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Office of the NASA Chief Engineer

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Superseding NASA-STD-5012B

METRIC/SI (ENGLISH)

STRENGTH AND LIFE ASSESSMENT REQUIREMENTS FOR LIQUID FUELED SPACE PROPULSION SYSTEM ENGINES

DOCUMENT HISTORY LOG

Status	Document Revision	Change Number	Approval Date	Description
Baseline			2006-06-13	Initial Release
Revision	A		2015-01-15	Throughout: Document revised to reflect NASA Technical Standards Program Office style and format. Section 1.2: Removed the 6K thrust limitation; encouraged tailoring for less complex engine systems. Sections 2.2 and 4.2.1.6: Replaced applicable document NSTS-08307 with NASA-STD-5020. Section 3.2: Clarified definitions of Pressure-Loaded Component/Structure and Pressurized System. Section 4.2.1.2.1: Changed the material requirements to reference NASA-STD-6016 for properties addressed in that Standard. Properties not addressed by NASA-STD-6016 were addressed by a separate requirement in this section. Section 4.2.1.5: Added g. to address nonlinear buckling analyses.

DOCUMENT HISTORY LOG (Continued)

Status	Document Revision	Change Number	Approval Date	Description
Revision	A		2015-01-15	Continued Sections 4.2.1.7.1 and 4.2.1.7.2: Added clarification related to section 3.2 definition changes and when a component is considered a pressure-loaded component. Section 4.2.1.11: Reworded this section to address materials that are susceptible to sustained load rupture, not just titanium alloys. Section 4.2.2.2: Clarified what an acceptable engine or component should be to meet the requirement. Section 4.2.2.3: Removed redundant requirements with section 4.2.2.2. Table 1: Updated note 4 to coincide with section 4.2.1.11 changes and to clarify failure modes. Table 1: Updated note 5 to point reader to additional requirements for composite and bonded structures.
Revision	B		2016-06-16	General Revision. Revised to include only the key and sufficient requirements for liquid-fueled space propulsion system engines. Numbered requirements, added the Requirements Compliance Matrix as Appendix A, and revised text to conform to the current template.

Revision	C		2025-12-31	**Table 1:** Moved table to section 5 when it is first mentioned in the guidance text. Updated AFSPCMAN 91-710 to SSCMAN 91-710 (revised in 2022). **Sections 1.0 -3.0**: Per NASA Technical Standards Program Office, removed "shall" statements from sections 1 through 3 and added any necessary replacement "shall" statements throughout sections 4 through 9 as noted below. **Section 2.2**: Revised/replaced the flow induced vibration requirement from MSFC-DMG-20M02540 to MSFC-SPEC-3746. MSFC-SPEC-3746 provides a more current set of requirements for controlling flow induced vibration for metal bellows and flexhoses. Updated ANSI/AIAA pressure vessel requirements to the latest revisions (S-080A and S-081B). **Section 3.2**: Added a definition for Maximum Design Pressure. This definition was inadvertently removed during the last standard revision. Added a definition for Stress Concentration. **Section 5.**: Added section 5.10 (Brittle Static Failure Mode) to address near brittle materials where static strength could be affected by a preexisting material flaw. **Section 5.1**: Added a reference to Appendix C which provides guidance language for controlling and verifying MDC loads. **Section 5.2**: Added guidance/rationale statements relative to minimum fatigue and creep properties. **Section 6.3**: Revised the requirement to the latest metal

DOCUMENT HISTORY LOG (Continued)

Status	Document Revision	Change Number	Approval Date	Description
				bellows and flexhose requirement per MSFC-SPEC-3746. **Section 8.2**: Added guidance text to help engine developers understand the fatigue requirements. **Section 9.3**: Added guidance text to clarify how the provider should correlate models.

FOREWORD

This NASA Technical Standard is published by the National Aeronautics and Space Administration (NASA) to provide uniform engineering and technical requirements for processes, procedures, practices, and methods endorsed as standard for NASA programs and projects, including requirements for selection, application, and design criteria of an item.

This Standard establishes the strength and life (fatigue and creep) requirements for NASA liquid-fueled space propulsion system engines. This Standard specifically defines the minimum factors of safety (FOS) to be used in analytical assessment and test verification of engine hardware structural integrity.

For additional information on this standard, submit a request via "Email Feedback" at https://standards.nasa.gov.

Original Signed by:
Joseph W. Pellicciotti
NASA Chief Engineer

12/31/2025___
Approval Date

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STRENGTH AND LIFE ASSESSMENT REQUIREMENTS FOR LIQUID-FUELED SPACE PROPULSION SYSTEM ENGINES

1. SCOPE

This NASA Technical Standard provides strength and life assessment requirements for NASA liquid-fueled space propulsion system engines. The term "life," as used in this NASA Technical Standard, refers to fatigue and creep. The requirements address analyses and tests to qualify an engine structurally. Engine hot-fire test requirements are not addressed in this standard; however, this standard does require that a minimum number of such tests are to be conducted in conjunction with structural analyses and tests to qualify the engine structurally.
These requirements define the minimum structural requirements acceptable to NASA. These requirements specify analyses and test factors, margins, and other parameters, where appropriate. In some cases, these requirements are expressed by reference to other NASA Technical Standards.

1.1 Purpose

This Standard provides a consistent set of requirements to be used in designing and assessing liquid-fueled space propulsion system engines. These requirements are intended to provide strength and life criteria that, in conjunction with other good engineering practices, will assist the program in meeting engine performance goals.

1.2 Applicability

1.2.1 This Standard is applicable to liquid-fueled engine hardware used for NASA spaceflight missions. For the purposes of this standard gas-gas thrusters are included as liquid engines. The engine system generally encompasses components from the engine inlet flanges to the thrust nozzle, including ancillary interfaces that connect to the vehicle. The engine project normally defines the engine system components in the engine specifications. This Standard presents acceptable minimum factors of safety (FOS) for use in analytical assessment and test verification of the flight hardware structural integrity.

In general, no distinction is made between engines used in crewed or uncrewed applications. Engines for flight systems transporting personnel are subjected to additional verification and/or safety requirements (such as fracture control) that are consistent with the established risk levels for mission success and flight crew safety.

1.2.2 This Standard is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers; applicable technical requirements may be cited in contract, program, and other Agency documents. This language applies to the Jet Propulsion Laboratory (a Federally Funded Research and Development Center), other contractors, recipients of grants, cooperative agreements, or other agreements only to the extent specified or referenced in the applicable contracts, grants, or agreements.

1.2.3 References to “this Standard” refer to NASA-STD-5012C; references to other documents state the specific document information.

1.2.4 Verifiable requirement statements are designated by the acronym “PSER” (Propulsion System Engine Requirement), numbered, and indicated by the word “shall. This Standard contains 28 requirements. To facilitate requirements selection by NASA programs and projects, a Requirements Compliance Matrix is provided in Appendix A. Explanatory or guidance text is indicated in italics beginning in section 4.

1.2.5 Explanatory or guidance text is indicated in italics beginning in section 4. In this Standard, all mandatory actions (i.e., requirements) are denoted by statements containing the term “shall.” The terms “may” denotes a discretionary privilege or permission, “can” denotes statements of possibility or capability, “should” denotes a good practice and is recommended but not required, “will” denotes expected outcome, and “are/is” denotes descriptive material.

1.3 Tailoring

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

2. APPLICABLE DOCUMENTS

2.1 General

2.1.1 Documents listed in this section contain provisions constituting requirements of this Standard as cited in the text. Latest issuances of cited documents apply unless specific versions are designated. Obtain approval from the delegated NASA Technical Authority to use a version other than as designated.

2.1.2 Access applicable documents at https://standards.nasa.gov or obtain documents directly from the Standards Developing Body, other document distributors, information provided or linked, or by contacting the office of primary responsibility for this Standard.

Note: References are provided in Appendix B.

2.2 Government Documents

Department of Defense

SSCMAN 91-710**,** Range Safety User Requirements Manual

Marshall Space Flight Center (MSFC)

MSFC-SPEC-3746**,** Flow-Induced Vibration Assessment Requirements for Metal Bellows and Flexhoses

NASA

NPR 7120.5**,** NASA Space Flight Program and Project Management Requirements

NASA-STD-5001A, Structural Design and Test Factors of Safety for Spaceflight Hardware

NASA-STD-5005**,** Standard for the Design and Fabrication of Ground Support Equipment

NASA-STD-5019 **,** Fracture Control Requirements for Spaceflight Hardware

NASA-STD-5020**,** Requirements for Threaded Fastening Systems in Spaceflight Hardware

NASA-STD-6016**,** Standard Materials and Processes Requirements for Spacecraft

2.3 Non-Government Documents

American Institute of Aeronautics and Astronautics (AIAA)

ANSI/AIAA S-080A-2018**,** Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components

ANSI/AIAA S-081B-2018**,** Space Systems – Composite Overwrapped Pressure Vessels (COPVs)

2.4 Order of Precedence

2.4.1 The requirements and standard practices established in this Standard do not supersede or waive existing requirements and standard practices found in other Agency documentation.

2.4.2 Conflicts between this Standard and other requirements documents will be resolved by the delegated NASA Technical Authority.

3. ACRONYMS, ABBREVIATIONS, AND DEFINITIONS

3.1 Acronyms, Abbreviations, and Symbols

AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
COPV	composite overwrapped pressure vessel

DWG	drawing
E	modulus of elasticity
ECF	environmental correction factor
ERG	Energetics Research Group
FAF	fatigue analysis factor
FEA	finite element analysis
FOS	factor of safety
FSE	flight support equipment
ft-lb	foot-pound(s)
Ftu	material ultimate tensile strength
Fty	material yield tensile strength
GSE	ground support equipment
HCF	high-cycle fatigue
J	Joule(s)
kPa	kilopascal(s)
LCF	low-cycle fatigue
MDC	maximum design condition
MDP	maximum design pressure
MEOP	maximum expected operating pressure
MMPDS	Metallic Materials Properties Development and Standardization
MS	Margin of Safety
MSFC	Marshall Space Flight Center
NA	not applicable
NASA	National Aeronautics and Space Administration
NPR	NASA Procedural Requirements
PSER	propulsion system engine requirements
psia	pound(s) per square inch absolute
SAP	Structural (Strength and Life) Assessment Plan
SI	Système Internationale or metric system of measurement
S-N	stress versus cycles to failure
SP	special publication
SPEC	specification
SSCMAN	Space Systems Command Manual
STD	standard

3.2 Definitions

Acceptance Test: A structural or pressure test conducted on the flight article to levels higher than maximum design condition (MDC), maximum expected operating pressure (MEOP), etc., to verify material quality and workmanship.

Buckling and Crippling: The propensity of a structure to collapse under loads less than the material ultimate strength because of load and geometry-induced lateral instability.

Burst Factor: A multiplying factor applied to the maximum design pressure (MDP) to obtain the burst pressure.

Burst Pressure: The minimum pressure level at which rupture of the pressurized hardware occurs.

Creep: A time-dependent deformation under load and thermal environments that results in cumulative, permanent deformation.

Design Service Life: See "Service Life."

Detrimental Yielding or Deformation: Yielding/deformation/deflections that adversely affect the form, fit, and function or integrity of the structure.

Development Test: A structural test (such as a pressure test) conducted on components to assess design concepts and guide the design.

Engine: Generally includes the nozzle, thrust chamber, pumps, and "local" valves, regulators, plumbing, etc., unless otherwise defined by program and/or contract.

Factor of Safety (FOS): A multiplying factor to be applied to MDC, MDP, etc., loads or stresses for analytical assessment (design factor), or test verification (test factor) of design adequacy in strength or stability.

Failure: Rupture, collapse, excessive deformation, or any other phenomenon resulting in the inability of a structure to sustain specified loads, pressures, and environment or to function as designed.

Fatigue: In materials and structures, the cumulative irreversible damage incurred by the cyclic application of loads and environments. Fatigue can initiate cracking and cause degradation in the strength of materials and structures. Generally considered in two regimes high cycle fatigue (HCF) characterized by low amplitude high cycle count in the elastic range, and low cycle fatigue (LCF) characterized by high amplitude low cycle count in the plastic range.

Fatigue Analysis Factor (FAF): A factor to compensate for large changes in life that occur because of small changes in stress. It is applied to the limit stress/strain before entering the stress/strain versus cycles to failure design curve to determine the fatigue life.

Ftu: Material ultimate tensile strength.

Fty: Material yield tensile strength.

Hazard: A condition that is likely to result in personnel injury or catastrophic failure of an engine, vehicle, payload, or facility.

Hot-Fire Test: A test of the engine propulsion systems and components by an actual firing of the engine, simulating flight conditions.

Limit Load: The maximum anticipated load, or combination of loads that a structure may experience during its design service life under all expected conditions of operation. For engine systems, this is referred to as the MDC load.

Liquid-Fueled Engine: An engine system in which the propellants are delivered to the engine in a liquid phase, regardless of thermodynamic state, for the purposes of providing thrust to the vehicle or spacecraft. For the purposes of this standard gas-gas thrusters are included as liquid engines.

Margins of Safety (MS): The fraction by which "allowable strength" exceeds the "applied load" that has been multiplied by the FOS.

$$MS = \frac{\text{Allowable Load}}{\text{(Applied Load) (FOS)}} - 1$$

where:

MS	=	margin of safety
Allowable Load	=	allowable load, pressure, stress, strain, or deflection
Applied Load	=	actual load, pressure, stress, strain, or deflection at MDC
FOS	=	factor from Table 1, Minimum Analysis FOS and Strength Test Factors

Maximum Design Condition (MDC): The most severe environment specified for the engine and its components.

Maximum Design Condition Load(s): The maximum design condition for each component should be the most critical condition, considering all loads and combinations of loads and environments that the engine and its components are expected to experience and survive without failure. All phases in the life of the hardware, including fabrication, assembly, testing, transportation, ground handling, checkout, firing, launch, flight, return, etc., are to be considered in defining the MDC load. When various types of loads from different sources occur simultaneously, combine these loads, as applicable, for establishing the MDC load. Load types to be considered include mechanical and displacement driven (steady-state and transient). Mechanical loads include forces, moments, and pressures which are load driven. Displacement driven loads include pre-loads, thermal expansion driven loads/stresses/strains, and misalignment loads, etc. The pressures may be Maximum Expected Operating Condition (MEOP) or Maximum Design Pressure (MDP), as applicable and determined with consideration of program failure tolerance requirements in determining the maximum pressure. Mechanical loads may be static, quasi-static, sinusoidal, transient, shock, impact, vibratory, acoustic, or random. See Appendix C for guidance in determining this load condition.

Maximum Design Pressure (MDP): The highest pressure defined by maximum relief pressure, maximum regulator pressure, or maximum temperature. Transient pressures should be considered in terms of structural response. Where pressure regulators, relief devices, and/or a thermal control system, e.g., heaters, are used to control pressure, collectively they are to be fault tolerant from causing the pressure to exceed the system's MDP per program failure tolerance requirements. The effects of maximum ullage pressure, fluid head related to vehicle quasi-static and dynamic accelerations, slosh, pressure transients and oscillations, temperature, and operating variability of regulators or relief valves are included in the MDP. When determining MDP, the maximum temperature to be experience pre-launch or post-landing is to be considered including abort to sites without active cooling. When MDP is not clearly limited by a pressure control system such as a combustion chamber or similar zero fault tolerant components the MEOP is used as the MDP.

Maximum Expected Operating Pressure (MEOP): The maximum pressure which pressurized hardware is expected to experience during its service life, in association with its applicable operating environments. MEOP includes the effects of temperature, transient peaks, and vehicle acceleration.

Net-Section Failure: A ductile mode of failure in which the net cross section loses its capability to sustain the mechanical load. The applied mechanical load is checked against the net-section failure load. (Refer to Table 1, Minimum Analysis FOS and Strength Test Factors, in this Standard.)

Point-Strain Failure: A ductile mode of failure in which a crack is initiated at a point in the structure by local concentrated total (elastic plus plastic) strain related to MDC loads. The maximum total concentrated strain at a point related to MDC loads is checked against the ultimate strain capability. If significant, the capability should be reduced for effects of triaxial loading. (Refer to Table 1.)

Point-Stress Failure: A brittle mode of failure in which a crack is initiated at a point in the structure by local concentrated stress related to MDC loads. The maximum concentrated stress at a point related to MDC loads is checked against the ultimate stress capability. This failure mode was intended to address brittle materials not addressed by the point strain failure mode such as composites and bonded joints. (Refer to Table 1.)

Pressure-Loaded Component/Structure: A component/structure not intended to store a fluid under pressure but experiencing significant pressure loads that may be in addition to other mechanical and thermal loads. The pressure-loaded component/structure is generally considered to be part of the engine. Turbine blades, pump housings, main propellant lines/valves/bellows, and main combustion chambers are typical examples. These components are analyzed and tested using the factors in Table 1 for general metallic components and structures or for composite/bonded structures, as appropriate.

Pressure Vessel: A container designed primarily for pressurized storage of gases or liquids and also for carrying out one of the following:

a. Storing energy of 19,310 J (14,240 ft-lb), or greater, based on the adiabatic expansion of a perfect gas.

b. Holding a gas or liquid at an MDP in excess of 103.4 kPa (15 psia) that will create a hazard if released.

c. Having an MDP greater than 689.5 kPa (100 psia).

Pressurized System: An interrelated configuration of pressurized components and/or pressure vessels. For purposes of this Standard, a pressurized system is defined as a system on the engine that stores and/or supplies pressurized hydraulic/pneumatic/purge fluid or gas for the actuation of engine system components or other system functions. Thruster valves for pressure-fed engines are included in this definition. These systems are usually pressurized before engine start and potentially when personnel are present.

Proof Factor: A multiplying factor applied to the MDC load, MDP, etc., to obtain the proof load or proof pressure for use in a proof test.

Proof Test: A structural or pressure test conducted on the flight article to levels higher than MDC, MDP, etc., to verify material quality and workmanship. The terms “proof test” and “acceptance test” are interchangeable.

Qualification Test: A test conducted on a separate flight-like structural test article at levels higher than MDC loads and at the MDC environment to verify the design.

Quasi-Static Load: A time-varying load in which the duration, direction, and magnitude are significant, but the rate of change in direction or magnitude and the dynamic response of the structure are not significant.

Responsible Organization: The Government or contractor organization that is directly responsible for hardware strength and life assessment verification.

Safety Critical: A condition where failure would result in a catastrophic hazard.

Safety Factor: See “Factor of Safety.”

Service Life: All significant loading cycles or events during the period beginning with manufacture of a component and ending with completion of its specified use. Fabrication, testing, handling, transportation, liftoff, ascent, on-orbit operations, descent, landing, and post-landing events are to be considered in establishing the service life of a component.

Service Life Factor: A multiplying factor to be applied to service life to assess design adequacy in fatigue or creep.

Stress Concentration: An area of highly localized stress/strain caused by a geometric discontinuity (fillet, notch, significant composite ply dropout, etc.).

Structural Integrity: The ability of the structure to meet the structural requirements by analysis and/or test.

S-N: Stress versus cycles to failure data (most often a curve).

Ultimate Load: The product of the MDC load multiplied by the ultimate FOS.

Ultimate Strength: Corresponds to the maximum load or stress that a structure or material can withstand without incurring rupture, collapse, or cracking.

Yield Load: The product of the MDC load multiplied by the yield FOS.

Yield Strength: The maximum load or stress that a structure or material can withstand without incurring permanent deformation. (The 0.2-percent offset method is usually used to determine the load/stress.)

4. GENERAL REQUIREMENTS

[PSER 1] A Structural Assessment Plan (SAP) **shall** be submitted to the responsible NASA Technical Authority for review and approval that includes detailed analyses and tests designed to ensure that the engine will not experience structural failure during its service life and to ensure the structural integrity of all engine systems and components.

4.1 Documentation

[PSER 2] The following minimum documentation requirements **shall** be developed and submitted as part of the program/project documentation of the strength and life assessments:

a. A SAP specifying how the particular engine program plans to satisfy the requirements of this Standard (including any program-approved tailoring) and documenting the program's structural strength requirements being followed, approach used for material allowables (fatigue, creep, and deviations from section 5.2), property verification approaches, alternate approaches, and other structural-related information pertinent to the particular program/project.

b. Analyses and test reports documenting analyses and/or tests performed, including the following information, to provide the objective evidence that the hardware complies with program requirements:

(1) Strength and life analyses as well as development, qualification, and acceptance/proof-test reports that will verify the capability of hardware to meet mission requirements with the factor of safety (FOS) specified in this Standard and in the SAP.

(2) Sufficient detail in the reports so that the results can be re-created.

(3) All material properties, loads, and other data from external sources as a referenced data source.

(4) Submittal of test plans before the test that address the specific test objectives and success criteria.

(5) Test reports documenting the results of a test to address the success criteria and provide reasonable correlation to the analysis predictions.

c. A Final and As-Built Assessment Report documenting the final and as-built assessment of the flight hardware that includes the following, as a minimum:

(1) The assessment, using analyses and test results, establishing the flight worthiness of actual flight hardware.

(2) The assessment of significant deviations in materials, workmanship, etc., from the design, as well as analytical adjustment needed as indicated by test results.

(3) Updated margin of safety (MS) and life factors for the final and as-built configurations.

5. STRENGTH AND LIFE ASSESSMENTS

[PSER 3] Strength and life assessments (detailed analyses, tests, and their verification) for the engine system and all its components **shall** utilize the FOS specified in Table 1, Minimum Analysis FOS and Strength Test Factors, for assessment of safety margins and comply with the strength and life assessment requirements delineated in the subsequent sections of this Standard.

Table 1—Minimum Analysis FOS and Strength Test Factors

Engine Hardware Type	Factored Load (See Sec 5.1)	Mode of Failure	Analysis FOS[1]	Test Factors[2]	
				Qualification	Acceptance/ Proof[3]
Metallic Structures and Components[4]					
Yield	mechanical only	net section yield	1.10[5]	NA	NA
Ultimate	mechanical only	net section ultimate	1.40	1.40	NA
Ultimate	MDC	stability ultimate	1.40	1.40	1.20
Ultimate-pressure or rotation, test configuration	MDC pressure or spin stress	net section ultimate	1.50	1.50[6,7]	1.20[6,7]
Ultimate	MDC	point strain ultimate	2.0[8]	NA	NA
Pressure Vessels and Pressurized Systems[4]	MDC (Pressure only)	SSCMAN 91-710 and either ANSI/AIAA S-080A-2018 or ANSI/AIAA S-081B-2018			
Fasteners and Preloaded Joints					
Yield	MDC	net section yield	1.10[5]	NA	NA
Ultimate	MDC	net section ultimate	1.40	1.40	1.20
Joint Separation	MDC	separation[9]	1.20	1.20	1.20
Safety Critical	MDC	separation[9]	1.40	1.40	1.20
Composite and/or Bonded Structures and Components – Ultimate Strength		(Unless noted, failure mode is ultimate point stress or strain.)			
Uniform areas	MDC	point ultimate	1.40	1.40	1.20[6]
Stress concentration areas	MDC	point ultimate	2.00	1.40[6]	1.20[6]
Bonds/joints	MDC	net section ultimate	2.00	1.40[6]	1.20[6]
Ablatives	MDC	point ultimate	1.70[10]	1.40[6,10]	1.20[6]
Pressure Checkout with Personnel Present					
Yield	checkout pressure	[11]	1.50[5]	NA	NA
Ultimate	checkout pressure	[11]	2.00	NA	NA

Notes:
1. Margins are to be written using the specified analysis FOS for all the specified loads and modes of failure.
2. Minimum factors to be used in the test program are to be defined in the SAP for a specific project.
3. Fracture control may require higher factors if the proof test will be used for flaw screening.
4. Bellows and components used on pressurized systems, generally lines 2” in diameter or less, are to meet the pressurized systems requirements.
5. For material susceptible to sustained load failure, such as titanium alloys, see section 7.0 of this NASA Technical Standard.
6. These tests are always required. (See section 5.1.7 in this NASA Technical Standard for additional requirements for composite and bonded structures.)
7. Test pressure = MDP x Test_Factor)1.20 x ECF $\geq$ 1.05 x MDP.
   Test speed = $\sqrt{}$ (MDC_Speed^2 x 1.20*Test_Factor x ECF) $\geq$ $\sqrt{}$ (MDC_Speed^2 x 1.05)
8. Factor to be applied to strain at MDC limit load.
9. Separation is not limited to unacceptable leakage, but also loss or electrical continuity, thermal conductance, shift in natural frequency, or similar if it is detrimental to fit/form/function.

10. Analysis and test factors apply at end of life. Qualification test occurs on a hot-fired (fully ablated) flight-type test article.
11. Net section failure mode for metallics and point stress/strain failure mode on ultimate only for composites or adhesive bonds.

5.1 Strength Assessments

[PSER 4] Engine components **shall** be evaluated under maximum design condition (MDC) loads, with the specified load adjusted using the factors provided in Table 1.

For Mechanical Only load cases the intent is for Displacement-Driven MDC loads to receive an analysis FOS of 1.0 and for Mechanical MDC Loads to receive an analysis FOS as specified in Table 1 to combine to the factored MDC load. When linear analysis is used, MDC Displacement-Driven loads that are relieving to the Mechanical MDC loads should not be included. This is because in a ductile part/assembly, these loads/stresses may be dissipated due to plastic deformation before final net section ultimate failure. These Displacement-Driven MDC loads should be included when elastic-plastic finite element analysis is used with mechanical loads scaled by FOS in Table 1 or above to demonstrate/determine a positive margin of safety.

Appendix C provides guidance for ensuring the MDC loads have been captured and verified during engine development and qualification testing. It is recommended that providers review Appendix C to avoid development issues related to uncontrolled loading.

5.2 Material Properties for Analyses

[PSER 5] All material selection and material properties (strength, mechanical, fatigue, creep, etc.) **shall** meet the requirements in NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft, and the attributes below, as applicable:

These material selections and properties should correspond to the manufacturing processes and environments at which the structure sustains loads or be conservative with respect to the environments. Note NASA-STD-6016 refers to NASA-STD-6030 for additively manufactured materials.

a. Use typical or mean values for physical properties (modulus, thermal expansion, etc.).

b. Use minimum fatigue and creep properties derived by a NASA-approved statistical sampling process when assessing design structural capability.

For the severe material environments of liquid engines, fatigue and creep are primary design drivers requiring allowables that envelope the majority of the material scatter. The minimum fatigue curve works in conjunction with the Life Analysis section (section 8) of this Standard to ensure adequate fatigue life. Guidance provided in Metallic Materials Properties Development and Standardization (MMPDS) on obtaining fatigue and creep curves is geared toward developing a mean curve with minimal guidance on the number of samples required for each stress/strain level. The minimum fatigue curve requirement is intended to capture natural material-dependent scatter under the best *possible conditions (polished samples, laboratory controls, etc.). Since fatigue and creep statistical-based properties are not specifically addressed in NASA-STD-6016, it is expected that the engine contractor will present an approach, as part of the SAP, to detail how minimum fatigue curves are addressed in assessing fatigue margin.*

c. Consider all operational environments, including temperature, cyclic load, sustained load, and shock (both mechanical and thermal related to heating and chilling) in the material strength allowables to be used.

d. Address and account for the sensitivity of a component to fracture, embrittlement, stress corrosion, and any other degradation under the service conditions.

For reusable and multi-mission hardware, these criteria are applicable throughout the design service life and all of the missions. Material property degradation under the service environments is an important design consideration. NASA-STD-6016 provides these requirements.

e. Structural assessment of materials exhibiting 3 percent or less ductility are to be documented in the SAP to address the brittle failure modes of the material.

5.3 Ground Support Equipment (GSE) and Flight Support Equipment (FSE)

[PSER 6] NASA-STD-5005, Standard for the Design and Fabrication of Ground Support Equipment, and NASA-STD-5001A, Structural Design and Test Factors of Safety for Spaceflight Hardware, **shall** be used in the design of engine ground support equipment (GSE) and flight support equipment (FSE) respectively.

NASA-STD-5005 and NASA-STD-5001A establish general characteristics, performance, design, test, safety, reliability, maintainability, and quality requirements for engine GSE and FSE that are delivered to NASA.

5.4 Transportation and Flight Structures

In general, transportation and handling equipment should be designed such that flight structures are not subjected to loads more severe than flight design conditions.

[PSER 7] Structural assessment of the engine system **shall** account for transportation and handling loads along with the steady-state loads plus dynamic, vibration, and shock loads, as appropriate.

5.5 Design and Analysis: Dimensional Tolerance

[PSER 8] Dimensions used in strength and life calculations **shall** be chosen using the tolerance specified so that the calculated margin is the minimum possible for the design.

Actual as-built dimensions may be used in strength and life assessments when available.

5.6 Weld and Braze Joints

[PSER 9] Welds and braze joints **shall** comply with the following items in addition to other applicable strength assessment requirements:

a. Include the bead stress concentrations, parent material misalignment/offsets, and residual stresses, as applicable, in stress levels related to weld/braze.

b. Modify weld/braze joints (strength, fatigue, creep, etc.) properties by the weld/braze joint efficiency factor based upon the classification (and/or process verification) of the joint. These factors will vary based on the manufacture material selection, process, inspection method, etc.

c. Structural spot welds are not permitted unless consumed by a structural weld because of inherent problems with spot weld inspections and reliability.

5.7 Composite and Bonded Structures

[PSER 10] When assessing composite and bonded structures, the assessment **shall** comply with the following attributes:

a. Use the safety and test factors for composite and bonded structures as specified in Table 1.

b. Perform proof tests of all flight units made of composite and bonded structures.

c. Document in the SAP any reduction in proof test factors if the acceptance proof test has the potential to damage fibers.

d. Include the effect of temperature, both higher and lower than nominal, in assessing the strength of composite or bonded structure’s adhesive.

Additional information concerning the processing and inspection of adhesive joints can be found in MSFC-SPEC-445, Adhesive Bonding, Process and Inspection, Requirements for.

e. Perform a series building block of tests to produce strength allowables for geometric discontinuities, such as inserts, using flight-like geometric configuration, and materials to show the manufacturing process is reliable and repeatable. Use a building block approach integrated with full scale testing in section 9.

f. Identify in the SAP the methods for assessing the strength of inserts in nonmetallic/composite structures, as they are special cases of bonded structures.

5.8 Buckling and Crippling

[PSER 11] To meet buckling and crippling assessment requirements, designs **shall** comply with the following attributes:

a. Consider buckling failure modes for all structural components that are subject to compressive and/or shear in-plane stresses under any combination of ground loads, flight loads, or loads resulting from temperature changes.

b. Use appropriate "knockdown factors" (correlation coefficients) to account for the difference between classical theory and empirical instability loads in analyses of buckling of thin-walled shells.

Typical knockdown factors are listed in NASA-SP-8007, Buckling of Thin-Walled Circular Cylinders.

c. When using nonlinear finite element analyses (FEAs) for buckling analysis, include material nonlinearities, geometric imperfections, local geometric features, manufacturing details, etc., which adversely affect the stability of the structure.

d. Check that structural members that are subject to instability will not collapse under ultimate loading using the selected analysis method.

e. Check to assure non-detrimental buckling loading will not degrade the functioning of any system or produce unaccounted for changes in loading.

f. Include the combination of all loads from any source and their effects on general instability, local instability, and crippling when evaluating buckling strength.

g. Assure that Ultimate Design loads for collapse have the following attributes:

(1) Ultimate Design loads (loads factored by ultimate FOS) do not include load components that tend to alleviate buckling in developing ultimate FOS such that only destabilizing loads (external pressure, thermal loads, torsional limit loads, etc.) have been increased by the ultimate FOS.

(2) The minimum load has been used to assess the buckling margin in cases where a load alleviates buckling.

5.9 Fasteners and Preloaded Joints

[PSER 12] For assessing fasteners and preloaded joints, designs **shall** comply with the following attributes:

a. Use NASA-STD-5020, Requirements for Threaded Fastening Systems in Spaceflight Hardware, for bolt design and joint separation in preloaded joints and document alternative methods to NASA-STD-5020 in the SAP.

b. Use design and test factors for fasteners and preloaded joints as specified in Table 1.

5.10 Brittle Static Failure Mode

[PSER 13] Engine components made of brittle materials (elongation <3%) **shall** be assessed for susceptibility to static strength reduction due to preexisting material flaws per NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware.

The other requirements in this standard generally assume failure modes consistent with ductile materials, but this requirement is intended to ensure brittle material failure modes, which can lead to sudden catastrophic engine failure, are adequately screened for static strength based on the content of NASA-STD-5019. This requirement is not intended to implement fracture beyond the brittle material or component.

6. PRESSURIZED HARDWARE

6.1 Design Requirements for Pressure Vessels and Pressurized Systems

[PSER 14] The design organization **shall** design engine system pressure vessels and pressurized systems in accordance with SSCMAN 91-710, Range Safety User Requirements Manual, ANSI/AIAA S-080A-2018, Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components, and ANSI/AIAA S-081B-2018, Space Systems – Composite Over Wrapped Pressure Vessels (COPVs), as applicable, in addition to the requirements in this Standard.

Fracture control requirements contained in these documents should be met and in conjunction with NASA-STD-5019 when levied.

6.2 Pressure-Loaded Components and Structures

In general, pressure-loaded components and structures as defined in this Standard are not considered pressure vessels. By definition, a pressure vessel is a container used to store pressurized fluid at specific energy or pressure levels or fluid that would be hazardous if released. Liquid-fuel engine components, such as main combustion chambers, high-pressure pumps, main propellant lines/bellows, and valves, etc., are not considered to be storage containers, so these components are not classified as pressure vessels. Such components are defined as pressure-loaded components.

[PSER 15] All of the following attributes for pressure-loaded components and structures **shall** be complied with:

a. Design pressure-loaded components and structures using MDC loads.

b. Design compartments or volumes that can become inadvertently pressurized as a result of a credible single-seal failure as a pressure-loaded component.

In the case of redundant seals, propagation of failure by the same mechanism may be considered highly unlikely beyond the redundant seal(s). The redundant seal(s) are required to have been acceptance tested (e.g., leak checked-See NASA-STD-7012) individually before flight and meet the requirements contained in this Standard.

6.3 Flexible Hoses and Bellows

[PSER 16] All of the following attributes for flexible hoses and bellows in the engine system **shall** be complied with:

a. Design all flexible hoses and bellows to exclude flow-induced vibrations in accordance with MSFC-SPEC-3746, Flow-Induced Vibration Assessment Requirements for Metal Bellows and Flexhoses.

In cases where design constraints preclude meeting MSFC-SPEC-3746 or a design cannot be confidently assessed, an alternate approach should be addressed in the SAP and submitted for approval by the delegated NASA Technical Authority.

b. Meet the safety factors listed in Table 1 and the life assessment requirements in section 8 of this Standard for flexible hoses and bellows.

6.4 Pressure Combined with External Load

[PSER 17] All of the following attributes **shall** be complied with when pressure is combined with an external load:

a. In circumstances where pressure loads have a relieving or stabilizing effect on structural load-carrying capability (e.g., injector interpropellant plate), use the minimum value of such relieving loads and do not multiply pressure loads by the safety factor in developing the design yield or ultimate load.

b. Meet the FOS for combined load conditions as specified in Table 1.

7. OTHER REQUIREMENTS

For some applications, it may be appropriate and required to use additional design considerations/factors such as fitting factors, casting factors, brazed/welded/bonded joints, impact factors, etc., in conjunction with the FOS specified in Table 1.

[PSER 18] Planned use of additional design considerations/factors **shall** be documented in the SAP and the following design factors utilized when applicable:

a. Use manufacturing-related factors (such as fitting factors, casting factors, weld/braze factors, additively manufactured factors (see NASA-STD-6030) in conjunction with the factors listed in Table 1.

b. Use a FOS of 1.4 on MDC loads for MS calculations intended to prevent impact such as an engine fully gimbaled, i.e., the clearance is to be zero or positive at 1.4×MDC loads.

c. Calculate MS on performance-driven clearances (for example, in turbomachinery) using an FOS of 1.0 to minimize performance impacts.

d. Use a maximum peak stress less than 80 percent of the material minimum yield strength for materials susceptible to sustained load rupture such as certain titanium alloys.

e. Accept local yielding of the engine structure when all the following conditions are met:

(1) The structural integrity of the component is demonstrated by adequate analysis and/or test.

(2) No detrimental deformations exist that adversely affect the component/system fit, form, or function.

(3) The service life requirements in section 8 of this Standard are met.

8. LIFE ANALYSIS

8.1 [PSER 19] Fatigue life assessments, including creep, **shall** be made using the load history and the material properties corresponding to the environment for all engine system components, including the following criteria:

a. Account for the number of cycles and/or time at each load level, considering all phases of fabrication, assembly, testing, transportation, ground handling, checkout, firing, launch, flight, return, etc.

b. Include the complete loading history, including low-cycle and high-cycle fatigue loads, sustained loads, preloads, assembly loads, and as appropriate, mean loading.

c. Include all loads from mechanical, thermal, pressure, and other sources, as appropriate.

d. Select materials that preclude cumulative strain damage as a function of time, i.e., creep.

Creep damage could result in rupture, detrimental deformation, or collapse, e.g., buckling, of compression members during the design service life.

e. If selecting a structural material that exhibits creep phenomena in the engine environment is unavoidable, assess all structural elements subject to creep to demonstrate the following factors:

(1) Creep Analysis Factor: The limit stress or strain multiplied by a minimum factor of 1.15 before entering the design curve to determine creep life.

(2) Service Life Factor: The analysis demonstrates a minimum calculated life of 10.0 times the service life.

8.2 [PSER 20] The engine and its components **shall** be assessed for low-cycle fatigue (LCF) and high-cycle fatigue (HCF) using the following criteria:

a. Methods of combining fatigue damage for cyclic loads to varying levels are documented in the SAP and approved by the delegated NASA Technical Authority.

b. Use standard methods such as the Modified Goodman Line for alternating loads combined with mean loads to determine the combined effect.

c. Use the following factors for assessing HCF and LCF life:

(1) Fatigue Analysis Factor (FAF) multiplied by the limit stress or strain before entering the life design curve to determine the low-cycle or high-cycle life. Factor to be used:

i. FAF = 1.25 rotating components
ii. FAF = 1.15 non-rotating components.

(2) Service Life Factor:

i. The LCF analysis to demonstrate a minimum calculated life of 4.0 times the service life.
ii. The HCF analysis to demonstrate a minimum calculated life of 10.0 times the service life.

(3) Stress Concentrations: The alternating and mean stress/strain are to include the effects of stress concentration factors when applicable.

Due to the dynamic stress uncertainty and the normal manufacturing variability (surface finish, dimensions, etc.), designing a part with adequate life can be a challenging task. Given these uncertainties, implementing strategies such as FAF and service life factors have been used in this Standard to ensure adequate fatigue margin. The service life factors and FAFs are both required for fatigue assessment. The service life factors provide better sensitivity in the LCF regime and the FAFs provide better sensitivity in the HCF regime. Rotating components *have elevated factors due to the increased likelihood of not completely capturing a fluid loading response or mechanical vibration (rotodynamic, etc.).*

8.3 [PSER 21] All structural components subject to combined fatigue and creep **shall** be evaluated using standard methods for accumulated damage.

8.4 [PSER 22] Methods for determining the final life predictions accounting for accumulated damage **shall** be recorded in the SAP and approved by the delegated NASA Technical Authority.

9. TESTING

Strength, fatigue, and hot-fire testing are required for the engine system and components such as turbomachinery, pressure vessels, and major load-carrying structures. Component-level vibroacoustic, acoustic and shock testing is performed per SMC-S-016, Test Requirements for Launch, Upper-Stage and Space Vehicles, in addition to other testing specified herein. Engine developers should use these tests to screen for workmanship and fleet-wise issues (mostly related to valves, sensors, mechanisms, etc.). These tests are required to be specified in the SAP.

9.1 Test Plan

[PSER 23] A detailed structural strength test plan for development, qualification, acceptance or proof, and hot-fire tests addressing the following attributes **shall** be developed by the design organization and included in the SAP:

a. Ensure that all testing complies with test factors specified in Table 1 and in appropriate sections of this Standard, if any.

b. Ensure that the interfacing structure through which the loads and reactions are applied to the test unit has been simulated in the test at the component level or through analysis.

9.2 Development Tests

[PSER 24] Development tests **shall** be conducted to provide confidence of new engine designs or concepts. These tests are expected for brittle materials and composites which use point stress failure modes in Table 1.

Tests during this phase provide confidence that the new design will accomplish mission objectives. While development test factors are not specified in Table 1, these tests are expected to be of levels that identify weaknesses in materials and deficiencies of the designs. In addition, development fatigue tests are used to guide the design. Levels and duration should be sufficiently severe to identify any credible weaknesses and provide confidence that the final design will pass qualification.

Generally, development tests do not suffice for qualification tests unless the tests fulfill all of the qualification test requirements.

9.3 Qualification Tests

[PSER 25] Qualification tests **shall** be conducted at conditions (level and duration) more severe than flight conditions to verify that flight-configured hardware meets strength requirements and will perform satisfactorily in the flight environments with margin consistent with those specified in this Standard assuring that:

a. There is no detrimental yielding at the MDC yield load and no failure at the MDC ultimate load.

b. The test article is instrumented appropriately for load, strain, and deflection.

Use engineering judgment to determine which components will undergo correlation and how they will be instrumented. The correlation plan should be outlined in the SAP and coordinated with the delegated NASA Technical Authority

c. Structural analysis is correlated to the test results and, if un-conservative results are indicated, the analysis assumptions revisited, and the final analysis re-evaluated.

d. Conduct qualification tests in the operational environment or account for the operational environment through use of an Environmental Correction Factor (see section 9.5.1 in this Standard).

e. If the engine is expected to operate with instabilities (combustion, rotodynamic, etc.) these are expected to be fully excited as part of qualification.

Qualification fatigue tests may be required if analysis in accordance with section 8 of this Standard cannot be confidently accomplished. Components such as engine electronic controllers and small thrusters may fall into this category. These tests are conducted on flight-configured hardware and in the appropriate flight environment. The component should be tested at the MDC alternating and mean stresses for four times the number of cycles established in section 8 of this Standard.

Hot-fire engine tests are also required to qualify the engine for service life.

9.4 Hot-Fire Tests

[PSER 26] Hot-fire engine tests required to qualify the engine for service life **shall** meet the following criteria and be documented in the SAP:

a. For pump-fed engine systems, in addition to component level strength/acceptance tests, perform hot-fire engine system tests for twice the expected service life on six engines/components/units that are structurally equivalent to the flight hardware.

The requirement for six engines has evolved from several successful manned pump-fed engine programs. The multiple engines requirement is intended to capture engine-to-

engine process variation that affects the structural performance. Clean-sheet, complex engine systems in preproduction phase, or low stable production engine numbers (samples) are unlikely to be well represented by a stationary ergodic statistical model meaning reliability-based approaches (Weibull analysis etc.) are not appropriate. Heritage engines may be able to leverage past unit success with approval from the delegated NASA Technical Authority. Hot-fire qualification engines typically exceed two times the service life requirement and are included in the six engines.

(1) If the developer wants to test fewer than six units, provide documented technical rationale from the developer to the delegated NASA Center Engineering Technical Authority and obtain approval before committing to the reduced test program.

b. For pressure-fed engines, in addition to component level strength/acceptance tests, a minimum of one qualification unit is required. Perform hot fire engine system tests for twice the expected service life on engines/components/units that are structurally equivalent to the flight hardware.

A single qualification unit for pressure fed engines is based on the hardware being derived from a heritage design. New designs, designs with significant changes from heritage, or uses in high value or crewed missions should have more qualification units as negotiated by the technical authority.

c. Post hot fire inspection of each unit is expected to verify no fatigue crack initiation, detrimental yielding, or other deleterious effects (rubbing, seal cracking, erosion, etc.)

9.5 Acceptance or Proof Tests

9.5.1 [PSER 27] All engine pressure vessels, pressurized components, major pressure-loaded components, and major rotating hardware **shall** be acceptance/proof-tested to the proof factors in Table 1 to ensure satisfactory workmanship and material quality and comply with the following criteria:

a. Perform proof (spin, pressure, or load) tests for all brazed, welded, composite, or bonded structures.

b. In cases where there are significant load conditions in addition to pressure, conduct a combined proof-pressure and external-loading test or increase the test pressure to encompass all loads. The resulting stress state from the increased test pressure should reasonably match the combined load flight case.

c. Perform nondestructive evaluation before and after proof testing.

d. Design parts so that no detrimental yielding occurs during proof tests and so that proof loads are limited to 95 percent on net-section yield and 80 percent on net-section ultimate.

e. Conduct proof tests in the operational environment or account for the operational environment through use of an Environmental Correction Factor (ECF):

$$\mathbf{ECF} = \frac{\textbf{Strength capability at test condition}}{\textbf{Strength capability at MDC temperature}}$$

If testing in the operational environment is not feasible, tests can be performed in a non-operational environment if an ECF is applied. The ECF should assume the worst case MDC temperature for that loading. An ECF is a factor to be multiplied by the test load to compensate for the environmental effect on the strength (E, Fty, Ftu, etc.) capability at test conditions versus the operating condition.

9.5.2 [PSER 28] Each engine system shall receive an acceptance hot-fire test at nominal level(s) and duration with a reasonable post-test inspection to be considered structurally acceptable.

APPENDIX A: REQUIREMENTS COMPLIANCE MATRIX

A.1 PURPOSE

Due to the complexity and uniqueness of space flight, it is unlikely that all of the requirements in a NASA technical standard will apply. The Requirements Compliance Matrix below contains this Standard's technical authority requirements and may be used by programs and projects to indicate requirements that are applicable or not applicable. Enter "Yes" in the "Applicable" column if the requirement is applicable to the program or project or "No" if the requirement is not applicable to the program or project. The "Comments" column may be used to provide specific instructions on how to apply the requirement or to specify proposed tailoring.

Table 2—Requirements Identification Matrix

NASA-STD-5012C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.	General Requirements	[PSER 1] A Structural Assessment Plan (SAP) **shall** be submitted to the responsible NASA Technical Authority for review and approval that includes detailed analyses and tests designed to ensure that the engine will not experience structural failure during its service life and to ensure the structural integrity of all engine systems and components.		
4.1	Documentation	[PSER 2] The following minimum documentation requirements **shall** be developed and submitted as part of the program/project documentation of the strength and life assessments: a. A SAP specifying how the particular engine program plans to satisfy the requirements of this Standard (including any program-approved tailoring) and documenting the program's structural strength requirements being followed, approach used for material allowables (fatigue, creep, and deviations from section 5.2), property verification approaches, alternate approaches, and other structural-related information pertinent to the particular program/project. b. Analyses and test reports documenting analyses and/or tests performed, including the following information, to provide the objective evidence that the hardware complies with program requirements:		

NASA-STD-5012C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
		(1) Strength and life analyses as well as development, qualification, and acceptance/proof-test reports that will verify the capability of hardware to meet mission requirements with the factor of safety (FOS) specified in this Standard and in the SAP. (2) Sufficient detail in the reports so that the results can be re-created. (3) All material properties, loads, and other data from external sources as a referenced data source. (4) Submittal of test plans before the test that address the specific test objectives and success criteria. (5) Test reports documenting the results of a test to address the success criteria and provide reasonable correlation to the analysis predictions. c. A Final and As-Built Assessment Report documenting the final and as-built assessment of the flight hardware that includes the following, as a minimum: (1) The assessment, using analyses and test results, establishing the flight worthiness of actual flight hardware. (2) The assessment of significant deviations in materials, workmanship, etc., from the design, as well as analytical adjustment needed as indicated by test results. (3) Updated margin of safety (MS) and life factors for the final and as-built configurations.		
5.	Strength and Life Assessments	[PSER 3] Strength and life assessments (detailed analyses, tests, and their verification) for the engine system and all its components **shall** utilize the FOS specified in Table 1, Minimum Analysis FOS and Strength Test Factors, for assessment of safety margins and comply with the strength and life assessment requirements delineated in the subsequent sections of this Standard.		

NASA-STD-5012C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
5.1	Strength Assessments	[PSER 4] Engine components **shall** be evaluated under maximum design condition (MDC) loads, with the specified load adjusted using the factors provided in Table 1.		
5.2	Material Properties for Analyses	[PSER 5] All material selection and material properties (strength, mechanical, fatigue, creep, etc.) **shall** meet the requirements in NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft, and the attributes below, as applicable: a. Use typical or mean values for physical properties (modulus, thermal expansion, etc.). b. Use minimum fatigue and creep properties derived by a NASA-approved statistical sampling process when assessing design structural capability. c. Consider all operational environments, including temperature, cyclic load, sustained load, and shock (both mechanical and thermal related to heating and chilling) in the material strength allowables to be used. d. Address and account for the sensitivity of a component to fracture, embrittlement, stress corrosion, and any other degradation under the service conditions. e. Structural assessment of materials exhibiting 3 percent or less ductility are to be documented in the SAP to address the brittle failure modes of the material.		
5.3	Ground Support Equipment (GSE) and Flight Support Equipment (FSE)	[PSER 6] NASA-STD-5005, Standard for the Design and Fabrication of Ground Support Equipment, and NASA-STD-5001A, Structural Design and Test Factors of Safety for Spaceflight Hardware **shall** be used in the design of engine ground support equipment (GSE) and flight support equipment (FSE) respectively.		
5.4	Transportation and Flight Structures	[PSER 7] Structural assessment of the engine system **shall** account for transportation and handling loads along with the steady-state loads plus dynamic, vibration, and shock loads, as appropriate.		
5.5	Design and Analysis: Dimensional Tolerance	[PSER 8] Dimensions used in strength and life calculations **shall** be chosen using the tolerance specified so that the calculated margin is the minimum possible for the design.		

NASA-STD-5012C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
5.6	Weld and Braze Joints	[PSER 9] Welds and braze joints **shall** comply with the following items in addition to other applicable strength assessment requirements: a. Include the bead stress concentrations, parent material misalignment/offsets, and residual stresses, as applicable, in stress levels related to weld/braze. b. Modify weld/braze joints (strength, fatigue, creep, etc.) properties by the weld/braze joint efficiency factor based upon the classification (and/or process verification) of the joint. These factors will vary based on the manufacture material selection, process, inspection method, etc. c. Structural spot welds are not permitted unless consumed by a structural weld because of inherent problems with spot weld inspections and reliability.		
5.7	Composite and Bonded Structures	[PSER 10] When assessing composite and bonded structures, the assessment shall comply with the following attributes: a. Use the safety and test factors for composite and bonded structures as specified in Table 1. b. Perform proof tests of all flight units made of composite and bonded structures. c. Document in the SAP any reduction in proof test factors if the acceptance proof test has the potential to damage fibers. d. Include the effect of temperature, both higher and lower than nominal, in assessing the strength of composite or bonded structure's adhesive. e. Perform a series building block of tests to produce strength allowables for geometric discontinuities, such as inserts, using flight-like geometric configuration, and materials to show the manufacturing process is reliable and repeatable. Use a building block approach integrated with full scale testing in section 9. f. Identify in the SAP the methods for assessing the strength of inserts in nonmetallic/composite structures, as they are special cases of bonded structures.		

NASA-STD-5012C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
5.8	Buckling and Crippling	[PSER 11] To meet buckling and crippling assessment requirements, designs **shall** comply with the following attributes: a. Consider buckling failure modes for all structural components that are subject to compressive and/or shear in-plane stresses under any combination of ground loads, flight loads, or loads resulting from temperature changes. b. Use appropriate “knockdown factors” (correlation coefficients) to account for the difference between classical theory and empirical instability loads in analyses of buckling of thin-walled shells. c. When using nonlinear finite element analyses (FEAs) for buckling analysis, include material nonlinearities, geometric imperfections, local geometric features, manufacturing details, etc., which adversely affect the stability of the structure. d. Check that structural members that are subject to instability will not collapse under ultimate loading using the selected analysis method. e. Check to assure non-detrimental buckling loading will not degrade the functioning of any system or produce unaccounted for changes in loading. f. Include the combination of all loads from any source and their effects on general instability, local instability, and crippling when evaluating buckling strength. g. Assure that Ultimate Design loads for collapse have the following attributes: (1) Ultimate Design loads (loads factored by ultimate FOS) do not include load components that tend to alleviate buckling in developing ultimate FOS such that only destabilizing loads (external pressure, thermal loads, torsional limit loads, etc.) have been increased by the ultimate FOS. (2) The minimum load has been used to assess the buckling margin in cases where a load alleviates buckling.		

NASA-STD-5012C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
5.9	Fasteners and Preloaded Joints	[PSER 12] For assessing fasteners and preloaded joints, designs **shall** comply with the following attributes: a. Use NASA-STD-5020, Requirements for Threaded Fastening Systems in Spaceflight Hardware, for bolt design and joint separation in preloaded joints and document alternative methods to NASA-STD-5020 in the SAP. b. Use design and test factors for fasteners and preloaded joints as specified in Table 1.		
5.10	Brittle Static Failure Mode	[PSER 13] Engine components made of brittle materials (elongation <3%) **shall** be assessed for susceptibility to static strength reduction due to preexisting material flaws per NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware.		
6.1	Design Requirements for Pressure Vessels and Pressurized Systems	[PSER 14] The design organization **shall** design engine system pressure vessels and pressurized systems in accordance with SSCMAN 91-710, Range Safety User Requirements Manual, ANSI/AIAA S-080A-2018, Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components, and ANSI/AIAA S-081B-2018, Space Systems – Composite Over Wrapped Pressure Vessels (COPVs), as applicable, in addition to the requirements in this Standard.		
6.2	Pressure-Loaded Components and Structures	[PSER 15] All of the following attributes for pressure-loaded components and structures **shall** be complied with: a. Design pressure-loaded components and structures using MDC loads. b. Design compartments or volumes that can become inadvertently pressurized as a result of a credible single-seal failure as a pressure-loaded component.		
6.3	Flexible Hoses and Bellows	[PSER 16] All of the following attributes for flexible hoses and bellows in the engine system **shall** be complied with: a. Design all flexible hoses and bellows to exclude flow-induced vibrations in accordance with MSFC-SPEC-3746, Flow-Induced Vibration Assessment Requirements for Metal Bellows and Flexhoses. b. Meet the safety factors listed in Table 1 and the life assessment requirements in section 8 of this Standard for flexible hoses and bellows.		

NASA-STD-5012C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
6.4	Pressure Combined with External Load	[PSER 17] All of the following attributes **shall** be complied with when pressure is combined with an external load: a. In circumstances where pressure loads have a relieving or stabilizing effect on structural load-carrying capability (e.g., injector interpropellant plate), use the minimum value of such relieving loads and do not multiply pressure loads by the safety factor in developing the design yield or ultimate load. b. Meet the FOS for combined load conditions as specified in Table 1.		
7.	OTHER REQUIREMENTS	[PSER 18] Planned use of additional design considerations/factors **shall** be documented in the SAP and the following design factors utilized when applicable: a. Use manufacturing-related factors (such as fitting factors, casting factors, weld/braze factors, additively manufactured factors (see NASA-STD-6030) in conjunction with the factors listed in Table 1. b. Use a FOS of 1.4 on MDC loads for MS calculations intended to prevent impact such as an engine fully gimbaled, i.e., the clearance is to be zero or positive at 1.4×MDC loads. c. Calculate MS on performance-driven clearances (for example, in turbomachinery) using an FOS of 1.0 to minimize performance impacts. d. Use a maximum peak stress less than 80 percent of the material minimum yield strength for materials susceptible to sustained load rupture such as certain titanium alloys. e. Accept local yielding of the engine structure when all the following conditions are met: (1) The structural integrity of the component is demonstrated by adequate analysis and/or test. (2) No detrimental deformations exist that adversely affect the component/system fit, form, or function. (3) The service life requirements in section 8 of this Standard are met.		

NASA-STD-5012C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
8.1	LIFE ANALYSIS	[PSER 19] Fatigue life assessments, including creep, **shall** be made using the load history and the material properties corresponding to the environment for all engine system components, including the following criteria: a. Account for the number of cycles and/or time at each load level, considering all phases of fabrication, assembly, testing, transportation, ground handling, checkout, firing, launch, flight, return, etc. b. Include the complete loading history, including low-cycle and high-cycle fatigue loads, sustained loads, preloads, assembly loads, and as appropriate, mean loading. c. Include all loads from mechanical, thermal, pressure, and other sources, as appropriate. d. Select materials that preclude cumulative strain damage as a function of time, i.e., creep. e. If selecting a structural material that exhibits creep phenomena in the engine environment is unavoidable, assess all structural elements subject to creep to demonstrate the following factors: (1) Creep Analysis Factor: The limit stress or strain multiplied by a minimum factor of 1.15 before entering the design curve to determine creep life. (2) Service Life Factor: The analysis demonstrates a minimum calculated life of 10.0 times the service life.		

NASA-STD-5012C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
8.2	LIFE ANALYSIS	[PSER 20] The engine and its components **shall** be assessed for low-cycle fatigue (LCF) and high-cycle fatigue (HCF) using the following criteria: a. Methods of combining fatigue damage for cyclic loads to varying levels are documented in the SAP and approved by the delegated NASA Technical Authority. b. Use standard methods such as the Modified Goodman Line for alternating loads combined with mean loads to determine the combined effect. c. Use the following factors for assessing HCF and LCF life: (1) Fatigue Analysis Factor (FAF) multiplied by the limit stress or strain before entering the life design curve to determine the low-cycle or high-cycle life. Factor to be used: i. FAF = 1.25 rotating components ii. FAF = 1.15 non-rotating components. (2) Service Life Factor: i. The LCF analysis to demonstrate a minimum calculated life of 4.0 times the service life. ii. The HCF analysis to demonstrate a minimum calculated life of 10.0 times the service life. (3) Stress Concentrations: The alternating and mean stress/strain are to include the effects of stress concentration factors when applicable.		
8.3	LIFE ANALYSIS	[PSER 21] All structural components subject to combined fatigue and creep **shall** be evaluated using standard methods for accumulated damage.		
8.4	LIFE ANALYSIS	[PSER 22] Methods for determining the final life predictions accounting for accumulated damage **shall** be recorded in the SAP and approved by the delegated NASA Technical Authority.		

NASA-STD-5012C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
9.1	Test Plan	[PSER 23] A detailed structural strength test plan for development, qualification, acceptance or proof, and hot-fire tests addressing the following attributes **shall** be developed by the design organization and included in the SAP: a. Ensure that all testing complies with test factors specified in Table 1 and in appropriate sections of this Standard, if any. b. Ensure that the interfacing structure through which the loads and reactions are applied to the test unit has been simulated in the test at the component level or through analysis.		
9.2	Development Tests	[PSER 24] Development tests **shall** be conducted to provide confidence of new engine designs or concepts. These tests are expected for brittle materials and composites which use point stress failure modes in Table 1.		
9.3	Qualification Tests	[PSER 25] Qualification tests **shall** be conducted at conditions (level and duration) more severe than flight conditions to verify that flight-configured hardware meets strength requirements and will perform satisfactorily in the flight environments with margin consistent with those specified in this Standard assuring that: a. There is no detrimental yielding at the MDC yield load and no failure at the MDC ultimate load. b. The test article is instrumented appropriately for load, strain, and deflection. c. Structural analysis is correlated to the test results and, if un-conservative results are indicated, the analysis assumptions revisited, and the final analysis re-evaluated. d. Conduct qualification tests in the operational environment or account for the operational environment through use of an Environmental Correction Factor (see section 9.5.1 in this Standard). e. If the engine is expected to operate with instabilities (combustion, rotodynamic, etc.) these are expected to be fully excited as part of qualification.		

NASA-STD-5012C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
9.4	Hot-Fire Tests	[PSER 26] Hot-fire engine tests required to qualify the engine for service life **shall** meet the following criteria and be documented in the SAP: a. For pump-fed engine systems, in addition to component level strength/acceptance tests, perform hot-fire engine system tests for twice the expected service life on six engines/components/units that are structurally equivalent to the flight hardware. (1) If the developer wants to test fewer than six units, provide documented technical rationale from the developer to the delegated NASA Center Engineering Technical Authority and obtain approval before committing to the reduced test program. b. For pressure-fed engines, in addition to component level strength/acceptance tests, a minimum of one qualification unit is required. Perform hot fire engine system tests for twice the expected service life on engines/components/units that are structurally equivalent to the flight hardware. c. Post hot fire inspection of each unit is expected to verify no fatigue crack initiation, detrimental yielding, or other deleterious effects (rubbing, seal cracking, erosion, etc.)		

NASA-STD-5012C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
9.5.1	Acceptance or Proof Tests	[PSER 27] All engine pressure vessels, pressurized components, major pressure-loaded components, and major rotating hardware **shall** be acceptance/proof-tested to the proof factors in Table 1 to ensure satisfactory workmanship and material quality and comply with the following criteria: a. Perform proof (spin, pressure, or load) tests for all brazed, welded, composite, or bonded structures. b. In cases where there are significant load conditions in addition to pressure, conduct a combined proof-pressure and external-loading test or increase the test pressure to encompass all loads. The resulting stress state from the increased test pressure should reasonably match the combined load flight case. c. Perform nondestructive evaluation before and after proof testing. d. Design parts so that no detrimental yielding occurs during proof tests and so that proof loads are limited to 95 percent on net-section yield and 80 percent on net-section ultimate. e. Conduct proof tests in the operational environment or account for the operational environment through use of an Environmental Correction Factor (ECF): $$\mathbf{ECF} = \frac{\textbf{Strength capability at test condition}}{\textbf{Strength capability at MDC temperature}}$$		
9.5.2	Acceptance or Proof Tests	[PSER 28] Each engine system shall receive an acceptance hot-fire test at nominal level(s) and duration with a reasonable post-test inspection to be considered structurally acceptable.		

APPENDIX B: REFERENCE DOCUMENTS

B.1 PURPOSE

This Appendix contains information of a general or explanatory nature but does not contain requirements. The latest issuances of these documents apply unless specific versions are designated. Reference documents may be accessed at https://standards.nasa.gov, obtained directly from the Standards Developing Body or other document distributors, or contact the office of primary responsibility.

B.2 GOVERNMENT DOCUMENTS

Department of Defense

MIL-STD-1540D**,** Product Verification Requirements for Launch, Upper-Stage, and Space Vehicles – Historical references (superseded by SMC-S-016)

SMC-S-016**,** Test Requirements for Launch, Upper-Stage and Space Vehicles

MSFC

MSFC-SPEC-445**,** Adhesive Bonding, Process and Inspection, Requirements for

NASA

NASA-SP-8007, Buckling of Thin-Walled Circular Cylinders (http://ntrs.nasa.gov/)

NASA-SP-8055, Prevention of Coupled Structure-Propulsion Instability (POGO), NASA space vehicle design criteria, structures

B.3 NON-GOVERNMENT DOCUMENTS

American Society of Mechanical Engineers (ASME)

ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1, 2, and 3. Rules for Construction of Pressure Vessels

Battelle Memorial Institute

MMPDS-10**,** Metallic Materials Properties Development and Standardization (MMPDS)

Energetics Research Group (Formerly Chemical Propulsion Information Agency)

JANNAF-GL-2022-0001, Guidelines for Combustion Stability Specifications and Verification Procedures for Liquid-Propellant Rocket Engines (formerly CPIA Publication 655, Combustion Stability Specifications and Verification Procedures)

APPENDIX C: MAXIMUM DESIGN CONDITION LOADS

C.1 PURPOSE

As a supplement to the requirements contained in NASA-STD-5012, Strength and Life Assessment Requirements for Liquid-Fueled Space Propulsion System Engines, there are a few common engine design practices that will help providers meet requirements by managing loads through design specifications or parameters. A majority of pump-fed engine system loads are self-induced either from combustion dynamics (harmonic and/or random excitation) or rotation machinery dynamics (mostly cyclic excitation). Using common design practices will assist providers in managing loads to avoid resonances and other uncontained loads.

C.2 MAXIMUM DESIGN CONDITION LOAD GUIDANCE

C.2.1 Combustion Stability

It is expected that combustion devices are designed to eliminate a majority of the harmonic combustion excitation through methods in documents such as the latest Energetics Research Group (ERG) combustion stability guideline revision, JANNAF-GL-2022-0001, Guidelines for Combustion Stability Specifications and Verification Procedures for Liquid-Propellant Rocket Engines (formerly CPIA-655), Combustion Stability Specifications and Verification Procedures; but any harmonic loading from combustion excitation should be assessed by avoiding resonance with neighboring components.

C.2.2 Vehicle-Coupled Loads (Pogo)

Although a majority of engine loads are self-induced, coupled loads from the vehicle effects such as Pogo (propulsion system coupling with the vehicle dynamics) can do significant damage to the engine components and performance. In practice, it is difficult to predict and envelope loads from a condition such as Pogo and is recommended that this loading condition be avoided using publication such as NASA-SP-8055, Prevention of Coupled Structure-Propulsion Instability. The vehicle and engine propellant feed system should be analyzed for this phenomen throughout the entire launch ascent. POGO suppressors are often implemented as part of either the engine system or vehicle propellant feed system, and it should not be assumed that a particular damper is effective for any combination of engine and vehicle.

C.2.3 Engine External Load Prediction

An engine system structural dynamics model has to be created to predict response to random and harmonic loadings. These load response predictions should be used in the structural assessment of the engine and its components. The load predictions should be anchored and/or validated during development and qualification testing using instrumented engine system hot-fire tests with accelerometers and/or strain gages. These loads (both random and cyclic) should be monitored throughout the program engine green run tests to verify load stability and highlight load exceedances that might be an indication of previously undetected issues or process creep.

C.2.4 Engine Internal Load Prediction

A majority of static mechanical loads on engine components comes from internal engine system fluid pressure. These static loads have dynamic components from either mechanical vibrations or cyclic pressure oscillations. For rotating machinery, eliminating synchronous excitation completely is not possible which drives the designs toward minimizing load amplitude. This should be addressed by designing rotating machinery with significant rotodynamic critical speed margin and component modal avoidance with the excitation frequency.

For rotodynamic margin, providers should ideally design the rotating stack to have a 20 percent frequency margin between the steady state operating speeds and any system rotodynamic natural frequencies. This could be accomplished by tuning the rotating assembly stiffness/mass and/or bearing stiffness. Additionally, rotating equipment that operates at shaft speeds above the first natural frequency needs to be shown to be stable (positive logarithmic decrement) for all system rotodynamic modes.

C.2.5 Component Structural Dynamic Capability

For component modal avoidance, turbopump flow-path components (inducers, impellers, diffuser vanes, blades, vanes, and nozzles) and the turbine disk should be designed to avoid structural modes resonating (in the frequency and spatial domain) with integer multiples of turbopump shaft frequency (N) of at least 4N and at least 3N times any upstream and downstream flow distortion (i.e., for the blades, at least 3 times the number of inlet guide vanes). Fourier analysis of the upstream/downstream excitation field should be used to guide inclusion of non-negligible energy at frequency multiples greater than 3N. Excitability of modes with reference to wave number should be assessed, including direct wave number excitation as well as Tyler-Sofrin aliased modes, suggested to be up to the 3^{rd} harmonic. A suggested frequency margin to resonance (Campbell diagram margin) should be between 10 percent and 15 percent depending on the component, the nature of the mode, level of verified accuracy of the natural frequencies, and perceived damping. A forced-response analysis capability has to be applied for higher-order modes for which a possible resonant condition cannot be avoided, as well as provisions for additional damping for those cases.

NASA propulsion engineering has expertise in both of the above mentioned areas, and teaming in these design areas is recommended to avoid design issues late in the development program. .

C.2.6 Presence of Dissolved Gases

The presence, or not, of dissolved gases (e.g., helium pressurant gas) in propellants should be considered in the determination of MDC loads, including internal loads, external loads, and vehicle-coupled loads. The evolution of dissolved gases (e.g., due to pressure drop) can significantly alter the speed of sound of the fluid, changing the fluid dynamics and associated loads relative to fully unsaturated propellants. Analyses should include bounding scenarios from fully unsaturated propellants to the maximum expected evolution of dissolved gases, as appropriate. Analytical models should be properly anchored to test data from a flight-like system configuration. component modal avoidance, turbopump flow-path components (inducers, impellers, diffuser vanes, blades, vanes, and nozzles) and

C.2.7 Instrumentation

It is highly advantageous to include complimentary strain gauges, accelerometers, and high speed pressure transducers during development, qualification, and hot-fire testing. This data will allow mapping the actual structural response and aid building realistic spectrum for fatigue and fracture assessments and avoid overly conservative MDC load definitions.