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

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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.

DOCUMENT HISTORY LOG (Continued)

Status	Document Revision	Change Number	Approval Date	Description
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.

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 that have been endorsed as standard for NASA programs and projects, including requirements for selection, application, and design criteria of an item.

This NASA Technical Standard is approved for use by NASA Headquarters and NASA Centers and Facilities and may be cited in contract, program, and other Agency documents as a technical requirement. It may also apply to the Jet Propulsion Laboratory and other contractors only to the extent specified or referenced in applicable contracts.

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

Requests for information should be submitted via "Feedback" at https://standards.nasa.gov. Requests for changes to this NASA Technical Standard should be submitted via MSFC Form 4657, Change Request for a NASA Engineering Standard.

Original Signed By:	***06/16/2016***
Ralph R. Roe, Jr. NASA Chief Engineer	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 National Aeronautics and Space Administration (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. The total system requirements for engine hot-fire tests are not addressed in these requirements; however, 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

The purpose of this NASA Technical Standard is to provide 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

This NASA Technical Standard is applicable to liquid-fueled engine hardware used for NASA spaceflight missions. 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 NASA Technical Standard presents acceptable minimum factors of safety (FOS) for use in analytical assessment and test verification of the flight hardware structural integrity. These requirements were derived from more complex engine systems with integral turbomachinery, liquid-cooled combustion devices, etc. It is expected that these requirements will require tailoring for less complex engine systems such as pressure-fed thrusters.

In general, no distinction is made between engines to be used for transporting personnel and those used for transporting hardware only. 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.

This NASA Technical Standard is approved for use by NASA Headquarters and NASA Centers and Facilities and may be cited in contract, program, and other Agency documents as a technical requirement. It may also apply to the Jet Propulsion Laboratory and other contractors only to the extent specified or referenced in applicable contracts.

Verifiable requirement statements are numbered and indicated by the word "shall"; this NASA Technical Standard contains 32 requirements. Explanatory or guidance text is indicated in italics beginning in section 4. To facilitate requirements selection and verification by NASA programs and projects, a Requirements Compliance Matrix is provided in Appendix A.

1.3 Tailoring

[PSER 1] Tailoring of this NASA Technical Standard for application to a specific program or project shall be formally documented as part of program or project requirements and approved by the responsible Technical Authority in accordance with NPR 7120.5, NASA Space Flight Program and Project Management Requirements.

2. APPLICABLE DOCUMENTS

2.1 General

The documents listed in this section contain provisions that constitute requirements of this NASA Technical Standard as cited in the text.

2.1.1 [PSER 2] The latest issuances of cited documents shall apply unless specific versions are designated.

2.1.2 [PSER 3] Non-use of specifically designated versions shall be approved by the responsible Technical Authority.

The applicable documents are accessible at https://standards.nasa.gov, may be obtained directly from the Standards Developing Body or other document distributors, or information for obtaining the document is provided.

2.2 Government Documents

Department of Defense

AFSPCMAN 91-710	Range Safety User Requirements Manual

Marshall Space Flight Center (MSFC)

MSFC-DWG-20M02540	Assessment of Flexible Lines for Flow Induced Vibrations

NASA

NPR 7120.5	NASA Space Flight Program and Project Management Requirements

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)

AIAA S-080-1998	Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
AIAA S-081-2000	Space Systems – Composite Overwrapped Pressure Vessels (COPVs)

2.4 Order of Precedence

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

2.4.2 [PSER 4] Conflicts between this NASA Technical Standard and other requirements documents shall be resolved by the responsible Technical Authority.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms, Abbreviations, and Symbols

=	equal
≥	equal to or greater than
>	greater than
-	minus
√	square root
AFSPCMAN	Air Force Space Command Manual
AIAA	American Institute of Aeronautics and Astronautics
ASME	American Society of Mechanical Engineers
COPV	composite overwrapped pressure vessel

DWG	drawing
E	modulus of elasticity
ECF	environment correction factor
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
S-N	stress versus cycles to failure
SP	special publication
SPEC	specification
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.

E: Modulus of elasticity.

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: 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.

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.

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

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

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

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

Maximum Design Condition Load(s): Each engine program defines this load condition. It should be based on 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 thermal (steady-state and transient). Mechanical loads include forces, moments, and pressures. 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.

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 NASA Technical Standard. Table 1 follows the last section in this NASA Technical 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. (Refer to table 1 following the last section in this NASA Technical Standard.)

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 following the last section in this NASA Technical Standard.)

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 (following the last section in this NASA Technical Standard) 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 NASA Technical 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 verification.

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.

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 5] An effective strength and life assessment program shall be established, defined, maintained, and documented in the Structural Assessment Plan (SAP) 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. (Refer to section 4.1.)

4.1 Documentation

[PSER 6] The following minimum documentation requirements shall be developed and submitted as part of the program/project documentation of the strength and life assessments:

a. An SAP specifying how the particular engine program plans to satisfy the requirements of this NASA Technical Standard 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 FOS specified in this NASA Technical 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 MS and life factors for the final and as-built configurations.

5. STRENGTH AND LIFE ASSESSMENTS

[PSER 7] Strength and life assessments (detailed analyses, tests, and their verification) for the engine system and all its components shall utilize the factors of safety specified in table 1 for assessment of safety margins and comply with the strength and life assessment requirements delineated in the subsequent sections of this NASA Technical Standard.

5.1 Strength Assessments

[PSER 8] Engine components shall be assessed at MDC loads utilizing the factors in table 1.

5.2 Material Properties for Analyses

[PSER 9] 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.)*

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. Since fatigue and creep are not specifically addressed in NASA-STD-6016, it is expected that the engine contractor will present an approach, as part of SAP.

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. Use the factors in table 1 with metallic materials that exhibit ductility greater than 3 percent.

f. 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 10] NASA-STD-5005, Standard for the Design and Fabrication of Ground Support Equipment, shall be used in the design of engine GSE and FSE.

NASA-STD-5005 establishes 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 11] 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 12] 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 13] 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.

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 14] 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 and approve in the SAP any reduction in proof test factors if the acceptance proof test has the potential to damage fibers

d. 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 of tests to produce strength allowables for geometric discontinuities, such as inserts, using flight-like geometric configuration, materials, and processes.

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 15] 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 16] 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.

6. PRESSURIZED HARDWARE

6.1 Design Requirements for Pressure Vessels and Pressurized Systems

[PSER 17] The design organization shall design engine system pressure vessels and pressurized systems in accordance with AFSPCMAN 91-710, Range Safety User Requirements Manual, AIAA S-080-1998, Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components, and AIAA S-081-2000, Space Systems – Composite Over Wrapped Pressure Vessels (COPVs), as applicable, in addition to the requirements in this NASA Technical Standard.

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

6.2 Pressure-Loaded Components and Structures

In general, pressure-loaded components and structures as defined in this NASA Technical 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 18] All of the following attributes for pressure-loaded components and structures shall be complied with:

The design organization has the responsibility to ensure compliance with these attributes.

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) individually before flight and meet the requirements contained in this NASA Technical Standard.*

6.3 Flexible Hoses and Bellows

[PSER 19] All of the following attributes for flexible hoses and bellows in the engine system shall be complied with:

The design organization has the responsibility to ensure compliance with these attributes.

a. Design all flexible hoses and bellows to exclude flow-induced vibrations in accordance with MSFC–DWG–20M02540, Assessment of Flexible Lines for Flow Induced Vibrations.

> *In cases where design constraints preclude meeting MSFC–DWG–20M02540 or a design cannot be confidently assessed, an alternate approach should be addressed in the SAP and submitted for approval by the responsible organization.*

b. Meet the safety factors listed in table 1 and the life assessment requirements in section 8 for flexible hoses and bellows.

6.4 Pressure Combined with External Load

[PSER 20] All of the following attributes shall be complied with when pressure is combined with an external load:

The design organization has the responsibility to ensure compliance with these attributes.

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 21] 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, etc.) in conjunction with the factors listed in table 1.

b. Use an 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 X MDC loads.

c. Calculate MS on performance-driven clearances (for example, in turbomachinery) using an FOS of 1 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 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 NASA Technical Standard are met.

8. LIFE ANALYSIS

8.1 [PSER 22] 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- 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 23] 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 responsible 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 to include the effects of stress concentration factors when applicable.

8.3 [PSER 24] All structural components subject to combined fatigue and creep shall be evaluated using standard methods for accumulated damage.

8.4 [PSER 25] Methods for determining the final life predictions accounting for accumulated damage shall be recorded in the SAP and approved by the responsible Technical Authority.

8.5 [PSER 26] The engine and its components shall be assessed for susceptibility to preexisting material flaws per NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware.

9. TESTING

Strength, fatigue, and hot-fire testing are required for the engine system and components such as rotors, pressure vessels, and major load-carrying structures. Component level vibroacoustic, acoustic and shock testing is performed per MIL-STD-1540C and/or SMC-016 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 27] 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 NASA Technical 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 28] Development tests shall be conducted to provide confidence of new engine designs or concepts.

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 29] 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 sufficient margin 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).

Qualification fatigue tests may be required if analysis in accordance with section 8 of this NASA Technical Standard cannot be confidently accomplished. 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 NASA Technical Standard.

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

9.4 Hot-Fire Tests

[PSER 30] 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 duration 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. Hot-fire qualification engines typically exceed two times the service life requirement. Heritage engines may be able to leverage past unit success with approval from the responsible NASA Center Technical Authority.

i. If the developer wants to test fewer than six units, provide documented technical rationale from the developer to the responsible 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, the number of qualification units required for any given engine development shall be a minimum of one.

9.5 Acceptance or Proof Tests

9.5.1 [PSER 31] All engine pressure vessels, pressurized components, major pressure-loaded components, and major rotating hardware shall be acceptance/proof-tested to ensure satisfactory workmanship and material quality and comply with the following criteria:

a. Perform proof (spin, pressure, or load) tests for all brazed, 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.

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):

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

If testing in the operational environment is not feasible, tests can be performed in a non-operational environment if an ECF is applied. 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 32] 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.

Table 1—Minimum Analysis FOS and Strength Test Factors

Engine Hardware Type	Load	Mode of Failure	Analysis FOS[1]	Test Factors[2]	
				Qualification	Acceptance/ Proof[3]
Metallic Structures and Components[10]	*				
Yield	mechanical only	net section yield	1.10[4]	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	MDC pressure or spin stress	net section ultimate	1.50	1.50	1.20[5, 6]
Ultimate	MDC	point strain ultimate	2.0	NA	NA
Pressure Vessels and Pressurized Systems[10]	MDC (Pressure only)	AFSPCMAN 91-710 and either AIAA S-080-1998 or AIAA S-081-2000			
Fasteners and Preloaded Joints					
Yield	MDC	net section yield	1.10[4]	NA	NA
Ultimate	MDC	net section ultimate	1.40	1.40	1.20
Joint Separation	MDC	separation leakage	1.20	1.20	1.20
Safety Critical[7]	MDC	separation leakage	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[5]
Stress concentration areas	MDC	point ultimate	2.00	1.40	1.20[5]
Bonds/joints	MDC	net section ultimate	2.00	1.40[5]	1.20[5]
Ablatives	MDC	point ultimate	1.70[8]	1.40[5, 8]	1.20[5]

Table 1—Minimum Analysis FOS and Strength Test Factors (Continued)					
Engine Hardware Type	**Load**	**Mode of Failure**	**Analysis FOS[1]**	**Test Factors[2]**	
				Qualification	**Acceptance/ Proof[3]**
Pressure Checkout with Personnel Present					
Yield	checkout pressure	[9]	1.50[4]	NA	NA
Ultimate	checkout pressure	[9]	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. For material susceptible to sustained load failure, such as titanium alloys, see section 7.0 of this NASA Technical Standard.
5. These tests are always required. (See section 5.1.7 in this NASA Technical Standard for additional requirements for composite and bonded structures.)
6. Test pressure = MDP x 1.20 x ECF $\geq$ 1.05 x MDP.
   Test speed = $\sqrt{}$ (MDC speed^2 x 1.20 ECF) $\geq$ $\sqrt{}$ (MDC speed^2 x 1.05)
7. Joints for which separation would be a catastrophic event.
8. Analysis and test factors apply at end of life. Qualification test occurs on a hot-fired (fully ablated) flight-type test article.
9. Net section failure mode for metallics and point stress/strain failure mode on ultimate only for composites or adhesive bonds.
10. Bellows and components used on pressurized systems, generally lines 2” in diameter or less, are to meet the pressurized systems requirements.

APPENDIX A

REQUIREMENTS COMPLIANCE MATRIX

A.1 Purpose

This Appendix provides a listing of requirements contained in this NASA Technical Standard for selection and verification of requirements by programs and projects. *(**Note**: Enter "Yes" to describe the requirement's applicability to the program or project; or enter "No" if the intent is to tailor, and enter how tailoring is to be applied in the "Rationale" column.)*

NASA-STD-5012B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
1.3	Tailoring	[PSER 1] Tailoring of this NASA Technical Standard for application to a specific program or project shall be formally documented as part of program or project requirements and approved by the responsible Technical Authority in accordance with NPR 7120.5, NASA Space Flight Program and Project Management Requirements.		
2.1.1	Applicable Documents	[PSER 2] The latest issuances of cited documents shall apply unless specific versions are designated.		
2.1.2	Applicable Documents	[PSER 3] Non-use of specifically designated versions shall be approved by the responsible Technical Authority.		
2.4.2	Order of Precedence	[PSER 4] Conflicts between this NASA Technical Standard and other requirements documents shall be resolved by the responsible Technical Authority.		
4.	General Requirements	[PSER 5] An effective strength and life assessment program shall be established, defined, maintained, and documented in the Structural Assessment Plan (SAP) 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. (Refer to section 4.1.)		

NASA-STD-5012B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
4.1	Documentation	[PSER 6] The following minimum documentation requirements shall be developed and submitted as part of the program/project documentation of the strength and life assessments: a. An SAP specifying how the particular engine program plans to satisfy the requirements of this NASA Technical Standard 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 FOS specified in this NASA Technical 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.		

NASA-STD-5012B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
		(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 MS and life factors for the final and as-built configurations.		
5.	Strength and Life Assessments	[PSER 7] Strength and life assessments (detailed analyses, tests, and their verification) for the engine system and all its components shall utilize the factors of safety specified in table 1 for assessment of safety margins and comply with the strength and life assessment requirements delineated in the subsequent sections of this NASA Technical Standard.		
5.1	Strength Assessments	[PSER 8] Engine components shall be assessed at MDC loads utilizing the factors in table 1.		

NASA-STD-5012B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
5.2	Material Properties for Analyses	[PSER 9] 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. Use the factors in table 1 with metallic materials that exhibit ductility greater than 3 percent.		
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 10] NASA-STD-5005, Standard for the Design and Fabrication of Ground Support Equipment, shall be used in the design of engine GSE and FSE.		

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NASA-STD-5012B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
5.4	Transportation and Flight Structures	[PSER 11] 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 12] 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.		
5.6	Weld and Braze Joints	[PSER 13] 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. c. Structural spot welds are not permitted unless consumed by a structural weld because of inherent problems with spot weld inspections and reliability.		

NASA-STD-5012B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
5.7	Composite and Bonded Structures	[PSER 14] 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 and approve 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 of tests to produce strength allowables for geometric discontinuities, such as inserts, using flight-like geometric configuration, materials, and processes. 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 15] 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.		

NASA-STD-5012B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
		(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 16] 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.		
6.1	Design Requirements for Pressure Vessels and Pressurized Systems	[PSER 17] When designing engine system components defined as pressure vessels and pressurized systems, the requirements in AFSPCMAN 91-710, Range Safety User Requirements Manual, AIAA S-080-1998, Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components, and AIAA S-081-2000, Space Systems – Composite Over Wrapped Pressure Vessels (COPVs), as applicable, in addition to the requirements in this NASA Technical Standard, shall be met by the design organization.		
6.2	Pressure-Loaded Components and Structures	[PSER 18] All of the following attributes for pressure-loaded components and structures shall be complied with: *(The design organization has the responsibility to ensure compliance with these attributes.)* 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.		

NASA-STD-5012B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
6.3	Flexible Hoses and Bellows	[PSER 19] All of the following attributes for flexible hoses and bellows in the engine system shall be complied with: *(The design organization has the responsibility to ensure compliance with these attributes.)* a. Design all flexible hoses and bellows to exclude flow-induced vibrations in accordance with MSFC–DWG–20M02540, Assessment of Flexible Lines for Flow Induced Vibrations. b. Meet the safety factors listed in table 1 and the life assessment requirements in section 8 for flexible hoses and bellows.		
6.4	Pressure Combined with External Load	[PSER 20] All of the following attributes shall be complied with when pressure is combined with an external load: *(The design organization has the responsibility to ensure compliance with these attributes.)* 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 21] 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, etc.) in conjunction with the factors listed in table 1. b. Use an 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 X MDC loads.		

NASA-STD-5012B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
		c. Calculate MS on performance-driven clearances (for example, in turbomachinery) using a FOS of 1 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 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 NASA Technical Standard are met.		

NASA-STD-5012B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
8.1	Life Analysis	[PSER 22] 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- 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-5012B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
8.2	Life Analysis	[PSER 23] 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 responsible 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 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 to include the effects of stress concentration factors when applicable.		
8.3	Life Analysis	[PSER 24] All structural components subject to combined fatigue and creep shall be evaluated using standard methods for accumulated damage.		

NASA-STD-5012B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
8.4	Life Analysis	[PSER 25] Methods for determining the final life predictions accounting for accumulated damage shall be recorded in the SAP and approved by the responsible Technical Authority.		
8.5	Life Analysis	[PSER 26] The engine and its components shall be assessed for susceptibility to preexisting material flaws per NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware.		
9.1	Test Plan	[PSER 27] A detailed 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 NASA Technical 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 28] Development tests shall be conducted to provide confidence of new engine designs or concepts.		

NASA-STD-5012B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
9.3	Qualification Tests	[PSER 29] 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 sufficient margin 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).		
9.4	Hot-Fire Tests	[PSER 30] 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 duration on six engines/components/units that are structurally equivalent to the flight hardware. a. If the developer wants to test fewer than six units, provide documented technical rationale from the developer to the responsible 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, perform a minimum of one qualification unit for any given engine development.		

NASA-STD-5012B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
9.5.1	Acceptance or Proof Tests	[PSER 31] All engine pressure vessels, pressurized components, major pressure-loaded components, and major rotating hardware shall be acceptance/proof-tested to ensure satisfactory workmanship and material quality and comply with the following criteria: a. Perform proof (spin, pressure, or load) tests for all brazed, 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. 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): $\mathbf{ECF} = \dfrac{\textbf{Strength capacity at test condition}}{\textbf{Strength capability at operating condition}}$		
9.5.2	Acceptance or Proof Tests	[PSER 32] 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.		

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Table 1—Minimum Analysis FOS and Strength Test Factors

Engine Hardware Type	Load	Mode of Failure	Analysis FOS[1]	Test Factors[2]	
				Qualification	Acceptance/ Proof[3]
Metallic Structures and Components[10]	*				
Yield	mechanical only	net section yield	1.10[4]	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	MDC pressure or spin stress	net section ultimate	1.50	1.50	1.20[5, 6]
Ultimate	MDC	point strain ultimate	2.0	NA	NA
Pressure Vessels and Pressurized Systems[10]	MDC (Pressure only)	AFSPCMAN 91-710 and either AIAA S-080-1998 or AIAA S-081-2000			
Fasteners and Preloaded Joints					
Yield	MDC	net section yield	1.10[4]	NA	NA
Ultimate	MDC	net section ultimate	1.40	1.40	1.20
Joint Separation	MDC	separation leakage	1.20	1.20	1.20
Safety Critical[7]	MDC	separation leakage	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[5]
Stress concentration areas	MDC	point ultimate	2.00	1.40	1.20[5]
Bonds/joints	MDC	net section ultimate	2.00	1.40[5]	1.20[5]
Ablatives	MDC	point ultimate	1.70[8]	1.40[5, 8]	1.20[5]

Table 1—Minimum Analysis FOS and Strength Test Factors (Continued)					
Engine Hardware Type	**Load**	**Mode of Failure**	**Analysis FOS[1]**	**Test Factors[2]**	
				Qualification	**Acceptance/ Proof[3]**
Pressure Checkout with Personnel Present					
Yield	checkout pressure	[9]	1.50[4]	NA	NA
Ultimate	checkout pressure	[9]	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. For material susceptible to sustained load failure, such as titanium alloys, see section 7.0 of this NASA Technical Standard.
5. These tests are always required. (See section 5.1.7 in this NASA Technical Standard for additional requirements for composite and bonded structures.)
6. Test pressure = MDP x 1.20 x ECF ≥ 1.05 x MDP.
   Test speed = $\sqrt{}$ (MDC speed^2 x 1.20 ECF) ≥ $\sqrt{}$ (MDC speed^2 x 1.05)
7. Joints for which separation would be a catastrophic event.
8. Analysis and test factors apply at end of life. Qualification test occurs on a hot-fired (fully ablated) flight-type test article.
9. Net section failure mode for metallics and point stress/strain failure mode on ultimate only for composites or adhesive bonds.
10. Bellows and components used on pressurized systems, generally lines 2” in diameter or less, are to meet the pressurized systems requirements.

APPENDIX B

REFERENCE DOCUMENTS

B.1 Purpose and/or Scope

This Appendix contains information of a general or explanatory nature but does not contain requirements.

B.2 Government Documents

MSFC

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

NASA

NASA-STD-5001	Structural Design and Test Factors of Safety for Spaceflight Hardware
NASA-SP-8007	Buckling of Thin-Walled Circular Cylinders (http://ntrs.nasa.gov/)

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)