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BASELINE

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Constellation Program

CONSTELLATION PROGRAM STRUCTURAL DESIGN AND VERIFICATION REQUIREMENTS

REVISION AND HISTORY PAGE

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Baseline	-	Baseline	09/15/06
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PREFACE

CxP 70135, Structural Design and Verification Requirements, presents common structural design and verification requirements to ensure consistent design, development, and verification of Constellation Program flight hardware.

Chapter 3.0 of this document describes general design requirements, design loads, factors of safety and margins of safety, design and stress analysis requirements, and structural materials criteria and discusses secondary structure accommodation for human interface and nonstandard fasteners. Chapter 4.0 contains verification requirements. Chapters 4.30.3 and 6.0 specify testing and analysis requirements. Chapter 7.0 addresses inspection and maintenance requirements.

This document is under the control of the Constellation Program Control Board, and any changes or revisions will be approved by the Program Manager.

CONCURRENCE

CONSTELLATION PROGRAM

STRUCTURAL DESIGN AND VERIFICATION REQUIREMENTS

15 SEPTEMBER 2006

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1.0 INTRODUCTION

Structural design requirements for flight hardware are related to the methods to be used for structural design verification. This requirements document includes both structural design and verification requirements to assure that both are considered in the specification of detailed requirements for a component of Constellation Program flight hardware. Where appropriate, this document specifies design methodology to prevent conflicting analytical approaches utilized by different design and procurement organizations and the related impact on Program cost and schedules.

1.1 PURPOSE

The purpose of this requirements document is to specify common structural requirements for consistent design, development, and verification of all Constellation flight hardware.

1.2 SCOPE

The requirements in this document shall apply to all Constellation flight hardware including all Program elements, Orbital Replacement Units, Orbital Support Equipment, Flight Support Equipment, and payloads. It is important to note that these requirements are to be included in all subsystem structural integrity activities and especially in the procurement specifications of subcontracted mechanical, actuation, fluid and propulsion subsystems.

This is a design requirements document. Post-delivery anomalies and non-conformances will require case-specific analysis and/or test that are beyond the scope of this document.

1.3 CHANGE AUTHORITY/RESPONSIBILITY

Proposed changes to this document shall be submitted by a Constellation Program Change Request (CR) to the appropriate Constellation Control Board for consideration and disposition.

The CR must include a complete description of the change and the rationale to justify its consideration. All such requests will be processed in accordance with CxP 70100, Constellation Program Configuration Management Plan.

The appropriate NASA Office of Primary Responsibility (OPR) identified for this document is TBR.

1.4 INTENDED USE

This document is intended for use by the Constellation Program and shall be a requirement for each Program participant.

1.5 APPROVAL BY NASA

Structural design and verification approvals required by this document shall be provided by the Constellation Program's designated technical authority.

1.6 PRECEDENCE

The Constellation Architecture Requirements Document (CARD) defines the performance requirements for all Constellation Hardware. In the event of any conflict between the CARD and this document, the CARD takes precedence. In the event of any conflict between the text of this specification and an applicable document cited herein, the text of this specification takes precedence.

2.0 DOCUMENTS

2.1 APPLICABLE DOCUMENTS

The following documents include specifications, models, standards, guidelines, handbooks, and other special publications. The documents listed in this paragraph are applicable to the extent specified herein. Inclusion of applicable documents herein does not in any way supersede the order of precedence specified in paragraph 1.6.

APPLICABLE DOCUMENT NO.	TITLE	Referenced in paragraph(s)…
CxP 70137	CxP Loads Control Plan	3.5, 3.5.1, 3.5.2, 3.9.1
NASA-STD-5012	Strength and Life Assessment Requirements for Liquid Fueled Space Propulsion System Engines	Table 3.10.1-1, 3.17, 4.17
NASA-STD-6016	Standard Manned Spacecraft Requirements for Materials and Processes	3.11.4, 4.11.2, 4.11.4
MMPDS-01	Metallic Materials Properties Development and Standard	3.11.2
CA3193-PO	Fracture Control Requirements for Constellation Spaceflight Hardware	3.11.4, 3.14, 3.20.1, 3.20.5, 4.11.4, 4.13, 4.14, 4.16.3, 4.18.2.1, 4.20.1, 7.1.1, 7.1.2

APPLICABLE DOCUMENT NO.	TITLE	Referenced in paragraph(s)…
CA3222-PO	Design and Verification Criteria for Constellation Glass, Ceramics and Windows in Human Spaceflight Applications	3.15, Table 3.10.1-1, 4.15
CxP 70023	Design Specification for Natural Environments	3.23.2, 4.13
CxP 70130	EVA Design and Construction Specification	3.23.3
CxP 70024	Human Systems Integration Requirements	3.23.4
20M02540	Assessment of Flexible Lines for Flow Induced Vibration	3.20.7
NASA-STD-6008	NASA Fastener Integrity	3.25
MSFC-STD-486	Standard Torque Limits For Threaded Fasteners	3.25.2
SAE AS 8879	Screw Threads, UNJ Profile, inch	3.25.7
NSTS 08307	Criteria for Preloaded Bolts	3.25.8, 4.25.8
ANSI/AIAA-S-080-1998	Standard for Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components	3.10.1, 3.18, 3.18.2, 3.18.2.2
ASTM E1417-95a	Practice for Liquid Penetrant Examination	4.16.3
NASA-STD-5019	Fracture Control Requirements for Spaceflight Hardware	4.18.2, 4.18.2.2, 4.18.3.2
NSTS 08123	Certification of Flex Hose and Bellows for Flow Induced Vibration	**Error! Reference source not found.**
MSFC-SPEC-626	Test Control Document for Assessment of Flexible Lines for Flow Induced Vibration	**Error! Reference source not found.**
MSFC-RQMT-3479	Fracture Control Requirements for Composite and Bonded Vehicle and Payload Structures	3.19.8, 3.19.9, 3.19.10, 3.19.11, 3.19.12, 4.19.3.1, 4.19.3.3, 4.19.3.4, 4.19.5

2.2 REFERENCE DOCUMENTS

The following documents contain supplemental information to guide the user in the application of this document.

REFERENCED DOCUMENT NO	TITLE	Referenced in paragraph(s)…
MIL-HDBK-17	Composite Materials Handbook	3.19.3
NASA SP-8003	Flutter, Buzz, and Divergence	4.29.4.2, 4.30.1.1.1
FAA-FAR Part 25	Airworthiness Standards: Transport Category Airplanes	4.30.1.1.1, 4.30.1.2.1
AFSC DH 3-2 (DN 4C7)	USAF Space Vehicles, Design Handbook, Series 3-0	4.30.1.1.1
MIL-A-008870 (USAF)	Airplane Strength and Rigidity – Flutter, Divergence and Other Aeroelastic Instabilities	4.30.1.1.1, 4.30.1.2.1
NASA-TM-X-73305	Astronautic Structures Manual	6.1
JSC 19652	Instructions for the Preparation of Stress Analysis Reports	6.2.1
(OSHA 29 CFR 1919.79)	OSHA Regulations (Standards – 29CFR) Wire Rope 1919.70	3.10.1
AIAA-S-110-2005	Space Systems – Structures, Structural Components and Structural Assemblies	3.10.1
NASA SP-8007	Buckling of Thin-walled Circular Cylinders.	4.6
NASA-STD-5012	Strength and Life Assessment Requirements for Liquid Fueled Space Propulsion System Engines	3.10.1
NWC TP 6575	Parachute Recovery Systems Design Manual	3.26.1.2
NASA SP-8008	Prelaunch ground wind loads	4.30.3.2

3.0 DESIGN REQUIREMENTS

3.1 DESIGN ORGANIZATION STRUCTURAL ASSESSMENT PROGRAM

The organization responsible for structural design shall establish and maintain an effective structural analysis, structural test, and structural assessment program to evaluate and verify the structural integrity of Constellation Program flight hardware structure for both transport to and from orbit, and for on-orbit and planetary operations.

3.1.1 Structural Assessment After Critical Design Review (CDR)

Because the hardware design and the design data will evolve as the data such as loads, mass properties, temperatures and other environments are verified, it is NASA's intent to update the hardware certification database so that the flight hardware is certified to the latest definition of the design and the latest definition of operating environments. It is therefore probable that the design database will mature after CDR, and design changes will need to be considered in response to these developments.

The organization responsible for structural design shall establish a program to evaluate how post-CDR changes in the natural and induced environments may affect the hardware.

3.2 APPROVAL OF DETAILED DESIGN CRITERIA

a) Any detailed design criteria used by the responsible design organization shall be consistent with this requirements document.

b) Detailed criteria which are not consistent with the requirements of this document shall be approved by NASA per paragraph 1.5.

3.3 STRENGTH AND STIFFNESS

a) Constellation Program structures shall have strength and stiffness in all necessary configurations and stages to support ultimate load without failure.

b) Detrimental deformation shall not occur at limit loads imposed during transportation to and from orbit and on-orbit operations, lunar or planetary operations, ground handling and transportation, or during proof or acceptance testing.

c) Yielding shall not occur at limit loads imposed during ground transportation or handling operations.

3.4 MARGIN(S) OF SAFETY

Constellation Program flight hardware structure shall have +0.00 or positive Margin(s) of Safety (MS) for all limit and ultimate design load conditions, including the effect of aging on the hardware, with the following exception for permissible yielding.

3.4.1 Criteria for Yielding

Yielding of structure shall be acceptable only if all of the following conditions are satisfied:

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

b) There shall be no detrimental deformations that adversely affect the component/system function.

c) The service life requirements are met.

d) Unless otherwise specified, hydraulic, electrical, and other systems are not required to operate at loads and related deformations in excess of limit load.

e) Requirement 3.3 (c) shall be met.

f) The item is not a component of rotating machinery (see section 3.21).

3.5 LIMIT LOADS

a) Constellation Program structure shall meet its performance requirements as defined in the appropriate system's CxP SRDs when exposed to all appropriate static, transient, and random loads, pressure, and thermal effects for all phases of hardware service life, considering, when applicable, combined loading effects.

b) Limit load and load spectra shall be derived in accordance with the Constellation Program Loads Control Plan, CxP 70137.

c) Analyses shall be performed for all anticipated loading events to establish limit loads.

d) Any load uncertainty factors used for design and assessment shall be approved by the appropriate NASA Loads Control Panel.

e) The probability of any structural load exceeding the defined structural limit loads shall be less than or equal to $^{1}/_{741}$ during the Program life for time-consistent loads.

f) When time consistency is unknown, the probability of any load associated with an independent event exceeding the defined limit loads shall be less than or equal to $^{1}/_{741}$. Load combinations shall be made by computing a root-sum-square of the peak independent time-consistent loads that meet this criterion, or a Monte Carlo analysis producing a load combination that meets this probability criterion may be used.

g) For evaluating system structural integrity in the event of independent non-structural system failures, the probability of any load exceeding the defined limit loads shall be less than or equal to $^{1}/_{44}$.

h) The probability of any random load exceeding the defined random limit loads shall not be more than $^{1}/_{741}$.

3.5.1 Integrated Loads

The coordination, generation, and dissemination responsibility for integrated element interface loads is defined in the Constellation Program Loads Control Plan, CxP 70137.

a) For integrated flight, Constellation Program systems shall be designed to maintain required functionality and positive margins when subjected to all static and dynamic loads and thermal environments.

b) The Constellation flight vehicle structures shall maintain positive margins of safety for all induced loads and deformations, including dynamic interactions between mated stages.

c) All integrated configurations shall be considered.

3.5.2 Detailed Design Loads

Detailed design loads shall be derived for all life cycles of hardware in accordance with the Constellation Program Loads Control Plan, CxP 70137.

3.5.3 Redistributed Loads

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 mechanical devices shall meet all structural requirements using the redistributed loads after 1 or 2 credible system failures commensurate with the hazard levels. Operational procedures may be used to restore the load path or limit the applied loads after the first failure in order to meet the requirements.

3.6 BUCKLING AND CRIPPLING

a) 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 shall consider buckling failure modes.

b) Buckling shall not cause structural members that are subject to instability to collapse when ultimate loads are applied

c) Buckling shall not cause deformation at limit loads that degrades the functioning of any system or produces unaccounted changes in loading.

d) Diagonal tension designs shall not be precluded.

3.6.1 Design Loads for Collapse

a) Design loads for collapse shall be ultimate loads, except that any load component that tends to alleviate buckling shall not be increased by the ultimate FS.

b) Destabilizing external pressure or torsional limit loads shall be increased by the ultimate FS but stabilizing internal-pressure loads shall not be increased unless they reduce structural capability.

3.7 DYNAMIC INTERACTIONS

3.7.1 Dynamic Coupling

Constellation Program flight vehicle structure shall be free of instability or other interactions of the control system with the elastic modes.

3.7.2 Slosh

Propellant tanks shall be designed to prevent or suppress coupling between liquids and vehicle structure and between fluids and the flight control system.

3.7.3 Pogo

All Constellation Program flight vehicle structures shall not exhibit unstable dynamic coupling with the liquid propulsion system for all mission configurations.

3.8 THERMAL EFFECTS

Constellation Program structures shall meet the performance requirements as defined in the appropriate system's CxP SRDs when thermal effects are combined, when applicable, with induced static and dynamic loads.

3.9 MATH MODELS

Loads and deformations utilized in Constellation Program flight hardware verification shall be based on verified structural math models.

3.9.1 Flight Hardware Math Models for Loads

Structural math models used to develop design loads for Constellation Program flight hardware consistent with each phase of the Program shall be in accordance with the Constellation Loads Control Plan, CxP 70137.

3.9.2 Flight Hardware Math Models for Stress

The math models used to generate stresses, strains and internal loads for structural analysis shall be verified by the methodology selected from the requirements in paragraph 4.9.2 of this document.

3.9.3 Temperature Input for the Stress Model

Temperatures for the stress model shall be taken from a verified thermal math model.

3.10 FACTOR(S) OF SAFETY

3.10.1 Minimum Factors of Safety

All Constellation Program flight hardware structure shall be designed to the minimum factors of safety (FS) specified in Table 3.10.1-1, Minimum Factors of Safety for Structure, or as modified by the factors specified in sections 3.0 and 4.0 of this document. Yielding is permitted per the specifications of paragraphs 3.4.1 and 4.4.1. Maximum design pressure is referred to here and in the rest of this document as MDP.

Table 3.10.1-1 Minimum Factors of Safety for Structure

	Yield	Ultimate
A. Minimum Factors of Safety for Metallic Flight Structures (NASA-STD-5001A)		
Prototype	1.00	1.40
Protoflight	1.25	1.40

Table 3.10.1-1 Minimum Factors of Safety for Structure

		Yield	Ultimate
B. Minimum Factors of Safety for Non-metallic Flight Structures (NASA-STD-5001A)			
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		
C. Minimum Factors of Safety for Structural Soft Goods (NASA-STD-5001A) [excluding parachute & parafoil systems]			
Safety critical			4.0
Proof or Acceptance Test Factor	1.2		
Qualification Test Factor	4.0		
Not safety critical			2.0
Proof or Acceptance Test Factor	1.2		
Qualification Test Factor	2.0		
D. Minimum Factors of Safety for Parachute and Parafoil Systems			
1. Subsonic systems			1.6
2. Supersonic systems			1.7
3. Safety critical components			2.0
E. Minimum Factors of Safety for Wire Ropes and Cables (OSHA 29 CFR 1919.79)			4.0
Proof or Acceptance Test Factor	2.0		
F. Minimum Factors of Safety for Glass and Ceramic Structures, including windows			
Design factors for windows, glass and ceramic structure are defined in CA3222-PO, Design and Verification Criteria for Glass, Ceramics and Windows in Human Spaceflight Applications.			
G. Minimum Factors of Safety for Rotating Machinery (liquid fueled engines see line H.1)		1.1	1.5
High-Cycle Fatigue Factor of Safety	1.33		
Low-Cycle Fatigue Factor of Safety	4.0		
H. Minimum Factors of Safety for Pressure			

Table 3.10.1-1 Minimum Factors of Safety for Structure

		Yield	Ultimate
1. Engine Structures and Engine Compartments in Liquid Fueled Space Propulsion Systems			
Design and verification criteria for liquid fueled space propulsion systems are defined in NASA-STD-5012.			
2. Hydraulic and Pneumatic Systems (MSFC-HDBK-505B)			
a. Lines and fittings less than 1.5 inches (38 mm) dia. (OD)			
Proof Pressure[1]	=1.50 X MDP		
Ultimate Pressure	=4.00 X MDP		
b. Lines and fittings, 1.5 inches (38 mm) dia. or greater			
Proof Pressure[1]	=1.50 X MDP		
Ultimate Pressure	=2.50 X MDP		
c. Reservoirs/Pressure Vessels			
Proof Pressure[1]	=1.50 X MDP		
Ultimate Pressure	=2.00 X MDP		
d. Actuating cylinders, valves, filters, switches, line-installed alignment bellows and heat pipes			
Proof Pressure[1]	=1.50 X MDP		
Ultimate Pressure	=2.50 X MDP		
e. Flex hoses, all diameters			
Proof Pressure[1, 4]	=2.00 X MDP		
Ultimate Pressure	=4.00 X MDP		
3. Pressurized Structures (ANSI/AIAA-S-080-1998)			
a. Metal structures shall meet the factors above in (A) except for doors, hatches and habitable modules.			
b. Non-metal pressurized structures shall meet the factors above in (B) except for doors, hatches and habitable modules			
c. Doors, Hatches and Habitable Modules			
▪ Internal pressure only		1.65	2.00
Proof Pressure[1]	=1.50 X MDP		
▪ Negative pressure differential		N/A	1.50
4. Combined pressure, thermal and mechanical loading[2, 3, 5] (AIAA-S-110-2005)			
$K_1L_{mechanical} + K_2L_{thermal} + K_3L_{pressure}$ = Total (Limit or Ultimate) Load			

Table 3.10.1-1 Minimum Factors of Safety for Structure

	Yield	Ultimate

Notes:

1. Proof factor determined from fracture mechanics service life analysis shall be used if greater than minimum factor.
2. See paragraph 6.1.1 when pressure loads have a relieving or stabilizing effect on structural capability.
3. See paragraph 4.8 when thermal conditions are relieving
4. In a system with fluid lines and flex hoses, the individual flex hoses shall be proof tested to 2.00 X MDP at the assembly level.
5. K_i = design factor of safety on yield or ultimate from this table, as applicable, when term is additive to the algebraic sum, ΣL

   K_i = 1.0 when term is subtractive to the algebraic sum, ΣL

   $L_{mechanical}$ = internal loads (forces, stresses, and/or strains) due to externally applied mechanical limit loads; e.g., inertial loads, aerodynamic pressure

   $L_{thermal}$ = internal loads (forces, stresses, and/or strains) due to thermally-induced loads at the maximum and minimum predicted temperatures including modeling uncertainty margins

   $L_{pressure}$ = internal loads (forces, stresses, and/or strains) due to design limit pressures

3.10.1.1 Factor of Safety for Crushing Pressure Differential

A crushing pressure differential on habitable modules shall use an ultimate factor of safety of 2.0 if certification for these loads is by analysis only.

3.10.1.2 Post-landing Factor of Safety of Pressure Vessels

Minimum design factors of safety for pressure vessels shall be maintained under conditions encountered at any continental United States or contingency landing site without post-landing services.

3.10.2 Emergency Events

Program-defined emergency design loads shall be specified as ultimate loads.

3.10.3 Analysis-only Factors of Safety

In this document, there are no published “analysis-only” factors of safety that automatically allow structural verification without testing. A higher factor of safety alone is insufficient to account for structural uncertainties or modeling errors that a test program will uncover.

For metallic structures only, it may be permissible to verify structural integrity by analysis alone without strength testing, provided an acceptable engineering rationale is developed. Increasing the design factors of safety does not by itself justify this “no-test” approach. Some examples of criteria on which to base such an approach are as follows:

- The structural design is simple (e.g., statically determinate) 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.
- 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.
- 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.

If a “no test” option is proposed, the approach and the factors of safety to be used in the structural analysis and life verification shall be included in the structural verification plan and approved in writing by NASA per paragraph 1.5.

3.11 STRUCTURAL MATERIALS CRITERIA

Material selection and documentation requirements shall be as defined in NASA-STD-6016, Standard Manned Spacecraft Requirements for Materials and Processes.

3.11.1 Material Design and Analysis Thickness

The drawing minimum thickness shall be used in stress calculations of pressure vessels, stability critical structure, and single load path structure. Actual as-built dimensions may be used in stress calculations when available.

3.11.2 Structural Material Allowable Properties

a) Material “A” or equivalent allowable values shall be used in all applications where failure of a single load path could result in a loss of structural integrity in primary structure.

b) Material “B” or equivalent allowable values shall not be used except in redundant structure in which the failure of a component would result in a safe redistribution of applied loads to other load-carrying structure.

c) MMPDS-01 material “S” allowables may be used in lieu of “A” or “B” allowables where batch lot acceptance testing is a procurement requirement.

d) “S” or equivalent material properties shall be approved by NASA per paragraph 1.5.

e) Design allowables specific to the material used in a structure may be developed if a selection of that material is tested to determine the mechanical properties of the actual material used in that particular item. Use of these "premium" properties shall require NASA approval, per paragraph 1.5.

f) Where values for mechanical properties of new materials or existing materials in new environments are not available, they shall be determined by analytical or test method approved by NASA per NASA-STD-6016.

3.11.3 Avoiding Creep

a) Materials shall be selected to preclude accumulated damage from creep in Constellation Program flight hardware environment.

b) If selection of a structural material which exhibits creep phenomena in the Constellation program flight hardware environment is unavoidable, then NASA approval per paragraph 1.5 shall be obtained prior to use.

3.11.4 Castings

Any component manufactured with a casting shall meet the appropriate fracture control requirements in CA3193-PO and the material properties development requirements in NASA-STD-6016.

3.12 DESIGN FACTORS

3.12.1 Joint Fitting Factor

In the structural analysis of fittings, a fitting factor of 1.15 shall be used on limit and ultimate loads for joints which contain fittings 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.

A fitting factor need not be used with limit and ultimate loads 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.

3.12.1.1 Joint Fitting Factor Application

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

3.12.1.2 Joint Fitting Factor for Integral Fittings

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

3.12.2 Bearing Factor

A bearing factor of 2.0 shall be used in conjunction with the yield and ultimate FS for the design of a joint subjected to shock or hammering action.

3.13 STRUCTURAL LIFE REQUIREMENTS

All structural components shall have adequate structural life according to the specific requirements identified in the appropriate system's CxP SRD.

3.13.1 Cumulative Damage During Service Life

All flight hardware structure shall be designed to preclude failure resulting from cumulative damage due to cyclic or repeated loading and sustained stress during the design service life.

3.13.2 Creep

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 design service life.

3.14 FRACTURE CONTROL

Constellation program hardware shall be designed and verified for fracture control per the requirements of CA3193-PO, Constellation fracture control requirements.

3.15 GLASS, CERAMICS AND WINDOW DESIGN CRITERIA

The structural design and verification requirements for windows, ceramics and glass shall be in accordance with CA3222-PO, Constellation requirements for glass and ceramics.

3.16 BERYLLIUM STRUCTURES

Beryllium may be used in the Constellation Program for structural components as long as the verification meets the requirements in section 4.16.

3.17 LIQUID FUELED SPACE PROPULSION SYSTEM STRUCTURES

Design of structural components of liquid fueled space propulsion systems shall comply with NASA-STD-5012, Strength and Life Assessment Requirements for Liquid Fueled Space Propulsion System Engines. Factors of safety and other design and verification criteria may be found in this document.

3.18 PRESSURIZED STRUCTURES

Pressurized structures are typically large tanks or habitable structures that carry external flight loads as well as containing the internal fluids or gases. The analysis and verification requirements tailored from ANSI/AIAA-S-080-1998 and specified herein shall be met.

3.18.1 Factor of Safety Requirements

Pressurized structures shall be designed to the minimum factors of safety in Table 3.10.1-1.

3.18.2 Pressurized Structures with Non-hazardous Leak-Before-Burst (LBB) Design

Pressurized structures with non-hazardous leak before burst design shall meet the requirements of ANSI/AIAA S-080-1998, Section 5.2.1.

3.18.2.1 Habitable Structures and Enclosures

Habitable structures and enclosures shall be designed to meet leak before burst criteria

3.18.2.2 Pressurized Structures with Brittle Fracture or Hazardous LBB Failure Mode

Pressurized structures with non-hazardous leak before burst design shall meet the requirements of ANSI/AIAA S-080-1998, Section 5.2.2.

3.19 COMPOSITES/BONDED STRUCTURE DESIGN

3.19.1 General Design Requirements

All composite/bonded structures shall, as a minimum, meet prescribed structural design requirements specified in this document.

3.19.2 Composites/Bonded Structure Design Factors of Safety

Composite/bonded structure shall be designed to the factors of safety listed in Table 3.10.1-1.

3.19.3 Composites/Bonded Structure Design and Analysis Practices

The designer/manufacturer shall use only manufacturing processes and controls (coupon tests, sampling techniques, etc.), design standards and analysis practices that are demonstrated to be reliable and consistent with established aerospace industry practices for composite/bonded structures. MIL-HDBK-17 may be used as a reference.

3.19.4 Composites/Bonded Structure Life Requirements

Composite/bonded structures shall be designed for a minimum of four service lifetimes when considering maximum damage/flaws due to manufacture and handling which could not be detected by the inspection process specified.

3.19.5 Composite Structure Inadvertent Damage Protection

A comprehensive plan for the prevention of inadvertent damage to manufactured composite structural components that may result from handling, transportation, storage or final assembly shall be prepared by the hardware developer and approved by the Constellation Program designated technical authority.

3.19.6 Composites/Bonded Structure Strength and Stiffness Requirements

Constellation Program composite/bonded structures shall have strength and stiffness in all necessary configurations and stages to support ultimate load without failure.

3.19.7 Bonded Joints

All bonded joints shall, as a minimum, meet prescribed structural design requirements specified in this document.

3.19.8 Special Considerations for Composite Rotating Machinery

Composite rotating machinery shall comply with the design requirements specified in MSFC-RQMT-3479, Appendix A.

3.19.9 Special Considerations for Composite Hazardous Fluid Containers (Including Lines, Ducts and Fittings)

Composite hazardous fluid containers (including lines, ducts and fittings) shall comply with the design requirements specified in MSFC-RQMT-3479, Appendix A.

3.19.10 Special Considerations for Composite Habitable Modules

Composite habitable modules shall comply with the design requirements specified in MSFC-RQMT-3479, Appendix A.

3.19.11 Special Considerations for Composite Solid Rocket Motor Cases and Nozzles

Composite solid rocket motor cases shall comply with the design requirements specified in MSFC-RQMT-3479, Appendix A.

3.19.12 Special Considerations for Composite Propellant Tanks and Other COPVs

Composite propellant tanks and other COPVs shall comply with the design requirements specified in MSFC-RQMT-3479, Appendix A.

3.20 DESIGN REQUIREMENTS FOR PRESSURE SYSTEMS

3.20.1 Fracture Control for Pressure Vessels

Pressure vessels shall be designed and fabricated under an approved fracture control program and be in accordance with requirements specified in CA3193-PO.

3.20.2 Pressure Control

Where pressure regulators, relief devices, and/or a thermal control system (e.g., heaters) are used to control pressure, they shall collectively be two-fault tolerant from causing the pressure to exceed the MDP of the system.

3.20.3 Pressure Stabilized Vessels

Volumes which are pressure stabilized and must contain a minimum pressure to maintain the required ultimate factors of safety to insure structural integrity under launch, ascent and landing loads shall meet all the requirements for pressure vessels.

3.20.4 Burst Discs

When burst discs are used as the second and final control of pressure to meet the requirements of paragraph 3.20.2, they shall be designed to the following requirements:

a) Burst discs shall incorporate a reversing membrane against a cutting edge to insure rupture.
b) Burst disc design shall not employ sliding parts or surfaces subject to friction and/or galling.

c) Stress corrosion resistant materials shall be used for all parts under continuous load.

3.20.5 Dewars

Dewar/cryostat systems shall be designed in accordance with the fracture control for pressure vessel requirements in CA3193-PO and the following:

a) Pressure containers shall be leak-before-burst (LBB) designs as determined by a fracture mechanics analysis.

b) Containers of hazardous fluids and all non-LBB designs shall employ a fracture mechanics safe-life approach to assure safety of operation.

c) Outer shells (i.e., vacuum jackets) shall have pressure relief capability to preclude rupture in the event of pressure container leakage.

d) If pressure containers do not vent external to the dewar but instead vent into the volume contained by the outer shell, the outer shell relief devices shall be capable of venting at a rate to release full flow without outer shell rupture.

e) Relief devices shall be redundant and individually capable of full flow.

f) Pressure relief devices which limit maximum design pressure shall be certified to operate at the required conditions of use.

g) Non-hazardous fluids may be vented into the inter-element volume if analysis shows that a worst case credible volume release will not affect the structural integrity or thermal capability of the integrated vehicle or will not become a catastrophic hazard.

h) Dewar/cryostat systems shall maintain structural integrity under all external loads.

3.20.6 Secondary Volumes

Secondary compartments or volumes that are integral or attached by design to pressure system components and which can become pressurized as a result of a credible single barrier failure shall be designed for safety consistent with structural requirements.

3.20.6.1 Non-credible Failures in a Secondary Pressurized Volume

a) Redundant seals in series which have been acceptance pressure tested individually prior to flight shall not be considered credible single barrier failures.

b) Failures of structural parts, such as pressure lines and tanks, and properly designed and tested welded or brazed joints shall not be considered single barrier failures.

c) In order to be classified as a non-credible failure, the item shall be designed for a safety factor of 2.5 on the MDP, and shall be certified for all operating environments including fatigue conditions.

3.20.6.2 Allowable Venting for a Secondary Pressurized Volume

If external leakage would not present a catastrophic hazard, the secondary volume shall either be vented or equipped with a relief provision in lieu of designing for system pressure.

3.20.7 Flow Induced Vibration

All flexible hoses and bellows shall be designed to exclude or minimize flow induced vibrations in accordance with 20M02540.

3.21 STRUCTURAL DESIGN REQUIREMENTS FOR ROTATING MACHINERY

The design of rotating machinery (e.g. blades, vanes, disks, shafts, spacers, couplings, etc.) from a structural standpoint is based on the relationship between the loads that will be imposed on the component and the capacity of the component to withstand those loads. The requirements in this section were derived from Volume 1A of the *Rotating Machinery Engineering Design Guide*, Engineering Directorate, NASA (Lewis) Glenn Research Center, published in January 1996.

a) Loads shall include, but not be limited to the following effects: pressure, centrifugal, inertia, thrust, and thermal.

b) Local yielding shall not occur in any component of a machine element.

c) This section shall not apply to rotating machinery in liquid fueled space propulsion systems (see section 3.17).

3.21.1 Temperature Requirements for Rotating Machinery

Components shall be designed using material strengths for the maximum temperature environment.

3.21.2 Cumulative Damage During Service Life for Rotating Machinery

All rotating machinery components shall be designed to preclude failure resulting from cumulative damage due to cyclic or repeated loading and sustained stress during the design service life.

3.21.3 Creep for Rotating Machinery

All rotating machinery components 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) during the design service life.

3.21.4 Structural Design Requirements for Rotor Assemblies and Components

3.21.4.1 Stiffness Requirements for Shafts

a) The bent shaft natural frequencies shall be separated from the maximum operating speed.

b) The rigid shaft natural frequencies shall be separated from all steady-state operating speeds.

3.21.4.2 Radial Clearances from Flow Path to Rotating Components

a) The recommended minimum radial clearance between rotor and casing is .010 inch.

b) Abradable materials and/or honeycomb shrouds shall be provided over all rotating components (i.e. labyrinths, blades, etc.) if minimum radial clearances between rotor and casing are less than 0.020 inches.

3.21.4.3 Structural Design Requirements for Disks and Rings

a) The stress in disks and rings shall be determined at the Maximum Operating Speed.

b) The stress limits shown in Table 3.21.4-1 shall be met for disks and rings:

Table 3.21.4-1 Stress Limits for Components of Rotating Machinery

Component	Stress State	Stress Limits
Disk Web	Combined primary & secondary effective steady stress	< 100% of 0.2% F_{ty}
Disk Bore	Combined primary & secondary effective steady stress	< 100% of 0.2% F_{ty}
Disk or Rotor Average Section	Primary tangential stress	< 70% of F_{tu}
Disk Average Section	Primary tangential stress	< 70% of 10 hour stress-rupture life

[Effective primary stress < 0.2% plastic creep stress for required life.]

3.21.4.3.1 Design Requirements for Holes in Disk Webs

Holes shall be permitted in the disk but not in the disk web.

3.21.4.3.2 Blade-Disk Coupling Restrictions

To prevent high cycle fatigue, the blade-disk modes shall not resonate with the ball bearing passing frequency, the vane passing frequency, the strut passing frequency or the first four engine orders.

3.21.5 Structural Design Requirements for Shafts, Spacers, Flanges and Pilots

a) Bolted flanges shall be capable of carrying torque by clamping friction, otherwise drive devices (pins, keys, splines, etc.) shall be used.

b) Pilots shall be designed with interference fits to compensate for initial out-of-roundness between mating parts and to compensate for relative growth at the Maximum Operating Speed.

c) Thermal expansions or contractions of components shall not cause detrimental loosening, tightening or running clearance changes.

d) Two trip devices shall be incorporated in the design of the shaft for tripping the rotor at maximum operating speed.

e) The stress shall be determined at the Maximum Operating Speed.

f) Stress limits with applicable factors of safety are as follows:

Table 3.21.5-1 Stress Limits for Shafts, Spacers, Flanges & Pilots

Stress State	Stress Limit
Tangential stress	< 0.2% F_{ty}
Tangential stress	< 0.2% plastic creep
Effective stress	0.2% F_{ty}
Torsional stress	< 60% critical torsional buckling stress
Maximum transient effect stress after single blade failure	< F_{tu}

3.21.6 Structural Design Requirements for Rotor Blades

Rotor blades shall be designed for operation at the maximum operating speed, including consideration of fluid forces and inertia loads.

3.21.6.1 Rotor Blade Stiffness Requirements

The rotor blade natural frequencies shall be separated from the engine order excitation lines.

3.21.6.2 Rotor Blade Life Requirements

All rotor blades shall be designed to preclude failure resulting from cumulative damage due to cyclic or repeated loading and sustained stress during the design service life.

3.21.7 Structural Design Requirements for Static Assemblies and Components

3.21.7.1 Structural Design Requirements for Casings

a) The casings shall be designed for the maximum operating pressure at maximum inertial loading.

b) The casings shall be capable of containing a single blade failure.

c) The casing design should be capable of containing a single disk failure. If this goal is not met, the rotor assembly shall be positioned such that a disk failure does not cause a catastrophic failure, or sufficient shielding shall be placed around the critical areas to avoid catastrophic failures.

3.21.7.2 Structural Design Requirements for Vanes

3.21.7.2.1 Vane Design Strength

Vanes shall be designed for conditions at maximum operating speed and maximum inertial loads.

3.21.7.2.2 Vane Stiffness Requirements

The vane natural frequencies shall be separated from the engine order excitation lines and speed lines.

3.21.7.2.3 Vane Life Requirements

All vanes shall be designed to preclude failure resulting from cumulative damage due to cyclic or repeated loading and sustained stress during the design service life.

3.22 DESIGN REQUIREMENTS FOR STRUCTURAL SOFT GOODS

Straps, fabrics, inflatable structures, gossamer structures and others that carry structural loads upon launch or deployment are considered structural soft goods. For parachute or parafoil system design requirements, see section 3.27.1, Minimum Factors of Safety for Soft Goods

These items shall meet the minimum factors of safety specified in Table 3.10.1-1.

3.22.1 Structural Design Requirements for Soft Goods

These items shall, as a minimum, meet prescribed structural design requirements specified in this document.

3.23 DESIGNING FOR POST-DAMAGE STRUCTURAL INTEGRITY

3.23.1 Structural Degradation from Material Erosion - General

Potential structural erosion, e.g., Plasma Environmental Effects Compatibility-induced, atomic oxygen, and other natural environments, during the design life shall be included in the design and analysis of the structure.

3.23.2 External Structural Integrity after MM/OD Impact

Constellation Program micro-meteoroid and orbital debris critical flight structure (see Figure 3.23-1Figure 3.23-1) shall be designed to meet the performance requirements as defined in The appropriate system's CxP SRDs when exposed to impacts by meteoroids and space debris as defined in CxP 70023, the Design Specification for Natural Environments.

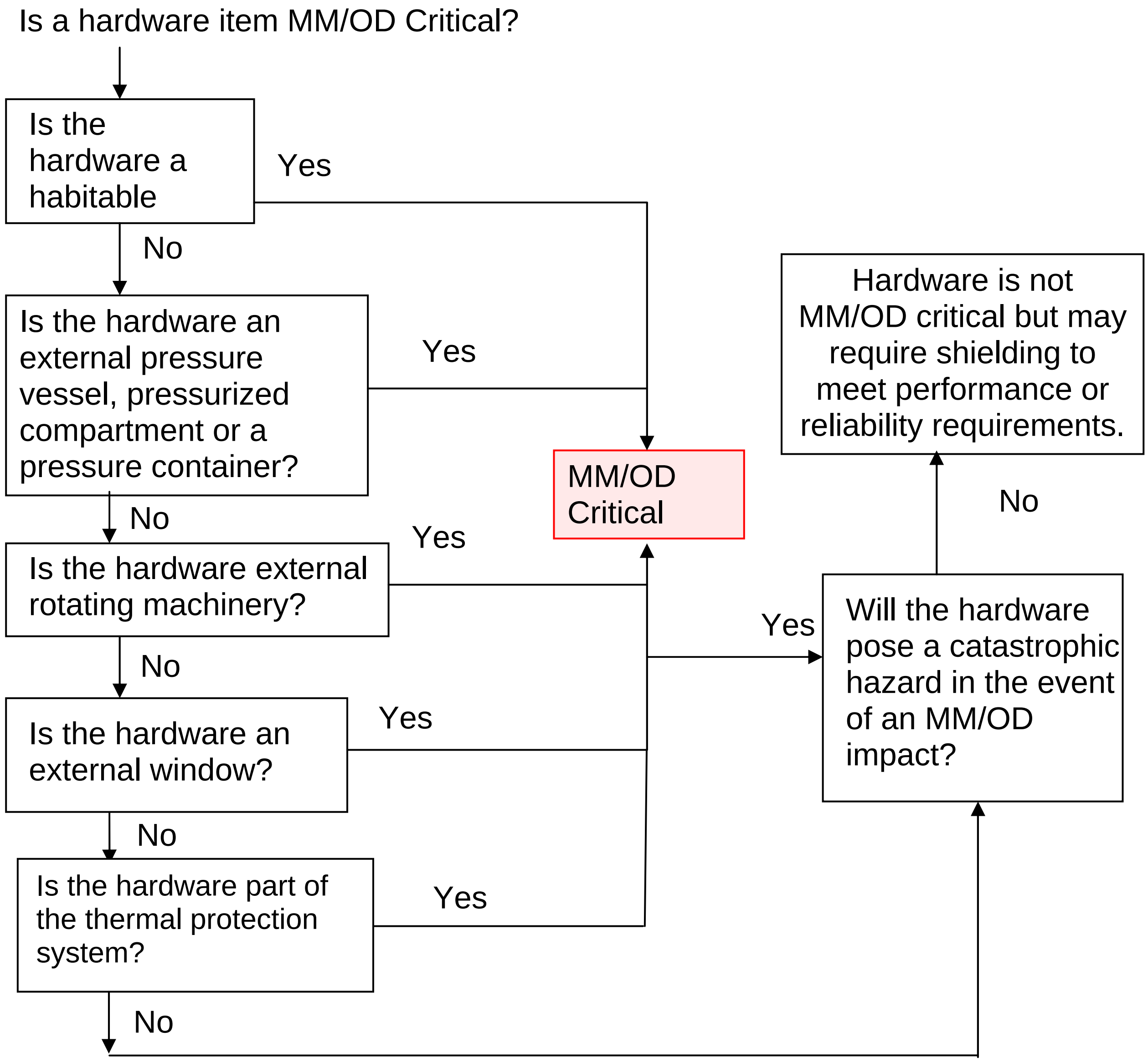

Figure 3.23-1

3.23.3 External Structural Integrity After EVA Crew Induced Loads

Constellation Program external structure shall meet its performance requirements as defined in the appropriate system's CxP SRDs when exposed to EVA crew induced loading as defined in CxP 70130, EVA Design and Construction Specification.

3.23.4 Internal Structural Integrity after IVA Crew Induced Loads

Constellation Program internal structure shall meet its performance requirements as defined in the appropriate system's CxP SRDs when exposed to IVA crew induced loading as defined in CxP 70024, Human Systems Integration Requirements.

3.24 SECONDARY STRUCTURE ACCOMMODATION FOR HUMAN INTERFACE

3.24.1 Inspection, Maintenance and Repair

Interior secondary structures, stand-offs, attachment hardware, utility runs, partitions, walls, and close-out structure shall be designed for accessibility to other hardware for inspection, maintenance, and repair.

3.24.2 Interior Close-out

Close-out structure shall be used to prevent items from becoming lost in the low-gravity environment.

3.24.3 Ground and In-space Operational Access Doors

Secondary structures such as compartment doors and access panels which provide access for EVA maintenance shall be operational in both ground and in-space environments.

3.24.4 Fasteners for Close-out Panels and Access Doors

For close-out panels and access doors that will be used multiple times during ground processing and mission operations, multiple-use fasteners shall be specified.

3.25 FASTENERS AND JOINTS

Fasteners shall meet the specifications in NASA-STD-6008.

3.25.1 Structural Fastener Retention

a) Non-verifiable retention methods such as liquid locking compounds (LLCs) shall not be used per NASA-STD-6016.

b) Fastener systems used in non-permanent installation applications that utilize prevailing torque self-locking features shall have the locking feature located on the externally threaded fastener.

3.25.1.1 Fastener Retention Redundancy

Each ground-installed fastener, in joints not subject to rotation, whose failure would cause a redistribution of structural loads shall incorporate two separate verifiable locking features.

Preload may be used as one of the locking features combined with conventional vibration-rated aerospace secondary locking, so long as the preload level is adequate to produce the intended locking effect. (See notes on Fastener Preload, section 3.25.8)

3.25.1.2 Structural Fasteners in Joints Subject to Rotation

Structural fasteners used in joints that are subject to rotation in operation shall either

- Utilize at least one non-friction locking device, or
- Utilize a self-locking nut with a shoulder bolt or a standard bolt in a sleeve, wherein the grip length or the length of the sleeve shall ensure that sufficient end play is provided to preclude binding when the self-locking nut is tightened.

3.25.1.3 Use of Snap Rings and Cotter Pins

Where snap rings or cotter pins are used, new snap rings or cotter pins shall be used once the previous snap ring or cotter pin is removed.

3.25.2 Structural Fastener Torque Specification

a) Preload torques and running torques (also known as prevailing torques), along with their acceptable ranges, shall be specified on the drawings controlling their installation.

b) The required torque for fasteners with locking features shall be clearly specified on the drawing as “above running torque.”

c) MSFC-STD-486 or equivalent specifications shall be used to establish torque and re-torque limits for threaded fasteners and for use of torque wrenches on such fasteners.

3.25.2.1 Torque Application

Torque shall be applied from the nut of the fastening system to the maximum extent practical when a nut is accessible. Where clearance is a problem, torque may be applied from the bolt head of the fastening system to achieve the proper preload.

3.25.2.2 Running Torque

a) Running (self-locking or prevailing) torque and breakaway torque values exhibited during installation through the locking feature shall meet the requirements of the self-locking fastener procurement specification for each installation.

b) Fasteners that do not meet the running torque specification shall be replaced.

3.25.2.3 Wrenching Torque Requirements

Design torque values shall not exceed the specification wrenching torque values for fasteners and nuts.

3.25.3 Inserts

a) Threaded inserts shall be used in applications that require tapped holes in aluminum, magnesium, plastic, or other materials that are susceptible to galling or thread damage.

b) Fasteners shall engage the entire length of the threaded insert to ensure full development of joint tensile strength.

3.25.4 Thread Engagement

If nuts or nutplates are used, a minimum of two complete screw threads shall protrude beyond the end of the nut or nutplate).

3.25.5 Grip Length Adjustment

3.25.5.1 Adjusting with Dash Numbers

a) Fasteners more than two dash numbers above or below the specified dash number shall not be used to adjust grip length.

b) Fasteners two dash numbers above or below the specified dash number may be used where no interference results and the minimum thread protrusion requirements are satisfied.

3.25.5.2 Adjusting with Washers

a) Washers shall not be used to provide fastener joint fit-up in lieu of grip length adjustment unless torque-tension testing with the adjusted number of washers has been performed.

b) The number of washers used in combination with a fastener shall be limited to four, two under the head (one countersunk) and two flat washers under the nut.

c) Countersunk washers shall be used under fastener heads with the countersink adjacent to the fastener head.

3.25.6 Structural Strength Issues in Fastener Specifications

a) Structural fasteners shall not be used where threads are placed in bearing.

b) The unthreaded portion of the shank shall not protrude through the parts being joined such that the nut bottoms out on the unthreaded shank.

3.25.7 Fastener Thread Specification Requirements

a) Fatigue-sensitive structural fasteners and fasteners with ultimate tensile strength of 160 ksi or higher shall be of unified thread form UNJ, class 3 fit, designed and procured in accordance with SAE AS 8879.

b) Externally threaded fasteners utilizing the UNR or UNJ thread form shall have threads that are rolled after heat treatment.

3.25.8 Preloaded Joint Criteria

a) Preloaded joints shall be assessed in accordance with NSTS 08307, Criteria for Preloaded bolts, unless all of the following criteria are met:

1. The joint is not a tension joint in which gapping cannot be tolerated. A “tension joint” is defined as a joint in which the largest component of the applied load is tension.
2. Fastener prying effects are correctly accounted for.
3. The fastener is in a local pattern of two or more fasteners.
4. The fastener is a high-quality military standard, national aircraft standard, or equivalent commercial fastener that is fabricated and inspected in accordance with aerospace flight quality hardware specifications.
5. The fastener preload is well controlled, using test-verified torque-tension relationships and nominally 65 percent of F_{ty}. Exceptions shall be documented with rationale, such as secondary structural application.
6. The joint fittings are metallic.
7. No significant thermal loading that changes preload is present during mechanical loading.

8. The joints are not for pressure containment, including crew module environmental containment, or hazardous material containment.

b) If the above criteria are met, bolted connection margins of safety may be assessed without fastener preload, yield, or gapping considerations.

3.25.9 Nonstandard Fasteners

NASA approval per paragraph 1.5 shall be obtained for the use of nonstandard or specially manufactured fasteners.

3.26 CRITICAL SEAL REDUNDANCY

Critical seals shall be redundant per Table 3.26-1.

Table 3.26-1 Seal Redundancy and Verifiability Requirements

Seal	Redundancy and Verifiability Requirements [2,3,4,5]		
	0.5 < D ≤ 6.0 inches	D > 6.0 inches	D ≤ 0.5 inches
Feed-through connection [1]	A	B	C
Rotary	A	B	C
Windows	A	B	C
Hatches/Doors	A	B	C
Mating Mechanisms	A	B	C
Structural Seals	A	B	C

Notes:

(1) Includes valves, gages, transducers, etc.
(2) D = Major diameter of the seal.
(3) A = Interface shall have a minimum of two seals. The assembly shall be verifiable prior to launch.
(4) B = Interface shall have a minimum of two seals. Each seal shall be verifiable prior to launch and on orbit or during a planetary mission. Structural seals shall not be required to be verifiable during a mission.
(5) C = Interface shall have a minimum of one seal. The assembly shall be verifiable prior to launch.

3.27 DECELERATION SYSTEMS

All deceleration devices will be considered structural systems and shall comply with the appropriate requirements contained within this document.

3.27.1 Special Considerations for Parachute Systems

All parachute system components shall maintain positive margins of safety using appropriate factors of safety, de-rating factors and material design allowables for all anticipated loading environments.

3.27.1.1 Factors of Safety for Parachute Systems

Parachute system components shall be designed to the minimum factors of safety as defined in Table 3.10.1-1.

3.27.1.2 De-rating of the Ultimate Factor of Safety for Textile Components in Parachute Systems

The ultimate factor of safety for textile components of the parachute system shall be de-rated to account for the materials used, attachment methods and environmental conditions particular to the parachute design. NWC TP 6575, “Parachute Recovery Systems Design Manual” describes de-rating factors.

3.28 WIRE ROPE DESIGN REQUIREMENTS

Wire rope used as part of a spacecraft structural system shall be designed to the minimum ultimate factor of safety specified in Table 3.10.1-1.

3.29 FLUTTER

3.29.1 Classical Flutter

a) Constellation atmospheric flight vehicles shall be free from flutter at 1.32 times the maximum dynamic pressure expected at any point along the dispersed ascent, entry, and abort design trajectories with and without control surfaces activated.

b) The dynamic pressure margin shall be determined separately at constant density and at constant Mach number.

3.29.2 Stall Flutter

a) Separated aerodynamic-flow effects associated with lifting and stabilizing surfaces in high angle-of-attack maneuvers shall not result in structural failure or loss of control in Constellation atmospheric flight vehicles.

b) The vehicle shall be free of stall flutter at 1.32 times the dynamic pressure expected for this type of maneuver.

3.29.3 Panel Flutter

a) External surfaces shall be free of panel flutter at dynamic pressures up to 1.5 times the local dynamic pressure expected at any Mach number along the dispersed ascent, entry, and abort design trajectories;

b) The dynamic pressure margin shall be determined separately at constant density and at constant Mach number.

3.29.4 Control Surface Buzz

a) Constellation atmospheric flight vehicles, with or without control surfaces activated, shall be free of control surface buzz at dynamic pressures up to 1.32 times the maximum dynamic pressure expected at any point along the dispersed ascent, entry, and abort design trajectories.

b) The dynamic pressure margin shall be determined at constant density and at constant Mach number.

3.30 AEROELASTICITY

3.30.1 Static Aeroelasticity

3.30.1.1 Divergence

a) Constellation atmospheric flight vehicles shall be free from divergence at dynamic pressures up to 1.32 times the maximum dynamic pressure expected at any point along the dispersed ascent, descent, and abort trajectories with and without control surfaces activated.

b) The dynamic pressure margin shall be determined separately at constant density and at constant Mach number.

3.30.1.2 Aeroelastic Effects on Control Surfaces

Aeroelastic effects shall not reduce control surface authority below that which is required for vehicle control at all dynamic pressures and Mach numbers at any point along the dispersed ascent, entry and abort design trajectories.

3.30.2 Dynamic Aeroelasticity

Constellation vehicle flight structure shall be designed to prevent:

a) all detrimental instabilities due to coupled vibration modes;

b) detrimental loads and dynamic responses associated with structural flexibility; and

c) adverse interaction between the structure and other vehicle systems.

3.30.3 Vortex Shedding

Constellation vehicle flight structures shall be designed to prevent instabilities and excessive dynamic response due to vortex shedding produced by ground winds and gusts during both the pre-launch and launch phases.

4.0 STRUCTURAL VERIFICATION REQUIREMENTS

Structural integrity shall be verified by inspection, analysis or test, or a combination of the three methods.

4.1 STRUCTURAL VERIFICATION PLAN

a) The organization responsible for structural design shall submit a detailed structural verification plan (SVP) for the flight hardware to NASA.

b) The SVP shall identify the methods of verification for each hardware element

c) The SVP shall identify the methods of verification for the structural and dynamic math models.

d) The SVP shall identify the proposed development, qualification and acceptance tests.

4.1.1 Structural Assessment After Critical Design Review (CDR)

Detailed verification planning and certification requirements need to be responsive to design and environment changes, even after CDR. Because of this requirement and the latest information technology, considered thought should be given to ideas such as automating the primary structure stress report.

The SVP shall identify the proposed methods of updating the hardware verification after CDR.

4.2 VERIFICATION OF DETAILED DESIGN CRITERIA

The responsible organization shall present any deviations to the design criteria identified in section 3.0 of this document as a waiver to NASA per paragraph 1.5.

4.3 STRENGTH AND STIFFNESS VERIFICATION

The responsible organization shall show by analyses and/or tests that the hardware meets Program design requirements and has the required strength, stiffness and integrity at the design temperature distribution to assure function and personnel safety.

4.3.1 Verification Tests

a) Strength verification of primary structure shall be by static test or appropriate dynamic strength test.

b) The responsible organization shall choose a test method from the three options provided in section 5.1, and provide verification test reports per section 5.3 of this document which will partially or completely verify the capability of the respective flight hardware to meet the design requirements specified herein.

4.3.2 Verification Analyses

The responsible organization shall submit stress analyses per section 6.0 of this document which will verify the capability of the respective flight hardware to meet the design requirements specified herein.

4.4 MARGINS OF SAFETY VERIFICATION

a) The responsible organization shall deliver a detailed stress analysis report to NASA per section 6.0 of this document.

b) The stress analysis report shall contain a margin of safety summary table showing the minimum margin of safety for each and every part in the flight vehicle or element structure and the critical condition or mode of failure for each and every part in the flight vehicle or element structure.

4.4.1 Yielding Verification

a) The stress analysis report (see section 6.0) shall identify any parts in which yielding will occur at limit load.

b) The structural integrity of the yielded component shall be demonstrated by analysis and/or test per section 5.0 and/or 6.0.

c) The functional integrity of the yielded component and/or system shall be demonstrated by analysis and/or test per section 5.0 and/or 6.0.

d) The service life of the yielded part shall be assessed by analysis and/or test per section 4.13, 5.0 and/or 6.0.

4.5 LOADS REPORTS

This requirement shall be verified by analysis provided in the published reports used to specify the design loads for the hardware.

a) Published load reports shall be used to document the design loads and load spectra for the hardware.

b) Design loads releases shall support stress analysis delivery milestones as specified in section 6.2.3.

c) The responsible organization shall identify the version and modification history of the math models used in loads development.

d) The methodology and additional testing on the ground, in flight, on orbit, and on lunar/planetary operations required to validate the integrated system math models and design loads shall be developed and documented in the Structural Verification Plan.

4.5.1 Integrated Loads Verification

The loads, thermal environments and dynamic-elastic interactions between mated stages shall be verified by integrated analysis and/or test.

4.5.2 Detailed Design Loads Verification

The detailed design loads shall be partially verified by analysis provided in the published loads report per section 4.5(a), which shall show that the Loads Control Plan was properly implemented.

4.5.3 Verification for Redistributed Loads

This requirement shall be verified by analysis, test or both.

4.6 VERIFICATION FOR BUCKLING AND CRIPPLING

a) This requirement shall be verified by analysis, test or both per sections 5.0 and 6.0 of this document.

b) Evaluation of buckling strength shall consider the combined action of primary and secondary stresses and their effects on general instability, local or panel instability, and crippling.

c) Analyses of buckling of thin-walled shells shall use “knockdown factors” (correlation coefficients) to account for the difference between classical theory and empirical instability loads. Typical knockdown factors are listed in NASA SP-8007, Buckling of Thin-Walled Circular Cylinders

4.7 VERIFICATION FOR DYNAMIC INTERACTIONS

4.7.1 Verification of Dynamic Coupling

a) Freedom from undesirable interactions between the control system and the elastic vehicle modes shall be demonstrated by analysis supported by test.

b) This analysis shall account for the effect of engine thrust and the most adverse possible values shall be assumed for structural damping and stiffness at critical times during the mission profile.

4.7.2 Verification of Propellant Tanks Subject to Slosh Loads

a) These requirements shall be verified by analysis, test or both.

b) Analysis to characterize the extent of slosh shall account for tank characteristics, including size, geometry, internal hardware or structure, structural stability, internal insulation and venting provisions, liquid boiling, bubble entrapment, draining and settling, liquid level, fluid material compatibility and slosh frequencies, temperature and pressure variations and control system parameters.

4.7.3 Verification of Pogo Prevention

This requirement shall be verified by analysis as specified below.

4.7.3.1 Model Required for Pogo Verification

Coupling of the structure with the liquid-propulsion system shall be evaluated with the aid of a mathematical model that incorporates physical characteristics determined by tests and accounts for:

a) Elastic-mode coupling of the vehicle structure, propellant feed lines and tank-fluid system.

b) Engine Characteristics, including engine-mounting flexibility, turbo pump transfer functions, cavitation characteristics and propellant flow rates.

c) Delivery system characteristics, including flexible supports, accumulators, pressure-volume compensators, fluid or gas injection, fluid damping and flow resistances.

4.7.3.2 Stability Analysis for Pogo Verification

a) Stability analysis shall be performed using mathematical models to cover the entire rocket-powered flight regime.

b) Uncertainties in the parametric values shall be accounted for by appropriate statistical means for establishing that the probability of pogo instability during a space-vehicle flight is sufficiently small.

c) As a minimum requirement, the total coupled system shall be stable for any allowable combination of system parameter variations.

4.8 VERIFICATION OF THERMAL EFFECTS

a) This requirement shall be verified by analysis, test or both.

b) Thermal stresses/loads shall be combined with mechanical and pressure stresses/loads when they are additive but shall not be combined when they are relieving.

4.9 MATH MODEL VERIFICATION

All static and dynamic math models that are used to develop design loads or to represent or certify individual or integrated Constellation flight vehicle structures shall be test validated.

These tests shall be performed at the flight vehicle level or at the component or subsystem level and the results combined.

4.9.1 Loads Model Verification

a) The loads model shall be verified according to the schedule in the Constellation Loads Control Plan, CxP 70137.

b) The loads model shall be validated by modal survey testing to ensure the model is sufficiently accurate for load and deflection predictions.

c) The modal survey test shall include appropriate techniques to identify nonlinearities and characterize their effects.

Model verification may be accomplished by a combination of spacecraft or element level and component level modal survey tests.

4.9.1.1 Resolution and Fidelity for Loads Analysis

a) The frequency range for load analyses, as determined by the resolution and fidelity of the integrated vehicle models and forcing functions, shall be supplied by the CxP.

b) The spacecraft, element or component dynamic model shall have sufficient fidelity to capture the subject's dynamic behavior in this frequency range.

c) Subsystem resonances and overall spacecraft, element or component modes shall be modeled up to a model upper bound frequency, which shall be at least 1.4 times the cutoff frequency of the load analysis.

4.9.1.2 Modal Survey Test Requirements

a) The modal survey test shall measure and correlate all significant modes below the model upper bound frequency, consistent with the model resolution requirement described in 4.2.2.2.

b) Significant modes may be selected based on an effective mass calculation, but this set should be augmented by modes which are critical for specific load or deflection definition.

c) Boundary interface degrees of freedom that carry loads in the flight configuration shall be constrained in verification testing.

d) If alternate boundary conditions are utilized, additional testing and analysis shall be required to verify effects of the alternate configuration.

4.9.1.3 Mass Representation in the Modal Test

Accurate mass representation of the test article shall be demonstrated with orthogonality checks using the analytical mass matrix $[M_A]$ and the test mode shapes $[ø_T]$.

- The orthogonality matrix is computed as $[ø_T]^T[M_A][ø_T]$.
- As a goal, the off-diagonal terms of the orthogonality matrix should be less than 0.1 for significant modes based on the diagonal terms normalized to 1.0.

4.9.1.4 Correlation Requirements for Loads Model Verification

Evidence of successful correlation between verification test data and the test article math model shall consist of frequency and mode shape comparisons.

a) Mode shape correlation shall be demonstrated qualitatively with mode shape descriptions and mode shape deflection plot comparisons.

- The **goal** for frequency correlation is less than ±5% differences on the significant modes and ±10% on higher order modes. (revisit “significant”)

b) Quantitative mode shape comparisons shall be provided via cross-orthogonality checks using the test modes, the analytical modes, and the analytical mass matrix.

- diagonal terms greater than 0.9 is one **goal** for this cross-orthogonality check
- off-diagonal terms less than 0.1 for modes critical to the integrated interface loads and system internal loads is the other **goal**.

c) Failure to satisfy the goals of items (a) and (b) shall be accompanied by an assessment of the effects of model uncertainty on critical loads.

4.9.1.5 Simplified Loads Model Verification

Under certain conditions, simplified loads model verification by sinusoidal sweep test is allowed with approval from the appropriate Loads Control Panel.

a) The natural frequencies of the spacecraft, element or component shall be calculated with the flight configuration boundary conditions fixed.

b) Components with a minimum frequency lower than or equal to the model upper bound frequency per paragraph 4.9.1.1 shall not use this simplified model verification method to verify the frequency.

c) If the simplified method is applicable, mode shape correlation is not required.

4.9.2 Stress Model Verification

If stress analysis is used to verify or certify any structure, the model shall meet the following requirements:

a) Testing for static model verification shall include full-scale testing to launch and landing loads, and limited subassembly qualification testing as appropriate.

b) Deflection and strain data taken during static tests shall be compared with model predictions through the entire load range.

c) Checks shall be made for linearity and correlation to prediction.

1. Models shall correlate to test within 10% of predicted values for salient deflections.
2. Models shall correlate to test within 0% - 10% of predicted values for salient strains, with any deviations being model predictions higher than test results.

3. If the math model predictions are outside the above stated correlation criteria, the math model shall be updated until it meets the criteria and the analysis re-run.
4. A model that analytically under predicts stress shall be corrected and/or margins of safety recalculated based upon test stress levels.

4.9.2.1 Thermal Math Model Verification

a) The math models used to predict structural design temperature distributions shall be validated using test data.

b) The model shall be considered verified when predicted temperatures are within the following criteria compared with the test data:

- ±10°C or 10% of the maximum temperature range in the model, whichever is smaller (revisit this topic)

c) The algorithms used to extrapolate structural design temperature distributions to the stress model grid map shall be verified using test data.

4.10 VERIFICATION OF MINIMUM FACTORS OF SAFETY

The stress analysis report provided per section 6.0 shall contain a margin of safety summary table showing the factor(s) of safety used in analyzing each and every part in the flight vehicle structure. Inspection of this report shall verify that the factors of safety used in the design and analysis of the hardware meet the specifications of section 3.10.

4.11 VERIFICATION OF MATERIALS

Material selection and documentation requirements shall be as defined in NASA-STD-6016.

4.11.1 Verification of Material Thickness for Design and Analysis

The stress analysis report shall clearly identify the dimensions of the part being analyzed and shall compare these dimensions to the drawing dimensions for the part.

4.11.2 Verification of Material Properties

a) The stress analysis report shall provide a reference for any material property data used in the analysis.

b) The reference used in the stress analysis report shall conform to NASA-STD-6016.

c) If NASA approval was required for use of certain material properties, the approval documentation shall be included in the stress analysis report.

d) If the “premium properties” option described in 3.11.2 (e) is chosen, a materials test report shall be provided for each produced part which justifies the design allowables developed through the material specific testing along with the stress analysis report for each part designed and certified to these properties.

e) The stress analysis report shall clearly identify which parts are single load path.

4.11.3 Verification of Material Creep Susceptibility

The material selection shall be verified by inspection of the stress analysis report.

4.11.4 Verification for Castings

Any component manufactured with a casting shall be verified by the appropriate analysis and testing per the fracture control requirements in CA3193-PO and the material properties development requirements in NASA-STD-6016.

4.12 DESIGN FACTOR VERIFICATION

The stress analysis report per section 6.0 shall identify all of the design factors used in the analysis of every part. Inspection of this report shall verify that the factors used in the design and analysis of the hardware meet the specifications of section 3.12.

4.13 VERIFICATION OF STRUCTURAL LIFE

a) Structural service life shall be verified by analysis and/or test based on a rationally derived cyclic loading spectrum that includes transport to and from orbit, on-orbit, lunar or planetary mission events, thermal stresses, ground transportation, and testing loads.

b) The responsible organizations shall identify the specific analytical approach for life verification for cyclic and sustained loads in the design environment, which includes atomic oxygen, radiation, plasma environmental effects incompatibilities, debris, and meteoroid environments as defined in CxP 70023, the Design Specification for Natural Environments.

c) The service life analysis shall have a scatter factor of 4.0 applied to the established design life of the component (service life capability = 4 × required design life (add factor of 2 for durability analysis)).

d) Fracture analyses per the requirements of CA3193-PO (see sections 3.14 and 4.14) shall be performed to demonstrate structural life for fracture critical structure.

e) The service life capability of all non-fracture critical structural parts shall be verified by any one of the following analytical methods listed below.

   1. Stress-life (S-N fatigue).
   2. Strain-life (e-N).
   3. Durability (e.g., fracture mechanics for metallic parts and damage mechanics for composite parts)

f) The service life analysis loading spectrum shall include at least one limit load cycle (factor of safety = 1.0)

g) For components whose design is subject to a cyclic or repeated load condition, or a randomly varying load condition, a cyclic life analysis shall be performed.

h) Temperature distributions shall be included in the structural life assessment.

4.13.1 Verification of service life considering cumulative damage

4.13.1.1 Fatigue Verification

In the fatigue analysis, the limit stress/strain shall be multiplied by a minimum factor of 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.

4.13.1.1.1 Life Cycle History

A design-life cycle history shall be developed in sufficient detail that a cumulative damage assessment can be analytically verified for all applicable components. In general, these data can be shown by a component load history profile including usage cycles, load intensities and environments.

4.13.1.1.2 Low Cycle Fatigue Analysis

For low cycle fatigue analysis, the minimum number of cycles used shall be 1000.

4.13.1.1.3 Method Selection for Combining Damage

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

b) For repeated load combined with a steady load, such standard methods as the Modified Goodman Diagram shall be used to determine the combined effect.

4.13.1.1.4 Stress Concentration Factors – Fatigue Analysis

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

4.13.1.2 Durability Analysis

If selected as the analysis method of life verification, durability analysis shall be performed with an equivalent initial flaw size of

- 0.005" for metallic materials
- an equivalent initial flaw size for composite materials established by the procuring authority.

4.13.2 Verification of Creep Life

a) This requirement shall be verified by analysis.

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

4.14 FRACTURE CONTROL VERIFICATION

All Constellation Program hardware shall meet the verification requirements specified via CA3193-PO.

4.14.1 Proof Test for Flaw Screening

When proof tests are used for flaw screening, the proof test factor shall be the larger of the values determined by the fracture mechanics analysis derived proof test requirements to meet service life or those specified in Table 3.10.1-1.

4.15 GLASS, CERAMICS AND WINDOW DESIGN VERIFICATION

All Constellation Program hardware shall meet the verification requirements specified via CA3222-PO.

4.16 VERIFICATION OF BERYLLIUM STRUCTURES

4.16.1 Identification of Beryllium Structures

a) All beryllium structures shall be reported to NASA by component identification, part identification (drawing number) and beryllium alloy. The only beryllium alloys exempt from this review are those where beryllium is a minor constituent (less than 4 percent) such as copper-beryllium, nickel-beryllium and the beryllium-oxide ceramics.

b) Drawings of both the part and the component shall be submitted to NASA to aid in identifying the beryllium part location and its function.

4.16.2 Verification Documentation for Beryllium Structures

4.16.2.1 Internal Loads Analysis for Beryllium Structures

A formal internal loads analysis shall be submitted to NASA for review that includes appropriate boundary conditions, external load application locations, bounded static and dynamic loads used for design, distortions and forces that affect the short transverse (through the thickness) direction stresses and thermal loads.

4.16.2.2 Stress Analysis for Beryllium Structures

a) A formal stress analysis shall be submitted for review per section 6.0.

b) The formal stress analysis shall be in sufficient detail to address the effects of elastic stress concentrations, tolerances and displacements that may occur in the short transverse direction of the beryllium material.

4.16.3 Manufacturing Process Requirements for Beryllium Structures

Manufacturing and material processes for beryllium hardware shall be subject to NASA approval per paragraph 1.5. The following requirements must be included in the process specifications:

1) Machined/mechanically disturbed surfaces of a structural beryllium part must be chemically milled to ensure removal of surface damage.

2) All beryllium parts must be penetrant inspected for crack like flaws with a high sensitivity fluorescent penetrant per ASTM E1417-95a.

3) All fracture critical beryllium parts must meet the fracture control requirements of CA3193-PO.

4.16.4 Verification testing of Beryllium Structures

The structural verification of beryllium structures shall comply with one of the following three options:

1. For two or more beryllium parts of the same design and geometry which are both produced by the same manufacturer using identical materials and process specifications, a verification test program shall be implemented.

   a) This test program shall demonstrate the ultimate load carrying capability of the part by statically testing one of the parts to a minimum of 1.4 times the maximum limit load. This test may be performed on a dedicated test article if the article is made by the same manufacturer using the same material and process specifications as the flight hardware. Otherwise, one of the flight articles must be used.

   b) There shall be no failures.

   c) A detailed, post-test inspection of the hardware shall be performed to ensure its structural integrity prior to flight if a flight article is used for testing.

   d) The remaining flight articles shall be proof-tested to the limit load.

   e) The test article used for the 1.4 times limit load test shall include all possible sources of out-of-plane loading that may occur from the assembly of the beryllium part or installation of the beryllium part into the spacecraft. This includes the effects of attachments and out-of-plane loading from clamp-up, fastener torque, shims, etc.

   f) For those areas of the beryllium part where the failure criteria are not well-defined, sufficient testing of these regions shall be performed to establish confidence in the stress analysis.

   g) For beryllium structures that are subjected to buckling loads, ultimate loads testing shall be performed to demonstrate a minimum buckling margin of safety of 10 percent (based on 1.4 times the part limit load).

2. For beryllium parts that are one of a kind, with no dedicated test article, a comprehensive ultimate load test shall be implemented in which the flight article is subjected to a minimum loading of 1.4 times limit load.

   a) The requirements for this testing shall be per Option 1.

   b) In addition, a complete and detailed structural inspection of the tested structure shall be performed to ensure the integrity of the tested structure prior to flight.

3. Other combinations of criteria and or testing that are equivalent to those above must be submitted to NASA for approval per paragraph 1.5.

4.17 VERIFICATION OF LIQUID FUELED SPACE PROPULSION SYSTEM STRUCTURES

Verification of structural components of liquid fueled space propulsion systems shall comply with NASA-STD-5012, Strength and Life Assessment Requirements for Liquid Fueled Space Propulsion System Engines.

4.18 VERIFICATION OF PRESSURIZED STRUCTURES

Pressurized structure strength shall be verified by analysis per section 6.0 and by testing per section 5.2.2.

4.18.1 VerificatIon of minimum factors of safety

The stress analysis report provided per section 6.0 shall contain a margin of safety summary table showing the factor(s) of safety used in analyzing each pressurized structure. Inspection of this report shall verify that the factors of safety used in the design and analysis of the hardware meet the specifications of section 3.10.

4.18.2 Pressurized Structures with Non-Hazardous Leak-Before-Burst (NHLBB) Design

a) The NHLBB failure mode verification analysis shall meet the requirements of NASA-STD-5019 paragraph 5.1.4.

b) Test verification of the LBB failure mode shall meet the following requirements:

1. The testing may be conducted on coupons which duplicate the materials (parent materials, weld-joints, and heat affected zone) and thickness of the pressurized structure or on a pressurized structure representative of the flight hardware.
2. Test specimens shall contain a pre-fabricated part-through crack.
3. Fatigue load cycles shall be applied to the test specimen with the maximum stress corresponding to the MDP level and minimum stress kept to zero, until the part-through crack propagates through the specimen’s thickness to become a through crack.
4. NHLBB failure mode is demonstrated if the length of the through crack becomes greater than or equal to 10 times the specimen thickness and remains stable.
5. The NHLBB testing shall be conducted to establish that all critical areas will exhibit a NHLBB mode of failure.

4.18.2.1 Special Verification for Habitable structures and Enclosures

Habitable structures and enclosures classified as LBB shall meet the appropriate verification requirements in CA3193-PO.

4.18.2.2 Special Verification for Pressurized Structures with Brittle Fracture or Hazardous LBB Failure Mode

When fracture mechanics crack growth analysis is required to demonstrate damage tolerance of a pressurized structure, the requirements in sections 6.1 and 6.4 of NASA-STD-5019 shall be met.

Damage tolerance testing in lieu of damage tolerance analysis is acceptable alternative to demonstrate damage tolerance provided the structure meets the quality assurance specifications of section 7.1, and shall meet the requirements in sections 6.2 and 6.4 of NASA-STD-5019.

4.18.3 Design service life verification for pressurized structures

4.18.3.1 Analytical Life Verification for Pressurized Structures

a) When a fatigue analysis is required to demonstrate the fatigue-life of an unflawed pressurized hardware, the requirements of section 4.13.1.1 of this document shall apply.

b) The limit for accumulated fatigue damage shall be 80% of the normal limit.

4.18.3.2 Combined Analysis & Test Verification of Life for Pressurized Structures

a) Per NASA-STD-5019 paragraph 6.3, an acceptable alternative to analytical prediction of fatigue life is fleet leader testing of unflawed specimens to demonstrate fatigue-life of a specific pressurized structure together with stress analysis.

b) The required test duration is four (4) times the specified service life.

4.19 COMPOSITES/BONDED STRUCTURE VERIFICATION

4.19.1 General Verification Requirements

a) Composite/bonded structural design shall be verified by a combination of analysis, test and inspection.

b) Test articles shall be designed and fabricated to the same requirements, drawings and specifications as the flight article.

4.19.2 Verification of Factors of Safety for Composite/Bonded Structures

This requirement shall be verified by analysis and inspection.

4.19.2.1 Structural Analysis for Composite/Bonded Structural Verification

a) Structural analysis per section 6.0 shall contain a margin of safety summary table showing the factor(s) of safety used in analyzing each composite/bonded part in the flight vehicle structure.

b) Inspection of this report shall verify that the factors of safety used in the design and analysis of the hardware meet the specifications of section 3.10.

4.19.3 Acceptance of Composite/Bonded Structure

Acceptance of composite/bonded structures shall be by one of the following methods.

4.19.3.1 Acceptance Proof Test

An acceptance proof test shall be conducted to no less than 120 percent of the limit load.

a) The proof test shall be conducted on each composite/bonded flight article.

b) Test loads on the composite shall not exceed 80 percent of the ultimate strength.

c) The flight article shall receive pre and post proof test NDE including special visual inspection per MSFC-RQMT-3479, Section 6.1.

d) The flight article shall be subject to a Damage Threat Assessment per MSFC-RQMT-3479, Section 5.3.2.1.

e) The test may be accomplished at the component or subassembly level if the loads on the test article duplicate those in a fully assembled test article.

f) Caution should be exercised when testing to prevent detrimental deformation to any metallic fittings and fasteners in the flight assembly and damage to the composite.

4.19.3.2 Acceptance by Demonstration of Successful History

Composite hardware may be accepted without proof test if the manufacturer of the composite article can demonstrate a successful history of building a like design and meeting the following criteria:

1. Certified and controlled specifications are used,
2. Personnel are properly trained and certified, and

3. 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 per paragraph 1.5.

4.19.3.3 Acceptance by Damage Tolerance Approach

Composite structures may be accepted using a damage tolerance approach that shall comply with the requirements of MSFC-RQMT-3479, Paragraph 5.3.2.

4.19.3.4 Verification of Design and Analysis Practices for Composite/Bonded Structure

a) The designer/manufacturer shall report all standards used in the design and manufacturing process for the composite or bonded structure

b) The verification data package shall include summary reports of all coupon tests, sampling techniques and development testing used in the design and manufacturing of the composite or bonded structure.

c) The verification data package shall include all documentation as required by MSFC-RQMT-3479, Section 7.0

4.19.4 Composite/Bonded Structure Life Verification

The required life for a composite/bonded structure shall be demonstrated by durability testing or a combination of testing and analysis. Guidance for durability and structural life verification for composite/bonded structure is provided in MIL-HDBK-17-3F, Composite Materials Handbook.

4.19.4.1 Flaw Growth Rate for Composite/Bonded Structure Life Verification

The growth rate or no-growth of damage that may occur from fatigue, corrosion, manufacturing flaws or impact damage under repeated loads expected in service for composite/bonded structure shall be established by test or analysis supported by test.

4.19.5 Verification of Composite Structure Protection Against Inadvertent Damage

The damage protection plan for composite structure shall be verified by inspection per MSFC-RQMT-3479, Section 5.3.2.2.

4.19.6 Composite/Bonded Structure Strength and Stiffness Verification

It shall be demonstrated by test and or analysis supported by test that the composite structure shall be capable of carrying ultimate loads with damage up to the threshold of detectability considering the inspection procedures employed.

4.19.6.1 Damage Growth For Residual Strength of Composite/Bonded Hardware

The damage growth, between initial detectability and the value selected for residual strength testing of composite/bonded hardware, factored to obtain inspection intervals, shall allow for development of an inspection program.

4.19.6.2 Strength Verification for Composite Structures for which Damage Tolerance is Impractical

a) Composite/bonded structural components for which the damage tolerance method is shown to be impractical shall be verified by component fatigue tests or analysis supported by tests to be able to withstand the repeated loads of variable magnitude expected in service.

b) Sufficient component, subcomponent, element or coupon tests shall be performed to establish the fatigue scatter factor and any environmental effects on the structural life.

c) Damage up to the threshold of detectability and ultimate load residual strength capability shall be considered in the testing and analysis.

4.19.7 Special Conderations for Bonded Joints

4.19.7.1 Limit Load Capability Verification of Bonded Joints

For any bonded joint, the failure of which would pose a catastrophic hazard, the limit load capacity shall be substantiated by one of the following methods:

1. The maximum disbonds of each bonded joint consistent with the capability to withstand the required loads shall be determined by analysis, tests or both. Disbonds of each bonded joint greater than these values shall be prevented by design.

2. Proof testing shall be conducted on each production article that will apply the critical limit design load to each critical bonded joint.

3. Repeatable and reliable non-destructive inspection shall be established and periodic inspections shall be performed that ensure the strength of each bonded joint.

4.19.7.2 Thermal Effects on Bonded Joints

All proof testing to confirm the capability of bonded joints shall be performed at the temperature extremes corresponding to the load conditions.

4.19.8 Special Considerations for Composite Rotating Machinery

4.19.8.1 Damage Tolerance of Composite Rotating Machinery

Composite rotating machinery shall meet the requirements of paragraph 4.19.3.3.

4.19.8.2 Test Articles for Composite Rotating Machinery

Two distinct full scale test articles for each component type shall be tested per MSFC-RQMT-3479, paragraph 5.3.2.6 as a minimum.

4.19.8.3 Composite Rotating Machinery Flight Article Proof Testing

a) Each composite rotating machinery flight article shall be proof tested to 1.20 times limit load.

b) Proof loading shall be less than 80 percent of the flight article ultimate strength.

c) Acceptance of composite rotating machinery per paragraph 4.19.3.2 shall not be permitted.

4.19.9 Special Considerations for Composite Hazardous Fluid Containers (Including Lines, Ducts and Fittings)

4.19.9.1 Damage Tolerance of Composite Hazardous Fluid Containers

Composite hazardous fluid containers shall meet the requirements of paragraph 4.19.3.3.

4.19.9.2 Test Articles for Composite Hazardous Fluid Containers

Two distinct full scale test articles for each component type shall be tested per MSFC-RQMT-3479, paragraph 5.3.2.6 as a minimum.

4.19.9.3 Composite Hazardous Fluid Containers Flight Article Proof Testing

a) Each composite hazardous fluid container flight article shall be proof tested to 1.50 times MDP.

b) Acceptance of composite hazardous fluid containers per paragraph 4.19.3.2 shall not be permitted.

4.19.10 Special Considerations for Composite Habitable Modules

4.19.10.1 Damage Tolerance of Composite Habitable Module Pressure Bearing Walls

The composite habitable module pressure bearing wall shall meet the requirements of paragraph 4.19.3.3.

4.19.10.2 Test Criteria for Composite Habitable Module Pressure Bearing Walls

It shall be demonstrated by test on a flight-like full scale test article that the composite pressure bearing walls support MDP times the ultimate factor of safety with a through flaw in the wall of a length that is the maximum of 10 times the wall thickness or one-inch, whichever is greater. This testing may be done on a separate full-scale component or on the article used for the four lifetime damage tolerance full-scale component test after that test is completed.

4.19.10.3 Composite Habitable Module Flight Article Proof Testing

a) Each composite habitable module article shall be proof tested to 1.50 times MDP.

b) Acceptance of composite habitable modules per paragraph 4.19.3.2 shall not be permitted.

4.19.11 Special Considerations for Composite Solid Rocket Motor Cases and Nozzles

4.19.11.1 Damage Tolerance of Composite Solid Rocket Motor Cases and Nozzles

Composite solid rocket motor cases and nozzles shall meet the requirements of paragraph 4.19.3.3.

4.19.11.2 Damage Tolerance Testing of Composite Solid Rocket Motor Cases and Nozzles

A flight-like composite motor case and nozzle shall be inflicted with flaws as in the damage tolerance tests, subjected to a full rocket hot firing and then be subjected to design ultimate load without failure or leakage.

4.19.11.3 Proof Test Criteria for Composite Solid Rocket Motor Cases and Nozzles Flight Articles

a) Each composite solid rocket motor case and nozzle flight article shall be proof tested to 1.20 times MDP.

b) If recovered and re-used, the flight article shall be proof-tested between flights and receive post-proof test NDE per MSFC-RQMT-3479.

c) Acceptance of composite solid rocket motor cases and nozzles per paragraph 4.19.3.2 shall not be permitted.

4.19.12 Special Considerations for Composite Propellant Tanks other than COPVs

4.19.12.1 Damage Tolerance for Composite Propellant Tanks other than COPVs

Composite propellant tanks other than COPVs shall meet the requirements of paragraph 4.19.3.3.

4.19.12.2 Test Articles for Composite Propellant Tanks other than COPVs

Two distinct full scale test articles for each component type shall be tested per MSFC-RQMT-3479, paragraph 5.3.2.6 as a minimum.

4.19.12.3 Proof Test Criteria For Composite Propellant Tanks Other Than COPVS

a) Each composite propellant tank that is not a COPV shall be proof tested to 1.20 times MDP.

b) If recovered and re-used, the flight article shall be proof-tested between flights and receive post-proof test NDE per MSFC-RQMT-3479.

c) Acceptance of composite propellant tanks that are not COPVs per paragraph 4.19.3.2 shall not be permitted.

4.20 STRUCTURAL VERIFICATION FOR PRESSURE SYSTEMS

Pressure vessels shall be subject to acceptance proof and qualification pressure tests as defined in Table 3.10.1-1.

4.20.1 Verification of Fracture Control for Pressure Vessels

Fracture control of Constellation pressure vessels shall be per CARD CA3193-PO.

4.20.2 Verification of Pressure Control Devices

This requirement shall be verified by inspection and analysis.

4.20.3 Verification of Pressure Stabilized Vessels

Pressure vessels which are pressure-stabilized and must contain a minimum pressure to maintain the required ultimate factors of safety to insure structural integrity under launch and landing loads shall meet the following requirements:

a) The existence of the minimum required vessel pressure shall be verified prior to the application of safety critical loads into the system.

b) This verification shall include a single fault tolerant pressure decay monitoring technique which is implemented such that the system pressure decay characteristics can be certified to insure minimum design safety factors will exist at the time of subsequent structural load application.

4.20.4 Burst Disc Verification

a) Verification of selection of a stress corrosion resistant material shall be by inspection of the stress analysis report for the pressure system.
b) The burst disc design shall be qualified for the intended application by testing at the intended use conditions including temperature and flow rate.
c) Qualification shall be for the specific part number used, and it shall be verified that no design or material changes exist between flight assemblies and assemblies making up the qualification database.
d) Each flight assembly shall be verified for membrane actuation pressure either by
    1. Use of special tooling or procedures to prevent cutting edge contact during the test
    2. Demonstration of a rigorous lot screening program approved by NASA per paragraph 1.5.

4.20.5 Verification Of Dewars

a) MDP assessment for the pressure container shall envelop the pressure achieved under maximum venting conditions.

b) This requirement shall be verified by analysis.

c) This requirement shall be verified by inspection.

d) This requirement shall be verified by inspection and/or test.

e) This requirement shall be verified by inspection of the drawings and device specifications.

f) Certification of the pressure relief device shall include testing of the same part number from the flight lot under the expected use conditions.

g) This requirement shall be verified by analysis.

h) The proof test factor for each flight pressure container shall be a minimum of 1.1 times MDP. Qualification burst and pressure cycle testing is not required if all the requirements of Section 3.21.5 and **Error! Reference source not found.** are met.

4.20.6 Secondary Volume Verification

This requirement shall be verified by analysis.

4.20.6.1 Non-Credible Failures in a Secondary Pressurized Volume

This requirement shall be verified by analysis.

4.20.6.2 Allowable Venting for a Secondary Pressurized Volume

This requirement shall be verified by inspection, analysis or test.

4.20.7 Verification of Hoses And Bellows Subject to Flow-Induced Vibration

a) Certification of hardware shall be in accordance with NSTS 08123.

b) When certification by test is required, requirements in MSFC-SPEC-626 shall apply.

4.21 STRUCTURAL VERIFICATION REQUIREMENTS FOR ROTATING MACHINERY

This requirement shall be verified by analysis per section 6.0, demonstrating that all margins of safety are greater than or equal to 0.0 and that the factors of safety from Table 3.10.1-1 were properly applied.

a) The stress analysis report shall identify all load cases considered.

b) Effective stresses (for ductile materials only) shall be calculated using the maximum distortion-energy theory (Von Mises-Hencky Theory).

c) This section shall not apply to rotating machinery in liquid-fueled space propulsion systems.

4.21.1 Verification of Temperature Requirements for Rotating Machinery

a) Prediction of temperatures shall be based on comprehensive heat-transfer analyses and experimental evaluation during development testing.

b) A temperature increment of 50°F or 5% of the maximum metal temperature, whichever is lower, shall be applied to the result of such analysis as a factor of safety to arrive at maximum temperatures or thermal gradients.

4.21.2 Verification of Fatigue Life for Rotating Machinery

The fatigue life of rotating machinery shall be verified according to the requirements in section 4.13.1.1 and the following paragraphs.

4.21.2.1 Low Cycle Fatigue Life

a) The primary, secondary, and peak stresses resulting from thermal cycles at start-up, maximum power transients, and shutdown shall be combined and used to determine the low cycle fatigue life of the component.

b) The number of cycles to failure shall be four (4) times the number of predicted operating cycles for low-cycle fatigue.

4.21.2.2 High Cycle Fatigue Life

a) For all components except blades and vanes, the predicted alternating stress and steady state stress shall be within the material property data as defined by modified Goodman diagrams (Figure 4.21-1), constructed with the safety factors from Table 3.10.1-1 (1.33 on fatigue, 1.5 on ultimate, and 1.1 on yield strengths).

b) Factors from sections 3.12 and 6.0 affecting stress concentration factors and analysis procedures shall be applied to calculate the alternating stresses.

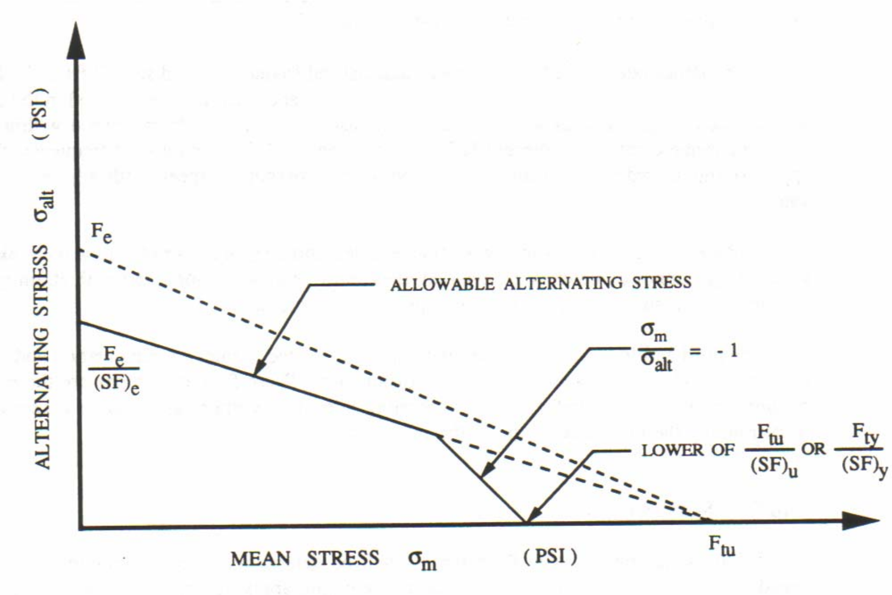

Figure 4.21-1 Modified Goodman Diagram for Factors of Safety for Rotating Structures

4.21.3 Verification of Creep Life for Rotating Machinery

The stress analysis report shall verify that maximum primary stresses are below stresses compatible with secondary plastic creep rates.

4.21.4 Structural Verification Requirements for Rotor Assemblies and Components

4.21.4.1 Verification of Shaft Stiffness Requirements

The bent and rigid shaft frequencies shall be verified by analysis per section 6.0 and shall demonstrate the margins specified herein.

a) The bent shaft frequency shall be no lower than 115% of the Maximum Operating Speed, calculated with rigid bearings. This criterion assumes a well-balanced rotor system and either fluid film journal bearings or rolling element bearings mounted in dampers.

b) If the rolling element bearings do not have dampers, then the bent shaft frequency shall be no lower than 125% of the Maximum Operating Speed, calculated with rigid bearings.

c) The rigid shaft frequencies shall have a 15% speed margin with any steady-state operating speed.

4.21.4.2 Verification of Radial Clearances for Rotating Components

a) The radial clearance shall be verified by analysis showing the magnitude of the positive clearance.

b) The radial clearance analysis shall include the effects of bearing clearances, relative rotor and housing vibration amplitudes, concentricity tolerances, relative radial and axial thermal movements, rotational stresses, and relative expansions resulting from transient conditions during start-up and shut-down.

4.21.4.3 Structural Verification Requirements for Disks and Rings

a) This requirement shall be verified by analysis per section 6.0.

b) Margins of safety shall be calculated based on the factors of safety in Table 3.10.1-1 and the stress limits of Table 3.21.4-1.

4.21.4.3.1 Verification Requirements for Holes and Disks in Webs

The structural integrity of the material around holes in the disk shall be verified by analysis.

a) A three-dimensional finite-element analysis of the disk assembly shall be performed to predict the calculated stress around any hole.

b) The finite element model shall have sufficient definition to capture the stress concentration factors, or stress concentration factors shall be applied to areas such as the dovetails and holes.

4.21.4.3.2 Verification of Blade-Disk Coupling Restrictions

a) The blade-disk system natural flexural frequency separation from the specified excitations shall be verified by analysis demonstrating that there is a margin of at least 25% on the speed above the Maximum Operating Speed.

b) A low-cycle fatigue analysis shall be conducted at Maximum Operating Speed. The low-cycle fatigue life shall be greater than the number of expected start-ups and shut-downs.

4.21.5 Structural Verification Requirements for Shafts, Spacers, Flanges And Pilots

a) These requirements shall be verified by analysis per section 6.0.

b) Margins of safety shall be calculated based on the factors of safety in Table 3.10.1-1 and the stress limits of Table 3.21.5-1.

4.21.6 Structural Verification Requirements for Rotor Blades

a) Steady-state stress due to centrifugal loads shall be determined at the maximum operating speed.

b) The steady-state stress shall be combined with the maximum steady-state stresses due to fluid forces and untwist forces and inertia loads.

c) Combined steady-state stress shall be less than 100% of 0.2% tensile yield strength.

4.21.6.1 Verification of Rotor Blade Stiffness Requirements

a) The first natural frequency, when displayed on a Campbell diagram, shall have a 10% margin on frequency above the Maximum Operating Speed 2nd engine order (E.O. 2) excitation line (Figure 4.21-2 shows a typical Campbell diagram).

b) Coincidence between the lower order blade natural frequencies and stimuli from the first four integral engine orders, frame struts, adjacent stage vanes etc., shall be avoided in the data taking speed range.

c) Blades with thin tips may also have a tip mode resonance within the operating range excited by adjacent IGV or stator vanes. These modes of resonance shall be avoided in the operating range.

d) A 10% margin on frequency shall apply to engine orders and frame struts, and a 15% margin on speed with adjacent stage vanes.

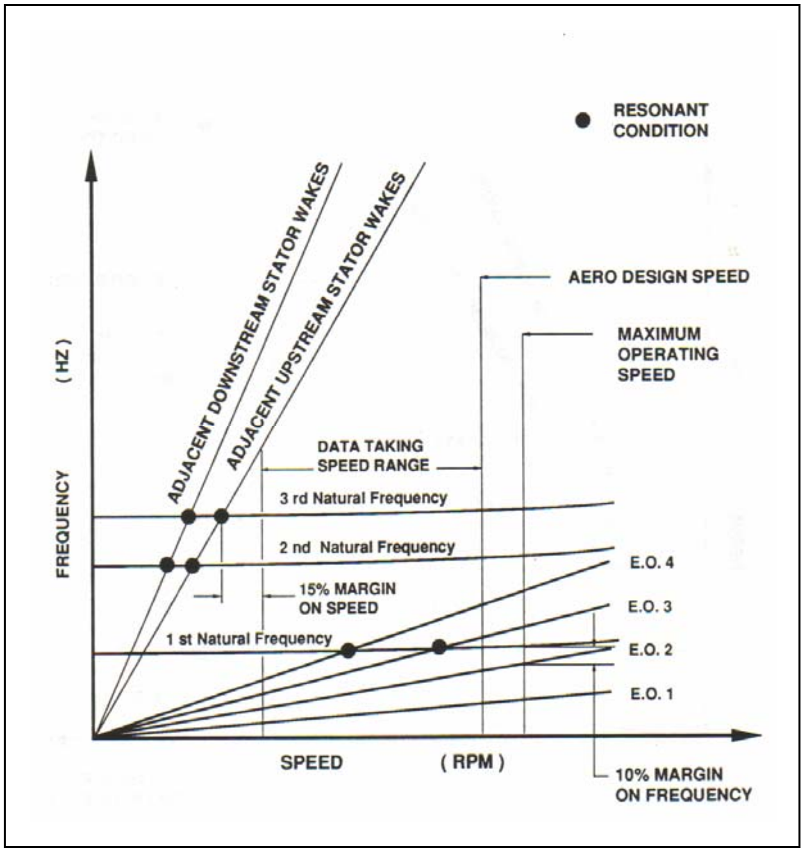

Figure 4.21-2 Typical Campbell Diagram for a Rotor Blade

4.21.6.2 Rotor Blade Life Verification

This requirement shall be verified by high-cycle fatigue analysis conducted for each set of blades per section 4.13.1 and the following specifications.

a) The mean stresses shall be set equal to the combined steady-state stress.

b) The range of alternating stresses shall be from zero to max stresses caused by the fluid forces.

c) The alternating stress shall be multiplied by a stress concentration factor appropriate for the fillet at the airfoil attachment.

d) Material fatigue properties shall be obtained from test specimens that reflect the effects of manufacturing processes and surface finishes used for the manufactured blades at maximum operating temperature.

e) A modified Goodman diagram similar to Figure 4.21-1 shall be constructed.

4.21.7 Structural Verification Requirements for Static Assemblies and Components

4.21.7.1 Structural Verification Requirements for Casings

a) This requirement shall be verified by analysis with the following specifications:

- The stress shall be determined at two loading conditions
    - The maximum operating pressure plus maximum inertia loads
    - Burst speed of single rotor blade
- The effective stress at maximum operating pressure plus maximum inertia loads shall be less than 0.2% tensile yield strength.

b) This requirement shall be verified by test demonstrating that blade failure is contained.

c) This requirement shall be verified by test or inspection of the installation drawings, whichever is appropriate to the design solution chosen.

4.21.7.2 Structural Verification Requirements for Vanes

4.21.7.2.1 Vane Strength Verification

a) This requirement shall be verified by analysis per section 6.0.

b) Steady-state stress due to fluid forces shall be determined at the maximum operating speed and combined with those at maximum inertia loads.

c) Combined steady-state stress shall be less than 100% of 0.2% tensile yield strength.

4.21.7.2.2 Verification of Vane Stiffness Requirements

a) The first natural frequency, when displayed on a Campbell diagram, shall have a 10% margin on frequency above the Maximum Operating Speed 2nd engine order excitation line (Figure 4.21-3 shows a typical Campbell Diagram for a stator vane).

b) First or second integral order resonances within the data-taking speed range shall be avoided.

c) Coincidence between natural frequencies and stimuli from adjacent stage blades shall be avoided in the data taking speed range.

d) A 10% margin on frequency shall apply to engine orders and a 15% margin on speed with adjacent stage blades.

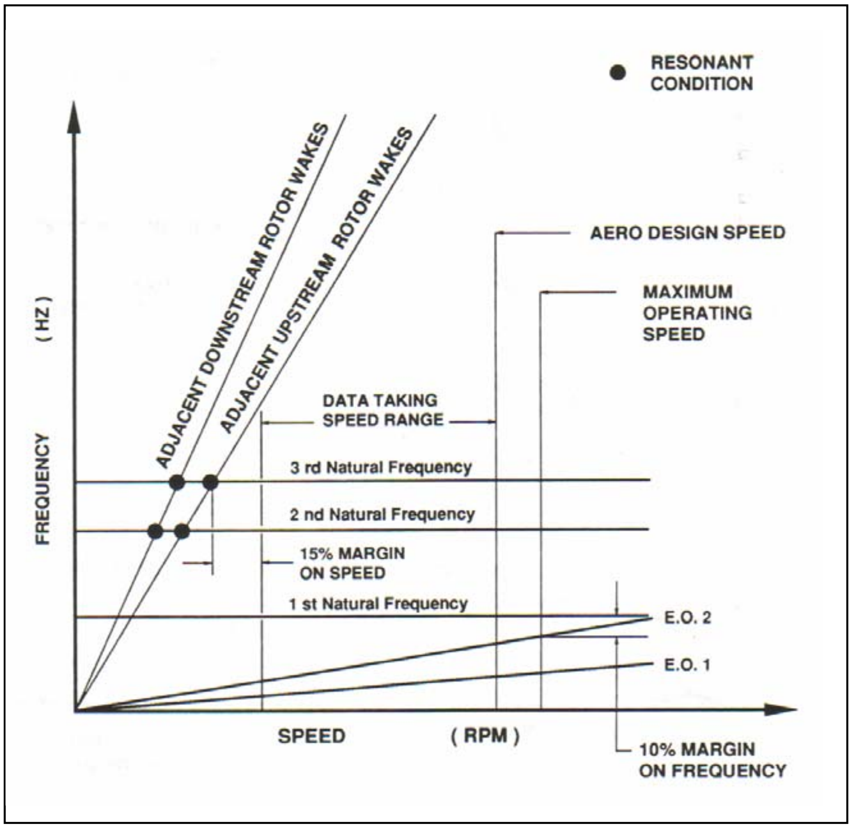

Figure 4.21-3 Typical Campbell Diagram for Stator Vane.

4.21.7.2.3 Verification of Vane Life

This requirement shall be verified by high-cycle fatigue analysis conducted for each set of vanes per section 4.13.1 and the following specifications.

a) The mean stresses shall be set equal to the combined steady-state stress.

b) The range of alternating stresses shall be from zero to max stresses caused by the fluid forces.

c) The alternating stress shall be multiplied by a stress concentration factor appropriate for the fillet at the airfoil attachment.

d) Material fatigue properties shall be obtained from test specimens that reflect the effects of manufacturing processes and surface finishes used for the manufactured blades at maximum operating temperature.

e) A modified Goodman diagram similar to Figure 4.21-1 shall be constructed.

4.22 VERIFICATION OF STRUCTURAL SOFT GOODS

Structural soft goods shall be verified by acceptance tests and qualification tests as described below and per section 5.0.

4.22.1 Verification of Soft Goods Factors of Safety

Soft goods factors of safety shall be verified by inspection of the test reports which shall show the relevant factors applied to the design loads for each structural soft goods item tested.

4.22.2 Structural Verification for Soft Goods

4.22.2.1 Verification Testing for Safety-Critical Softgoods

4.22.2.1.1 Ultimate Loads Testing for Safety-Critical Softgoods

For those structural softgoods whose failure would pose either a critical or catastrophic hazard, the ultimate loads test shall be to a minimum of 4.0 times the design limit load.

4.22.2.1.2 Qualification Testing for Safety-Critical Softgoods

For those structural softgoods whose failure would pose either a critical or catastrophic hazard, the qualification loads test shall be to a minimum of 4.0 times the design limit load.

4.22.2.1.3 Proof Testing for Safety-Critical Soft Goods

For those structural soft goods whose failure would pose either a critical or catastrophic hazard, each flight soft good shall be proof tested to a minimum of 1.2 times the design limit load.

4.22.2.2 Verification Testing for Non-Hazardous Soft Goods

4.22.2.2.1 Ultimate Loads Testing for Non-Hazardous Soft Goods

For those structural soft goods whose failure is non-hazardous, the ultimate loads test shall be to a minimum of 2.0 times the design limit load.

4.22.2.2.2 Qualification Testing for Non-Hazardous Soft Goods

For those structural soft goods whose failure is non-hazardous, the qualification loads test shall be to a minimum of 2.0 times the design limit load

4.22.2.2.3 Proof Testing for Non-Hazardous Soft Goods

For those structural soft goods whose failure is non-hazardous each flight soft good shall be proof tested to a minimum of 1.2 times the design limit load.

4.23 VERIFICATION OF STRUCTURAL INTEGRITY AFTER DAMAGE DUE TO ORBITAL ENVIRONMENTS

4.23.1 Structural Verification After General Material Erosion

This requirement shall be verified by analysis, test or both.

4.23.2 Structural Verification After MM/OD Impact Damage

This requirement shall be verified by a probability-of-no-penetration (PNP) analysis supported by hypervelocity impact test data to show that MMOD critical items meet the requirements specified in the appropriate CxP SRD's.

4.23.3 Structural Verification After EVA Crew Inadvertent Contact

This requirement shall be verified by test per section 5.0 and/or analysis per section 6.0 demonstrating the performance requirements are met.

4.23.4 Structural Verification After IVA Crew Inadvertent Contact

This requirement shall be verified by test per section 5.0 and/or analysis per section 6.0 demonstrating the performance requirements are met.

4.24 SECONDARY STRUCTURE VERIFICATION

These requirements shall be verified by inspection of installation drawings, analysis, and/or test.

4.25 VERIFICATION OF FASTENERS AND JOINTS

This requirement shall be verified by inspection of Quality records and vendor data.

4.25.1 Verification of Structural Fastener Retention

Locking feature installation shall be verified by inspection of the installation procedures and the Quality records for the hardware being delivered.

a) The location of the locking feature shall be verified by inspection of the relevant installation drawing(s).

b) Installation procedures shall require functional verification of locking features, such as measurement of running (self-locking) torque or visual inspection of lock wire integrity to be performed and recorded for each individual structural fastener.

4.25.1.1 Fastener Retention Redundancy

a) Fastener retention redundancy shall be verified by inspection of the relevant installation drawing(s).

b) If preload is used as one of the locking features, the preload shall be verified by analysis per paragraph 4.25.7.

4.25.1.2 Verification for Structural Fasteners in Rotating Joints

The retention feature utilized for a structural fastener in a rotating joint shall be verified by inspection of the relevant installation drawing(s).

4.25.1.3 Verification of Snap Rings and Cotter Pins

The verification that no snap ring or cotter pin has been reused shall be inspection of the Quality records delivered with the hardware.

4.25.2 Verification of Fastener Torque Specification

a) The specified torque value shall be verified by inspection of the fastener specification and the relevant installation drawing(s).

b) Torque-tension testing shall be required for the following applications:

   1. Where fastener/lubricant combination friction factor (k) values are unknown,

   2. Where the failure of a single bolt in a tension application would cause a critical or catastrophic hazard or functional problem.

c) Torque tables that are used to establish torques shall be based on torque-tension testing data using the same fastener/fitting combinations to be used in flight, including washers.

d) The data used to create the tables shall be made available to NASA upon request.

4.25.2.1 Verification of Torque Application

This requirement shall be verified by inspection of the relevant installation drawing(s) and procedures.

4.25.2.2 Running Torque Verification

Verification shall be by inspection of the relevant installation drawing(s) and the Quality records for the hardware being delivered.

4.25.2.3 Wrenching Torque Verification

Verification that the design torque value does not exceed the wrenching torque value shall be accomplished by inspection of the fastener specification and the relevant installation drawing(s).

4.25.3 Verification of Inserts

Appropriate use of inserts shall be verified by inspection of the relevant installation drawing(s).

4.25.4 Verification of Thread Engagement

This requirement shall be verified by inspection of the relevant installation drawing(s).

4.25.5 Grip Length Verification

a) The grip length specification and the use of washers shall be verified by inspection of the appropriate installation drawing(s) and procedures.

b) Torque-tension tests per paragraph 3.25 shall be performed to verify the use of washers in joint fit-up if applicable.

4.25.6 Verification for Strength Issues in Fastener Specifications

This requirement shall be verified by inspection of the relevant installation drawing(s), Quality records and by analysis.

4.25.7 Verification Of Thread Specification

These requirements shall be verified by inspection of the relevant installation drawing(s).

4.25.8 Preload Verification

This requirement shall be verified by analysis and test, with additional testing possible required to specifically satisfy the specifications in NSTS-08307.

a) If the conditions in paragraph 3.25.8 are satisfied, then the fastener margin of safety shall be assessed in the gapped condition in the usual manner for interacting shear, bending, and tension, as applicable, with the tension portion of the interaction calculated using the applied tensile load.

b) If the conditions in paragraph 3.25.8 are not met, and the joint has been designed using NSTS- 08307, then the preload verification shall be per NSTS-08307.

c) Preloaded joints must demonstrate a joint separation factor of 1.4 for safety critical joints and 1.2 for other joints.

d) Preloaded joints must demonstrate no gapping in a qualification test with a factor of 1.4 for a prototype test program, or in an acceptance test with a proof factor of 1.2 for a protoflight test program.

4.25.9 Verification of Nonstandard Fasteners

Verification of nonstandard fasteners shall comply with section 4.25.

4.26 VERIFICATION OF SEAL REDUNDANCY

Seal redundancy shall be verified by inspection, analysis and test per Table 3.26-1 and the following acceptance and qualification tests as appropriate.

4.26.1 Seals with Major Diameter less than or equal to Six Inches

a) For seals with major diameter of less than 6 inches, qualification testing shall be conducted to verify the sealing capability of the seal assembly.

b) This testing shall include structural deflections, pressure differential and thermal effects as appropriate.

4.26.2 Seals with Major Diameter Greater Than Six Inches

a) For seals with major diameter of greater than or equal to six inches, qualification and acceptance testing of the permanent installation shall be conducted to verify the sealing capability of each seal.

b) The qualification testing shall include structural deflections, pressure differential and thermal effects as appropriate.

c) Qualification demonstration in a 1g environment shall be conducted to verify that each seal can be verified on-orbit for those seals notes as “B” in Table 3.26-1.

d) Qualification analysis shall be conducted to extrapolate the 1g demonstration to a 0g environment.

4.27 VERIFICATION OF DECELERATION SYSTEMS

These requirements shall be verified by analysis, test or both. The system provider shall provide the details of the structural verification methods to be used in the Structural Verification Plan (SVP) for approval by NASA per paragraph 1.5.

4.27.1 Verification Requirements for Parachute Systems

a) A detailed structural verification plan shall be submitted for the parachute system describing the component and system development, qualification and acceptance testing required to verify the structural margins of all system components.

b) The plan shall contain at a minimum:

   1. The proposed development, qualification and acceptance tests for both the parachute system and its components, including pull tests of all critical textile-to-textile and textile-to-mechanical joints.

   2. The number and description of full-scale instrumented canopy tests including test environments and load conditions.

   3. The number and description of canopy re-use tests to verify the de-rating factors used in the structural analysis and the allowable number of re-uses of the canopy.

   4. The methods of verification for any structural, dynamic or aerodynamic math models used to certify the structural performance of the parachute system.

4.27.1.1 Verification of Factors of Safety

a) A detailed structural analysis per section 6.0 shall be provided, containing a margin of safety summary table showing the factor(s) of safety used in analyzing each and every part in the parachute system. Inspection of this report shall verify that the factors of safety used in the design and analysis of the hardware meet the specifications of section 3.10.

b) The stress report shall include all test data and assumptions used to develop the material design allowables, design loads and margins of safety for all of the metallic and non-metallic components of the parachute system.

4.27.1.2 De-Rating of the Ultimate Factor of Safety for Textile Components

a) The structural analysis report provided per section 6.0 shall contain all de-rating factors applied to the ultimate factors of safety for the textile components and the justification for these de-rating factors including supporting test data.

b) Inspection of this report shall verify that the de-rating factors used in the design and analysis of the textile components meet the requirements of paragraph 3.27.1.2

4.28 WIRE ROPE VERIFICATION REQUIREMENTS

Verification of wire ropes shall be by analysis and test.

a) When used as part of a spacecraft structural system, all wire rope shall be proof tested to a minimum of 2.0 times limit load.

b) The stress analysis report provided per section 6.0 shall contain a margin of safety summary table showing the factor(s) of safety used in analyzing any wire rope components.

c) Inspection of the stress analysis report shall verify that the ultimate factor of safety used in the design and analysis of wire rope components meets the requirements of section 3.10.1.

4.29 FLUTTER VERIFICATION

The requirements in this section shall be verified by analysis, test or both.

4.29.1 Classical Flutter Verification

a) The flutter evaluation shall account for all pertinent aerodynamic, elastic, inertial and damping parameters and coupling mechanisms (e.g., mechanical, elastic and aerodynamic) as well as the effects of control-system characteristics and mechanical play, misalignments, launch-vehicle/spacecraft interface stiffness and degrees of freedom of the cryogenic tank-support structure.

b) If staging can occur in the atmosphere, the changes in vibration-mode characteristics and in the characteristics of the newly-activated control surfaces should be accounted for as well as the location of any lifting control surfaces.

4.29.1.1 Wind Tunnel Testing

If analytical methods are insufficient, or when analysis indicates that instability may occur within 1.32 times the dynamic pressure (1.15 times the velocity), wind tunnel tests shall be conducted to demonstrate that the vehicle is free of classical flutter.

a) The test specimens shall be either dynamically-similar models or full-scale elements of the vehicle, which must be tested in relevant environments.

b) It shall also be demonstrated by influence-coefficient, structural stiffness, and/or vibration tests of full-size vehicles in the flight configuration that the scale models adequately simulate the dynamic characteristics of the vehicle.

c) Dynamic characteristics of the scale models shall also reflect the variation in modulus of elasticity with the anticipated service temperatures.

4.29.2 Stall Flutter verification

A parametric evaluation of vehicle stall flutter characteristics shall be conducted to determine the aeroelastic characteristics necessary to avoid limit-cycle amplitude responses that could induce adverse loads on the structure.

The evaluation shall consider:

1) Separated-flow characteristics under all anticipated conditions of angle of attack and velocity;

2) Stiffness, inertia and damping characteristics of the aerodynamic surfaces; and

3) All significant degrees of freedom.

4.29.2.1 Wind Tunnel Testing

If analytical methods are insufficient, or when analysis indicates marginal stability, wind tunnel tests shall be conducted per paragraph 4.29.1.1.

4.29.3 Panel Flutter Verification

a) If test data do not exist for selected panels with the lowest flutter margin of similar structural configuration, edge support conditions and aerodynamic parameters, wind tunnel tests shall be conducted on dynamically-scaled models or full-scale components to demonstrate that external panels are free of panel flutter under the conditions defined in paragraph 3.29.3.

b) Thermally-induced loads, mechanically applied loads and pressure differentials across the panels shall be simulated in the tests.

4.29.4 Control Surface Buzz Evaluation through Testing

Wind-tunnel testing shall be conducted to demonstrate that the vehicle is free of control surface buzz under the conditions cited in paragraph 4.29.1.1.

4.29.4.1 Test Parameters

a) The test specimens shall be either dynamically-similar models or full-scale components

b) Mach number and Reynolds number should be simulated in the tests.

4.29.4.2 Flight Test

At least one flight test vehicle shall be instrumented to detect control surface buzz in flight test regions of greatest dynamic pressure. For recommended practices, refer to NASA SP-8003.

4.30 AEROELASTICITY VERIFICATION

These requirements shall be verified by analysis, test or both.

4.30.1 Static Aeroelasticity Verification

4.30.1.1 Divergence Verification

The analysis shall include, as appropriate, such factors as static and transient thermal effects on distortion and stiffness, load magnitudes and distributions for all critical loading conditions, stiffness characteristics of the control-surface actuator system, system tolerances, misalignments and mechanical play.

4.30.1.1.1 Wind Tunnel Testing

a) If analytical methods are insufficient, wind tunnel tests shall be conducted per paragraphs (a) and (b) to demonstrate that the vehicle is free of divergence under the conditions cited in paragraph 3.30.1.1.

b) For recommended practices, refer to NASA-SP-8003, FAA-FAR Part 25, AFSC DH 3-2 (DN 4C7) and MIL-A-008870 (USAF).

4.30.1.2 Verification of Aeroelastic Effects on Control Surfaces

The analysis shall include, as appropriate, such factors as static and transient thermal effects on distortion and stiffness, load magnitudes and distributions for all critical loading conditions, stiffness characteristics of the control-surface actuator system, system tolerances, misalignments and mechanical play.

4.30.1.2.1 Wind Tunnel Testing

a) If analytical methods are insufficient, wind tunnel tests shall be conducted per paragraphs 4.29.1.1 (a) and (b) to demonstrate that the vehicle is not subject to detrimental aeroelastic effects on control surface authority under the conditions cited in paragraph 3.30.1.2.

b) For recommended practices, refer to FAA-FAR Part 25 and MIL-A-008870(USAF).

4.30.2 Dynamic Aeroelasticity

4.30.2.1 Dynamic Aeroelastic Instability Evaluation by Analysis

The dynamic aeroelastic instability evaluation shall be performed by analysis and/or test.

The analysis shall account for:

1. Configuration effects, such as center-of-gravity offset leading to a coupled response;
2. Unsymmetrical stiffness distribution;
3. Variation in characteristics of the release-restraint device on the vehicle launch pad;
4. Variation in the thrust loads and unsymmetrical thrust effects resulting from engine sequencing and non-uniformity in combustion (including applicable engine-out conditions);

5. Unsymmetrical aerodynamic effects;
6. Changes in stiffness due to structural temperature;
7. Internal stress redistribution with increasing load level;
8. Effects of clearances and mechanical play.

4.30.2.2 Dynamic Aeroelastic Instability Evaluation by Test

a) When tests are conducted as a supplement to analysis to verify freedom from undesirable axial-lateral coupling, the test specimens shall be either dynamically-similar models or full-scale components.

b) If dynamically-similar models are used, the adequacy of structural simulation shall be verified by influence-coefficient, structural-stiffness and/or vibration testing.

4.30.3 Vortex Shedding Verification

Verification of the flight vehicle structure's response to ground winds and gusts during pre-launch and launch shall be by analysis. Supplemental testing may also be part of the verification for this requirement.

4.30.3.1 Vortex Shedding Evaluation by Analysis

The analysis required to show that instabilities and excessive dynamic response due to vortex shedding produced by ground winds and gusts are precluded in Constellation flight vehicle structures shall account for, as a minimum:

1. The full range of specified ground wind and gust conditions.
2. The profile shape of the vehicle.
3. Vehicle mass, stiffness, propellant loading and tank-pressurization conditions.
4. Vehicle protuberances and surface roughness.
5. The characteristics of the release-restraint device on the vehicle launch pad.
6. Any changes in stiffness due to structural temperature.
7. The effects of clearances and mechanical play.
8. The proximity and shape of umbilical masts, gantries and other large structures.

9. Tank venting system characteristics, including valve tolerances and settings for design ullage and vent pressure.

10. Effects of any structural tie-offs or dampers used between the vehicle and launch-support structure to assist the vehicle in withstanding wind loads

Refer to NASA SP-8008 for recommended practices.

4.30.3.1.1 Vortex Shedding Load Combination Criteria

The wind and gust loads as well as the other transient and quasi-static loads (including gravity effects, and any vehicle attachment loads due to the release-restraint devices, structural tie-offs or dampers) shall be combined with the periodic vortex shedding loads calculated from the peak-wind profile to obtain the resultant elastic-vehicle static and dynamic loads.

4.30.3.2 Vortex Shedding Evaluation by Test

When tests are conducted as a supplement to analysis to verify freedom from instabilities and excessive dynamic response due to vortex shedding produced by ground winds and gusts, the test specimens and test methods shall meet the requirements of the next two paragraphs. Refer to NASA SP-8008 for recommended practices.

4.30.3.2.1 Dynamically-Similar Wind-Tunnel Models

Dynamically-similar wind-tunnel models of the vehicle and its restraint on the launch pad shall meet the following specifications:

a) The vehicle model shall incorporate all protuberances.

b) The influence of adjacent towers and launch equipment shall be simulated.

c) Tests shall be conducted in all critical configurations for all orientations with respect to the wind at both subcritical and supercritical Reynolds numbers.

4.30.3.2.2 Full-Scale Tests

a) Full-scale tests including the flight vehicle, or a representative test article, shall be restrained at the launch pad and include the surrounding structure.

b) These tests shall provide measurements of vehicle dynamic response such as bending moments and accelerations as well as simultaneous measurements of the frequency and damping of the critical vibration modes of the vehicle on its launch pad in all necessary configurations.

5.0 STRUCTURAL TEST REQUIREMENTS

a) 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 NASA per paragraph 1.5 for approval.

b) All static testing shall provide data to develop a test-verified strength math model.

c) Requirements for successful strength correlation are listed in section 4.9.2.

5.1 VERIFICATION TEST OPTIONS

5.1.1 Static Test to Ultimate Loads

a) A designated structural test article shall be static tested to ultimate loads for the critical load conditions to demonstrate the minimum required factors of safety per Table 3.10.1-1.

b) Sufficient instrumentation shall be utilized to identify (monitor) high strain areas and verify that the internal loads distribution, strains and displacements are consistent with the structural math models as described in section 4.9.2.

5.1.2 Protoflight Static Test

a) Flight structure (or a dedicated test article) shall be static tested to 1.2 times the design limit loads.

b) Sufficient instrumentation shall be utilized to identify (monitor) high strain areas and verify the internal loads distribution, strains and displacements are consistent with the structural math model.

c) After verification of the analytical static math model per section 4.9.2, ultimate load capability can then be verified by a formal stress analysis.

d) The minimum yield factor of safety shall be 1.25 for the structure to be verified by this option.

e) Use of this option requires prior approval of NASA per paragraph 1.5.

5.1.3 Element and Critical Component Static Test

The hardware developer shall demonstrate prior experience in successful structural design and analysis, math modeling, and structural testing of previous spacecraft. This option requires prior written approval by NASA per paragraph 1.5.

5.1.3.1 Element Tests and Model Verification

a) Flight structure or a designated test article shall be proof tested to 1.1 times the design limit loads.

b) Sufficient instrumentation shall be utilized to identify (monitor) high strain areas and verify the internal loads distribution, strains and displacements are consistent with the structural math model.

c) After verification of the analytical static math model per section 4.9.2, ultimate load capability can then be verified by a formal stress analysis

5.1.3.2 Complementary Component Testing to Ultimate Load

a) In addition to the 1.1 times limit load proof test, several critical structural elements and/or components shall be tested to ultimate load to verify their ultimate strength capability. These components shall be identified prior to initiating the test program and shall be approved by NASA per paragraph 1.5.

b) These critical structural elements and/or components verification tests may be conducted on dedicated test articles having the same configuration, materials and workmanship as the flight article.

5.2 VERIFICATION TESTS REQUIREMENTS

5.2.1 General Requirements

All test plans and requirements shall be coordinated with and approved by NASA per paragraph 1.5.

5.2.1.1 Static Strength Tests

a) Test loads shall duplicate or envelop all flight loads and include pressure and temperature effects as specified in the SVP.

b) When a separate verification structure (dedicated test article) is used, the tests shall be accomplished at the limit and ultimate levels specified by the required factors of safety.

c) Testing to an ultimate FS is for structural design verification only and not for attached systems.

5.2.1.2 Dynamic Strength Tests

Sinusoidal dynamic tests may be used when warranted by load conditions, test article size, and boundary conditions. Other forms of dynamic testing may be warranted, e.g., impact testing.

5.2.2 Test Boundary Conditions

The stiffness and boundary conditions of the interfacing flight structure through which the loads and reactions are applied shall be simulated for statically indeterminate structure.

5.2.3 Pressurized Structure Verification Tests

5.2.3.1 Qualification Test Requirements for Pressurized Structures

Qualification testing on pressurized structure shall be conducted on flight-quality hardware to demonstrate structural adequacy of the design. The test fixtures, support structures, and methods of environmental application shall not induce erroneous test conditions. The sequences, combinations, levels and duration of loads, pressure, and environments shall demonstrate that design requirements have been met.

Qualification testing shall include pressure cycle testing and burst testing. The following items delineate the required tests:

a) Pressure Cycle Testing: Requirements for application of external loads in combination with internal pressure during testing shall be evaluated based on the relative magnitude and on the destabilizing effect of stresses due to the external loads. If limit combined tensile stresses are enveloped by the MDP stress, the application of external load is not required. Unless otherwise specified, the peak pressure shall be equal to the MDP during each pressure cycle, and the number of cycles shall be four (4) times the predicted number of operating cycles or 50 MDP cycles, whichever is greater.

   If the application of external loads is required, the load shall be cycled for four (4) times the predicted number of operating cycles of the most severe design condition (e.g., destabilizing load with constant minimum internal pressure or maximum additive load with MDP).

b) Burst Testing: After the pressure cycle testing, the test article shall be pressurized (pneumatically or hydrostatically, as applicable and safe) to the design burst pressure specified in Table 3.10.1-1, while simultaneously applying the ultimate external loads, if appropriate. The design burst pressure shall be maintained for a period of time sufficient to assure that the proper pressure is achieved.

5.2.3.2 Acceptance Proof Test

Every pressurized structure shall be proof pressure tested in accordance with the requirements of this document to verify that the hardware has sufficient structural integrity to sustain the subsequent service loads, pressure, temperatures, and environments. The temperature shall be consistent with the critical use temperature, or test pressures shall be suitably adjusted to account for temperature effects on strength and fracture toughness.

Proof-test fluids shall be compatible with the materials in the pressurized hardware. If such compatibility data is not available, testing shall be conducted to demonstrate that the proposed test fluid does not deteriorate the test article.

Accept/reject criteria shall be formulated prior to acceptance proof test. When sufficient data do not exist to establish these criteria, a development test program shall be conducted to generate the required data. Every pressurized structure shall not leak, rupture, or experience detrimental deformation during acceptance testing.

5.2.3.2.1 Acceptance Test Requirements for Pressurized Structures with Non-Hazardous LBB

Acceptance tests shall be conducted on every pressurized structure before commitment to flight. Accept-reject criteria shall be formulated prior to tests. The test fixtures and support structures shall be designed to permit application of all test loads without jeopardizing the flightworthiness of the test article. The following are required as a minimum:

a) Non-Destructive Inspection: A complete inspection shall be performed prior to proof test to establish the initial condition of the hardware.

b) Proof Pressure Test: Every pressurized structure shall be proof-tested to verify that the materials, manufacturing processes, and workmanship meet design specifications and that the hardware is suitable for flight. Unless otherwise specified, the proof pressure shall be greater than or equal to 1.1 x MDP and shall meet the test factors specified in Table 3.10.1-1.

c) Leak Check: Leak checks shall be conducted at MDP after proof-pressure testing.

5.2.3.2.2 Acceptance Test Requirements for Habitable Structures and Pressurized Structures with a Brittle Failure Mode or Hazardous LBB

The acceptance test requirements for habitable structures and pressurized structures which exhibit brittle fracture failure mode or hazardous LBB failure mode are identical to those with non-hazardous LBB failure mode as defined in Section 5.2.3.2.1, except that proven NDE techniques shall be employed to detect flaws or cracks smaller than or equal to the allowable initial flaw sizes as determined by damage tolerance analysis. Furthermore, NDE shall also be performed on fracture critical welds after proof testing.

5.3 REPORTS

5.3.1 Qualification Test Reports

a) Qualification tests shall be documented.

b) The documentation shall include 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, stresses and forces compared against the actual internal loads, stresses and forces developed during test and a summary of test data which is applicable to the structural verification.

5.3.2 Engineering Analysis Reports

An engineering analysis report shall be prepared for each structural qualification test. The report shall compare the test results to the analysis of the test configuration.

6.0 STRESS ANALYSIS REQUIREMENTS

Structural margins of safety for limit and ultimate loads shall be evaluated in order to ensure that adequate margin exists for the combination of mechanical, pressure, and thermal loads.

6.1 STRESS/LOAD COMBINATION RESTRICTIONS

Guidelines for combining mechanical loads may be found in NASA-TM-X-73305. The following restrictions shall be applied for load combinations.

6.1.1 Combining with Pressure Stress/Load

a) In circumstances where pressure loads have a relieving or stabilizing effect on structural load capability, the minimum value of such relieving loads shall be used.

b) The pressure loads shall not be multiplied by the FS in calculating the design limit or ultimate load if they are relieving or stabilizing to the structure.

c) Factors of safety for combined load conditions are defined in paragraph 3.10.

For example, the ultimate compressive load in pressurized vehicle tankage shall be calculated as follows:

Ultimate Load = (Ultimate FS X Mechanical Load) - (Min Pressure Load)

6.1.2 Combining Low Frequency And Random Loads For Components And Attachments

Low frequency loads and random vibro-acoustic loads shall be combined according to Table 6.1-1, Load Combination Criteria for Components.

Table 6.1-1 Load Combination Criteria for Components

Axis	Steady State Load (Limit)	Low Frequency Transient Load[1]	Random Load[2]
V_i	QS_i	+/- Si	+/- R_i
Combined Loads Load in Each Axis Acting Simultaneously			
Load Set	V_1 Axis	V_2 Axis	V_3 Axis
1	$QS_1 +/-(S_1^2 + R_1^2)^{1/2}$	$QS_2+/-.3\cdot(S_2^2 + R_2^2)^{1/2}$	$QS_3+/-.3\cdot(S_3^2 + R_3^2)^{1/2}$
2	$QS_1 +/-.3\cdot(S_1^2 + R_1^2)^{1/2}$	$QS_2+/-(S_2^2 + R_2^2)^{1/2}$	$QS_3+/-.3\cdot(S_3^2 + R_3^2)^{1/2}$
3	$QS_1 +/-.3\cdot(S_1^2 + R_1^2)^{1/2}$	$QS_2+/-.3\cdot(S_2^2 + R_2^2)^{1/2}$	$QS_3+/-(S_3^2 + R_3^2)^{1/2}$

[1]quasi-static portion removed
[2]3-sigma Gaussian random load

6.2 STRUCTURAL ANALYSIS DOCUMENTATION

The responsible design organizations shall provide stress analysis documentation of all structure to assure compliance with strength and deformation requirements.

6.2.1 Stress Analysis Format

The stress analysis reports shall be prepared in accordance with standard aerospace industry practices for flight hardware. Guidelines for stress analysis reports are documented in JSC 19652, Instructions for the Preparation of Stress Analysis Reports.

6.2.2 Solution Description and Verification

If the results from other than closed form solutions, e.g., computer models, are presented in a stress analysis, both the logic and sufficient checks shall be present to assure that the data presented is a solution to the configuration and condition being analyzed.

6.2.3 Stress Analysis Maturity and Deliveries

a) Stress analysis reports (revisit “reports”) shall be submitted to NASA 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), as delineated in the following paragraphs.

b) These analyses shall be current with respect to loads and the design at the time of the review.

6.2.3.1 Stress Analysis for Preliminary Design Review

The PDR stress analysis shall be sufficiently detailed to assure the structural integrity of all major structure elements and the credibility of weight calculations. Additionally, a preliminary fatigue analysis shall be submitted for PDR.

6.2.3.2 Stress Analysis for Critical Design Review

a) This analysis shall fully substantiate the structural integrity of each detailed part and provide the basis for stress signatures required on all drawings.

b) Life requirements shall be addressed in this analysis.

6.2.3.3 Interim Design Reviews

Current stress analyses shall be available to support interim reviews other than those specified above.

6.2.3.4 Stress Analysis for Design Certification Review (DCR)

This analysis shall include changes or additions to the formal CDR stress analysis data package and shall fully substantiate the structural integrity of each detailed part including structural verification tests, life verification, and detailed evaluation of the "as-built" hardware.

6.2.3.5 Stress Analysis for Flight Readiness Review

These data shall include only revisions to update the stress analysis reports for the flight design configuration with all significant changes from the DCR.

6.2.4 Fatigue and Fracture Analysis Deliveries

Fatigue and fracture analyses shall be submitted with the stress analysis reports.

7.0 QUALITY ASSURANCE, STRUCTURAL INSPECTION AND MAINTENANCE REQUIREMENTS

The type, extent, and frequency of structural inspections, and the special instrumentation required to maintain safety shall be documented in an inspection plan. The plan shall be approved by NASA.

7.1 QUALITY ASSURANCE FOR PRESSURIZED STRUCTURE

A quality assurance program, based on a comprehensive study of the product and engineering requirements shall be established to assure that the necessary NDE and acceptance tests are performed effectively to verify that the product meets the requirements of this document. The program shall insure that no damage or degradation has occurred during material processing, fabrication, inspection, acceptance tests, shipping, storage, operational use and refurbishment; and that defects which could cause failure are detected or evaluated and corrected. As a minimum, the following consideration shall be included in structuring the quality assurance program.

7.1.1 Inspection Plan

An inspection master plan shall be established prior to start of fabrication. The plan shall specify appropriate inspection points and inspection techniques for use throughout the program. For fracture critical parts, the inspection requirements in CA3193-PO shall be met. Acceptance and rejection standards shall be established for each phase of inspection, and for each type of inspection technique.

7.1.2 Inspection Techniques

The selected NDE techniques for pressurized structures which need to demonstrate their damage tolerance by fracture mechanics analysis or testing shall meet the requirements in CA3193-PO. Two or more NDE methods shall be used for a part or assembly that cannot be adequately examined by only one method.

The detection capability of each selected NDE technique shall be capable of detecting allowable initial flaw size corresponding to a 90% probability of detection (POD) at a 95% confidence level.

7.1.3 Inspection Data

Inspection data in the form of flaw histories shall be maintained throughout the life of the pressurized structure. These data shall be reviewed periodically and assessed to evaluate trends and anomalies associated with the inspection procedures, equipment and personnel, material characteristics, fabrication processes, design concept and structural configuration. The result of this assessment shall form the basis of any required corrective action.

8.0 GLOSSARY

The following definitions and terms shall be used for design and analysis of the stage or vehicle to establish uniform structural nomenclature in all documentation:

ACCEPTANCE TESTS

Acceptance tests are used to verify and to demonstrate that the hardware is acceptable for flight and performs to specifications. It also serves as a quality screen to detect deficiencies, and to provide the basis for delivery of an end item(s) to the contract customer. Most acceptance tests include performance and functional testing, leak checks, proof pressure, random vibration, and thermal cycle tests.

A-BASIS MATERIAL PROPERTIES

The lower of either a statistically calculated number, or the specification minimum (see S-basis). 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.

B-BASIS MATERIAL PROPERTIES

At least 90 percent of the population of values is expected to equal or exceed the B-basis mechanical property allowable, with a confidence of 95 percent.

BURST SPEED, ROTATING MACHINERY

The burst speed for rotating machinery is the calculated speed at which the rotor disk average tangential stress equals the material ultimate tensile strength of the rotor disk multiplied by a material utilization factor of 0.7.

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, 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.

CONDITION

A phenomenon, event, time interval, or combination thereof to which the space vehicle is exposed. (See Design Condition.)

CREDIBLE FAILURE

A failure resulting from a Program-accepted load or design condition.

CREDIBLE LOAD, DESIGN CONDITION

A Program-accepted load or design condition.

CREDIBLE SINGLE BARRIER FAILURE

Potential leaks within a component that permit 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 FLAW SIZE

The flaw size which, for a given applied stress, causes unstable flaw propagation.

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

See Seals, Critical

DERATING FACTORS

The load and loss factors applied to the factor of safety for each textile load bearing component to account for the strength degradation of textiles due to mechanical, environmental and material conditions.

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.)

DESIGN ORGANIZATION

The organization which has the responsibility for the detailed design, analysis, and verification of the flight hardware being discussed. Normally the design organization will be a contractor organization.

DESIGN SPEED, ROTATING MACHINERY

The nominal fluid characteristics for rotating machinery are designed based upon this speed.

DETERMINISTIC

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.)

DETRIMENTAL DEFORMATION

Structural deformation, deflection, or displacement which: (1) causes unintentional contact, misalignment, or divergence between adjacent components; (2) causes significant internal load redistribution in a structure; (3) causes a component to exceed the dynamic space envelop established for that component; (4) reduces the strength or rated life of the structure below specified levels; (5) degrades the effectiveness of thermal protection coatings or shields; (6) jeopardizes the proper functioning of equipment; (7) endangers personnel; (8) degrades the aerodynamic or functional characteristics of the vehicle; 9) reduces confidence below acceptable levels in the ability to ensure flight-worthiness by use of established analytical or test techniques; or (10) induces leakage above specified rates.

DISCONTINUITY AREA

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.

ELEMENT

Constellation Program 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 with other Constellation elements or systems (e.g. Crew Module (CM), Core Stage).

FAIL-SAFE

A structural design criterion in which it must be shown that the structure remaining, after failure of any single structural member, can withstand the resulting redistributed internal limit loads without failure.

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.

FAILURE, CREDIBLE

A failure of a component, device, or structure which is from an accepted or credible design condition.

FASTENER, STRUCTURAL

See Structural Fastener.

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, STATIC

The phenomena where flaws grow as a function of sustained stress, time, flaw size, and environment.

FLAWS OR CRACK-LIKE DEFECTS

Defects which behave like cracks that may be initiated during material production, fabrication, or testing or may be developed during the service life of a component.

FRACTURE

Fracture is used herein in a broad sense to encompass the development, accumulation and/or growth of damage in various forms such as cracks, flaws, notches, delaminations, disbonds, cuts, voids, etc. whose growth could lead to component failure.

FRACTURE CONTROL PLAN

The plan which specifies fracture control activities to be imposed on the design, analysis, testing, change control, and documentation of components. The intent of this document is to establish procedures required to prevent catastrophic damage associated with cracks or crack-like flaws from occurring during the service life of these components.

FRACTURE CONTROL

The rigorous application of those branches of engineering, assurance management, manufacturing, and operations technology dealing with the understanding and prevention of flaw propagation leading to catastrophic failure.

FRACTURE CRITICAL COMPONENT (OR PART)

A classification which assumes that fracture or failure of the part resulting from the occurence of a crack will result in a catastrophic hazard. Such classification is required on structural components unless the contrary is demonstrated using the criteria of paragraph 4.2 of SSP 30558.

FRACTURE MECHANICS

An engineering discipline which describes the behavior of cracks or crack-like flaws in materials under stress.

INITIAL FLAW SIZE

The maximum size of the flaw, as determined by proof test or nondestructive inspection, which could exist in parts without failure in proof test or detection by inspection.

INTERFACE

The common boundary between components, assemblies, or systems of a space vehicle. An interface may be physical, functional, or procedural.

LEAK BEFORE BURST

A fracture mechanics design concept in which it is shown that any initial flaw will grow through the wall of a pressure vessel and cause leakage rather than burst (catastrophic failure).

LOAD DE-RATING FACTORS

The type of de-rating factor that is used to addresses uncertainties in load magnitude and in the geometry of the load paths when analyzing textiles in a parachute system. Examples of these factors include dynamic load factor, line convergence factor and unsymmetrical suspension line load distribution.

LOAD, FLUCTUATING

An oscillating load in which the duration, direction, magnitude, frequency content, and phase are significant. Dynamic response of the structure may or may not be significant. Examples are loads caused by pogo-type instability, flutter, buffeting, aerodynamic noise, acoustic noise, and rotating equipment.

LOAD, IMPULSE

A suddenly applied pulse or step change in loading in which the duration, direction, magnitude, and rate of change in direction or magnitude are significant. Examples are loads produced by physical impact, vehicular pyrotechnics, and external explosions.

LOAD, LIMIT

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

LOAD, QUASI-STATIC

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

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.

LOAD, STEADY

A load of constant magnitude and direction with respect to the structure. Examples are loads caused by joint preloads, clamping, and constant thrust.

LOADS, TIME-CONSISTENT

A set of time-consistent loads is one in which all of the load events being assessed occur at the same time during a vehicle's mission or life.

LOSS DE-RATING FACTOR FACTORS

The type of de-rating factor that is used to addresses the mechanical and environmental conditions which degrade the strength of the parachute textile material. Examples of these factors include joint efficiency loss, abrasion loss, re-use, cyclic, environmental effects (e.g. temperature, water, chemicals, aging and sunlight), humidity, and storage in the space environment.

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. A detailed discussion of Margins of Safety including combined stresses is presented in Sec. 1.5.3.5 of MIL-HDBK-5. 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

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.

MAXIMUM OPERATING SPEED, ROTATING MACHINERY

The Maximum Operating Speed for rotating machinery is equivalent to Design Speed multiplied by a factor of 1.1.

NON-DESTRUCTIVE EVALUATION (NDE)

Inspection techniques which do not cause physical, mechanical, or chemical changes to the part being inspected or otherwise impair its adequacy for operational service. These inspection techniques are applied to materials and structures to verify required integrity and to detect flaws.

NON-SAFETY CRITICAL STRUCTURES

Structures which if they fail will not create a catastrophic hazard.

POGO

“POGO” is a potentially dangerous type of oscillation found in rocket engines. This oscillation results in variations of thrust from the engines, generally caused by variations in fuel flow rate, placing stress on the frame of the vehicle. The main cause of POGO is when a surge in engine pressure increases back pressure against the fuel coming into the engine, reducing engine pressure, causing more fuel to come in and increasing engine pressure again. If the cycle happens to match a resonant frequency of the rocket then dangerous oscillations can occur through positive feedback, which can in extreme cases tear the vehicle apart.

PRESSURE VESSEL

A container designed primarily for pressurized storage of gases or liquids and:
(1) Contains stored energy of 14,240 foot-pounds (19,307 joules) or greater based on adiabatic expansion of a perfect gas; or
(2) Contains a gas or liquid in excess of 15 psia (103.4 kPa) which will create a hazard if released; or
(3) Stores a gas which will experience a MDP greater than 100 psi (689.5 kPa).

PRESSURIZED STRUCTURE

A structure designed to carry vehicle loads in which pressure is a significant contributor to the design loads.

PRIMARY STRUCTURE

(See Structure, Primary.)

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.

RANDOM VIBRATION

The oscillating haphazard motion of a structure caused by acoustical and/or mechanical forcing functions.

ROTATING MACHINERY

Machinery which has rotating parts.

SAFE-LIFE

A design criterion under which a flaw is assumed consistent with the inspection process specified and it can be shown that the largest undetected flaw that could exist in the structure will not grow to failure in four service lifetimes when subjected to the cyclic and sustained loads in the environments encountered; also, the period of time for which the integrity of the structure can be ensured in the expected operating environments.

SAFETY FACTOR (FS)

A constant which has been defined for yield and ultimate design criteria which is multiplied by limit load to obtain the yield and ultimate design loads. FS has an historical basis and is necessary to assure no failures due to uncertainties which result from the design process, manufacturing process, and the loading environment.

S-BASIS MATERIAL PROPERTIES

The S-value is the minimum property value specified by the governing industry specification (as issued by standardization groups such as SAE Aerospace Materials Division, ASTM, etc.) or federal or military standards for the material. (See MIL-STD-970 for order of preference for specifications.) For certain products heat treated by the user (for example, steels hardened and tempered to a designated F_{tu}), the S value may reflect a specified quality-control requirement. Statistical assurance associated with this value is not known.

SEALS, CRITICAL

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.

SEAM

A series of stitches that joins two or more pieces of fabric or material.

SECONDARY STRUCTURE

(See Structure, Secondary.)

SERVICE LIFE

The interval beginning with determination of initial crack size for analysis based on inspection or flaw screening proof test of a part through completion of its specified mission including testing, transportation, lift-off, ascent, on-orbit operations, and descent and landing as applicable.

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 design service life including ground handling, transport to and from orbit including abort conditions, and on-orbit operations.

STRESS, RESIDUAL

Stress that remains in a structure due to processing, fabrication, or non-uniform yielding.

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.

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.

SYSTEM

Constellation Program physical entities that have functional capabilities allocated to them necessary to satisfy Architecture-level mission objectives. Systems can perform all allocated functions within a mission phase, or through mated operations with other Constellation systems (e.g. Crew Exploration Vehicle (CEV), Lunar Surface Access Module.)

TIME-CONSISTENT LOADS

See Loads, Time-Consistent

ULTIMATE LOAD, PRESSURE, OR STRESS

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

VALIDATION

The process that ensures a system meets NASA's expectations for intended use. Unique validation activities may not be required if validation is satisfied through verification or acceptance testing activities.

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.

VERIFICATION TEST

Tests conducted on flight-quality structures at specified load levels to demonstrate that all structural design requirements have been achieved.

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 shall withstand without incurring detrimental deformations; analytically, the maximum load that a structure shall withstand without exceeding the yield stress of the material; also the product of the limit load multiplied by the yield FS. (Also Yield Strength.)

Appendix A Verification Requirements for NASA-STD-5017

Appendix B Verification Requirements for JSC 62809