NASA TECHNICAL STANDARD

NASA-STD-5012A

National Aeronautics and Space Administration
Washington, DC 20546-0001

Approved: 01-15-2015
Supersedes: NASA-STD-5012

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

MEASUREMENT SYSTEM IDENTIFICATION:
METRIC/SI (ENGLISH)

APPROVED FOR PUBLIC RELEASE — DISTRIBUTION IS UNLIMITED

DOCUMENT HISTORY LOG

Status	Document Revision	Approval Date	Description
Baseline		06-13-2006	Initial Release
Revision	A	01-15-2015	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. 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.

FOREWORD

This 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 Standard is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers.

This Standard establishes the strength and life (fatigue and creep) requirements for NASA liquid-fueled space propulsion system engines. This document 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, corrections, or additions to this Standard should be submitted via "Feedback" in the NASA Standards and Technical Assistance Resource Tool at https://standards.nasa.gov.

Original Signed By:
Ralph R. Roe, Jr.
NASA Chief Engineer

01/15/2015
Approval Date

TABLE OF CONTENTS

LIST OF TABLES

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

1. SCOPE

This 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 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 Standards.

1.1 Purpose

The purpose of this 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 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 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 may require tailoring for less complex engine systems, such as pressure-fed thrusters. Generally, designs are to be verified by both analyses and tests.

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 Standard is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers, and may be cited in contract, program, and other Agency documents as a technical requirement. This Standard may also apply to the Jet Propulsion Laboratory or to other contractors, grant recipients, or parties to agreements only to the extent specified or referenced in their contracts, grants, or agreements.

Requirements are numbered and indicated by the word "shall." Explanatory or guidance text is indicated in italics beginning in section 4.

1.3 Tailoring

Tailoring of this Standard for application to a specific program or project shall be formally documented as part of program or project requirements and approved by the Technical Authority.

2. APPLICABLE DOCUMENTS

2.1 General

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

2.1.1 The latest issuances of cited documents shall apply unless specific versions are designated.

2.1.2 Non-use of specific versions as designated shall be approved by the responsible Technical Authority.

The applicable documents are accessible via the NASA Standards and Technical Assistance Resource Tool at https://standards.nasa.gov or may be obtained directly from the Standards Developing Organizations or other document distributors

2.2 Government Documents

<u>Department of Defense</u>

AFSPCMAN 91-710	Range Safety User Requirements Manual
MIL-STD-1522	Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems

<u>Marshall Space Flight Center (MSFC)</u>

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

NASA

NASA-STD-5005	Standard for the Design and Fabrication of Ground Support Equipment
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	Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
AIAA S-081	Space Systems – Composite Overwrapped Pressure Vessels (COPVs)

2.4 Order of Precedence

In the case of conflict, the technical requirements of this Standard take precedence.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms and Abbreviations

=	equal
≥	equal to or greater than
>	greater than
-	minus
√	square root
AFSPCMAN	Air Force Space Command Manual
AIAA	American Institute of Aeronautics and Astronautics
AR	Office of Aviation Research
ASME	American Society of Mechanical Engineers
COPV	composite overwrapped pressure vessel
DOT	Department of Transportation
DWG	drawing
E	modulus of elasticity
ECF	environment correction factor
FAA	Federal Aviation Administration

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
MIL	military
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
psia	pound(s) per square inch absolute
SAP	structural assessment plan
SI	Système International
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."

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

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

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 versus cycles to failure (S-N) design curve to determine the fatigue life. The FAF is to be:

FAF = 1.25 rotating components
FAF = 1.15 non-rotating components

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

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

Maximum Design Condition Load: Each engine program defines this load condition, but 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 that they must 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. See section 4.2.1.1 of this Standard.

Maximum Design Pressure: The highest pressure defined by maximum relief pressure, maximum regulator pressure, or maximum temperature. Transient pressures should be considered. Where pressure regulators, relief devices, and/or a thermal control system, e.g., heaters, are used to control pressure, collectively they are to be two-fault tolerant from causing the pressure to exceed the system's MDP. 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 experienced during an abort to a site without cooling facilities is to be considered.

Maximum Expected Operating Pressure: The maximum pressure expected to occur on a component in association with its applicable operating environments during its service life.

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. Table 1 follows the last section 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. (Refer to table 1 following the last section in this 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. (Refer to table 1 following the last section in this 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, 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 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 document, 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.

Shall: Indicates a mandatory requirement.

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. REQUIREMENTS

4.1 General Requirements

4.1.1 Strength and Life Assessments

a. The responsible design element personnel shall establish and maintain an effective program to assess and verify engine system structural integrity.

b. Structural verification plans shall be described in the structural assessment plan (SAP).

c. This assessment shall generally include both analyses and tests and use the FOS specified in this document.

c. This assessment shall generally include both analyses and tests and use the FOS specified in this document.

Verification of the engine primary structure by analysis only is not considered to be a viable option without prior and written approval from the responsible NASA Center Engineering Technical Authority.

d. The engine shall be assessed at MDC loads using the factors specified in table 1, which follows the last section in this Standard.

(1) Analyses shall be performed using material properties and loads that correspond to the appropriate environment.

(2) Tests shall be run in the actual environment.

(3) If the proper environment cannot be imposed or used, as required in section 4.1.1.c.(2) above, adjustments shall be made to account for their absence.

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

a. In general, the design of GSE and FSE shall not impose critical loads on the hardware.

b. NASA-STD-5005, Standard for the Design and Fabrication of Ground Support Equipment, shall be used to establish general characteristics, performance, design, test, safety, reliability, maintainability, and quality requirements for engine GSE and FSE that are delivered to NASA.

4.1.3 Transportation of Flight Structures

a. As a goal, flight structure design shall be based on flight loads and conditions rather than on transportation and handling loads.

b. Transportation equipment design shall be such that flight structures are not subjected to loads more severe than flight design conditions.

c. Transportation loads, a function of the transportation mode, shall include the steady-state loads plus dynamic, vibration, and shock loads determined by analyses or tests.

4.2 Detailed Requirements

4.2.1 Strength Analysis

Strength analyses required for the engine components shall use the following criteria.

4.2.1.1 Load Conditions

a. The MDC load shall be used in the strength assessment of the engine components.

b. Each engine program shall define the MDC load, 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.

c. All phases in the life of the hardware, including fabrication, assembly, testing, transportation, ground handling, checkout, firing, launch, flight, return, etc., shall be considered in defining 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 MEOP or MDP, as applicable. Mechanical loads may be static, quasi-static, sinusoidal, transient, shock, impact, vibratory, acoustic, or random.

d. When various types of loads from different sources occur simultaneously, these loads shall be combined, as applicable, in defining the MDC load.

e. MDC loads shall be derived for all load cycles of the hardware.

4.2.1.2 Material Properties for Analyses

a. 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.

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.

b. Typical or mean values shall be used for physical properties (modulus, thermal expansion, etc.).

c. Minimum fatigue and creep properties derived by a NASA-approved statistical sampling process shall be used 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, definition is needed for these properties. It is expected that the engine contractor will present an approach to the NASA Technical Authority/engineering review board for approval. Similar approaches have been successfully implemented on past liquid engine programs.

d. Material strength allowables used shall consider all operational environments, including temperature, cyclic load, sustained load, and shock (both mechanical and thermal related to heating and chilling).

e. In addition, the sensitivity of a component to fracture, embrittlement, stress corrosion, and any other degradation under the service conditions shall be addressed.

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.

4.2.1.3 Design and Analysis: Dimensional Tolerance

The dimensions used in strength and life calculations shall be chosen using the tolerance specified so that the calculated margin is the minimum.

Actual as-built dimensions may be used in stress calculations when available.

4.2.1.4 Weld and Braze Joints

a. Design of welds/brazes shall include the effects on stress levels related to weld/braze bead stress concentrations, parent material misalignment/offsets, and residual stresses.

b. The material properties used in the assessments of weld/braze joints (strength, fatigue, creep, etc.,) shall be adjusted for weld/braze joint efficiency based upon the classification (and/or process verification) of the joint.

c. Because of inherent problems with inspections and reliability, the use of structural spot welds shall not be permitted.

4.2.1.5 Buckling and Crippling

a. Ultimate loading shall not cause structural members that are subject to instability to collapse.

b. Buckling deformation from limit loads shall not degrade the functioning of any system or produce unaccounted changes in loading.

c. Evaluation of buckling strength shall include the combination of all loads from any source and their effects on general instability, local instability, and crippling.

d. Buckling failure modes shall be considered 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.

e. Design loads for collapse shall be ultimate loads.

(1) Any load component that tends to alleviate buckling shall not be increased by the ultimate FOS.

In some cases where a load alleviates buckling, the minimum load should be used to assess the buckling margin.

(2) Destabilizing (external pressure, thermal loads, torsional limit loads, etc.,) loads shall be increased by the ultimate FOS.

(3) Stabilizing (internal pressure, thermal loads, etc.,) loads shall not be increased unless they reduce structural capability.

f. Analyses of buckling of thin-walled shells shall use appropriate “knockdown factors” (correlation coefficients) to account for the difference between classical theory and empirical instability loads.

g. Analyses of buckling using nonlinear finite element analyses (FEAs) shall include material nonlinearities, geometric imperfections, local geometric features, manufacturing details, etc., that adversely affect the stability of the structure.

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

4.2.1.6 Fasteners and Preloaded Joints

a. Bolt design and joint separation in preloaded joints shall be in accordance with NASA-STD-5020, Requirements for Threaded Fastening Systems in Spaceflight Hardware.

Alternative methods to NASA-STD-5020 require prior NASA approval.

b. Design and test factors for fasteners and preloaded joints shall be as specified in table 1 (following the last section of this Standard).

4.2.1.7 Hardware that Experiences Pressure Loading

4.2.1.7.1 Design Requirements for Pressure Vessels and Pressurized Systems

a. Pressure vessels and pressurized systems for engines shall meet the requirements of both this Standard and AFSPCMAN 91-710, Range Safety User Requirements Manual, and either AIAA S-080, Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components, AIAA S-081, Space Systems – Composite Over Wrapped Pressure Vessels (COPVs), or MIL-STD-1522, Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems.

b. When using these referenced documents for pressurized systems, the term MDP shall be substituted for the term MEOP as applicable.

c. The term MDP shall be used in all cases involving personnel safety.

4.2.1.7.2 Pressure-Loaded Components and Structures

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 and valves, etc., are not considered to be storage containers, so these components are not classified as pressure vessels. Such components as these are pressure-loaded components.

a. Liquid-fuel engine components considered pressure-loaded components, such as those listed above, shall be designed using the safety factors in table 1 (following the last section of this Standard) for metallic or composite/bonded structures as applicable.

b. Pressure-loaded components and structures shall be designed to MDC loads.

4.2.1.7.3 Flexible Hoses/Bellows

a. All flexible hoses and bellows shall be designed to exclude or minimize flow-induced vibrations in accordance with MSFC–DWG–20M02540, Assessment of Flexible Lines for Flow Induced Vibrations.

b. In addition, flexible hoses and bellows shall meet the safety factors listed in table 1 (following the last section of this Standard).

4.2.1.7.4 Inadvertent Pressurized Volumes

Compartments or volumes that can become inadvertently pressurized as a result of a credible single-seal failure shall be designed and assessed for these potential pressure loads.

However, propagation of failure by the same mechanism may be considered highly unlikely to the remainder of redundant seals in a series that have been acceptance tested individually before flight, seals designed to a FOS of 2.5 on the MDP, and seals certified for all operating environments, including fatigue conditions.

4.2.1.7.5 Pressure Combined with External Load

a. In circumstances where pressure loads have a relieving or stabilizing effect on structural-load capability, the minimum value of such relieving loads shall be used and not be multiplied by the safety factor in calculating the design yield or ultimate load.

b. FOS for combined load conditions shall be as specified in table 1 (following the last section of this Standard).

4.2.1.8 Composite and Bonded Structures

a. Safety and test factors for composite and bonded structures shall be as specified in table 1 (following the last section of this Standard).

b. All flight units shall be proof-tested.

c. Hardware shall be designed so that proof tests do not exceed 75 percent of the ultimate stress capability.

d. In addition to initial proof test of the flight article, ablative chambers or nozzles shall demonstrate by qualification test the “end of life” factor specified in table 1 (following the last section of this Standard) using a hot-fired and fully ablated flight-type test article.

e. Since adhesive strength is sensitive to temperature, the effect of temperature, both higher and lower than nominal, shall be included in establishing the strength allowable for composite or bonded structures.

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

f. A series of tests shall be performed to produce a strength allowable for inserts using flight-like geometric configuration, materials, and processes.

Inserts in nonmetallic/composite structures are a special case of bonded structures.

This testing by itself is not sufficient to satisfy the structural testing requirement, which is intended to test the structure in the flight configuration.

4.2.1.9 Factors of Safety

The required FOS to be used in the strength analyses and strength tests are specified in table 1 (following the last section of this Standard).

a. The FOS specified in table 1 (following the last section of this Standard) shall be used in the strength analyses and strength tests.

b. These factors shall be supported by hot-fire testing in addition to static-load tests and pressure tests on qualification and flight units.

4.2.1.10 Margins of Safety (MS)

The engine and its components shall be assessed to show non-negative MS using FOS specified in table 1 (following the last section of this Standard).

MS is the fraction by which "allowable strength" exceeds the "applied load" that has been multiplied by the FOS.

$$\text{MS} = \frac{\text{Allowable Load}}{(\text{Applied Load})\,(\text{FOS})} - 1 \geq 0$$

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 (following the last section of this Standard).

4.2.1.11 Other Design Factors

For some applications, it may be appropriate and required to use other design factors, such as fitting factors, casting factors, impact factors, etc., in conjunction with the FOS specified in table 1 (following the last section of this Standard).

a. While brazed, welded, and bonded joints require other special factors consistent with their processing and criticality, these factors shall be at least as severe as those in table 1 (following the last section of this Standard).

b. MS in situations intended to prevent impact, such as an engine fully gimbaled, shall use a FOS of 1.4 at MDC loads, i.e., the clearance is to be zero or positive at 1.4 X MDC loads.

MS on performance-driven clearances (for example, in turbomachinery) are generally calculated using a FOS of 1.

c. The factors in table 1 (following the last section of this Standard) shall be used with materials that exhibit sufficient ductility (>3 percent) or that meet NASA-STD-6016.

For materials not in this category, additional factors may be required. For example, some metallic hardware, such as titanium alloy, has been shown to be susceptible to failure near the yield load.

d. For materials susceptible to sustained load rupture, such as titanium alloys, the maximum peak stress shall be less than 80 percent of the material minimum yield strength.

e. The need for other design factors shall be determined in conjunction with the responsible NASA Center Engineering Technical Authority and specified in the SAP.

4.2.1.12 Local Yielding

Local yielding of the engine structure shall be acceptable when **all** of the following conditions are met:

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

b. There are no detrimental deformations that adversely affect the component/system function.

c. The other criteria of table 1 (following the last section of this Standard) are met.

Section 4.2.1.12 does not relieve the developer from other requirements in this Standard. Excluding the yield criterion, all other factors in table 1 are to be met.

d. The service life requirements are met.

4.2.2 Strength Tests

Strength tests are generally required for components such as rotors, pressure vessels, and major load-carrying structures.

a. The SAP shall identify the hardware that requires structural testing and the type of test to be performed.

The types of tests are development, qualification, and acceptance or proof tests. Test factors are specified in table 1 (following the last section of this Standard).

b. The interfacing structure through which the loads and reactions are applied to the test unit shall be simulated in the test at the component level or through analysis.

4.2.2.1 Development Tests

Development tests are required to support new engine designs or concepts. Tests during this phase provide confidence that the new design will accomplish mission objectives.

a. While development test factors are not specified in table 1 (following the last section of this Standard), these tests shall be to levels that identify weaknesses in materials and deficiencies of the designs.

Some destructive tests are often required. Results from these tests are used to guide the final design.

b. Development test requirements shall be specified in the SAP.

Generally, development tests do not suffice for qualification tests unless the tests fulfill all of the requirements in sections 4.2.2.2 and 4.2.2.3.

4.2.2.2 Qualification Tests

Qualification tests are required to verify that flight hardware meets strength requirements. These tests are conducted on flight-configured hardware at conditions (level and duration) more severe than flight conditions to establish that the hardware will perform satisfactorily in the flight environments with sufficient margin.

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

b. The test article shall be instrumented for load, strain, and deflection as appropriate.

c. Structural analysis shall be correlated to the test results and, if unconservative results are indicated, the analysis assumptions revisited and the final analysis reevaluated.

d. Qualification test requirements shall be specified in the SAP.

e. For pump-fed engine systems, in addition to strength tests, hot-fire engine system tests shall occur on six engines/components/units that are structurally equivalent to the flight hardware for the engine to be considered structurally qualified.

(1) These tests shall exercise the expected environment and exceed the service life requirement for the engine and its components.

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

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.

f. For pressure-fed engines, the number of qualification units required for any given engine development shall be a minimum of one.

Typically, the number required is one to three, based on a combination of factors including but not limited to application, design complexity, and design heritage.

Rationale: The decision on number of qualification units is established by the responsible NASA Center Engineering Technical Authority in coordination with the program based on the criteria above. For new engine developments, end-item to end-item variability is to be addressed by the additional requirement for development testing.

(1) These tests shall exercise the expected environment and exceed the service life requirement for the engine and its components.

(2) The developer shall provide documented technical rationale for the number of qualification engines to the responsible NASA Center Engineering Technical Authority and obtain approval.

4.2.2.3 Acceptance/Proof Tests

a. All engine pressure vessels, pressurized components, major pressure-loaded components, and major rotating hardware shall be proof-tested to ensure satisfactory workmanship and material quality.

Proof (spin, pressure, or load) tests are required for all brazed, composite, or bonded structures.

b. In cases where there are significant load conditions in addition to pressure, a combined proof-pressure and external-loading test shall be conducted or the test pressure be increased to encompass all loads.

c. Nondestructive evaluation shall be performed before and after proof testing.

d. Parts shall be designed so that no detrimental yielding occurs during proof tests and so that proof loads are limited to 95 percent on net-section yield and 75 percent on net-section ultimate.

Proof factors are specified in table 1 (following the last section of this Standard). Note that fracture control may require a higher test factor than those listed in table 1, if the proof test will be used for flaw screening.

e. Proof-test requirements shall be specified in the SAP.

f. In addition to component proof tests, each engine shall be hot-fire tested at nominal level and duration to be considered structurally acceptable.

Hot-fire engine tests are also required to qualify the engine for service life, as specified in section 4.2.2.2 in this Standard. These tests should be documented in program documentation and consider the engine purpose, reliability, complexity, mission life, etc.

4.2.2.4 Test-Level Corrections for Environment

Qualification and proof tests shall be conducted in the operational environment or have the operational environment accounted for through use of an Environmental Correction Factor (ECF).

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.

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

4.2.3 Life Analysis

4.2.3.1 Material Properties

Material properties for life analysis are specified in section 4.2.1.2 of this Standard.

4.2.3.2 Loads Spectra

a. A design-load history shall be developed in sufficient detail for the cumulative damage to be analytically predicted for all applicable components.

b. The component-load history shall include the number of cycles or time at each significant load level, considering all phases of fabrication, assembly, testing, transportation, ground handling, checkout, firing, launch, flight, return, etc.

c. Both low- and high-cycle fatigue loads, sustained loads, preloads, and assembly loads shall be considered in the life assessment.

d. Loads from mechanical, thermal, pressure, and atmospheric sources shall be included as appropriate.

e. The life assessments below shall be made using this significant load history and the material properties corresponding to the environment of each event.

4.2.3.3 Creep Analysis

a. All flight hardware structures shall be designed to preclude cumulative strain as a function of time, i.e., creep, which could result in rupture, detrimental deformation, or collapse, e.g., buckling, of compression members during the design service life.

b. Materials shall be selected to preclude accumulated damage from creep in the engine environment.

c. If selecting a structural material that exhibits creep phenomena in the engine environment is unavoidable, then all structural elements subject to creep shall be assessed to demonstrate the following factors:

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

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

4.2.3.4 Fatigue Analysis

a. The engine and its components shall be assessed for low-cycle fatigue (LCF) and high-cycle fatigue (HCF) using the following guidelines:

(1) For cyclic loads to varying levels, standard methods such as Miner's Method shall be used to determine the combined damage.

(2) For alternating load combined with a mean load, standard methods such as the Modified Goodman Line shall be used to determine the combined effect.

(3) All structural elements shall be designed and analyzed to demonstrate the following factors:

A. Fatigue Analysis Factor

i. A FAF shall be multiplied by the limit stress/strain before entering the S-N design curve to determine the low-cycle/high-cycle life.

ii. The FAF shall be:

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

B. Service Life Factor

i. The LCF analysis shall demonstrate a minimum calculated life of 4.0 times the service life.

ii. The HCF analysis shall demonstrate a minimum calculated life of 10.0 times the service life.

C. Stress Concentrations. The alternating and mean stress/strain shall include the effects of stress concentration factors when applicable.

b. All structural components subject to combined fatigue and creep shall be evaluated using standard methods such as Miner's accumulated damage procedure for final life predictions.

4.2.3.5 Fatigue Tests

Fatigue tests generally fall into two categories: development or qualification fatigue tests.

4.2.3.5.1 Development Fatigue Tests

Development fatigue tests are used to guide the design.

a. Levels and duration shall be sufficiently severe to identify any credible weakness and provide confidence that the final design will pass qualification.

b. Development test requirements shall be specified in the SAP.

4.2.3.5.2 Qualification Fatigue Tests

Qualification fatigue tests may be required if analysis in accordance with section 4.2.3.4 of this Standard cannot be confidently accomplished. These tests are conducted on flight-configured hardware and in the appropriate flight environment. The component is tested at the MDC alternating and mean stresses for four times the number of cycles established in section 4.2.3.2 of this Standard.

a. The test article shall be instrumented for load, strain, and deflection as appropriate.

b. Qualification fatigue test requirements shall be specified in the SAP.

4.2.4 Documentation

The following documentation requirements are the minimum required to fully document the strength and life assessments for an engine program.

These documents shall be used to develop data requirements for specific programs.

4.2.4.1 Structural Assessment Plan

a. The responsible organization shall submit the SAP as early as possible but no later than preliminary design review and update it at significant program milestones and as the structural assessment approaches evolve.

b. The SAP shall specify how the particular engine program plans to satisfy the requirements of this document.

The SAP would include topics such as which pressures are applicable (MEOP, MDP, MDC) for analysis, the loads spectra, etc., for the engine being assessed.

c. The SAP shall also describe the development, qualification, and acceptance/proof test approaches for the specific engine hardware.

4.2.4.2 Analyses and Test Reports

a. The responsible organization shall document analyses and/or tests to show that the hardware complies with program requirements.

b. The responsible organization shall submit 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 FOS as specified in this document and in the SAP.

c. Reports shall be in hard copy and electronic format.

d. The electronic reports shall be assembled using a common commercially available software package.

e. Sufficient detail shall be included in the reports so that the results can be recreated.

f. All material properties, loads, and other data from external sources shall contain references to the data source.

4.2.4.2.1 Test Reports

a. Test plans shall be submitted 30 working days before the test and test result reports submitted 45 working days after the test or as specified in the SAP.

b. The intent to run a specific test shall be declared in the SAP.

c. Test plans shall specify test success criteria.

d. Test results shall correlate the test outcomes with the analysis predictions.

4.2.4.2.2 Final and As-Built Assessment Report

a. The responsible organization shall provide a final and as-built assessment of the flight hardware.

b. This assessment shall be accomplished using analyses and test results to establish the flight worthiness of actual flight hardware.

c. The report shall include assessment of significant deviations in materials, workmanship, etc., from the design, as well as analytical adjustment needed as indicated by test results.

c. MS shall be updated for the final and as-built configurations.

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					
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	MDP or spin	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	MEOP, MDP, or MDC as applicable	AFSPCMAN 91-710 and either AIAA S-080, AIAA S-081, or MIL-STD-1522			
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]
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 4.2.1.11 of this Standard.
5. These tests are always required. (See section 4.2.1.8 in this 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; point stress failure mode on ultimate only for composites or adhesive bonds.

APPENDIX A

REFERENCE DOCUMENTS

A.1 Purpose and/or Scope

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

A.2 Government Documents

Department of Transportation/Federal Aviation Administration/Office of Aviation Research

MMPDS-04	DOT/FAA/AR-MMPDS, Metallic Materials Properties Development and Standardization (MMPDS)

MSFC

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

NASA

NASA-SP-8007	Buckling of Thin-Walled Circular Cylinders

A.3 Non-Government Documents

American Society of Mechanical Engineers (ASME)

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