2.1.8 Qualification: Pressure cycle qualification test data, subsequent leak tests, and supporting analysis shall be used to qualify the fitting/joint design for the predicted operational and surge (transient) pressure cycles. ***[PSR-238h]***

3.10.2.1.9 Qualification: Analysis and test data showing the proof, burst, yield and ultimate *combined load safety factors of the fittings/joints shall meet or exceed those specified in JSC 65828.* ***[PSR-238i]***

3.10.2.1.10 Qualification: Analysis, procedures, and test data qualifying the leak rate of the fluid fittings/joints as suitable for propulsion system service at maximum design pressure (MDP) shall be provided. ***[PSR-238j]***

3.10.2.1.11 Qualification: Engagement/disengagement cycle test data to qualify the fitting shall be provided for four times (4x) the predicted processing cycle life, performed in combination with additional environmental testing when appropriate. ***[PSR-238k]***

3.10.2.1.12 Qualification: Compatibility data for fitting/joint materials for the fluid and environmental exposure conditions and durations shall be provided. ***[PSR-238l]***

3.10.2.1.13 Qualification: Test data shall show the ability of the fitting/joint design to meet leakage requirements for the operational environments given dispersions in assembly parameters. ***[PSR-238m]***

3.10.2.1.14 Qualification testing shall verify specification leakage rates for all relevant assembly parameters, considering actual assembly procedures and criteria, manufacturing tolerances, positive restraint installation variability, angular, lengthwise and radial misalignment, under and over-torque, thread relaxation, backoff rotation of the fitting at the maximum extent allowed by the positive restraint, line loading, and location of adjacent support brackets. ***[PSR-238n]***

3.10.2.1.15 Qualification: A sealing surface repair seal , if used to repair a leaking joint, shall be qualified and accepted with the same requirements. ***[PSR-238o]***

3.10.2.1.16 Acceptance: Parts shall be of the design drawing materials. ***[PSR-238p]***

3.10.2.1.17 Acceptance: Parts shall meet the design drawings requirements for surface finish, flatness, tolerances, or other mechanical features. ***[PSR-238q]***

3.10.2.1.18 Acceptance: For flange joints, parts shall be leak tested at 1.0xMDP after final mating, inclusive of each independent redundant seal in a flange joint. ***[PSR-238r]***

3.10.2.1.19 Acceptance: Parts shall be cleaned and verified per the drawing or system requirements. ***[PSR-238s]***

3.10.2.1.20 Acceptance: The parts shall be assembled in the presence of a designated observer (i.e. Mandatory Inspection Point (MIP)) who can attest to the work being done correctly, verify sealing surfaces are free of FOD and not scratched at the time of assembly, and take photos of the sealing surfaces for documentation purposes. ***[PSR-238t]***

3.10.2.1.21 Acceptance: The torque check operation shall have 24 hours between first torque and final torque check. ***[PSR-238u]***

3.10.2.1.22 Acceptance: For mechanical fittings, the parts shall be leak tested at 1.0xMDP after final mating. ***[PSR-238v]***

Rationale (for all of 3.10.2.1): Welded joints are considered superior to mechanical joints containing sealing features in terms of reliability and performance for controlling catastrophic hazards associated with fluid leakage/release from spacecraft onboard propulsion systems. However, in the limited instances where fittings are used, this requirement ensures an adequate level of rigor and robustness in the design, qualification, and acceptance of the fitting hardware for a hazardous propulsion system application. Doing so allows mechanical fittings to: (1) meet the intent of 1 FT to catastrophic leakage failure modes and (2) be accepted as a variance to 1 FT tolerance, without the requirement for redundant seals or surfaces to be independently verified or accepted by leak testing at the unit installed level. Reference SAE AS85421, General Specification for Beam Seal Separable Fittings. The details for use of positive restraints in maintaining correct mating torque is left to the requirements in NASA-STD-5020, including appendices. The 24-hour re-torque requirement has proven valuable in addressing torque relaxation that can lead to leakage on multiple types of fittings, thus reducing the likelihood of developing a leak much later in the vehicle AI&T flow or while in flight. *(ref)* (Martinez, 2011, p. 17). The proximate cause of the OV-103 OMS/RCS Pod leak was found to be a scratched Dynatube beam seal fitting. Operational human error was the root cause of this incident, along with improper training. The most probable cause was that the mass spectrometer probe operator probed the wrong RCS propellant system (i.e. MMH instead of N2O4). This categorization was given as a result of the incident being a consequence of either an inadequate inspection of the Dynatube sealing surface or an error made during the leak check of the Dynatube as discussed in (ref) (Nufer, 2010, pp. 36-41) During the second visit to Skylab, a leak of NTO on the Apollo Spacecraft Service Module (SM) caused a significant drop in multiple SM temperatures before isolation was most likely due to improper torque verification (ref) Skylab Mission Report Second Visit (Kleinknecht, 1974, pp. 17-4 to 17-10), with additional details provided in (ref). “Lessons Learned from 50+ Years in Human Spaceflight and Safety,” (Johnson, 2018, p. 7). Also reference lesson learned LLIS 701, Static Cryogenic Seals for Launch Vehicle Applications. (LLIS-701, 1999)

3.11 IN-SPACE FLUID TRANSFER AND SEPARABLE SPACECRAFT MODULES

This section provides requirements for spacecraft elements that are 1) docked or mated for the purpose of fluid transfer or 2) mated during spaceflight with fluids transferring across an interface and subsequently separated in flight. Note that requirements associated with tank design and verification to accommodate propellant transfer, propellant quantity gauging before/during/after propellant transfer, and vehicle controllability during fluid momentum changes and slosh behavior within the tanks during propellant transfer, are covered in other sections of this standard.

3.11.1 In-Space Fluid Transfer

The hardware and operations used for in-space transfer of pressurant gas and propellant between interfacing systems, elements, and/or vehicles (e.g. propellant refueling) is comparable to ground servicing, however there are some significant unique hazards and considerations for in-space transfer. Even when non-operational and secured for some or all parts of a given mission, the fluid transfer hardware must still maintain structural integrity and sealing effectiveness at all times while in service.

3.11.1.1 The fluid transfer system including the coupling and mating mechanisms shall comply with ANSI/AIAAS-157, In Space Storable Fluid Transfer for Prepared Spacecraft, with requirements herein taking precedence in the event of a conflict. ***[PSR-239S]***

Rationale: This document provides requirements for development of prepared interfaces for in-space fluid transfer including, but not necessarily limited to, initial fueling, refueling, and refilling) of storable propellants, pressurant gases, and other storable fluid commodities. Although an equivalent in-space cryogenic fluid transfer standard is not available at this time, many of the hazard controls and design requirements associated with storable systems would also apply to cryogenic systems.

3.11.1.2 Fluid transfer systems containing fluid couplings shall incorporate 2 sealing barriers against external leakage (i.e. one-fault tolerance) in the flight and ground-half couplings individually, and with both halves of the coupling mated, in addition to having an isolation valve located upstream and downstream of the coupling, to prevent inadvertent release of fluid commodities to the ambient external environment. ***[PSR-240SC]***

Rationale: The intent of this requirement is to ensure that two-fault tolerance to the overboard leakage/release of hazardous propulsion system fluids is provided, inclusive of the isolation valves. Propellant leakage of various fluid couplings has occurred on past projects/programs, leading to significant adverse impacts and hazards. This level of fault tolerance can be satisfied by an isolation valve, with leak detection, and a fluid transfer coupling with 2 barriers.

3.11.1.3 The operation of fluid couplings shall include 1 fault tolerant (1FT) sealing features that are in place prior to and during the engagement or disengagement of poppets in the fluid coupling in a manner to prevent spillage of hazardous fluid commodity. ***[PSR-241SC]***

Rationale: If the propulsion system is wetted with a hazardous commodity, then the engagement of sealing features on the mated fluid coupling prior to opening the poppets that communicate with the hazardous fluid will prevent spillage. If spillage from the coupling constitutes a hazard (e.g. couplings mounted in the near vicinity of a docking ring/port, etc.), then the alternative is to purposefully vent hazardous fluid to a controlled and designated safe location before connecting or disconnecting the coupling. These requirements are rooted in past history spanning multiple projects/programs involving human spacecraft development and operations over a period of decades, and they are collectively intended to ensure that this type of hardware contains the necessary design features and will continue to function properly throughout the design life, thus avoiding multiple propulsion system hazards. During the Shuttle program, iron nitrates caused the ground half Quick Disconnect (QD) poppet to not seat during demating which resulted in leakage onto the vehicle, including the tiles and eventually corrosion of electrical connectors (undetected till later). Procedures modified to isolate QD from the source using a valve. (Ref) (Nufer, 2010, p. 22)

3.11.1.4 Fluid couplings shall incorporate filter elements installed immediately upstream of servicer half coupling and then at some point downstream of the client half coupling, to prevent detrimental particulate contamination from entering the propulsion system, jamming the coupling, or entering the servicer spacecraft. [PSR-236G] ***[PSR-242G]***

3.11.1.5 Fluid couplings shall have caps or covers that remain installed on the client and servicer halves individually when not mated, to provide protection from inadvertent physical contact, corrosion, or contamination, with the cap qualified to remain in place on the coupling while in flight and uncovered for in-space fluid transfer. [PSR-228M]. ***[PSR-243G]***

3.11.1.6 Fluid couplings shall undergo leak checks of the spacecraft (client) and servicer spacecraft halves individually, and with both halves mated together, to verify in-specification leak rates prior to and during in-flight fluid transfer operations. ***[PSR-244G]***

3.11.1.7 Fluid transfer system and operation shall have isolation valves upstream and downstream of the fluid transfer coupling (FTC) that are used for starting/stopping fluid flow rather than relying on the FTC for that function, and for the purpose of contingency leak isolation in the event that an FTC leakage failure is detected prior to and during fluid transfer. ***[PSR-245G]***

Rationale (for 3.11.1.4 – 3.11.1.7): An FTC with a sealing or poppet mechanism may fail during the process of disconnecting which could provide an unintended flow path to the bulk propellants or other hazardous quantity causing a variety of hazards associated with inadvertent leakage/release of raw propellant. Such functional issues for an FTC can be driven by contamination, corrosion, damage from inadvertent physical contact, degradation from long-term exposure to the space environment, etc. Collectively, these requirements for FTCs, including the use of caps/covers to provide protection when not mated, are intended to address those concerns. Note that in-space propellant/fluid transfer is a process that moves commodities from a servicer spacecraft/module (i.e. supplier of the commodity) to a client spacecraft/module (i.e. receiver of the commodity). This means that commodity flow moves in a single direction only from upstream (servicer) to downstream (client).

3.11.2 Separation of Spacecraft Modules

3.11.2.1 The design of spacecraft propulsion system fluid lines and associated disconnects at the interface between separable modules/elements shall comply with the 'fluid lines separation' requirements of paragraph F-5 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-246S]***

Rationale: The content of paragraph F-5 (Fluid Lines – Separation Provision) is aimed at ensuring that the fluid lines and associated disconnects at the interface between separable modules/elements are designed with: self-sealing shutoff features on the correct side(s) of the interface that will function automatically to prevent hazardous fluid loss when the halves are demated/disengaged; an ability for the closed shutoff features to be re-opened automatically when the halves are re-mated/re-engaged; and a purposeful 'weak link' on the discarded half of the disconnect that will break in a controlled manner, without adverse effects on the self-sealing shutoff function of the retained half, if those items are ever forcibly separated/severed.

3.12 FILTERS AND FILTRATION

Filters and FOD screens of various sizes and types have been used on past and current human spaceflight projects/programs to mitigate the potentially hazardous effects of particulate contamination and foreign object debris (FOD) within a spacecraft propulsion system, which is intended to be built and maintained in a specified precision-clean state. Examples of potentially hazardous effects associated with excess particulate/FOD contamination include component malfunctions, internal leakage, plugging or erosion of flow control orifices and engine/thruster injector elements, etc. Note that FOD screens are typically much thinner and coarser than filters, and they are intended to capture large objects such as temperature probes, pump impeller blades, rotary bearings, etc. that could break off into the fluid flow stream and pose a hazard to the propulsion system hardware located downstream. Specifically, a FOD screen does have a filtration and pressure drop rating but not a dirt-holding capacity rating, as the expectation is that the value entrapped is small. While there are a variety of precision cleanliness levels and standards applied to propulsion system hardware, there are no existing standards to govern the selection, sizing, and performance verification of filters within a propulsion system. The NESC-RP-19-01498, Filtration of Spaceflight Propulsion and Pressurant Systems report contains important filter-related descriptions/definitions and serves as the guideline reference document for the following requirements and processes, which are intended to ensure that the threats posed by particulate contamination and the hazard controls provided by filters or FOD screens are considered and implemented at system level. This section is divided into the following 4 basic steps of the overall process.

- Identify the Sources of Contamination
- Determine Sensitivity of Components to Particulates
- Incorporate Filters in the System and Components, including GSE interfaces
- Specify each filter, including qualification and acceptance test requirements

3.12.1 Identification of Sources and Quantities of Contamination

3.12.1.1 For a human-rated spacecraft propulsion system, all potential sources of particulate contamination and NVR shall be identified, quantified, and controlled, including but not limited to, the following items, for the purpose of sizing/selection of system filters and individual component filters based on the sensitivity of the system or components: ***[PSR-247G]***

a) Particulate contamination built into the piece-parts and components provided by a *hardware vendor/supplier for integration into the propulsion system.*

b) *Particulate contamination introduced during manufacturing and assembly/integration operations, including the cutting and welding of hardware items at the subassembly and subsystem levels.*

c) *Particulate contamination introduced by the liquid and gaseous fluids used during manufacturing, cleaning/flushing, assembly/integration, ground testing, flight commodity servicing/deservicing, flight operation (ice from combustion gases), and hardware maintenance operations.*

d) *Particulate contamination that is self-generated by the cyclic operation of components that contain metallic moving parts and experience mechanical wear.*

e) *Particulate contamination that is self-generated by the degradation of non-metallic soft goods in the system, whether from mechanical wear, propellant exposure, thermal effects, or other conditions.*

f) *Excessive use of lubricants, which may or may not pass through a filter depending on the exact temperature and velocity conditions of the fluid flow stream.*

g) *Contamination that is trapped in 1-G in section of lines or components but is then released in zero-g.*

Rationale: Particulate contamination and larger FOD that could result in a catastrophic hazard involving the spacecraft propulsion system can originate from many sources. This includes external sources during manufacturing, assembly/integration, ground testing, flight commodity servicing/deservicing, and hardware maintenance operations. It also includes self-generation as components that contain moving parts (e.g. valves, regulators, pumps, etc.) are operationally cycled and experience mechanical wear. Evaluation of the ability to clean or sample trapped or settled contamination in parts of the system (e.g. tanks, lines, components) that could be released in micro-gravity is a critical factor in ensuring the proper size filter. All of these contributors must be identified, quantified, and controlled throughout the propulsion system’s life cycle. Reference LLIS-1334, Cleanliness of Diaphragm Propellant Tanks (2000). (LLIS-1334, 2003)

3.12.1.2 For propellant tanks containing an internal surface tension PMD, the amount of particulate contamination that could accumulate on the screens shall be quantified via contamination analysis to serve as an input to source quantification and to the PMD flow/delta P analysis and performance testing described in section 3.6.6. ***[PSR-248G]***

Rationale: The intent of this requirement is to acknowledge that propellant tank PMD screens can become partially restricted due to the build-up of particulate contamination over time while in service. To comply with this requirement, the contamination analysis must consider all possible sources of particulate contamination, including the specified precision cleanliness level and surface area of the tank and all upstream hardware items, the interface filtration level for all liquid propellants, pressurant gases, and test/purge gases entering the system, and the total throughput of all propellants and pressurant gases passing through the PMD during flight. The results from this analysis will serve as an input to the PMD flow/delta P analysis and performance testing discussed herein.

3.12.2 Sensitivity to Contamination

3.12.2.1 For all spacecraft propulsion system components, a list shall be generated of the minimum orifice diameters, including tolerance, minimum clearances between moving parts including tolerance stack-up, and thermal effects, sealing surface material combinations, etc. that could be adversely affected by the presence of particulate contamination. ***[PSR-249G]***

Rationale: Particulate contamination in a spacecraft propulsion system, whether introduced from external sources, liberated by dynamic environments (e.g. shock/vibe, etc.), or self-induced from cyclic operation of components with moving parts, is a recurring common-cause threat to system performance. It can also result in a variety of catastrophic hazards, including excess pressure drop and/or complete flow blockage, erosion of flow control orifices resulting in anomalous fluid flow rates, damage to metallic and/or non-metallic seals resulting in leakage, sluggish performance and/or jamming of mechanisms in valves and other components, accelerated decomposition of propellants such as hydrazine and hydrogen peroxide, particle impact ignition in a highly oxidizing environment (e.g. oxygen, nitrogen tetroxide, hydrogen peroxide etc.), etc. Accordingly, a thorough and methodical assessment of the key elements of sensitivity to contamination within a given propulsion system is needed to identify and control the related hazards. This process begins with a comprehensive list of key dimensions where particulate accumulation could induce anomalous performance of the hardware.

3.12.2.2 The sensitivity of component function (e.g. valve response time and cycle life, internal/external leakage, flow control orifice dimensions, etc.) to the presence of particulate contamination within the lines and components of a human rated spacecraft propulsion system shall be evaluated (by test if no existing data is available) based on the list of minimum dimensions determined in section 3.12.2.1, with the results serving as an input to the selection of precision cleanliness levels and sizing/placement of filters for the propulsion system hardware. ***[PSR-250G]***

Rationale: The intent of this requirement is to utilize the list of minimum dimensions generated in the prior paragraph as an early input to a particulate sensitivity assessment that focuses on propulsion component functionality, ultimately resulting in an informed decision on propulsion hardware cleanliness levels and filter sizing/placement to protect against associated hazards. It is recognized that there is an iterative nature to the particulate sensitivity and precision cleanliness implementation process.

3.12.2.3 The sensitivity of monopropellant decomposition to the presence of particulate contamination within the lines, filters, and components of a human rated spacecraft propulsion system shall be evaluated by test if no existing data is available based on the potential sources, materials, and sizes of particulate determined in section 3.12.2.1, with the results serving as an input to the selection of precision cleanliness levels for the propulsion system hardware. ***[PSR-251G]***

Rationale: One possible adverse effect of particulate contamination in a propulsion system includes decomposition of monopropellants, thus generating gaseous byproducts and heat energy within the system, resulting in significant performance degradation and potential catastrophic failure of the hardware. The intent of this requirement is to ensure that the effects of particulate contamination on monopropellant decomposition are considered early-on when establishing the appropriate precision cleanliness levels and filter sizing/placement for propulsion system hardware.

3.12.2.4 The sensitivity of the propulsion system and its components, including filters, to particle impact ignition within an oxidizer system shall be used as an input to the hardware design configuration and selection of precision cleanliness levels and sizing/placement of filters for the propulsion system hardware. ***[PSR-252G]***

Rationale: Particle impact ignition within the oxidizer lines and components of a propulsion system, thus consuming all adjacent metallic and non-metallic materials of construction, results in catastrophic failure of the hardware. The intent of this requirement is to ensure that the effects of particulate contamination on particle impact ignition are considered early-on when establishing the appropriate precision cleanliness levels and filtration requirement for propulsion system hardware. NASA-STD-6016 and requirements herein described how to complete the compatibility assessment of the particles within the system, determine the maximum transient velocities with the system, and evaluate the materials of construction. This information needs to be considered during the hardware design process (e.g. materials selection, line diameters driving pressure drops, velocities, and peak water-hammer pressure, etc.), specification of precision cleanliness levels for the hardware, and the sizing/placement of filters in the system. The NESC-RP-19-01498, page 32-34 discusses consideration.

3.12.3 Incorporation of Filters

Filters are required in several locations within a human rated spacecraft propulsion system to address the potential hardware malfunctions and hazards associated with particulate contamination.

3.12.3.1 The spacecraft propulsion system shall utilize filters to protect active and passive fluid components subject to malfunction from particulate contamination, in accordance with the requirements of paragraph F-29 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-253S]***

Rationale: Paragraph F-29 (Filter Protection of Sensitive Fluid Components) drives the use of filters to protect active and passive propulsion system components that are subject to malfunction from particulate contamination. It also addresses the placement of filters (i.e. upstream and/or downstream of components) depending on zero-g exposure and bidirectional (backflow) flow conditions, in addition to the design for full-service life vs. the need for periodic maintenance. The intent is to protect against potential hardware malfunctions and hazards caused by particulate contamination, which is critical based on past failure history. Note that part 4 of paragraph G-4 (Protection from Debris – Electrical & Mechanical Systems) also covers the topic of filters or FOD screens in moving fluid systems to trap particulate contamination.

3.12.3.2 The spacecraft propulsion system shall include filters for all liquids and gases entering the vehicle on the flight side of the GSE interface to capture particulate located downstream of the GSE interface filter and generated by the ground servicing interface connection, with sizing (i.e. maximum particle rating and total dirt capacity) driven by the propulsion system contamination sensitivity analysis in section 3.12.2. ***[PSR-254G]***

Rationale: The intent of this requirement is to have flight vehicle filters that serve as a supplement the GSE interface filters by capturing particulate located between the GSE filters and the flight servicing connection. The rationale is that particulate can be shed or exist at the interface downstream of the GSE filter.

3.12.3.3 Filters shall be present at the inlet (upstream) and outlet (downstream) of each pyro valve, whether NO or NC, in a spacecraft propulsion system to trap self-generated metallic particulate that could be liberated into the working fluid during pyro valve actuation (i.e. firing), with the filters sized to trap particulate violating the specified cleanliness level of the integrated system and verified by test. ***[PSR-255G]***

Rationale: Rapid shearing or puncturing of the parent metal flow barrier during commanded actuation of a normally closed pyro valve, or rapid wedging of a sealing ram into the seat during commanded actuation of a normally open pyro valve, can generate significant quantities of metallic particulate that could be ingested by other propulsion system components due to the flow of working fluid or zero-g migration effects, thus causing a possible functional failure of the exposed hardware. The presence of filters as driven by this requirement, whether integral to the pyro valve housing or separate components of their own, is intended to mitigate the threat posed by particulate contamination. Note that filters at the inlet of a pyro valve are not considered mandatory if the only propulsion system hardware located upstream are tanks with no internal features or moving parts (e.g. diaphragms, screens, baffles, bellows, etc.). Reference LLIS-420, Viking Orbiter Pressure Regulator Leakage (1975). (LLIS-420, 1996)

3.12.3.4 In the design of a spacecraft propulsion system, system filters shall be located downstream of all pressure vessels that contain pressurant gases, pneumatic or purge gases, and liquid or gaseous propellants. ***[PSR-256G]***

Rationale: Pressure vessels containing pressurant gases, pneumatic or purge gases, and liquid or gaseous propellants are characterized by a significant amount of internal volume and surface area that can accumulate excess particulate contamination from the fluids and/or the vessels themselves. Without a system filter, that contamination can be transported downstream by the fluid flow, thus posing a risk to the normal functioning of other components in the propulsion system, such as valves, regulators, flow control orifices, pumps, engine/thruster injectors, etc. The intent of a system filter is to limit the size and quantity of particulate contamination that can migrate into other hardware items, particularly those containing moving parts, tight clearances, and small flow paths, located further downstream in the propulsion system, thus controlling any associated hazards. Because propellant, pressurant, and pneumatic tanks may be arranged in different configurations (e.g. tanks plumbed in series, tanks plumbed in parallel, etc.), the location of such filters can vary depending on the situation while still meeting the intent of this requirement. For example, with propellant tanks plumbed in series or in parallel, a filter could be placed at the outlet of each individual tank or downstream of the tank combination to achieve a similar objective. Technical considerations affecting this type of design trade include size, mass, mounting configuration, dirt capacity, pressure drop, and the results of a system level failure modes and effects analysis (FMEA).

3.12.3.5 The system shall be assessed for parts that may be shed in the failure of an upstream component and the need for a FOD screen to prevent failure of a downstream component. ***[PSR-257G]***

Rationale: This mitigates the catastrophic failure of engines or valves. For example, the Shuttle MPS added the pre-valve screens after an 8” Fill/Drain valve failure that liberated a needle bearings into the LO2 flow stream during MPTA testing. Reference LLIS-6137 Shuttle MPS Integrated Contamination (LLIS-6137, 2010) and (ref) AIAA 2011-5838, Lessons Learned from the Design, Certification, and Operation of the Space Shuttle Integrated Main Propulsion System (IMPS) (Martinez, 2011, p. 9)

3.12.4 Filter Specification, Qualification, and Acceptance Test Requirements

The filtration system and filters are a critical part of propulsion system reliability and hazard control. The cited NESC Technical Bulletin describes a process for filtration design and implementation as applied to spacecraft propulsion systems, with an intent to ensure that the risks posed by particulate contamination to component/system performance and propulsion system hazards are adequately controlled. Note that several additional references are provided in the technical bulletin that are viewed as important aids to the selection/sizing, testing, and implementation of filters in propulsion systems.

3.12.4.1 The design and implementation process for filters in a spacecraft propulsion system shall follow the design process described in NASA Engineering and Safety Center (NESC) Technical Bulletin No. 22-02, Revisiting Filtration Standards and Definitions for Spaceflight Propulsion and Pressurant Systems, which includes the following steps: ***[PSR-258G]***

a) *List the individual elements and their cleanliness level upstream of the filter, and account for any additional system filters that are upstream*
b) *Determine the multiplying factor for lifetime*
c) *Determine the particle decay rate*
d) *Total the particle counts*
e) *Convert to test dust*
f) *Determine the allowable pressure drop range*
g) *Determine the necessary dirt holding capacity*
h) *Specify the capacity margin; Factors of 2x to 4x are typical, with a value of 4x considered minimally acceptable for human spaceflight applications.*

Rationale: Per NESC TB 22-02, "Contamination has been accepted as the root cause of many spaceflight system anomalies. Some of these could have been prevented if an appropriate filtration approach had been specified and implemented. No standards exist for sizing, building, and verifying the performance of spaceflight propulsion/pressurant filters." The Space Shuttle program implemented program requirements and specifications for filtration, however these are not NASA standards. Conservative propulsion system filter sizing mitigated the threat of high particulate levels caused by process issues. Reference LLIS - 1334, Cleanliness of Diaphragm Propellant Tanks (2000). (LLIS-1334, 2003)

3.12.4.2 The sizing, fabrication, and performance verification of filters for a spacecraft propulsion system shall meet the intent of NESC-RP-19-01498, Filtration of Spaceflight Propulsion and Pressurant Systems. ***[PSR-259G]***

Rationale: The cited NESC report provides a recent technical assessment of filtration requirements and design. It also provides a methodology or procedure for sizing filter capacity.

3.12.4.3 For fluid filters used in a spacecraft propulsion system, qualification testing at the unit or multi-unit module (MUM) level per SMC-S-016, Test Requirements for Launch, Upper Stage, and Space Vehicles, shall include shock and vibration tests that encompass all relevant environments from ascent and re-entry mission phases, in addition to pyro valve activation events and engine/thruster firings during in-space operation, to ensure all performance and life requirements are met and no particulate generation beyond stated cleanliness levels can occur. ***[PSR-260G]***

Rationale: Fluid filters are available with a variety of different construction types, including wire cloth, etched disk, sintered, additively manufactured, single-piece perforated FOD screen elements, etc. Regardless of the construction type, a filter must meet its key performance and life requirements (e.g. filtration level, dirt capacity, fluid throughput, flow/delta P, structural and external leakage integrity, etc.) and avoid self-generation of particulate contamination when exposed relevant flight environments, including shock and vibration from ascent and re-entry mission phases, in addition to pyro valve activation events and engine/thruster firings during in-space operation. The intent of this requirement is to ensure such critical content is included as part of filter qualification testing at the unit or multi-unit module (MUM) level per SMC-S-016, which does not definitively require shock testing for a 'pressure component' (i.e. Eval Required (ER) vs. Required (R)) and does not attempt to describe all potential sources of shock and vibration, including ascent and re-entry environments, in addition to pyro valve activation and engine/thruster firings.

3.12.4.4 A filter specification shall be developed that follows the Appendix I. Filter Requirements in NESC-RP-19-01498, Filtration of Spaceflight Propulsion and Pressurant Systems. ***[PSR-261G]***

Rationale: This includes specification of the key filter requirements for each filter that control hazards such as the type, filter rating, allowable pressure drop, material compatibility, number of qual units, packaging, labeling, bubble point (e.g. SAE ARP 901), cleanliness per SAE ARP 599, drying, contaminate tolerance, maximum particle size, contamination loading and collapse test, lot acceptance testing of a unit to qual requirements, weld requirements, repair requirements, and cleaning and passivation after welding.

3.12.4.5 X-ray or visual inspection for contamination being induced by the filter itself, built into an assembled filter in a housing, or caused by weld spatter from assembly into a part shall be performed. ***[PSR-262G]***

Rationale: Reference LLIS-471 Contamination from Failures caused by Fluid Filters – Scout Program (LLIS-471, 1995).

3.12.4.6 Qualification of system filters and other components with integral inlet screens/filters for use in a spacecraft propulsion system shall include fluid flow testing to quantify pressure drop characteristics and verify no structural failure or element collapse at the maximum specified dirt capacity, worst-case fluid flow, including back-flow, and conditions expected in service. ***[PSR-263G]***

Rationale: The design verification process for system filters and component inlet filters used in a spacecraft propulsion system must ensure that the chosen filter element will remain within the pressure drop budget assumed for the propulsion system application and structurally survive the worst-case fluid flow conditions expected in service, inclusive of any applicable transients, when loaded to the maximum specified dirt capacity. The topic of Element Collapse Pressure Differential (ECDP) is discussed in section 8.3.2.2 in the NESC-RP-19-01498, Filtration of Spaceflight Propulsion and Pressurant Systems. This verification is considered critical to controlling the hazards associated with excessive flow restriction when fully loaded with particulate and the release of particulate downstream following a structural failure/collapse.

3.12.4.7 Filters shall be tested at the propulsion system level under surge/transient pressure conditions, including those that could involve reverse or backflow events, and then inspected and/or functionally tested afterward to screen for internal damage. ***[PSR-264G]***

Rationale: This is required to check for transient pressures causing filter failure and to check for back-flow of filters after being subjected to a flight-like propulsion system performance environment during system level qualification hot fire testing. Such steps are considered necessary because there's no direct way to verify the functionality of a filter when installed in a fluid system, and it's possible for an internal structural failure to occur that compromises filtration capability with only a subtle change in pressure drop that can be difficult to discern in-place. To facilitate this activity, test plans/procedures can be written to include those steps and the filters themselves can be installed using mechanical joints (e.g. separable threaded fluid fittings, bolted flange joints, etc.) rather than welds, which will simplify the removal, inspection/testing, and re-installation (or replacement) process, thus restoring the system level qualification hot fire test article to a fully functional configuration for use in possible troubleshooting of in-flight anomalies that involve the propulsion system.

3.12.4.8 Filter performance testing during qualification shall be conducted in a vertical orientation to avoid the potential settling of particulate on one side of the filter element in a 1-g environment, thus providing a better simulation of particle distribution and filter performance in a 0-g flight environment. ***[PSR-265G]***

Rationale: Depending on the flow velocities and physical configuration/geometry of a filter, particulate contamination could settle on one side of the filter element in a 1-g environment. This could potentially produce different performance than the 0-g flight environment. Performing qualification testing with the filter in a vertical orientation is intended to mitigate that effect by inducing a more even distribution of particulate across the filter element, thus providing a better simulation of particle distribution and filter performance in a 0-g flight environment.

3.12.5 Alternate to the Use of Wire Cloth and Etched Disc Filters

Hydrogen peroxide, and other propellants that may decompose, in some cases may not be compatible with the use of filters as they may cause an unacceptable higher rate of decomposition along with any contaminates in the system.

3.12.5.1 Propulsion systems which do not use filters (system, component inlets) due to propellant incompatibility with the fluids that can cause hazardous decomposition shall demonstrate through tests, such as a system level wetted decomposition test and inspections, that all sources of contamination are controlled, and that system/component *design is not sensitive to contamination that result in catastrophic failure modes.* ***[PSR-266G]***

Rationale: Contamination can cause valve leakage overboard, excessive decomposition rates, engine burn through, etc. Note: Hydrogen Peroxide systems may have filters; however, the filters are typically downstream of the pyro isolated propellant tank and have very short exposure window after system activation, also verified as part of qualification and acceptance testing.

3.13 PYROTECHNIC VALVES

There are two basic classifications of pyrotechnically operated valves (i.e. pyro valves) used in spacecraft propulsion systems: normally closed (NC) pyro valves and normally open (NO) pyro valves. Both NC and NO pyro valves are single-use items that can only be reconfigured once in their service life. Parent Metal NC pyro valves are quite common and provide a high-reliability isolation function that allows safe long-term storage of a propulsion system without concern for undesired commodity leakage, propellant vapor migration, or flow of the working fluid (e.g. propellant vapor, pressurant gas, pneumatic gas, purge gas, etc.) into other parts of the system. NO pyro valves are less common and enable nominal or contingency isolation of one or more sections of a propulsion system during spacecraft operations. The following paragraphs are intended to invoke requirements from existing standards and also provide some new requirements governing the design, testing, integration, and usage of NC and NO pyro valves in a propulsion system application, thus maximizing the likelihood of functional success and controlling the potentially catastrophic hazards associated this hardware.

3.13.1 Normally Closed (NC) Parent Metal Hermetic Sealing vs. Normally Open (NO)

3.13.1.1 NC parent metal pyro valves used in a human rated spacecraft propulsion system shall incorporate an all-metal permanent closure element (i.e. internal flow barrier), without welds or other mechanical joints, that is impermeable to the internal leakage of fluid across the element per the definitions in NASA-SPEC-5022, NASA Manufacturing and Test Requirements for Normally Closed Pyrovalves for Hazardous Flight Systems Applications. ***[PSR-267S]***

Rationale: The term ‘parent metal pyro valve’ is used to describe this type of all-metal construction, particularly when the barrier is an integral part of the inlet/outlet tube stubs with no fusion joints or other forms of mechanical connection involved. Upon being commanded to open, an electrical signal ignites an explosive charge contained within the pyro valve, which produces hot high-pressure combustion gas that acts on a piston and ram to rapidly shear-off the nipple or disk flow barrier, thus allowing internal flow of the working fluid through the valve.

3.13.1.2 NO pyro valves that are used to provide permanent isolation of one or more sections of a spacecraft propulsion system shall meet the following: ***[PSR-268G]***

a) If hermetic isolation by the pyro valve barrier is required to prevent propellant vapor migration internal to the system or propellant leakage/release external to the system, then perform metallurgical verification of friction welding and 1 x10-6 sccs helium leakage testing at MDP on the closed flow barrier as part of the Destructive Lot Acceptance Test (DLAT) protocol.

b) If non-zero leakage is considered acceptable (not hermetic), then perform helium leakage testing to the specified leak rate at MDP on the closed flow barrier as part of the DLAT protocol.

Rationale: The NO pyro valve may be used following a nominally completed usage event involving the propulsion system, or an unplanned contingency isolation scenario involving some type of component failure or external leakage from the system. Metallurgical verification of hermeticity after pyro valve actuation/firing during DLAT involves a combination of non-destructive imagery (e.g. x-ray, CT scan, etc.) and destructive physical analysis (DPA) of the internal sealing surfaces (e.g. physical cross sections, visual/microscopic inspections, etc.). This added level of rigor is needed to supplement GHe leak testing during DLAT when a NO pyro valve is part of the hazard control strategy for internal propellant vapor migration or external propellant leakage/release. Otherwise, GHe leak testing alone during DLAT is considered sufficient.

3.13.2 General Requirements for Pyro Valves

3.13.2.1 The pyro devices and firing circuits associated with a pyro valve in a human rated spacecraft propulsion system shall meet the requirements of JSC 62809, Human Rated Spacecraft Pyrotechnic Specification. ***[PSR-269S]***

Rationale: JSC 62809 provides a comprehensive and uniform set of technical requirements that ensure the utmost safety and reliability of pyro-actuated devices, including pyro valves in spacecraft propulsion systems. Over time, it has become a widely accepted technical standard that is routinely imposed on NASA projects and programs. Reference NESC Bulletin No. 23-01, Including Key Design Features in Safety-Critical Pyrotechnic Firing Circuits.

3.13.2.2 Pyro valves used in human rated spacecraft propulsion systems shall feature NASA Standard Initiators (NSIs) that meet the requirements of JSC 28596, NASA Standard Initiator User's Guide. ***[PSR-270S]***

Rationale: This JSC document provides a comprehensive and uniform set of requirements that ensure the utmost safety and reliability of pyro-actuated devices that use NSIs, including pyro valves for spacecraft propulsion systems. Over time, it has become a widely accepted technical standard that is routinely imposed on many NASA projects and programs. Reference LLIS-1120 International Space Station (ISS) Program Program/ Extravehicular Activity (EVA)/Simplified Aid for EVA Rescue

(SAFER (LLIS-1120, 1999) and LLIS-428, Electroexplosive Device Degradation with Time (~1975). (LLIS-428, 1996)

3.13.2.3 Pyro valves used in human rated spacecraft propulsion systems shall feature explosives and explosive devices that meet the requirements of NASA-STD-8719.12, Safety Standard for Explosives, Propellants, and Pyrotechnics. ***[PSR-271S]***

Rationale: This NASA document provides a comprehensive and uniform set of requirements governing the processes, procedures, practices, and methods for safely handling and storing explosives and pyro devices used in spacecraft propulsion systems. Over time, it has become a widely accepted technical standard that is routinely imposed on many NASA projects and programs.

3.13.2.4 Pyro valves used in a human rated spacecraft propulsion system shall avoid the use of Titanium and its alloys as materials of construction in pyro valve bodies/housings, and aluminum and its alloys as materials of construction in pyro valve primer chamber assemblies (PCAs). ***[PSR-272G]***

Rationale: Titanium and its alloys in a pyro valve body/housing, and aluminum and its alloys in a pyro valve PCA, can ignite/burn and fail structurally, thus creating a catastrophic hazard in the propulsion system, when subjected to the high temperatures and high frictional energy dissipation events associated with firing of the pyro device(s), rapid relative motion of the internal piece-parts, shearing of the parent metal flow barrier (for NC pyro valves), and seating of the ram at the end of valve actuation.

3.13.2.5 Normally closed (NC) pyro valves used in a human rated spacecraft propulsion system shall meet the requirements of NASA-SPEC-5022, NASA Manufacturing and Test Requirements for Normally Closed Pyrovalves for Hazardous Flight Systems Applications. ***[PSR-273S]***

Rationale: This NASA document provides a comprehensive and uniform set of requirements governing the design, analysis, manufacturing, inspection, and testing of normally closed (NC) parent metal shear-section pyro valves. Over time, it has become a widely accepted technical standard that is routinely imposed on many NASA projects and programs. Reference LLIS-486, Conduct Post Test Examination of Lot Acceptance Hardware for Incipient Failures. (LLIS-486, 1996)

3.13.2.6 For normally open (NO) pyro valves used in a human rated spacecraft propulsion system, a tailored version of NASA-SPEC-5022 shall be provided for approval by the NASA engineering technical authority. ***[PSR-274G]***

Rationale: There is no specific analogous specification for NO pyro valves.

3.13.2.7 For a human rated spacecraft propulsion system, the use of pyro valves shall avoid situations where the inlet and outlet are both wetted with liquid propellant upon activation/firing of the device, to prevent the rapid decomposition/detonation of propellant and ignition/combustion of hardware materials of construction. ***[PSR-275G]***

Rationale: There is limited test data relative to hot combustion gas 'blow-by' for pyro valves being activated/fired in a 'wet-wet' mode (i.e. inlet and outlet both wetted with liquid propellant), which is known to have caused decomposition/detonation of hydrazine in the past. As a result, it is best to avoid such situations in the interest of hazard control. As an alternative, it may be possible to conduct thorough pyro valve qualification and lot acceptance testing with liquid propellants in a flight-representative system configuration to demonstrate that no adverse effects occur, but the burden of addressing this risk on a statistical basis is considered excessive. NASA LLIS-591 Pyrovalve Blow-by May Interact Violently with Propellant. (LLIS-591, 1998)

3.13.2.8 For a pyro valve used in a spacecraft propulsion system, the scope of qualification testing shall include actuation of the pyro valve after exposure to all relevant environments and operating conditions, with the test setup and test campaign possessing the following key attributes: [1] ***[PSR-276G]***

- *a) Use of a flight-representative pyro device, firing circuit, and power source elements.*[2]
- *b) Use of a flight-representative mounting configuration for the pyro valve and interfacing tubing.*[3]
- *c) Use of ground test instrumentation to characterize the pyro shock environment produced by actuating the valve and transmitted to the interfacing tubing, mounting structure, and adjacent propulsion system components.*[4]
- *d) Evaluation of worst-case command timing for the firing of redundant pyro devices contained within the pyro valve.*[5]
- *e) Evaluation of worst-case command timing for the actuation of redundant pyro valves contained within the propulsion system.*[6]
- *f) Exposure to flight-representative environmental conditions and fluid commodities, including liquid and/or vapor phase propellant as applicable, during pyro valve actuation.*[7]
- *g) Evaluation of worst-case pressure transients resulting from the actuation of all pyro valves contained within the propulsion system.*[8]

Rationale: The actuation of pyro valves in flight is a highly energetic and dynamic event which, historically, has caused multiple catastrophic hazards to be realized on a spacecraft while in service. Most of these items are also applicable to NO pyro valves. Reference NESC Bulletin No. 23-01, Including Key Design Features in Safety-Critical Pyrotechnic Firing Circuits, LLIS-944, Pyrovalve Anomaly Studies (LLIS-944, 2000), LLIS-1725, Control Blow-by from Pyrotechnic Devices (LLIS-1725, 2006), LLIS-2045, Failure of Pyrotechnic Operated Valves with Dual Initiators (LLIS-2045, 2009), and NESC Tech. Bulletin 20-01, Latching Safety Critical Signals in Pyrotechnic Circuits.

[1] The acceptability of any proposed deviations to this requirement, which is aimed at duplicating the key physical configurations and functional performance attributes of the pyro valve, its mounting provisions, it's firing circuit and flight vehicle propulsion system, and its interfacing hardware/software, must be evaluated as part of the design review and test planning process for the system level hot fire test article, with the technical rationale for each instance documented in a report as a Test Like You Fly (TLYF) exception and approved by the project/program.

[2] The lack of firing of the pyro devices within a pyro valve upon being commanded, thus resulting in no flow of the working fluid between isolated sections of the system will result in loss of commodity and control. Inadvertent firing of redundant pyro devices within a pyro valve prior to being commanded, thus causing undesired premature flow of the working fluid between isolated sections of the system. The term 'flight-representative pyro device and firing circuit elements' refers to the power source, controller avionics, electrical cabling, and pyro device necessary to provide flight-like actuation of the pyro valve during component level (i.e. unit level) qualification testing of the component.

[3] The term 'flight-representative mounting configuration' refers to the structural mounting provisions for the pyro valve and interfacing tubing that will provide an accurate representation of the pyro shock environment generated by pyro valve actuation and transmitted to the interfacing tubing, adjacent propulsion system components, and secondary support structure (e.g. tubing supports, valve panel mounting features, etc.). High pyro shock levels of this nature can cause a possible functional or structural failure of exposed hardware.

[4] The term 'ground test instrumentation' involves the use of strain gauges, accelerometers, laser vibrometers, high speed video cameras, etc. to characterize the loads, deflections, stresses, and excitation modes associated with rapid and highly energetic pyro valve actuation event. This is important since excessive pyro shock levels have previously caused structural and/or functional failure of the hardware in service, resulting in a hazardous condition for the spacecraft.

[5] The intent is to ensure that redundant pyro devices in an individual pyro valve are qualification tested to evaluate the effects of firing commands being received simultaneously and also over a range of possible stagger conditions that could occur in flight, thus verifying the safety and effectiveness of the pyro valve function in service. Need to ensure that single commands and staggered dual commands will allow the pyro valve to function successfully. Also need to ensure that simultaneous commands will not cause a functional failure of the pyro valve mechanism and/or an excessive pressure build up within the pyro device housing that leads to a structural failure/rupture of

the unit. That type of anomaly has occurred in the past on a particular pyro valve configuration, but not in other configurations. Note that purposeful staggering of the commands to reduce peak pressure and add effective structural margin to the pyro device housing is considered a viable mitigation approach following an observed functional or structural failure during ground tests. However, such a solution is not mandated in the requirements of JSC-62809, Human Rated Spacecraft Pyrotechnic Specification, to avoid any design, test, and/or integration impacts for pyro valves that haven't displayed a susceptibility to this phenomenon.

[6] High magnitude pressure surges and water-hammer transients in the working fluid driven by the extremely short response time of a pyro valve when commanded open, thus causing a possible functional failure of downstream pressure transducers, exceedance of MDP and structural failure/rupture of exposed hardware, or a destructive ACD event within the propulsion system. The intent of this item is to ensure that redundant pyro valves contained with a spacecraft propulsion system are commanded in a flight representative manner relative to the sequence and timing, thus verifying that the effects of water hammer and/or adiabatic compression transients will not damage the pyro valve itself or the propulsion system as a whole.

[7] Production of heat energy, exposure of fresh un-passivated metal, and generation of metallic particulate from shearing of the parent metal nipple or disk feature, thus causing a possible ignition event and/or a functional failure of other components from ingestion of contamination. Again, the ignition risk is greatly increased by the presence of Titanium in the pyro valve and other adjacent propulsion system hardware. 'Blow-by' of hot combustion gas from the explosives in the pyro device flowing around the piston and ram into the working fluid, thus causing a possible ignition/combustion event and structural failure within the pyro valve and propulsion system. The term 'flight representative environmental conditions and fluid commodities' refers to the pressures, temperatures, and liquid/gaseous fluid commodities to which the pyro valve will be exposed during actuation while in service. The intent is for ground testing to duplicate or envelope those key conditions to ensure safe and reliable operation of the pyro valve itself and the propulsion system as a whole. Reference LLIS-420, Viking Orbiter Pressure Regulator Leakage (1975). (LLIS-420, 1996)

[8] The intent of this item is to ensure that the pressure transients resulting from the actuation of all pyro valves contained within the propulsion system being operated in a flight-like manner will not damage the pyro valve itself or the propulsion system as a whole. High pressures and temperatures in the working fluid resulting from a particular command timing scheme used for redundant pyro valves in the system, thus causing a possible destructive ACD event within the propulsion system.

3.14 THIN WALL FLEXIBLE PRESSURE BOUNDARY (TWFPB) HARDWARE ITEMS: BELLOWS, FLEX HOSES, AND DIAPHRAGMS

3.14.1 TWFPB Failure Modes and Effects Analysis

3.14.1.1 The propulsion system design documentation shall establish the criticality and identify any zero-fault tolerant, non-isolatable or non-detectable, or other hazardous failure modes of TWFPB hardware items in the propulsion system and its components. ***[PSR-277G]***

Rationale: This ensures that all possible failure modes and effects associated with a TWFPB hardware item are identified in order to address fault tolerance to catastrophic hazards and establish fracture criticality. The hazardous failure modes include release of bulk fluids, release of hazardous quantities that could cause issues such as toxicity or corrosion, or over-pressurization and rupture of components. Note the TWFPB hardware items are not eligible for consideration as DFMR, despite having an all-welded construction, based on their unique geometric characteristics and an extensive failure history in service.

3.14.2 TWFPB Design, Analysis, and Test Requirements

Not all bellows are subject to JSC-67035; only those that are considered fracture critical. The content of JSC-67035 provides an alternate approach to fracture control that meets the intent of NASA-STD-5019, which cannot be effectively applied to a thin bellows or other TWFPB hardware item. Alternative approaches are acceptable but must provide a risk neutral alternative to the specific requirements and must be approved by the responsible fracture control board.

3.14.2.1 Fracture critical bellows, diaphragms, and flex hoses shall comply with the content of JSC-67035, Best Practices and Guidelines for Thin Wall Flexible Pressure Boundaries for Human Spaceflight Applications. ***[PSR-278S]***

Rationale: Thin-walled parts such as bellows, diaphragms, etc. are not readily able to comply with the requirements for flaw screening and closed-form fracture analysis per NASA-STD-5019, and there are numerous historical examples of in-service failures involving thin wall flexible pressure boundary (TWFPB) hardware items. As a result, JSC-67035 was generated by a multi-center, multi-tech discipline team to provide solid guidelines for developing an alternate fracture control approach to NASA-STD-5019 that will provide the design, analysis, manufacturing, testing, and inspection rigor for TWFPB hardware items that are not amenable to standard fracture control methods. As documented in a NASA Office of Chief Engineer (OCE) memo that accompanied the release of JSC-67035, each project/program is expected to develop an implementation requirements document that addresses all aspects of JSC-67035, with tailoring as appropriate. Additional standards for flex hoses may also be used, such as SAE AS1424 Hose Assemblies, Metal, Medium Pressure, High Temperature, however the design, analysis, test, and inspection requirements in JSC-67035 take precedence.

3.14.3 Flow Induced Vibration

3.14.3.1 The flexible line segments and flex hoses used in the fluid lines of a human rated spacecraft propulsion system shall comply with the requirements of MSFC-SPEC-3746, Flow-Induced Vibration Assessment Requirements for Metal Bellows and Flex hoses. ***[PSR-279S]***

Rationale: This type of failure can result in various catastrophic hazards associated with the unexpected leakage/release of liquid and gaseous fluid commodities from the spacecraft. The cited MSFC-SPEC document provides a comprehensive and uniform set of requirements to ensure that flexible line segments and flex hoses in the propulsion system are not susceptible to degradation and premature structural failure from fatigue induced by flow-induced vibration (FIV) while in service. Note that MSFC-SPEC-3746 is a relatively new document that imposes the familiar requirements of MSFC-DWG-20M02540, Assessment of Flexible Lines for Flow-Induced Vibration, and MSFC-SPEC-626, Test Control Document for Assessment of Flexible Lines for Flow Induced Vibration.

3.15 SPACECRAFT ENGINES AND THRUSTERS

This section is generally applicable to any spacecraft engine or thruster, whether new design or heritage, that provides translation or attitude control maneuvers of any size, any propellant type, and engine cycle (pump or pressure) that may be operated in space or during launch aborts. The engines may perform both steady state burns and pulsing. The engine is defined to include any pressure vessel, valve or other mechanisms, electrical device, or instrumentation that are part of the end item specification. These engine components are mechanisms subject to all general requirements listed herein.

This section addresses what in-flight duty cycles should be run during ground testing, what margins on mixture ratio (MR)/flowrate, propellant temperature/pressure, pressurant gas bubble ingestion, and stability should be used, and what life factor for pulses and steady state operation. It is not possible or practical to test an engine over all possible combinations of these conditions, however that is not required when using a strategy that demonstrates thruster performance and life at the center and corners of the operating box. The overall intent is to ‘test like you fly’ (TLYF), for both nominal and fault cases.

3.15.1 Operating Conditions and Heritage

3.15.1.1 The engine flight operating box, along with the qualification box indicating margin, shall be defined for critical parameters including, but not limited to, thrust (include throttling if applicable), chamber pressure, mixture ratio range, inlet pressure range, inlet temperature range, hardware temperature range, pressurant gas saturation levels, pressurant gas bubbles, pulse width, duty cycles and durations. ***[PSR-280G]***

Rationale: The definition of this operating box is required to define the engine qualification test program, which is expected to include margin on the various key parameters mentioned in the requirement statement. The service life and maximum design condition (MDC) are defined in NASA-STD-5012. Over this operating box and service life, it is expected that there may be multiple maximum design conditions that produce different strength and life issues in different parts of the engine. Note that SMC-S-025 includes additional definition of test requirements over the full operating box.

3.15.1.2 A heritage engine/thruster that is either built with a new or different facility or built with a new manufacturing process, used in a new spacecraft propulsion system, used in the same propulsion system but at different operating conditions, or used with a different propellant specification, formulation (e.g. MON3, MON25), shall require qualification to the standards and requirements documented herein. ***[PSR-281G]***

Rationale: Small changes in the propulsion system configuration, engine/thruster duty cycles, or operating conditions that a heritage engine/thruster will experience can cause catastrophic failure modes of the hardware. There are multiple lessons learned examples of this situation involving individual engines/thrusters and fully integrated propulsion systems spanning NASA and private industry projects/programs, though publicly available specifics of instances involving engines/thrusters are rare. Reference NASA LLIS 346, 595, 4770, etc. Note that section 3.15.5.1 [PSR-296G] defines the specifics of a delta-qualification hot fire test campaign needed to address heritage engines/thrusters being used outside of their previously qualified range of operation on past projects/programs.

3.15.2 Strength and Life Requirements, Service Life Qualification

3.15.2.1 Spacecraft propulsion system engines/thrusters shall comply with NASA-STD-5012, Strength and Life Assessment Requirements for Liquid-Fueled Space Propulsion System Engines, regardless of whether it is a gas or liquid propellant engine. ***[PSR-282S]***

Rationale: NASA-STD-5012 includes the definition of service life of the engine. Errant structural design of liquid-fueled rocket engines can contribute to unexpected failures of spacecraft propulsion systems, and NASA-STD-5012 provides a complete and comprehensive treatment of the requirements content needed to address the associated risks of catastrophic hardware failure while in service. Note that JSC 65828 paragraphs 3.2.9.1 and 3.3.1.7, both covering Liquid Propulsion

Engines with thrust levels <6000 lbf, are no longer needed, as NASA-STD-5012 has been updated to cover all engines.

3.15.2.2 For pump fed engines/thrusters in a spacecraft propulsion system, the scope of design verification hot fire testing with flight-representative propellants and pressurant gas shall meet the requirements in NASA-STD-5012 with the addition of a verification test for 1.1 x duration of the maximum single burn profile with variable conditions (such as throttling profile) or 1.1x the duration upon which the engine has reached steady state engine temperatures at steady conditions, where variable conditions include but are not limited to, propellant inlet pressures and temperatures, engine/thruster hardware temperatures, pressurant saturation level, ambient backpressure levels (sea level to hard vacuum as appropriate), and mission usage profiles encompassing at least 3 sigma Monte Carlo predictions for nominal and contingency (1 fault) scenarios. ***[PSR-283SC]***

Rationale: This requirement assumes the use of a new or modified engine/thruster, the use of an existing engine/thruster in a new application or environment, or the use of an existing engine/thruster from a new manufacturing location or supplier. It is necessary because the test content of SMC-S-016 applied to propulsion system hardware herein does not explicitly address hot fire testing for engines/thrusters, which has led to conflicts on the need for and scope of such testing in the past. The number of units required for hot-fire is per NASA-STD-5012. The rationale for the sufficiency of the 2x burn count life in NASA-STD-5012 is that the required hot-fire tests are performed on 6 engines, life analysis is performed that encompasses all loads measured in test, qualification tests are performed, and qualification fatigue tests are performed if life analysis can't be confidently accomplished. The intent on 1.1x times the maximum burn profile is intended to capture a series of engine burn or throttle profiles or inlet conditions where the engine does not return to steady state temperatures. All of these multipliers are intended to serve as key controls for hazards associated with this critical propulsion system hardware throughout its service life. The total propellant throughput, maximum single burn duration, and total pulse count parameters (inclusive of vehicle reuse as appropriate), in addition to the applicable environments and operating conditions for the hardware, should be derived from the spacecraft system requirements document (SRD) and other related project/program documents, confirmed jointly by the Propulsion, GNC, and other interfacing technical discipline teams, and captured in the engine/thruster performance specification. Note that NASA-STD-5012 requires qualification engines/thrusters to undergo a post-test teardown and inspection to identify any signs of distortion, damage, excessive wear, or other unexpected discrepant conditions. Also note that the scope of this requirement covers engines/thrusters fed with propellant by an electric pump located further upstream in the propellant feed system. In that case, all qualification hot fire testing is expected to be performed with a flight-representative pump and feed line configuration at the engine/thruster inlet.

3.15.2.3 For bipropellant pressure fed engines/thrusters in a spacecraft propulsion system, the scope of design verification hot fire testing with flight-representative propellants and pressurant gas shall include at least one (1) engineering development unit (EDU) and one (1) qualification unit, (note that additional thrusters may be needed for system level qualification), where the test article is chosen to bound worst case ATP thermal variation, such as chamber maximum temperature, that would affect service life, each demonstrating a minimum factor of 2x on total burn time, 1.1x on maximum single burn or burn profile duration, and 4x on total pulse count, spread across the full range of applicable operating conditions for the hardware with margin including, but not limited to, propellant inlet pressures and temperatures, engine/thruster hardware temperatures, valve voltage levels, pressurant saturation level, gas bubble ingestion, ambient backpressure levels (sea level to hard vacuum as appropriate), and duty cycles encompassing 3 sigma Monte Carlo predictions for nominal and contingency (1 fault) scenarios and 2 sigma Monte Carlo predictions for 2 fault scenarios if required by the program. ***[PSR-284SC]***

Rationale: This requirement applies to the use of a new or modified engine/thruster, the use of an existing engine/thruster in a new application or environment, or the use of an existing engine/thruster from a new manufacturing location or supplier. It is necessary because the test content of SMC-S-016 applied to propulsion system hardware does not explicitly address hot fire testing for engines/thrusters, which has led to conflicts on the need for and scope of such testing in the past. The number of test units required includes one additional EDU and does not include the additional engines/thrusters needed for pod/cluster level or system level hot fire qual testing. An EDU is defined to be a test article that is structurally equivalent to the flight hardware for the specific test objective being accomplished, as a minimum, and that production engines or flight engines can used as part of the number of units required. The 4x factor on total hot-fire pulse count above that specified in NASA-STD-5012 is required, for human-rated vehicles, given the complexity and uncertainty of completing life analysis, the sufficiency of qualification tests that are not done during at a full engine level hot-fire, and the fewer number of hot-fire engines and their variability. The intent on 1.1x times the maximum burn profile is intended to capture a series of engine burn profiles where the engine does not return to steady state temperatures. All of these multipliers are intended to serve as key controls for hazards associated with this critical propulsion system hardware throughout its service life. The total propellant throughput, maximum single burn duration, and total pulse count parameters (inclusive of vehicle reuse as appropriate), in addition to the applicable environments and operating conditions for the hardware, should be derived from the spacecraft system requirements document (SRD) and other related project/program documents, confirmed jointly by the Propulsion, GNC, and other interfacing technical discipline teams, and captured in the engine/thruster performance specification. Note that NASA-STD-5012 requires qualification engines/thrusters to undergo a post-test teardown and inspection to identify any signs of distortion, damage, excessive wear, or other unexpected discrepant conditions.

3.15.2.4 For monopropellant pressure-fed engines/thrusters in a spacecraft propulsion system (e.g. liquid or gas, with or without catalyst beds), the scope of design verification hot fire testing shall include at least one (1) engineering development unit (EDU) and one (1) qualification unit, where the test articles are chosen to bound worst case ATP thermal variation that would affect service life, each demonstrating a minimum factor of 2x on total propellant throughput, 2x on maximum single burn duration, and 4x on total pulse count, spread across the full range of applicable operating conditions for the hardware with margin including, but not limited to, propellant inlet pressures and temperatures, engine/thruster hardware temperatures, valve voltage levels, pressurant saturation level, ambient backpressure levels (sea level to hard vacuum as appropriate), and duty cycles encompassing 3 sigma Monte Carlo predictions for nominal and contingency (1 fault) scenarios and 2 sigma Monte Carlo predictions for 2 fault scenarios if required by the program. ***[PSR-285SC]***

Rationale: The intent of this requirement is to establish a common framework and set of requirements for monopropellant engine/thruster qualification testing to demonstrate performance and life. An EDU is defined to be a test article that is structurally equivalent to the flight hardware for the specific test objective being accomplished, as a minimum, and that production engines or flight engines can used as part of the number of units required. All of the stated factors have been used successfully on past projects/programs. It is recognized that the 4x factor on total pulse count may be a challenge for certain monopropellant hydrazine thrusters due to catalyst attrition over time, however it is critical to understand the margin and any impending failure modes with respect to 2X life as a purpose for testing to 4X. For examples of catalyst bed attrition, see section on thruster duty cycle effects in AIAA 1997-2949, Incorporating Lessons Learned in Spacecraft Propulsion Design. (Hearn, 2012)

3.15.2.5 For all engine types, the number of cold starts and hot restarts, expected as part of its total service life, shall be specified and shall be included as part of service life qualification tests. ***[PSR-286G]***

Rationale: The intent is that the service life qualification testing for 4x pulse count includes the expected number of pulses at cold conditions and hot restart conditions. Cold starts may have higher ignition transients. Hot restarts may have different propellant injector manifold priming characteristics. Monopropellant engines are sensitive to catalyst bed issues arising from cold starts and hot restarts.

3.15.2.6 To evaluate the effect of deep thermal cycles on an engine, such as chamber, nozzle, and coating life, the qualification engine(s) shall experience 4x times the number of deep thermal cycles estimated to be seen in flight operation, with a cycle defined as a temperature swing between 10% and at least 75% of the maximum steady state operating temperature relative to the standard ambient temperature condition. ***[PSR-287G]***

Rationale: A deep thermal cycle, alternately referred to as a full thermal cycle, is classically defined as a temperature excursion from ambient to maximum steady state operating temperature and back. These excursions can affect the low cycle fatigue/fracture life of an engine's combustion chamber, nozzle, and protective coating. Monopropellant engine catalyst beds can also be adversely affected by deep thermal cycles. Failures of those hardware items could lead to a hazardous engine combustion chamber/nozzle failure and burn through event. As a result, the qualification test campaign is expected to include the deep thermal cycle conditions predicted to occur in service, with the specified factor applied. This is an important part of engine/thruster life demonstration. Note that maximum steady state operating temperature is intended to include the worst-case effects of propellant pressure, temperature, and gas saturation conditions at the thruster inlet, inclusive of relevant failures (e.g. thermal control, pressure regulation, etc.). Also note that the 10% and 75% trigger points reflect a practical implementation of a thermal cycle where the engine/thruster hardware doesn't need to cool to ambient or achieve the full maximum steady state operating temperature in order to consume life.

3.15.2.7 The transient overpressure events occurring in the pressurized sections of the engine (e.g. lines, ducts, housings, valves, transducers, injector, chamber, etc.) shall be measured by test over the full range of operational conditions using instrumentation with sampling and frequency response consistent with measuring the amplitude of transients and then evaluated with appropriate dynamic amplification factors (DAF) per PSR-155G, which includes attenuation or amplification, to establish MDP. ***[PSR-288G]***

Rationale: Transient (i.e. short duration on the order of a millisecond or even less) high amplitude spikes may cause catastrophic failure. These transient events need to be characterized by test, and the instrumentation frequency response must be sufficient to provide an accurate representation of the phenomenon. Analysis is allowed to transfer measured pressure spikes to other locations such that the number of instrumentation locations can be limited. Measuring transient pressures is best done during the development phase, such these transient pressure are included in the MDP specification and verified as part of qualification of the design. A similar approach is taken for establishing component MDPs. The definition to include pressure transients and fault tolerance in the MDP is consistent between NASA-STD-5012 and JSC-65828.

3.15.2.8 The proof and burst pressures shall be based on the established MDP, including DAF factors (attenuation/amplification) per 155G , meet test factors per NASA STD-5012 Table 1, and be tested per 9.5.1 (PSER 31). ***[PSR-289SC]***

Rationale: Rupture of combustion chambers dues to overpressures has occurred due to higher than expected sharp/rapid rate transient pressures and lack of ductility in the material.

3.15.2.9 Engines/thrusters in their final state of assembly for delivery, with all parts of the 'thruster' which could affect performance of the 'thruster' and measure that performance in flight, and after any subsequent hardware change that affects the propellant flow path shall undergo a hot-fire acceptance test per NASA-STD-5012, section 9.5.2 and SMC-S-025, section 7.1.3 at altitude conditions and for durations to establish pulse mode and steady state thermal performance. ***[PSR-290SC]***

Rationale: Integrated hot-fire acceptance testing of the full engine/thruster assembly prior to delivery and after any subsequent hardware change that affects the propellant flow path is a critical verification of in-specification performance and workmanship screen for undesirable conditions that could result in catastrophic hazards, such as those posed by FOD, improper hardware configurations, incorrect assembly steps, etc. Note that this requirement also applies to an engine/thruster assembly built from individual parts/components that were previously hot fire acceptance tested on a different engine/thruster assembly because screenable workmanship defects could still be introduced into the deliverable product during the integration/assembly process. Also note that the use of flight-representative propellant feed lines, TWFPBs, and reservoirs/accumulators is expected during hot fire acceptance testing, in accordance with paragraph 3.15.4.1(e) [PSR-293SC]. The use of altitude is specified to replicate flight ignition and shutdown conditions, and to avoid the potential for propellant reaction products and combustion residual interactions associated with atmospheric pressure conditions and/or atmospheric constituents.

3.15.3 Reusable Engines

3.15.3.1 For the next mission, after accounting for actual usage for each engine with the required cycle life and on-time factors, a reusable engine with detailed inspections, proof tests, and refurbishment to criteria established through qual testing after each use shall have a qualified minimum remaining life for the next mission, where prediction is based on 3 sigma Monte Carlo for nominal, contingency (1 fault), and if required 2 fault scenarios. ***[PSR-291G]***

Rationale: A spacecraft that is returned to earth presents the possibility of full inspections and refurbishment that may be used to inform remaining life on engine-by-engine basis. Actual pulse counts/on-time/maximum single burn for a given mission and given engine can be used to determine remaining life if inspections are acceptable.

3.15.3.2 The engine qualification tests shall include, but are not limited to, environmental exposure effects (i.e. saltwater, ambient air, reentry heating), propellant exposure, chamber wear, injector wear, valve leakage, valve response times, corrosion, instrumentation health, etc., per PSR-05SC with the inspection pass/fail criteria bounded by qualification thruster end-of-life inspection results and documented in OMRSD per PSR-07G. ***[PSR-292G]***

Rationale: The inspection of reusable hardware upon return and before the next flight is a critical hazard control. This inspection criteria must have a solid basis in the qualification of the engine.

3.15.4 SMC-S-025 Applicability and Conflicts

3.15.4.1 Human-rated spacecraft rocket engines and associated propulsion systems of any thrust level, propellant type, or propellant phase (gas/liquid) shall comply with the requirements of SMC-S-025, Evaluation and Test Requirements for Liquid Rocket Engines, including unit qualification and acceptance, LRE and system level tests of the engine, with the following clarifications, exceptions, and modifications with NASA-STD-5012 taking precedence. ***[PSR-293SC]***

a. The content of SMC-S-025 is considered applicable to all LREs regardless of propellant combination, whether pump-fed or pressure-fed and over or under 1000 lbf of thrust with exceptions noted herein.

b. Sections 4.5, 4.6, 5, and A.1 are not applicable and are superseded in their entirety by requirements in this section of the propulsion standard.

c. Table 4-1 is not applicable due to conflict with NASA-STD-5012.

d. The propellants, pressurant gases, and pneumatic gases used for qualification and acceptance hot fire testing of all LREs are flight-representative in terms of meeting the fluid procurement and usage specifications.

e. The propellant feed lines used for qualification and acceptance hot fire testing of all LREs are flight representative in terms of:

   i. Inside diameter, with a line length that falls within the design range of actual line lengths on the flight vehicle.

   ii. The TWFPB hardware items (e.g. bellows, flex hoses, etc.), and any reservoirs or accumulators located between the LRE interface and the nearest upstream isolation valve on the flight vehicle, are installed in the test stand due to the influence on feed system pressure drop, compliance/stiffness, and flow-induced vibration (FIV) which can interact with the LRE, thus affecting its performance and life.

f. The power source and electrical circuits used to provide power and switching for LRE components (e.g. valves, TVC actuators/controllers, instrumentation, etc.) during qualification *and acceptance hot fire testing of individual LREs are flight representative in terms of voltage level, current delivery, and transient response characteristics.*

g. *Pneumatically driven actuators used to control valves or provide gimbal motion during qualification and acceptance hot fire testing of individual LREs are flight representative and exercised over the full pressure and temperature ranges for the hardware and pneumatic gases expected on the flight vehicle.*
h. *Teardown and inspection (T&I) of the LRE is performed at the conclusion of qualification hot fire testing to identify unexpected conditions; areas of excessive damage, distortion, discoloration, or wear; and/or signs of incipient hardware failure per NASA-STD-5012 and duplicate in paragraph 7.9.2-3 in SMC-S-025 (and paragraph 4.6.1 in SMC-S-016), in a manner that does not prevent determination of root cause of any unexpected condition.*
i. *Individual LREs undergoing qualification hot fire testing in a vacuum environment are instrumented with pressures and/or accelerometers (or microphones for an ambient backpressure environment) that have been calibrated to detect combustion instability.*

Rationale: The SMC-S-025 standard establishes a thorough set of requirements for evaluation and testing of propulsion system liquid rocket engines (LREs) and their components and systems. However, that content needs some clarifications and modifications, as outlined in the sub-paragraphs of this requirement, to ensure adequate implementation for human rated spacecraft propulsion system hardware. Sub-paragraphs (a) and (b) are intended to help define the scope of this requirement, ensuring applicability to all types of LREs. Sub-paragraph (c) is intended to ensure consistency with NASA-STD-5012 in terms of pump-fed verification engine quantity. The minimum number of test articles (EDU + Qual) for a pump-fed engine is increased to 6 to be consistent with NASA-STD-5012. Sub-paragraph (d) is intended to acknowledge the importance of flight-representative fluids in qualification and acceptance hot fire testing of LREs. Sub-paragraph (e) is intended to acknowledge the importance of a flight-representative feed line configuration (e.g. line inner diameter and length, presence of flexible component volumes in close proximity to the LRE interface, etc.) due to the influence on feed system pressure drop, compliance/stiffness, and flow induced vibration (FIV) during qualification and acceptance hot fire testing of an LRE, thus enabling a potential interaction which could affect LRE performance and life. Sub-paragraph (f) is intended to acknowledge the critical role of flight-representative power systems on electrical component response time performance during LRE qualification and acceptance hot fire testing. Sub-paragraph (g) is intended to ensure that the performance impacts of pressure and temperature ranges experienced by pneumatically driven actuators in service are included in qualification and acceptance hot fire testing of LREs. Sub-paragraph (h) is intended to re-emphasize the importance of post-test teardown and inspection (T&I) of an LRE at the conclusion of qualification hot fire testing to assess the true condition at end of life, with a goal of preserving the hardware to the greatest extent practical, such as by using NDE techniques. Sub-paragraph (i) is intended to ensure that instrumentation capable of detecting combustion instability is present during qualification hot fire testing of LREs, which is a critical supplement to stability analysis since instabilities of this type can lead to rapid catastrophic failure of the hardware.

3.15.4.2 The scope of engine qualification and acceptance testing shall include all sections of SMC-S-016, Test Requirements for Launch, Upper Stage, and Space Vehicles, in addition to engine/thruster level hot fire testing using flight-representative propellants and pressurant gas that demonstrates in-specification functional performance and life across the full range of operating conditions for the hardware including, but not limited to, propellant inlet pressures, inlet temperatures, valve voltage/current levels, steady state firing, and pulse mode firing with duty cycles defined in the thruster specification. ***[PSR-294G]***

Rationale: The content of SMC-S-016 does not explicitly address acceptance hot fire testing for engines/thrusters at the component or subassembly level, which has led to conflicts on the need for and scope of such testing. The intent here is to include a rigorous hot fire test at the nominal, minimum, and maximum range of the operating conditions as part of acceptance testing on every deliverable unit, which has historically proven critical in controlling catastrophic hazards (instability and cooling related chamber burn-through, etc.), quantifying performance, screening for workmanship-related defects, and evaluating anomalies that may occur in flight. Reference LLIS-496, Improper Welded Joints in Rocket Engine Combustion Chamber (1995), (LLIS-496, 1997) which detected in ATP hot-fire failure.

3.15.4.3 The engine development and/or qualification hot fire test program shall include performing run-to-depletion tests, which includes the potential for both bipropellants (simultaneous and staggered) or monopropellants to be depleted and in some tank PMD designs for pressurant gas to flow into engine. ***[PSR-295G]***

Rationale: It is important to understand the consequences of a failure mode involving unintended depletion of propellant such as caused by depletion of the propellant tanks, inadvertent closure of an isolation valve or breakdown of PMDs that allow pressurant gas to be ingested into the engine , the hazards associated with this event, and any mitigations that may be required to prevent depletion or detect it quickly and shutdown/isolate the affected engine(s)/thruster(s) before a catastrophic event occurs. Those items serve as critical controls for the hazard. Ideally, this type of testing would demonstrate robustness of the engine/thruster design to propellant depletion scenarios driven by other hardware failures elsewhere in the propulsion system. However, such testing may damage the engine(s)/thruster(s) being used for the evaluation so the use of engineering development units (EDUs) representative of the flight units, as an alternative to the qualification units that are identical to the flight units, is considered acceptable. Note that heritage test data for the propellant depletion phenomena could be leveraged where available. In the event of a damaging event that results from this testing, the hazard potential would be confirmed, and additional effort would shift from demonstrating robustness to providing fault-tolerant prevention of propellant depletion. Reference LLIS-572, Damage to Bipropellant Main Engines from Premature Oxidizer Depletion (1997). (LLIS-572, 1997)

3.15.5 Delta -Qualification

3.15.5.1 If the required range of engine operation is outside the documented qualified range of engine operation or does not include at least 10% of life related testing at the extremes of documented qualified range of engine operation, then engine delta-qualification testing shall include additional operational duration at min/max extremes of inlet pressures (in terms of allowable MR variation, thrust level range, etc.), duty cycle, duration and transient operation (fuel/ox start-up and shut-down lead lag testing), consisting of 10% of required life at each extreme of operational conditions or mission representative testing including an additional factor of 2 for margin. ***[PSR-296G]***

Rationale: Changes in engine operation include such changes as new pulse profiles (EPW, duty cycles) or the temperature of the propellant or the hardware, to meet a new specific mission event requirement or changes due to a better understanding of the environment. Historically there are examples changes in planned operations or unexpected environments or usage that led to failures or issues in flight when operated at untested, but allowed, conditions. (ref) (Hernandez, 2011, pp. 26, Table 6) (ref) (Vaughan, 1972, pp. 10,17)

3.15.6 Combustion Stability

3.15.6.1 All engines and system shall implement the recommendations contained in JANNAF-GL-2022-0001 (update to CPIA Publication 655), Guidelines for Combustion Stability Specifications and Verification Procedures for Liquid Propellant Rocket Engines. ***[PSR-297S]***

Rationale: JANNAF-GL-2022-0001 provided important combustion stability verification requirements starting early in the development that will avoid costly issues if not detected early in the program thus allowing a fix. Reference LLIS-351, Galileo Messerschmitt-Bolkow-Blohm (MBB) Ten Newton Hot Start Phenomena. (LLIS-351, 1994)

3.15.6.2 To ensure that there are no detrimental combustion-propellant feed system dynamic interactions (e.g. chug), engine/thruster hot fire qualification testing shall be conducted with a flight-representative feed system and an enveloping range of operating conditions (e.g. pressure, temperature, gas saturation, gas bubble ingestion, duty cycle, throttling, etc.) with high speed pressure and accelerometer measurements to characterize the chug phenomenon (if any) and accumulate sufficient burn-time to envelope the worst-case duration of exposure over the full design life of the vehicle. ***[PSR-298G]***

Rationale: Engine/thruster combustion-propellant feed system dynamic interactions (e.g. chug) have been observed on past programs, and the cumulative effects of this phenomenon can cause significant damage to the exposed hardware, leading to a potentially catastrophic hazard involving the propulsion system while in service. To address this risk, engine/thruster hot fire testing with a flight-representative feed system and an enveloping range of operating conditions (e.g. pressure, temperature, gas saturation, duty cycle, etc.) is needed to characterize the phenomenon and demonstrate hardware survival under the associated conditions. This can be accomplished as part of engine/thruster or propulsion system hot fire qualification testing, both of which are covered elsewhere in this document. Note that an early hot fire development test of a similar nature is highly recommended for risk reduction purposes, prior to initiating the formal hot fire qualification test campaign.

3.15.7 Thermal Limitations and Control

3.15.7.1 The engine interface with the environment, including the interaction with other engines, reflected external thruster plume re-entering enclosure, and the active and passive thermal control of the thruster using either heaters, insulation, or heat rejection, shall be defined. ***[PSR-299G]***

Rationale: Engine chamber heat will need to be able to radiate without damage to vehicle structure and may require insulation if embedded. Engines may either be heated or cooled due to the environment and need temperature control for safe operation. Operation of adjacent engines can cause an engine to exceed thermal limits. This is a critical interface to replicated with fully defined thruster duty cycle testing as required herein. The possibility that thermal heat sinks become saturated and no longer effective during certain operating profiles is tested as part of the system.

3.15.7.2 The thruster safe operating thermal limitations shall be defined through testing by mapping the mission duty cycle %, pulse width, duration, and environmental conditions. ***[PSR-300G]***

Rationale: Exceeding these limitations can cause hazardous conditions such as propellant boiling in the injector and reduced thrust, exceeding the temperature limits of the materials in the injector, valve (seat, solenoid), or chamber, causing localized cooling of the engine injector below the freezing point of the propellant, etc.

3.15.7.3 Engines/thrusters that use liquid propellant to regeneratively cool the thrust chamber assembly and for which the transition from nucleate boiling to film boiling would cause a burn-through hazard shall maintain a burn out safety factor (BOSF) of 1.4 on the critical heat flux (CHF) at which this transition occurs and demonstrate this margin by test. ***[PSR-361G]***

Rationale: The critical heat flux (CHF) is the heat flux at which boiling of the fluid flow in a regeneratively cooled thrust chamber assembly transitions from nucleate to film boiling. This transition results in a dramatic increase in hardware surface temperatures that can lead to rapid burn-through of the hardware. The use of a BOSF, typically in the range of 1.2 to 1.7, has been implemented on past projects/programs with various propellant combinations, including Space Shuttle and others, as a control for this hazard. ref AIAA 98-1055 Forced Convection Boiling and Critical Heat Flux of Ethanol in Electrically Heated Tube Tests, Michael L. Meyer and Diane L. Linn, 19980017166.pdf

3.15.8 Engine/Thruster Ignition Systems

3.15.8.1 High voltage electrical spark ignition systems/equipment used in human rated propulsion systems shall comply with the 'problem electrical components' requirements of paragraph E-7 in JSC-08080-2, JSC Design and Procedural Standards and vacuum tested per ***PSR-333S****.* ***[PSR-301S]***

Rationale: Paragraph E-7 (Problem Electrical Components – Restrictions on Use) is intended to prohibit certain electrical and electronic parts in specific applications due to known failure mechanisms that make them a reliability risk. Item #4 of the list in E-7 is of particular interest to spark ignition systems since it prohibits the use of sealed parts, inclusive of high voltage sealed cables/housings, with high internal voltages in a vacuum environment since the internal pressure could leak down over the life of the part. The test should include sufficient time at vacuum to ensure that pressure decay of sealed components has time to manifest. This decay can be exacerbated by longer mission durations and exposure to dynamic environments over multiple flights, and it is a common-cause condition that can result in non-ignition of multiple engines/thrusters due to corona effects. Of course, the concern is most relevant to spacecraft that remain in-space for long durations, experience multiple flights, and contain engines/thrusters with multiple engine starts/pulses. (ref) (Robinson, 2010, p. 3)

3.15.9 Overpressures; Control of Hard Starts, Zots, and Pops

Nearly all propellants can form and accumulate either an explosive mixture of propellants or deposits of fuel oxidizer reaction products (FORP). A 'hard start' is a transient overpressure event that can produce catastrophic damage to the engine/thruster combustion chamber and/or injector. It is caused by the detonation of mixtures of accumulated propellants, either frozen or liquid, or reaction products of fuel and oxidizer. Detonation of condensed fuel propellants in the oxidizer injector is termed a "Zot" (i.e. explosion), however other forms injector explosions could occur associated with other mechanisms for transport of propellants between manifolds. Pops are overpressures in the combustion chamber that occur during steady state operation. The delay of ignition, either hypergolic or spark, or the lead-lag of fuel and oxidizer flow into the combustion chamber are key parameters that impact the magnitude of overpressure. The following requirements establish the magnitude of the overpressure and mitigations that control hazards associated with this phenomenon.

3.15.9.1 For bipropellant engines/thrusters operating with hypergolic propellants, or with other propellants that create mixtures prior to combustion (pre-mix), the amplitude of overpressure/amplitude of pressure transients (spikes) associated with these explosive mixtures during engine/thruster start transients, steady-state operation, and shutdown transients shall be measured as part of engine/thruster qualification hot fire testing using high speed instrumentation (piezoelectric 100KHz+) in the combustion chamber and injector manifolds under the expected range of mission duty cycle firing profiles, operational firing altitudes, hardware and propellant temperatures, and include valve lead-lag variation within tolerances, GHe saturation, valve poppet travel times, valve variability, and temperature. ***[PSR-302G]***

Rationale: Hypergols and other bipropellants that are allowed to pre-mix can form a combustible mixture that could generate a transient overpressure in the injector, an ignition device cavity, and/or the combustion chamber during engine/thruster startup, steady state operation, and shutdown. The maximum dynamic pressure amplitude of this event is required for engine/thruster structural analysis, and the value is dependent on multiple factors including altitude of operation; engine/injector design; propellant combination; propellant pressures, temperatures, and saturation levels; engine hardware temperatures; and pulse mode duty cycles. During the Apollo Program, a lunar module up-firing RCS engine ruptured during ground testing due to explosive mixtures produced in the combustion chamber caused by operating at low engine temperatures, saturated propellants, short pulse firings, and higher test cell attitude pressures. The fix was to maintain the engine flange temperatures above 120 °F. (Vaughan, 1972, p. 10).

3.15.9.2 The minimum allowable time for safe engine restart that allows the residual propellants or FORP to evaporate after a pulse shall be verified by ground hot fire testing over the full range of expected operating conditions in flight, with any TLYF exceptions documented and evaluated for acceptability. ***[PSR-303G]***

Rationale: Given that residual propellants and/or FORP may form during engine operation and then evaporate after shutdown, the minimum allowable time for safe engine restart needs to be determined. Additional precautions introduced for the purpose of ensuring safety during ground hot fire testing (e.g. thruster purges) that represent a TLYF exception must also be documented and evaluated for acceptability.

3.15.9.3 The minimum electrical pulse width, duty cycle %, and duration shall be characterized *through testing to establish regions of operation where the injector temperature decreases due to evaporative cooling of propellant in the injector dribble volume below qualified levels.* ***[PSR-304G]***

Rationale: This is the opposite of injectors ratcheting up in temperature during duty cycle pulse trains. Injectors can also ratchet down in temperature at short pulse widths. Controlling the residual propellants or FORP formation requires operating at hardware and propellant temperatures and duty cycles, that do not allow FORP to form. "Cold" propellants and cold hardware temperature during long strings or short pulses can most likely lead to FORP formation at the injector elements. FORP typically form a low pressures and temperatures that are associated with condensation or freezing. Mixtures of hydrocarbons, such as Rocket Propellant 1 (RP1), with liquid oxygen are extremely shock sensitive and explosive. (ref) (McCamy, 1956, p. 7) Cryogenic oxygen and methane could form a solid or liquid mixture in vacuum environment at cold temperatures. MMH and NTO can form many type of FORP products, some type accumulate but then quickly react explosively as surrounding heat raises the temperature of FORP. This can manifest as "pops" or combustion spikes during engine operation, both ignition transient and steady state. These products can lead to explosions in the injector (aka zots) due to various transport mechanisms, such as condensation of fuel in the oxidizer manifold or leaking oxidizer entering the fuel manifold. (ref) (Durning, 2011, p. 1)

3.15.9.4 Material compatibility assessments shall include the consideration of high pressure and high temperature events that could lead to combustion of metal parts with the propellant oxidizer or damage to the combustion chamber. ***[PSR-305G]***

Rationale: Injectors manufactured out of titanium or oxidizer incompatible materials (i.e. aluminum) are especially subject to catastrophic hazards with FORP. Chambers made from low ductility materials should be avoided.

3.15.10 Engine and Valve Leak Detection

3.15.10.1 Leak detection of an engine, for any propellant type during both operational/enabled phases or during isolated or non-isolated inactive periods shall be implemented. ***[PSR-306G]***

Rationale: This is a key hazard control for the effects of leakage such as accumulation of propellant resulting in a flow blockage, hard-start, cooling beyond thruster qualified limits, or loss commodity. Leakage during isolated or non-isolated manifold operation could also present a hazard when thruster firing is enabled. Plugging of the injector manifolds or plugging of the chamber throat has been observed on actual small thrusters. Valve leakage on the Apollo Service Propulsion Systems engine caused significant flow blockage and delays. *(ref)* Study of propellant valve leakage in a vacuum Phase I report (Gift, Study of propellant valve leakage in a vacuum Phase I report, 1966), *(ref)* Study of Propellant Valve Leakage in a Vacuum Phase II (Gift, Study of Propellant Valve Leakage in a Vacuum Phase II, 1966),

3.15.10.2 The sensitivity of the engine leak detection system or method(s) shall be determined by *test of the engine and analysis with simulated leakage levels 1) to establish the maximum allowable leak rate for safe operation of the engine and 2) to establish the minimum detectable leak of the leak detection method as part of engine qualification.* ***[PSR-307G]***

Rationale: These are two key tests to run with the engine with flight instrumentation to show that, at minimum detectable leak rate, there are no engine catastrophic failure modes and to demonstrate the sensitivity of the leak rate measurements.

3.15.10.3 For evaluation of catastrophic hazards, an engine or thruster valve shall be assumed to be capable of developing a leak, without having been actuated, due to inlet pressure changes such as water-hammer, temperature changes, vibration/shock exposure, and seal degradation, creep, and swell. ***[PSR-308G]***

Rationale: Several instances of oxidizer and fuel valve leaks have occurred where leakage developed without a prior actuation cycle. As such, a successful prior leak check is not considered solid rationale for the current valve state or health. Static thruster valves may develop leaks without valve actuation due to pressure, vibration, and thermal cycles, in addition to seal degradation, creep, and swell. For example, during on STS-42 thruster valve leakage occurred, due to exposure to cold temperatures 50 °F and the fact that Teflon seals can non-uniformly contract. Subsequent throat plug removal resulted in liquid being spilled from the thruster. (Ref). (Nufer, 2010, p. 42), LLIS-59, ; RCS Thruster Ferry Plug Removal; Hypergol Exhaust System Indicator Lamp, (LLIS-59, 1992) and LLIS-148, Reaction Control System (RCS) Thruster Valves. (LLIS-148, 1992)

3.15.11 Thrust Vector Control (TVC)

The use of Thrust Vector Control (TVC) of the delta-V engines is an alternative to pulsing attitude control spacecraft engines or differential throttling of multiple engines to maintain thrust through the center of gravity (CG) or to complete maneuvers. The use of TVC has some benefits in that off-pulsing engines combined with a variable CG can result in challenges related to engine cycle life, thermal stability, system and engine start-up and shutdown dynamics, valve mechanism wear, etc. The design and test of the TVC is a complex multi-discipline (GNC, Propulsion, Structures, Mechanism, Thermal, Power) with the need to focus on integrated engine level testing in a vacuum environment. The TVC system must address the following requirements, in addition to requirements for GNC performance, electrical devices, wiring, power, and mechanisms. Reference LLIS-15301, Fidelity of the Dawn Thrust Gimbal Assembly Life Testing. (LLIS-15301, 2012)

3.15.11.1 The TVC mechanism shall meet all requirements in NASA-STD-5017 for design, analysis, and test, including best practices in Appendix A. ***[PSR-309S]***

Rationale: Human spaceflight requires high reliability, and the cited standard's requirements and best practices, such as for lubrication selection and testing, for fabrication, for motor and bearing selection, etc., are key to achieving high reliability for mechanisms in propulsion system hardware. As such, implementation of all content in the standard is expected.

3.15.11.2 The TVC system shall be 1FT as a minimum to catastrophic loss of control. ***[PSR-310G]***

Rationale: A failure of a single actuator or component in its string (controller, power, etc.) must not lead to catastrophic loss of control. The isolation and recovery from a failed TVC actuator can include down modes to RCS attitude control or the use of redundancy in the TVC actuators and power or the use of multiple engines with TVC for redundancy.

3.15.11.3 TVC actuators shall be capable of holding engine position in the event of loss of power and with maximum forces produced by engine thrust and other disturbances. ***[PSR-311G]***

Rationale: This capability allows for isolation and recovery of a failed actuator string and shutdown of an engine if necessary before it propagates to loss of control.

3.15.11.4 For a single TVC actuator to be considered as redundant, the design shall contain features which provide full electrical and mechanical redundancy through the output attach point on the driven engine/thruster. ***[PSR-312G]***

Rationale: For individual TVC actuators to be considered as redundant, they must contain electrical and mechanical design features that provide the stated level of redundancy all the way to the output attach point on the driven engine/thruster. Otherwise, the unit is subject to single-point electrical failures (e.g. loss of power) and mechanical failures (e.g. jam due to FOD, corrosion, etc.) which could compromise redundancy, thus failing to provide the intended level of fault tolerance.

3.15.11.5 In lieu of fault tolerance, load bearing structure of a TVC actuator shall meet the requirements of JSC 65828, Structural Design Requirements and Factors of Safety for Spaceflight Hardware, and JSC 68529, Loads and Structural Dynamics Requirements for Spaceflight Hardware. ***[PSR-313SC]***

Rationale: This is consistent with NASA-STD-8719.29, paragraph 4.3.1.2. Note that TVC actuators are considered as mechanisms that are also governed by NASA-STD-5017.

3.15.11.6 TVC position measurements shall be redundant with voting logic and sensor fault detection. ***[PSR-314G]***

Rationale: This is a critical measurement for fault detection.

3.15.11.7 The TVC system shall report faults and the results of built-in-test (BIT) sequences for the hardware. ***[PSR-315G]***

Rationale: From a hazard control perspective, it is considered critical to maintain real-time visibility into the health and status of the TVC actuator and controller hardware that governs the gimballing of engines/thrusters on a human rated spacecraft. BIT functionality during controller power-up and upon command.

3.15.11.8 The TVC system shall meet the engine level test requirements per SMC-S-025 Section 7.3.9, with the added clarification that 7.3.9-6 includes the mission cycles and durations for vacuum operation and exposure. ***[PSR-316S]***

Rationale: Numerous failure modes and performance issues can exist in TVC systems that require fully integrated tests in a flight representative manner to uncover issues with the design, such as with lubrication and exposure to vacuum or ground environment. *(ref)*. Lubrication of Space Systems. (Fusaro, 1994) Issues were experienced with Space Shuttle rudder speed brake. (ref) (Handschuh, 2017), *(ref),* (Hernandez, 2011, pp. 16-18)

3.16 FDIR, INSTRUMENTATION, DATA RATES, AND SOFTWARE

3.16.1 Fault Detection Isolation and Recovery (FDIR)

3.16.1.1 The propulsion system shall provide the capability to detect faults, annunciate the condition, and transmit sufficient data to the ground and to isolate and recover from failure modes and hazards identified during system design, development, or mission operations that would result in a catastrophic event. ***[PSR-317G]***

Rationale: This is derived from NPR 8705.2 paragraphs 3.2.3, 3.2.8 and 3.2.9 to control catastrophic hazards. For a propulsion system, these hazards include propellant tank or line rupture or leaks, combustion chamber failures, overboard leakage, etc. for which there may not be isolation capability but for which there could be other actions or dissimilar redundancy to avoid loss of crew. Annunciate is defined to mean to display health and status data onboard to the crew for nominal operations and flight anomaly resolution. Transmit sufficient data is defined as critical health, status, and engineering data that is required for operational decisions, flight anomaly resolution, and catastrophic event reconstruction.

3.16.1.2 All spacecraft propulsion failure modes that can potentially lead to catastrophic failure shall be verified by test to be able to be detected, isolated, and recovered from within the time limit necessary to mitigate the catastrophic failure. ***[PSR-318G]***

Rationale: This is a key requirement that demonstrates the mitigation is effective or establishes the residual risk remaining if catastrophic failure cannot be prevented.

3.16.1.3 Instrumentation that is required to control a catastrophic hazard shall be either: ***[PSR-319G]***

a) redundant, ideally dissimilar redundancy,

b) or if redundant instrumentation is not possible, then secondary cues be identified for the purpose of fault detection to control a catastrophic hazard

Rationale: Flight instrumentation is used by the flight crew, the flight control team on the ground, and the onboard Fault Detection Isolation and Recovery (FDIR) to diagnose and control hardware failures or other anomalous conditions that could lead to a catastrophic hazard. This is derived from NASA-STD-8719.29 paragraphs 4.3.1, 4.3.6, and 4.3.7 to provide at least single failure tolerance to catastrophic events. The intent of this requirement is to ensure that those efforts are not reliant on a single piece of instrumentation with no means of identifying an erroneous reading or false fail off. Instead, redundant pieces of instrumentation, ideally dissimilar, are necessary for this purpose. Examples include one or more pressure transducers used in conjunction with a valve position indicator to infer the open/closed state of the hardware, etc.). Inappropriate fault protection actions can be as hazardous as the failure the system was designed to protect against. Reference LLIS-343, Mars Observer Inappropriate Fault Protection Response Following Contingency Mode Entry due to a Postulated Propulsion Subsystem Breach. (LLIS-343, 1994)

3.16.1.4 In addition to FDIR, the propulsion system instrumentation shall provide sufficient health and status insight to support flight anomaly resolution and failure event reconstruction. ***[PSR-320G]***

Rationale: Access to spacecraft and launch vehicle health, status, and engineering data is a key element of command decision making and anomaly resolution during the mission. Making the data available to both the mission ops and crew could prevent the crew from executing an abort or prevent a situation from developing into a catastrophic event. Post-flight, the data will be used to understand system performance and make further improvements to operation and safety, as well as inform future commit to flight decision making. The design optimization will establish how much data should be displayed, recorded, and transmitted and during which periods to support nominal operations, flight anomaly resolution, and catastrophic event reconstruction.

3.16.1.5 When a measurement is used to control a catastrophic hazard, the measurement shall be a direct means of monitoring the critical parameter, such as fluid pressure, temperature, pump speed, or position of a valve or inhibit. ***[PSR-321G]***

Rationale: This requirement assures more accurate measurement of necessary data and avoids the potential for confusing or incorrect fault understanding. An indirect method may be a sensor on an actuator; however, a direct method would be a sensor on the valve shaft cam. One example of a past issue involved the Orbiter MPS LO2/LH2 fill and drain valve cam key shear failure, which led to an unknown valve state and confusion during pre-launch operations. Another indirect method may be a surface thermocouple (TC) that can debond, versus an immersion TC that provides direct fluid measurement.

3.16.1.6 *Instrumentation that is wetted by propellants shall be examined for hazard criticality and failure/fracture that (a) could allow leakage of propellants, such as hydrazine or hydrogen peroxide, into regions that are not compatible with the fluids, or (b) that if broken due to fatigue could generate FOD.* ***[PSR-322G]***

Rationale: Catastrophic failures of sensor diaphragms is credible.

3.16.1.7 *FDIR software shall screen for instrumentation signals that are off-scale low (OSL)/off-scale high (OSH) and corrected for bias/offset.* ***[PSR-323G]***

Rationale: Need to screen for erroneous data. Inappropriate fault protection actions can be as hazardous as the failure the system was designed to protect against. LLIS-343. (LLIS-343, 1994)

3.16.2 Instrumentation Data Rates

The term 'data rate' refers to the sampling of output signals from the various pieces of instrumentation that are present in a spacecraft propulsion system. Examples include pressure transducers, temperature sensors, position indicators, propellant quantity gauges, etc.. The requirements in this section are intended to ensure that the instrumentation and data rates used for monitoring and control of a propulsion system are adequate to detect and respond to anomalous conditions that develop and could lead to catastrophic hazards.

3.16.2.1 *Data rates used for propulsion system instrumentation shall ensure that in-flight fault detection, isolation, and recovery (FDIR) operations can be accomplished successfully within the worst-case time-to-effect for all associated catastrophic hazards.* ***[PSR-324G]***

Rationale: The data rates used for propulsion system instrumentation are critical to in-flight performance evaluation and enable the effective implementation of a FDIR strategy to detect off-nominal conditions and control catastrophic hazards. Data rates that are too low will not allow FDIR operations to be successfully accomplished within the worst-case time-to-effect for the various catastrophic hazards associated with the propulsion system.

3.16.2.2 *Data rates used for recording combustion chamber pressure (Pc) measurements or other instrumentation intended to detect and characterize engine/thruster operation in a spacecraft propulsion system for later downlink shall capture at least three (3) data samples during the minimum commandable electrical pulse width (EPW) for the engine/thruster.* ***[PSR-325G]***

Rationale: Catastrophic failure modes can develop quickly in a firing engine/thruster, even at minimum EPW during pulse-mode operation. Hazards can also be realized from an unintended/uncommanded firing of one or more engines/thrusters on a spacecraft. As a result, an adequate set of engine/thruster instrumentation, combined with high-rate onboard data processing and FDIR software, can be used to mitigate this risk. The instrumentation used to detect and characterize engine/thruster operation in a spacecraft propulsion system, whether in the form of a Pc measurement or another direct sensing technique, must have enough fidelity to reliably discern engine/thruster health during a commanded firing of minimum EPW and detect an uncommanded engine/thruster firing of minimum EPW. Based on past experience, a minimum of three (3) data points is needed for this purpose, with anything less providing insufficient insight into engine/thruster operation and performance. It is the joint responsibility of the Prop, GNC, Avionics, and FSW teams to find the 'right' combination of key attributes in those interfacing systems to allow this important performance requirement to be met.

3.16.3 System Leak detection – Internal and External

3.16.3.1 The propulsion system shall incorporate a minimum of one pressure and temperature sensor in each isolatable section of the propellant delivery system. ***[PSR-326G]***

Rationale: The intent of this requirement is to ensure that pressure and temperature excursions, whether increasing or decreasing, in each isolated segment of the propellant delivery system can be used to detect an external leak. This would also allow monitoring of pressure and temperature during a thermally induced pressure rise that could result in back-relief event. In some cases, small, trapped volumes such as between series redundant thruster valves, are not practical for this purpose.

3.16.3.2 Spacecraft propulsion systems FDIR shall employ a combination of system-level and localized leak detection methods to identify leakage of overboard pressurant or propellant commodity, at a hazardous level, and allow isolation of the leak site. ***[PSR-327G]***

Rationale: There are several catastrophic hazards associated with leakage – inadvertent pressurant or propellant depletion, thruster leakage leading to frozen prop ice and/or FORP accumulation in engines, freezing of propellant lines, getting toxic propellant residue on ground/flight crew or adjacent incompatible hardware, degradation of solar arrays due to build-up of propellant residue, and vehicle rate build-up from a large directional leak (GNC). The detection methods typically include monitoring of system pressures and/or temperatures for unexplained out-of-family decay due to external leakage. There are numerous approaches to propulsion system leak detection on spacecraft, which can be used on the ground and also in flight. From a spacecraft standpoint, leak detection methods are generally divided into: (1) Direct measurement, e.g., quantity probe, hazardous gas sampling, (2) Calculated based on fluid state (pressure, volume, temperature), e.g. Ideal Gas Law (PVT) equation, and (3) Inferred via known properties and conditions of the fluid and measurement of the temperature changes at/near the leak site, e.g., thruster injector temperature sensor, mechanical joint temperature sensor. Lessons learned examples include Shuttle APU coolant causing flash freezing and blockage of coolant flow (ref. LLIS-12, Leak Checks of Critical Systems (Orbiter APU Coolant) After Installation, Maintenance, or Modifications Which Require System Disconnects), numerous RCS engine propellant leaks (ref. Johnson, Gary, Lessons Learned from 50+ Years in Human Spaceflight and Safety, JS-2018-009, NNJ13RA01B (Johnson, 2018), and LLIS-6148, Continuous Hazardous Gas Monitoring In The Shuttle Aft During Flight. (LLIS-6148, 2010)

3.16.3.3 A method for detecting external leakage of non-isolatable bulk propellant from a human rated spacecraft propulsion system shall be included in the design and verified by test to ensure the detection effectiveness (i.e. sensitivity threshold and time to detect) is sufficient to help control or mitigate the catastrophic hazards associated with loss of propellant commodity. ***[PSR-328G]***

Rationale: The detection method and level of sensitivity must be capable of preventing the 'loss of commodity' hazards by allowing sufficient time for mission operation contingency workarounds, such as declaring loss of mission (LOM) and completing crew return successfully, in response to the detection of a propellant leak. Note that propulsion systems with an all-welded DFMR construction in the propellant tank 'node' which don't contain separable fluid fittings; flange joints, sensors/transducers, service valves, fill/drain valves, TWFPBs, or test ports containing seals; etc. are considered exempt from this requirement.

3.16.4 Instrumentation Types and Hazards

3.16.4.1 Resistance Temperature Detectors (RTDs) or thermistors with a qualified configuration and installation process/procedure shall be used for temperature measurements that participate in the control of catastrophic hazards in spacecraft propulsion systems. ***[PSR-329G]***

Rationale: RTDs provide the highest linearity, accuracy, stability, survivability in dynamic environments, and a wide temperature range for use in propulsion system temperature sensing. This is particularly important when temperature measurements contribute to hazard control. Thermistors have a shorter response time, but they also have a relatively limited temperature range and non-linear resistance vs. temperature relationship, experience self-heating from the required external current source, and can be somewhat fragile when exposed to dynamic environments. Thermocouples (TCs) have an exceptionally wide temperature range and rapid response, making them uniquely suitable for data collection in specific instances such as high temperature engine/thruster combustion chambers, but they are less accurate than RTDs and may drift and provide erroneous readings so their use in flight vehicle hazard control is not considered viable. Reference LLIS-1581, Thermal Sensor Installation Failures (LLIS-1581, 2004) and LLIS-1739, Thermal Sensor Installation Failures Remain a Problem (LLIS-1739, 2005) for a description of installation issues.

3.17 PROPULSION SYSTEM ELECTRICAL

This section is intended to address all applicable requirements pertaining to the electrical aspects of hardware in a human rated spacecraft propulsion system. These items are considered critical to the prevention of catastrophic hazards.

3.17.1 Protective

3.17.1.1 Electrical systems/equipment used in human rated spacecraft propulsion systems shall comply with the 'protective covers or caps' requirements of paragraph E-11 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-330S]***

Rationale: Paragraph E-11 (Protective Covers or Caps for Electrical Receptacles and Plugs) drives the use of protective covers or caps on exposed electrical receptacles and plugs on flight hardware and interfacing electrical GSE/TSE, whenever those items are not connected to their mating parts. Intent is to protect the hardware from exposure to mechanical damage, dust, dirt, and other FOD.

3.17.2 Electrical Bonding

3.17.2.1 Spacecraft propulsion systems and their components shall comply with the electrical bonding requirements of NASA-STD-4003, Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment. ***[PSR-331S]***

Rationale: The cited NASA standard provides uniform and rigorous engineering and technical requirements for electrical bonding of spacecraft hardware being developed for NASA projects/programs. An ineffective electrical bonding approach can contribute to malfunction, fires, shocks, and unexpected failures of select components in the propulsion system that receive electrical power and/or exchange data signals with other vehicle subsystems (e.g. transducers, valves, TVC actuators, heaters, controllers, etc.), thus causing documented hazards to be realized. Reference LLIS-151,. Throat Plug and Purge Adapter Assembly Grounding (LLIS-151, 1992)

3.17.3 Propulsion Device Power Switching

3.17.3.1 The electrical power switching configuration used for components in a human-rated spacecraft propulsion system shall provide single-fault tolerance to a catastrophic hazard resulting from inadvertent application of power to the hardware, using independently-controlled series-redundant switches that are: (a) both located on the supply/high side of the circuit, or (b) one located on the supply/high side and one located on the return/low side of the circuit. ***[PSR-332G]***

Rationale: Electrically powered components in a spacecraft propulsion system, such as engine/thruster valves and associated drivers, tank or manifold isolation valves, electronic pressure regulators, TVC actuators and controllers, propellant line heaters, etc., could potentially create a catastrophic hazard from inadvertent/uncommanded operation. In those instances, the power switching configuration of the electrical circuits must provide 1FT to the associated hazards using independently controlled, series-redundant switches, with: (a) both switches located on the supply/high side of the circuit or (b) one switch located on the supply/high side and one switch located on the return/low side of the circuit. Based on past safety reviews of this topic, a short-to-ground resulting in the unplanned application of power to a component is considered credible (vs. a short-to-power that is not considered credible), which precludes locating both switches on the return (low) side of a component. Practical experience involving a failed-on thruster during the Gemini program is consistent with the view that a hazard is more likely to occur with a switch configuration that allows continuous exposure of the component to supply/high side power in the circuit. Reference NASA SP-4203, On the Shoulders of Titans: A History of Project Gemini. (Hacker, 1977, pp. 312-321)

3.17.4 Corona Suppression

*3.17.4.1 The electrical and electronic components used in a human rated propulsion system shall meet the 'corona suppression' requirements of paragraph E-6 in JSC-08080-2, JSC Design and Procedural Standards. [**PSR-333S**]*

Rationale: Paragraph E-6 (Corona Suppression) is intended to ensure that electrical and electronic systems and components, such as actuators or ignition systems, with susceptibility to corona based on Paschen Curve criteria are designed to avoid detrimental corona discharge under all operating conditions while in service. That type of discharge event could lead to premature failure of the hardware and produce a catastrophic hazard. Note that MSFC-STD-531, High Voltage Design Criteria, has been superseded by NASA-HDBK-4007, Spacecraft High Voltage Paschen and Corona Design Handbook. Reference LLIS-598, Protect Against Corona Discharge and High Voltage Breakdown (1960's-Present). (LLIS-598, 1998)

3.18 FLIGHT AND GROUND OPERATIONS INTERFACE

This section focuses on testing and servicing of flight hardware, per the OMRSD [PSR-07G], so that no damage unknowingly occurs to flight hardware that could end up having a catastrophic consequence during the flight mission. Apollo 13 is a prime example of flight hardware testing that caused undetected damage and resulted in later flight failure. This section extracts requirements that protect the flight hardware from damage, both detected and undetected, that could manifest later as an in-flight failure. Many of these are extracted requirements that control critical hazards to the flight hardware from NASA-STD-5005, Standard for The Design and Fabrication of Ground Support Equipment, and NASA-STD-8719.24 that are at the interface between flight hardware and the range, regardless of what range this system will be operated in. Note that many of the requirements in NASA-STD-8719.24 are covered by the other requirements in this document for the flight hardware materials, structures, etc. These hazards include misconnection of fluid servicing QDs, pressure vessels rupture, cryogenic valve icing, etc. The control of these hazards can have implications for the design and testing of the propulsion system and its components. Also note that the content of the cited document covers a broad scope from a ground safety perspective which is similarly covered by flight perspective.

3.18.1 Hardware Time and Cycle Tracking

3.18.1.1 The tracking of time and cycle exposure for propulsion system hardware items shall meet the requirements of paragraph G-10 in JSC-08080-2, JSC Design and Procedural Standards, over the full 'service life' of the hardware as defined in paragraph 3.44 of SMC-S-016, Test Requirements for Launch, Upper Stage, and Space Vehicles. ***[PSR-334S]***

Rationale: Paragraph G-10 (Time/Cycle Critical Part Control) is intended to track 'time and cycle' parameters for propulsion system components with some aspect of limited life in service (e.g. storage life, propellant wetted life, actuation cycle life, etc.). This important concept can apply to single-use or multi-use vehicles, and the scope spans the full service life of the hardware, as defined in the cited SMC-S-016 specification. The intent is to ensure that no hardware item exceeds its certified life while in service, and the task represents a joint effort between the engineering, safety and mission assurance, ground operations, and flight operations teams. Parameters that are frequently tracked include, but are not limited to, storage duration (shelf life); time at pressure; propellant wetted duration; tank pressure cycles; valve open/closed cycles; pressure regulator slam starts and full-flow/lock-up cycles; engine/thruster pulse count, cumulative on-time, cold starts, and deep thermal cycles; TVC actuator full-stroke cycles, direction reversals, and limit load cycles; controller power-up cycles and cumulative on-time; etc. In past programs, certain hardware items have failed prematurely due to an unexpectedly high number of cycles during ground testing/checkout that weren't included in the original design specification and qualification test campaign for the component. Those added cycles were collectively accrued at the supplier prior to delivery, as part of hardware integration/assembly onto the vehicle, during pre-launch, post-recovery, and ground turnaround operations, and during in-flight operations. For a reusable vehicle, this type of tracking can be accomplished through the OMRSD as required per PSR-07G.

3.18.2 Flight Operations

3.18.2.1 The flight operations products developed and maintained under configuration control, including but not limited to the following, shall include propulsion-related content: ***[PSR-335G]***

a. Launch Commit Criteria (LCC)
b. Flight Rules (FR)
c. Telemetry lists
d. Integrated schematic diagrams relating fluids, power, and instrumentation
e. Minimum Equipment List (MEL)
f. Powered Equipment List (PEL)
g. Console handbooks and associated online databases
h. Propulsion system software user's manual including command and data dictionary

Rationale: The control of catastrophic hazards in a spacecraft propulsion system relies on a variety of design attributes, analysis/test protocols, and flight operations practices, some of which are rooted in the products listed here. The intent is to ensure that all of the key flight operations products provide an appropriate level of technical content governing the usage and operations of a hazardous propulsion system, with significant involvement from the Propulsion engineering team in development of these products. Reference LLIS-6076, MPS Databook. (LLIS-6076, 2010)

3.18.2.2 RESERVED for future requirements concerning flight crew interface that provides insight into propulsion system operation and FDIR that are time critical and not conducive to ground control inputs due to communication delays. ***[PSR-336G]***

3.18.3 Flight Hardware-to-Ground Interface Protections

Servicing ports for a spacecraft propulsion system, sometimes referred to as fluid couplings, quick disconnects, test point couplings, service valves, etc., are fluid components comprised of two halves, a ground-half and a flight-half, or supplier/receiver halves, which are capable of being mated and demated in a manual or automated fashion and may include sealing features that are actuated at some point during the engagement or disengagement event to prevent spillage. This hardware is typically used for pressure monitoring and/or fluid transfer to/from the propulsion system during ground processing operations such as testing, inert gas purging, aspirating/evacuating, applying blanket pressure, and flight commodity servicing/deservicing/decontamination.

3.18.3.1 The ground test or processing facilities shall have a general operating procedure manual with specific protections for the test articles and flight vehicle hardware. ***[PSR-337G]***

Rationale: This includes the use of protections for COPVs, flex hoses, etc. such as removable covers.

3.18.3.2 Procedural documents that govern the ground testing and operation of human rated spacecraft propulsion systems, including any interfacing equipment, shall comply with the 'hazard indication' requirements of paragraph G-18 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-338S]***

Rationale: Paragraph G-18 (Safety Precautions – Test and Operating Procedures) is intended to ensure that ground testing and operations procedures, including those involving Test Support Equipment (TSE) and/or Ground Support Equipment (GSE), to be labeled as hazardous when appropriate and contain associated warning statements that clearly indicate any step which, if not correctly followed, would result in injury to personnel, damage to a system or equipment, or an adverse environmental impact. Such labeling is a critical part of the hazard control strategy and intended to ensure full preparedness when critical steps occur that could put personnel and hardware at risk. Reference LLIS-403, Viking Thrusters Fired on Launch Pad (1975) (LLIS-403, 1996) ; LLIS-426, Surveyor Rocket Motor Almost Fired (~1965) (LLIS-426, 1996); LLIS-499, Maintenance team fatality due incorrect pressure gauge reading (LLIS-499, 1996); LLIS-885, Verify Configuration of Flight Hardware Prior to Test (1998) (LLIS-885, 2000); and LLIS-1529, Ensure Test Monitoring

Software Imposes Limits to Prevent Over-test (2003) (LLIS-1529, 2004).

3.18.3.3 The ground equipment that interfaces with a human rated spacecraft propulsion system shall comply with the 'verification test provisions' requirements of paragraph F-11 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-339S]***

Rationale: Paragraph F-11 (Fluid Supplies – Verification Test Provisions) is intended to ensure that GSE, facilities, fluid containers, and other equipment that directly interfaces with a spacecraft propulsion system is designed to enable routine verification tests/checkouts immediately before each connection is made to ensure all fluid inputs to the spacecraft are compatible, thus serving as a control for potentially catastrophic hazards.

3.18.3.4 Test Article-to-Test Facility ICD requirements shall define the propulsion system fill rates, pressurization rates, temperature limits, and environmental (humidity, salt air, etc.) limits. ***[PSR-340G]***

3.18.3.5 The propulsion test article shall be monitored and protected with 1 fault tolerance, against exposure to pressures above MDP, exposure to voltage and current levels above certified hardware limits, and exposure to vibration and shock levels above certified hardware limits. ***[PSR-341G]***

3.18.3.6 The test article shall be protected against back emf, back flow of fluids including contamination, or back pressure. ***[PSR-342G]***

3.18.3.7 The ground equipment that interfaces with a human rated spacecraft propulsion system shall comply with the 'protecting flight equipment' requirements of paragraph G-24 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-343S]***

Rationale (for 3.18.3.4 – 3.18.3.7): The above requirements are collectively intended to protect the flight vehicle or test article hardware from damage. Paragraph G-24 (Protecting Flight Equipment from Support Equipment) is intended to ensure that all GSE, airborne support equipment (ASE), STE, and facility equipment that interfaces with a spacecraft propulsion system contain features/devices in the design that will help protect the flight vehicle from damage caused by hardware malfunction, procedural errors, and/or operator errors. Examples involving fluid systems include, but are not limited to, interface filters (contamination), pressure relief devices (over pressurization), accumulators (pressure transients), and flow meters (flow rate/velocity, total quantity transferred). Examples involving electrical/electronic systems include, but are not limited to, surge suppressors (overvoltage), circuit breakers and fuses (overcurrent), ammeters (current flow, total charge transferred), and electromagnetic interference (EMI) filters (electromagnetic effects). Of course, software monitoring/control could be part of the overall protection strategy too. The intent is to ensure that all interfacing ground and flight systems are methodically evaluated for failure modes and other threats to the propulsion system in order to ensure that protective features are adequate to safeguard the flight hardware and ground personnel. Lesson learned examples include over-pressurization of the

Shuttle OMS tank rupturing the burst disk. Reference LLIS-77 OMS/RCS System Control Logic (LLIS-77, 1992) and LLIS-583, Test Contingency Planning Should Consider Facility Power Interruptions (1996). (LLIS-583, 1998)

3.18.3.8 Filters at the interface between GSE and the flight vehicle shall be installed on the GSE side such that there are no other components besides the fluid coupling itself (e.g. QD, threaded fitting, etc.) that can liberate particles between the filter and the coupling. ***[PSR-344G]***

Rationale: The purpose of an interface filter in the GSE is to provide a 'last chance' opportunity to prevent particulate contamination from the GSE being released into the flight propulsion system. Accordingly, there should be no other components besides the fluid coupling itself (e.g. QD, threaded fitting, etc.) that can liberate particles between the filter and the coupling hardware. Lack of interface filter element (out of configuration) allowed upstream contamination to lodge in QD poppet and upon QD un-mating the bulk propellant in the rocket stage was allowed to escape, killing the ground crew. (Nufer, 2010, pp. 11-13). Note that other requirements in this standard provide protection against contamination located downstream of the GSE interface filter from being introduced into the vehicle during fluid commodity servicing. Examples include PSR-73G, which drives fluid sampling at the interface and visual inspection of the ground and flight half coupling surfaces to ensure cleanliness prior to mating, and PSR-254G, which drives a filter element to be included on the flight side of the interface to capture particulate generated during connection of the ground and flight half couplings. Past experience has shown that a threaded fitting configuration can be a particularly significant contributor to FOD generation.

3.18.3.8.1 GSE interface filter qualification shall be in accordance with the maximum particulate rating as specified by the flight program filter specification. ***[PSR-345G]***

3.18.3.8.2 Acceptance of each GSE/Vehicle interface filter shall be accomplished by the test method of SAE ARP 901 to the bubble point as defined in the filter specification. ***[PSR-346G]***

3.18.3.8.3 Certification of each interface filter and disconnect assembly cleanliness shall be according to SAE ARP 599 to the subsystem cleanliness level specified. ***[PSR-347G]***

Rationale (for 3.18.3.8.1 – 3.18.3.8.3): GSE interface filters must meet the same qualification and acceptance requirements as the flight filters in order to use as a hazard control for contamination of the flight system that could lead to common cause failures.

3.18.3.9 The initiation/termination of fluid flow during propellant transfer operations shall rely on reconfigurable valves in the propulsion system design rather than the mating/demating of fluid quick disconnects (QD's) alone. ***[PSR-348G]***

Rationale: Fluid QDs, whether manually operated or remotely actuated by another means (e.g. motor drive, pneumatic/hydraulic pressure, etc.) contain internal design features that automatically open and close the flow path when the QDs are mated and demated, respectively. In some cases, those mechanisms can fail to function as intended, resulting in a hazardous leakage/release of propellant when the QDs are operated (among other possible consequences). As one notable past example involving the Space Shuttle OMS/RCS propulsion system, a buildup of iron nitrate in the oxidizer servicing system caused the ground half QD poppet to seat improperly during demating, which resulted in significant propellant leakage onto the vehicle that caused damage to the thermal protection system tiles and corrosion of exposed electrical connectors (not detected until later). In response, servicing procedures were modified to isolate QDs from their fluid source using a valve. LLIS-55, Quick Disconnect F.O.D.; Quick Disconnect (QD) Design. (LLIS-55, 1992) A similar incident occurred on the Titan II rocket resulting in the death of 2 ground crew. (Nufer, 2010, p. 11)

3.18.3.10 *Ground fluid servicing and test port connections for a human rated spacecraft propulsion system shall comply with the 'prevention of incorrect connection' requirements of paragraph F-3 in JSC-08080-2, JSC Design and Procedural Standards.* ***[PSR-349S]***

Rationale: Paragraph F-3 (Service Points – Positive Protection from Interchangeability of Fluid Service Lines) is intended to ensure that all incompatible fluid connections between ground equipment and the flight vehicle, from a fluid compatibility and/or functional standpoint, are impossible to connect based on connector type, size/geometry, and/or physical location/proximity. Note that this requirement also extends to caps/covers for fluid connections. Note that a similar requirement exists in NASA-STD-8719.24, paragraphs 12.1.10.2.2 and 12.1.10.2.3.11. In one notable past example involving the Space Shuttle OMS/RCS propulsion system, a common fluid coupling design allowed the flight cap for a ¼ inch air half coupling (AHC) to be inadvertently installed on a flight ½ inch AHC, which actuated the poppet causing oxidizer release and ground personnel injury. (Nufer, 2010, pp. 16-17)

3.18.3.11 The fluid 'quick disconnects' used on a human rated spacecraft propulsion system shall comply with the requirements of the following paragraphs in the Annex to NASA-STD-8719.24, NASA Payload Safety Requirements: ***[PSR-350SC]***

a. Paragraph 12.1.10.2.3.4, which addresses self-sealing design features, internal/external leakage performance at high and low pressure, and cold gas flow in cryogenic systems.

b. Paragraph 12.1.10.2.3.5, which addresses bi-directional flow capability.

c. Paragraph 12.1.10.2.3.6, which addresses external leakage during mating and demating.

d. *Paragraph 12.1.10.2.3.8, which addresses positive locking devices in fluid quick disconnects (QDs) intended to prevent separation under pressure and flow conditions*
e. *Paragraph 12.1.10.2.3.9, which addresses external leakage and inadvertent demating when exposed to externally applied loads.*
f. *Paragraph 12.1.10.2.3.10, which addresses the loads imparted to interfacing fluid lines during mating and demating.*
g. *Paragraph 12.1.10.2.3.11, which addresses design features to avoid inadvertent mating of disconnects carrying incompatible fluids.*

Rationale: The cited paragraphs in NASA-STD-8719.24 collectively describe the design features and performance characteristics of fluid quick disconnects (QDs) used in the flow of propellants and other fluids of a spacecraft propulsion system. Fluid QDs most commonly appear at 'external' interfaces to the STE or GSE for the purpose of testing, purging, servicing, deservicing, and decontamination of a propulsion system. They can also appear at 'internal' interfaces between different sections/segments of the propulsion system itself. The requirements contained in these paragraphs are considered to be critical aspects of propulsion system hazard control.

3.18.3.12 Spacecraft propulsion system design shall allow for it to be drained and decontaminated during contingency ground operations. ***[PSR-351G]***

Rationale: Ground operations leading up to launch may result in needing to unload propellant and decontaminate the spacecraft propulsion system to eliminate a hazard, which must be planned for and designed accordingly to be accomplished in an effective, efficient manner. Note that the drain and decontamination must be completed with caution for certain propellants such as MON blends of NTO for which the loss of nitric oxide (NO) during the process can cause stress corrosion in the tanks. This meets NASA STD-8719.24, paragraph 12.1.3.2.

3.18.3.13 Gases used for purging propellant vapors from spacecraft compartments shall meet the 'dew point' requirements of paragraph F-21 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-352S]***

Rationale: Paragraph F-21 (Purge Gases – Dew Point Requirement) drives the gaseous fluid commodities used for purging propellant vapors from a spacecraft compartment to have a sufficiently low dew point that will preclude moisture condensation on the coldest hardware surfaces in the purge flow path.

3.18.3.14 Ground electrical connections for a human rated spacecraft propulsion system shall comply with the 'prevention of incorrect connection' requirements of paragraph E-1 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-353S]***

Rationale: Paragraph E-1 (Mating Provisions for Electrical Connectors) is intended to ensure that all incompatible electrical connections between ground equipment and the flight vehicle are impossible to be made based on connector type, size/geometry, physical location/proximity, and labeling. Reference LLIS-111 LH2 Quick Disconnects (QD) (LLIS-111, 1992)

3.18.3.15 The GSE and spacecraft shall comply with the 'protection against damage from pressurant depletion' requirements of paragraph F-12 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-354S]***

Rationale: During ground operations, the maintenance of fluid pressure is sometimes critical to prevent major damage to space vehicle propulsion system components such as a propellant tank or to prevent propellant issues. The requirements in paragraph F-12 (Protection of Pressurized Systems from Damage Due to Pressurant Depletion – Support Equipment) address interfacing equipment (i.e. GSE, ASE, or FSE) that provides sufficient pressure to the sensitive space vehicle component(s) in the event of a failure of the pressurant source, in addition to the monitoring and ability to recover from such a fault.

3.18.4 Hardware Warning Signs, Labels, and Markings

The term 'hardware marking' encompasses hardware classification, identification/tagging, and control to avoid inadvertent loss or damage; packaging, shipping, handling, and transport (PSH&T) to avoid inadvertent transit damage; and markings, design features, and testing to avoid improper installation in the system. The intent is for components to be adequately labeled with part information, commodity indicators, color coding, pressure ratings, directional flow arrows, etc. to eliminate loss, damage, or installation errors which could result in a hardware malfunction leading to a catastrophic hazard. The following requirements address those concerns.

3.18.4.1 Human rated spacecraft propulsion system components with a function that is dependent on the direction of fluid flow for proper operation in the system shall comply with the 'design, marking, and testing' requirements of paragraph F-8 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-355S]***

Rationale: Paragraph F-8 (Fluid Systems Components Whose Function Is Dependent on Direction of Flow – Protection Against Incorrect Installation) establishes key requirements for hardware design, physical marking, and post-installation checkout/testing of propulsion system components with a function that is dependent on the direction of fluid flow. The intent is to ensure that such components are not inadvertently installed backward, which has occurred in past projects/programs and could result in a catastrophic hazard.

3.18.4.2 Hardware items used in a human rated spacecraft propulsion system shall comply with the 'product identification and marking' requirements of paragraph G-22 in JSC-08080-2, JSC Design and Procedural Standards. ***[PSR-356S]***

Rationale: Paragraph G-22 (Product Identification and Traceability) establishes key requirements for spaceflight hardware identification and marking that are considered applicable to and necessary for spacecraft propulsion systems in the context of avoiding undetectable damage that could lead to hardware malfunction and a catastrophic hazard.

3.18.4.3 Spacecraft propulsion system hardware shall be classified, identified/tagged, and controlled in a manner consistent with the requirements of JPD 1720.14, Spaceflight Hardware Classification and Control. ***[PSR-357S]***

Rationale: The cited JSC Policy Directive (JPD) document defines and establishes key requirements for spaceflight hardware classification, identification/tagging, and control that are considered applicable to and necessary for spacecraft propulsion systems in the context of avoiding undetectable damage that could lead to hardware malfunction and a catastrophic hazard.

3.18.4.4 Components including vents shall have color codes, labels or warning signs, and directional arrows to identify hazards and direction of flow per NASA STD-8719.24, sections 12.6.1.2.1 and 12.10.8.5. ***[PSR-358S]***

Rationale: The intent is for components to be adequately labeled with part information, commodity indicators, color coding, pressure ratings, directional flow arrows, etc. to eliminate loss, damage, or installation errors which could result in a hardware malfunction leading to a catastrophic hazard.

3.18.4.5 Spacecraft propulsion system hardware shall comply with the packaging, handling, and transport (PH&T) requirements of NPR 6000.1, Requirements for Packaging, Handling, and Transportation for Aeronautical and Space Systems, Equipment, and Associated Components. ***[PSR-359S]***

Rationale: The cited NPR document defines and establishes key requirements for spaceflight hardware packaging, handling, and transportation that are considered applicable to and necessary for spacecraft propulsion systems in the context of avoiding undetectable damage that could lead to hardware malfunction and a catastrophic hazard.

APPENDIX A: REQUIREMENTS APPLICABILITY AND VERIFICATION MATRIX

A.1 Purpose

This Appendix provides a listing of requirements contained in this NASA Technical Standard for the selection and verification of requirements by programs and projects.

The applicability column is intended to capture the intent to levy individual requirements from this standard by a given project/program, either as written or possibly with relevant tailoring. In the ‘Applicable’ column, enter ‘Yes’ to accept the as-written requirement’s applicability to the project/program, enter ‘No’ to reject the as-written requirement’s applicability to the project/program, or enter ‘Tailored’ to accept a tailored version of the requirement for the project/program. For a ‘No’ or ‘Tailored’ entry, the technical rationale justifying those selections should be entered in the right-most column.

The Verification Method column is intended to capture the action(s) necessary by a contractor/partner to verify that the content of each requirement is being met. In cases where an existing technical standard, in whole or in part, is being levied (i.e. requirement numbers ending in S), the verification method(s) specified in the cited standard govern and the Verification Method column states ‘Per Std.’ In all other cases (i.e. requirement numbers ending in SC or G), the verification methods defined in NPR 7123.1, NASA Systems Engineering Processes and Requirements, apply, including analysis/assessment (A), demonstration (D), inspection (I), test (T) or a combination thereof. Two additional methods used in prior projects/programs have also been included for improved clarity in certain instances: review of design (RoD) and Inspection of Records (IoR). Those distinct tasks/actions have sometimes been considered a form of inspection (I), which is typically meant to indicate a qualitative and/or quantitative inspection of hardware items instead.

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.1	**Vehicle and Propulsion System Requirements**				
3.1.1	**Vehicle and Propulsion System Performance**				
3.1.1.1	Mission Critical Propulsion Performance Parameters	[PSR-01G]	A		
3.1.1.2	Design Specification Natural Environment SLS-SPEC-159	[PSR-02S]	Per Std		
3.1.2	**Critical Math Models**				
3.1.2.1	NASA-STD-7009 Compliance for Critical Math Models	[PSR-03S]	Per Std		
3.1.2.2	Critical Math Models Including Performance, MDP, Thermal, GNC, Slosh, Pogo, Power Models, etc.	[PSR-04G]	A		
3.1.3	**Single Use and Reusable Vehicle Propulsion Systems**				
3.1.3.1	Reusable Vehicle Service Life for Design and Qualification	[PSR-05SC]	A,T		
3.1.3.2	JSC-08080-2 a. G-1, Equipment Accessibility for Maintenance, b. G-52 Reuse of Flight Equipment	[PSR-06S]	Per Std		
3.1.3.3	Operations and Maintenance Requirements and Specifications Document (OMRSD)	[PSR-07G]	A		
3.1.4	**Redundancy and Fault Tolerance**				
3.1.4.1	Section 4.3 of NASA-STD-8719.29, NASA Tech. Req. for Human Rating	[PSR-08S]	Per Std		
3.1.4.2	Assess catastrophic hazards that result from 2 faults	[PSR-09G]	A		
3.1.4.3	JSC-08080-2, G-8 Design for Redundancy Verification	[PSR-10S]	Per Std		
3.1.5	**Failure Tolerance Exceptions in Propulsion Systems**				
3.1.5.1	Failure Tolerance Exceptions (or DFMR)	[PSR-11SC]	A		
3.1.6	**Separation or Protection of Redundant Functions**				
3.1.6.1	JSC-08080-2 G-2 Separation of Redundant Systems	[PSR-12S]	Per Std		
3.1.7	**GN&C and Thrusters/Engine Performance and Service Life ICD**				
3.1.7.1	Attitude control	[PSR-13G]	A		
3.1.7.2	Delta-V translational	[PSR-14G]	A		
3.1.7.3	Evaluation of Engine Options at SDR against GNC requirements	[PSR-15G]	A		
3.1.8	**Plume Impingement Loads, Dynamics, Heating, and Contamination**				

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.1.8.1	JSC-65829 Compliance for Plume loads	[PSR-16SC]	A,T		
3.1.8.2	Plume contamination	[PSR-17G]	A,T		
3.1.8.3	Plume Thermal Heating	[PSR-18G]	A,T		
3.1.8.4	Plume Ingestion	[PSR-19G]	A		
3.1.9	**Propellant Slosh Coupling with GN&C & Structure**				
3.1.9.1	JSC-65829 Section 6.6 Slosh + Impact on liquid acquisition, gauging	[PSR-20SC]	A		
3.1.9.2	Slosh control requirement, angular momentum transfer, damping	[PSR-21G]	A		
3.1.9.3	Models validated with tank test data	[PSR-22G]	A,T		
3.1.10	**Differential Draining Impact on Vehicle Center of Gravity**				
3.1.10.1	Series and parallel tank draining	[PSR-23G]	A,T		
3.1.11	**Loads and Structural Dynamics Requirements**				
3.1.11.1	JSC-65829 Compliance	[PSR-24S]	Per Std		
3.1.11.2	Transient thrust overshoot measurement – worst case conditions	[PSR-25G]	T		
3.1.11.3	Loads on propulsion components and plumbing	[PSR-26G]	A		
3.1.12	**Unstable Dynamic Coupling of Engine/Thruster, Feed System, and Vehicle Structure**				
3.1.12.1	JSC-65829, section 6.5 requirements LDR-041 and LDR-042, and section 4.1.3 requirement LDR-024	[PSR-27S]	Per Std		
3.1.12.2	Pump-Fed 6.4.4 and 7.3.7 of SMC-S-025,	[PSR-28S]	Per Std		
3.1.12.3	Pressure-Fed 6.4.4 and 7.3.7 of SMC-S-025,	[PSR-29S]	Per Std		
3.1.13	**Thermal Control of the Propulsion System**				
3.1.13.1	Thermal models to establish min/max temp limits not exceeded	[PSR-30G]	A,T		
3.1.13.2	Thermal Models meet NASA-STD-7009 & validated with test data	[PSR-31S]	Per Std		
3.1.13.3	Thermal Uncertainty on analysis per 3.62 and 4.4.2 of SMC-S-016	[PSR-32S]	Per Std		
3.1.13.4	Hardware and Fluids thermally controlled within ATP min max test	[PSR-33G]	A,T		
3.1.13.5	Hardware tested per SMC-S-016, section 6. unit, section 7. subsystem, and section 8. vehicle.	[PSR-34SC]	T		
3.1.13.6	Margin 5 °F + thermal uncertainty above propellant freezing	[PSR-35SC]	A,T		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.1.13.7	Max Pred. Temp has Margin of 50 °F below propellant decomposition	[PSR-36G]	A,T		
3.1.13.8	Engine inlet temperature within qual box and thermal uncertainty	[PSR-37G]	A,T		
3.1.13.9	Press. system controlled 20 °F above condensation prop vapor	[PSR-38G]	A,T		
3.1.13.10	Failure of passive insulation system requires active controls	[PSR-39G]	A,T		
3.1.13.11	Test data anchoring for critical thermal parameters (e.g. emissivity, contact resistance)	[PSR-40G]	T		
3.1.13.12	Active cooling system margins at initial design and after testing	[PSR-41SC]	A,T		
3.1.14	**Propulsion System Vents and Unintended Leaks - External and Internal**				
3.1.14.1	F1 JSC 08080 2B + compartment vent capability impact on prop MDP	[PSR-42S]	Per Std		
3.1.14.2	F9 JSC 08080 2B Spacecraft Venting-Induced Perturbing Forces	[PSR-43G]	RoD,A		
3.1.14.3	Vented propellants compatibility with surrounding materials	[PSR-44G]	A		
3.1.14.4	Vented fluid freezing hazard	[PSR-45G]	A,T		
3.1.15	**Anomaly, Issues, Problem Tracking and Resolution**				
3.1.15.1	G-15 JSC 08080 ‘resolution of equipment failures/anomalies’ and signoff	[PSR-46SC]	IoR		
3.2	**Propulsion System, Subassembly, and Component Testing**				
3.2.1	**General Testing Approach**				
3.2.1.1	Meet requirements of SMC-S-016	[PSR-47S]	Per Std		
3.2.1.2	Qual and ATP include leakage monitoring during vibe, shock, thermal testing	[PSR-48G]	IoR		
3.2.1.3	QBS comply with 4.10.1 SMC-S-016 and TOR-2013(3909)-1 for Heritage	[PSR-49SC]	A		
3.2.1.4	Trending of ATP data and out of family identification	[PSR-50G]	A		
3.2.1.5	Planetary surface dust assessment and testing	[PSR-51S]	Per Std		
3.2.2	**Propulsion System Level Qualification Test**				

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.2.2.1	Scope and Attributes of System level qual hot-fire testing (a thru r)	[PSR-52G]	A, RoD,T		
	a. section 8.0 in SMC-S-025		RoD, T		
	b. flight-representative fluid commodities		RoD, T		
	c. flight-representative propulsion system components		RoD		
	d. flight-representative propulsion system lines		RoD		
	e. flight-representative engines and pods		RoD		
	f. flight-representative thrust vector control (TVC)/controllers		RoD		
	g. flight-representative power sources, connectors, drivers, software		RoD		
	h. equivalent passive and active thermal control elements		RoD		
	i. flight-representative servicing/deservicing and ground turnaround interfaces		RoD		
	j. capability to fully saturate the liquid propellants with pressurant gas		RoD, T		
	k. hot fire sequences performed at vacuum (high altitude) conditions and, for entry vehicle applications, variable backpressure conditions ranging from high altitude to sea level		T		
	l. steady state and pulse mode operation of multiple engines in sequences with simultaneous and staggered firings representative of the mission design		T		
	m. nominal and contingency valve transient dynamic events		T		
	n. exposure of the hardware to all relevant external environments		T		
	o. structural coupling and thrust dynamics evaluation		T		
	p. engine/thruster chug and combustion stability evaluation		T		
	q. development instrumentation system needed to provide qualification data		RoD		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
	r. structured test readiness review (TRR) process with TAYO/TLYF review		A		
3.2.2.2	Complete qualification test prior to first uncrewed flight	[PSR-53G]	IoR		
3.2.3	**Propulsion System Development System Level Test**				
3.2.3.1	Conduct development test for any modifications or heritage gaps	[PSR-54SC]	IoR		
3.2.4	**Propulsion System Acceptance, Assembly, Integration, and Test (AI&T)**				
3.2.4.1	Hardware tested with test fluids at the max and min MPT	[PSR-55SC]	T		
3.2.4.2	Hot-fire testing of engine is required. clarification to SMC-S-016	[PSR-56G]	T		
3.2.4.3	End-to-end gas flow test of assembled prop system and F-20 JSC-08080-2	[PSR-57SC]	T		
3.2.4.4	JSC-08080-2 G-3 Electrical and Fluid Systems Checkout Provisions	[PSR-58S]	Per Std		
3.2.4.5	Cryogenic systems – tanking and engine green run	[PSR-59SC]	T		
3.2.4.6	Monopropellant loading and decomposition monitoring	[PSR-60G]	T		
3.2.5	**Propulsion System Allowable Leak Rate Assessment and Verification for Flight and Qualification articles**				
3.2.5.1	Define maximum acceptable leak rates	[PSR-61G]	IoR		
3.2.5.2	NASA-STD-7012 including supplementary 5.15-5.19	[PSR-62SC]	IoR		
3.2.5.3	Perform both global system and local leak tests per NASA-STD-7012	[PSR-63G]	T		
3.2.5.4	Joints shall be tested with LTR15 method	[PSR-64G]	T		
3.2.5.5	Leak check Flex hoses per LTR15 Section or LTR24 section 5.11b	[PSR-65SC]	T		
3.3	**Flight Operational Fluids; Propellant, Pressurant, Pneumatic; Procurement and Usage Specification**				
3.3.1	**General Fluid Procurement and Usage Requirements**				
3.3.1.1	Propellant specification in place for prop system	[PSR-66G]	IoR		
3.3.1.2	Change in propellant manufacturing – sample, functional testing	[PSR-67G]	IoR,T		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.3.1.3	Propellant storage system specification	[PSR-68G]	IoR		
3.3.1.4	Formal training in propellant hazards documentation	[PSR-69G]	IoR		
3.3.2	**General Fluid Interface Filtration and Sampling Requirements**				
3.3.2.1	Filtering at the GSE interface	[PSR-70G]	RoD		
3.3.2.2	Sampling of fluids containers per F-27 of JSC-08080-2	[PSR-71S]	Per Std		
3.3.2.3	Sampling of storage prior to loading spacecraft and prior to refilling	[PSR-72G]	T		
3.3.2.4	Sample at the interface	[PSR-73G]	T		
3.3.3	**Operational Fluids: Pressurant, Pneumatic, Purge, and Cold Gas Propulsion Gases**				
3.3.3.1	Type 1 helium per MIL-PRF-27407	[PSR-74S]	Per Std		
3.3.3.2	Nitrogen grades B or C per MIL-PRF-27401	[PSR-75S]	Per Std		
3.3.3.3	Pressurant Gas Hazards	[PSR-76G]	A		
3.3.4	**Operational Fluids: Monopropellants (May Also Be Used in Bipropellant or Dual Mode Propulsion Systems)**				
3.3.4.1	MIL-PRF-26536 Performance Specification Propellant, Hydrazine	[PSR-77S]	Per Std		
3.3.4.2	High Purity Hydrazine (N2H4) constituents not controlled	[PSR-78G]	A,T		
3.3.4.3	MIL-PRF-16005, Propellant, Hydrogen Peroxide	[PSR-79S]	Per Std		
3.3.4.4	CGA G-8.2, Commodity Specification for Nitrous Oxide	[PSR-80S]	Per Std		
3.3.5	**Monopropellant Hazards**				
3.3.5.1	Establish worst case fluid temperatures due to faults by test	[PSR-81G]	T		
3.3.5.2	Limit hydrazine Max Pred Temp (MPT) to < 160 °F	[PSR-82G]	A,T		
3.3.5.3	Hydrazine temp > 160 °F component level safe test	[PSR-83G]	T		
3.3.5.4	Monopropellant test for ACD	[PSR-84G]	T		
3.3.5.5	F-6 JSC-8080-2 Temperature and pressure monitoring	[PSR-85S]	Per Std		
3.3.5.6	AIAA SP-084-1999, Safety Hazards of Hypergols – Hydrazine	[PSR-86S]	Per Std		
3.3.5.7	Nitrous Oxide Hazards	[PSR-87G]	A,T		
3.3.5.8	NASA Hydrogen Peroxide Propellant Hazards Tech. Manual	[PSR-88S]	Per Std		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.3.5.9	Hydrogen Peroxide System Contamination Control	[PSR-89G]	IoR		
3.3.5.10	Cavitation in Hydrogen Peroxide Systems	[PSR-90G]	T		
3.3.5.11	Test Monopropellant and materials for catalytic effect at MPT	[PSR-91G]	A		
3.3.5.12	Evaluate gas bubble formation that could be compressed	[PSR-92G]	A		
3.3.5.13	Throat plugs to prevent Air (CO2) interactions with hydrazine	[PSR-93G]	RoD,IoR		
3.3.6	**Operational Fluids: Bipropellants**				
3.3.6.1	MIL-PRF-25508, Performance Specification, Propellant, Oxygen	[PSR-94S]	Per Std		
3.3.6.2	MIL-PRF-27201, Performance Specification, Propellant, Hydrogen	[PSR-95S]	Per Std		
3.3.6.3	MIL-PRF-26539, Performance Spec. Propellants, Dinitrogen Tetroxide	[PSR-96SC]	T		
3.3.6.4	Maintain NO content	[PSR-97G]	A,T		
3.3.6.5	MIL-PRF-27404, Performance Spec Propellant, Monomethylhydrazine	[PSR-98S]	Per Std		
3.3.6.6	MIL-PRF-32207, Performance Specification, Propellant, Methane	[PSR-99S]	Per Std		
3.3.6.7	MIL-DTL-25576, Detail Spec. Propellant, Rocket Grade Kerosene	[PSR-100S]	Per Std		
3.3.7	**Bipropellant MMH/NTO Hypergolic Systems Hazards**				
3.3.7.1	AIAA SP-086-2001 (NTO), and AIAA SP-085-1999 Monomethylhydrazine	[PSR-101S]	Per Std		
3.3.7.2	Low dew point environment at all seals and openings	[PSR-102G]	T,IoR		
3.3.7.3	Throat plug flow through purge and NTO/MON3 reaction at seats	[PSR-103G]	RoD,IoR		
3.3.7.4	Teflon-lined flex hoses for hypergolics; permeation, degradation	[PSR-104G]	IoR		
3.3.8	**Bipropellant Cryogenic Systems Hazards**				
3.3.8.1	Oxygen Hazards ASTM G88-21 and ASTM MNL 36	[PSR-105S]	Per Std		
3.3.8.2	ANSI/AIAA G-095A-2017, Guide to Safety of Hydrogen	[PSR-106S]	Per Std		
3.3.8.3	Cryogenic boil-off concentrating other hydrocarbons as residuals	[PSR-107G]	A,T		
3.3.8.4	Liquefaction of air or intrusion of moisture	[PSR-108G]	A,T		
3.3.8.5	Boiling liquid evaporative explosion. (BLEVE)	[PSR-109G]	A		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.3.8.6	Moisture content in cryogenic systems	[PSR-110G]	A,T		
3.3.9	**Propellant and Pressurant Data Property Traceability**				
3.3.9.1	Use of NIST, AFRPL-TR-69-149, AFRL-TR-76-76	[PSR-111G]	A		
3.3.9.2	NIST-approved methodology for required properties	[PSR-112G]	A,T		
3.4	**Materials and Processes (M&P) and Fluid Compatibility**				
3.4.1	**Materials and Processes Standard**				
3.4.1.1	NASA-STD-6016, Standard Materials and Processes Req. for Spacecraft	[PSR-113S]	Per Std		
3.4.1.2	STE and GSE to meet NASA-STD-6016	[PSR-114G]	A		
3.4.2	**Test and Assembly Fluids; Cleaning, Flushing, and Drying**				
3.4.2.1	ASTM D1193, Reagent Water, Type I and II, incl. Appendix X1.3	[PSR-115SC]	T		
3.4.2.2	TT-I-735, Isopropyl Alcohol, Grade A	[PSR-116S]	Per Std		
3.4.2.3	CGA G-11.1, Argon, (QVL) C, D, E, or F, or MIL-PRF-27415, Type I, A or B	[PSR-117S]	Per Std		
3.4.2.4	A-A-59150, (HFE) , Note Fuel compatibility Issues and availability	[PSR-118S]	Per Std		
3.4.2.5	MIL-PRF-25567, Leak Detection Compound, Oxygen Systems, Type I or II	[PSR-119S]	Per Std		
3.4.2.6	Assessment of compatibility for cleaning, flushing, testing, and/or assembly fluids with prop system materials and propellants	[PSR-120G]	A		
3.4.2.7	Verification of dryness	[PSR-121G]	T		
3.4.3	**Component Fluid Compatibility and Corrosion Assessment Test**				
3.4.3.1	System and component compatibility test	[PSR-122G]	T		
3.4.3.2	Fluid lines and Manufacturing tool materials compatibility	[PSR-123G]	A		
3.4.3.3	CRES material and flow decay evaluation	[PSR-124G]	A		
3.4.3.4	Failure of sensor diaphragm and Material compatibility	[PSR-125G]	A, T		
3.4.4	**Propellant Oxidizer and Material Ignition and Combustion**				
3.4.4.1	NASA-STD-6016 4.2.1.4 (Oxygen) or 4.2.1.3 (Other Than Oxygen)	[PSR-126SC]	A		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.4.5	**Soft Goods Material Selection, Propellant and Cleaning Fluid Exposure**				
3.4.5.1	NASA-STD-6016 4.2.1.3 [MPR 47 and 48]	[PSR-127S]	Per Std		
3.4.5.2	Cleaning fluids for Oxidizer and Fuel	[PSR-128G]	RoD, IoR		
3.4.5.3	Switching fluid exposed components between the oxidizer and fuel	[PSR-129G]	RoD, IoR		
3.4.6	**System and Component Contamination Control**				
3.4.6.1	Sections 4.2.6.7 and 4.2.6.8 of NASA-STD-6016,	[PSR-130S]	Per Std		
3.4.6.2	IEST-STD-CC1246, Product Cleanliness Levels + silting	[PSR-131SC]	IoR		
3.4.6.3	High volatility liquid solvent and component vacuum drying	[PSR-132G]	T		
3.4.6.4	ISO 14644-1, Cleanrooms + Class 8 or better	[PSR-133SC]	T		
3.4.6.5	Cleanliness Verification after assembly or R&R of components	[PSR-134G]	T		
3.4.6.6	Cleaning after any fit-check, trim-to-fit, and surface preparation	[PSR-135G]	T		
3.4.6.7	Tube subassemblies liquid flush, sampling, borescope, final flush	[PSR-136G]	I,T		
3.4.6.8	Surveillance of the cleaning process using borescope	[PSR-137G]	IoR		
3.4.6.9	Precision cleaning of borescope	[PSR-138G]	T		
3.4.6.10	Verified tube cutting process and tool maintenance	[PSR-139G]	T		
3.4.6.11	Protecting against system contamination during tube preparation	[PSR-140G]	IoR		
3.4.6.12	Cleanliness assessment after Welding, rework, R&R operation	[PSR-141G]	IoR		
3.4.6.13	TWFPB Cleaning	[PSR-142G]	IoR		
3.4.6.14	Flex hose Cleaning	[PSR-143G]	IoR		
3.4.7	**External FOD, Water, or Ambient Air Intrusion Control**				
3.4.7.1	NASA-STD-6016, paragraph 4.2.6.7, requirement MPR 206, AIA/NAS12	[PSR-144S]	Per Std		
3.4.7.2	G-4 in JSC-08080-2 Protection from debris' , except G-4 4.	[PSR-145S]	Per Std		
3.4.7.3	GSE that Interfaces with Openings	[PSR-146G]	RoD,IoR		
3.4.7.4	Positive Restraints	[PSR-147G]	RoD		
3.4.7.5	Periodic inspections and Closeout Photographs	[PSR-148G]	IoR		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.4.7.6	Dry purge or Seal against moisture-laden air intrusion	[PSR-149G]	A,IoR		
3.4.7.7	Ingestion of water into the propulsion system and engine chambers	[PSR-150G]	A,T		
3.4.8	**Welds and Bimetallic joints**				
3.4.8.1	Weld requirements per NASA-STD-6016 and Class A	[PSR-151S]	Per Std		
3.4.8.2	Sample lots for brittle intermetallics using SEM ref MIL-STD-1252	[PSR-152G]	I		
3.5	**Propulsion System Pressurized Hardware**				
3.5.1	**Maximum Design Pressure (MDP) and Factors of Safety**				
3.5.1.1	JSC 65828, Structural Design Requirements and Factors of Safety	[PSR-153S]	Per Std		
3.5.1.2	3.2.8 in JSC 65828, except 3.2.8.3 [STR0021] (RV 110% of MDP)	[PSR-154SC]	A		
3.5.1.3	NASA/TM-20210022275, Treatment of Transient Pressure Events	[PSR-155G]	A		
3.5.2	**Fracture Control Requirements for Spaceflight Hardware**				
3.5.2.1	NASA-STD-5019, Fracture Control Requirements	[PSR-156S]	Per Std		
3.5.3	**Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components**				
3.5.3.1	NASA-STD-5009, NDE for Fracture-Critical Metallic Components	[PSR-157S]	Per Std		
3.5.4	**Threaded Fasteners**				
3.5.4.1	NASA-STD-5020, Requirements for Threaded Fastening Systems	[PSR-158S]	Per Std		
3.6	**Pressure Vessels and Propellant Tanks**				
3.6.1	**Integrated Propellant Tank Design and Analysis**				
3.6.1.1	Pressure vessel, PMD, tank support and interfacing fluid lines	[PSR-159G]	A,T		
3.6.2	**Type I Metallic Pressure Vessels**				
3.6.2.1	JSC 65828, including paragraph 3.2.8.4 [STR0022], ANSI/AIAA-S-080	[PSR-160S]	Per Std		
3.6.2.2	NDE (section 3.6.2.3) and fracture for burst exception to JSC-65828	[PSR-161SC]	I		
3.6.2.3	NASA-STD-5009 NDE	[PSR-162S]	Per Std		
3.6.2.4	NDE (POD) of 90/95 that accounts for double-wall radiography	[PSR-163G]	T		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.6.2.5	Aspect Ratio Pass fail Threshold	[PSR-164G]	A,T		
3.6.3	**Type II and III Composite Overwrapped Pressure Vessels (COPVs).**				
3.6.3.1	JSC 65828, including paragraph 3.2.8.5 [STR0023]	[PSR-165S]	Per Std		
3.6.3.2	JSC-65828, STR066, STR0067, STR0068, and STR0070	[PSR-166SC]	A,T		
3.6.3.3	Bond line sensitivity studies	[PSR-167G]	A,T		
3.6.3.4	NDE POD of 90/95 that accounts for double-wall radiography of liner	[PSR-168G]	T		
3.6.3.5	NDE methods in NASA-STD-5009	[PSR-169S]	Per Std		
3.6.3.6	Aspect Ratio Pass fail Threshold	[PSR-170G]	A,T		
3.6.4	**Type IV. Composite Pressure Vessels with Plastic Liner**				
3.6.4.1	JSC ES 151001-1 “Use of ASME Code or CFR 49 (DOT) Pressure Vessels	[PSR-171G]	A		
3.6.4.2	AIAA-G-082: 2022 - Guide: Space Systems – COPV with A Plastic Liner (a through l)	[PSR-172SC]	A, IoR, T		
	a. Review by a NASA appointed Subject Matter Expert (SME)		A		
	b. Reactive media penetration of overwrap		A, T		
	c. Composite chemically compatibility with fluids		A, T		
	d. Controls for raw materials		A, IoR		
	e. Assessment for damage tolerance		A		
	f. Statistical basis for material properties		A, IoR		
	g. External pressure conditions on liner		A, T		
	h. Environment analyzed for mechanical damage to COPV/ damage control plan		A		
	i. Materials evaluated for space environment		A, T		
	j. Negative pressure differential		A, T		
	k. Ensure full saturation of liner when assessing permeation		A, T		
	l. NDT capabilities matched to flaw detection needs		A, T		
3.6.5	**Type V All Composite Pressure Vessel**				

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.6.5.1	Need for Standard developed in coordination with NASA	[PSR-173G]	A		
3.6.6	**Liquid Propellant Management Device (PMD)**				
3.6.6.1	PMD and gas-free liquid to the engine/thruster	[PSR-174G]	A,T		
3.6.6.2	Surface tension screen galleries minimum safety factor	[PSR-175G]	A		
3.6.6.3	Surface tension vanes minimum safety factors	[PSR-176G]	A		
3.6.6.4	Surface tension sponges minimum safety factors	[PSR-177G]	A		
3.6.6.5	Positive expulsion TWFPB, NASA-STD-5019, JSC-67035	[PSR-178G]	RoD,IoR		
3.6.6.6	Upstream Material compatibility due to permeation of propellant vapors	[PSR-179G]	A,T		
3.6.6.7	Diaphragm delta pressure limits	[PSR-180G]	A,T		
3.6.6.8	PMD qualification, SMC-S-016	[PSR-181SC]	T		
3.6.6.9	PMD Performance qualification and acceptance	[PSR-182G]	T		
3.6.7	**Tank Slosh Control Devices**				
3.6.7.1	Slosh mitigation devices	[PSR-183G]	A,T		
3.6.7.2	Performance of the slosh damping devices	[PSR-184G]	A,T		
3.6.7.2.1	Slosh suppression device structural margins	[PSR-185G]	A		
3.6.8	**Propellant Quantity Gauge**				
3.6.8.1	Need for propellant quantity gauging	[PSR-186G]	RoD,A		
3.6.8.2	Indirect gauging and Leakage Detection	[PSR-187G]	RoD,A		
3.6.8.3	Gauging Uncertainty or error is unusable commodity	[PSR-188G]	A		
3.6.8.4	Verification of the propellant quantity gauging	[PSR-189G]	A,T		
3.6.8.5	Loading Uncertainty Bookkept as unusable commodity	[PSR-190G]	A		
3.7	**Pressurization Subsystem**				
3.7.1	**Pressure Regulation and Isolation**				
3.7.1.1	Regulated outlet pressure range	[PSR-191G]	A,IoR		
3.7.1.2	Dynamic Stability	[PSR-192G]	A,T		
3.7.1.3	Slam start pressure transients	[PSR-193G]	A,T		
3.7.1.4	Overshoot pressure upon initiation or termination of flow	[PSR-194G]	A,T		
3.7.1.5	Overshoot pressure and liquid propellant in press lines	[PSR-195G]	A,T		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.7.1.6	Fault tolerance and failures in the electronic control	[PSR-196G]	A		
3.7.1.7	Serial stage and/or parallel leg in a redundant configuration tests	[PSR-197G]	T		
3.7.1.8	Sizing of the pressurant tanks for spec leakage	[PSR-198G]	A		
3.7.2	**Overpressure Protection – Pressure Relief**				
3.7.2.1	Prevent MDP exceedance with passive pressure relief features	[PSR-360G]	RoD,A		
3.7.2.2	Protect hardware items below their MDP	[PSR-199G]	A		
3.7.2.3	JSC-08080-2 F-18 Pressure Relief Valves Functional Testing	[PSR-200S]	Per Std		
3.7.2.4	Relief device and the migration of liquid propellant into RV inlet line	[PSR-201G]	A		
3.7.2. 5	Non-permeable vapor barrier at inlet to RV	[PSR-202G]	RoD,A		
3.7.3	**Control of Corrosive and Reactive Propellant Liquid and Vapors in the Pressurization System**				
3.7.3.1	F-15 in JSC-08080-2, separation of hypergolic reactants	[PSR-203S]	Per Std		
3.7.3.2	Ineffective means of preventing propellant vapor migration upstream	[PSR-204SC]	RoD,IoR		
3.7.3.3	Condensation of propellant vapors in the pressurization system	[PSR-205G]	A,T		
3.7.3.4	Use of a common pressurization system situations	[PSR-206G]	RoD,T		
3.7.3.5	Liquid retention device (LRD) at Tank and Press line	[PSR-207G]	RoD,A		
3.8	**Propulsion System Valves**				
3.8.1	**General Requirements**				
3.8.1.1	NASA-STD-5017, Design and Development Req. for Mechanisms	[PSR-208S]	Per Std		
3.8.1.2	Reserved for a future NASA-STD-5023 for valves	[PSR-209G]	N/A		
3.8.2	**Dimensional Analysis and Clearances**				
3.8.2.1	4.1.2 [DDMR2] of NASA-STD-5017 including effects or prop exposure	[PSR-210G]	A		
3.8.3	**Torque/Force Margin Analysis**				
3.8.3.1	4.3.3.1 [DDMR9] of NASA-STD-5017 including water hammer transients	[PSR-211SC]	A		
3.8.3.2	4.3.1.1 [DDMR9] of NASA-STD-5017, including prop exposure	[PSR-212SC]	A		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.8.4	**Cycle Life**				
3.8.4.1	Ground cycles in para. 4.19.3.2 [DDMR75] of NASA-STD-5017	[PSR-213SC]	A		
3.8.4.2	Flight operational cycles in para 4.19.3.2 [DDMR75] of NASA-STD-5017	[PSR-214SC]	A		
3.8.4.3	4x qual across full range of applicable operating conditions	[PSR-215G]	T		
3.8.5	**Valve Electrical**				
3.8.5.1	NASA-STD-8739.10, Electrical, Electronic, And Electromechanical (EEE)	[PSR-216S]	Per Std		
3.8.5.2	MIL-STD-461, EMI, EMC	[PSR-217S]	Per Std		
3.9	**Propellant Feed System**				
3.9.1	**Propellant Feed System and Engine Interface Conditions**				
3.9.1.1	Feed system & engine/thruster interface condition limits	[PSR-218G]	A		
3.9.1.2	Water-hammer pressure transients and components	[PSR-219G]	A		
3.9.1.3	Margin for local pressure slumps above cavitation / vapor	[PSR-220G]	A		
3.9.1.4	Pressurant gas dissolved in liquid propellant	[PSR-221G]	A		
3.9.2	**Propellant Feed System Activation; Priming and Repriming**				
3.9.2.1	Concept of operations for feed system activation at SDR	[PSR-222G]	A		
3.9.2.2	Redundant pressure measurements if hazard when (re)priming	[PSR-223G]	A, RoD		
3.9.2.3	Fluid system transient analysis during priming/repriming events	[PSR-224G]	A, T		
3.9.3	**Propellant Feed System Maximum Design Pressure Transients**				
3.9.3.1	MDP and Pressure Transients	[PSR-225G]	A, T		
3.9.3.2	NASA/TM-20210022275, Treatment of Transient Pressure Events	[PSR-226G]	A		
3.9.4	**Feed System Model Verification and Validation**				
3.9.4.1	Breadboard/prototype feed system test	[PSR-227G]	T		
3.9.4.2	Feed system analysis, anchoring to Prototype and Qual tests	[PSR-228G]	A, T		
3.9.4.3	Fluid transient models (priming, pulsing, etc.) meet NASA-STD-7009	[PSR-229G]	A		
3.9.5	**Propellant Isolation – Inhibits to Bulk Propellant Loss**				

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.9.5.1	Minimum of three (3) independently verifiable inhibits until system activation	[PSR-230G]	RoD, T		
3.9.5.2	Minimum of two (2) inhibits nominal system operation	[PSR-231G]	RoD, T		
3.9.5.3	Mechanical Joints & Two independent verifiable inhibits	[PSR-232G]	RoD, T		
3.9.5.4	Ground service valves & three (3) mechanical inhibits	[PSR-233G]	RoD, T		
3.9.6	**Feed System Back Pressure Relief**				
3.9.6.1	Redundant pressure relief provisions (e.g. back-relief) & MDP	[PSR-234G]	A, T		
3.9.7	**Fluid Line Design, Routing, and Installation**				
3.9.7.1	CAD for design routing and installation procedures	[PSR-235G]	RoD		
3.9.7.2	Fluid line design and analysis; loads, bubble traps, low points, etc.	[PSR-236G]	RoD		
3.9.7.3	Bent metallic tubing in propulsion systems	[PSR-362S]	RoD, I		
3.10	**General Requirements for Mechanical Fittings, Joints, and Flanges**				
3.10.1	**Use of Mechanical Fittings/Joints vs. Brazing or Welding**				
3.10.1.1	MS-15 of JSC-08080-2; limitations for use of mechanical fittings	[PSR-237G]	RoD		
3.10.2	**Mechanical Fitting, Joint, and Flange Design, Qualification, and Acceptance**				
3.10.2.1	Mechanical Fittings and Flanges; design, qualification, and acceptance	[PSR-238G]	A, T, I		
3.10.2.1.1	Design: Two seals or sealing surfaces	[PSR-238a]	A		
3.10.2.1.2	Design: Capable of independently performing the intended sealing	[PSR-238b]	A		
3.10.2.1.3	Design: Verifiable positive restraint to preclude loss of seal load	[PSR-238c]	A		
3.10.2.1.4	Qual: Provide certification data	[PSR-238d]	T		
3.10.2.1.5	Qual: Test data on individual seal is capable of independently performing	[PSR-238e]	T		
3.10.2.1.6	Qual: Vibration qualification test data	[PSR-238f]	T		
3.10.2.1.7	Qual: Thermal cycle qualification test data	[PSR-238g]	T		
3.10.2.1.8	Qual: Pressure cycle qualification test data	[PSR-238h]	T		
3.10.2.1.9	Qual: Proof, burst, yield and ultimate; JSC-65828	[PSR-238i]	T		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.10.2.1.10	Qual: Leak rate at maximum design pressure (MDP)	[PSR-238j]	T		
3.10.2.1.11	Qual: Engagement/disengagement cycle test data	[PSR-238k]	T		
3.10.2.1.12	Qualification: Engagement/disengagement cycle test data	[PSR-238l]	T		
3.10.2.1.13	Qualification: leakage given dispersions in operational environment	[PSR-238m]	T		
3.10.2.1.14	Qualification: testing leakage rates for all relevant assembly parameters	[PSR-238n]	T		
3.10.2.1.15	Qualification: Sealing surface repair seal (seal savers)	[PSR-238o]	T		
3.10.2.1.16	Acceptance: materials	[PSR-238p]	I		
3.10.2.1.17	Acceptance: surface finish, flatness, tolerances, etc.	[PSR-238q]	I		
3.10.2.1.18	Acceptance: Parts shall be proof pressure tested at 1.0xMDP	[PSR-238r]	T		
3.10.2.1.19	Acceptance: Parts shall be cleaned and verified	[PSR-238s]	T		
3.10.2.1.20	Acceptance: Mating process check (MIP), surface photo documentation	[PSR-238t]	I		
3.10.2.1.21	Acceptance: Torque check operation; 24 hours between initial and final	[PSR-238u]	T		
3.10.2.1.22	Acceptance: Parts shall be leak tested at 1.0xMDP after final mating	[PSR-238v]	T		
3.11	**In-Space Fluid Transfer and Separable Spacecraft Modules**				
3.11.1	**In-Space Fluid Transfer**				
3.11.1.1	ANSI/AIAA-S-157, In Space Storable Fluid Transfer for Prepared Spacecraft	[PSR-239S]	Per Std		
3.11.1.2	2 Sealing barriers in the unmated and mated coupling; + isolation valves	[PSR-240SC]	RoD, T		
3.11.1.3	1 FT sealing features in place during Poppet (dis)engagement	[PSR-241SC]	RoD. T		
3.11.1.4	Fluid couplings & filter elements	[PSR-242G]	RoD, T		
3.11.1.5	Fluid coupling caps or covers	[PSR-243G]	RoD, T		
3.11.1.6	Fluid coupling leak checks; mated and unmated	[PSR-244G]	T		
3.11.1.7	Isolation valves for starting/stopping fluid flow	[PSR-245G]	RoD, T		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.11.2	**Separation of Spacecraft Modules**				
3.11.2.1	F-5 in JSC-08080-2; module and fluid lines separation	[PSR-246S]	Per Std		
3.12	**Filters and Filtration** (ref. NESC-RP-19-01498, Filtration of Spaceflight Propulsion and Pressurant Systems)				
3.12.1	**Identification of Sources and Quantities of Contamination**				
3.12.1.1	All potential sources of particulate contamination and NVR	[PSR-247G]	A		
3.12.1.2	Propellant tanks containing an internal surface tension PMD	[PSR-248G]	A		
3.12.2	**Sensitivity to Contamination**				
3.12.2.1	Minimum Orifices, Clearances	[PSR-249G]	A		
3.12.2.2	Sensitivity to Contamination; Cleanliness Levels and Filtration	[PSR-250G]	A, T		
3.12.2.3	Sensitivity of decomposition input to cleanliness & filters	[PSR-251G]	T		
3.12.2.4	Sensitivity to particle impact ignition inputs to cleanliness & filters	[PSR-252G]	T		
3.12.3	**Incorporation of Filters**				
3.12.3.1	F-29 in JSC-08080-2	[PSR-253S]	Per std		
3.12.3.2	Filters on the flight side of the GSE interface	[PSR-254G]	RoD		
3.12.3.3	Inlet (upstream) and outlet (downstream) of each pyro valve	[PSR-255G]	RoD, T		
3.12.3.4	Downstream of all pressure vessels for all fluids	[PSR-256G]	RoD, A		
3.12.3.5	FOD screens	[PSR-257G]	RoD, A		
3.12.4	**Filter Specification, Qualification, and Acceptance Test Requirements**				
3.12.4.1	NASA Engineering and Safety Center (NESC) Technical Bulletin No. 22-02,	[PSR-258G]	A		
3.12.4.2	NESC-RP-19-01498, Filtration of Spaceflight Propulsion and Press. Sys	[PSR-259G]	A, I, T		
3.12.4.3	Fluid filters SMC-S-016 qualification including shock/vibe	[PSR-260G]	A, I, T		
3.12.4.4	Filter specification per Appendix I. in NESC-RP-19-01498,	[PSR-261G]	A		
3.12.4.5	X-ray or visual inspection for contamination, such as weld spatter	[PSR-262G]	I		
3.12.4.6	Qualification; filter component fluid flow tests	[PSR-263G]	T		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.12.4.7	System level filter tests under surge/transient conditions	[PSR-264G]	T		
3.12.4.8	Filter performance vertical tests simulate 0-g	[PSR-265G]	T		
3.12.5	**Alternate to the Use of Wire Cloth and Etched Disc Filters**				
3.12.5.1	Systems that do not use wire cloth or etched disc filters	[PSR-266G]	A, I, T		
3.13	**Pyrotechnic Valves**				
3.13.1	**Normally Closed (NC) Parent Metal Hermetic Sealing vs. Normally Open (NO)**				
3.13.1.1	NC parent metal pyro valves	[PSR-267S]	Per Std		
3.13.1.2	NO pyro valves	[PSR-268G]	I, T		
3.13.2	**General Requirements for Pyro Valves**				
3.13.2.1	JSC 62809, Human Rated Spacecraft Pyrotechnic Specification	[PSR-269S]	Per Std		
3.13.2.2	JSC 28596, NASA Standard Initiator User's Guide	[PSR-270S]	Per Std		
3.13.2.3	NASA-STD-8719.12, Safety Standard for … and Pyrotechnics	[PSR-271S]	Per Std		
3.13.2.4	Materials of construction in pyro valve bodies/housings	[PSR-272G]	RoD		
3.13.2.5	NASA-SPEC-5022, NASA Manufacturing and Test … NC Pyrovalves	[PSR-273S]	Per Std		
3.13.2.6	Tailored NASA-SPEC-5022 for NO Pyrovalves	[PSR-274G]	A, T, I		
3.13.2.7	Use when Inlet and outlet are both wetted with liquid propellant	[PSR-275G]	RoD, T		
3.13.2.8	Scope of Qualification testing	[PSR-276G]	T		
3.14	**Thin Wall Flexible Pressure Boundary (TWFPB) Hardware Items: Bellows, Flex hoses, and Diaphragms**				
3.14.1	**TWFPB Failure Modes and Effects Analysis**				
3.14.1.1	Establish the criticality and identify any zero-fault tolerant hazards	[PSR-277G]	RoD/A		
3.14.2	**TWFPB Design, Analysis, and Test Requirements**				
3.14.2.1	JSC-67035, Best Practices and Guidelines for TWFPB	[PSR-278S]	Per Std		
3.14.3	**Flow Induced Vibration**				
3.14.3.1	MSFC-SPEC-3746, Flow-Induced Vibration	[PSR-279S]	Per Std		
3.15	**Spacecraft Engines and Thrusters**				
3.15.1	**Operating Conditions and Heritage**				

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.15.1.1	Flight operating box, including the qualification box indicating the margin	[PSR-280G]	A		
3.15.1.2	Heritage engine/thruster qualification	[PSR-281G]	T		
3.15.2	**Strength and Life Requirements, Service Life Qualification**				
3.15.2.1	NASA-STD-5012, Strength and Life ..for Liquid-Fueled … Engines	[PSR-282S]	Per Std		
3.15.2.2	Pump-fed engine design verification hot fire testing	[PSR-283SC]	T		
3.15.2.3	Pressure-fed engine design verification hot-fire testing	[PSR-284SC]	T		
3.15.2.4	Monopropellant engine design verification hot fire testing	[PSR-285SC]	T		
3.15.2.5	Cold starts and hot restarts	[PSR-286G]	T		
3.15.2.6	Deep thermal cycles	[PSR-287G]	T		
3.15.2.7	Transient overpressure measurement	[PSR-288G]	T		
3.15.2.8	Proof and burst based on MDP	[PSR-289SC]	T		
3.15.2.9	Acceptance; NASA-STD-5012 Section 9.5.2 and SMC-S-025 Section 7.1.3	[PSR-290SC]	I, T		
3.15.3	**Reusable Engines**				
3.15.3.1	Accounting for actual usage for each engine; Remaining life	[PSR-291G]	A		
3.15.3.2	Inspections	[PSR-292G]	I		
3.15.4	**SMC-S-025 Applicability and Conflicts**				
3.15.4.1	SMC-S-025, Evaluation and Test Requirements for Liquid Rocket Engines (a through i)	[PSR-293SC]	A, IoR, I, RoD, T		
	a. SMC-S-025 is applicable to all engines		IoR, RoD		
	b. SMC-S-025 exceptions; sections 4.5, 4.6, 5, and A.1		A		
	c. Minimum # of test engines		T		
	d. Propellants and pressurant gases per spec		IoR, T		
	e. Flight representative plumbing and TWFPB		RoD		
	f. Flight Representative Electrical circuits		RoD, T		
	g. Pneumatic actuator system pressure/temperature allowable		RoD, T		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
	h. Teardown and inspection of the engine		I		
	i. Tests include instrumentation for combustion instability		A, T		
3.15.4.2	SMC-S-016 engine qual. and acceptance testing	[PSR-294G]	I, T		
3.15.4.3	Run-to-depletion tests for both bipropellants	[PSR-295G]	T		
3.15.5	**Delta -Qualification**				
3.15.5.1	engine delta-qualification testing	[PSR-296G]	T		
3.15.6	**Combustion Stability**				
3.15.6.1	JANNAF-GL-2022-0001 (update to CPIA Publication 655)	[PSR-297S]	Per Std		
3.15.6.2	Combustion-propellant feed system dynamic interactions	[PSR-298G]	T		
3.15.7	**Thermal Limitations and Control**				
3.15.7.1	Engine thermal interface with environment and other engines	[PSR-299G]	T		
3.15.7.2	Thruster safe operating thermal limitations	[PSR-300G]	T		
3.15.8	**Engine/Thruster Ignition Systems**				
3.15.8.1	JSC-08080-2, E7 Problem electrical components	[PSR-301S]	Per Std		
3.15.9	**Overpressures; Control of Hard Starts, Zots, and Pops**				
3.15.9.1	Transients due to accumulated propellants and explosive mixtures	[PSR-302G]	T		
3.15.9.2	Allowable safe time for engine restart	[PSR-303G]	T		
3.15.9.3	Injector ratcheting colder; Minimum EPW, duty cycles, duration limits	[PSR-304G]	T		
3.15.9.4	Pressure spikes and material compatibility	[PSR-305G]	T		
3.15.10	**Engine and Valve Leak Detection**				
3.15.10.1	Leak detection of an engine	[PSR-306G]	RoD, A		
3.15.10.2	Sensitivity of the engine leak detection	[PSR-307G]	T		
3.15.10.3	Valve leak initiation due to inlet pressure or temp cycle; material issue	[PSR-308G]	A		
3.15.11	**Thrust Vector Control (TVC)**				
3.15.11.1	NASA-STD-5017 for design, analysis, and test	[PSR-309S]	Per Std		
3.15.11.2	1FT as a minimum	[PSR-310G]	RoD, T		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.15.11.3	Capability of holding engine position	[PSR-311G]	A, T		
3.15.11.4	TVC actuator failure tolerance exception	[PSR-312G]	RoD, T		
3.15.11.5	Load bearing structure of a TVC actuator, JSC 65828 and JSC-65829	[PSR-313SC]	RoD, T		
3.15.11.6	TVC position measurements	[PSR-314G]	RoD, T		
3.15.11.7	TVC fault reporting	[PSR-315G]	RoD, T		
3.15.11.8	TVC tests per SMC-S-025 7.3.9, clarification that 7.3.9-6 is at vacuum	[PSR-316S]	Per Std		
3.16	**FDIR, Instrumentation, Data Rates, and Software**				
3.16.1	**Fault Detection Isolation and Recovery (FDIR)**				
3.16.1.1	FDIR capability and failure modes with catastrophic potential	[PSR-317G]	RoD, T		
3.16.1.2	FDIR response time before failure is catastrophic	[PSR-318G]	RoD, T		
3.16.1.3	Redundant instrumentation	[PSR-319G]	RoD, T		
3.16.1.4	Instrumentation sufficient to diagnose cause	[PSR-320G]	RoD, T		
3.16.1.5	Critical instrumentation shall be a direct measurement	[PSR-321G]	RoD, T		
3.16.1.6	Instrumentation that is wetted by propellants	[PSR-322G]	RoD, T		
3.16.1.7	Detect failed OSL/OSH instruments and correct for bias/offset	[PSR-323G]	RoD, T		
3.16.2	**Instrumentation Data Rates**				
3.16.2.1	Sufficient for Worst-case time-to-effect	[PSR-324G]	RoD, T		
3.16.2.2	Chamber pressure measurement at least 3 samples during min EPW	[PSR-325G]	RoD, T		
3.16.3	**System Leak detection – Internal and External**				
3.16.3.1	One pressure and temperature sensor in each isolatable section	[PSR-326G]	RoD, T		
3.16.3.2	FDIR for system-level and localized leak detection	[PSR-327G]	RoD, T		
3.16.3.3	Detecting external leakage of non-isolatable bulk propellant	[PSR-328G]	RoD, T		
3.16.4	**Instrumentation Types and Hazards**				
3.16.4.1	Resistance Temperature Detectors (RTDs)	[PSR-329G]	RoD, T		
3.17	**Propulsion System Electrical**				
3.17.1	**Protective**				

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.17.1.1	E-11 in JSC-08080-2, 'protective covers or caps'	[PSR-330S]	Per Std		
3.17.2	**Electrical Bonding**				
3.17.2.1	NASA-STD-4003, Electrical Bonding for .., Spacecraft,..	[PSR-331S]	Per Std		
3.17.3	**Propulsion Device Power Switching**				
3.17.3.1	1 FT from inadvertent application of power	[PSR-332G]	RoD, T		
3.17.4	**Corona Suppression**				
3.17.4.1	E-6 in JSC-08080-2 corona suppression	[PSR-333S]	Per Std		
3.18	**Flight and Ground Operations Interface**				
3.18.1	**Hardware Time and Cycle Tracking**				
3.18.1.1	Time and Cycle G-10 in JSC-08080-2, Service Life 3.44 of SMC-S-016	[PSR-334S]	Per Std		
3.18.2	**Flight Operations**				
3.18.2.1	Flight operations documentation	[PSR-335G]	A		
3.18.2.2	Reserved	[PSR-336G]	N/A		
3.18.3	**Flight Hardware-to-Ground Interface Protections**				
3.18.3.1	General operating procedure manual with specific protections	[PSR-337G]	A		
3.18.3.2	Hazard indication requirements of paragraph G-18 in JSC-08080-2	[PSR-338S]	Per Std		
3.18.3.3	Verification test provisions of paragraph F-11 in JSC-08080-2	[PSR-339S]	Per Std		
3.18.3.4	Test Article-to-Test Facility ICD requirements	[PSR-340G]	RoD, I		
3.18.3.5	Monitored and protected with 1 fault tolerance	[PSR-341G]	RoD, T		
3.18.3.6	Protected against back emf, back flow of fluids	[PSR-342G]	RoD, T		
3.18.3.7	Protecting flight equipment per G-24 in JSC-08080-2	[PSR-343S]	Per Std		
3.18.3.8	Filters on the GSE side near the QD at the spacecraft interface	[PSR-344G]	RoD, T		
3.18.3.8.1	GSE filter design and qualified as if flight filter	[PSR-345G]	RoD, T		
3.18.3.8.2	Acceptance bubble point of each GSE/Vehicle interface and final filter	[PSR-346G]	T		
3.18.3.8.3	Certification GSE filter disconnect cleanliness per ARP 599A	[PSR-347G]	T		
3.18.3.9	Initiation/termination of fluid flow using isolation valves	[PSR-348G]	RoD, I		

Section	Section Title and Requirement Topic or Synopsis	Requirement in this Standard	Verif Method	Applicable (Yes, Tailored, or No)	If Tailored or No, Enter Rationale
3.18.3.10	Prevention of incorrect connection per F-3 in JSC-08080-2	[PSR-349S]	Per Std		
3.18.3.11	Fluid ‘quick disconnects’ per specific paragraphs in NASA-STD-8719.24 (a through g)	[PSR-350SC]	RoD, T		
3.18.3.12	Capability to be drained and decontaminated during contingency	[PSR-351G]	RoD, T		
3.18.3.13	GSE purge gas dew point per F-21 in JSC-08080-2	[PSR-352S]	Per Std		
3.18.3.14	Prevention of incorrect connection per E-1 in JSC-08080-2	[PSR-353S]	Per Std		
3.18.3.15	Protection against damage from gas depletion per F-12 in JSC-08080-2	[PSR-354S]	Per Std		
3.18.4	**Hardware Warning Signs, Labels, and Markings**				
3.18.4.1	Design, marking, and testing per F-8 in JSC-08080-2	[PSR-355S]	Per Std		
3.18.4.2	Product identification and marking G-22 in JSC-08080-2	[PSR-356S]	Per Std		
3.18.4.3	JPD 1720.14, Spaceflight Hardware Classification and Control.	[PSR-357S]	Per Std		
3.18.4.4	NASA STD-8719.24 section 12.6.1.2.1, 12.10.8.5	[PSR-358S]	Per Std		
3.18.4.5	PR 6000.1, Requirements for Packaging, Handling, and Transportation	[PSR-359S]	Per Std		

APPENDIX B. LIST OF ACRONYMS AND ABBREVIATIONS

1FT	One Fault/Failure Tolerant or Single Fault/Failure Tolerant
2FT	Two Fault/Failure Tolerant or Dual Fault/Failure Tolerant
A	Analysis
A50	Aerozine 50
Abs	Absolute
ACD	Adiabatic Compression Detonation
ACS	Attitude Control System
AFRL	Air Force Research Laboratory
AHC	Air Half Coupling
AI&T	Assembly, Integration, and Test
AIA	Aerospace Industries Association
AIAA	American Institute of Aeronautics and Astronautics
AIT	Auto Ignition Temperature
AME	Ascent Main Engine
ANSI	American National Standards Institute
APS	Ascent Propulsion System
APU	Auxiliary Power Unit
AS	Aerospace Standard
ASE	Airborne Support Equipment
ASTM	American Society of Testing and Materials
ATP	Acceptance Test Procedure or Authority to Proceed
ATV	Automated Transfer Vehicle
Aux	Auxiliary
BIT	Built-In Test
BL	Baseline
BLEVE	Boiling Liquid Evaporative Explosion
BOSF	Burn Out Safety Factor
BP&G	Best Practices and Guidelines
BTI	Burn Time Integration
CAD	Computer Aided Design
CCP	Commercial Crew Program
CDR	Critical Design Review
CFR	Code of Federal Regulations
CG or CoG	Center of Gravity
CGA	Compressed Gas Association
CH4	Methane

CHF	Critical Heat Flux
CM	Command Module (Apollo Program) or Crew Module (MPCV Program)
CMM	Critical Math Model
COPV	Composite Overwrapped Pressure Vessel
COTS	Commercial Off The Shelf
COV	Coefficient of Variation
CPIAC	Chemical Propulsion Information Analysis Center
CRS	Commercial Resupply Services
CT	Computed Tomography
D	Demonstration
D&C	Design and Construction
DAF	Dynamic Amplification Factor
DC	Duty Cycle
DCP	Damage Control Plan
DDMR	Design and Development of Mechanisms Requirement
DDT&E	Design, Development, Test, and Evaluation
Delta P	Differential/Delta Pressure
Delta V	Differential/Delta Velocity
DFAT	Direct Field Acoustic Test
DFI	Development Flight Instrumentation
DFMR	Design for Minimum Risk
DI	Deionized
DLAT	Destructive Lot Acceptance Test
DM	Descent Module
DME	Descent Main Engine
DMM	Dry Mass Margin
DOT	Department of Transportation
DPA	Destructive Physical Analysis
DSNE	Design Specification for Natural Environments
DWG	Drawing
ECPD	Element Collapse Pressure Differential
EDL	Entry, Descent, and Landing
EDU	Engineering Development Unit
EEE	Electrical, Electronic, and Electromechanical
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
Eng	Engineering
EPW	Electrical Pulse Width

ER	Evaluation Required
EVA	Extravehicular Activity
FAYT	Fly As You Test
FDIR	Fault Detection, Isolation, and Recovery
FDV	Fill and Drain Valve
FED	Federal
FIV	Flow Induced Vibration
FMEA	Failure Modes and Effects Analysis
FOD	Foreign Object Debris
FORP	Fuel-Oxidizer Reaction Products
FR	Flight Rule
FS or FoS	Factor of Safety
FSE	Flight Support Equipment
FSW	Flight Software
FT	Fault Tolerant or Fault Tolerance
FTC	Fluid Transfer Coupling
G or g	Gravity
GAr	Gaseous Argon
GGVM	Gas Generator Valve Module
GH2	Gaseous Hydrogen
GHC	Ground Half Coupling
GHe	Gaseous Helium
GL	Guideline
GN2	Gaseous Nitrogen
GNC or GN&C	Guidance, Navigation, and Control
GO2	Gaseous Oxygen
GRO	Gamma Ray Observatory Spacecraft
GSE	Ground Support Equipment
H2	Hydrogen
H2O2	Hydrogen Peroxide
HA	Hazard Analysis
HDBK	Handbook
He	Helium
HFE	Hydrofluoroether
HPH	High Purity Hydrazine
HR	Hazard Report
HTV	H-II Transfer Vehicle
Hypergol	Hypergolic Propellant
I	Inspection

ICD	Interface Control Document
ID	Inner Diameter
IEST	Institute of Environmental Sciences and Technology
IFA	In-Flight Anomaly
IMPS	Integrated Main Propulsion System
IoR	Inspection of Records
IPA	Isopropyl Alcohol
IRD	Interface Requirements Document
ISO	International Standards Organization
ISS	International Space Station
IVA	Intravehicular Activity
JANNAF	Joint Army Navy NASA Air Force
JPD	JSC Policy Directive
JSC	Johnson Space Center
KSC	Kennedy Space Center
LAr	Liquid Argon
LCC	Launch Commit Criteria
LCH4	Liquid Methane
LCO2	Liquid Carbon Dioxide
LD or L&D	Loads and Dynamics
LDR	Loads and Dynamics Requirement
LEM	Lunar Excursion Module
LH2	Liquid Hydrogen
LHe	Liquid Helium
LLIS	Lessons Learned Information System
LM	Lunar Module
LN2	Liquid Nitrogen
LNG	Liquified Natural Gas
LO2	Liquid Oxygen
LOC	Loss of Crew
LOM	Loss of Mission
LOV	Loss of Vehicle
LRD	Liquid Retention Device
LRE	Liquid Rocket Engine
LTR	Leak Test Requirement
MAN	Manual
Mass Spec	Mass Spectrometer
MBB	Messerschmitt-Bolkow-Blohm
MDC	Maximum Design Condition

MDP	Maximum Design Pressure
MEL	Master Equipment List
M&P	Materials and Processes
MGA	Mass Growth Allowance
MGN	Magellan
MIL	Military
MIP	Mandatory Inspection Point
MLI	Multi-Layer Insulation
MMH	Monomethylhydrazine
MMOD	Micrometeoroid and Orbital Debris
MO	Mars Observer Spacecraft
MON	Mixed Oxides of Nitrogen
MON1	Mixed Oxides of Nitrogen with 1% Nitric Oxide (NO)
MON3	Mixed Oxides of Nitrogen with 3% Nitric Oxide (NO)
MON25	Mixed Oxides of Nitrogen with 25% Nitric Oxide (NO)
MPCV	Multi-Purpose Crew Vehicle
MPH	Monopropellant Hydrazine
MPR	M&P Requirement
MPS	Main Propulsion System
MPT	Maximum or Minimum Predicted Temperature
MPTA	Main Propulsion Test Article
MR	Mixture Ratio
MSC	Manned Spacecraft Center (now Johnson Space Center)
MSFC	Marshall Space Flight Center
MSL	Mars Science Laboratory
MUM	Multi-Unit Module
N2	Nitrogen
N2H4	Hydrazine
N2O	Nitrous Oxide
NAS	National Aerospace Standard
NASA	National Aeronautics and Space Administration
NBP	Normal Boiling Point
NC	Normally Closed
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
NESC	NASA Engineering and Safety Center
NO	Normally Open or Nitric Oxide
NPR	NASA Procedural Requirements
NSI	NASA Standard Initiator

NTO or N2O4	Nitrogen Tetroxide
NTRS	NASA Technical Reports Server
NVR	Non-Volatile Residue
O2	Oxygen
OAMS	Orbit Attitude and Maneuvering System
OCE	Office of Chief Engineer
OD	Outer Diameter
OMRSD	Operations and Maintenance Requirements and Specifications Document
OMS	Orbital Maneuvering System
OSH	Off-Scale High
OSL	Off-Scale Low
OV	Orbiter Vehicle
P	Pressure
Pc	Chamber Pressure
PCA	Primer Chamber Assembly
PDR	Preliminary Design Review
PEL	Powered Equipment List
PH&T	Packaging, Handling, and Transport
PMD	Propellant Management Device
POD	Probability of Detection
POGO	Coupled Structure-Propulsion Instability
PRA	Probabilistic Risk Assessment
PRCS	Primary Reaction Control System
PSER	Propulsion System Engine Requirement
PSH&T	Packaging, Shipping, Handling, and Transport
PSR	Propulsion Standard Requirement
PVT	Pressure-Volume-Temperature
Pyro	Pyrotechnic
QBS	Qualification by Similarity
QD	Quick Disconnect
Qual	Qualification
QVL	Quality Verification Level
R	Required or Requirement
R&R	Removal and Replacement
RCS	Reaction Control System
REFPROP	Reference Fluid Thermodynamic and Transport Properties Database
REM	Rocket Engine Module
REV	Revision

RoD	Review of Design
RP	Report
RP1	Rocket Propellant 1
RPM	Retro Propulsion Module
RPOD	Rendezvous, Proximity Operations, and Docking
RTD	Resistance Temperature Detector
RV	Relief Valve
SAE	SAE International (formerly Society of Automotive Engineers)
SAFER	Simplified Aid for EVA Rescue
SCAPE	Self-Contained Atmospheric Protective Ensemble
SCC	Stress Corrosion Cracking
SDR	System Definition Review
SEM	Scanning Electron Microscope
SLS	Space Launch System
SM	Service Module
SMC	Space and Missile Command
SME	Subject Matter Expert
SP	Special Publication
SPEC	Specification
SPS	Samples per Second or Service Propulsion System
SRD	System Requirements Document
SRR	System Requirements Review
SSC	Space Systems Command
SSP	Space Shuttle Program or Space Station Program
STD	Standard
STE	Special Test Equipment
STR	Structural Requirement
STS	Space Transportation System
SWRI	Southwest Research Institute
T	Test or Testing or Temperature (depends on context)
T&I	Teardown and Inspection
TA	Technical Authority
TAYF	Test As You Fly
TAYO	Test As You Operate
TB	Technical Bulletin
TBC	To Be Confirmed
TBD	To Be Determined
TBR	To Be Reviewed
TC	Thermocouple

TLYF	Test Like You Fly
TM	Technical Memorandum
TN	Technical Note
TRR	Test Readiness Review
TSE	Test Support Equipment
TVC	Thruster Vector Control
TWFPB	Thin-Walled Flexible Pressure Boundary (synonymous with TWPB)
TWPB	Thin-Walled Pressure Boundary (synonymous with TWFPB)
U.S.	United States of America
USAF	United States Air Force
VO	Viking Orbiter Spacecraft
VRCS	Vernier Reaction Control System
WIRE	Wide-Field Infrared Explorer
WSTF	White Sands Test Facility
Xe	Xenon
ZOT	Engine/Thruster Injector Explosion

APPENDIX C: LIST OF REFERENCES INCLUDING LESSONS LEARNED AND REPORTS

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