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Standard

Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components

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American National Standard

Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components

Sponsored by

American Institute of Aeronautics and Astronautics

Approved September 13, 1999

American National Standards Institute

Abstract

This Standard provides requirements for the analysis, design, manufacture, qualification, and acceptance for flight of metallic pressure vessels, pressurized structures, and pressure components for use in space systems. The document includes specific requirements addressing pressure vessels with hazardous and non-hazardous failure modes and special pressurized equipment such as batteries, heat pipes, cryostats, and pressure components.

American National Standard

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Foreword

This document was prepared following a draft military standard, Mil-Std-1522B (USAF), dated 14 July 1995, entitled "Requirements for Design and Operation of Pressurized Missile and Space Systems," developed by The Aerospace Corporation, El Segundo, California, under USAF contract F04701-88-C-0089. J.B. Chang was the principal investigator of this development effort. This contract was administered by the Air Force Space and Missile Systems Center (AF/SMC), Los Angeles, California. Dr. L. C-P Huang was the Air Force Project Manager. That military standard was never released officially. This American National Standard is intended to replace the current military standard.

Under the sponsorship of National Aeronautics and Space Administration (NASA) Headquarters, technical staff from Jet Propulsion Laboratory (JPL), Pasadena, California, also participated in the development of Mil-Std-1522B. Dr. M.C. Lou was the team leader.

The AIAA Aerospace Pressure Vessel Standard Working Group operates within the AIAA Structures Committee on Standards. It was formed in March 1996 with an emphasis on inclusion of aerospace prime companies, pressurized system suppliers, and all interested government agencies. Deliberations focused heavily on adapting the standard to address commercial procurement of aerospace pressurized systems. One of the goals of the project was to provide a performance standard which could be used by commercial launch operators in seeking licenses from the US Department of Transportation. Another goal was to assist the US Department of Defense in its transition to procuring aerospace hardware on a commercial basis to the maximum extent possible.

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At the time of approval of this Standard, the AIAA Aerospace Pressure Vessel Standards Working Group included the following members:

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The document was approved by the AIAA Structures Committee on Standards on December 2, 1998.

The document was accepted for publication by the Standards Executive Council on January 19, 1999.

This American National Standard is technically equivalent to ISO 146231-1, "Space systems - Pressure vessels and pressurized structures – Part 1: Metallic hardware."

1. Scope

1.1 Purpose

This standard establishes baseline requirements for the design, fabrication, test, inspection, operation and maintenance of the metallic pressurized hardware used in space systems such as spacecraft and launch vehicles. These requirements when implemented on a particular system, will assure a high level of confidence in achieving safe and reliable operation.

1.2 Application

This standard is applicable to space flight metallic pressurized hardware. Included are all pressure vessels, pressurized structures, batteries, heat pipes, cryostats, sealed containers, and pressure components such as lines, fittings, and hoses made of metals. A companion standard, AIAA-S-081, is applicable to space flight composite overwrapped pressure vessels (COPV).

The requirements specified in this standard may be tailored to specific programs with the agreement of the appropriate approval authority.

2. Reference Documents

The latest issue of the following are references for this standard.

Mil-Hdbk-5 *Metallic Materials and Elements for Aerospace Vehicle Structures*

Code of Federal Regulations - Title 49, Code of Federal Regulations (CFR)
Department of Transportation (DoT) CFR

American Society of Mechanical Engineers *ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 and 2.*

CINDAS/USAF CRDA Handbook Operation, Purdue University, Lafayette, Indiana.
Aerospace Structural Metals Handbook and Damage Tolerance Design Handbook,

3. Vocabulary

The following definitions of significant terms are provided to ensure precision of meaning and consistency of usage In the event of a conflict, the definitions listed here apply.

"A" Basis Allowable: The mechanical strength values guaranteed by the material producers/ suppliers such that at least 99% of the material they produce/supply will meet or exceed the specified values with a 95% confidence level.

Acceptance Tests: The required formal tests conducted on the flight hardware to ascertain that the materials, manufacturing processes, and workmanship meet specifications and that the hardware is acceptable for intended usage.

Allowable Load (Stress): The maximum load (stress) that can be accommodated by a structure (material) without rupture, collapse, or detrimental deformation in a given environment. Allowable stresses are commonly the statistically based ultimate strength, buckling strength, and yield strength, respectively.

Applied Load (Stress): The actual load (stress) imposed on the structure in the service environment.

"B" Basis Allowable: The mechanical strength values specified by material producers/suppliers such that at least 90% of the materials they produce/supply will meet or exceed the specified values with a 95% confidence level.

Brittle Fracture: A type of catastrophic failure mode in structural materials that usually occurs without prior plastic deformation and at extremely high speed. The fracture is usually characterized by a flat fracture surface with little or no shear lips (slant fracture surface) and at average stress levels below those of general yielding.

Burst Factor (BF): A multiplying factor applied to the maximum expected operating pressure (MEOP) to obtain the design burst pressure.

Burst Pressure: The pressure level at which rupture or unstable fracture of the pressurized hardware occurs.

Component: A functional unit that is viewed as an entity for the purpose of analysis, manufacturing, maintenance, or record keeping.

Critical Condition: The most severe environmental condition in terms of loads, pressures, and temperatures, or combinations thereof, imposed on systems, subsystems, and components during service life.

Critical Flaw: A specific shape of a flaw or a crack-like defect existing in the metallic hardware with sufficient size that unstable growth will occur under the specific operating load and environment.

Critical Stress Intensity Factor: The value of the stress intensity factor at which unstable fracture occurs.

Damage Tolerance: The ability of structures to resist failure due to the presence of flaws, crack-like defects, delaminations, scratches or impact damage for a specified period of un-repaired usage.

Design Burst Pressure: A pressure that the pressurized hardware must withstand without rupture in the applicable operating environment. It is equal to the product of the MEOP and a burst factor.

Design Safety Factor (DSF): A multiplying factor to be applied to limit loads and/or MEOP for purposes of analytical assessment and/or test verification of structural adequacy.

Destabilizing Pressure: A pressure that produces compressive stresses in the pressurized hardware.

Detrimental Deformation: The structural deformation deflection, or displacement that prevents any portion of the structure from performing its intended function, or that reduces the probability of successful completion of the mission.

Development Test Program: A test program that is conducted by the manufacturer in order to provide design information that may be used to check the validity of analytic techniques and assumed design parameters; to uncover unexpected system response characteristics; to evaluate design changes; to determine interface compatibility; to prove qualification and acceptance procedures and techniques; or to establish accept/reject criteria for nondestructive inspection (NDI); or any other purpose necessary to establish the validity of the design and manufacturing processes.

Ductile Fracture: A type of failure mode in structural materials generally preceded by a large amount of plastic deformation and in which the fracture surface is inclined to the direction of the applied stress.

Fatigue: The process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points and which may culminate in cracks or complete fracture after a sufficient number of fluctuations.

Fatigue Life: The number of cycles of applied external load and/or pressurization that the unflawed pressurized hardware can sustain before failure of a specified nature could occur.

Fittings: Pressure components of a pressurized system utilized to connect lines, other pressure components and/or pressure vessels within the system.

Flaw: A local discontinuity in a structural material, such as a scratch, notch, crack or void.

Flaw Shape (a/2c or a/c): The shape of a surface flaw, or a corner flaw, where **"a"** is the depth and **"2c" or "c"** is the length of the flaw.

Fracture Control: The application of design philosophy, analysis method, manufacturing technology, quality assurance, and operating procedures to prevent premature structural failure due to the propagation of cracks or crack-like defects during fabrication, testing, transportation and handling, and service.

Fracture Mechanics: An engineering discipline which describes the behavior of cracks or crack-like defects in materials under stress.

Fracture Toughness: A generic term for measures of resistance to extension of a crack.

Hazard: An existing or potential condition that can result in an accident.

Hydrogen Embrittlement: A mechanical-

environmental failure process that results from the initial presence or absorption of excessive amounts of hydrogen in metals, usually in combination with residual or applied tensile stresses.

Initial Flaw: A flaw or a crack-like defect in a structural material before the application of load and/or deleterious environment.

Leak-Before-Burst (LBB): A design concept in which potentially critical flaws will grow through the wall of the pressurized hardware and cause pressure relieving leakage rather than burst (catastrophic failure) at MEOP.

Limit Load: The maximum expected external load or combination of loads, which a structure may experience during the performance of specified missions in specified environments. When a statistical estimate is applicable, the limit load is that load not expected to be exceeded at 99% probability with 90% confidence.

Lines: Tubular pressure components of a pressurized system provided as a means for transferring fluids between components of the system. Flex hoses are included.

Loading Spectrum: A representation of the cumulative loading anticipated for the structure under all expected operating environments. Significant transportation and handling loads are included.

Margin of Safety (MS):

MS = (Allowable Load/ Limit Load x DSF) - 1

Note: Load may mean stress or strain.

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

Pressure Vessel: A container designed primarily for the storage of pressurized fluids and which (1) contains stored energy of 14,240 foot-pounds (19,130 joules) or greater, based on adiabatic expansion of a perfect gas, (2) contains gas or liquid which will create a mishap (accident) if released, or (3) will experience a MEOP greater than 100 psia (700 kPa). Special pressurized equipment such as batteries, heat pipes, cryostats and sealed containers are not included.

Pressure Component: A component in a pressurized system, other than a pressure vessel, pressurized structure, or special pressurized equipment that is designed largely by the internal pressure. Examples are lines, fittings, gauges, valves, bellows, and hoses.

Pressurized Hardware: Those hardware items which contain primarily internal pressure. Included are pressure vessels, pressurized structures, special pressurized equipment and pressure components.

Pressurized Structures: Structures designed to carry both internal pressure and vehicle structural loads. The main propellant tank of a launch vehicle is a typical example.

Pressurized System: A system which consists of pressure vessels, or pressurized structures, or both, and other pressure components such as lines, fittings, valves, and bellows that are exposed to and structurally designed largely by the acting pressure. Not included are electrical or other control devices required for system operation. A pressurized system is often called a pressure system.

Proof Factor: A multiplying factor applied to the limit load or MEOP to obtain proof load or proof pressure for use in the acceptance testing.

Proof Pressure: The proof pressure is used to give evidence of satisfactory workmanship and material quality and/or establish maximum initial flaw sizes for safe–life demonstration. It is equal to the product of MEOP and a proof factor.

Qualification Tests: The required formal contractual tests used to demonstrate that the design, manufacturing, and assembly have resulted in hardware designs conforming to specification requirements.

Residual Strength: The maximum value of load (stress) that a cracked or damaged hardware is capable of sustaining.

Residual Stress: The stress which remains in a structure after processing, fabrication, assembly, testing, or operation. A typical example is the

welding induced residual stress.

Safe-Life: The required cycles and period during which a structure, containing the largest undetected crack, is shown by analysis or testing not to fail in the expected service load and environment.

Service Life: The period of time (or cycles) starts with the manufacturing of the pressure vessel or the pressurized structure, and continues through all acceptance testing, handling, storage, transportation, launch operations, orbital operations, refurbishment, retesting, reentry or recovery from orbit, and reuse that may be required or specified for the item.

Special Pressurized Equipment: A piece of equipment that meets the pressure vessel definition, but which is not feasible or cost effective to comply with the requirements applicable to pressure vessels. Included are : batteries, heat pipes, cryostats and sealed containers.

Stress-Corrosion Cracking: A mechanical-environmental induced failure process in which sustained tensile stress and chemical attack combine to initiate and propagate a crack or a crack–like flaw in a metal part.

Stress Intensity Factor (*K*): A parameter that characterizes the stress-strain behavior at the tip of a crack contained in a linear elastic, homogeneous, and isotropic body.

Ultimate Load: The product of the limit load and the ultimate design safety factor. It is the load which the structure must withstand without rupture or collapse in the expected operating environments.

4. General Requirements

This section presents general requirements for all the metallic pressurized hardware. Included are requirements for system analysis, structural design, material selection, safe-life, fabrication and process control, quality assurance, and operation and maintenance.

4.1 System Analysis Requirements

A thorough analysis of the pressurized system in which the pressurized hardware will be operating shall be performed to establish the correct MEOP. The effect of each of the other component operating parameters on the MEOP shall be determined; failure tolerance requirements shall be considered; pressure regulator lock-up characteristics, valve actuation and water hammer, and any external loads shall be evaluated for the entire service life of the hardware.
Pressure vessels designed, fabricated, inspected and tested in accordance with the *American Society for Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section VIII, Divisions 1 and 2*, shall comply with system analysis requirements.

4.2 General Design Requirements

4.2.1 Loads, Pressures, and Environments

The anticipated load-pressure-temperature history and associated environments throughout the service life shall be determined in accordance with specified mission requirements. As a minimum, the following factors and their statistical variations shall be considered as appropriate:

a. The environmentally induced loads and pressures;

b. The environments acting simultaneously with these loads and pressures with their proper relationships; and

c. The frequency of application of these loads, pressures, environments, and their levels and duration.

These data shall be used to define the design load/environment spectra which shall be used for both design analysis and testing. The design spectra shall be revised as the structural design develops and the loads analysis matures.

Throughout this document, limit load and maximum expected operating pressure, MEOP, are used as the baseline external load and internal pressure.

Note:
The term maximum design pressure (MDP) can be used for design and testing of pressure vessels and related pressure components. The basic difference between MDP and MEOP is the degree of consideration of potential credible failure within a pressure system and the resultant effects on pressure of the pressure vessel(s) during system operation. MDP is associated with man-rated systems such as NASA Space Shuttle and Space Station and is based on the worst case combination of two credible system failures. The criteria to be used for the determination of pressure for a given design and application must be clearly established by the contracting parties.

4.2.2 Strength Requirements

All shall possess sufficient strength to withstand limit loads and simultaneously occurring internal pressures in the expected operating environments throughout their respective service lives without experiencing detrimental deformation. They shall also withstand ultimate loads and simultaneously occurring internal pressures in the expected operating environments without experiencing rupture or collapse.

Pressure vessels and pressurized structures shall be capable of withstanding ultimate external loads and ultimate external pressure (destabilizing) without collapse or rupture when internally pressurized to the minimum anticipated operating pressure.

All pressurized hardware shall sustain proof pressure without incurring gross yielding or detrimental deformation. Vessels tested to verify design shall sustain design burst pressure without burst in design verification test. When proof tests are conducted at temperatures other than design temperatures, the change in material properties at the proof temperature shall be accounted for in determining proof pressure.

Pressurized structures subject to instability modes of failure shall not collapse under ultimate loads nor degrade the functioning of any system due to elastic or plastic buckling, or time dependent deformation under limit loads. 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. Design loads for buckling shall be ultimate loads, except that any load component that tends to alleviate buckling shall not be increased by the ultimate design safety factor. Destabilizing pressures shall be increased by the ultimate design factor, but internal stabilizing pressures shall not be increased unless they reduce structural capability.

The margin of safety shall be positive and shall be determined by analysis or test at design ultimate and design limit levels, when appropriate, at the temperatures expected for all critical conditions.

4.2.3 Stiffness Requirements

Pressurized hardware shall possess adequate stiffness to preclude detrimental deformation at limit loads and pressures in the expected operating environments throughout their respective service lives. The stiffness properties of pressure vessels and pressurized structures shall be such as to prevent all detrimental instabilities of coupled vibration modes, minimize detrimental effects of the loads and dynamics response which are associated with structural flexibility, and avoid adverse contact with other vehicle systems.

4.2.4 Thermal Requirements

Thermal effects, including heating rates, temperatures, thermal gradient, thermal stresses and deformations, and changes in the physical and mechanical properties of the material of construction, shall be considered in the design of all pressurized hardware. . These effects shall be based on temperature extremes, which simulate those predicted for the operating environment plus a design margin as appropriate.

4.2.5 Stress Analysis Requirements

A detailed and comprehensive stress analysis of each pressurized hardware design shall be conducted under the assumption of no crack-like flaws in the hardware. The analysis shall determine stresses resulting from the combined effects of internal pressure, ground or flight loads, and thermal gradients. Both membrane stresses and bending stresses resulting from internal pressure and external loads shall be calculated to account for the effects of geometrical discontinuities, design configuration, and

structural support attachments. The analysis shall also include the effects of adding stresses from restraints, manufacturing mismatch, test conditions, residual stresses, and assembly stresses.

Loads shall be combined by using the appropriate design limit or ultimate safety factors on the individual loads and comparing the results to allowable loads. Design safety factors on external (support) loads shall be as assigned to primary structure supporting the pressurized system.

Classical solutions are acceptable if the design geometry and loading conditions are simple enough to warrant their application. Finite element or other proven equivalent structural analysis techniques shall be used to calculate the stresses, strains, and displacements for complex geometry and loading conditions. Local structural models shall be constructed, as necessary, to augment the overall structural model in areas of rapidly varying stresses.

Minimum material gauge as specified in the design drawings shall be used in calculating stresses. The allowable material strengths shall reflect the effects of temperature, thermal cycling and gradients, processing variables, and time associated with the design environments. Unless otherwise specified, “A” basis allowable shall be used in the calculations.

Minimum margins of safety associated with the parent materials, weldment and heat–affected zones shall be calculated and tabulated for all pressure vessels and pressurized structures, along with their locations and stress levels. The margins of safety shall be positive against the strength and stiffness requirements of sections 4.2.2 and 4.2.3, respectively.

4.2.6 Fatigue-Life Requirements

When a fatigue analysis is required to demonstrate the fatigue-life of an unflawed pressurized hardware, nominal values of fatigue characteristics, including stress-life (S-N) data and strain-life(ε-N) data of the structural materials, shall be used. These data shall be taken from reliable sources such as Mil-hdbk-5, and the Aerospace Structural Metals Handbooks The analysis shall account for the spectra of expected operating loads, pressures, and environments. The conventional fatigue damage accumulation technique, Miner’s Rule ($\sum n/N$), is an acceptable method for handling variable amplitude fatigue cyclic loading. Unless otherwise specified, a life-factor of four (4) shall be used in the fatigue analysis. The limit for accumulated fatigue damage shall be 80% of the normal limit.

Testing of unflawed specimens to demonstrate fatigue-life of a specific hardware together with stress analysis is an acceptable alternative to analytical prediction. Fatigue-life requirements are considered demonstrated when the unflawed specimens which represent critical areas such as membrane section, weld joints, heat-affected zone, and boss transition section, successfully sustain the limit loads and MEOP in the expected operating environments for the specified test cycles and duration without rupture. The required test duration is four (4) times the specified service life.

4.2.7 Safe-Life Requirements

When fracture mechanics crack growth analysis is required to demonstrate safe-life of a pressurized hardware, , undetected flaws shall be assumed to be in the critical locations and in the most unfavorable orientation with respect to the applied stress and material properties. The size of the flaws shall be based on either the appropriate non-destructive inspection (NDI) technique(s) or defined by the acceptance proof testing. The flaw shape (**a/2c**) in the range of 0.1 to 0.5 shall be considered.

Nominal values of fracture toughness and fatigue crack-growth rate data associated with each alloy, temper, product form, thermal, and chemical environments shall be used in the safe-life analysis. However, if proof test logic is used for the determining of the initial flaw size, an upper bound fracture toughness value shall be used in determining both the initial flaw size and the critical flaw size at fracture.

Pressurized hardware which experiences sustained stresses shall also show that the corresponding maximum stress intensity factor (K_{max}) during sustained load in operation is less

than the stress-corrosion cracking threshold (K_{Iscc}) data in the appropriate environment, i.e., $K_{max} < K_{Iscc}$. Detrimental tensile residual stresses shall be included in the analysis.

A state-of-the-art crack growth software package shall be used to conduct the safe-life analysis. Flaw shape (**a/2c or a/c**) changes shall be accounted for in the analysis. Retardation effects on crack growth rates from variable amplitude loading shall not be considered. Unless otherwise specified, a life factor of four (4) shall be used in the safe-life analysis. For those pressurized hardware items which are readily accessible for periodic inspection and repair, the safe-life shall be at least four (4) times the interval between scheduled inspection and/or refurbishment.

A safe-life analysis report shall be prepared to delineate the following:

a. Fracture mechanics data (fracture toughness and fatigue crack growth rates);

b. Loading spectrum and environments;

c. NDE method(s) and corresponding initial flaw sizes;

d. Analysis assumptions and rationale;

e. Calculation methodology;

f. Summary of significant results; and

g. References.

This report shall be closely coordinated with the stress analysis report and shall be periodically revised during the life of the program.

Safe life testing in lieu of safe life analysis is acceptable alternative to demonstrate safe-life, provided that, in addition to following a quality assurance program (Section 4.6) for each flight article, a crack growth test program is implemented on pre-flawed specimens representative of the structure design. These flaws shall not be less than the flaw sizes established by the acceptance proof test or the selected NDI method(s). The flaw shape (**a/2c**) for surface flaws shall range from 0.1 to 0.5; the flaw shape (**a/c**) for corner cracks shall range from 0.2 to1.0. Safe-life requirements of Section 4.4 are considered demonstrated when the pre-flawed test specimens successfully sustain the limit loads and pressure cycles in the expected operating environments without leaking. A life factor of four (4) on specified service life shall be applied in the safe-life demonstration testing. As a minimum, two duplicated tests shall be conducted.

The safe-life test report shall be prepared. It shall include the following:

a. Test specimen description;

b. Test set-up description;

c. Test loading spectrum and environment;

d. Test procedures;

e. Test results; and

f. References.

4.2.8 Miscellaneous Requirements

The structural design of all pressure vessels and pressurized structures shall employ proven processes and procedures for manufacture and repair. The design shall emphasize the need for access, inspection, service, repair, and refurbishment. For all reusable pressure vessels and pressurized structures, the design shall permit this hardware to be maintained in and refurbished to a flightworthy condition. Repaired and refurbished hardware shall meet all stipulated conditions of flightworthiness.

4.3 Materials Requirements

4.3.1 Material Selection

Metallic materials shall be selected on the basis of proven environmental compatibility, material strength, fracture properties, fatigue life, and crack growth characteristics consistent with overall program requirements. Unless otherwise specified, **"**A**"** basis allowable materials shall be used for pressure vessels and pressurized structures where failure of a single load path would result in loss of structural integrity. For redundant pressurized structures where failure of a structural element would result in a safe

redistribution of applied loads to other load-carrying members, "B" basis allowable materials may be used. The fracture toughness shall be as high as practicable within the context of structural efficiency and fracture resistance.

For pressurized hardware to be analyzed with linear elastic fracture mechanics, fracture properties shall be accounted for in material selection. These properties include plane strain fracture toughness (K_{Ic}); stress corrosion cracking toughness (K_{Iscc}); sub-critical crack-growth characteristics under sustained loading and fatigue-cyclic loading; the effects of fabrication and joining processes; the effects of cleaning agents, fluorescent penetrants, coatings and proof test fluids; and the effects of temperature, load spectra, and other environmental conditions.

Materials, which have a low K_{Iscc} in the expected operating environments, shall not be used in pressure vessels and pressurized structures unless adequate protection from the operating environments can be demonstrated by tests. If the material has a K_{Iscc} less than 60% of the plane-strain fracture toughness, K_{Ic}, under the conditions of its application, it shall be mandatory to show, by a "worst case" fracture mechanics analysis, that the low K_{Iscc} factor will not precipitate premature structural failure.

4.3.2 Material Evaluation

The metallic materials selected for design shall be evaluated with respect to material processing, fabrication methods, manufacturing operations, refurbishment procedures and processes, and other factors which affect the resulting strength and fracture properties of the material in the fabricated as well as the refurbished configurations.

The evaluation shall ascertain that the mechanical properties, strengths, and fracture properties used in design and analyses will be realized in the actual hardware and that these properties are compatible with the fluid contents and the expected operating environments. Materials which are susceptible to stress-corrosion cracking or hydrogen embrittlement shall be evaluated by performing sustained load fracture tests when applicable data are not available.

4.3.3 Material Characterization

The allowable mechanical properties, fatigue and fracture properties of all metallic materials selected for pressure vessels and pressurized structures shall be characterized in sufficient detail to permit reliable and high confidence predictions of their structural performance in the expected operating environments unless these properties are available from reliable sources such as *Mil-Hdbk-5*, *Damage Tolerant Design Handbook, Aerospace Structural Metals Handbook*, and other sources approved by the procuring agency. Where material properties are not available, they shall be determined by test methods approved by the procuring agency. The characterization shall produce the following strength and fracture properties for the parent metals, weld-joints, and heat-affected zones as a function of the fluid contents, loading spectra, and the expected operating environments, including proof test environments as appropriate:

a. Tensile yield strength, σ_{ys}, and ultimate tensile strength, σ_u;

b. Plane strain fracture toughness, K_{Ic}, effective fracture toughness, K_{Ie}, and stress-corrosion cracking threshold toughness, K_{Iscc}, and

c. Fatigue crack growth rates, **da/dN.**

d. Fatigue data S-N (ε–N)

Uniform test procedures shall be employed for determining material fracture properties as required. These procedures shall conform to recognized standards, such as standard test methods developed by the American Society for Testing and Materials (ASTM). The test specimens and procedures utilized shall provide valid test data for the intended application.

Sufficient tests shall be conducted so that meaningful nominal values of fracture toughness, fatigue data, and crack growth rate data corresponding to each alloy system, temper, product form, thermal and chemical environments and loading spectra can be established to evaluate compliance with safe-life requirements. Test plans and results shall be accepted by the appropriate authority.

4.4 LBB Demonstration Requirements

When the LBB failure mode demonstration is required, fracture mechanics principles shall be employed. It shall be shown by analysis or test that at MEOP, both the following conditions are satisfied: (1) an initial surface flaw with a flaw shape (**a/2c**) ranging from 0.1 to 0.5 will not fail, i.e., $K < K_{Ie}$; and (2) this surface flaw will grow through the wall of the pressurized hardware to become a through crack with a length equal to ten (10) times of the wall thickness and will remain stable.

If the LBB failure mode needs to be demonstrated by test, the testing may be conducted on coupons which duplicate the materials (parent materials, weld-joints, and heat-affected zone) and thickness of the pressure vessels or on a pressure vessel representative of the flight hardware. Test specimens shall contain a pre-fabricated part-through crack.. Fatigue load cycles shall be applied to the test specimen with the maximum stress corresponding to the MEOP level and minimum stress kept to zero, until the part-through crack propagates through the specimen's thickness to become a through crack. LBB 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. The LBB testing shall be conducted to establish that all critical areas will exhibit a LBB mode of failure.

4.5 Fabrication and Process Control

Proven processes and procedures for fabrication and repair shall be used to preclude damage or material degradation during material processing, manufacturing operations, and refurbishment. In particular, special attention shall be given to ascertain that the melt process, thermal treatment, welding process, forming, joining, machining, drilling, grinding, and repair operations are within the state-of-the-art and have been used on similar hardware.

The fracture toughness, mechanical and physical properties of the parent materials, weld-joints and heat-affected zones shall be within established design limits after exposure to the intended fabrication processes. The machining, forming, joining, welding, dimensional stability during thermal treatments, and through-thickness hardening characteristics of the material shall be compatible with the fabrication processes to be encountered.

Fracture control requirements and precautions shall be defined in applicable drawings and process specifications. Detailed fabrication instructions and controls shall be provided to ensure proper implementation of the fracture control requirements. Special precautions shall be exercised throughout the manufacturing operations to guard against processing damage or other structural degradation.

4.6 Quality Assurance

A quality assurance program, based on a comprehensive study of the product and engineering requirements shall be established to assure that the necessary NDI 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.

4.6.1 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 flaw geometry shall encompass defects commonly encountered. Acceptance and rejection standards shall be established for each phase of inspection, and for each type of inspection technique.

4.6.2 Inspection Techniques

The selected NDI techniques for pressurized hardware which need to demonstrate their safe-life by fracture mechanics analysis or testing shall have the capability to determine the size, geometry, location and orientation of a flaw or

defect; to obtain, where multiple flaws exist, the location of each with respect to the other and the distance between them; and to differentiate among defect shapes, from tight cracks to spherical voids. Two or more NDI methods shall be used for a part or assembly that cannot be adequately examined by only one method.

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

4.6.3 Inspection Data

Inspection data in the form of flaw histories shall be maintained throughout the life of the pressure vessel and 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.

4.6.4 Acceptance Proof Test

Every pressurized hardware shall be proof-pressure tested in accordance with the requirements of Sections 5.1, 5.2, 5.3, and 5.4, as appropriate, 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 hardware shall not leak, rupture, or experience detrimental deformation during acceptance testing.

4.7 Operations and Maintenance

4.7.1 Operating Procedures.

Operating procedures shall be established for each hardware. These procedures shall be compatible with the safety requirements and personnel control requirements at the facility where the operations are conducted. Step-by-step directions shall be written with sufficient detail to allow a qualified technician or mechanic to accomplish the operations. Schematics which identify the location and pressure limits of relief valves and burst discs shall be provided when applicable, and procedures to insure compatibility of the pressurizing system with the structural capability of the pressurized hardware shall be established.

Prior to initiating or performing a procedure involving hazardous operations with pressure systems, practice runs shall be conducted on non-pressurized systems until the operating procedures are well rehearsed. Initial tests shall then be conducted at pressure levels not to exceed 50% of the MEOP, or normal operating pressures, until operating characteristics can be established and stabilized. Only qualified and trained personnel shall be assigned to work on or with high pressure systems. Warning signs with the hazard(s) identified shall be posted at the operations facility prior to pressurization.

4.7.2 Safe Operating Limits.

Safe operating limits shall be established for each pressurized hardware, based on the appropriate analysis and testing employed in its design and qualification per Section 5. These safe operating limits shall be summarized in a format which will provide rapid visibility of the important structural characteristics and capability. The desired information shall include, but not be limited to, such data as fabrication materials, critical design conditions, MEOP, nominal operating or working pressure, proof pressure, design burst pressure, pressurization and depressurization, operational system fluid, cleaning agent, NDI techniques employed, permissible thermal and chemical environments, minimum margin of safety and potential failure mode. For pressure vessels or pressurized structures with a potential brittle fracture failure mode, the critical flaw sizes and maximum permissible flaw sizes shall also be

included. Appropriate references to design drawings, detail analyses, inspection records, test reports, and other backup documentation shall be indicated.

4.7.3 Inspection and Maintenance

The results of the appropriate stress, and safe-life analyses shall be used in conjunction with the appropriate results from the structural development and qualification tests to develop a quantitative approach to inspection and repair. Allowable damage limits shall be established for each pressurized hardware item so that the required inspection interval and repair schedule can be established to maintain hardware to the requirements of this document. NDI technique(s) and inspection procedures to reliably detect defects and determine flaw size under the condition of use shall be developed for use in the field and depot levels. Procedures shall be established for recording, tracking, and analyzing operational data as it is accumulated to identify critical areas requiring corrective actions. Analyses shall include prediction of remaining life and reassessment of required inspection intervals.

4.7.4 Repair and Refurbishment

When inspections reveal structural damage or defects exceeding the permissible levels, the damaged hardware shall be repaired, refurbished, or replaced, as appropriate. All repaired or refurbished hardware shall be re-certified after each repair and refurbishment by the applicable acceptance test procedure for new hardware to verify their structural integrity and to establish their suitability for continued service.

4.7.5 Storage Requirements

When pressurized hardware are put into storage, they shall be protected against exposure to adverse environments which could cause corrosion or other forms of material degradation. In addition, they shall be protected against mechanical damages resulting from scratches, dents, or accidental dropping of the hardware. Induced stresses due to storage fixture constraints shall be minimized by suitable storage fixture design. In the event storage requirements are violated, re-certification shall be required prior to acceptance for use.

4.7.6 Documentation

Inspection, maintenance, and operation records shall be kept and maintained throughout the life of each pressure vessel and each pressurized structure. As a minimum, the records shall contain the following information:

a. Temperature, pressurization history, and pressurizing fluid for both tests and operations;

b. Numbers of pressurization experienced as well as number allowed in safe-life analysis;

c. Results of any inspection conducted, including: inspector, inspection dates, inspection techniques employed, location and character of defects, defect origin and cause. This shall include inspection made during fabrication;

d. Storage condition;

e. Maintenance and corrective actions performed from manufacturing to operational use, including refurbishment;

f. Sketches and photographs to show areas of structural damage and extent of repairs;

g. Acceptance and re-certification test performed, including test conditions and results; and

h. Analyses supporting the repair or modification which may influence future use capability.

4.7.7 Reactivation

Pressurized hardware items which are reactivated for use after an extensive period in either an unknown, unprotected, or unregulated storage environment shall be re-certified to ascertain their structural integrity and suitability for continued service before commitment to flight. Re-certification tests for pressurized hardware shall be in accordance with the appropriate Re-certification Test Requirement.

5. Specific Requirements

This section presents specific requirements for metallic pressure vessels, pressurized structures, special pressurized equipment, including batteries, cryostats, heat pipes and sealed containers, as well as pressure components, such as

lines, fittings and fluid return hoses. Included are factor of safety requirements, failure mode demonstration requirements, cyclic and burst test requirements, vibration test requirements, safe-life demonstration requirements, and other special requirements.

5.1 Pressure Vessels

One of the two alternative approaches for the design, analysis and verification of metallic pressure vessels shall be selected as illustrated in Figure 1. Selection of the approach to be used is dependent on the desired efficiency of design coupled with the level of analysis and verification testing required.

Approach A, Figure 1, illustrates the steps required for verification of a metallic pressure vessel designed with a burst factor (BF) equal to 1.5 or greater. Based on the results of the failure mode determination, one of two distinct verification paths must be satisfied: 1) leak-before-burst (LBB) with leakage of the contents not creating a condition which could lead to a mishap (such as toxic gas venting or pressurization of a compartment not capable of the pressure increase; and 2) brittle failure mode or hazardous LBB failure mode in which, if the pressure vessel leaks, the leak causes a hazard. The verification requirements for path 1 are delineated in Section 5.1.1 and the verification requirements for path 2 in Section 5.1.2.

Approach B, Figure 1, illustrates the steps required for verification of a metallic pressure vessel designed employing the *ASME Boiler and Pressure Vessel Code*.

5.1.1 Pressure Vessels with Non-Hazardous LBB Failure Mode

The LBB failure mode shall be demonstrated per requirements specified in Section 4.4.

5.1.1.1 Factor of Safety Requirements

Pressure vessels which satisfy the non-hazardous LBB failure mode criterion may be designed conventionally, wherein the design safety factors and proof factors are selected on the basis of successful past experience. Unless otherwise specified, the design burst factor shall be 1.5, as a minimum.

5.1.1.2 Fatigue-Life Requirements

Fatigue-life of the pressure vessel exhibiting LBB failure mode shall be demonstrated per requirements specified in Section 4.2.6.

5.1.1.3 Alternative Requirements

The fatigue-life requirements (Section 4.2.6) may be replaced by safe-life requirements (Section 4.2.7) for mission reliability considerations, since a leaking pressure vessel, even with a non-hazardous fluid, might jeopardize the planned mission duration. If this option is chosen, then qualification and acceptance testing shall performed in accordance with Section 5.1.2.3 and Section 5.1.2.4 respectively (Path 2 in Figure 1)

5.1.1.4 Qualification Test Requirements

Qualification tests 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 types of instrumentation and their locations in qualification tests shall be based on the results of the stress analysis of Section 4.2.5. The instrumentation shall provide sufficient data to ensure proper applications, levels, and duration of loads, pressure, and environments and shall demonstrate that design requirements have been met.

Qualification testing shall include vibration testing and pressure testing.

a. Vibration Testing: A maximum expected flight-level vibration environment shall be established from the predominant vibration source encountered during the mission. Qualification testing shall be performed using an environment that produces twice the power for three times the duration for each orthogonal axis.

b. Pressure Testing: Required qualification pressure testing levels are shown in Table 1. Requirement for application of external loads in combination with internal pressures during testing must be evaluated based on the relative magnitude and destabilizing effect of stresses due to the external load. If limit combined tensile stresses are enveloped by test pressure stresses, the application of external loads shall not be required. If the application of external loads is

required, the load shall be cycled to limit 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 a constant maximum expected operating pressure). Qualification test procedure shall be approved by the procuring agency and the appropriate launch or test range approval authority.

Leak checks shall be performed after proof-pressure testing. During the leak check, the pressure level shall be maintained at MEOP for thirty (30) minutes minimum.

Acceptance tests shall be conducted on every pressure vessel 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 flight-worthiness of the test article. The following are required as a minimum:

a. Non-Destructive Inspection: An inspection, consistent with Section 4.6.2, shall be performed on every pressure vessel prior to proof-pressure test to establish the initial condition of the pressure vessel. If the safe-life requirements are required , proven NDI methods that are capable of detecting flaws with their POD consistent with the initial flaw size assumed in the safe-life analysis shall be used. Post-proof inspection shall be conducted at weld joints as a minimum;
b. Proof Pressure Test: Every pressure vessel shall be proof-pressure tested at the proper temperature to verify that materials, manufacturing processes, and workmanship meet design specifications and that the hardware is suitable for flight. The proof pressure shall be equal to:

Proof = (1 + BF)/2 x (MEOP) for burst factor less than 2.0 or

1.5 x (MEOP) for BF equals to or greater than 2.0.

Unless otherwise approved by the appropriate approval authority, during the proof pressure test the proof pressure level shall be maintained for five (5) minutes minimum.

5.1.1.6 Re-certification Test Requirements

All refurbished pressure vessels shall be re-certified after each refurbishment by the acceptance test requirements for new hardware to verify their structural integrity and to establish their suitability for continued service before commitment to flight. Pressure vessels which have exceeded the approved storage environment (temperature, humidity, time, etc.) shall also be re-certified by the acceptance test requirements for new hardware.

5.1.1.7 Special Provision

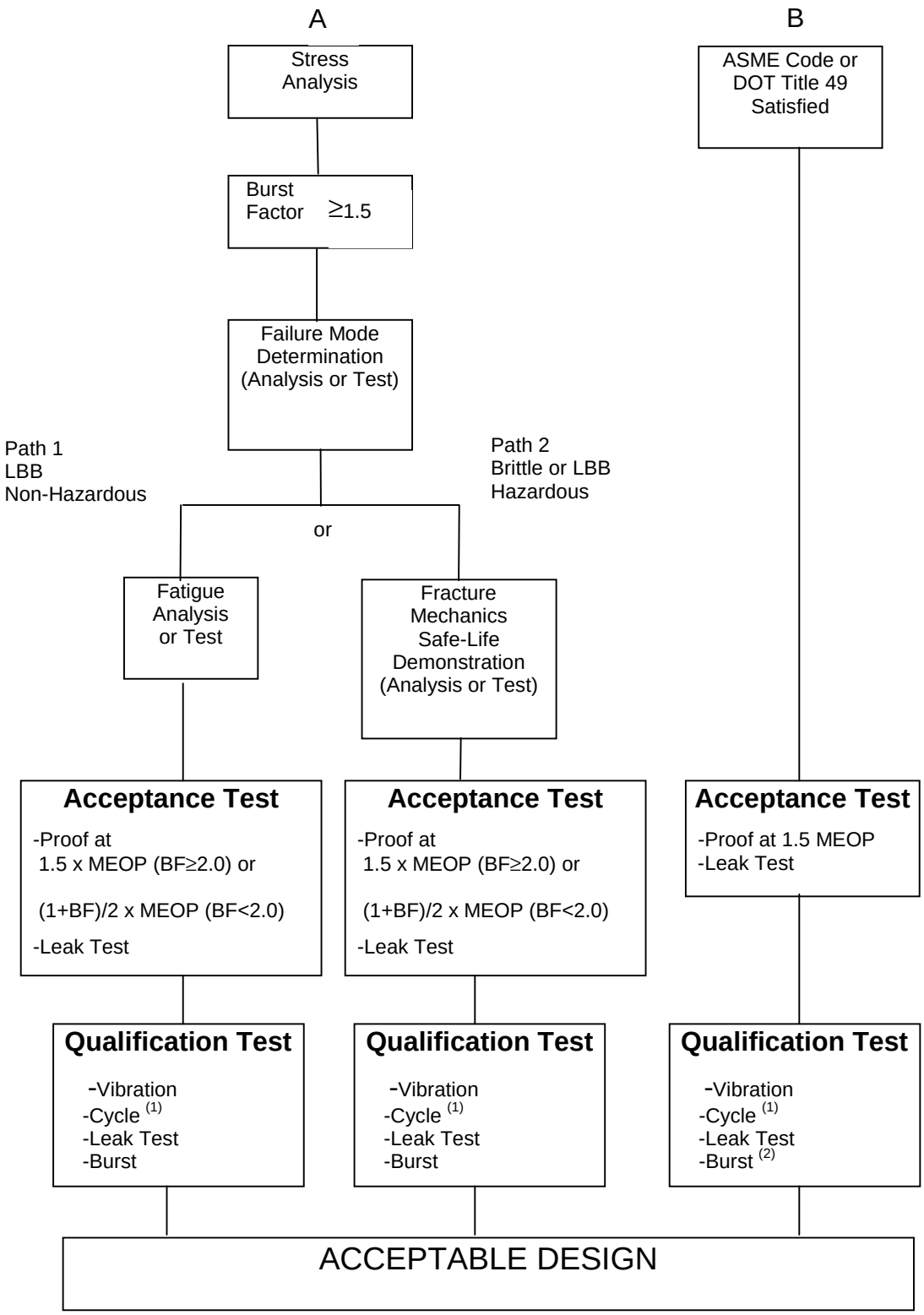
In cases involving a design that will be used in a low cycle, single application, a proof test of each flight unit to a minimum of 1.5 times MEOP and a conventional fatigue analysis showing a minimum of 10 design lifetimes may be used in lieu of the required pressure testing as defined in Section 5.1.1.4b. This option presupposes demonstration of good design and high quality is inherent in the hardware. The implementation of this option needs prior approval by the launch site operator.

Table 1. Qualification Pressure Test Requirements

Test Item	No Yield after	No Burst at[1]
Vessel #1 [2]		Burst Factor X MEOP
Vessel #2	Cycle at 1.5 x MEOP for 2xpredicted number of service life cycles in sequence (50 cycles minimum) or	Burst Factor X MEOP
	Cycle at 1.0 x MEOP for 4xpredicted number of service life cycles in sequence (50 cycles minimum)	Burst Factor X MEOP

(1) After demonstrating no burst at the defined test level, increase pressure to actual burst of vessel. Record actual burst pressure

(2) Test may be deleted with the agreement of the appropriate approval authority



NOTES: (1) See Table 1
(2) Burst or disposition vessel

Figure 1. Pressure Vessel Design Verification Approach

5.1.2 Pressure Vessels with Brittle Fracture or Hazardous LBB Failure Mode

5.1.2.1 Factor of Safety Requirements

Unless otherwise specified, the design burst factor shall be 1.5, as a minimum.

5.1.2.2 Safe-Life Requirements

Safe life shall be demonstrated per requirements specified in Section 4.2.7.

5.1.2.3 Qualification Test Requirements

Qualification tests 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 include erroneous test conditions. The types of instrumentation and their locations in qualification tests shall be based on the results of the stress analysis of Section 4.2.5. The instrumentation shall provide sufficient data to ensure proper application of the accept/reject criteria, which shall be established prior to test. The sequences, combinations, levels, and duration of loads, pressure and environments shall demonstrate that design requirements have been met.

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

a. Vibration Testing: Vibration qualification testing shall be performed in accordance with Section 5.1.1.4a.

b. Pressure Testing: Required qualification pressure testing levels are shown in Table 1. Requirement for application of external loads in combination with internal pressures during testing shall be evaluated based on the relative magnitude and/or destabilizing effect of stresses due to the external load. If limit combined tensile stresses are enveloped by test pressure stresses, the application of external loads shall not be required. If the application of external loads is required, the load shall be cycled to limit 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 constant maximum expected operating pressure). Qualification test procedure shall be approved by the procuring agency and the appropriate launch or test range approval authority.

Leak check shall be performed as specified in Section 5.1.1.4b.

5.1.2.4 Acceptance Test Requirements

The acceptance test requirements for pressure vessels which exhibit brittle fracture, or hazardous LBB failure mode, are identical to those with ductile fracture failure mode as defined in Section 5.1.1.5

The proof-pressure test can be conducted at cryogenic temperature if it is deemed necessary. Otherwise, proven NDI methods that can detect flaws with their POD consistent with the initial flaws assumed in the safe-life analysis shall be employed. The pressure vessel shall not burst, leak, or exhibit detrimental deformation at the proof test pressure. After the proof test, NDI shall be performed on the weld-joints as a minimum.

5.1.2.5 Re-certification Test Requirements

Requirements of Section 5.1.1.6 shall be met.

5.1.2.6 Special Provision

Requirements per Section 5.1.1.7 except that the fracture mechanics safe-life analysis shall be performed. The flaw sizes and shapes shall be based on the proof test or selected NDI method(s).

5.1.3 Pressure Vessels Designed Employing the ASME Boiler Code or DoT Requirements

Metallic pressure vessels may be designed and manufactured per the rules of the *ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 or 2*.

5.1.3.1 Qualification Test Requirements

Qualification testing shall consist of the pressure testing and vibration testing defined in Section 5.1.1.4.

5.1.3.2 Acceptance Test Requirements

ASME Code pressure vessels shall be proof-pressure tested at 1.5 x MEOP.

5.1.3.3 Special Requirements

ASME Code pressure vessels shall be shown compatible with the fluid(s) to be contained and shall be verified to be LBB designs.

5.2 Pressurized Structures

Pressurized structures are typically large tanks that carry external flight loads as well as containing the internal fluids. The analysis and verification requirements specified here shall be met.

5.2.1 Pressurized Structures with Non-Hazardous LBB Failure Mode

The LBB failure mode shall be demonstrated per requirements specified in Section 4.4.

5.2.1.1 Factor of Safety Requirements

Unless otherwise specified, pressurized structures which satisfy the LBB failure mode shall be designed to an ultimate safety factor of 1.25 for unmanned systems and 1.40 for manned systems, as a minimum.

5.2.1.2 Fatigue-Life Demonstration

Requirements of Section 4.2.6 shall be met.

5.2.1.3 Qualification Test Requirements

Qualification testing shall be conducted on flight-quality hardware to demonstrate structural adequacy of the design. Because of the potential test facility size limitation, the qualification testing may be conducted at the component level, provided that the boundary conditions are correctly simulated. 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 MEOP stress, the application of external load is not required. Unless otherwise specified, the peak pressure shall be equal to the MEOP during each pressure cycle, and the number of cycles shall be four (4) times the predicted number of operating cycles or 50 MEOP 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 MEOP).

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, 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.

5.2.1.4 Acceptance Test Requirements

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 MEOP.

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

5.2.1.5 Re-certification Test Requirements

Requirements of Section 5.1.1.6 shall be met.

5.2.2 Pressurized Structures with Brittle Fracture or Hazardous LBB Failure Mode

5.2.2.1 Factor of Safety Requirements

Requirements of Section 5.2.1.1 shall be met.

5.2.2.2 Safe-Life Demonstration Requirements

Requirements of Section 4.2.7 shall be met.

5.2.2.3 Qualification Testing Requirements

Qualification testing shall include pressure cycle testing and burst testing. The requirements specified in Section 5.2.1.3 for pressure cycle testing and burst testing shall be met.

5.2.2.4 Acceptance Test Requirements

The acceptance test requirements for 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 5.2.1.4, except that proven NDI techniques shall be employed to detect flaws or cracks smaller than or equal to the allowable initial flaw sizes as determined by safe-life analysis. Furthermore, NDI shall also be performed on fracture critical welds after proof testing.

5.2.2.5 Re-certification Test Requirements

Requirements of Section 5.2.1.5 shall be met.

5.3 Special Pressurized Equipment

Batteries, cryostats (or dewars), heat pipes, and sealed containers are classified as special pressurized equipment. This section presents the detailed requirements for this equipment. If a special pressurized equipment can not meet the corresponding requirements specified in this section, it shall be treated as a pressure vessel and the applicable requirements specified in Section 5.1 shall be met.

5.3.1 Batteries

Batteries with pressurized metallic cells that exceed an internal pressure of 100 psi shall meet the requirements delineated below.

5.3.1.1 Batteries with LBB Failure Mode

The metallic battery cells shall be demonstrated to have an LBB failure mode as described in Section 4.4; and when sealed battery cases are used, they shall also be demonstrated to have an LBB failure mode.

5.3.1.1.1 Factor of Safety Requirements

Unless otherwise specified, the design burst factor for metallic battery cells and sealed battery cases shall be 1.5 as a minimum.

5.3.1.1.2 Fatigue-Life Demonstration Requirements

Requirements of Section 4.2.6 for metallic battery cells shall be met.

5.3.1.1.3 Qualification Test Requirements

Qualification tests shall be conducted on flight quality batteries to demonstrate structural adequacy of the design. The following delineate the required tests:

a. Vibration Testing: Vibration testing shall be performed on batteries per requirements of Section 5.1.1.4a.

b. Thermal Vacuum Testing: Thermal vacuum testing shall be performed on batteries.

c. Pressure Testing: A pressure cycle test shall be conducted on battery cell cases. The peak pressure shall be equal to the MEOP of the battery cells during each cycle, and the number of cycles shall be four (4) times the predicted number of operating cycles or 50 cycles, whichever is greater. After the completion of the pressure cycle test, the pressure shall be increased to actual burst of the battery cell case. The actual burst pressure shall be greater than or equal to 1.5 times MEOP of the battery cell. For batteries having sealed cases, similar tests shall be conducted on the sealed cases, if applicable.

5.3.1.1.4 Acceptance Test Requirements

Acceptance tests shall be conducted on batteries before being committed to flight. The following are required as a minimum:

a. Non-Destructive Inspection: Selected NDI technique(s) shall be performed prior to proof-pressure test to establish the initial condition of the hardware.

b. Proof Pressure Test: Battery cells, whenever feasible, shall be proof-pressure tested to 1.25 times the MEOP of the cells. For sealed battery cases, proof-pressure tests shall be performed at a level of 1.25 times the MEOP of the cases.

5.3.1.1.5 Re-certification Testing Requirements

Requirements of Section 5.1.1.6 shall be met.

5.3.1.1.6 Special Requirements

Batteries shall be designed so that battery cells are within containment devices (or cases). It shall be demonstrated that these containment devices (or cases) are capable of preventing the escape of any hazardous contents above an insignificant quantity deemed acceptable by the launch site operator or other safety agency.

5.3.1.2 Batteries with Brittle Fracture Failure Mode

Batteries with battery cells exhibiting brittle fracture failure mode shall meet the requirements defined in Section 5.1.1.2. A thermal vacuum test per Section 5.3.1.1 shall be conducted as part of the qualification testing.

5.3.2 Cryostats (or Dewars)

Cryostats (or dewars) with pressure containers shall meet the requirements delineated in sections described below.

5.3.2.1 Cryostats (or Dewars) with LBB Failure Mode

Pressure containers of the cryostat (or dewar) shall be demonstrated to exhibit LBB failure mode as described below.

5.3.2.1.1 Factor of Safety Requirements

Unless otherwise specified, the minimum burst factor for the pressure container of a cryostat shall be 1.5.

5.3.2.1.2. Qualification Test Requirements

Qualification tests shall be conducted on flight quality hardware to demonstrate structural adequacy of the design. The following items delineate the required tests:

a. Vibration Testing: Vibration testing shall be performed on cryostats per Section 5.1.1.4a.

b. Pressure Testing: The cryostat (dewar) pressure container shall be pressurized to a minimum pressure of 1.5 times MEOP. Pressure at the test conditions, if other than the use conditions, shall be adjusted for equivalency to the use conditions. The pressure shall be maintained for a period of time sufficient to assure that the proper pressure was achieved.

5.3.2.1.3 Acceptance Test Requirements

Acceptance tests shall be conducted on every cryostat (or dewar) before being committed to flight. The following are required as a minimum:

a. Non-Destructive Inspection: Selected NDI technique(s) shall be performed prior to proof-pressure test to establish the initial condition of the hardware.

b. Proof-Pressure Testing: Cryostats shall be proof-pressure tested to 1.25 times the MEOP of the pressure container.

5.3.2.1.4 Re-certification Test Requirements:

Requirements of Section 5.1.1.6 shall be met.

5.3.2.1.5 Special Requirements

Outer shells (i.e., vacuum jackets) shall have pressure relief capability to preclude rupture in the event of pressure container leakage. If pressure containers do not vent externally to the cryostats (or dewars) but instead vent into the volume contained by outer shells, the relief devices of outer shells must be capable of venting at a rate to release full flow without outer shells rupturing. Relief devices must be redundant and individually capable of full flow. Furthermore, pressure relief devices must be certified to operate at the

required condition of use.

5.3.2.2 Cryostats (or Dewars) with Brittle Fracture Failure Mode

Cryostats (or dewars) with pressure containers exhibiting brittle fracture failure mode shall meet requirements defined in Section 5.1.2.

5.3.3 Heat Pipes

Heat pipes shall meet the requirements defined as follows:

5.3.3.1 Factor of Safety Requirements

Unless otherwise specified, the design burst factor for heat pipes shall be 2.5 as a minimum.

5.3.3.2 Qualification Test Requirements

Pressure testing shall be conducted to demonstrate no failure at the design burst pressure. Effects of operating environments and internal fluids must be accounted for.

5.3.3.3 Acceptance Test Requirements

All pressure-containment welded joints of the heat pipes which contain hazardous fluids shall be inspected using a suitable NDI technique whenever feasible. A proof-pressure test shall be conducted to a minimum level of 1.5 times MEOP on all heat pipes. Effects of operating environments and internal fluids shall be accounted for.

5.3.3.4 Re-certification Test Requirements

Requirements of Section 5.1.1.6 shall be met.

5.3.3.5 Special Requirements

Materials used in heat pipes must be shown compatible with the fluid(s) contained under environmental conditions of use, including high temperatures.

5.3.4 Sealed Containers

Sealed containers shall meet the requirements listed below:

5.3.4.1 Sealed Containers with Non-Hazardous LBB Failure Mode

The LBB failure mode shall be demonstrated as defined in Section 4.4, except those containers made of aluminum, stainless steel, or titanium sheets which are acceptable as LBB designs at differential pressure up to two atmospheres.

5.3.4.1.1 Factor of Safety Requirements

Unless otherwise specified, the design burst factor shall be 1.5 as a minimum.

5.3.4.1.2 Fatigue-Life Requirements

Not required.

5.3.4.1.3 Qualification Test Requirements

Sealed containers containing non-electronic equipment shall only be subjected to pressure testing specified by the procuring agency. For sealed containers containing electronic equipment, other qualification tests if required, including functional, thermal vacuum, thermal cycling, random vibration, and pyro shock, shall be conducted.

5.3.4.1.4 Acceptance Test Requirements

Unless otherwise specified, sealed containers with a differential pressure of more than two atmospheres shall be proof-pressure tested to a minimum level of 1.1 times MEOP.

5.3.4.1.5 Re-certification Test Requirements

Requirements of Section 5.1.1.6 shall be met.

5.3.4.2 Sealed Containers with Brittle Fracture or Hazardous LBB Failure Mode

Sealed containers that exhibit a brittle fracture failure mode or contain hazardous fluid, or both, shall meet the requirements as defined in Section 5.1.2. For sealed containers containing electronic equipment, qualification tests including functional, thermal vacuum, thermal cycling, and pyro shock, shall be conducted in addition to random vibration and pressure testing.

5.4 Pressure Components

5.4.1 Factor of Safety Requirements

Pressure components shall be designed to the minimum factor given in Table 2.

5.4.2 Safe-Life Analysis Requirements

Not required.

5.4.3 Qualification Test Requirements

Not required on lines and fittings. Internal/ external pressure testing shall be conducted on all other pressure components, including flex lines, to demonstrate no failure at the design burst pressure.

5.4.4 Acceptance Test Requirements

Acceptance test requirements shall be satisfied by the completion of leak and/or proof tests for the assembled pressurized system.

5.4.5 Re-certification Test Requirements

Re-certification of lines, fittings, and other pressure components shall be as delineated in Section 5.1.1.6 as applied to the refurbished systems.

Table 2. Pressure Components Safety Factors

		Proof	Design Burst
Lines and fittings	diameter < 38 mm (1.5 in.)	1.5	4.0
	diameter ≥ 38 mm (1.5 in.)	1.5	2.5
Fluid Return Sections		1.5	3.0
Fluid Return Hose		1.5	5.0
Other pressure Components		1.5	2.5
Components subject to low or negative pressures shall be evaluated at 2.5 times maximum external pressure expected during service life.			

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