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STRUCTURAL DESIGN REQUIREMENTS AND FACTORS OF SAFETY FOR SPACEFLIGHT HARDWARE

FOR HUMAN SPACEFLIGHT

JULY 15, 2014

National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
Houston, Texas

Structural Design Requirements and Factors of Safety for Spaceflight Hardware For Human Spaceflight

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Prepared By:

Karen S. Bernstein
Structures Branch
Lyndon B. Johnson Space Center

Approved By:

Gregory F. Galbreath
Branch Chief, Structures Branch
Lyndon B. Johnson Space Center

Approved By:

Stanley R. Donahoo for

Bruce Sauser
Division Chief, Structural Engineering Division
Lyndon B. Johnson Space Center

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

REVISION HISTORY AND CHANGE LOG

Rev.	Date	Originator	Description	Approval
Draft	4/28/2010	K. S. Bernstein	RFI Release 1 (Initial version of document to support RFI release of Commercial Crew Transportation Request for Information)	
Baseline	1/31/2011	K. S. Bernstein	- An applicable document number was updated from JSC-65830 to NASA-STD-5020 and the title of the applicable document was revised. - Some of the content regarding structural design requirements for solid rocket motors was clarified. - "Derating" was changed to "design" in the section on fabric structures, and the definition of "derating" was removed from the glossary in section B. - The definition of "A basis" was revised in section B.	
A	10/21/2011	K. S. Bernstein	A change was made to the call-out for AIAA standards S-80 and S-081, which address metallic pressure vessels and composite overwrap pressure vessels. The words "the design requirements specified in" were deleted from each callout. Vendors are expected to use the entire standard, tailored at the point of application. In addition, this release of the document includes format changes to comply with configuration management processes at JSC, and editorial changes in the Forward to update the description of the document. The references to JSC 62550 were updated to NASA-STD-5018, which had not been released when the structures standard was first published. The references to NASA-STD-5020 were reverted back to JSC 65830 because the NASA standard has not yet been released. Reference to the upcoming standard was added as a comment to the requirement. The references to JSC 65831 were updated to NASA-STD-5019, which had not been released when the structures standard was first published.	ES CCB

B	6/4/2014	K. S. Bernstein	A correction was made to the numbering of requirements, starting at STR0045. The way mechanical loads and pressure loads are applied to the Habitable Module were revised. When these conditions exist simultaneously, the structure is assessed for a yield factor of 1.0 and an ultimate factor of 1.4 on both load conditions. Added a section describing environmental seals and pointing to the JSC TPS Standard. There is no shall statement in this new section. The requirement and rationale statements for structural welds were revised to reflect lessons learned on MPCV. Paragraph titles for design requirements on critical seals were modified to clarify which size penetration each requirement applies to.	
B change 1	7/15/14	K.S. Bernstein	Note 1 in the factor of safety table for pressurized systems (Table 3.3.1-6) was revised to align with the new content of section 3.3.2. In section 3.3.1.9 an error was correction. The content of equation 1 had been mistakenly omitted in Rev. A and Rev. B of this document. In the section on combined loads (3.3.2), the equations added in the B revision were modified again and put into a table to clarify how protoflight programs must approach the combined load conditions. Special consideration must be given to habitable modules built with composite materials. Table numbers were changed throughout the document due to the addition of this new table. Rationale statements were modified in sections 3.3.2.1 through 3.3.2.4 to align with the switch from equations to a table and to improve understanding.	

Note: Dates reflect latest signature date of Revision.

FORWARD

This is a standard published by the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) that is intended to provide uniform structural design and factor of safety requirements in support of the development of human-rated spaceflight hardware. The material covered in this standard is based on the consensus judgment of a working group of structural engineers supporting the NASA JSC Structural Engineering Division, and founded on agency-wide consensus positions developed under the Constellation Program and lessons learned by the Space Shuttle Program's Structures Working Group.

The technical content of this standard is primarily based on the Constellation Program Structural Design and Verification Requirements (SDVR) document, CxP 70135 Change 004. It incorporates lessons learned from implementation of the SDVR within the CxP Orion and Ares projects, which highlighted a number of issues. The goal in writing this new standard was to maintain intent of the original requirement while reorganizing the content to improve document structure, clarify intent or remove redundancy. In some cases, requirements were removed because they are addressed in other standards being released concurrently, for example the new standard for fasteners and mechanical joints. In addition, detailed rationale statements were added for each requirement to provide guidance on interpretation and, in some cases, a discussion of the recommended verification method.

This standard focuses on design and factor of safety requirements. Details related to methods of verification of each requirement will be negotiated and approved via the structural verification plan submitted to the Technical Authority at the responsible NASA center for review and approval.

This standard was compiled with contributions from Rod Kujala/JSC, Karen Bernstein/JSC, Vince Fogt/JSC and Paul Romine/JSC.

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1 INTRODUCTION

1.1 PURPOSE

This document establishes the structural requirements for human-rated spaceflight hardware including launch vehicles, spacecraft and payloads. These requirements are applicable to Government Furnished Equipment activities as well as all related contractor, subcontractor and commercial efforts. These requirements are not imposed on systems other than human-rated spacecraft, such as ground test articles, but may be tailored for use in specific cases where it is prudent to do so such as for personnel safety or when assets are at risk.

The requirements in this document are focused on design rather than verification. Implementation of the requirements is expected to be described in a Structural Verification Plan (SVP), which should describe the verification of each structural item for the applicable requirements. The SVP may also document unique verifications that meet or exceed these requirements with NASA Technical Authority approval.

1.2 APPLICABILITY

This document recommends engineering practices for NASA programs and projects. It may be cited in contract, program, and other Agency documents as a technical requirement.

Determining the suitability of this standard and its provisions is the responsibility of program/project management and the performing organization. This standard is applicable to the development of new hardware. Applicability to existing hardware with previous flight history will be addressed in the program Systems Requirements Document (SRD). Project-specific tailoring may generate other project-specific requirements that are derivatives of this standard.

Other program standards such as International Space Station (ISS) requirements may also be applicable. For ISS specific events refer to the SSP 50808, International Space Station (ISS) to Commercial Orbital Transportation Services (COTS) Interface Requirements Document (IRD).

The requirements specifically excluded from this standard are materials and processes, design loads determination, fracture control, glass, fasteners, liquid propulsion engines greater than 6000 lbs thrust, ISS specific events, ground support equipment and facilities. Appropriate standards should be used for these topics, as applicable.

The scope of this document is to define the structural design requirements for primary and secondary structures sometimes also called safety critical structures.

1.3 IMPLEMENTATION

The convention used in this document to distinguish between requirements and goals is as follows: "shall" is used to indicate requirements that must be implemented and verified, and "should" is used to indicate goals that must be addressed by the design but do not need to be verified. Each "shall" requirement is contained in its own subsection and indicated with a unique number using the format: [STRxxxx] for traceability purposes.

The purpose of the Rationale statement is to indicate why the requirement is needed, the basis for its inclusion in a requirements document, and to provide context and examples to stakeholders. It is important to note that the rationales are not binding and only provide supporting information.

1.3.1 Tailoring

The responsible NASA Center will charter a Loads and Structures Panel (LSP) for reviewing and approving the implementation of the requirements of this document. The LSP is the responsible NASA Technical Authority for the program for structural design requirements.

In the event that a particular requirement of this document cannot be met for a specific component, alternative tailored requirements may be proposed. Tailored requirements must be demonstrated to be "risk neutral" per the program risk assessment process. Risk neutral approaches have equivalent risk to the requirements in this document. The approach will be approved by the NASA LSP and documented in the SVP.

1.4 CONSTRAINTS AND PRECONDITIONS

The criteria of this document were developed in the context of structural designs that are amenable to engineering analyses by current state-of-the-art methods and conforming to standard aerospace industry practices. More specifically, the designs are assumed to use materials having mechanical properties that are well characterized for the intended service environments and all design conditions. For reusable and multi-mission hardware, these criteria are applicable throughout the service life and all of the missions.

Design considerations should include material property degradation under the service environments. Material allowables should be chosen to minimize the probability of structural failure due to material variability. Allowables should be based on sufficient material tests to establish values on a statistical basis. Further, the service environments and limit loads should be well defined. Aerospace standard manufacturing and process controls should be used in hardware fabrication and handling. Test hardware should be representative of the flight configuration.

2 DOCUMENTS

The documents listed as applicable documents contain provisions that constitute requirements of this standard as cited in the text of Section 3. Reference documents are provided for additional information or to provide guidance to meet the requirements in Section 3 but are not levied as requirements.

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

2.1 APPLICABLE DOCUMENTS

ANSI/AIAA S-080-1998	Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components, September 13, 1999
ANSI/AIAA S-081A-2006	Space Systems - Composite Overwrapped Pressure Vessels (COPVs), July 24, 2006
JSC 65829	Loads and Structural Dynamics Requirements for Spaceflight Hardware
JSC 65830, rev. 2	Interim Requirements and Standard Practices for Mechanical Joints with Threaded Fasteners in Spaceflight Hardware
NASA-STD-5019	Fracture Control Requirements for Spaceflight Hardware
NASA-STD-5012	Strength and Life Assessment Requirements for Liquid Fueled Space Propulsion System Engines, Baseline, June 13, 2006

2.2 REFERENCE DOCUMENTS

AIAA S-110-2005	Space Systems – Structures, Structural Components, and Structural Assemblies, July 12, 2005
DOT/FAA/AR-MMPDS-01	Metallic Materials Properties Development and Standardization, January 2003
JSC 19652	Instructions for the preparation of Stress Analysis Reports, Revision A, September 1987
MIL-DTL-83420M	Wire Rope, Flexible, for Aircraft Control, General Specification for, w/ Amendment 1, February 17, 2009
MSFC-DWG-20M02540	Assessment of Flexible Lines for Flow Induced Vibration, Revision E, Jan 15, 1992
MSFC-SPEC-626	Test Control Document for Assessment of Flexible Lines for Flow Induced Vibration, February 28, 1990

MIL-HDBK-17-2	Composite Materials Handbook Volume 2, Polymer Matrix Composites Materials Properties, Revision F, June 17, 2002
MIL-HDBK-17-4	Composite Materials Handbook Volume 4, Metal Matrix Composites, Revision A, June 17, 2002
MIL-HDBK-17-5	Composite Materials Handbook Volume 5, Ceramic Matrix Composites, June 17, 2002
NASA SP-8007	Buckling of Thin-Walled Circular Cylinders, September 1965
NASA-STD-5018	Strength Design and Verification Criteria for Glass, Ceramics and Windows in Human Space Flight Applications, September 2006
NASA-STD-5020	Requirements and Standard Practices for Mechanical Joints with Threaded Fasteners in Spaceflight Hardware
NASA-STD-6016	Standard Materials and Processes Requirements for Spacecraft, Baseline, July 11, 2008
NASA-TM-X-73305	Astronautic Structures Manual, August 1975
NSTS 08123	Certification of Flex Hoses and Bellows for Flow Induced Vibration, Revision C, April 12, 1994
NSTS/ISS 18798	Interpretations of NSTS/ISS Payload Safety Requirements, Revision B, September 1997
NWC TP 6575	Parachute Recovery Systems Design Manual, March 1991
SMC-S-005	Space and Missile Systems Center Standard, Space Systems – Flight Pressurized Systems, June 3, 2009
SSP 50808	International Space Station (ISS) to Commercial Orbital Transportation Services (COTS) Interface Requirements Document (IRD), Revision A, May 9, 2008.

2.3 ORDER OF PRECEDENCE

This document establishes requirements for structural design and test factors but these factors do not supersede or waive established Agency requirements found in other documentation. Conflicts between this standard and other requirements documents will be resolved by the NASA Technical Authority.

3 STRUCTURAL REQUIREMENTS

3.1 STRUCTURAL ASSESSMENT PROGRAM

3.1.1 Structural Verification Plan

[STR0001] The organization responsible for structural design shall develop and maintain a comprehensive Structural Verification Plan (SVP) that documents the full structural analysis, test, and assessment program for approval by the NASA Technical Authority.

> <u>*Rationale:*</u> *The purpose of this plan is to establish an understanding and agreement between the organization responsible for structural design and the NASA Technical Authority. The SVP development, negotiation and approval process serves as the means to tailor the design requirements for their unique application to each design and organization, ensuring the meet-or-exceed implementation of the requirements as described in Section 1.4.*
>
> *A comprehensive SVP specifies how the design requirements of this document will be met and verified. It demonstrates that the organization responsible for design and development understands all relevant requirements and has implemented them in a consistent and integrated manner. The SVP will identify the analyses, tests, inspections, demonstrations or appropriate combinations of these that comprise verification of the requirements in this document.*
>
> *The content and format of the SVP is not formally defined; however the document should include the following as a minimum;*
>
> a. *A requirements applicability matrix that identifies which requirements are applicable to the system or hardware being delivered and rationale for exclusion if not levied.*
> b. *A list of applicable requirements documents.*
> c. *A brief description and sketches of hardware primary and secondary structure.*
> d. *The proposed method for verification of the primary and secondary structure items. Include proposed factors of safety, stress analysis methodology (i.e., hand or computer analysis), verification approach for the analytical models that will be used for stress calculations, and the proposed strength testing. Rationale must be provided if no strength testing is planned.*
> e. *Description of special materials (e.g., composites, beryllium, and glass) and the corresponding special measures which will be taken to verify their strength according to the requirements of this or other applicable requirements documents*

f. Brief description of the source of material allowables which will be used for the strength analysis for each primary and secondary structure item.

g. Specific implementation of fastener and preloaded joint requirements as defined in JSC 65830, rev. 2.

h. Derivation of design loads for primary structure, secondary structure, and components or experiments as described in JSC 65829.

i. Proposed method for dynamic math model verification of the primary and significant secondary structural hardware as defined in JSC 65829. Rationale must be provided if no dynamic testing is planned.

j. Summary and schedule of all loads and stress analyses, planned tests (includes strength, pressure, dynamic, random vibration, and acoustic tests), and math model correlation activities as described in this document and other relevant specifications.

The initial delivery of the SVP should be at the Preliminary Design Review (PDR). The fidelity at PDR should be detailed enough to define the structural verification approach including planned development testing. The SVP must be maintained and updated because the hardware design and the design data will evolve as the data such as loads, mass properties, temperatures and other environments are verified. The SVP should be updated between PDR and CDR to support these evolutions and to update the structural verification approach, as needed. By CDR, the SVP should be finalized and approved by the NASA Technical Authority.

It is probable that the design database will mature after Critical Design Review (CDR), and design changes will need to be considered in response to these developments. The organization responsible for structural design will need to establish a program to evaluate how post-CDR changes in the natural and induced environments may affect the hardware and the type of document updates that will be provided.

3.1.2 Stress Analysis

[STR0002] Design stress analysis reports, including a margin of safety summary table and an indentured parts list, shall be prepared in accordance with standard aerospace industry practices for flight hardware and available for review by the NASA Technical Authority.

<u>Rationale</u>*: The stress analysis report will document analysis results and conclusions. The purpose of the stress analysis report is to verify the capability of the respective flight hardware to meet the design requirements specified in this document. At a minimum, content similar to that summarized in JSC 19652, Instructions for the preparation of Stress Analysis Reports, should be included.*

The margin of safety summary table shows the minimum margin of safety for the flight vehicle or element structure, the critical condition or mode of failure and the critical load for the flight vehicle or element structure.

An indentured parts list identifies each and every part of the vehicle. If parts are non-structural or acceptable by inspection, the summary should state so. If a part is accepted by similarity to other parts, the summary table should indicate this clearly.

Stress analysis reports are typically prepared in support of the following four design reviews: Preliminary Design Review (PDR); Critical Design Review (CDR); Design Certification Review (DCR); and Flight Readiness Review (FRR).

3.1.3 Structural Test Plans

[STR0003] A test plan showing the proposed loading conditions, structural configuration to be tested, and method of test, including load application and instrumentation, shall be prepared and submitted to the NASA Technical Authority for each unique structural test.

Rationale: The SVP should describe the structural tests that will be performed and identify which test plans will be submitted to the NASA Technical Authority. Test plans for qualification tests, proof tests and model verification are generally covered by this requirement.

The test plan includes a summary of the objectives of the test, a description of the test article configuration including locations of instrumentation, a description of the test boundary conditions, a summary of the applied loads and their method of application, a summary of projected internal loads and the stresses and forces compared to predicted flight conditions.

3.1.4 Structural Test Reports

[STR0004] A test report showing the results of each unique structural test shall be prepared and submitted to the NASA Technical Authority.

<u>Rationale</u>: The test report includes stresses and forces developed during test and a summary of test data which is applicable to the structural verification. The report should also include a comparison of the test results to the analysis of the test configuration, demonstrating that the test objectives were met.

3.2 STRUCTURAL DESIGN

Structures are components and assemblies designed to sustain loads or pressures, provide stiffness and stability, or provide support or containment. Internal components are excluded if their failure would not result in a critical or catastrophic hazard.

3.2.1 Structural Strength

3.2.1.1 Ultimate Structural Strength

[STR0005] Flight hardware structure shall maintain structural integrity with +0.00 or positive Margin(s) of Safety (MS) when exposed to limit loads multiplied by ultimate factors of safety during the service life, including the effect of aging on the hardware.

<u>Rationale</u>: Structural integrity is lost when the structure can no longer maintain its load-carrying capacity.

Limit loads multiplied by ultimate factors of safety are sometimes called "ultimate loads".

Aging is intended to account for degradation of mechanical properties due to service life environments, such as potential structural erosion caused by plasma environmental effects, atomic oxygen, and other natural environments, during the design life.

Factor of safety requirements are contained in Section 3.3.1.

A definition of service life is provided in Section B.

3.2.1.2 Detrimental Deformation

[STR0006] Flight hardware structure shall have no detrimental deformation when exposed to limit loads multiplied by yield factors of safety during its service life.

<u>Rationale</u>: Detrimental deformation is structural deformation, deflection, or displacement which causes any of the following:

a. *Causes unintentional contact, misalignment, or divergence between adjacent components*
b. *Causes significant internal load redistribution in a structure*
c. *Causes a component to exceed the dynamic space envelop established for that component*
d. *Reduces the strength or rated life of the structure below specified levels*
e. *Degrades the effectiveness of thermal protection coatings or shields*
f. *Jeopardizes the proper functioning of equipment*
g. *Endangers personnel*
h. *Degrades the aerodynamic or functional characteristics of the vehicle*
i. *Reduces confidence below acceptable levels in the ability to ensure flight-worthiness by use of established analytical or test techniques*
j. *Induces leakage above specified rates*

Protoflight hardware structure will have no detrimental deformation when exposed to acceptance or proof test loads.

3.2.1.3 Yielding during Ground Transportation

[STR0007] Flight hardware structure shall not yield when exposed to ground limit loads multiplied by yield factors of safety during ground transportation, rollout or handling operations.

<u>Rationale</u>: Yielding of the hardware during transportation could damage the structure, rendering the service life inadequate. Loads during ground

transportation should be limited to avoid any damage, including non-detrimental yielding.

3.2.1.4 Yield Margins of Safety

[STR0008] Flight hardware structure shall have +0.00 or positive Margin(s) of Safety (MS) for all yield design load conditions, including the effect of aging on the hardware, except for cases of non-detrimental deformation.

> *Rationale: Structural yield margins of safety need to be assessed for all cases where material yield is detrimental.*
>
> *In certain cases, yielding of structure may be acceptable if all of the following conditions are satisfied:*
>
> a. *The structural integrity of the component should be demonstrated by adequate analysis and/or test.*
>
> b. *The service life requirements are met.*
>
> c. *The load case is not related to any ground handling or transport conditions.*
>
> *Unless otherwise specified, hydraulic, electrical, and other systems are not required to operate at loads and related deformations in excess of limit load.*

3.2.2 Buckling and Crippling

3.2.2.1 Buckling and Crippling Analysis

[STR0009] Design analyses of thin walled shell structures subject to buckling load conditions during the service life shall account for the differences between idealized model geometry and the physical structure.

> *Rationale: Discrepancies between analytically and empirically derived buckling load capability are due in part to the differences between idealized model geometry and the physical structure. “Knockdown factors” (correlation coefficients) are used to adjust predicted values to account for the differences. Typical knockdown factors for thin walled circular cylinders are listed in NASA SP-8007, Buckling of Thin-Walled Circular Cylinders.*
>
> *Evaluations of buckling conditions should consider the combined action of primary and secondary stresses and their effects on general instability, local or panel instability, and crippling.*

3.2.2.2 Structural Members Subject to Instability

[STR0010] Flight hardware structure shall not collapse due to buckling when exposed to limit loads multiplied by ultimate factors of safety during the service life.

> *Rationale: All structural components that are subject to compressive and/or in-plane shear stresses under any combination of ground loads, flight loads, or*

loads resulting from temperature changes need to consider buckling failure modes.

Evaluation of buckling conditions should consider the combined action of primary and secondary stresses and their effects on general instability, local or panel instability and crippling.

3.2.2.3 Deformation Due to Buckling

[STR0011] Flight hardware structure shall not deform in any manner that degrades the function of the structure or produces unaccounted for changes in loading due to buckling when limit loads are applied unless the structure was designed to crush during the load event.

> <u>Rationale</u>: *All structural components that are subject to compressive or in-plane shear stresses under any combination of ground loads, flight loads, or loads resulting from temperature changes need to consider buckling failure modes.*
>
> *Evaluations of buckling conditions should consider the combined action of primary and secondary stresses and their effects on general instability, local or panel instability, and crippling.*
>
> *Structures designed to crush may only collapse during the event for which the design intended.*

3.2.3 Structural Life

3.2.3.1 Fatigue Life

[STR0012] Flight hardware structure shall have a minimum fatigue life of 4.0 times the service life.

> <u>Rationale</u>: *Flight hardware structure design should preclude failure resulting from cumulative damage due to cyclic or repeated loading and sustained stress.*
>
> *Methods used for load spectra development applicable to general flight structure are defined in JSC 65829, Loads and Structural Dynamics Requirements for Spaceflight Hardware.*
>
> *The design assessment should consider all relevant load cycles over the service life as well as self-induced conditions due to operation.*
>
> *Fatigue life may be evaluated using a suitable method such as Miner's Method unless covered by fracture control.*

3.2.3.2 High-Cycle Fatigue Life

[STR0013] Flight hardware structure subjected to high-cycle fatigue shall have a minimum fatigue life of 10.0 times the service life.

> <u>Rationale</u>: *The definition of high-cycle fatigue is included Section B. A definition of low-cycle fatigue is also provided for comparison.*

3.2.3.3 Creep Avoidance

[STR0014] All flight hardware structure 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 service life.

> *Rationale: Materials are to be selected to preclude accumulated damage from creep in the flight hardware environment.*
>
> *If selection of a structural material which exhibits creep phenomena in the flight hardware service environment is unavoidable, then approval of the NASA Technical Authority is required prior to use.*
>
> *Details of the material selection and method of creep assessment should be included in the SVP.*

3.2.3.4 Creep Life

[STR0015] Flight hardware structure shall have adequate structural life with a creep life of 4.0 times the service life.

> *Rationale: Flight hardware design should preclude accumulated damage from creep in the service life environment.*
>
> *Details of the material selection and method of creep assessment should be included in the SVP.*
>
> *Creep life may be evaluated using a suitable method such as Time-Fraction Rule to determine total damage.*

3.2.4 Metallic Structures

Factor of safety requirements for metallic flight structures are contained in Section 3.3.1.2. Specific requirements for beryllium structures are provided in Section 3.3.1.2.1.

3.2.5 Non-Metallic Structures

Factor of safety requirements for non-metallic flight structures are contained in Section 3.3.1.3. Requirements for soft goods and their factors of safety are included in Sections 3.2.6 and 3.3.1.4 respectively. This document does not cover glass requirements, which are contained in NASA-STD-5018, Strength Design and Verification Criteria for Glass, Ceramics and Windows in Human Space Flight Applications.

3.2.5.1 General Design Requirements for Composite/Bonded Structures

[STR0016] Structural integrity of all composite and bonded flight structure, including bonded joints, shall be verified by testing that takes into account exposure to worst-case environmental conditions during the service life.

> *Rationale: Composite components are to be subjected to qualification and acceptance proof testing. Qualification testing is performed to ensure adequate design strength. Proof testing is to ensure flight component quality and integrity.*

Acceptance proof test loads should not exceed 80 percent of the composite material ultimate strength.

Testing may be accomplished at the flight component or subassembly level if the loads on the flight component or sub-assembly envelope those in a fully assembled test article. Testing of fracture critical parts may be accomplished in conjunction with residual strength verification tests of damaged and flawed components per NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware to the appropriate test factors.

Details of the testing, including any rationale to exclude certain tests, should be defined in the SVP.

3.2.5.2 Composites/Bonded Structure Design and Analysis Practices

[STR0017] The designer/manufacturer shall use only manufacturing processes and controls (coupon tests, sampling techniques, building block approach, etc.) and design standards and analysis practices that are demonstrated to be reliable and consistent with established aerospace industry practices for composite/bonded structures.

<u>Rationale</u>*: The process dependent nature of composite materials necessitates reliance on well established design and fabrication standards as well as process/quality control procedures. This helps to ensure adequate final flight component design and quality.*

The intent of this requirement is to address geometry, size scale effects and other development uncertainties.

3.2.5.3 Composite Structure Inadvertent Damage Protection

[STR0018] A plan to minimize inadvertent damage to manufactured composite structural components that may result from handling, transportation, storage or final assembly shall be prepared by the hardware developer.

<u>Rationale</u>*: Inherent susceptibility of composite materials to damage necessitates well defined handling, transportation, storage or final assembly procedures.*

3.2.6 Structural Soft Goods

Factor of safety requirements for structural soft goods are contained in Section 3.3.1.4. All deceleration devices are considered structural systems and are required to show compliance with the appropriate requirements contained within this document.

3.2.7 Parachute and Parafoil Systems

Factor of safety requirements for parachute and parafoil systems are contained in Section 3.3.1.5.

3.2.8 Pressurized Hardware

Factor of safety requirements for pressurized hardware are contained in Section 3.3.1.6.

Section B contains a definition of pressurized hardware. Separate definitions are provided for pressure vessels, habitable modules and pressurized structures to differentiate between them.

3.2.8.1 Pressurized Hardware Design Requirements

[STR0019] Pressurized hardware shall maintain dimensional stability required for functionality of structural and mechanical attachments, pressure connections, and openings for doors or hatches throughout their service life in the applicable environments.

> *Rationale: The intent of this requirement is to ensure successful function and operation of structural and mechanical attachments, pressure connections, and openings for doors or hatches by taking into account worst-case dimensional variations over the service life environment. This requirement also applies to habitable modules.*

3.2.8.2 Pressure Control

[STR0020] Pressure regulators, relief devices and thermal control systems (e.g. heaters) shall collectively be two-fault tolerant from causing the pressure to exceed the Maximum Design Pressure (MDP) of the system.

> *Rationale: A definition of Maximum Design Pressure is provided in Section B. Two-fault tolerance pressure control is a heritage approach used for Shuttle payload and International Space Station requirements to define maximum system pressure used for structural design purposes.*
>
> *In cases where MDP is not defined because two-fault tolerant pressure control is not provided, a Maximum Expected Operating Pressure (MEOP) condition may be substituted with approval of the NASA Technical Authority. This substitution is limited to cases where a two-fault tolerant pressure regulation device logic is unobtainable or impractical, such as solid rocket motors, combustion chambers, and pyrotechnic devices. Solid rocket motors, combustion chambers, and pyrotechnic devices may use MEOP without special approval.*
>
> *SMC-S-005, Section 4.1.2 provides guidance for performing a system functional analysis to determine that the pressurized system will not lead to unsafe conditions. This guidance should be applied considering any two malfunctions or errors to be compliant with the two-fault tolerance requirement.*
>
> *NSTS/ISS 18798 provides guidance for using a single burst disk in place of the second and third controls in a two-fault tolerant pressure control system. This guidance is documented in the memo TA-88-074, “Fault Tolerance of Systems using Specially Certified Burst Disks.”*

3.2.8.3 Relief Devices

[STR0021] All pressure relief devices shall provide full-flow relief at a pressure of 110% MDP or lower.

Rationale: Flow rate capability of the individual pressure relief devices in the redundant system should be sufficient to prevent over-pressure or rupture. SMC-S-005, Section 5.8 provides guidance for the design and verification of pressure relief devices.

3.2.8.4 Metallic Pressurized Hardware

[STR0022] Metallic pressure vessels, pressurized structures, special pressurized equipment and pressure components shall comply with ANSI/AIAA-S-080, Standard for Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components, with the following exceptions:

a. Applicable loads and environments to be used in place of those defined in the AIAA standard are derived following JSC 65829, Loads and Structural Dynamics Requirements for Spaceflight Hardware.

b. Applicable minimum factors of safety to be used in place of those defined in the AIAA standard are defined in Section 3.3.1.6.

c. Applicable design pressures to be used in place of those defined in the AIAA standard are defined in Section 3.2.8.2.

d. Applicable design pressures to be used in place of those defined in the AIAA standard for cryostats (dewars) are the higher of MDP or the pressure achieved under maximum venting conditions.

Rationale: The AIAA standard for metallic pressurized hardware is tailored to account for human spaceflight safety factor requirements and design loads.

3.2.8.5 Composite Overwrapped Pressure Vessels

[STR0023] Composite Overwrapped Pressure Vessels (COPVs) shall comply with ANSI/AIAA-S-081, Standard for Space Systems - Composite Overwrapped Pressure Vessels (COPVs), with the following exceptions:

a. Applicable loads and environments to be used in place of those derived following the AIAA standard are defined in JSC 65829, Loads and Structural Dynamics Requirements for Spaceflight Hardware.

b. Applicable minimum factors of safety to be used in place of those defined in the AIAA standard are defined in Section 3.3.1.6.

c. Applicable design pressures to be used in place of those defined in the AIAA standard are defined in Section 3.2.8.2.

Rationale: The AIAA standard for COPVs is tailored to account for human spaceflight safety factor requirements and design loads.

3.2.8.6 Pressure Stabilized Structures

[STR0024] Pressure stabilized structures shall maintain the minimum required internal pressure to withstand limit load multiplied by the appropriate ultimate factor of safety for all phases of service life.

> *<u>Rationale</u>: Pressure stabilized structures are those structures that must contain a minimum pressure to maintain structural integrity. The applicable factors of safety are those defined for pressurized structures.*
>
> *NSTS/ISS 18798 provides guidance to design a single-fault tolerant pressure monitoring technique to ensure the minimum design factors of safety will exist when the structural load is applied. This guidance is documented in the memo TA-89-064, "Verification of the National Space Transportation System (NSTS) Payload Propellant Tank Pressures for Pressure Stabilized Tanks."*

3.2.8.7 Doors and Hatches in Habitable Modules

[STR0025] Habitable modules shall withstand applicable loads with the doors or hatches in the open and closed condition for the applicable ground and mission environments.

> *<u>Rationale</u>: Habitable module structural integrity must be maintained throughout all phases of service life for all hardware configurations, including conditions where the hatches and doors are opened or closed.*

3.2.8.8 Flow-Induced Vibrations

[STR0026] All flexible hoses and bellows shall be designed to exclude or control flow-induced vibrations.

> *<u>Rationale</u>: The configuration of flexible hose and bellow designs should mitigate any detrimental effects on structural integrity or life caused by flow induced vibration.*
>
> *Preferred analytical methods for assessment of formed convolutes are provided in MSFC-DWG- 20M02540, Assessment of Flexible Lines for Flow Induced Vibration.*
>
> *Methods for certification of hardware are provided in NSTS 08123, Certification of Flex Hoses and Bellows for Flow Induced Vibration and MSFC-SPEC-626, Test Control Document for Assessment of Flexible Lines for Flow Induced Vibration.*

3.2.8.9 Restraints for Flexible Hoses

[STR0027] Flexible hose installations shall be restrained to prevent whiplash in the event of a burst.

> *<u>Rationale</u>: SMC-S-005, Section 5.11.2 provides guidance for designing the restraints of flexible hose installations that are six feet long or greater, including*

factors of safety and the method to calculate the design load. The need for restraints on flex hoses shorter than six feet should be evaluated based on the specific design and environmental conditions for each installation and the potential result of whiplash.

3.2.8.10 Secondary Volumes

[STR0028] Secondary compartments or volumes that are integral or attached by design to pressurized system components and can become pressurized as a result of a credible single barrier failure in the pressurized system component shall be designed for pressure with a minimum factor of safety of 1.5 based on MDP of the pressurized system.

<u>Rationale</u>*: If external leakage would not present a catastrophic hazard, the secondary volume may be vented or equipped with a relief provision in lieu of designing for system pressure. Failures of redundant seals in series that have been acceptance pressure tested individually prior to flight are not considered to be a credible single barrier failure. Failures of structural parts, such as pressure lines and tanks, or welded/brazed joints designed in accordance with Section 3.2.8.4 are not considered to be a credible single barrier failure.*

Metal bellows or diaphragms are normally considered to be credible single barrier failure unless they are designed to the pressure component factors of safety in Section 3.3.1.6 and meet the life requirements in Section 3.2.3.

3.2.9 Liquid Propulsion Engine Structures

Factor of safety requirements for liquid fueled space propulsion systems with less than 6000 pounds of thrust are contained in Section 3.3.1.7. This document does not cover requirements for larger engines, which are contained in NASA-STD-5012, Strength and Life Assessment Requirements for Liquid Fueled Space Propulsion System Engines.

3.2.9.1 Engines with Less Than 6000 Pounds of Thrust

[STR0029] The design of engine structures and engine compartments in liquid fueled space propulsion systems with less than 6000 pounds of thrust shall comply with the following sections of NASA-STD-5012, Strength and Life Assessment Requirements for Liquid Fueled Space Propulsion System Engines:

a. Section 4.2.1.11, “Other Design Factors” in conjunction with NASA-STD-5012, Table 1
b. Section 4.2.4.3.b, “Creep Analysis” to demonstrate 10.0 times the service life
c. Section 4.2.2.3, “Acceptance/Proof Tests” to limit proof loads to 95% on net section yield and 75% on net section ultimate

<u>Rationale</u>*: NASA-STD-5012 is not applicable to engines with a thrust less than 6000 pounds. These requirements plus the factor of safety requirements in Section 3.3.1.7 are a tailoring of NASA-STD-5012 for smaller engines.*

3.2.10 Solid Rocket Motors

Factor of safety requirements for solid rocket motors are contained in Section 3.3.1.8. Applicable design pressures to be used in place of those defined in the AIAA standards are defined in Section 3.2.8.2. Solid rocket motors may use MEOP without special approval.

3.2.11 Rotating Machinery

Factor of safety requirements for rotating machinery are contained in Section 3.3.1.9. Examples of rotating machinery include motors, gyroscopes, flywheels, transmissions, high-speed gears, and pumps that are not part of the liquid propulsion engine system. Liquid propulsion engine systems are covered by Section 3.2.9.

3.2.11.1 Design Loads for Rotating Machinery

[STR0030] Design loads for rotating machinery shall consider all applicable loads over the service life including self-induced loads due to operation.

> Rationale: The design load case definition should consider all relevant loads and load cycles over the service life as well as self-induced conditions due to operation.

3.2.11.2 Rotor Dynamics

[STR0031] Critical speeds shall not be of a type or of a frequency response that would be deleterious to the safety and operation of the rotating machinery system.

> Rationale*: The design load case definition should consider all relevant loads and load cycles over the service life as well as self-induced conditions due to operation. The required frequency margins for any rotating machinery system should be specified by the system's procuring authority. Safe operational and Maximum Design Speeds (MDS) must be defined to ensure safe operation and structural integrity and to prevent over-speed of the system.*

3.2.11.3 Stability Requirements for Rotating Machinery

[STR0032] Rotating machinery design shall be free of instability.

> Rationale*: Acceptable methods to prevent instability and permit stable performance include vibration isolation, damping or related means.*

3.2.11.4 Strength Requirements for Rotating Machinery

[STR0033] Rotating machinery components shall maintain structural integrity at Maximum Design Speed (MDS) taking into account the applicable factors of safety.

> Rationale*: To ensure adequate design margins of safety, stresses induced at maximum design speed must be increased by the appropriate factors of safety.*

Maximum Design Speed is defined in Section B. Factor of safety requirements for rotating machinery are contained in Section 3.3.1.9.

3.2.12 Wire Rope and Cables

Factor of safety requirements for wire rope and cables used as part of a spacecraft structural system are contained in Section 3.3.1.10.

3.2.13 Fasteners and Fastened Joints

[STR0034] Structural fasteners and fastened joints shall comply with JSC 65830, rev. 2, Interim Requirements and Standard Practices for Mechanical Joints with Threaded Fasteners in Spaceflight Hardware.

> *Note: When released, NASA-STD-5020, Requirements and Standard Practices for Mechanical Joints with Threaded Fasteners in Spaceflight Hardware, may be used in place of JSC 65830.*
>
> *Rationale: Fastened joints themselves need to maintain structural integrity for failure modes such as fastener bearing on the joint, fastener tear-out of the joint and insert pull-out of the joint. For composite joints, there is also the potential need for the joint itself to maintain structural integrity for pull-through of the fastener head (or nut pull-through) as well as for crushing of the joint due to applied preload for the fastener. These are considerations that are not covered in JSC 65830 or NASA-STD-5020 and should be addressed in the SVP.*
>
> *Factor of safety requirements for fasteners and fastened joints are defined by the appropriate factors of safety for the joined structure such as Section 3.3.1.2 for metallic flight structures and Section 3.3.1.2 for joints considered to be discontinuities in composite structures. A specific fitting factor is defined in Section 3.3.1.11.*

3.2.14 Seals

The requirements in this section apply to critical seals. A seal is a critical seal if it meets any of the following:

a. a seal through which leakage would constitute a catastrophic or critical failure within habitable module pressure shells,

b. a seal through which atmosphere within any habitable volume module may leak to the external environment, or

c. a seal through which flow may intrude into the spacecraft habitable module during atmospheric entry.

This document does not define seal performance or leak rate requirements, which are typically provided in the system requirements or subsystem specifications. Other requirements may define redundancy requirements for items not considered to be critical seals above. Safety requirements and failure analysis may define additional redundancy requirements to the ones listed below.

Factor of safety requirements for seal assemblies are defined by the appropriate factors of safety for the sealed structure such as Section 3.3.1.2 for metallic flight structures and Section 3.3.1.6 for pressurized hardware.

3.2.14.1 Critical Seal Redundancy for Sealing Penetrations Smaller than or equal to 0.5”

[STR0035] Critical seals with a major outer diameter less than or equal to 0.5 inches shall have a minimum of one seal at the interface.

> <u>Rationale</u>: *This requirement applies for feed-through connection, rotary, window, hatches/doors, mating mechanisms, and structural seals. Feed-through connections include valves, gages and transducers. Critical seals should be leak tested at the assembly level after final installation prior to launch. For hatches/doors that are sealed immediately prior to launch this may constitute complete testing in the assembly building and abbreviated testing at the pad.*

3.2.14.2 Critical Seal Redundancy for Sealing Penetrations Larger than 0.5”

[STR0036] Critical seals with a major outer diameter greater than 0.5 inches shall have a minimum of two seals at the interface.

> <u>Rationale</u>: *This requirement applies for feed-through connection, rotary, window, hatches/doors, mating mechanisms, and structural seals. Feed-through connections include valves, gages and transducers. Critical seals should be leak tested at the assembly level after final installation prior to launch. For hatches/doors that are sealed immediately prior to launch this may constitute complete testing in the assembly building and abbreviated testing at the pad.*

3.2.14.3 Critical Seal Test Ports

[STR0037] Assemblies containing critical seals with a major outer diameter greater than 6 inches shall include leak test ports and conductance grooves within the seal interstitial area to accommodate redundant seal verification.

> <u>Rationale</u>: *Leak test ports and conductance grooves are needed to leak test each seal individually.*

3.2.14.4 Sealing Interfaces on the Outer Mold Line

Seals for interfaces on the outer mold line, such as those at access panels, windows, hatches and control surfaces are addressed in JSC-65827, the standard for Thermal Protection System Design.

3.3 DESIGN FACTORS

3.3.1 Factors of Safety

This section contains factors of safety applicable to primary and secondary structures. The factors of safety should be used for analysis to demonstrate positive margins of safety and for qualification, proof or acceptance tests as specified in the applicable tables. Yielding is permitted in some instances.

The factors of safety tables in this section include acceptance, proof and qualification test factors. The proof factor is the minimum required. A higher proof test factor may be determined by fracture mechanics analysis when the proof test is used for flaw screening. Certain acceptance and proof test requirements may exceed the minimum factor of safety on yield for the hardware being provided. Hardware providers should ensure that no detrimental deformation will occur during acceptance testing.

Current standard NASA structural verification criteria are deterministic, and experience has shown these deterministic criteria to be adequate. The probabilistic method uses knowledge (or assumptions) of the statistical variability of the design variables to select design criteria for achieving an overall acceptable reliability and confidence level. Any proposed use of probabilistic criteria to supplement deterministic factors of safety requires NASA Technical Authority approval.

Guidelines for combining mechanical stresses may be found in Section A3 of NASA-TM-X-73305, Astronautic Structures Manual.

The factors apply to nominal design conditions, which may include abort scenarios. Program-defined emergency design loads are generally applied with an ultimate factor of safety of 1.0. The specific conditions that constitute nominal and emergency cases are defined in the SRD.

Factors of safety are in some cases higher for ISS specific events which are documented in SSP 50808.

3.3.1.1 Mechanical and Thermal Factors of Safety

[STR0038] The factors of safety and test factors shall be applied to both mechanical and thermal stresses/loads.

> <u>Rationale</u>*: A majority of the factors of safety in this document apply to mechanical stresses and loads. Examples of mechanical loads are: inertial, aerodynamic pressure, random vibration, shock and crew-induced loads.*
>
> *Thermal stresses and loads are derived from thermal models that are often uncertain and unverified, and typically are available later in the design phase than required for structural design. The same factor of safety is applied to thermal stresses and loads as mechanical due to this uncertainty. A lower factor of safety may be proposed if the thermal data used for structural design can be demonstrated to have a low level of uncertainty.*

3.3.1.2 Metallic Structures

[STR0039] Metallic flight hardware structure shall be designed and tested to the minimum factors of safety specified in Table 3.3.1-1.

> Rationale: *Criteria are specified for design and test of flight articles when the actual flight hardware is tested (protoflight), and when qualification tests are conducted on a separate (prototype) article.*
>
> *Post-separation factors are intended for re-use hardware that is refurbished after a mission. Hardware that separates from the vehicle that would constitute a catastrophic or critical hazard if it were to fail post-separation must analyze to full factors of safety for that condition.*
>
> *Untested structures are those with no structural loads test to qualification or proof levels. Applicable structures may include pallets, components (chassis), brackets, blanket or cabling supports, and other secondary structures. Some organizations use a higher factor of safety for untested structures. The use of a higher factor of safety is not necessarily sufficient to account for analysis uncertainty and possible unconservatism in load factor calculation and application. Untested factors of safety may be used with approval of the NASA Technical Authority. Acceptable criteria to justify these factors of safety include:*
>
> *a. The structural design is simple, with easily determined load paths; it has been thoroughly analyzed for all critical load conditions; and there is a high confidence in the magnitude of all significant loading events.*
>
> *b. The structure is similar in overall configuration, design detail, and critical load conditions to a previous structure which was successfully test verified, with good correlation of test results to analytical predictions.*
>
> *c. Development and/or component tests have been successfully completed on critical, difficult to analyze elements of the structure. Good analytical model correlation to test results has been demonstrated.*
>
> *For components and secondary structures, the tests in items b) & c) could include random vibration testing, where that has been determined to be the major portion of the expected flight loading for the component/structure.*

Table 3.3.1-1 - Minimum Factors of Safety for Metallic Flight Structures

Minimum Factors of Safety for Metallic Flight Structures		Yield	Ultimate
Prototype		1.00	1.40
Qualification Test Factor	1.40		
Protoflight		1.25	1.40
Proof Test Factor	1.20		
Factors for hardware post-separation, not going to orbit, prototype program		1.00	1.25
Qualification Test Factor	1.25		

3.3.1.2.1 Beryllium Structures

[STR0040] Structural hardware constructed of beryllium shall be designed and tested to the minimum factors of safety specified in Table 3.3.1-2.

> *Rationale: Special consideration must be given to beryllium structures due to the brittle nature of the material and sensitivity to flaws that can be induced during the fabrication process. Fabrication requirements are provided in NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft; however, unique qualification and proof testing should be defined for the specific application. The test plans should include consideration of the number of identical items fabricated, the degree of out-of-plane loading due to the anisotropic nature of beryllium, and the ability to perform detailed inspections of the hardware after test.*
>
> *The buckling margin of safety applies to beryllium structures subjected to buckling loads. The buckling margin should be determined using the ultimate factor of safety times limit load.*

Table 3.3.1-2 – Minimum Factors of Safety for Beryllium Structures

Minimum Factors of Safety for Beryllium		Yield	Ultimate
Prototype		1.00	1.40
Qualification Test Factor	1.40		
Acceptance/Proof Test Factor	1.00		
Minimum buckling margin of safety	10%		

3.3.1.3 Non-Metallic Flight Structures

[STR0041] Non-metallic flight hardware structure shall be designed and tested to the minimum factors of safety specified in Table 3.3.1-3.

<u>Rationale</u>: Criteria are specified for design and test of flight articles when the actual flight hardware is tested (protoflight), and when qualification tests are conducted on a separate (prototype) article.

See the glossary in Section B for the definition of a discontinuity. Examples of discontinuity areas in non-metallic structures include: reinforced holes or cut-outs; bolted, pinned, mechanically fastened or other junctions with fittings; rapid ply drops or pad-ups; core ramps for sandwich structures; pre-form junctions; adhesive joints; or discrete areas with load introduction or boundary conditions.

Composite discontinuities that are development tested (e.g. M&P testing for ramp downs and tapers) can be counted as tested structures. Either use results from development testing or heritage data to justify using the tested factor of safety. When test or heritage data is not available use an ultimate factor of safety of 2.0.

An ultimate factor of safety greater than the test factors defined in the table may be needed if fracture control requires testing to higher levels.

Table 3.3.1-3 – Minimum Factors of Safety for Non-metallic Flight Structures

Minimum Factors of Safety for Non-metallic Flight Structures		Yield	Ultimate
Prototype			
Uniform areas		N/A	1.40
Discontinuity areas		N/A	2.00
Qualification Test Factor	1.40		
Acceptance/Proof Test Factor	1.05		
Protoflight			
Uniform areas			1.50
Discontinuity areas			2.00
Acceptance/Proof Test Factor	1.20		

3.3.1.4 Structural Soft Goods

[STR0042] Structural soft goods shall be designed and tested to the minimum factors of safety specified in Table 3.3.1-4.

<u>Rationale</u>: Straps, fabrics, inflatable structures, gossamer structures and other soft goods that carry structural loads upon launch or deployment are structural soft goods. Soft goods whose failure can result in either a critical or catastrophic hazard are safety critical structural soft goods.

Parachute and parafoil systems have specific factor of safety requirements in Section 3.3.1.5.

All structural soft goods are required to be test verified.

Table 3.3.1-4 – Minimum Factors of Safety for Structural Soft Goods

Minimum Factors of Safety for Structural Soft Goods		Ultimate
Safety critical		4.00
Qualification Test Factor	4.00	
Acceptance/Proof Test Factor	1.20	
Not safety critical		2.00
Qualification Test Factor	2.00	
Acceptance/Proof Test Factor	1.20	

3.3.1.5 Parachute and Parafoil Systems

[STR0043] Parachute and parafoil systems shall be designed and tested to the minimum factors of safety specified in Table 3.3.1-5.

> *Rationale: The factors of safety in this section cover all material types used in parachute and parafoil systems such as fabric and steel cables.*
>
> *The preferred method to develop design factors for fabrics is provided in NWC TP 6575, Parachute Recovery Systems Design Manual. MIL-DTL-83420M, General Specification for Flexible Wire Rope for Aircraft Control provides procurement guidance for steel cable and wire rope to guarantee strength properties and justify use of the noted factors of safety. Safety critical components in parachute and parafoil systems are typically items where a single point failure can result in a catastrophic hazard.*

Table 3.3.1-5 – Minimum Factors of Safety for Parachute and Parafoil Systems

Minimum Factors of Safety for Parachute and Parafoil Systems	Ultimate
Subsonic systems, manned	1.60
Subsonic systems, unmanned	1.50
Supersonic systems	1.70
Safety critical components	2.00

3.3.1.6 Pressurized Hardware

[STR0044] Pressurized hardware shall be designed and tested to the minimum factors of safety specified in Table 3.3.1-6.

> *Rationale: Proof tests are conducted as an acceptance test of each production unit including the qualification article. The proof factor is the minimum required. A higher proof test factor may be determined by fracture mechanics analysis when the proof test is used for flaw screening.*

Additional factor of safety requirements for liquid propulsion engine structures and solid rocket motors are provided in Sections 3.3.1.7 and 3.3.1.8 respectively.

MEP = Maximum External Pressure

[STR0045] see flex hose testing shall statement in note 4.

Table 3.3.1-6 – Minimum Factors of Safety for Pressurized Hardware

Minimum Factors of Safety for Pressurized Hardware		Yield(1)	Ultimate(1)
Lines and fittings less than 1.5 in (38 mm) outside diameter		1.00	1.40
Proof Pressure	1.50 X MDP		
Design Burst Pressure	4.00 X MDP		
Negative pressure differential	2.50 X MEP		
Lines and fittings, 1.5 in (38 mm) outside diameter or greater		1.00	1.40
Proof Pressure	1.50 X MDP		
Design Burst Pressure	2.50 X MDP		
Negative pressure differential	2.50 X MEP		
Other pressure system components such as actuating cylinders, valves, regulators, filters, switches, heat pipes and line-installed alignment bellows		1.00	1.40
Proof Pressure	1.50 X MDP		
Design Burst Pressure	2.50 X MDP		
Negative pressure differential	2.50 X MEP		
Metallic Pressure Vessels and Sealed Containers		1.00	1.40
Proof Pressure	1.50 X MDP		
Design Burst Pressure	2.00 X MDP		
Negative pressure differential(2)	1.00 X MEP		
Composite Overwrapped Pressure Vessels		1.00(3)	1.40
Proof Pressure	1.25 X MDP		
Design Burst Pressure	2.00 X MDP		
Negative pressure differential(2)	1.00 X MEP		
Doors, Hatches and Habitable Modules		1.65	2.00
Internal pressure only			
Proof Pressure	1.50 X MDP		
Negative pressure differential(2)		N/A	1.50
Negative pressure differential if certified by Analysis Only		N/A	2.00
Flex hoses, all diameters		1.00	1.40
Proof Pressure(4)	2.00 X MDP		
Design Burst Pressure	4.00 X MDP		
Negative pressure differential	2.50 X MEP		

Minimum Factors of Safety for Pressurized Hardware		Yield[1]	Ultimate[1]
Pressurized Structures, if not solid rocket motor cases or specified below:		1.10	1.40
Proof Pressure	1.10 X MDP		
Ultimate Pressure	1.40 X MDP		
Negative pressure differential[2]	1.00 X MEP		
Metallic Propellant Tanks that are Pressurized Structures		1.10	1.40
Proof Pressure	1.05 X MDP		
Negative pressure differential[2]	1.00 X MEP		
Composite Propellant Tanks that are Pressurized Structures		N/A	1.50
Proof Pressure	1.20 X MDP		
Negative pressure differential[2]	1.00 X MEP		

NOTES:

1. The ultimate factors of safety are used for the pressure only load case when a burst pressure is not defined. The yield factors of safety or the proof pressure may be used for the pressure only load case to prevent yielding depending on the specific application. Yield and ultimate factors of safety for pressurized hardware under combined loads are discussed in Table 3.3.2-1.
2. Must be capable of withstanding maximum external pressure multiplied by ultimate factor of safety (Negative Pressure Differential) without collapse or rupture when internally pressurized to the minimum anticipated operating pressure.
3. The yield factor of safety is only applicable to the metallic portion of the COPV.
4. In a system with fluid lines and flex hoses, the individual flex hoses shall be proof tested to 2.00 X MDP; this factor does not apply at the assembly level.

3.3.1.7 Liquid Propulsion Engine Structures

[STR0046] Engine structures and engine compartments in liquid fueled space propulsion systems with less than 6000 pounds of thrust shall be designed and tested to the minimum factors of safety specified in NASA-STD-5012, Table 1.

> <u>Rationale</u>*: NASA-STD-5012 is not applicable to engines with a thrust less than 6000 pounds. These requirements plus the factor of safety requirements in Section 3.2.9.1 are a tailoring of NASA-STD-5012 for smaller engines.*

3.3.1.8 Solid Rocket Motors

[STR0047] Solid rocket motors shall be designed and tested to the minimum factors of safety specified in Table 3.3.1-7.

> <u>Rationale</u>*: Proof tests are conducted as an acceptance test of each production unit including the qualification article. The proof factor is the minimum required. A higher proof test factor may be determined by fracture mechanics analysis when the proof test is used for flaw screening.*

MEP = Maximum External Pressure

Solid rocket motors may use MEOP instead of MDP.

Table 3.3.1-7 – Minimum Factors of Safety for Solid Rocket Motors

Minimum Factors of Safety for Solid Rocket Motors		Yield	Ultimate
Metallic solid rocket motor cases that are pressurized structures		1.10	1.40
Proof Pressure	1.05 x MDP		
Negative Pressure Differential(1)	1.00 x MEP		
Composite solid rocket motor cases that are pressurized structures		N/A	1.50
Proof Pressure	1.20 x MDP		
Negative Pressure Differential(1)	1.00 x MEP		
Solid propellant, insulation, liner and inhibitor			2.00

Notes:

1. Must be capable of withstanding maximum external pressure multiplied by ultimate factor of safety (Negative Pressure Differential) without collapse or rupture when internally pressurized to the minimum anticipated operating pressure.

3.3.1.9 Rotating Machinery

[STR0048] Rotating machinery shall be designed and tested to the minimum factors of safety specified in Table 3.3.1-8, where the speed of the spin test is defined by Equation 1.

Rationale: The requirements in this section are intended to address design issues for equipment where rotational effects are structurally significant and where a failure would cause a catastrophic or critical hazard. Examples include motors, gyroscopes, flywheels, transmissions, high-speed gears, and pumps that are not part of the liquid propulsion engine system. Liquid propulsion engine systems are covered by Section 3.3.1.7.

FS_{spin} = the larger of the two values given in the table for proof and qualification spin tests

Qualification and proof tests should be conducted in the operational environment. If testing in the operational environment is not feasible, tests can be performed in a nonoperational environment if an Environmental Correction Factor (ECF) is applied. Section B contains a definition of ECF.

Table 3.3.1-8 – Minimum Factors of Safety for Rotating Machinery

Minimum Factors of Safety for Rotating Machinery		Yield	Ultimate
Rotating Machinery		1.10	1.40
Proof Spin Test Factor	the greater of 1.05 or 1.1 x ECF		
Qualification Spin Test Factor	the greater of 1.05 or 1.2 x ECF		

Equation 1 – Proof and Qualification Spin Test Speed

$$Test\ Speed = \sqrt{FS_{spin} \cdot (Maximum\ design\ speed)^2}$$

3.3.1.10 Wire Ropes and Cables

[STR0049] Wire ropes and cables shall be designed and tested to the minimum factors of safety specified in Table 3.3.1-9.

> <u>Rationale</u>*: Typically large variations in strength properties are inherent to wire rope and cable in structural designs. MIL-DTL-83420M, General Specification for Flexible Wire Rope for Aircraft Control provides procurement guidance for steel cable and wire rope to guarantee strength properties and justify use of lower factors of safety.*

Table 3.3.1-9 – Minimum Factors of Safety for Wire Ropes and Cables

Minimum Factors of Safety for Wire Ropes and Cables		Ultimate
Wire Ropes and Cables		4.00
Acceptance/Proof Test Factor	2.00	

3.3.1.11 Fasteners and Fastened Joints

[STR0050] Design analysis of structural joints and fittings shall consider a fitting factor of 1.15 to be applied to limit and ultimate load conditions for all phases of service life.

> <u>Rationale</u>*: The fitting factor is used to account for potential variations in internal load paths within the actual structure that are not covered by idealized analytical models.*
>
> a. *Application of the factor is intended for fittings or joints whose strength is not proven by limit and ultimate load tests in which the actual stress conditions are simulated and measured in the fitting and surrounding structure.*
>
> b. *A fitting factor need not be used where the type of joint, such as a continuous row of fasteners in sheet or plate, a welded or bonded joint, or a scarf joint in*

metal or plastic, etc., is strength verified based on comprehensive limit and ultimate tests.

c. *This factor should apply to all portions of the fitting, the means of fastening, and the bearing on the members joined.*

d. *In the case of integral fittings, the part should be treated as a fitting up to the point where the section properties become typical of the member away from the joint.*

3.3.2 Combined Loading

[STR0051] Structures shall be designed and tested for combined loading as specified in Table 3.3.2-1.

<u>Rationale</u>: The most severe combination of thermal, mechanical, and pressure loads occurring at the same time or during the same mission event should be combined in a rational manner. Test cases should consider an ECF when the flight environments cannot be replicated during testing.

Table 3.3.2-1 Factors of Safety for Combined Loads

Metallic Structure	**Prototype**	Yield	1.0 x (Pressure + Mechanical + Thermal)
		Ultimate & Qualification	1.4 x (Pressure + Mechanical + Thermal)
	Protoflight	Yield	1.0 x (Pressure + Mechanical + Thermal)
		Ultimate	1.4 x (Pressure + Mechanical + Thermal)
		Qualification Test Factor	1.2 x (Pressure + Mechanical + Thermal)
Composite or Bonded Structure	**Prototype**	Ultimate & Qualification	1.4 x (Pressure + Mechanical + Thermal)
		Acceptance Proof Test	1.05 x (Pressure + Mechanical + Thermal
	Protoflight*,**	Ultimate	1.4 x (Pressure + Mechanical + Thermal)
		Qualification Test Factor	1.2 x (Pressure + Mechanical + Thermal
		Acceptance Proof Test	

Notes:

* For protoflight, habitable modules constructed from advanced composite materials, there are other considerations such as allowable strain in the matrix, bearing and discontinuity stresses, where testing to 1.2 x limit load may risk damaging the structure. For specific cases, a qualification test factor no lower than 1.1 is acceptable, possibly combined with component testing, if the data is provided to show that the structure will be sufficiently exercised by a 1.1 x limit load test such that the ultimate capability can be predicted by analysis.

** Demonstration that the manufacturer of the composite article has a successful history of building a like design, certified and controlled specifications are used, personnel are properly trained and certified, and proposed nondestructive testing techniques are adequate to validate the quality and integrity of the hardware. This option must be supported by documentation demonstrating compliance with the listed criteria and approved by NASA.

3.3.2.1 Combining with Mechanical Stress/Load

[STR0052] The mechanical stresses/loads shall not be multiplied by the factor of safety in calculating the design yield or ultimate stress/load if they are relieving or stabilizing to the structure.

> <u>Rationale</u>*: Multiplying a stabilizing mechanical load by a factor of safety above 1.0 increases the relieving or stabilizing effect and may result in inaccurate structural margins. For this case, the ultimate factor of safety for mechanical loads in the combined loads equation is 1.0 instead of 1.4.*
>
> *i.e. : (1.0 x Mechanical) + (1.4 x (Thermal + Pressure))*
>
> *when mechanical loads are relieving or stabilizing.*

3.3.2.2 Combining with Thermal Stress/Load

[STR0053] Thermal stresses/loads shall be combined with mechanical and pressure stresses/loads when they are additive but not when they are relieving.

> <u>Rationale</u>*: Multiplying a stabilizing thermal stress or load by a factor of safety above 1.0 increases the relieving or stabilizing effect and may result in inaccurate structural margins. For this case, the ultimate factor of safety for mechanical loads in the combined loads equation is 1.0 instead of 1.4.*
>
> *i.e. : (1.0 x Thermal) + (1.4 x (Mechanical+ Pressure))*
>
> *when thermal loads are relieving or stabilizing.*

3.3.2.3 Combining with Pressure Stress/Load

[STR0054] The pressure stresses/loads shall not be multiplied by the factor of safety in calculating the design yield or ultimate stress/load if they are relieving or stabilizing to the structure.

> <u>Rationale</u>*: Multiplying a stabilizing pressure load by a factor of safety above 1.0 increases the relieving or stabilizing effect and may result in inaccurate structural margins. For this case, the ultimate factor of safety for pressure loads in the combined loads equation is 1.0 instead of 1.4.*
>
> *i.e. : (1.0 x Pressure) + (1.4 x (Thermal +Mechanical))*
>
> *when pressure loads are relieving or stabilizing.*

3.3.2.4 Relieving Pressure Loads

[STR0055] 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.

> <u>Rationale</u>*: There may be a range of pressure load magnitudes which are relieving or stabilizing to the structure. In order to ensure that lowest structural margin is calculated, the minimum value of the relieving pressure load must be used.*

3.3.3 Life Factors

3.3.3.1 Fatigue Analysis Factor

[STR0056] The design analysis used to assess the fatigue life of flight hardware structure shall multiply limit stress/strain by a Fatigue Analysis Factor (FAF), 1.15 on typical fatigue properties or 1.0 on lower bound fatigue properties, prior to entering the stress versus cycle life (S/N) design curve to determine the low-cycle and high-cycle fatigue life.

> *Rationale: The FAF and the life factors from Section 3.2.3 are intended to provide margin to account for material fatigue curve data scatter. Other factors should be considered if applicable to account for effects such as surface finish, anodizing, temperature, environment, size effect, corrosion, plating, spraying, cyclic frequency, etc.*
>
> *Low-cycle and high-cycle fatigue are defined in Section B.*

3.3.3.2 Rotating Machinery Fatigue Analysis Factor

[STR0057] The design analysis used to assess fatigue life for rotating machinery shall multiply limit stress/strain by an additional Fatigue Analysis Factor (FAF), 1.25 for rotating components and 1.15 for non-rotating components, prior to entering the S-N design curve to determine the low-cycle/ high-cycle fatigue life.

> *Rationale: The FAF and the life factors from Section 3.2.3 are intended to provide margin to account for material fatigue curve data scatter. Other factors should be considered if applicable to account for effects such as surface finish, anodizing, temperature, environment, size effect, corrosion, plating, spraying, cyclic frequency, etc.*
>
> *Low-cycle and high-cycle fatigue are defined in Section B.*

3.3.3.3 Creep Life Factor

[STR0058] The design analysis used to assess the creep life of flight hardware structure shall multiply the limit stress/strain by a minimum factor of 1.15 prior to entering the design curve to determine creep life.

> *Rationale: This factor along with the life factors from Section 3.2.3 is intended to provide margin to account for material data scatter.*

3.3.4 Bearing Factor for Joints Subjected to Hammering Action

[STR0059] Parts that have clearance (free fit), and are subject to pounding or vibration, must have a bearing factor large enough to provide for the effects of normal relative motion.

> *Rationale: A bearing factor is typically used in conjunction with the yield and ultimate factors of safety. Joints subjected to shock or hammering action should*

be assessed with a bearing factor of 2.0. A fitting factor is not used in conjunction with this bearing factor when the bearing factor is larger.

The bearing factor applies to joints within mechanical systems that have significant free play, such as a trunnion pin in retractable landing gear. This factor accounts for local dynamic amplification. This requirement is not intended for preloaded joints with threaded fasteners.

3.4 STRUCTURAL LOADS AND ENVIRONMENTS

The structural design requirements defined in this document assume the use of limit loads, loads spectra and environments developed in accordance with the requirements of JSC 65829, Loads and Structural Dynamics Requirements for Spacecraft. Additional requirements for loads conditions not addressed in that document are provided in the following sections.

3.4.1 Redistributed Loads

[STR0060] Structures that are deployed, extended, or otherwise un-stowed to a configuration where they cannot withstand subsequent induced loads, or whose load paths are controlled by electro-mechanical devices shall be designed to maintain the applicable nominal design factors of safety using the redistributed loads after one or two credible system failures commensurate with the hazard levels.

<u>*Rationale*</u>*: Maximum loads for deployable or on-orbit configurable hardware may not be caused by flight events while it is in its stowed configuration. Evaluation of hardware in all of its deployed or operating configurations is vital to ensure proper identification of the bounding load cases.*

Operational procedures may be used to restore the load path or limit the applied loads after the first failure.

3.4.2 Loads Due to Friction (Relieving)

[STR0061] Flight hardware structure shall be designed and analyzed such that friction is not considered when it is relieving.

<u>*Rationale*</u>*: The level of friction acting to restrain hardware at any location in a given design under load is inherently uncertain. It is difficult to accurately and consistently determine frictional restraint due to factors such as surface finish, cleanliness, lubrication, preparation, planarity tolerances, and the specific amount of preload under combined loads such as random vibration, thermal, mechanical, and pressure.*

The standard NASA and United States aerospace industry design practice is to develop robust hardware using bounding design analyses that do not consider the beneficial effects of friction in cases where it acts to reduce induced stresses/loads or improve structural margins of safety.

3.4.3 Loads Due to Friction (Additive)

[STR0062] Flight hardware structure shall be designed and analyzed such that friction forces are included when they increase the magnitude of the applied load or stress or when they are detrimental to the function of the part.

> <u>Rationale</u>*: Detrimental effects due to friction need to be considered to ensure that all sources of external load impacting critical induced forces, stresses and deflections are considered. Friction may introduce internal paths within the structure that would not be otherwise exercised if neglected.*
>
> *The standard NASA and United States aerospace industry design practice is to develop robust hardware using bounding design analyses that consider the detrimental effects of friction in cases where it acts to increase induced stresses/loads or decrease structural margins of safety.*

3.4.4 Design Loads for Collapse

[STR0063] Design loads for collapse shall be ultimate loads, unless a load component alleviates buckling in which case the ultimate factor of safety is not applied to that component.

> <u>Rationale</u>*: For combined load cases, which may include any combination of mechanical, pressure or thermal loads acting on structure, applying a factor of safety to a load component that tends to alleviate buckling will result in an unconservative assessment of buckling load capability.*

3.4.4.1 Destabilizing External Pressure or Torsional Loads

[STR0064] Destabilizing external pressure or torsional limit loads shall be increased by the ultimate factor of safety.

> <u>Rationale:</u> *All combined mechanical, pressure and thermal load components, including external pressure or torsional loads, that act to reduce structural stability should be increased by the appropriate ultimate factor of safety.*

3.4.4.2 Stabilizing Internal Pressure Loads

[STR0065] Internal-pressure loads that stabilize the structure shall not be increased by the ultimate factor of safety unless they reduce structural capability.

> <u>Rationale:</u> *Load components that tend to increase structural stability, such as internal pressure, are not increased by a factor of safety. However, there may be conditions where internal pressure reduces structural capability or margins of safety. Analyses should be performed for both conditions to determine the appropriate application of the FS.*

3.5 MATH MODELS

3.5.1 Model Verification by Test

[STR0066] Math models used to generate stresses, strains, internal loads or predict deflections for structural analysis and design shall be test verified.

> *<u>Rationale</u>: Test verification of model predictions will ensure sufficient accuracy for data used in design development and structural integrity assessments.*
>
> *The static test article requires adequate instrumentation to provide sufficient test data for correlation with the strength model.*
>
> *The model verification test approach, methods, configuration, etc is outlined in the SVP. Detailed test information is to be provided in a dedicated test plan. Test results and model correlation results are also to be documented in dedicated reports submitted for NASA Technical Authority review.*
>
> *In some cases testing alone can be used to demonstrate hardware structural integrity. Analysis only approaches are also possible. In either case the approach should be submitted for NASA Technical Authority review and approval in the SVP.*

3.5.2 Model Verification Test Factors

[STR0067] Model verification test input load levels shall apply appropriate test factors.

> *<u>Rationale</u>: Three test options are generally available for model verification testing. Applicable test factors are based on whether or not testing is performed using prototype or protoflight hardware.*
>
> *a. Ultimate Load Test – Testing is generally performed on a dedicated prototype unit. Test levels correspond to limit load multiplied by the applicable ultimate factor of safety defined in Section 3.3.1.*
>
> *b. Protoflight Test Option 1 – Test is performed on dedicated prototype or protoflight structure. Test levels correspond to limit load multiplied by a test factor of 1.2. Test results are used to correlate model predictions per the guidelines of Section 3.5.3. Note a minimum yield factor of safety of 1.25 should be used for design in conjunction with this option to preclude potential for yielding due to test.*
>
> *c. Protoflight Test Option 2 – Test is performed on dedicated prototype or protoflight structure. Test levels correspond to limit load multiplied by a test factor of 1.1. Test results are used to correlate model predictions per the guidelines of Section 3.5.3. Use of this option requires additional critical subcomponent testing at levels up to ultimate load.*
>
> *The model verification test approach must be reviewed and approved by the NASA Technical Authority. Details of the approach should be provided in the SVP and related test plans.*

3.5.3 Model Verification Test Correlation

[STR0068] Adequate correlation of critical model predictions and test measured data shall be demonstrated using the following guidelines:

1. Math model predictions for critical deflections within 10 percent of the test data;
2. Math model predictions for critical stresses/strains within 10 percent of the test data;
3. If math model predictions are outside the above stated correlation criteria, the math model will be updated until it meets the criteria and the analysis rerun;
4. If the math model predictions are within the correlation criteria but under predict the test data, the stress analysis for flight load conditions must be updated to reflect structural margins based on stresses that are adjusted according to the correlation results.
5. If the test article demonstrates non-linear response the effect on structural margins must be evaluated and included in the stress analysis if significant.

<u>Rationale</u>*: Inability to adequately correlate model predictions with test data results in increased uncertainty in analytical predictions developed using those models. An understanding of the implications of the additional uncertainty on predicted responses and corresponding impacts on structural design is necessary to manage risks.*

3.6 STRUCTURAL MATERIALS

Requirements for materials used in the fabrication, processing and testing of flight hardware and components are defined in NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft.

3.6.1 Structural Material Allowable Properties

[STR0069] Primary structure where failure of a single load path could result in a loss of structural integrity shall use Material "A" allowables as defined in Metallic Materials Properties Development and Standardization (MMPDS) or MIL-HDBK-17-2, -4, and -5; or equivalent.

<u>Rationale</u>*: See NASA-STD-6016, Section 4.1.6 for additional material design allowable requirements. Equivalent approaches to Material "A" may be allowed via the Material Usage Agreement (MUA) process defined in NASA-STD-6016.*

Material "A" or "A-basis" allowables are specified to assure reliability for critical structures.

3.6.2 Material Design and Analysis Thickness

[STR0070] Stress calculations of pressure vessels, stability critical structure, and single load path structure shall use drawing minimum thickness unless it is for a layered composite structure.

> _Rationale_*: The intent of this requirement is to ensure the stress analysis captures the thickness variability of the part for conservatism for metallic structures.*
>
> *Layered composite structures are excluded from this requirement because there are factors that apply to them (fiber volume - percentage of fibers, ply thickness) which strongly affect strength and stiffness that are not an independent function of overall material thickness. These additional factors render the minimum thickness calculation method incomplete for conservative analysis.*
>
> *Actual as-built dimensions may be used in stress calculations when available.*

3.6.3 Acceptable Dimensional Variations for Welded Joints

[STR0071] Flight vehicle structures that contain welded joints shall account for the effects of stress concentration factors, parent material misalignment/offsets, residual stress and defects resulting from the weld and weld repair process in their structural strength and life analysis.

> _Rationale_*: The structural design of the welded joint should account for the acceptable dimensional variations for the welded joint and joint repair. As-built dimensions of the welded joint or welded joint repair may be used to establish design allowables.*
>
> *The acceptable dimensional variations and the sensitivity of the nondestructive method used for the welded joint and joint repair may be specified on the engineering drawings.*

A. ACRONYMS AND ABBREVIATIONS

AIAA	American Institute of Aeronautics and Astronautics
CDR	Critical Design Review
COPV	Composite Overwrap Pressure Vessel
DCR	Design Certification Review
ECF	Environmental Correction Factor
FAF	Fatigue Analysis Factor
FRR	Flight Readiness Review
FS	Factor of Safety
ISS	International Space Station
kPa	kiloPascal
LSP	Loads and Structures Panel
MDP	Maximum Design Pressure
MDS	Maximum Design Speed
MEOP	Maximum Expected Operation Pressure
MEP	Maximum External Pressure
MMPDS	Metallic Materials Properties Development and Standardization
MS	Margin of Safety
MUA	Materials Usage Agreement
PDR	Preliminary Design Review
psia	pounds per square inch (absolute)
S-N	Stress Level Versus Number of Cycles to Failure
SRD	System Requirements Document
SVP	Structural Verification Plan

B. DEFINITIONS

For the purposes of this document, the following definitions apply.

Acceptance Tests: Tests performed on flight hardware and software to confirm equipment performs as qualified and is generally free of latent manufacturing, material, or workmanship defects for delivery of products. For hardware, acceptance testing is typically performed at operating and non-operating performance and environment limits without intruding into qualification margins.

A-Basis Material Properties: The lower of either a statistically calculated number, or the specification minimum. The statistically calculated number indicates that at least 99 percent of the population of values is expected to equal or exceed the A-basis mechanical design property, with a confidence of 95 percent.

Allowable Load or Stress: The load or stress which is consistent with the limits imposed by the structural criteria being addressed when considering minimum material dimensions and material properties. An allowable load based on yield criteria is the maximum load at which structural yielding will not occur. An allowable load based on ultimate criteria is the maximum load at which structural failure will not occur. If configuration-specific tests are used to determine allowable load, test data must be corrected to minimum dimensions and minimum material allowable properties.

Catastrophic Hazard: The presence of a potential risk situation caused by an unsafe condition that can result in a disabling or fatal personnel injury, or loss of one of the following: launch or servicing vehicle, International Space Station (ISS), or major ground facility.

Component: A hardware item that is considered as a single structural entity. The terms “component” and “part” are interchangeable in this document.

Credible Single Barrier Failure: Potential leaks within a component that permits fluid to directly contact the materials behind the barrier or expose secondary compartments to system pressure conditions.

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

Critical: The extreme value of a load or stress; the combination of loads causing the maximum stress in a structural member; or the most severe environmental condition imposed on a structure during its service life. The design of the structure is based on an appropriate combination of such critical loads, stresses, and conditions.

Critical Seals: A critical seal is one through which leakage would constitute a catastrophic or critical failure. Seals through which atmosphere of any habitable volume may leak to the external environment are critical seals. Seals through which flow may intrude into the spacecraft during atmospheric entry are critical seals.

Design Condition: A condition important in structural design and which may involve a specific point in time or integrated effects over a period of time in terms of physical units such as pressure, temperature, load, acceleration, attitude, rate, flux, etc. (See Condition)

<u>Deterministic:</u> Denotes that values used in design are discrete and not random. Deterministic values are determined on the basis of available information and experience. (See Probabilistic)

<u>Detrimental Deformation:</u> Structural deformation, deflection, or displacement which:

a) Causes unintentional contact, misalignment, or divergence between adjacent components
b) Causes significant internal load redistribution in a structure
c) Causes a component to exceed the dynamic space envelop established for that component
d) Reduces the strength or rated life of the structure below specified levels
e) Degrades the effectiveness of thermal protection coatings or shields
f) Jeopardizes the proper functioning of equipment;
g) Endangers personnel
h) Degrades the aerodynamic or functional characteristics of the vehicle
i) Reduces confidence below acceptable levels in the ability to ensure flight-worthiness by use of established analytical or test techniques
j) Induces leakage above specified rates

<u>Development Test:</u> Any test that provides data needed to reduce risk, to define or mature requirements, to design hardware or software, to define manufacturing processes, to define qualification or acceptance test procedures, or to investigate anomalies discovered during test or operations.

<u>Discontinuity Area:</u> A local region of a composite or non-metallic structure consisting of built-up plies chopped fiber or reinforced regions around fittings, joints or interfaces where the stress state and load distribution within the region may be difficult to characterize. A region is considered a discontinuity area until uniform section properties in the structure can be considered in the structural analysis. Bonded joints are considered discontinuities.

<u>Element:</u> Physical entities that have functional capabilities allocated to them necessary to satisfy System-level mission objectives. Elements can perform all allocated functions within a mission phase, or through mated operations.

<u>Environmental Correction Factor (ECF):</u> An adjustment factor used to account for differences in the environment (thermal and chemical) in which the part is used and the environment in which it is tested.

$$ECF = \frac{Strength\ Capability\ at\ Test\ Conditions}{Strength\ Capability\ at\ Operating\ Conditions}$$

Factor of Safety (FS): Multiplying factors to be applied to limit loads or stresses for purposes of analytical assessment (design factors) or test verification (test factors) of design adequacy in strength or stability. Factors of safety are deterministically-based and are necessary to assure no failures due to uncertainties that result from the design process, manufacturing process, and the loading environment

Failure: A rupture, collapse, or seizure; an excessive wear; or any other phenomenon resulting in the inability of a structure to sustain required loads, pressures, and environments.

Fatigue: The cumulative irreversible damage in materials and structures incurred by the cyclic application of loads and environments. Fatigue is usually considered as the number of cycles to crack initiation or to failure.

Fatigue, Low-Cycle: A low-frequency, high-amplitude loading condition created by thermal, pressure, or structural loads that can propagate flaws to failure. An example of a low-cycle loading condition is the aerothermal loading of a turbine blade during launch.

Fatigue, High-Cycle**:** A high-frequency, low-amplitude loading condition created by structural, acoustic, or aerodynamic vibrations that can propagate flaws to failure. An example of a high-cycle fatigue loading condition is the vibration loading of a turbine blade due to structural resonance.

Fitting: A part or terminal used to join one structural member to another.

Flight Vehicle: A vehicle, which is generally composed of multiple elements, used to transport persons or things to a location outside of the Earth's atmosphere.

Habitable Module: A pressurized, life-supporting enclosure or module that is normally intended to support life without the need for spacesuits or special breathing apparatus. The enclosure may be one that is continuously inhabited, or one that is used for crew transference, or for crew accessible stowage so long as life support is a requirement for the design. Single mission or multi-mission module designs are included.

Limit Load: The maximum load expected on the structure during its service life including ground handling, transport to and from orbit including abort conditions, and on-orbit operations.

Load Spectrum: A representative distribution with respect to time of the cumulative static and dynamic loadings anticipated for a structural component or assembly under all expected operating environments.

Margin of Safety (MS): The parameter utilized by the structural discipline to express structural capability in terms of structural requirements which include factor of safety. Margins of safety are expressed for both yield and ultimate criteria. The basic equation defining margin of safety for uniaxial stress (which does not apply for combined stresses) is:

$$MS = \frac{\text{allowable stress (yield or ultimate)}}{\text{FS (yield or ultimate)} \times \text{limit applied stress}} - 1$$

Math Model, Structural: The mathematical equations, boundary values, initial conditions, and modeling data needed to describe the conceptual model of a structure.

Maximum Design Pressure (MDP): The Maximum Design Pressure (MDP) for a pressurized system is the highest pressure defined by the maximum relief pressure, maximum regulator pressure, maximum temperature and transient pressure excursions based on two credible system failures.

Maximum Design Speed (MDS): The highest possible operating speed based on a combination of credible failures; critical equipment must consider two credible failures. Certain liquid propulsion system engines will not meet this definition.

Maximum Expected Operating Pressure (MEOP): The maximum pressure which the pressurized hardware is expected to experience during its service life, in association with its applicable operating environments.

Mission: A flight to a destination in space, intended to accomplish specific scientific and technical objectives.

Negative Pressure Differential: The Maximum External Pressure (MEP) multiplied by the ultimate factor of safety.

Non-Safety Critical Structures: Structures which if they fail will not create a catastrophic hazard.

Pressure Vessel: A container designed primarily for pressurized storage of gases or liquids and:

a) Contains stored energy of 19,307 joules (14,240 foot-pounds) or greater based on adiabatic expansion of a perfect gas; or

b) Contains a gas or liquid in excess of 103.4 kPa (15 psia) which will create a hazard if released; or

c) Stores a gas which will experience a MDP greater than 689.5 kPa (100 psi).

Pressurized Hardware: Any hardware item that is exposed to and largely structurally designed to carry acting pressure, such as pressure vessels, other pressurized components such as lines, fittings, valves, and bellows, and pressurized structures and habitable modules.

Pressurized Structure: A structure designed to carry vehicle loads in which pressure is a significant contributor to the design loads. Pressurized structures are typically large tanks or habitable structures that carry external flight loads as well as containing the internal fluids or gases.

Pressurized System: A system that consists of pressure vessels, pressurized structures, or both, and other pressure components such as lines, fittings, valves, and bellows that are exposed to and structurally designed largely to carry or store pressurized gases or liquids. Not included are electrical or other control devices required for system operation.

Preloaded Joint: A preloaded joint is a joint in which the preload is necessary to have adequate life due to cyclic loads, or to assure that no joint separation and resulting stiffness change occurs, or to assure that no joint separation occurs which would affect pressure seals.

Probabilistic: Denotes that the values used in design are random, not discrete. Probabilistic values are chosen on the basis of statistical inference. (See Deterministic.)

Proof Load or Pressure: The product of the limit load or pressure and the proof factor.

Proof Test: A load or pressure in excess of limit load or maximum design pressure applied in order to verify the structural integrity of a part or to screen initial flaws in a part.

Prototype Structure: A separate flight-like structural test article used in a test program to verify structural integrity of the design. Prototype tests and qualification tests are synonymous.

Protoflight Structure : Flight hardware utilized for ground qualification testing in lieu of a dedicated test article. The approach includes the use of reduced test levels and/or durations and post-test hardware refurbishment where required.

Qualification Test: Formal test conducted with defined qualification margin as part of the certification program to qualify a design, manufacturing process, and acceptance testing program to produce equipment able to accomplish the full range of performance requirements in all predicted service life environments.

Random Vibration: The non-deterministic oscillatory response of a structure caused by acoustical and/or mechanical forcing functions. The magnitude and spectral content of random vibration is known only in terms of statistical average properties.

Rotating Machinery: Devices with spinning parts such as fans, centrifuges, motors, pumps, gyros and flywheels.

Safety Critical: An event, system, subsystem or process that if lost or degraded, would result in a critical or catastrophic hazard.

Service Life: The service interval for a part beginning with manufacture and extending through its planned and specified usage. The service life includes all loadings and environments encountered during this period including manufacturing, testing, transportation, launch, on-orbit, descent, landing, and post landing events. A “service life” is sometimes referred to as a “lifetime.” In this sense, “lifetime” means a specified life as opposed to an analytically predicted life

Service Life Factor (Life Factor): A multiplying factor to be applied to the maximum expected number of load cycles in the service life to determine the design adequacy in fatigue or fracture.

Soft Goods: Cloth, fabric and articles made of cloth or fabric.

Spacecraft: A self-contained vehicle or system that is developed to operate in space or planetary body. A spacecraft consists of a support structure onto which are attached scientific instruments and related systems for communication, power, propulsion, and control.

Spaceflight Hardware: All flight hardware including launch vehicle, spacecraft and, payloads.

Static Load: A load of constant magnitude and direction with respect to the structure.

Stiffness: Structural resistance as a function of deflection or rotation under an applied force or torque.

Strength, Material: The stress level that a material is capable of withstanding in a local structural configuration and expected operating environments. Units are expressed in force per unit area using the original dimensions of the unloaded section.

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

Strength, Yield: Corresponds to the maximum load or stress that a structure or material can withstand without incurring permanent deformation.

Stress, Allowable: The maximum stress that can be permitted in a material for a given design condition to prevent rupture/collapse for ultimate conditions or detrimental deformation for yield conditions.

Stress, Applied: The stress induced by applied loads and thermal gradients.

Stress, Limit: The maximum stress expected in the structure during its service life including ground handling, transport to and from orbit including abort conditions, and on-orbit operations.

Stress, Thermal: The stress from temperature gradients and differential thermal expansion between structural components, assemblies, or systems.

Structural Adequacy or Integrity: A structure that complies with correctly specified design requirements.

Structural Design Temperatures: Temperature distributions of the structure when it is subjected to critical combinations of loads, pressures, and temperatures.

Structural Fastener: A fastener used in either the primary or secondary load path of a structure.

Structural Seal: A structural seal is one which is mounted in a static structural interface and prevents air flow from a high-pressure area to a lower pressure area.

Structural Thermal Effects: Thermal effects on the structure include heat transfer rates, temperature levels and cycles, thermal stresses and deformations, and mechanical and physical property changes.

Structure: All components and assemblies designed to sustain loads or pressures, provide stiffness and stability, or provide support or containment.

Structure, Primary: That part of a flight vehicle or element which sustains the significant applied loads and provides main load paths for distributing reactions to applied loads. Also the main structure which is required to sustain the significant applied loads, including pressure and thermal loads, and which if it fails creates a catastrophic hazard. If a component is small enough and in an environment where no serious threat is imposed if it breaks, then it is not primary structure.

Structure, Secondary: The internal or external structure which is used to attach small components, provide storage, and to make either an internal volume or external surface usable. Secondary structure attaches to and is supported by primary structure.

Tailoring: Adapting existing requirements to specific program or project needs.

Ultimate Load, Pressure, or Stress: Ultimate Load, Pressure, or Stress - The maximum load, pressure, or stress that a structure should withstand without incurring rupture or collapse; also, the product of the limit load multiplied by the ultimate FS. (Also Ultimate Strength.)

Verification: A formal process, using the method of test, analysis, inspection or demonstration, to confirm that a system and its components satisfy all specified performance and operational requirements

Vibration Mode: A characteristic pattern of displacement assumed by a vibrating system in which the motion of every particle is simple harmonic with the same frequency. Also referred to as Elastic Mode.

Yield Load, Pressure, or Stress: The maximum load, pressure, or stress that a structure can withstand without incurring detrimental deformations; analytically, the maximum load that a structure can withstand without exceeding the yield stress of the material; also the product of the limit load multiplied by the yield FS. (Also Yield Strength)