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Space systems — Bellows — Design and operation

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National foreword

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Foreword

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ISO 10785 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

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Introduction

The bellows for space systems is usually used under severe conditions, such as high pressure, extremely low temperatures, large deflection, or high inner flow speed. The design safety factor of the bellows tends to be small in order to satisfy two different function requirements simultaneously. One is the function of the pressure bearing component, which all pressure components have, and the other is the special function to accommodate installation misalignment, thermal expansion or contraction and displacement induced by large deformation of the pressurized propellant tank.

There are many items to be considered for design and manufacture such as hoop stress, bulging stress, buckling strength, flow-induced vibration, and cyclic deflection.

This International Standard establishes general and specific requirements for bellows in order to provide safe and reliable bellows hardware and operations.

Some examples of the design safety factors are shown in Annex A at the end of this International Standard.

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Space systems — Bellows — Design and operation

1 Scope

This International Standard specifies general and detailed requirements for bellows used in space systems. It establishes requirements with regard to material, design, analysis, fabrication, material, testing, inspection and operation for space use.

This International Standard is applicable to metallic bellows which are used as pressure bearing components and are integrated into a pressure system. This International Standard is not applicable to engine bellows or valve bellows.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 14623:2003, *Space systems — Pressure vessels and pressurized structures — Design and operation*

3 Terms and definitions

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

3.1
acceptance test
required formal test conducted on flight hardware to ascertain that the materials, manufacturing processes and workmanship meet specifications and that the hardware is acceptable for intended usage

3.2
bellows
corrugated single-layer or multi-layer elastic casing, when integrated into a duct assembly, capable of performing linear, shear and angular movements

NOTE 1 A bellows consists of both a convolution section and a mechanical linkage section, which serves as a bellows restraint. The most common mechanical linkage types are gimbal-type and braided-type. In some cases a bellows contains an internal liner or flow tube for the purpose of improving flow capability.

NOTE 2 See Figure 1.

3.3
bellows stiffness
ratio between an applied force and the resulting bellows displacement

3.4
burst pressure
pressure level at which rupture or unstable fracture of the pressurized hardware item occurs

3.5
bulging stress
meridional or axial stress at the convolution section induced by pressure

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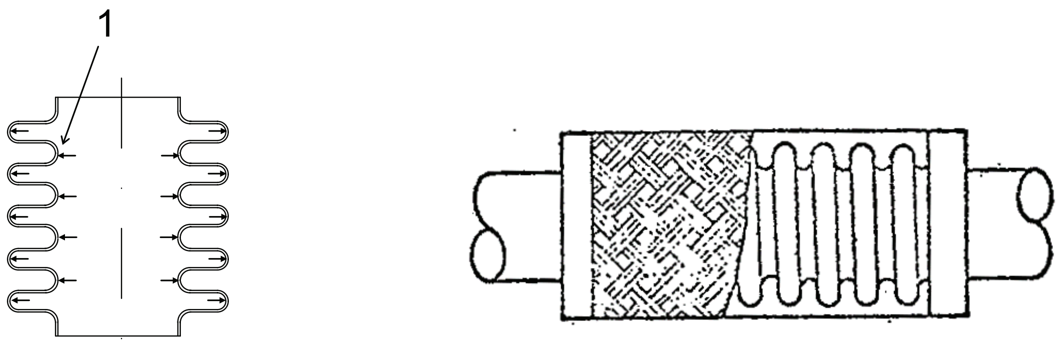


Key

1 internal pressure

Figure 1 — Bellows

3.6
component
functional unit that is viewed as an entity for the purpose of analysis, manufacturing, maintenance, or record keeping

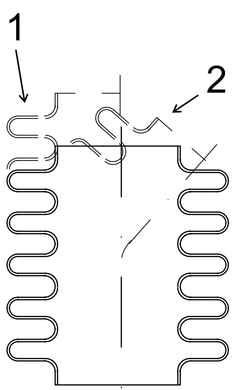
NOTE Adapted from ISO 14623:2003.

3.7
critical condition
most severe environmental condition in terms of loads, deflection, pressures and temperatures, or combination thereof, imposed on systems, subsystems, structures and components during service life

[ISO 14623:2003, definition 2.12]

3.8
deflection
contraction or expansion along its longitudinal axis, angular rotation, or lateral offset

NOTE See Figure 2.



Key

1 axial deflection

2 angular rotation

Figure 2 — Deflection

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3.9
design burst factor
multiplying factor applied to maximum expected operating pressure (MEOP) or maximum design pressure (MDP) [3.20] to obtain the design burst pressure

3.10
design burst pressure
differential pressure that pressurized hardware must withstand without bursting in the applicable operational environment

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

[ISO 14623:2003, definition 2.16]

3.11
design safety factor
design factor of safety
factor of safety
multiplying factor to be applied to the limit load and/or maximum expected operating pressure (MEOP) or maximum design pressure (MDP) [3.20]

[ISO 14623:2003, definition 2.17]

3.12
detrimental deformation
structural deformation, deflection or displacement that prevents any portion of the structure or other system from performing its intended function or that jeopardizes mission success

NOTE Adapted from ISO 14623:2003, definition 2.19.

3.13
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

[ISO 14623:2003, definition 2.23]

3.14
fatigue life
number of cycles of stress or strain of a specified character that a given structure or component of a structural assembly can sustain (without the presence of flaws) before failure of a specified nature occurs

NOTE Adapted from ISO 14623:2003, definition 2.24.

3.15
fracture
type of failure mode in a material/structure which is generally preceded by a large amount of plastic deformation

3.16
flaw
local discontinuity in a structural material

EXAMPLES Crack, cut, scratch, void, delamination disbond, impact damage and other kinds of mechanical damage.

NOTE Adapted from ISO 14623:2003, definition 2.25.

3.17
hoop stress
circumferential stress at the convolution section induced by pressure

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3.18
leak-before-burst
LBB
design concept which shows that at maximum expected operating pressure (MEOP) [3.20] potentially critical flaws will grow through the wall of a metallic pressurized hardware item and cause pressure relieving leakage rather than burst or rupture (catastrophic failure)

NOTE Adapted from ISO 14623:2003, definition 2.35.

3.19
limit load
maximum expected load, or combination of loads, which a structure or a component in a structural assembly is expected to experience during its service life, in association with the applicable operating environments

NOTE 1 Load is a generic term for thermal load, pressure, external mechanical load (force, moment, or enforced displacement) or internal mechanical load (residual stress, pretension, or inertial load).

NOTE 2 The corresponding stress or strain is called limit stress or limit strain.

NOTE 3 Limit load is sometimes referred to as design limit load.

NOTE 4 Adapted from ISO 14623:2003, definition 2.36.

3.20
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

NOTE 1 MEOP includes the effects of temperature, transient peaks, relief pressures, regulator pressure, vehicle acceleration, phase changes, transient pressure excursions, and relief valve tolerance.

NOTE 2 Some projects may replace MEOP with maximum design pressure (MDP), which takes into account more conservative conditions.

NOTE 3 Adapted from ISO 14623:2003, definition 2.41.

3.21
mechanical linkage section
section within bellows assembly that will serve as the bellows restraint for thrust force by pressure, deflection, or other factors

3.22
personnel's approach
action or state of a ground crew approach when near to the bellows or another component while the component is pressurized

3.23
proof factor
multiplying factor applied to the limit load or maximum expected operating pressure (MEOP) or maximum design pressure (MDP) [3.20] to obtain proof load or proof pressure for use in acceptance testing

[ISO 14623:2003, definition 2.50]

3.24
proof test pressure
pressure level used to give evidence of satisfactory workmanship and material quality and/or establish maximum initial flaw sizes for safe-life demonstration

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3.25
qualification test
required formal contractual tests conducted at load levels and durations in order to demonstrate that the design, manufacturing, and assembly of flight-quality structures have resulted in hardware that conforms to specification requirements

NOTE In addition, the qualification test may validate the planned acceptance programme, including test techniques, procedures, equipment, instrumentation, and software.

3.26
repair
action on a nonconforming product to make it acceptable for the intended use

NOTE 1 Repair includes remedial action taken on previously conforming product to restore it for use, for example as part of maintenance.

NOTE 2 Unlike rework, repair can affect or change parts of the nonconforming product.

3.27
refurbishment
renovation and restoration to intended use condition

3.28
service life
period of time (or number of 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

[ISO 14623:2003, definition 2.57]

3.29
work hardening effect
effect of strengthening material by plastic deformation

NOTE The representative material is 300 series corrosion-resistant steel.

4 Abbreviated terms

LBBleak-before-burst

MDPmaximum design pressure

MEOPmaximum expected operating pressure

NDInon-destructive inspection

QAquality assurance

S-Nstress versus number of cycles to failure

NOTE Plots of S-N data are used in the fatigue test.

5 Requirements

5.1 General

Clause 5 presents the requirements for design, stress analysis, material selection and characterization, fabrication and process control, and quality assurance, as well as operational requirements including maintenance, repair, refurbishment and storage for bellows in a pressure system.

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Safety requirements such as the design safety factor and safety measures in operation should comply with appropriate facility/agency requirements. Examples of design safety factor are shown in Annex A.

5.2 Design requirements

5.2.1 Loads, pressures, and environments

The anticipated pressure-temperature-deflection history and other associated environments throughout the service life of bellows in a pressure system shall be determined in accordance with specified mission requirements, also including flight ultimate conditions.

The fundamental parameters or conditions in loads, pressures, and environments for bellows are considered as follows:

a) internal/external pressure;

b) temperature;

c) fluid (working medium);

d) flow velocity;

e) deflection;

f) pre-loads;

g) life-cycle;

h) vibration, shock, acceleration;

i) externally applied installation loads;

j) handling loads.

NOTE Give additional specific requirements for pre-loads, such as minimizing pre-loads, if it is not possible to estimate pre-loads by measuring misalignment of adjacent structures before and after mounting the bellows, taking into account the acceptable rigidity of each part, which are suitably arranged.

5.2.2 Strength

The bellows in a pressure system shall possess sufficient strength to withstand MEOP and maximum deflection, or other additional loads in the expected operating environments throughout the service life. It shall sustain proof test pressure without experiencing leakage and incurring detrimental deformation. It shall also withstand design burst pressure without experiencing rupture or collapse.

The bellows design safety factor is described in Annex A.

5.2.3 Stiffness

There are various types of deflection that the bellows can accommodate. These are axial deflection, angular rotation, lateral offset, torsion, etc. The spring rate of the bellows for each direction shall comply with system requirements to withstand maximum expected load to the adjacent members and maximum expected vibration modes of the system.

Bellows with a linkage mechanism shall possess adequate axial stiffness against pressure to preclude excessive load to the adjacent members.

Bellows stiffness is a part of design and shall be analysed and, if necessary, verified by testing.

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5.2.4 Thermal effects

The design of the bellows shall consider the following thermal effects, as appropriate:

a) temperature;

b) thermal gradients;

c) thermal stresses and deformations;

d) changes in the physical and mechanical properties of the materials of construction; and

e) thermal cycle.

5.2.5 Stress analysis

5.2.5.1 General

A detailed and comprehensive stress analysis of each new design of the bellows shall be conducted to demonstrate acceptable stress levels. For the convolution section, the following stresses shall be evaluated using reliable analyses methods:

a) hoop stress by pressure;

b) bulging stress by pressure; and

c) bending stress by deflection.

A detailed and comprehensive buckling stability analysis shall be conducted using a reliable analysis method.

A detailed analysis of the linkage strength shall be performed to demonstrate the pressure separating load of the bellows and to prevent unacceptable axial deformation.

The spring rate of the bellows for axial deflection, angular rotation, lateral offset, and torsion shall be calculated accounting for deformation of convolutions and restraints of the linkage mechanism.

The adjacent members of bellows shall be comprehensively and numerically evaluated for stress introduced by the bellows stiffness.

5.2.5.2 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.

5.2.6 LBB failure modes

LBB failure shall be demonstrated by analysis or test. The LBB demonstration can be omitted by procuring authority if there are adequate data from similar designs that have been demonstrated to exhibit LBB failure modes.

5.2.7 Fatigue life

Conventional fatigue-life analysis shall be performed as appropriate on the bellows for its anticipated duty cycle throughout the service life. Nominal values of fatigue-life characteristics for stress-life data (S-N) shall be used. These data shall be taken from reliable sources that are approved by the procuring authority.

The cumulative linear damage rule (Miner’s rule) is an acceptable method for handling variable amplitude fatigue cyclic loading as specified in ISO 14623. Unless otherwise specified, a life factor of four shall be used in the fatigue analysis of the pressure and deflection cycle.

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The fundamental parameters in bellows fatigue life shall be as follows:

a) pressure cycle;

b) deflection cycle;

c) flow-induced vibration;

d) mechanically induced vibration; and

e) temperature cycle.

When both static load and high cyclic load shall be considered, mean stress shall be converted into the equivalent stress range using the modified Goodman chart, and fatigue life shall be evaluated.

The possibility of flow-induced vibration inside the bellows shall be verified by analysis or test.

Testing of unflawed specimens to demonstrate fatigue life of a bellows 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.

5.2.8 Leakage

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

5.2.9 Damage tolerance (safe life)

Bellows with brittle fracture or hazardous LBB failure mode shall meet the requirements of safe life demonstration set forth in ISO 14623 by analysis or test. 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 test.

When stress is a significant part of the total stress test and if a proof test is used for establishing the initial flaw size, stress by imposed load or deflection shall also be counted simultaneously with the proof pressure test.

5.2.10 Miscellaneous

A detailed motion analysis of each new design of the bellows, including mechanical linkage, shall be conducted to demonstrate the accommodation of duct movements by deflection of its convoluted portion.

The mechanical linkage of the bellows shall operate smoothly in order to minimize the reaction force applied to adjacent members (line, other fluid component, etc.). The reaction force shall be under the duct system requirements. Also, the mechanical linkage of the bellows shall be free from sticking caused by solidification of circumferential moisture.

The reaction force on adjacent members resulting from the bellows' deflection shall be calculated and the stress analysis shall be performed.

5.3 Material requirements

5.3.1 Material selection

Metallic materials shall be selected on the basis of proven environmental compatibility, compatibility to adjacent parts material, material strength, weldability, ductility, fracture toughness, and fatigue life characteristics consistent with overall programme requirements.

Materials commonly used for bellows manufacturing should be corrosion-resistant steel or heat-resistant steel.

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5.3.2 Material evaluation

The selected metallic material 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 refurbished configurations.

The evaluation shall ascertain that the mechanical properties, strength, and fatigue properties used in design and analysis will be realized in the actual hardware and that these properties are compatible with the fluid contents and the expected operating environments.

5.3.3 Material characterization

The allowable mechanical and fatigue properties of all selected metallic materials shall be obtained from reliable sources approved by the procuring authority (customer). Where material properties are not available, they shall be determined by test methods approved by the procuring authority.

It is acceptable to use the increased material strength by work hardening effect, which is obtained by forming thin sheet into the shape of the bellows. The source of the work hardening characteristics shall be demonstrated when it is used.

5.4 Fabrication and process control requirements

5.4.1 Introduction

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 paid to fabrication of the bellows' convolution in order to ascertain that forming, welding and heat treatment involve only proven manufacturing techniques and forming limits. Welding, forming, joining, machining, drilling, grinding, and repair operations, etc. as applied to mechanical linkages are also within the state-of-the-art and have been used on similar hardware.

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

Special precautions shall be exercised throughout the manufacturing operations to guard against processing damage.

5.4.2 Contamination control and cleanliness requirements

The cleanliness of the bellows shall be adjusted to the system requirements or the requirements that are approved by the procuring authority.

The bellows shall be designed to control contaminations generated from bellows parts, especially from internal liners or internal mechanical linkage.

5.5 Quality assurance requirements

5.5.1 Quality assurance programme

A quality assurance (QA) programme shall be established to ensure that the product and engineering requirements, drawings, material specifications, process specifications, workmanship standards, design review records, failure mode analyses, NDI, and acceptance tests are effectively used to ensure that the newly applied bellows meets its specified requirements. The programme shall ensure that materials, parts, subassemblies, and assemblies conform to applicable drawings and process specifications; that damage or degradation during material processing, fabrication, inspection, acceptance tests, shipping, storage, operational use and refurbishment is identified, documented, and corrected; and that defects that could cause failure are detected, evaluated, and corrected.

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5.5.2 Inspection plan

An inspection master plan shall be established prior to the start of fabrication. A specific inspection plan shall be prepared for the manufacturing process for bellows, for example, forming bellows or welding bellows. The plan shall specify inspection points and inspection techniques for use throughout the programme, beginning with material procurement and continuing through fabrication, assembly, acceptance proof testing, operation and refurbishment, as appropriate. Especially for the manufacturing process for bellows, for example, forming or welding shall be prepared. 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. 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.

5.5.3 Inspection techniques

Inspection shall include both visual inspection on the inside and the outside of each bellows with appropriate magnification and NDI as necessary. By visual inspection, it shall be confirmed that there is no harmful processing damage and no dents or corrosion.

5.5.4 Inspection data

Inspection data, including flaw histories, shall be maintained throughout the life of the bellows as proof of their completion and for possible analysis later in the event of a production or service problem. These data shall be periodically reviewed and assessed to evaluate trends and anomalies associated with the inspection procedures, hardware, personnel, material characteristics, fabrication processes, design concept, and structural configuration. The result of this assessment shall form the basis of any required corrective action.

5.5.5 Acceptance test requirements

An acceptance test of every production part shall verify conformance to the basic requirements of the engineering procurement document.

Typical tests conducted as an acceptance test for the bellows are:

a) dimensional check;

b) proof pressure test;

NOTE If stress by deformation is critical, the proof factor shall be determined by considering it.

c) leakage test;

d) spring rate test (if critical); and

e) buckling stability test (if critical).

The implementation of acceptance test requirements shall ensure that the programme is carried out in the most efficient manner. For example, after a bellows made by a subcontractor is verified by an acceptance test, tests shall not be repeated unless obvious handling damage has occurred in shipping.

5.6 Operation and maintenance requirements

5.6.1 Operating procedures

Operating procedures shall be established for each bellows. 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 where applicable, and procedures to ensure compatibility of the pressurizing system with the structural capability of the pressurized hardware shall be established.

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Prior to initiating or performing procedures involving pressurized 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 which shall not 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.

During operation or storage, appropriate protective covers should be used to prevent damage to the bellows convolution section.

5.6.2 Safe operating limit

Safe operating limits shall be established for each bellows, 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 items:

a) fabrication materials;

b) design pressure;

c) proof pressure;

d) design burst pressure;

e) pressurization and depressurization sequence;

f) operational cycle limits;

g) temperature;

h) operational system fluid, cleaning agent;

i) permissible thermal and chemical environments;

j) other critical design conditions; and

k) allowed deflection.

5.6.3 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 bellows so that the required inspection interval and repair schedule can be established to maintain hardware to the requirements of this document.

An NDI technique and inspection procedure for reliably detecting defects and determining flaw size under the conditions of use shall be developed for use in the field and depot levels. Procedures shall be established for recording, tracking and analysing operational data as it is accumulated, to identify critical areas requiring corrective action. Analyses shall include predictions of remaining life and reassessment of required inspection intervals.

5.6.4 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. In particular, a conservative estimate of fatigue damage is required.

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5.6.5 Storage

When bellows 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 damage 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 that non-conformance with storage requirements are violated, re-certification shall be required prior to acceptance for use.

5.6.6 Documentation

Inspection, maintenance and operation records shall be kept and maintained throughout the life of each bellows. Operation records for pressure systems are substitutable for each bellows' documentation after the bellows is integrated into the duct system. Records shall include the following:

a) temperature, pressurization history, and pressurizing fluid for both tests and operations (if critical);

b) pressurization history and pressurizing fluid (if critical);

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

d) storage conditions;

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

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

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

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

5.6.7 Reactivation

If a bellows is reactivated for use after an extensive period in either an unprotected or an unregulated storage environment, it shall be re-certified to ascertain its structural integrity and suitability for continued service before commitment to flight. Re-certification tests for a bellows shall be in accordance with the appropriate re-certification test requirements specified in 5.5.5. Inspection for corrosion and incidental damage prior to a re-certification test shall be performed.

5.7 Specific qualification test requirements

The qualification test shall verify the structural integrity, operability and functionality of newly designed bellows for all conditions to which they are subjected during the service life.

Typical tests conducted as a qualification test for bellows are:

a) dimensional check and check of basic materials;

b) proof test;

c) leakage test;

d) spring rate test (if needed, spring rate test should be performed during assembly of the bellows);

e) burst pressure test;

f) buckling stability test (if critical);

g) deflection test (same as the motion capability test);

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h) full specified life time test of bellows and/or fatigue cycling test (pressure cycle, deflection cycle, thermal cycle);

i) pressure drop test (if critical);

j) vibration test (if critical);

k) flow fatigue test (if critical); and

l) bellows stiffness (if critical).

Suitable modifications to correct the difference between test temperature and operating temperature shall be performed if required.

If critical, a destructive metallurgical sectioning test and a verification of minimum inside diameter should be performed.

If critical, a combined test for pressure and deflection shall be conducted.

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Annex A
(informative)

Design safety factors

For a manned space system, the minimum bellows proof test factor should be 1,5 and the minimum design burst factor should be 2,5.

For unmanned space systems, if the presence of a ground crew is allowed during pressurization of the bellows (up to MEOP), the minimum proof test factor for the bellows shall be 1,5 and the minimum burst factor should be 2,5. If the presence of ground crew is not allowed during pressurization of the bellows (up to MEOP), the minimum proof test factor for the bellows can be reduced to 1,25 and the minimum burst factor can be reduced to 1,5.

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