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Space systems — Pressure vessels and pressurized structures — Design and operation

Systèmes spatiaux — Réservoirs et structures sous pression — Conception et fonctionnement

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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Introduction

From the beginning of the space age, hazard control has been a prime consideration in manned or unmanned flights in outer space. The rapid development of space activities and their associated technologies required the implementation of ever-increasing amounts of energy sources. Space activities can be hazardous and could cause harm to people and damage to public and private property and the environment. It is therefore necessary to develop methods and tools that can analyse hazardous situations and provide realistic recommendations in terms of safety and safety risk control. Furthermore, building space systems such as telecommunication satellites and their launch systems is costly; it is necessary to achieve high mission reliability. The variety of professional disciplines linked to these activities requires international standards to protect Earth populations against the consequences of a possible mishap caused by the failure of a highly pressurized hardware item.

There is significant history to the analysis and design of pressure vessels and pressurized structures for use in space systems. This International Standard establishes the preferred methods for these techniques in both the traditional metallic tanks, and the newer composite overwrapped pressure vessels. The emphasis is equally on adequate design and safe, as well as reliable, operation.

Space systems — Pressure vessels and pressurized structures — Design and operation

1 Scope

This International Standard, based on general space experience and practice, specifies general and detailed requirements for metallic pressure vessels, composite overwrapped pressure vessels with metallic liners and metallic pressurized structures used in space systems. It is not applicable to pressure components (lines, fittings, valves, hoses, etc.) or to special pressurized hardware (batteries, heat pipes, cryostats and sealed containers).

2 Terms and definitions

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

2.1
A-basis allowable
mechanical strength value above which at least 99 % of the population of values is expected to fall, with a confidence level of 95 %

cf. **"B" basis allowable** (2.6)

2.2
acceptance tests
required formal tests conducted on flight hardware to ascertain that the materials, manufacturing processes and workmanship meet specifications and that the hardware is acceptable for intended usage

2.3
allowable load (stress)
maximum load (stress) that can be accommodated by a material/structure without potential rupture, collapse or detrimental deformation in a given environment

NOTE Allowable loads (stresses) commonly correspond to the statistically based minimum ultimate strength, buckling strength, and yield strength, respectively.

2.4
applied load [stress]
actual load [stress] imposed on the structure in the service environment

2.5
autofrettage
vessel-sizing operation where pressure-driven deflection is used to plastically yield the metal liner into the overlying composite in order to induce initial compressive stress states in the metal liner

2.6
B-basis allowable
mechanical strength value above which at least 90 % of the population of values is expected to fall, with a confidence level of 95 %

cf. **"A" basis allowable** (2.1)

2.7
brittle fracture
catastrophic failure mode in a material/structure that usually occurs without prior plastic deformation and at extremely high speed

NOTE 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.

2.8
burst factor
multiplying factor applied to the maximum expected operating pressure (MEOP), or maximum design pressure (MDP), to obtain the design burst pressure

NOTE 1 Burst factor is synonymous with *design factor of safety for burst*.

NOTE 2 **design burst pressure** (2.16) sometimes referred to as *burst pressure*, is synonymous with "ultimate pressure".

2.9
burst strength after impact
BAI
actual burst pressure of a composite overwrapped pressure vessel after it has been subjected to an impact event

2.10
component
functional unit that is viewed as an entity for purpose of analysis, manufacturing, maintenance, or record keeping

2.11
composite overwrapped pressure vessel
pressure vessel with a fibre-based composite system fully or partially encapsulating a liner

NOTE The liner serves as a fluid permeation barrier and may or may not carry substantial pressure loads. The composite overwraps generally carry pressure and environmental loads.

2.12
critical condition
most severe environmental condition in terms of loads, pressures and temperatures or combination thereof imposed on systems, subsystems, structures and components during service life

2.13
critical flaw
specific shape of flaw with sufficient size such that unstable growth will occur under the specific operating load and environment

2.14
critical stress intensity factor
stress intensity factor at which unstable fracture occurs

2.15
damage tolerance
ability of a material/structure to resist failure due to the presence of flaws, cracks, delaminations, impact damage or other mechanical damage for a specified period of unrepaired usage

2.16
design burst pressure
burst pressure
"ultimate pressure"
differential pressure that pressurized hardware must withstand without burst in the applicable operational environment

NOTE Design burst pressure is equal to the product of the MEOP or MDP and a design burst factor.

2.17
design safety factor
design factor of safety
factor or safety
multiplying factor to be applied to the limit load and/or MEOP(or MDP)

2.18
destabilizing pressure
differential pressure that produces compressive stresses in pressure hardware

2.19
detrimental deformation
structural deformation, deflection, or displacement that prevents any portion of the structure or other system from performing its intended function

2.20
development test
test to provide design information that may be used to check the validity of analytic technique 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, to check manufacturing technology, or to establish accept/reject criteria

2.21
ductile fracture
type of failure mode in a material/structure generally preceded by a large amount of plastic deformation

2.22
elastically responding metallic liner
metallic liner of a composite overwrapped pressure vessel that responds elastically (experiences no plastic response) at all pressure up to and including the vessel's acceptance proof pressure after the autofrettage operation

2.23
fatigue
process of progressive localized permanent structural change occurring in a material/structure 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

2.24
fatigue life
number of cycles of stress or strain of a specified character that a given material or structure can sustain before failure of a specified nature could occur

2.25
flaw
local discontinuity in a structural material such as a scratch, notch or crack

2.26
flaw shape
shape of a surface crack or corner crack

NOTE For a surface crack, the flaw shape is expressed as $a/2c$, where a is the crack depth and $2c$ is the crack length. For a corner crack, the flaw shape is expressed as a/c, where a is the crack depth and c is the crack length

2.27
fracture control
application of design philosophy, analysis method, manufacturing technology, verification methodology, quality assurance, and operating procedures to prevent premature structural failure caused by the propagation of cracks or crack-like flaws during fabrication, testing, transportation, handling and service

2.28
fracture mechanics
engineering discipline that describes the behaviour of cracks or crack-like flaws in materials or structures under stress

2.29
fracture toughness
generic term for measures of resistance to the extension of a crack

2.30
hazard
existing or potential condition that can result in an accident

2.31
hydrogen embrittlement
mechanical-environmental 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

2.32
impact damage
induced fault in the composite overwrap or the metallic liner of a composite overwrapped pressure vessel that is caused by an object strike on the vessel or vessel strike on an object

2.33
impact damage protector
physical device that can be used to prevent impact damage

2.34
initial flaw
flaw in a structural material before the application of load and/or deleterious environment

2.35
leak-before-burst
LBB
design concept which shows that at MEOP potentially critical flaws will grow through the wall of a metallic pressurized hardware item or the metal liner of a composite overwrapped pressure vessel and cause pressure relieving leakage rather than burst or rupture (catastrophic failure)

2.36
limit load
highest predicted load or combination of loads that a structure can experience during its service life in association with the applicable operating environments

NOTE The corresponding stress is called *limit stress*.

2.37
loading case
particular condition of pressure/temperature/loads that can occur for some parts of pressurized structures at the same time during their service life

2.38
loading spectrum
representation of the cumulating loading anticipated for the structure under all expected operating environments

NOTE Significant transportation and handling loads are included.

2.39
margin of safety
MS
margin expressed by the following equation:

$$\mathrm{MS} = \left(\frac{\text{Allowable load}}{\text{Limit load} \times \text{Factor of safety}} \right) - 1$$

NOTE Load can mean stress or strain.

2.40
maximum design pressure
MDP
highest pressure defined by maximum relief pressure, maximum regulator pressure, and/or maximum temperature, including transient pressures, at which a pressure vessel retains two-fault tolerance without failure

NOTE In this document, the term MDP is only applicable to pressure vessels.

2.41
maximum expected operating pressure
MEOP
highest differential pressure which a pressurized hardware item is expected to experience during its service life and retain its functionality, in association with its applicable operating environments

2.42
mechanical damage
induced flaw in the composite overwrap or metallic liner of a composite overwrapped pressure vessel, caused by surface abrasions or cuts or impact

2.43
metal-lined composite overwrapped pressure vessel
composite overwrapped pressure vessel having a metallic liner

NOTE Throughout this document, the term “composite overwrapped pressure vessel” means metal-lined composite overwrapped pressure vessel.

2.44
metallic hardware items
hardware items made of metallic materials

NOTE In this document, the term covers metallic pressure vessels, metallic pressurized structures and metallic liners of composite overwrapped pressure vessels.

2.45
plastically responding metallic liner
metallic liner of a composite overwrapped pressure vessel that could at least once experience plastic response when pressurized to any pressure up to and including acceptance proof pressure after the autofrettage operation

2.46
pressure vessel
container designed primarily for the storage of pressurized fluid that fulfils at least one of the following criteria:

a) contains gas or liquid with high energy level;

b) contains gas or liquid which will create a mishap (accident) if released;

c) contains gas or liquid with high pressure level

NOTE 1 This definition excludes pressurized structures, pressure components and pressurized hardware.

NOTE 2 Energy and pressure level are defined by each project, and approved by the procuring authority (customer); if appropriate values are not defined by the project, the following levels are used:

— stored energy is 19 310 J or greater based on adiabatic expansion of perfect gas;

— MEOP is 0,69 MPa or greater.

2.47
pressurized hardware
hardware items that contain primarily internal pressure

NOTE In this document, the term covers all pressure vessels and **pressurized structures** (2.48).

2.48
pressurized structure
structure designed to carry both internal pressure and vehicle structural loads

EXAMPLE Launch vehicle main propellant tanks, crew cabins or manned modules.

2.49
pressurized system
system which consists of pressure vessels, or pressurized structures, or both, and other pressure components such as lines, fittings, valves and bellows, which are exposed to, and structurally designed largely by, the acting pressure

NOTE Electrical or other control devices required for system operations are covered by this term.

2.50
proof factor
multiplying factor applied to the limit load or MEOP (or MDP) to obtain proof load or proof pressure for use in the acceptance testing

2.51
proof pressure
product of MEOP (or MDP) and a proof factor

NOTE The proof pressure is used to provide evidence of satisfactory workmanship and material quality and/or to establish maximum initial flaw sizes for the safe-life demonstration of a metallic hardware item.

2.52
qualification tests
required formal contractual tests used to demonstrate that the design, manufacturing, and assembly have resulted in hardware designs conforming to specification requirements

2.53
residual strength
maximum value of load and/or pressure (stress) that a cracked or damaged body is capable of sustaining

2.54
residual stress
stress that remains in a structure after processing, fabrication, assembly, testing, or operation

EXAMPLE Welding-induced residual stress.

2.55
safe life
required period during which a metallic hardware item, even containing the largest undetected crack, is shown by analysis or testing not to fail catastrophically in the expected service load and environment

2.56
sealed container
single, independent (not part of a pressurized system) container, component or housing that is sealed to maintain an internal non-hazardous environments, and has stored energy of less than 19 310 J and an internal pressure of less than 0,69 MPa

2.57
service life
period of time (or cycles) that starts with the manufacturing of the pressurized hardware and continues through all acceptance testing, handling, storage, transportation, launch operations, orbital operations, refurbishment, re-testing, re-entry or recovery from orbit and reuse that may be required or specified for the item

2.58
sizing pressure
pressure to which a composite overwrapped pressure vessel is taken with the intent of yielding the metallic liner

NOTE The sizing operation, also referred to as autofrettage, is considered to be part of the manufacturing process and is conducted prior to acceptance proof testing.

2.59
stress-corrosion cracking
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

2.60
stress intensity factor
parameter used in linear elastic fracture mechanics to characterize the stress–strain behaviour at the tip of a crack contained in a linear elastic and homogeneous body

2.61
stress-rupture life
minimum time during which composite hardware maintains structural integrity, considering the combined effects of stress level(s), time at stress level(s), and associated environments

2.62
ultimate load
product of the limit load and the design ultimate factor of safety

2.63
visual damage threshold
impact energy level shown by a test or tests that creates an indication that is barely detectable by a trained inspector using an unaided visual inspection technique

2.64
yield load
product of the limit load and the design yield factor of safety

3 General requirements

3.1 Introduction

This clause presents general requirements for the analysis, design and verification of pressurized hardware, covering:

a) system analysis,

b) structural design and analysis,

c) material selection,

d) fatigue and /or safe-life demonstration,

e) fracture and/or damage control,

f) quality assurance, and

g) operation and maintenance.

3.2 System analysis requirements

A detailed analysis of the pressurized system in which the pressurized hardware will be operated 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 and environments, shall be evaluated for the entire service life of the hardware.

3.3 General design requirements

3.3.1 Loads, pressures and environments

The entire 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;

c) the frequency of application of those loads, pressures and environments including their level, number of cycles, duration and sequence.

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

MDP and MEOP are two baseline pressure levels that can be used for design and testing of pressure vessels. In this document, MEOP is used as the baseline pressure level. If it is required that MDP be used as the baseline pressure level, MDP may be substituted for MEOP.

3.3.2 Strength

3.3.2.1 Pressure vessels

All pressure vessels 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 be able to withstand ultimate loads and simultaneously occurring internal pressures in the expected operating environments without experiencing rupture or collapse. They shall be also capable of withstanding ultimate external loads and ultimate external pressures (destabilizing) without collapse or rupture when internally pressurized to the minimum anticipated operating pressure.

All pressure vessels shall be able to sustain proof pressure in proof-testing without detrimental deformation and design burst pressure in qualification test without collapse or rupture.

When a proof or qualification test is conducted at a temperature other than design temperature, the change of material properties at the temperature shall be accounted for in determining the load/pressure. The margin of safety shall be positive and shall be determined by analysis or test at the design ultimate and design limit levels, as appropriate, at the temperatures expected for all critical conditions.

3.3.2.2 Pressurized structures

From the load/pressure time history, the critical loading cases for a pressurized structure shall be selected taking into account load/temperature/differential pressure combinations. For each critical loading case, the margin of safety shall be determined for every part of the pressurized structure, accounting for the worst combination of loads, differential pressures and temperature, with corresponding design safety factors.

All pressurized structures shall sustain the following:

a) proof pressure without gross yielding or detrimental deformation in proof-testing;

b) design burst pressure without rupture or collapse in qualification testing.

When a proof pressure test is conducted at a temperature other than the design temperature, 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 because of elastic buckling deformation under limit loads. Evaluation of buckling strength shall consider the combined action of all stresses and their effects on general instability, local or panel instability, and crippling. Design loads for buckling shall be ultimate loads, except that any loads component that tends to alleviate buckling shall not be increased by the ultimate design factor of safety. Destabilizing pressure shall be increased by the ultimate design factor, but internal stabilizing pressure shall not be increased unless it reduces structural capability. The minimum margin of safety must be positive and shall be demonstrated by analysis or tests.

3.3.3 Stiffness

All pressurized hardware shall possess adequate stiffness to preclude detrimental deformation at limit loads and pressure in the expected operating environments throughout their respective service lives. The stiffness properties of pressurized hardware shall prevent all detrimental effects of the loads and dynamic responses that are associated with structural flexibility, and avoid adverse interaction with other vehicle systems. Where applicable, the minimum internal pressure required for structural stabilization shall be identified and included in the acceptance data package.

3.3.4 Thermal

The design of all pressurized hardware shall consider the following thermal effects, as appropriate:

a) heating rates;

b) temperatures;

c) thermal gradients;

d) thermal stresses and deformations;

e) changes in the physical and mechanical properties of the materials of construction.

The effects shall be based on temperature extremes that simulate those predicted for the operating environments, plus a design margin as appropriate.

3.3.5 Stress analysis

3.3.5.1 Metallic hardware items

A detailed and comprehensive stress analysis of each new design of the metallic hardware items shall be conducted under the assumption that there are no crack-like flaws in the hardware. The analysis shall determine stresses resulting from the combined effects of pressure, ground or flight loads, and temperature and its gradients. Both membrane stresses and bending stresses resulting from internal pressures and external loads shall be calculated to account for the following effects, as appropriate:

a) geometrical discontinuities;

b) design configuration;

c) structural support attachments;

d) material and geometry nonlinear effects.

Loads and pressures shall be combined using the appropriate design safety factor on the individual loads and pressures, and the corresponding results shall be compared to material allowable. Design safety factors on external (support) loads shall be as assigned to the primary structure supporting the pressurized system. For all metallic hardware items, 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 stress, strains and displacements for complex geometries and loading conditions. Local structure models shall be constructed, as necessary, to augment the overall structural model in areas of rapidly varying stresses. The analysis methodology shall be verified using reliable test results.

Minimum material gage as specified in the design drawings shall be used in calculating stresses. However, if based on adequate test and theoretical ground, nominal material gages can be used for buckling analysis with the agreement of the procuring authority (customer). When appropriate, influence of tolerances (including overall dimensions and thickness) shall be considered for evaluating the most critical condition.

The allowable of material strength shall reflect the effects of temperature, thermal cycling and gradients, processing variables, and time associated with the design environments. Minimum margins of safety associated with the parent materials, weld joints and heat-affected zones shall be calculated and tabulated for all metallic hardware items along with their locations and stress levels. The margin of safety shall be positive against the strength and stiffness requirements of 3.3.2 and 3.3.3, respectively.

3.3.5.2 Composite overwrapped pressure vessel

A detailed and comprehensive stress analysis of the composite overwrap of a new composite overwrapped pressure vessel design shall be conducted with the assumption that there is no mechanical damage existing in the overwrap. Loads and pressures shall be combined by using the appropriate design factors of safety on the individual load and pressure and comparing the results to the material allowable.

Finite element method or other proven equivalent structural analysis techniques using appropriate composite theories shall be employed to analyse the composite overwrap. Effects of ply orientation, stacking sequence and geometrical discontinuities shall be assessed. The effect of variation in material thickness and its gradients as specified in the design documentation shall be used in calculating the stresses and strains in the composite overwrap. Local structural models shall be constructed, as necessary, to augment the overall structural model in areas of rapidly varying stresses. The analysis methodology shall be verified by test results. The margins of safety shall be positive for all load conditions applied on the composite overwrap by using A-basis allowable.

3.3.5.3 Stress analysis report

Records of the stress analysis shall be maintained and shall be included in the stress analysis report, which consists of the input parameters, data, assumptions, rationales, methods, references and a summary of significant analysis results. The analysis shall be revised and updated whenever changes to input parameters occur, in order to maintain currency for the life of the program.

3.3.6 LBB failure mode demonstration

3.3.6.1 General

LBB failure mode for all metallic pressure vessels, metallic pressurized structures and the elastically responding metallic liners of composite overwrapped pressure vessels shall be demonstrated by analysis or test. For plastically responding liners of composite overwrapped pressure vessels, LBB failure mode shall be demonstrated by test only.

The LBB demonstration may be omitted if there are adequate data from similar designs that have been demonstrated to exhibit LBB failure mode.

3.3.6.2 LBB analysis

When LBB failure mode is demonstrated by analysis, linear elastic fracture mechanics principles shall be employed. It shall be shown that, at MEOP, an initial surface crack with a flaw shape ($a/2c$), ranging from 0,1 to 0,5, will meet the following conditions:

a) it will not fail as a surface crack;

b) it will grow through the wall of the hardware to become a through crack with a length equal to 10 times the wall thickness of the metallic hardware item and will remain stable.

3.3.6.3 LBB test

When LBB failure mode is demonstrated by testing coupons or full-scale articles with pre-fabricated surface crack(s) shall be used as test specimens. Coupons shall duplicate the materials (parent metals, weld joints and heat-affected zones) and the thickness of the metallic hardware items. When the full-scale article is used, it shall be representative of the flight hardware. The flaw shape of the prefabricated surface crack(s) shall range from 0,1 to 0,5. If coupons are used as the test specimens, stress (or strain) cycles shall be applied to the specimens with the maximum stress (or strain) corresponding to the MEOP level and minimum stress (or strain) kept to zero, or actual minimum stress (or strain), whichever is the more conservative, until the surface crack grows through the specimen's thickness to become a through crack. LBB failure mode is demonstrated if the length of the through crack becomes $\geqslant$ 10 times the specimen's thickness and remains stable.

3.3.7 Fatigue life

3.3.7.1 Metallic hardware items

When conventional fatigue analysis is used to demonstrate the fatigue life of an unflawed metallic hardware item, nominal values of fatigue-life characteristics, including stress-life (S-N) data or strain-life (ε-N) data of the structural material or materials, shall be used. These data shall be taken from reliable sources that are approved by the procuring authority (customer). The analysis shall account for the spectra of expected operating loads, pressure and environments. The cumulative linear damage rule (Miner's rule) is an acceptable method for handling variable amplitude fatigue cyclic loading. Unless otherwise specified, a life factor of four shall be used in the fatigue analysis. The limit for the accumulated fatigue damage using Miner's rule shall be 80 % of normal limit. In the mathematical form, Miner's rule is expressed as:

$$\Sigma\, n_i / N_i \leqslant 0{,}8$$

where

n_i is four times the number of cycles applied at stress level i;

N_i is the number of cycles to failure at stress level i, and the summation is i = 1 to k.

Testing of unflawed specimens to demonstrate fatigue-life of a metallic hardware item is an acceptable alternative to analytical prediction. Fatigue-life requirements are met when the unflawed specimens, representing critical areas such as membrane section, weld joints, heat-affected zones and boss transition section, or a full-scale article, successfully sustain the service loads and pressures in the expected operating environments for the specified test cycles and duration without rupture. The required test duration is at least four times the specified service life or number of cycles.

3.3.7.2 Composite overwrapped pressure vessels

For the composite overwraps of a composite overwrapped pressure vessel, the analysis shall address the alternating stress response for all spectra of expected operating loads, pressures and environments. Testing of unflawed specimens using coupons or full-scale articles is an acceptable option. When this option is adapted, the test requirements specified in 3.3.7.1 shall be met.

3.3.7.3 Fatigue analysis or test report

A fatigue analysis or test report shall be prepared and shall be closely coordinated with the stress analysis report. The fatigue analysis report shall document loading spectra, environments, fatigue (S-N) or (ε-N) data and analysis results. The fatigue-test report shall present the specimen configuration, test set-up, test loading spectra/environment, and the test results.

3.3.8 Safe-life demonstration

3.3.8.1 General

The safe life of metallic hardware items shall be demonstrated by analysis, test or both and shall be at least four times the specified service life for those hardware items that are not accessible for periodic inspections and repair. The safe life of the hardware item containing hazardous fluids ends when leakage occurs. For the metallic hardware item which is readily accessible for periodic inspection and repair, the safe life shall be at least four times the interval between scheduled inspections.

3.3.8.2 Safe-life analysis

When fracture mechanics crack growth analysis is used to determine the safe life of a metallic hardware item, undetected flaws shall be assumed to be in the critical locations and in the most unfavourable orientation with respect to the applied stress and material properties. The assumed flaw sizes shall be based on either the flaw detection capabilities of appropriate non-destructive inspection (NDI) techniques or defined by the acceptance proof testing. The flaw shape ($a/2c$) in the range of 0,1 to 0,5 shall be considered for surface cracks. For corner cracks, the flaw shape (a/c) in the range of 0,2 to 1,0 shall be considered.

Nominal values of fracture toughness and fatigue crack-growth rate data associated with each alloy, temper, product form, and thermal and chemical environments shall be used in the safe-life analysis. However, if proof test logic is used for establishing 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. A metallic hardware item 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 stress shall be included in the analysis.

A proven crack growth methodology shall be used to conduct the safe-life analysis. For part-through cracks (surface flaws or corner cracks), the flaw shape changes shall be accounted for in the analysis. Retardation effects on crack growth rates from variable amplitude loading shall not be considered without approval by the procuring authority (customer).

3.3.8.3 Safe-life test

For metallic pressure vessels, metallic pressurized structures and the elastically responding metallic liners of composite overwrapped pressure vessels, the safe-life test is an acceptable option for safe-life demonstration. For the plastically responding liners, safe-life shall be demonstrated only by testing. Coupons or full-scale articles with pre-fabricated flaws shall be used in the safe-life test as appropriate. These flaws shall not be less than the flaw sizes established by the selected NDI method or methods or by the acceptance proof testing. Safe life is considered demonstrated when the pre-flawed specimens successfully sustain the limit loads and pressure cycles in the expected operating environments without leaking.

3.3.8.4 Safe-life analysis or test report

When safe life is demonstrated by analysis, an analysis report shall be prepared and shall be closely coordinated with the stress analysis report. In the report, loading spectra, environments, assumed initial flaw sizes, crack-growth models, fatigue crack growth rates and fracture data shall be delineated. A summary of significant results shall be clearly presented.

When safe-life is demonstrated by test, a test report shall be prepared. The report shall document, as a minimum, the specimen configurations, initial crack sizes, test set-up, test procedures, test pressure-cycle spectra and environments, and significant test results.

3.3.9 Leakage

All pressurized hardware shall meet leak rate requirements ensuring that operation of the system is maintained throughout the intended lifetime.

3.3.10 Miscellaneous

The structural design of all pressurized hardware shall employ proven processes and procedures for manufacture and repair. The design shall emphasize the following needs:

a) access;

b) inspection;

c) service;

d) repair (include replacement of some parts);

e) refurbishment.

For all reusable pressurized hardware, the structural design shall permit the hardware to be maintained in and refurbished to a flight-worthy condition. Repaired and refurbished hardware shall meet all stipulated conditions of flight worthiness.

3.4 Composite overwrapped pressure vessel-specific design requirements

3.4.1 General

The following gives the specific design requirements for a composite overwrapped pressure vessel. Included are

— stress-rupture life,

— damage control,

— corrosion control, and

— embrittlement control.

3.4.2 Stress-rupture life

A composite overwrapped pressure vessel shall be designed to meet the design life, considering the time it is under sustained load. There shall be no credible stress-rupture-failure modes based on stress-rupture data for a probability of survival of 0,999.

3.4.3 Damage control

3.4.3.1 General

All composite overwrapped pressure vessels shall be placed under damage control except for those vessels that have a design burst factor of 4,0 or greater and a total wall thickness of 6,35 mm or greater.

Mechanical damage that could degrade the performance of the composite overwrapped pressure vessel below the minimum strength requirements specified in 3.3.2 shall be prevented. For mechanical damage mitigation, a minimum of one of the following approaches shall be adapted:

a) **Approach A:** using mechanical damage protection or indication or both;

b) **Approach B:** demonstrating damage tolerance abilities by testing.

3.4.3.2 Damage control plan

A damage control plan shall be prepared for the new composite overwrapped pressure vessel that is under damage control. The damage control plan shall contain a threat analysis which documents the conditions (source and magnitude of threat and state of pressurization of the composite overwrapped pressure vessel) under which mechanical damage can occur. The damage control plan shall delineate all events and inspection points from the time at which the composite overwrapped pressure vessel reinforcing matrix is cured to the end of vessel life. As a minimum, visual inspection shall be conducted prior to

a) each pressurization when rupture of the composite overwrapped pressure vessel could create a hazardous condition, and

b) closeout after which inspection is impossible or impractical, or mechanical damage is no longer credible.

The damage control plan shall identify the approach to be taken for the composite overwrapped pressure vessel-specific design.

3.4.3.3 Approach A, mechanical damage protection/indication

3.4.3.3.1 General

Mechanical damage protection covers shall provide isolation from a potential mechanic damage event. When this approach is adapted, the following requirements shall apply.

3.4.3.3.2 Protective covers

The effectiveness of protective covers shall be demonstrated by testing. Protective covers or standoffs which isolate the vessel are required when personnel will be exposed to pressurized composite overwrapped pressure vessels (having stored energy level in excess of 19 310 J or containing hazardous fluids). The protective cover shall be designed to completely protect the vessel under the worst credible threat defined in the damage control plan. Protective covers shall not be removed before the last moment prior to launch.

3.4.3.3.3 Indicators

The effectiveness of the indicators to provide positive evidence of a mechanical damage event shall be demonstrated by testing. The use of an indicator as the sole means of mitigating threats for pressurized composite overwrapped pressure vessels as defined in the damage control plan, during personnel workaround, is prohibited.

3.4.3.4 Approach B, damage tolerance demonstration

3.4.3.4.1 General

Mechanical damage tolerance demonstration is another approach to satisfying the damage control requirement. This approach may be used as a complement to mechanical damage protective covers.

3.4.3.4.2 Impact damage tolerance

Impact damage tolerance of a composite overwrapped pressure vessel shall be demonstrated by testing. Impact damage shall be induced using a drop type impactor with a 12,7 mm diameter, hemispherical tup (a pendulum type arrangement is allowed if an analysis substantiates energy levels equivalent to a drop test). The minimum impact energy levels shall be the greater of the worst-case threat, or visual damage threshold (VDT). The damage shall be induced at the most damage critical condition (e.g. pressurized versus. unpressurized) and locations. After inducing impact damage to the composite overwrapped pressure vessel, the vessel shall be tested to failure to show that the BAI of the damaged vessel is equal to or greater than its design burst pressure.

3.4.3.4.3 Other mechanical damage tolerance

Damage tolerance of other mechanical damage such as abrasions and surface cuts shall be demonstrated by analysis or testing. The sizes of abrasion or cut shall be based on the threat analysis. It shall be shown that other credible mechanical damage will not degrade the burst strength of the composite overwrapped pressure vessel to below its design burst pressure.

3.4.4 Corrosion control and prevention

Operational, test and manufacturing support fluids that come in contact with the composite overwrapped pressure vessel shall be identified, along with the frequency of contact, duration of contact and fluid temperatures. These fluids shall be compatible with the liner and composite material and shall not result in general corrosion, stress corrosion and galvanic corrosion. The composite overwrapped pressure vessel design shall provide for isolation of the metallic liner from electrically conductive elements in the reinforcing composite matrix.

3.4.5 Embrittlement control

All known embrittlement mechanisms such as hydrogen and liquid metal embrittlement, applicable to the metallic liner, fibre and resin shall be identified and controlled in the design, fabrication and operation of the composite overwrapped pressure vessel.

3.5 Material requirements

3.5.1 Metallic materials

3.5.1.1 Metallic material selection

Materials used for fabricating metallic hardware items shall be selected on the basis of proven environmental compatibility, material strengths, fracture properties, fatigue life, crack growth and stress corrosion cracking characteristics consistent with the overall program requirements. Materials' A-allowable values shall be used for metallic hardware items where failure of a single load path would result in loss of structural integrity. Materials' B-allowable values may be used for redundant structural elements where failure of one element would result in a safe redistribution of applied loads to other elements. The fracture toughness shall be as high as practicable within the context of structural efficiency and fracture resistance. For metallic hardware items to be analysed with linear elastic fracture mechanics, the following fracture properties shall be accounted for in material selection:

a) fracture toughness;

b) threshold values of stress intensity under sustained loading;

c) sub-critical crack growth characteristics under cyclic loading.

The effects of fabrication and joining processes; the effect of cleaning agents, dye (fluorescent) penetrants, coating, and proof test fluids and the effects of temperature, load spectra, and other environmental conditions shall be accounted for.

3.5.1.2 Metallic material evaluation

The materials selected for design shall be evaluated with respect to the materials processing, fabrication methods, manufacturing operations, refurbishment procedures and processes, and other pertinent 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, strength 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 that are susceptible to stress-corrosion cracking or hydrogen embrittlement shall be evaluated by performing sustained load-fracture tests when applicable data are not available

3.5.1.3 Metallic material characterization

The allowable mechanical strength, and fracture properties of all materials selected for metallic hardware items 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. Where material properties are not available, they shall be determined by recognized standard test methods or methods approved by the procuring authority (customer). 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.

a) tensile yield strength, ultimate tensile strength, and elongation;

b) plane strain fracture toughness K_{IC}, effective fracture toughness K_{IE}, and stress-corrosion cracking threshold toughness K_{ISCC};

c) fatigue crack-growth rate (da/dN) versus stress intensity factor range ΔK; and

d) fatigue data S-N (ε-N).

The test specimens and procedures utilized shall provide valid test data for the intended application. Enough tests shall be conducted so that meaningful nominal values of fracture toughness and flaw-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 the safe-life requirements of 3.3.8.2. The test plan and test results shall be approved by the procuring authority (customer).

3.5.2 Composite materials

3.5.2.1 Composite materials selection

Composite material systems used for fabricating composite overwrapped pressure vessels shall be selected on the basis of proven environmental compatibility, material strength/modulus, stress-rupture life data, and compatibility with metal liner materials. If an electrically conductive fibre reinforcement is used, the design shall incorporate a means to prevent galvanic corrosion with metallic components.

The effects of fabrication processes, coatings, fluids and the effects of temperature, load spectra, and other environmental conditions which affect the strength and stiffness of the material in the fabricated configuration, shall be included in the rationale for selecting the composite material system.

3.5.2.2 Composite material system characterization

The elastic and strength properties of the composite materials selected shall be characterized in sufficient detail to permit reliable and high confidence predictions of the structural performance in their expected operating environments. Composite material systems allowable properties on the as-wrapped vessel shall be declared for each fibre/resin system. Supporting data to justify and validate the declared allowable shall include items a) and/or b) as given below, and may include supporting data from items c) and d) for quality control purposes, for checking new in-coming yarn lots:

a) previous qualification burst test results;

b) burst test results from design development tests;

c) A-basis fibre strength values from impregnated strand testing;

d) fibre manufacturer's literature and certification test results.

The supporting data shall provide justification for the declared elastic and strength properties, and sustained load behaviour consistent with the operating and non-operating environments.

Uniform test procedures shall be employed by determining material properties as required. These procedures shall conform to recognized standards. The test specimens and procedures utilized shall provide valid test data for the intended application.

The stress-rupture life data of composite materials shall be characterized if there is no existing data.

3.5.2.3 Composite material strength allowable

A-basis strength allowable shall be generated from bursting of sub-scale and/or full-scale composite overwrapped pressure vessels. Coupons are acceptable specimens only if data are available which show the correlation between delivered fibre strengths in coupons and vessels. Test results from at least two lots of yarn shall be used in the A-allowable calculations unless all of the vessels are fabricated from the same lot of material. The results from production vessels of different configurations and sub-scale vessels may be pooled together if they have comparable thickness.

3.5.2.4 Composite material control

A material control system shall be in place to control raw materials. This shall include the following as a minimum:

a) procurement of the materials to approved specifications;

b) validation (inspection) checks for resin/resin constituent, chemistry/purity and reinforcing fibre material properties against the material specification and purchase order requirements;

c) controlled environmental storage as applicable;

d) shelf-life control.

3.6 Fabrication and process control requirements

3.6.1 Metallic hardware items

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 ascertaining that the melt process, thermal treatment, welding process, forming, joining, machining, drilling, grinding, repair and re-welding operations, etc. are within the state-of-the-art and have been proven on similar hardware. Mechanical, physical and fracture 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 dimensional stability of the materials during machining, forming, joining, welding and thermal treatments shall be ensured, and through-thickness hardening characteristics shall be compatible with the manufacturing processes. Fracture control requirements and precautions shall be defined in applicable drawings, process specifications or other appropriate documents. 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-damaged or other structural integrity degradation.

3.6.2 Composite overwrap

The composite overwrap fabrication process shall be a controlled documented process. Incorporated materials shall have certifications that demonstrate acceptable variable ranges to ensure repeatable and reliable performance. An inspection plan shall be developed per 3.7.2 to identify all critical parameters essential for verification. The amount of incorporated material on the article from the composite fabrication shall be verified.

3.7 Quality assurance requirements

3.7.1 Quality assurance program

A quality assurance program, based on a comprehensive study of the product and engineering requirements, such as drawings, material specifications, process specifications, workmanship standards, design review records and failure mode analysis, shall be established to ensure that the necessary NDI and acceptance tests are effectively performed and to verify that the product meets the requirements of this International Standard.

The program shall ensure that materials, parts, subassemblies, assemblies and all completed and refurbished hardware conform to applicable drawings and process specifications, 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.

3.7.2 Inspection plan

An inspection master plan shall be established prior to the start of fabrication. The plan shall specify inspection points and inspection techniques for use throughout the program, beginning with material procurement and continuing through fabrication, assembly, acceptance proof test, operation and refurbishment, as appropriate. In establishing inspection points and inspection techniques, consideration shall be given to the material characteristics, fabrication processes, design concepts, structural configuration and accessibility for inspection of flaws. For metallic hardware items, the flaw geometry shall encompass defects commonly encountered, including surface cracks, corner cracks or through cracks. Acceptance and rejection criteria shall be established for each phase of inspection and for each type of inspection technique.

3.7.3 Inspection techniques

3.7.3.1 Metallic hardware items

The most appropriate NDI technique or techniques for detecting commonly encountered flaw types shall be used for all metallic hardware items along with their flaw detection capabilities. The selected NDI techniques shall have the capability to determine the size, geometry, location and orientation of a flaw, to obtain – where multiple flaws exist – the location of each with respect to the other and the distance between them and to differentiate among flaw types – 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 flaw detection capability of each selected NDI technique for metallic hardware items shall be based on past experience on similar hardware. Where this experience is not available or is not sufficiently extensive to provide reliable results, the capability, under production or operational inspection conditions, shall be determined experimentally and demonstrated by tests approved by the procuring authority (customer) on a representative material product form, thickness and design configuration.

The flaw detection capability shall be expressed in terms of detectable crack length and crack depth. The selected NDI technique should be capable of detecting allowable initial flaw size corresponding to a 90 % probability of detection (POD) at a 95 % confidence level.

3.7.3.2 Composite overwraps

As a minimum, after overwrapping, all composite overwrapped pressure vessels shall be subjected to visual inspection for detecting impact damage. State-of-the-art NDI techniques shall be selected for inspecting other mechanical damage induced on the composite overwrap as appropriate. The NDI procedures shall be based on use of multiple NDI methods to perform survey inspections or diagnostic inspections. Survey NDI inspections shall be conducted when the location of the potential damage zone is unknown, while diagnostic NDI inspections shall be performed within a localized suspect zone to characterize the type and extent of the damage. All NDI techniques, whether used as a single inspection technique or as a combination of methods, shall have the capability to detect impact and other mechanical damages that may cause the composite overwrapped pressure vessel to fail to meet the requirements of its performance specification or the requirements of this International Standard.

The damage detection capability of each selected NDI technique or combination of NDI techniques as applied to the composite overwrap shall be based on similar data from prior test programs. Where this data is not available or is not sufficiently extensive to provide reliable results, the capability — under production of operational inspection conditions — shall be determined experimentally and demonstrated by tests on representative material product form, thickness, design configuration and damage source articles.

3.7.4 Inspection data

Inspection data in the form of flaw histories shall be maintained throughout the life of the pressurized hardware. These data shall be periodically reviewed and assessed to evaluate trends and anomalies associated with the inspection procedures, hardware 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.

3.7.5 Acceptance proof test

Each piece of pressurized hardware shall be proof-pressure tested to verify that the hardware has sufficient structural integrity to sustain the subsequent service loads, pressures, temperatures and environments. The temperature shall be consistent with the critical use temperature or, as an alternative, tests may be conducted at an alternate temperature if the test pressures are suitably adjusted to account for temperature effects on strength and fracture toughness. Proof-test fluids shall not pose a hazard to test personnel and shall be compatible with the structural materials in the pressurized hardware. If such compatibility data is not available, required 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 testing. Pressurized hardware shall not leak, rupture or experience detrimental deformation during acceptance proof testing.

3.8 Operation and maintenance requirements

3.8.1 Operating procedures

Operating procedures shall be established for each pressurized hardware item. These procedures shall be compatible with the safety requirements and personnel control requirements of 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 a relief valve and burst disc, shall be provided when applicable and procedures to ensure 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 nominal operating pressure until operating characteristics can be established. Only qualified and trained personnel shall be assigned to work on or with high-pressure systems. Warning signs with the hazard identified shall be posted at the operations facility prior to pressurization.

3.8.2 Safe operating limit

Safe operating limits shall be established for each pressurized hardware item, based on the appropriate analysis and testing employed in its design and qualification. These safe operating limits shall be summarized in a format, that provides rapid visibility of the important structural characteristics and capability. The desired information shall include, but not be limited to, the following data:

a) fabrication materials;

b) critical design conditions;

c) MEOP;

d) nominal operating or working pressure;

e) proof pressure;

f) design burst pressure;

g) pressurization and depressurization sequence;

h) operational cycle limits;

i) design and operating temperatures;

j) operational system fluid, cleaning agent;

k) permissible thermal and chemical environments;

l) admissible leakage levels versus pressure values.

For pressurized hardware items with a potential brittle fracture failure mode, the critical flaw sizes and maximum permissible flaw sizes shall also be included as appropriate. Applicable references to design drawings, detail analyses, inspection records, test reports and other backup documentation shall be indicated.

3.8.3 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 pressure vessel and pressurized structure so that the required inspection interval and repair schedule can be established to maintain hardware to the requirements of this document.

NDI technique and inspection procedures for reliably detecting defects and determining flaw size under the condition of use shall be developed for use in the field and at depot levels. Procedures shall be established for recording, tracking and analysing 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.

3.8.4 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 recertified after each repair and refurbishment by the appropriate proven acceptance test procedure to verify its structural integrity and to establish its suitability for continued service.

3.8.5 Storage

When pressure vessels and pressurized structures are put into storage, they shall be protected against exposure to adverse environments that 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.

3.8.6 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) number of pressurization cycles experienced, as well as the number allowed in safe-life analysis or test;

c) results of any inspection conducted, including inspector, inspection dates, inspection techniques employed, location and character of defects, defect origin and cause, taking in inspection made during fabrication;

d) storage condition;

e) maintenance and corrective action performed from manufacturing to operational use, including refurbishment;

f) sketches and photographs to show areas of structural damage and the extent of repair;

g) acceptance and re-certification testing performed, including test condition and results;

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

3.9 Reactivation requirements

Pressure vessels and pressurized structures 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 requirements. A purposeful inspection for corrosion and incidental damage prior to re-certification testing shall be performed.

3.10 Service-life extension requirements

For LBB non-hazardous pressurized hardware, the allowable service life can be determined by conventional fatigue analysis or testing. It can be extended without additional test or inspection, if there is available adequate data such as actual pressure, loads and environments from the past period of service life.

Actual loading spectrum and environmental data should be used as the fatigue equivalent condition of the qualification test by using analysis or both analytical and experimental methods. The part of cumulative damage corresponding to the past period of a service life should be evaluated. For brittle or LBB hazardous pressurized hardware, the allowable service life shall be determined by fracture mechanic analysis.

4 Specific requirements

4.1 General

This clause presents specific requirements for pressurized hardware. Included are factor of safety requirements, failure mode demonstration requirements, cyclic and burst test requirements, vibration test requirements, safe-life demonstration requirements and other requirements specifically applicable to special items.

4.2 Pressure vessels

4.2.1 General

Two types of pressure vessel are covered in this document: metallic pressure vessels and composite overwrapped pressure vessels. The specific requirements for these two types of pressure vessel are delineated in the following.

4.2.2 Metallic pressure vessels

4.2.2.1 General approach

Based on the results of the failure mode determination, one of two verification approaches shall be satisfied:

a) **Approach 1:** 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);

b) **Approach 2:** brittle fracture failure mode or hazardous LBB failure mode in which, if the metallic pressure vessel leaks, the leak will cause a hazard.

The verification requirements for Approach 1 are given in 4.2.2.2 and the verification requirements for Approach 2 in 4.2.2.3.

4.2.2.2 Metallic pressure vessels with non-hazardous LBB failure mode

4.2.2.2.1 LBB demonstration

A metallic pressure vessel containing non-hazardous fluid and exhibiting LBB failure mode is considered *not fracture critical*. Analysis or test per requirements specified in 3.3.6 shall demonstrate the LBB failure mode.

4.2.2.2.2 Design factor of safety

Metallic pressure vessels which satisfy the non-hazardous LBB failure mode criterion may be designed conventionally, wherein the design factors of safety and proof test factors are selected on the basis of successful past experience. Unless otherwise specified, the minimum burst factor shall be 1,5.

The factor of safety to the external (supporting) loads shall be same as that assigned to the primary structures. The minimum ultimate safety factor to the external loads shall be 1,25 for unmanned systems and 1,4 for manned systems.

4.2.2.2.3 Fatigue-life demonstration

The fatigue life of the metallic pressure vessel with a non-hazardous LBB failure mode shall be demonstrated by analysis or test as specified in 3.3.7.

4.2.2.2.4 Qualification test requirements

Qualification tests shall be conducted on flight-quality metallic pressure vessels to demonstrate structural adequacy of the design. The test fixtures, support structures and methods of environmental application shall be representative of operational conditions. The types of instrumentation and their locations in qualification tests shall be based on the results of the stress analysis according to 3.3.5. The instrumentation shall provide sufficient data to ensure proper application of the accept/reject criteria, which shall be established prior to testing. The sequences, combinations, levels and duration of loads, pressures and environments shall demonstrate that design requirements have been met. Qualification testing shall at least include vibration, pressure and leak tests. The following delineates the required testing.

a) Vibration testing

Vibration qualification testing shall be conducted. When the vibration loads are enveloped by the other qualification tests, and approved by the procuring authority (customer), the vibration tests are not required.

b) Pressure testing

Required qualification pressure testing levels the shall be as shown in Table 1. The 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 times the predicted number of operating cycles of the most severe design condition (for example, destabilizing load with constant minimum internal pressure or maximum additive load with a constant MEOP).

c) Leak test

The leak test shall be conducted after the pressure cycle test.

The qualification test procedure shall be approved by the procuring authority (customer). In the case of changing manufacturing, the qualification test shall be repeated unless specified otherwise by the procuring authority.

Table 1 — Qualification pressure test requirements

Test item	No yield after	No burst[a]
Vessel No. 1[b]	—	Burst factor × MEOP
Vessel No. 2	Pressure: 1,5 × MEOP Cycle: 2 × predicted number or Pressure: 1,0 × MEOP Cycle: 4 × predicted number	Burst factor × MEOP

[a] Unless otherwise specified, after demonstrating no burst at the design burst pressure test level, increase pressure to actual burst of vessel.

[b] Test may be deleted at discretion of the procuring authority (customer).

4.2.2.2.5 Acceptance test

Acceptance tests shall be conducted on every metallic pressure vessel before commitment to flight. Accept/reject criteria shall be formulated prior to testing. 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) Nondestructive inspection

A complete inspection by the selected NDI technique shall be performed prior to the proof pressure test to establish the initial condition of the hardware. The NDI prior to proof test can be substituted for that of the manufacturing process.

b) Proof-pressure test

Every metallic pressure vessel shall be proof-pressure tested to verify that the materials, manufacturing processes and workmanship meet design specifications, and that the hardware is suitable for flight. Maximum duration of proof test shall not exceed the appropriate time to avoid potential crack propagation due to a stress corrosion cracking mechanism.

The following is the guideline for the minimum proof-pressure (p_{proof}) levels:

— p_{proof} = (1 + burst factor)/2 × (MEOP), for a burst factor less than 2,0;

— p_{proof} = 1,5 × (MEOP), for a burst factor equal or greater than 2,0.

c) Leak test

The leak test shall be conducted after the proof pressure test.

4.2.2.2.6 Re-certification test

All refurbished metallic pressure vessels shall undergo the same acceptance tests as specified for new vessels, in order to verify their structural integrity and to establish their suitability for continued service before commitment to flight. Deviations from this requirement are only allowed if it can be demonstrated that the refurbished parts of the metallic pressure vessel are not affected by the corresponding tests.

Metallic pressure vessels that have exceeded the specified storage environment (temperature, humidity, time, etc.) shall also be re-certified by the acceptance test requirements for new hardware.