



TECHNICAL STANDARD
FOR
HIGH-PRESSURE GAS EQUIPMENT FOR SPACE USE

March 19, 2020

JAPAN AEROSPACE EXPLORATION AGENCY

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1. General

1.1 Purpose

This technical standard provides technical standard of high-pressure gas equipment installed in launch vehicle and payload developed or launched by Japan Aerospace Exploration Agency (JAXA).

1.2 Scope

This technical standard shall apply to the following high-pressure gas equipment (including purchased item) which is installed in unmanned launch vehicle and payload. High temperature condition which causes creeping problem of material is out of scope in this standard.

The scope of this standard is depicted in Table 1.2-1. The equipment that should be applied to Minister of Economy, Trade and Industry in accordance with High-Pressure Gas Safety Act for special approval of technical standard or license of special filling (hereafter referred to as applied equipment) are illustrated in Figure 1-1 for reference.

Table 1.2-1 Scope of This Technical Standard

No	Classification	Disposable equipment	Reusable equipment	Note
1	Metallic pressure vessel installed in launch vehicle and payload	Applicable	Applicable	Gas reservoir, propellant tank, heat pipe, and pressure vessel for Ni-H ₂ battery
2	Composite overwrapped pressure vessel (COPV) installed in launch vehicle and payload	Applicable	Applicable	Gas reservoir, and propellant tank
3	Propellant tank for launch vehicle (Metallic)	Applicable	Not applicable	
4	Pressure piping, fitting, bellows, and other component	Applicable	Applicable	

1.3 Measurement Unit

This technical standard shall not provide unit of symbol in equation, unless otherwise specified. When it is necessary for calculation, however, SI basic unit (m [length], kg [Mass], s [Time], etc.) and derived units (N [force], Pa [Pressure and

Stress], etc.) shall be used. If unit other than SI basic unit is used, coefficient shall be used for conversion.

1.4 Related Documents

Unless otherwise specified, the latest issue of the following documents shall be applied. When these documents conflict with this technical standard, this technical standard shall have precedence.

1.4.1 Applicable documents

- | | | |
|------|--|--|
| (1) | MMPDS-01 | Metallic Materials Properties Development and Standardization |
| (2) | AFML-TR-68-115 | Aerospace Structural Metals Handbook |
| (3) | AMS2645 | Fluorescent Penetrant Inspection |
| (4) | ASTM-E1742 | Standard Practice for Radiographic Examination |
| (5) | MIL-STD-889 | Dissimilar Metals |
| (6) | AWS D17.1 | Specification for Fusion Welding of Aerospace Applications |
| (7) | ASTM-E1417 | Standard Practice for Liquid Penetrant Examination |
| (8) | SAE-AMS-STD-2154 | Inspection, Ultrasonic, Wrought Metals, Process For |
| (9) | JMR-001 | System Safety Standards (JAXA Document) |
| (10) | JMR-002 | Launch Vehicle Payloads Safety Standards (JAXA Document) |
| (11) | SE-019-094-2H | Material Selection List and Use Instruction SRB/SRM (NASA Document) |
| (12) | Metallic Materials Specification Handbook (Federal Specification) | |
| (13) | JIS B 8266 Appendix 8 (Regulations) Stress and Fatigue Analyses for Pressure Vessels | |
| (14) | NASA-CR 124075 | Isogrid Design Handbook |
| (15) | NASA-CR 912 | Shell Analysis Manual |
| (16) | ASTM D 2290 | Standard test method for apparent tensile strength of ring or tubular plastics and reinforced by split disk method |
| (17) | ASTM D 3039 | Standard test method for tensile properties of fiber resin composite |

(18) JIS-K-6251	Vulcanized rubber and thermoplastic rubber - Method of obtaining tensile properties
(19) JIS B 8277	Expansion joint for pressure vessels
(20) ISO14623	Space Systems - Pressure Vessels and Pressurized Structure - Safe Design and Operation
(21) NDIS 3414	Method of Visual Testing (The Japanese Society for Non-Destructive Inspection Standard)
(22) NAS 1514	Radiographic Standard for Classification of Fusion Weld Discontinuities
(23) ASTM-E164	Standard Practice for Contact Ultrasonic Testing of weldments
(24) CSA-115016	Special Treatment Method for Technical Standards Conformity Examinations of High-Pressure Gas Equipment for Space Use
(25) ASTM-D2344	Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates
(26) JIS K 7078	Testing Method for Apparent Interlaminar Shear Strength of Carbon Fiber Reinforced Plastics by Three Point Loading Method
(27) JIS K 7057	Fiber-Reinforced Plastics: Determining Apparent Interlaminar Shear Strength by the Short-Beam Method

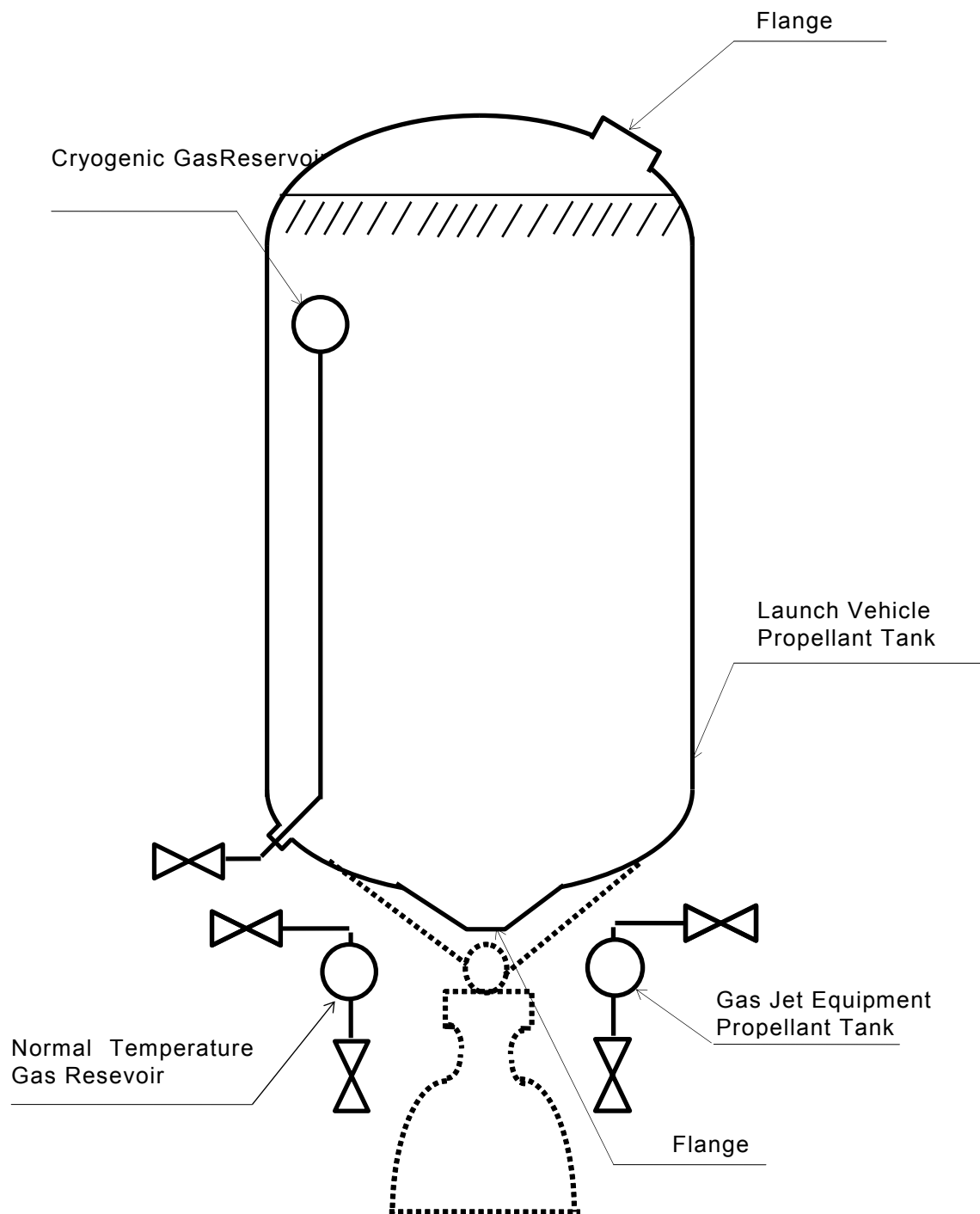
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1.4.2 Reference documents

- | | | |
|-----|---|--|
| (1) | CSA-113004 | Design Criteria for Metallic Pressure Vessels (JAXA Document) |
| (2) | MIL-STD-1522A | Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems |
| (3) | CR 68815 | JAXA Glossary of Space Related Terms |
| (4) | JIS B 0190 | Glossary of Terms Used for Structure of Pressure Vessels |
| (5) | NASA SP-8040 | Fracture Control of Metallic Pressure Vessels |
| (6) | JIS B 8285 | Welding Procedure Qualification Tests for Pressure Vessels |
| (7) | Mechanical Design Handbook (MARUZEN), edited by the Mechanical Design Handbook Editorial Committee of Japan | |
| (8) | Glossary of Technical Terms in Welding and Jointing (SANPO PUBLISHING CO.), edited by the Japan Welding Society | |

- | | |
|--|--|
| (9) JMR-006 | Configuration Management Standard (JAXA Document) |
| (10) JMR-004 | Reliability Program Standard (JAXA Document) |
| (11) JMR-005 | Quality Assurance Program Standard (JAXA Document) |
| (12) Aeronautical and Space Sciences Engineering Handbook (MARUZEN), edited by the Japan Society for Aeronautical and Space Sciences | |
| (13) NASA TN D-8008 | Outgassing Data for Spacecraft Materials |
| (14) MRN89-441 | Out-gassing Data for Organic Materials for Space Use |
| (15) AIAA-83-1274 | High-performance Prestressed Composite Tanks for Space Use |
| (16) NASA-CR-72753 | Development of a Filament-overwrapped Cryoformed Metal Pressure Vessel |
| (17) NASA-CR-72124 | Computer Program for the Analysis of Filament-reinforced Metal-shell Pressure Vessels |
| (18) Bulletin of the Institute of Space and Aeronautical Science, University of Tokyo, Vol. 15, No. 4, "Developmental Research on Carbon-Fiber-Reinforced Plastic Rocket Motor Case" | |
| (19) JERG-0-003 | Technical Standard for High-Pressure Gas equipment for Space Use Handbook (JAXA document) |
| (20) "Reinforced Plastics Handbook" edited by the Reinforced Plastics Association, Nikkan Kougyou Weekly | |
| (21) JEAG 4224-2009 | Technical guidance of plant equipment diagnosis of the nuclear power plant - Radiation wall thickness diagnosis technology |
| (22) CSA-114011 | Conformity evaluation of high-pressure gas equipment for space use (JAXA Document) |
| (23) JIS B 8265 | Construction of pressure vessel - General principles |
| (24) JIS B 8267 | Construction of pressure vessel |
| (25) JIS B 8265 | Annex T(Regulations) "Allowable pressure confirmation testing" |
| (26) JIS B 8210 | Safety devices for protection against excessive pressure – Safety valves |

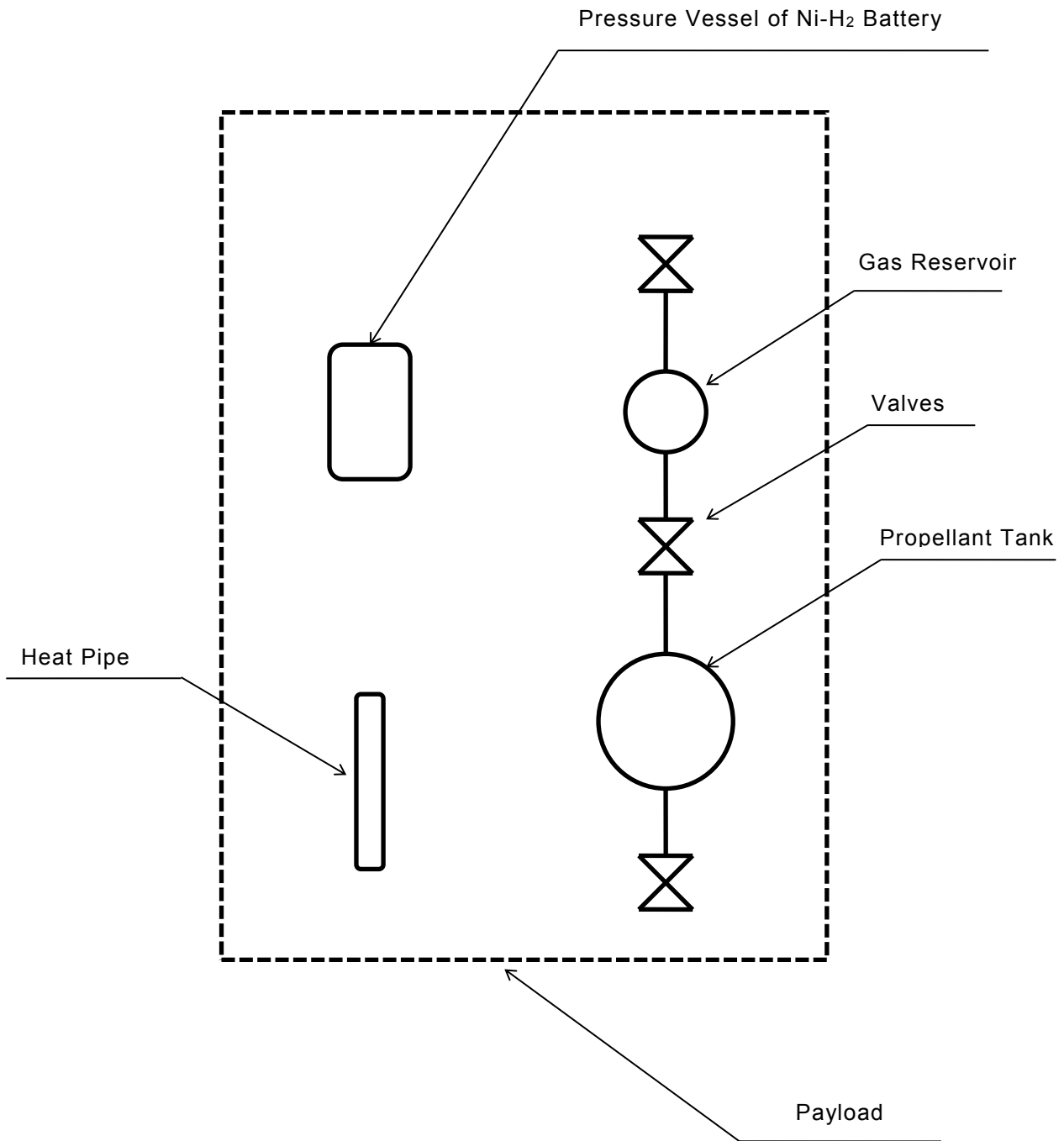
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Note 1) Solid line indicates within the scope.

Note 2) Dotted line indicates out of the scope.

Figure 1-1 (1/2) Applied Equipment Installed in Launch Vehicles (Example)



Note 1) Solid line indicates within the scope.

Note 2) Necessity of application of Heat Pipe and application of Pressure Vessel of Ni-H₂ Battery depends on the equipment design specification.

Figure 1-1 (2/2) Applied Equipment Installed in Payloads (Example)

1.5 Definition of Terms

The terms used in this standard are defined as follows.

Acceptance Test

Acceptance test is the official test conducted for flight hardware to ascertain that the hardware is acceptable for delivery. This test is conducted to confirm whether any defects exist in materials or fabricating processes of the hardware fabricated according to the approved design.

Allowable Stress

Allowable stress is the limit of stress allowed in design, and differs according to the type and division of stress. It is usually expressed as multiples of basic allowable stress.

Autofrettage

Autofrettage is a pressurization process performed after composite materials are formed to expand the elastic deformation range of a metallic liner for COPV operation.

Basic Allowable Stress

Basic allowable stress is the value of tensile stress used as the basis of allowable stress specified by characteristics of material and temperature.

Backing

Backing is a metallic plate, tape or flux, which is attached to the bottom of a groove from the back.

Bending Stress

Bending stress is a component of primary stress that is proportional to the distance from the centroid of a cross-section. It excludes structural discontinuities and stress concentration and is limited to stress generated by mechanical loads.

Buckling strength

Buckling, or buckling load, divided by the buckling safety factor.

Buckling stress

Stress arising in a structural member just before it buckles due to an external force.

Buckling load

Load applied to a structural member just before it reaches a buckled state due to an external force.

Burst Pressure

Burst pressure is the pressure applied to high-pressure gas equipment when actually busted.

Burst Pressure Test

The burst pressure test is a test to confirm that high-pressure gas equipment does not burst when design burst pressure is applied.

Burst Test

The burst test is a test to apply pressure to high pressure equipment until it burst.

Composite Material

Composite material is fiber reinforced plastics composing surface layer of the COPV.

Composite Overwrapped Pressure Vessel (COPV)

COPV is a pressure vessel which is composed with liner (inner layer) and composite material (surface layer).

Cylindrical Composite Overwrapped Pressure Vessel

A cylindrical composite overwrapped pressure vessel is a cylindrical pressure vessel which is composed with liner and filament winding composite material.

Damage Control

An act of control executed to prevent deterioration of COPV's fracture strength below its functional requirements due to mechanical damage.

Damage Prevention Control

Consisting of administrative and control activities to prevent damage, development of a damage prevention control plan, compliance with the plan, and creation and maintenance of damage prevention control record

Damage Tolerant Design

Design that will not lead to a fracture due to a damage, a crack, a peel, an impact or other mechanical damage within a specific period of time, when such damage is not repaired.

Design Burst Pressure

For metallic high-pressure gas equipment, design burst pressure is the product of the MEOP and the safety factor for tensile strength. For COPV, it is the product of the MEOP and the safety factor for design burst pressure.

Design Temperature

Design temperature is provided as a preset condition in a range of temperature used by high-pressure gas equipment.

Fiber

Fiber is a primary reinforcing component for composite materials. It may be a glass fiber, aramid fiber, or carbon fiber.

Filament Winding

Filament winding is the process of winding a fiber impregnated with matrix resin on the outer surface of a liner.

Flux

Flux is a material used to remove impurities, including oxide, from base materials and filler materials; to protect the surfaces of base materials; or to refine weld metals during welding and brazing.

Gas Reservoir

A gas reservoir is a container used to store high-pressure gas.

General Primary Membrane Stress

General primary membrane stress is membrane stress generated by pressure or other mechanical load, in structures having no discontinuous part in general and local construction.

Groove

A groove is a channel or furrow-like space provided in the base metals or between base metals to be welded.

Hazardous Leakage

A hazardous leakage is a leakage of poisonous gas (N_2H_4 , MMH, or NTO), or a leakage which results in a hazard such as breakage of external sections of high-pressure gas equipment caused by a pressure increase due to leakage.

Helical Winding

Helical winding is a method of winding a fiber helically by filament winding.

High-Pressure Gas Equipment

High-pressure gas equipment is the equipment which operates high-pressure gas defined in the High-Pressure Gas Safety Law Article 2.

Hoop Winding

Hoop winding is a method of winding a fiber on the cylindrical part by filament winding. It is also called circumferential winding.

In-plane Winding

In-plane winding is a fiber winding method in which filament winding is performed for a spherical liner. A fiber is wound along a plane passing through the center of article. The plane is continuously shifted so the whole article is overwrapped with the composite.

Launch Vehicle Propellant Tank

The launch vehicle propellant tank is a propellant tank that receives structural loads as a part of the airframe of a launch vehicle.

Leak-Before-Burst (LBB)

LBB is a fracture mechanism design concept in which it is shown that any initial flaw will grow through the wall of high-pressure gas equipment and cause leakage rather than burst.

Leak Test

The leak test is a gas leak test conducted at a pressure not less than the MEOP.

Limit Pressure

Limit pressure is the maximum pressure expected to be applied to the propellant tanks in the operational environment.

Limit Load

Limit load is the maximum load of complex or single load applied in the operation.

Local Membrane Stress

Local membrane stress is the average of membrane stress at any cross-section. Construction discontinuity is considered, but stress concentration is excluded. Only membrane stress generated by mechanical loads is considered.

Local Primary Membrane Stress

Local primary membrane stress is membrane stress generated by pressure or other mechanical load, which becomes large locally due to influence of discontinuity and the like of construction. The membrane stress has secondary stress characteristics but causes large distortion in other parts of construction.

Matrix Resin

A matrix resin fixes a fiber during composite materials forming. It may be impregnated into a fiber beforehand or at the time of forming.

Maximum Expected Operating Pressure (MEOP)

The MEOP is the maximum expected pressure at which high-pressure gas

equipment will actually operate.

Metallic Liner

A metallic liner is metallic hardware that forms the inner layer of a COPV.

Mill Sheet

A Mill sheet is a data sheet developed by a material manufacturer which describes information including test results, fabricated date, order dimensions, quantities, and identification number for tracing the fabricating process from melting to product. Material test report.

E

Mises Equivalent Stress

Mises equivalent stress is quantity which evaluates whether an object under three dimensional stress is yielding or not and is expressed by the equation below.

$$\sigma_e = [1/2 \times \{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\}]^{1/2}$$

where $\sigma_1, \sigma_2, \sigma_3$: principal stress

Mis-match

Mis-match is the discrepancy between the reference surfaces of base materials. When base materials with slightly differing thicknesses are welded together, top or bottom surfaces of the materials specified as reference surfaces are commonly welded to joint such surfaces evenly. The discrepancy that may exist between the base material reference surfaces is called mis-match.

Non-hazardous Leakage

Non-hazardous leakage is leakage that is not hazardous.

Non-metallic Liner

A non-metallic liner is a non-metallic seal composed of an inner layer of the COPV.

Out-gassing

Out-gassing is a phenomenon where a gas, such as water vapor (steam), carbon dioxide, oxygen, hydrogen, or nitrogen, is emitted from the surface or inside of a substance when the substance is exposed to high vacuum or high temperature, or such a gas itself.

Payload

Payload is a cargo item launched by a launch vehicle. For a rocket, payloads include satellites or space probes carried on board.

Peak Stress

Peak stress is the stress increment to primary and secondary stresses due to stress concentration or local stress generated by local structural discontinuities such as uneven surfaces and notches.

Penetration Bead

Penetration bead is regular corrugated bead generated on the opposite side (back side) of the electrode in one-side welding.

POGO

POGO is self-induced vibration manifoldly generated from vibrations of a liquid propellant launch vehicle body and a propellant feed system.

Pressure Cycle Test

The pressure cycle test is a test to confirm that high-pressure gas equipment possesses the specified life by applying pressure simulating the actual pressure pattern.

Pressure Vessel

A pressure vessel is a container used to store pressurized gas whose pressure is greater than or equal to 1.0 [MPa] at operating temperatures (design temperature) or to store liquid gas whose pressure is greater than or equal to 0.2 [MPa] at operating temperatures (design temperature).

Primary Bending Stress

Primary bending stress is bending stress generated by pressure or other mechanical load, in structures having no discontinuous part in general and local construction.

Proof Factor

Proof factor is a design coefficient used to determine defect detection pressure test. The proof factor determines proof life.

Proof Pressure Test

A proof pressure test is a test to confirm whether the part can endure the specified pressure safely or not by applying pressure to the part to receive the internal (external) pressure of high-pressure gas equipment.

Proof Test (Defect Detection Pressure Test)

Defect detection pressure test is a test to assure that a fabricated pressure vessel is free of initial defects significant enough to burst the vessel during operation.

Proof Test Pressure (Defect Detection Test Pressure)

Defect detection test pressure is the pressure used for proof tests. It is equal to

the product of the MEOP and a proof factor. It may also be calculated based on initial flaw size.

Propellant Tank

A propellant tank is a container used to store liquid propellant for launch vehicles and their payloads.

Qualification Test

The qualification test is a test to confirm that systems or subsystems of the launch vehicles and their payloads possess sufficient functions, capabilities, environmental tolerance, and durability to undergo launch and on-orbit operation.

Secondary Stress

Secondary stress is a vertical stress or shearing stress generated by constraints of neighboring structures or self constraints, and is self-limiting.

Shakedown

When the stress exceeds yield strength of a material due to loading cycles which correspond to primary and secondary stress, the material shows elasto-plastic behavior and deformation of the material may progress. Shakedown refers to a phenomenon in which elastic behavior of the material appears after initial elasto-plastic behavior and deformation will not occur.

Sloshing

Sloshing is the back-and-forth movement of liquid propellant in the propellant tanks for liquid propellant launch vehicles.

Stress Corrosion Cracking

Stress corrosion cracking is a phenomenon in which a corrosive environment and a constant sustained tensile stress embrittle an alloy causing a flaw which eventually destroys the alloy.

Stress Intensity

Stress intensity is twice the maximum shearing stress at a point given by the equivalent strength of combined stress, which is the algebraic difference of the maximum value and the minimum values of principal stresses. When there are three principal stresses, $\sigma_1 > \sigma_2 > \sigma_3$, stress intensity S is defined by $S = \sigma_1 - \sigma_3$.

Stress Rupture

A phenomenon where a crack develops over time under a continuous load and eventually leads to a rupture.

Stress Rupture Strength

Tensile strength when a rupture occurs due to stress rupture under a continuous load.

Structural Element

A structural element is an element of high-pressure gas equipment required to retain pressure.

Ultimate

Ultimate refers to the point at which the structure is collapsed or destroyed or at which the structure no longer supports the loads.

Ultimate Load

Load limit multiplied by tensile strength, design burst pressure, or ultimate load safety factor. Requirements are usually for no failure under the ultimate load.

E

Waiver

A waiver is a written authorization granted for use or acceptance of equipment not conforming to the specified requirements.

Weldability

Weldability is a property indicating whether a material is suitable for welding and the degree of difficulty in welding. Weldability can be roughly classified in terms of welding procedures (jointability) and usability of a welded structure.

Welding Bead

Welding bead is welding metal and deposited metal produced by the weld path; often simply called bead.

Welding Deformation

Welding deformation is deformation in materials or structures due to welding. It is commonly called welding distortion. Lateral bending is most general and is called angular deformation.

Yield Ratio

Yield ratio is defined as material yield stress divided by tensile strength.

Special treatment

If conditions do not meet requirements in the technical standards, the reasons for not satisfying those requirements and alternative measures, a description of contents of studies for assuring safety, and the like, confirming that the intent of the technical standards is satisfied and showing conformance to the provisions of the technical standards.

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Porosity

Spherical cavities created in welds due to gas entrainment. Blowholes.

2. Design and Fabrication Procedure for High-Pressure Gas Equipment for Space Use

2.1 Development Flow

High-pressure gas equipment installed in launch vehicle and the payload shall generally be developed according to the flow specified in Figure 2-1. Although slight changes due to individual system requirements shall be accepted, validity of the design shall be verified by prototype model which is fabricated as same configuration as flight model and tested before flight model is fabricated. This scheme is different from ground use high-pressure gas equipment and is required to allow space use high-pressure gas equipment to adopt lower safety factor than that for ground use. Reusable high-pressure gas equipment requires additional process for re-flight. Reusable high-pressure gas equipment shall comply with requirements in paragraph 6 of “Reuse”.

Design and fabrication shall also be appropriately managed in accordance with the separately specified configuration management program, reliability program, quality assurance program and system safety program.

2.1.1 Design

(1) Design condition

Specify the design conditions according to paragraph 3.1. In particular, take into account of all environmental conditions (including pressures and loads) to which high-pressure gas equipment are exposed from the fabrication to completion of planned flights. Accordingly set design conditions for design rating.

(2) Structural type

Set structural type described in paragraph 3.2 according to the design conditions.

(3) Selection of material

Conduct trade-off of materials described in paragraph 3.3 based on the structural type described in 3.2, and select appropriate materials. Conduct a materials test and work test if necessary when select materials.

(4) Calculation of thickness

Calculate thickness according to paragraph 3.4.

(5) Detailed analysis

Perform detailed analysis according to 3.5 and confirm that proper margin is allowed for strength, buckling (if necessary), and life, and that the design is satisfied with the design conditions described in paragraph 3.1. If the design is not satisfied, look back structural type, material, thickness and others, and perform the analysis again.

2.1.2 Qualification test

After the design described in paragraph 2.1.1 completed, fabricate a prototype model as the same configuration as the flight model and verify validity of the design by conducting qualification test such as vibration test, pressurized cycle test, and burst test. Additionally set valid fabricating process and inspection process. Verify validity and quality of those processes through the qualification test or other method.

When necessary, conduct a material basic test, determine and verify the welding method, and conduct the prototype model test as development test prior to the qualification test to confirm design data, fabrication method and test method needed to fabricate a prototype model to be used for qualification test.

2.1.3 Flight model fabrication

Fabricate flight hardware after the qualification test is completed and validity of the design and the fabricating process is verified. Conduct an acceptance test for flight hardware to verify the possibility of accepting the deliverable item. An acceptance test is conducted to verify that the flight hardware fabricated according to the approved design does not have any material or fabricating flaw.

2.2 Exemption Provision

When one of the following conditions is met, a part of the requirements in this standard shall be exempted from application at design/fabrication compatibility review.

2.2.1 High-pressure gas equipment of safety factor 4 or more

(1) Exempt conditions

Some requirements in this technical standard are exempt when metallic high-pressure gas equipment possess a tensile strength safety factor greater than or equal 4, when a COPV possesses a safety factor greater than or equal to 4 for design burst pressure.

(2) At design conformity assessments

The following review provisions in paragraph 3, "Design" can be exempted by submitting thickness calculation results of shell plate, head and piping when compatibility in terms of design is reviewed.

3.5.1 Stress analysis

3.5.2 Judgment of LBB occurrence (analysis and test)

3.5.3 Fatigue damage analysis and test

3.5.4 Crack growth analysis and test

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(3) At fabrication conformity assessments

Some requirements in paragraph 4, "Fabrication" may be exempted by submitting documents specified below for fabrication compatibility review.

- a. A mill sheet for metallic materials used, an inspection report for composite and nonmetallic materials, etc.
- b. Result of pressure test using more than 1.5 times of MEOP
- c. Result of leak test using more pressure than MEOP
- d. Nondestructive inspection results for welds
- e. Thickness measurements (when the minimum thickness cannot be confirmed on the mill sheet)

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(4) Qualification tests

The qualification tests described in paragraph 5.2 may be exempt.

If specific capability such as the environmental tolerance, the tendency of material quality change, and so on is not enough for this standard, some appropriate qualification tests should be added.

2.2.2 High-pressure gas equipment that have been qualified

(1) Exempt conditions

Exempt items include the follow: those developed by organizations such as NASDA, ISAS, NAL, NASA, and ESA for use in satellites, rockets, or related projects; items developed for other spacecraft, subjected to design conformance reviews based on these technical standards and issued conformance certification; and devices that have passed safety reviews at launch sites in the US, Europe, and elsewhere, and for which certification tests have been completed (hereinafter, "qualified equipment").

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Qualified equipment shall be used for projects subject to this technical standard in the following three ways:

- a. Use equipment newly fabricated using the same design.
- b. Use equipment already fabricated.
- c. Use equipment fabricated with slight modifications in the same design that will not affect item strength.

(2) At design conformity assessments

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Some requirements in paragraph 3, “Design” may be exempt by submitting the documents specified below for design compatibility review.

- a. Operating conditions (pressure, temperature, vibration, etc.) do not exceed those qualified at the time of device development.
- b. Design data prepared for a qualification test of the qualified equipment shall meet the requirements of this technical standard.
- c. If any analysis required in this technical standard has not been conducted for a qualification test of the qualified equipment, conduct the analysis according to this technical standard.

(3) At fabrication conformity assessments

If using an item already fabricated according to the same design, the some requirements in paragraph 4, “Fabrication” can be exempted by submitting the inspection records (including mill sheets, proof pressure test records, leak test records, nondestructive inspection records, and dimension (thickness) inspection records) for design compatibility review.

2.2.3 Purchased item

(1) Corresponding conditions

There is a product catalog, product specifications, etc., allowing purchase by specification of a model number, etc., and the following conditions a.–d. are described in a product catalog, technical data, product specification, or other source.

- a. Operational condition is within the operation range.
- b. Test equivalent to a qualification test is performed.
- c. Safety factor shall be more than 1.5 for yield stress and more than 2.5 for tensile strength.
- d. The purchased item has heritage on the ground or in space.

(2) At design conformity assessments

(1) Examination items required by section 3 “Design” can be exempted by submitting documents indicating the relevant conditions, except for the following items.

- 3.1.3.1 Safety coefficients related to pressure
- 3.1.5(3) Lifetime requirements for operational and displacement cycles

Also, the following examination items required by section 4 “Manufacturing” do not apply:

- 4.1 Finishing and molding

- 4.2 Welding
- 4.3 Heat processing
- 4.7.1 Material acceptance inspections
- 4.7.2 Parts inspections (for metallic materials)
- 4.7.3 Welded parts inspections

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(3) At fabrication conformity assessments

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Some requirements in paragraph 4, “Fabrication” may be exempted by submitting the inspection record (including proof pressure test record, leak test record, and functional test record) or the certificate issued according to acceptance inspection procedure for design compatibility review.

2.2.4 High-pressure gas equipment for space use certified as conforming to other technical standards

For flight items of high-pressure gas equipment developed and certified as conforming to the following standards, if documentation cannot be obtained from the accrediting body*1 confirming conformity to the requirements of this standard (documentation confirming design and qualification test results, inspection reports for flight item testing, etc.), or if such data is unavailable due to export restrictions or other such reasons, then submit the certificate from the accrediting body as the examination material.

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- (1) ISO 14623 “Space systems - Pressure vessels and pressurized structures - Design and operation”

- (2) Example criteria for container security regulations

- (3) Other standard that is considered to be equivalent.

When submitting confirmation documentation from accrediting bodies, attach the following documents at a minimum.

- a. A statement describing operating conditions (MEOP, expected life, etc.), design conditions (safety factor), a development test and a certification test conducted; and
- b. A certificate of a material’s quality and performance as a flight product, a dimension inspection report, a nondestructive testing report, a proof pressure and airtight test report, and a pressure cycle life report.

If documentation from the accrediting body confirming conformity to the requirements of this standard cannot be obtained, or if certifications from the accrediting body are unavailable, submit evidence of launch-site safety reviews performed in the United States, Europe, etc.

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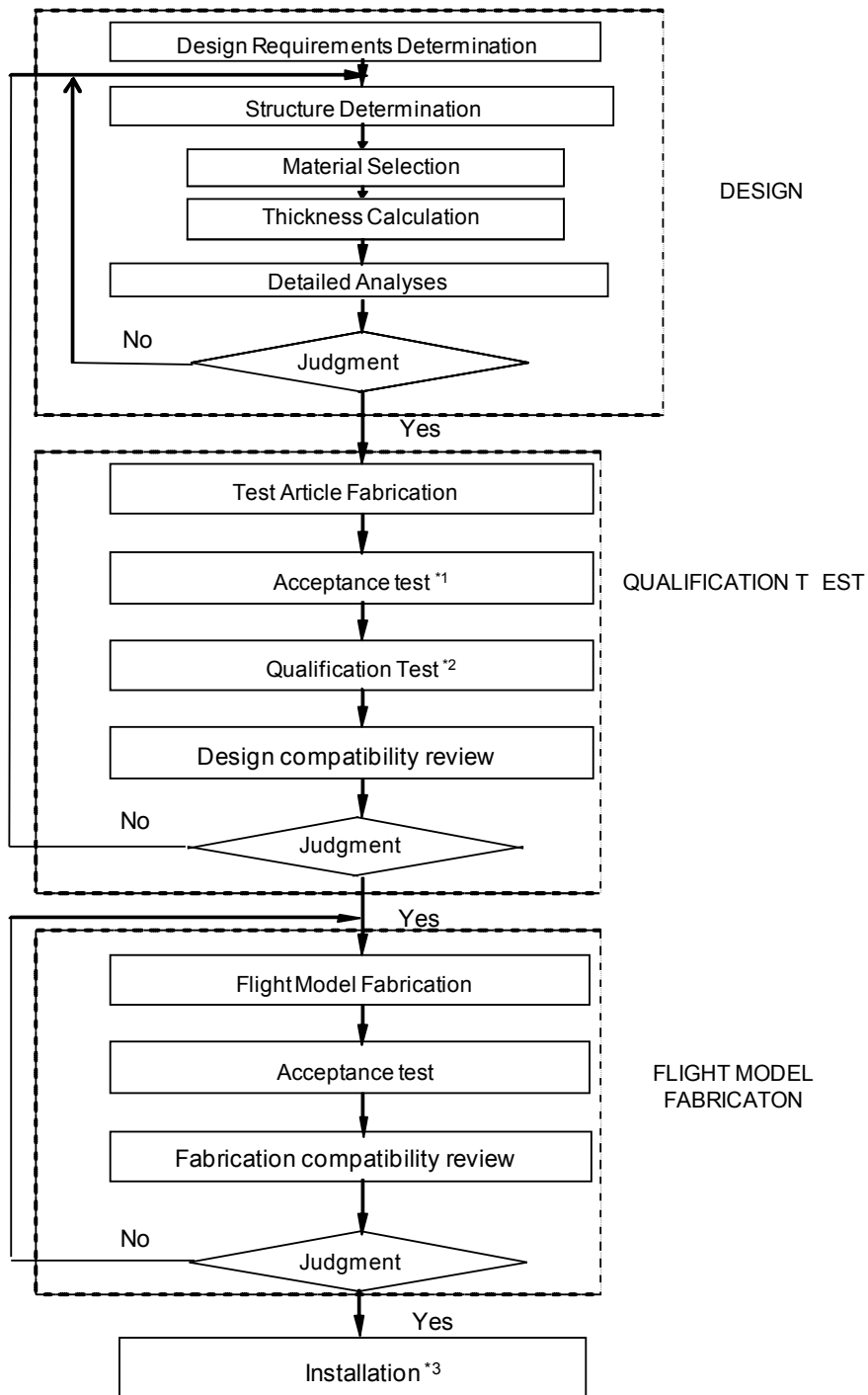
*1: Here, accrediting bodies are defined as government institutions such as

NASA or ESA, or public third-party organizations such as KHK.

2.3 Special Treatment

If the requirements of this technical standard are not satisfied, perform special treatment and submit a special treatment report with conformity assessments for these technical standards as pertaining to design and fabrication. This report should indicate considerations regarding the reasons for not satisfying the provisions of this technical standard, alternative measures, the basis for ensuring safety, etc. Exemptions from conformity assessments in the relevant parts of these technical standards will be permitted only when the contents of this report can be confirmed as valid. Note that the reporting method must be based on the technical document CSA-115016 “Special Treatment Method for Technical Standards Conformity Examinations of High-Pressure Gas Equipment for Space Use.”

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*1 As a part of qualification test, test identical with the acceptance test performed by the flight model shall be conducted

*2 Development test (material basic test and determination and confirmation of welding method, and prototype test) can be conducted before qualification test.

*3 When malfunction is found and equipment is exchanged during installation, rectification shall be reviewed.

Figure 2-1 High-pressure Gas Equipment Design and Fabrication Flow

3. Design

3.1 Setting of Design Conditions

3.1.1 Function and performance requirements

High-pressure gas equipment shall endure the environmental conditions of pressure, load, and temperature, and others expected from the fabrication phase to the completion of the planned number of flights and meet functional and performance requirements of the system incorporating the high-pressure gas equipment.

3.1.2 Load and temperature conditions

The following load history shall be taken into account for setting load conditions.

Fabrication test phase	Proof test pressure
	Proof test pressure (Defect detection pressure test, if conducted)
	Leak test pressure
Ground handling phase	Load applied during transportation
	Load applied during assembly
	Leak test pressure
	Load applied by ground surface wind
	Load applied during propellant loading test
	Load applied during captive firing test (CFT)
	Load applied during cryogenic checkout
Flight phase	Load applied during flight

3.1.2.1 Maximum Expected Operating Pressure (Limit pressure)

Establish the MEOP for high-pressure gas equipment (which is limit pressure for launch vehicle propellant tanks).

Consider all pressure conditions to which the high-pressure gas equipment are exposed from the fabrication phase to the completion of the planned number of flights in establishing the MEOP.

Calculate the enveloped values of the pressure distribution history and make its maximum pressure the MEOP (limit pressure).

Consider pressures applied during the fabrication test (except proof pressure test and defect detection pressure test), ground handling and flight.

(1) Limit pressure to launch vehicle propellant tank

For propellant loading and flight, pressure at the liquid head of the propellant generated by acceleration shall be considered in addition to the pressurization

pressure at ullage. Acceleration during flight shall be established considering static acceleration along the axis of the vehicle and dynamic acceleration due to low frequency vibration. For low- frequency vibrations, consider propellant sloshing, POGO, transient response at engine ignition, transient response due to sudden gusts of wind, and so on.

$$[\text{MEOP (limit pressure)}] = [\text{Maximum pressurized pressure at ullage}] + [\text{liquid head pressure}]$$

Limit pressure shall be the maximum pressure in every vehicle axis direction.

The maximum pressurization pressure at ullage shall be determined considering the followings:

- 1) Nominal operating pressure,
- 2) Pressure control range,
- 3) Pressure overshoot,
- 4) Pressure measurement error,
- 5) Pressure applied during vent valve operation,
- 6) Pressure loss in pipes during vent valve operation,
- 7) Ambient atmosphere pressure, and
- 8) Other

$$[\text{Liquid head pressure}] = [\text{Propellant density}] \times [\text{Acceleration in the vehicle axis direction during flight}] \times [\text{Height of liquid surface}]$$

(2) MEOP of high-pressure gas equipment other than launch vehicle propellant tanks

The pressure increment caused by acceleration as well as pressurization pressure during flight shall be considered. However, pressure increment smaller than the pressurization pressure may be ignored.

(3) Correction pressure for a cryogenic propellant tank at normal temperature

At normal temperature, a cryogenic propellant tank and the like shall be pressurized at a pressure equal to or less than the limit pressure corrected for the ratio of material yield stress at design temperature and material yield stress at normal temperature as shown in the following equation.

$$[\text{Pressurized pressure at normal temperature}] \leq [\text{Limit pressure at design temperature}] \times [\text{Yield stress at normal temperature}] / [\text{Yield stress at design temperature}]$$

Design burst pressure for a cryogenic propellant tank and the like at normal temperature shall be corrected with for the ratio of tensile strength at design

temperature and tensile strength at normal temperatures as shown in the following equation.

$$\begin{aligned} [\text{Design burst pressure at normal temperature}] = & [\text{Design burst pressure at design} \\ & \text{temperature}] \times [\text{Tensile strength at normal temperature}] \\ & / [\text{Tensile strength at design temperature}] \end{aligned}$$

3.1.2.2 Load during flight

During flight, high-pressure gas equipment receives the flight load (external load) and the pressure load. The flight load shall be considered to be the following loads at a certain time during the flight.

Validity evaluation criteria for the flight load or that of analysis method is out of scope, since the flight load shall be given by space system.

(1) Launch vehicle propellant tank

Examples of the compressive loads in the vehicle axis direction

- 1) Engine thrust
- 2) Inertial force in the vehicle axis direction
- 3) Payload inertial force
- 4) Air drag
- 5) Load due to low frequency vibration response

Examples of shearing forces perpendicular to the vehicle axis

- 1) Aerodynamic force during flight in attack angle
- 2) Aerodynamic force due to gusty wind
- 3) Engine thrust component perpendicular to the vehicle axis (while steering)
- 4) Inertial force component perpendicular to the vehicle axis
- 5) Load due to low frequency vibration response

Examples of bending moments

- 1) Moment generated due to distributed shearing force perpendicular to the vehicle axis

Use conservative value of parameter which has variance, such as wind direction and wind velocity. Figure 3.1.2-1 shows the limit load of the H-II launch vehicle during flight for reference.

(2) High-pressure gas equipment other than launch vehicle propellant tank

For high-pressure gas equipment other than launch vehicle propellant tank, the

following accelerations and environmental conditions during flight shall be considered.

a. Quasistatic acceleration

Specify quasistatic acceleration with a sum of static acceleration and vibration load in the vehicle axis direction and perpendicular to the vehicle axis which affect the center of gravity of high-pressure gas equipment at the time of a vehicle launch.

b. Sinusoidal wave vibration acceleration

Specify sinusoidal wave vibration acceleration by converting a transient response and self-induced vibration propagating from the main body of a launch vehicle at the time of a vehicle launch and completion of the first- and second-stage firing and so forth.

c. Acoustic and random vibration environment

Specify acoustic and random vibration environment either by random vibration at equipment installation surface on a launch vehicle or payload defined as random vibration response due to acoustically induced vibrations during vehicle launch and transonic aerodynamic vibrations, or acoustic vibration which correlates with sound strength directly imparted on the installed equipment. Note that acoustic and random vibration environments may not be equivalent to each other due to differences in boundary conditions when the installed equipment is small or its mass to volume ratio is large.

d. Impact environment

When retention or release device or a similar device using pyrotechnics is operated, ignition of pyrotechnics, loosening of retention release mechanism or collision of movable parts may cause an impact. The impact force shall be described in a Fourier spectrum by the response spectrum or impact response spectrum.

3.1.2.3 Load during ground handling

During ground handling, launch vehicle propellant tank is loaded the ground handling load in addition to the pressure load. The ground handling load shall be considered the following loads.

Examples of the compressive load in the vehicle axis direction

- 1) Load induced by the launch vehicle airframe in vehicle axis direction
- 2) Mass of the payload

Examples of the shearing forces perpendicular to the vehicle axis

- 1) Aerodynamic force due to ground surface wind

2) Static load generated during transportation

3) Load due to low-frequency vibrations during transportation

Examples of bending moment

1) Moment generated due to distributed shearing force perpendicular to the vehicle axis.

For high-pressure gas equipment other than launch vehicle propellant tanks, ground handling load shall be smaller than the flight load. Ground handling load shall be calculated by multiplying analyzed ground handling load by the special factor, considering operator's safety and uncertainty of load. The special factor shall be greater than 1.06.

Validity evaluation criteria for the ground handling load or that of analysis method is out of scope, since the ground handling load shall be given by the system.

3.1.2.4 Temperature condition

Design temperature of high-pressure gas equipment shall be set considering all temperature conditions to which the equipment will be exposed through the completion of the planned number of flights. Consider the temperatures during fabrication testing, ground handling, and flight.

High temperature condition which causes creeping problem of material is out of scope in this standard.

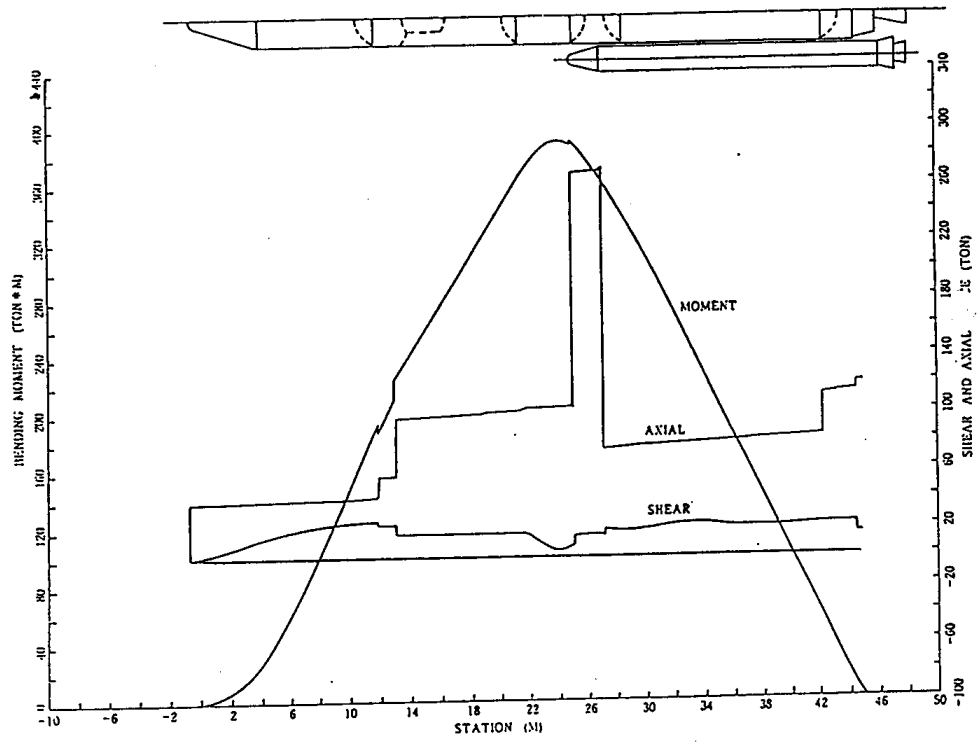


Figure 3.1.2-1 Limit Load of H-II Launch Vehicle during Flight (Example)

3.1.3 Safety factor

Safety factor for high-pressure gas equipment is shown below.

3.1.3.1 Safety factor for pressure

For metallic high-pressure gas equipment, safety factor for material strength is specified in Table 3.1.3-1. For COPV, safety factor for design burst pressure is specified in Table 3.1.3-2.

Table 3.1.3-1 Safety Factor for Material Strength of Metallic High-Pressure Gas Equipment

No.	Structural Category	Safety Factor		Condition (Note 1)
		Yield Stress (σ_y)*	Tensile Strength (σ_u)	
1	Pressure Vessel	1.5 or more	2.0 or more	Possible to approach
2	Pressure Vessel	(1+[safety factor for tensile strength])/ 2 or more	1.5 or more, less than 2.0	Impossible to approach (Note 2)
3	Pressure Piping and Fitting (38.1 mm or more in diameter)	1.5 or more	2.5 or more	Possible to approach (Note 3)
4	Pressure Piping and Fitting (Less than 38.1 mm in diameter)	1.5 or more	4.0 or more	Possible to approach (Note 3)
5	Bellows	1.0 or more	1.5 or more	Impossible to approach (Note 2)
6	Bellows	1.5 or more	2.5 or more	Possible to approach
7	Other Components	1.5 or more	2.5 or more	Possible to approach (Note 3)
8	Launch Vehicle Propellant Tank	1.0 or more	1.25 or more	Impossible to approach

*: or 0.2% of proof stress (hereafter referred to as yield stress)

Table 3.1.3-2 Safety Factor for Design Burst Pressure of COPV

No.	Safety Factor	Conditions (Note 1,4)
1	2.0 or more	Possible to approach
2	1.5 or more, less than 2.0	Impossible to approach (Note 2)

Note 1 Indicates whether personnel can approach the equipment when MEOP is applied and stabilized. When pressure of less than one fourth of the

design burst pressure is applied, personnel can approach the equipment at any time.

Note 2 Personnel can approach when LBB occurrence is confirmed. When LBB occurrence is not confirmed, personnel can approach the vessel after pressure is stabilized when pressure of less than half of design burst pressure is applied to pressure vessel.

Note 3 When pressure piping, fitting, and other components do not meet the above safety factor requirements, such components shall be categorized as pressure vessel.

Note 4 If the capacity is 500 L or less and tensile testing is performed on the base material of liners (excluding nonmetal liners) or welded parts during certification testing, access by personnel must always possible when the following pressures are applied:

Carbon fiber composite pressure vessels: 1/2.25 of design burst pressure or less

Aramid fiber composite pressure vessel: 1/3 of design burst pressure or less

Glass fiber composite pressure vessel: 1/3.5 of design burst pressure or less

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3.1.3.2 Safety factor for flight load

For metallic high-pressure gas equipment, the safety factor for material strength is defined in Table 3.1.3-3.

For COPV, the safety factor for yield stress (metallic liner) and ultimate load is defined in Table 3.1.3-4.

The load shall be the flight load which is shown in paragraph 3.1.2.2.

Table 3.1.3-3 Safety Factors for Material Strength of Metallic High-Pressure Gas Equipment for Flight Load

Structural Category	Safety Factor	
	Yield Stress (σ_y)	Tensile Strength (σ_u)
Metallic high-pressure gas equipment	1.0 or more	1.25 or more

Table 3.1.3-4 Safety Factors for Yield Stress (Metallic Liner) and Ultimate load of COPV for Flight Load

Structural Category	Safety Factor	
	Yield Stress (Metallic Liner) (Note 1)	Ultimate load
COPV	1.0 or more	1.25 or more

Note 1 Safety factor for metallic liner does not yield when used.

3.1.3.3 Safety factor for buckling

If high-pressure gas equipment requires consideration of buckling, use the safety factors for tensile strength, design burst pressure, and ultimate load listed in Tables 3.1.3-1 through 4 as the buckling safety factor.

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3.1.3.4 Safety factor for ground handling (only for launch vehicle propellant tanks)

Safety factor for ground handling shall be safety factor for launch vehicle propellant tank in Table 3.1.3-1.

The load shall be the ground handling load which is shown in paragraph 3.1.2.3.

3.1.4 Interface requirements

(1) Interface with the system

High-pressure gas equipment shall be installed in a launch vehicle or payload system using a neighboring structure, supporting truss or bracket. The interface shape shall satisfy environmental requirements (e.g. load, vibration, impact, heat transfer) from the system.

Cryogenic propellant tank shall be appropriately insulated to maintain a temperature increases in propellant caused by aerodynamic heating within allowable limits.

(2) Interface with fitting

High-pressure gas equipment shall be capable of having propulsion system fittings such as piping to supply propellant, pressurization piping, various valves, baffles, thermo-sensors and pressure sensors; electric system fittings such as wire harness; and pyrotechnics installed. The interface shape shall be suitable for fittings such as flanges, bosses or brackets.

(3) Interface with Ground-Support Equipment

High-pressure gas equipment shall have, in general, piping to load and unload liquid and gas. The interface shape shall be compatible with a pipe of Ground-Support Equipment (GSE). The interface shape shall be selected appropriately considering connection/disconnection with piping of GSE, leakage resistance, and so on.

Cryogenic propellant tank shall be appropriately insulated to keep propellant evaporation losses within allowable limits.

3.1.5 Life requirements

The required life of high-pressure gas equipment shall be appropriately set considering the period from the fabrication phase to the completion of the

planned number of flight as follows.

(1) Number of flight

The high-pressure gas equipment needs the specified number of flight for the life assessment.

(2) Life requirement for pressure cycle

The number of pressure loading cycle shall be considered all pressure loading from the first proof test to the end of mission. The number shall include certain extra pressure loadings that are needed by retesting or launch abort.

(3) Life requirement for operational cycle and displacement cycle

The operational life of the high-pressure gas equipment having movable mechanism such as electromagnetic valve and fill and drain valve shall be considered all operational cycle from the acceptance test to the end of mission. For the bellows, displacement cycle is used as for the operational cycle. The number shall include certain extra cycles for retesting and launch delay.

3.2 Structure Type Setting

3.2.1 Structure type of metallic pressure vessel

A metallic pressure vessel stores fluid such as propellant or pressurized gas and consists of shell part which receives pressure load, mounting part which is used to connect to launch vehicle or payload, and piping part which is used to pressurize gas or used to load/unload propellant.

Shell forms various shapes such as sphere, ellipsoid, cylinder, cone or these combination. Shape of the shell shall be selected considering capacity, weight, and installation and so on. Mounting shape shall be selected so that metallic pressure vessel is installed in rocket or payload.

Examples of the structure type of metallic pressure vessel are shown in Figure 3.2-1.

3.2.2 Structure type of launch vehicle propellant tank

Structure of launch vehicle propellant tank shall, in general, consist of cylinder part and head (dome) part. It shall also include a flange to connect to the neighboring structure, a lid to access an inner tank, a hole through which fluid such as propellant and pressurizing gas is loaded and unloaded, and mounting on which various fittings are installed.

Cylinder part structure shall be selected considering the strength to withstand various loads (internal load, and external load which affects launch vehicle during flight and ground handling), fabricability, and handlability.

Head part structure shall also be selected considering affecting loads (internal pressure load, and propagation of external load to a cylinder part such as engine propulsion and inertial force), fabricability, and mass.

Head structure shall be spherical shell, ellipsoidal shell, or other shaped shell. A tank with a common bulkhead which separates space of a tank.

Because the launch vehicle propellant tank structure affects the launch vehicle length and weight, basic specification of the tank shall be determined after detailed investigation during system design for the entire launch vehicle.

Examples of the structure are shown in Figure 3.2-2.

3.2.3 Structure type of COPV

COPV consist of liner layer (inner layer) and filament winding layer (outer layer). Liner may be metallic liner or non-metallic (plastic or rubber) liner.

Both metallic and non-metallic liner shall preserve gas permeation barrier of the vessel. Metallic liner shall share to bear pressure loads, while non-metallic liner shall not share in this technical standard.

To apply compressive stress to metallic liners, metallic liner may be subjected to autofrettage by applying internal pressure after composite material forming is completed. The pressure to produce autofrettage shall be about 100 to 110% of the proof test pressure.

(1) Spherical COPV

Spherical COPV shall consist of spherical liner and in-plane filament winding layer. The total number of windings, winding angle, winding pitch and such shall be determined considering geometric properties such as the shape of the port and vessel diameter, as well as liner material, external load supporting method and such.

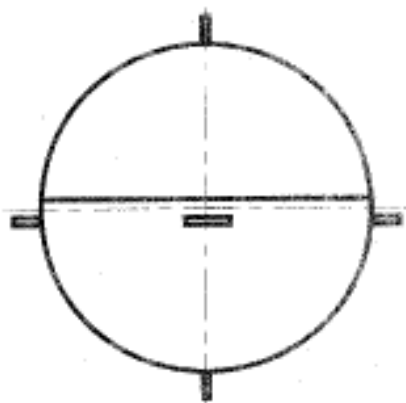
Figure 3.2-3 shows an example of the structure of a spherical COPV.

(2) Cylindrical COPV

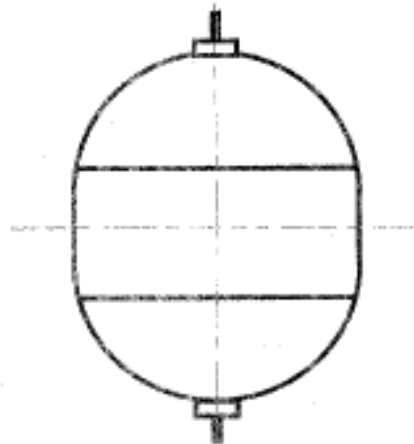
The structure of a cylindrical COPV consists of a liner, a body-head unit with a reinforced filament winding layer, and a body reinforcement hoop layer (a full-wrap structure) or one in which only the body is reinforced with a hoop layer for a metal pressure vessel (a hoop-wrap structure).

Filament winding may be performed by in-plane winding, helical winding, or hoop winding. These winding patterns are illustrated in Figure 3.2-4, and Figure 3.2-5 shows the hoop-wrap structure. Determine the winding method and other aspects of container construction in consideration of its geometric form, such as its base shape, container diameter, container length, and positioning of the hoop layer end, as well as the liner materials, metal pressure vessel materials, the method for supporting external loads, etc.

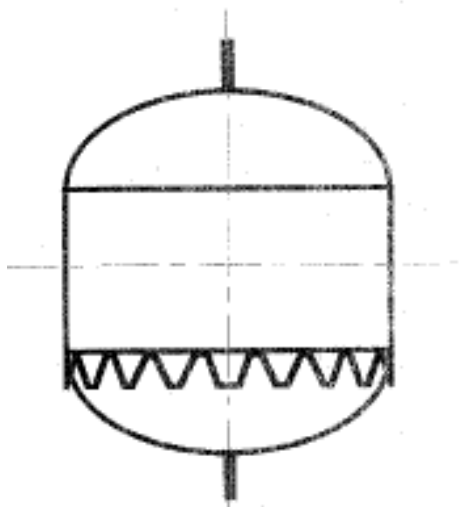
In designing COPV, the rupture mode and rupture position should be specified after structural type is determined. For long cylindrical COPV, cylinder part should be selected as design evaluation part since the stress status of shell is easily identified.



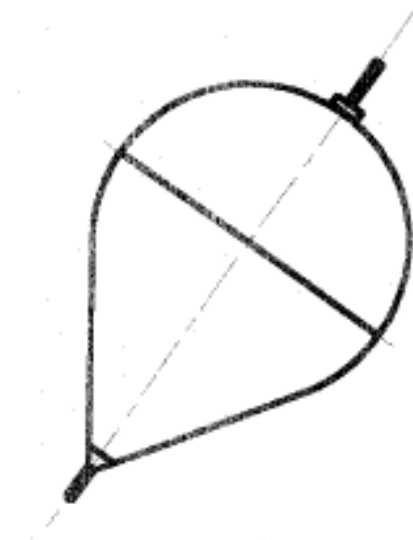
Spherical Vessel



Cylindrical Vessel (Spherical Dome)

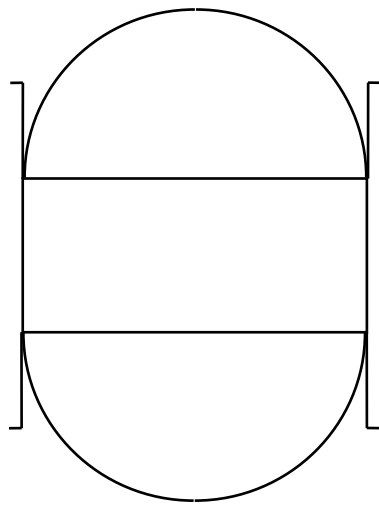


Cylindrical Vessel (Ellipsoidal Dome)

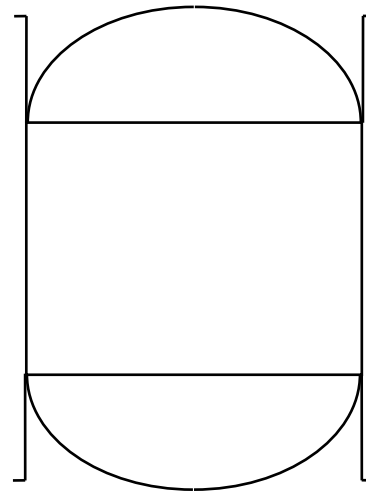


Teardrop Vessel

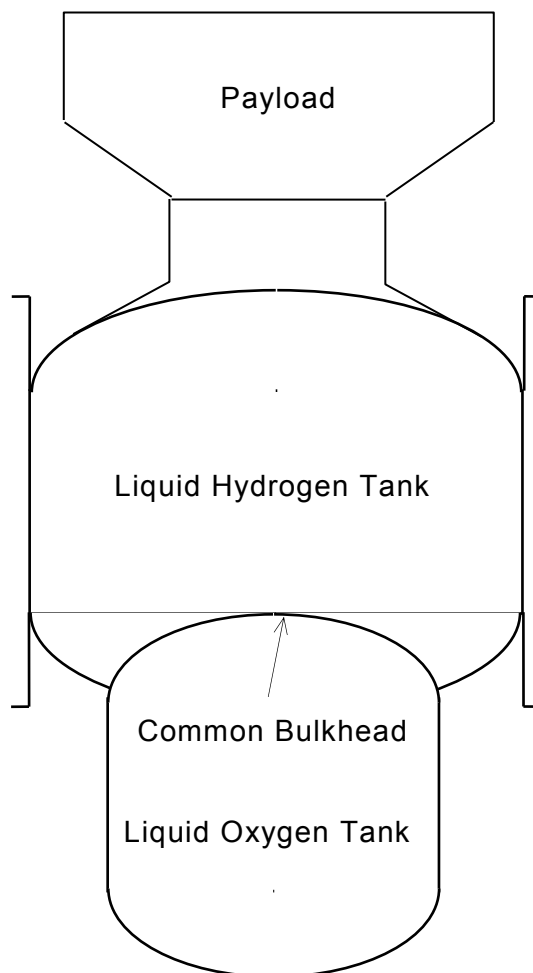
Figure 3.2-1 Examples of Structures of Metallic Pressure Vessel



Cylindrical Tank
(Spherical Dome)



Cylindrical Tank
(Ellipsoidal Dome)



Tank with a Common Bulkhead
(2nd-stage Tank of H-II Launch Vehicle)

Figure 3.2-2 Examples of Structures of Launch Vehicle Propellant Tank

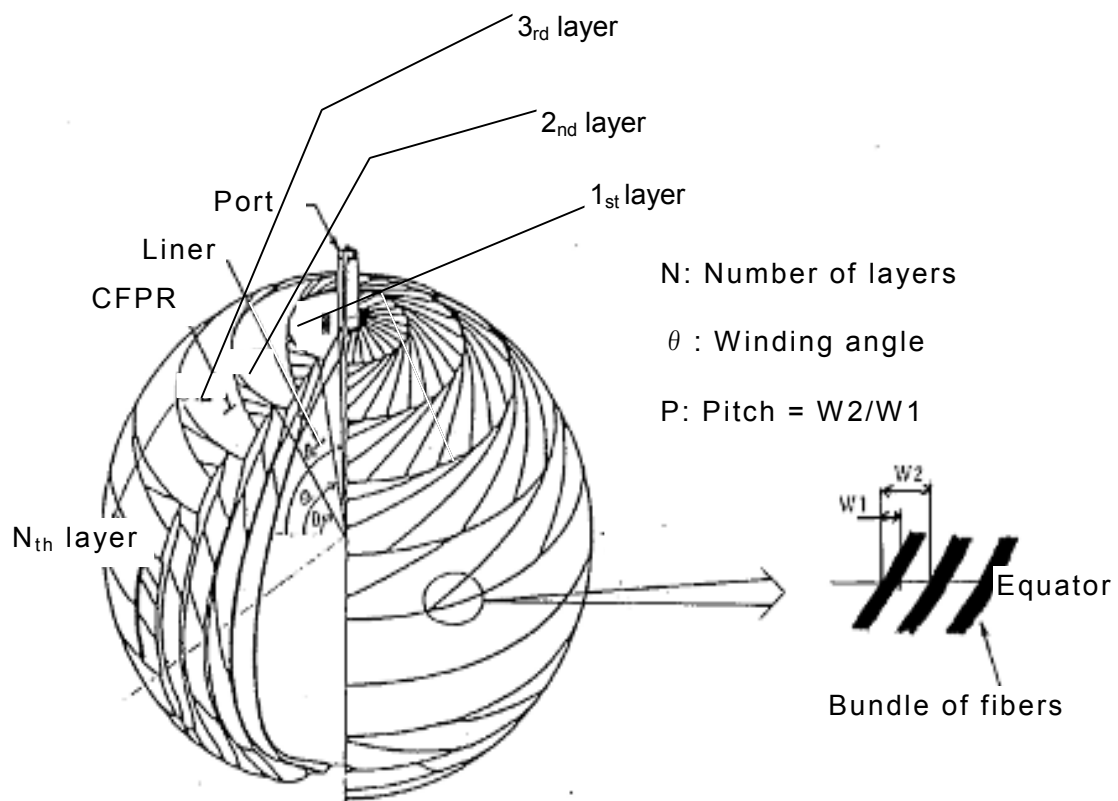
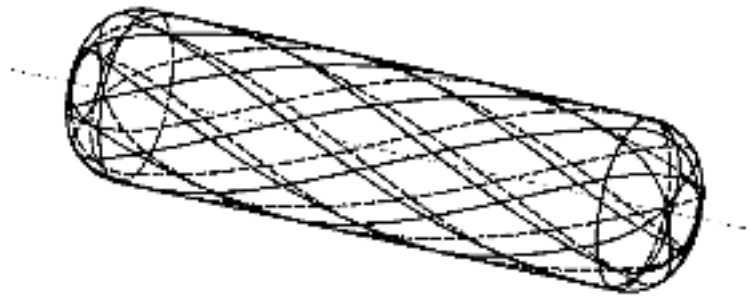
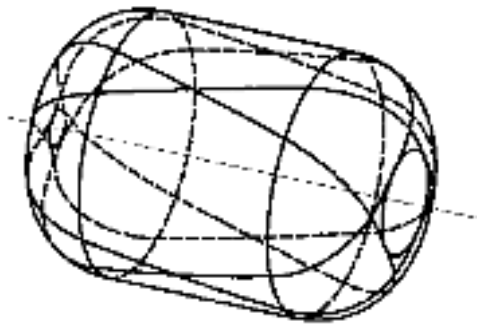


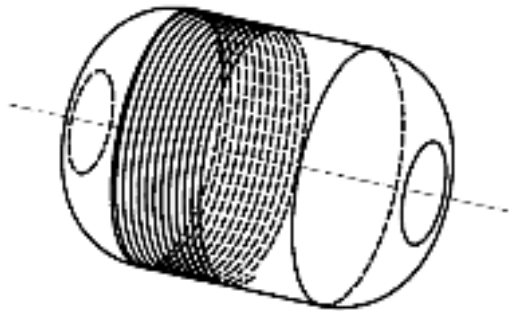
Figure 3.2-3 Example of Structure of Spherical Composite Overwrapped Pressure Vessel (COPV)



Helical Winding

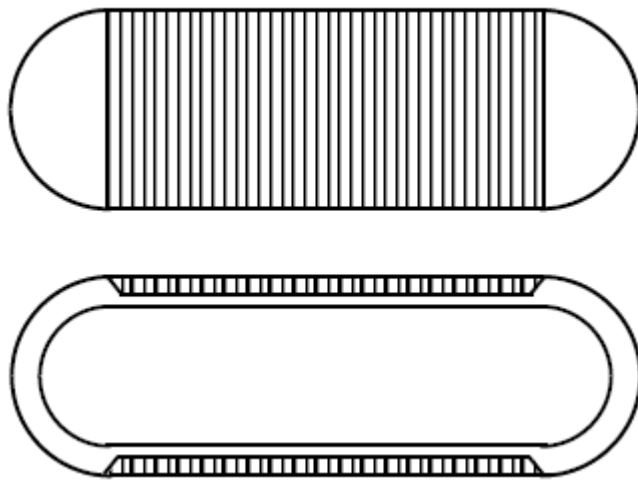


In-plane Winding



Hoop Winding

Figure 3.2-4 Overview of Filament Winding Types



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Figure 3.2-5 Example hoop-wrap construction

3.3 Material Selection

Materials for high-pressure gas equipment should be selected in consideration of the characteristics described in paragraph 3.2 “Structure Type Setting” and paragraphs 3.3.1–3.3.4. However, if materials other than those specified in the following standards (1)–(3) are used for high-pressure gas equipment with a safety factor of less than 3.5, perform the basic testing of materials as described in paragraph 5.1.1.

- (1) AMS Standards
- (2) MIL Standards
- (3) FS Standards

3.3.1 Mechanical property

(1) Metallic material

Metallic material used for high-pressure gas equipment shall possess specific material strength and adequate reliability. The specific value applied to the design shall be equivalent to A value in MMPDS-01. Factors which affect mechanical properties include temperature, pressure loading time, number of cyclic loads, and processing conditions for base material and welded parts. Consider these factors when selecting materials.

The yield ratio of the metallic materials used for launch vehicle propellant tanks shall satisfy the following so that plastic collapse is brought ultimately. If metallic materials do not satisfy the following, show grounds to be safe.

$$\text{Yield Ratio} = \frac{\text{Yield Stress}}{\text{Tensile Strength}} \leq 0.85$$

(2) Composite material

Select composite material considering filament winding, cure condition, other necessary conditions, and rupture characteristics.

(3) Non-metallic liner

Non-metallic material used for liner of COPV shall have greater breaking strain than composite material under the same operating temperature. The characteristic value shall have adequate reliability. In addition, select material considering the processing conditions of shaping, bonding and others.

3.3.2 Fracture property

Material to use shall possess appropriate fracture property to flaw growth due to cyclic and continuous loads in the operating environment.

Fracture toughness to flaw growth due to cyclic and continuous loads may not be considered for material used for non-metallic liners.

3.3.3 Compatibility

Materials used shall be adequately compatible with all environmental conditions such as loaded fluids and others without causing corrosion, stress corrosion cracking, and others.

(1) Compatibility with loaded fluids

Materials contacting the fluids loaded into high-pressure gas equipment shall be compatible with such fluids and shall not degrade equipment materials, or accelerate deterioration or decomposition of loaded fluids.

Select materials according to NASA document SE-019-094-2H.

Composite material used for COPV which do not contact the loaded fluids shall not be considered the compatibility with the loaded fluids.

(2) Compatibility with the external environment

When exposed to external environments, materials shall resist environmental effects by themselves or with proper protective finishing.

For non-metallic materials used in a COPV, consider the following environmental tolerances different from those for metallic materials.

- a. Out-gassing: Out-gassing generated from materials shall be within specified limits.
- b. Radioresistance: Materials shall endure the radiation environment to which the COPV is exposed on the orbit.
- c. Impermeability: Materials shall have the required impermeability to gas and loaded fluid under the operating environment.

(3) Compatibility with fluids used

Fluids used in factories and tests shall not contaminate or degrade materials during material treatment, processing, inspection, test, transportation, or storage. Furthermore, material reactions shall not produce any hazardous products.

(4) Compatibility with dissimilar metals

When dissimilar metals are used contacted each other, select a combination of metals which is less likely to cause dissimilar metal corrosion according to the requirements in MIL-STD-889.

(5) Compatibility between composite material and liner

Select a combination of composite and liner which does not cause degradation by

corrosion of liner or provide appropriate treatment to prevent such degradation. In particular, consider corrosion when conductive fiber is used as composite.

3.3.4 Fabricability

Fabricability is important element in selecting materials. When determining the fabrication method, consider materials and fabricability required to produce products with specified shapes, performance, and quality. In other words, ensure the following major requirements regarding fabricability is satisfied.

(1) Quality and availability

Materials shall possess appropriate quality and availability.

(2) Forming properties and machinability

Materials shall be shaped by forming or machining to obtain required shape, dimensions, and appropriate material strength.

Materials used for COPV shall be shaped by forming to obtain required shape, dimensions, and appropriate breaking elongation.

(3) Weldability

Materials shall possess adequate weldability if fabrication process includes welding.

(4) Formability of composite material

Materials used for COPV shall be shaped by filament winding and heat curing to obtain required shape, dimensions, and appropriate material strength.

3.4 Thickness Calculation

3.4.1 Thickness calculation for metallic pressure vessel

Calculate thickness according to the equations below. If other equations are used, provide the rationale and sources.

3.4.1.1 Thickness of cylindrical shell plate

This applies to a cylindrical shell with the minimum thickness of the shell plate being equal to or less than 0.25 of the inner diameter of the shell.

$$t = \frac{PD}{2S_m - 1.2P} \quad (3.4.1)$$

where

t: Minimum thickness of shell plate

P: MEOP

D: Inner diameter of the shell

S_m: Design stress intensity

$$S_m = \text{Small value among} \left[\begin{array}{c} \frac{\text{Material Yield Stress } (\sigma_y)^*}{\text{Safety Factor for Yield Stress}^{**}} \\ \text{and} \\ \frac{\text{Material Tensile Strength } (\sigma_u)^*}{\text{Safety Factor for Tensile Strength}^{**}} \end{array} \right]$$

* Use the value specified at the design temperature.

For materials used at cryogenic temperature, yield stress or tensile strength at normal temperature may be used if the cryogenic yield stress or tensile strength at cryogenic temperature exceeds those at normal temperature. For weld parts, consider the increased weld thickness specified in paragraph 4.2.1 (2).

** Use the value which is specified in Table 3.1.3-1 and is actually used.

For the piping

$$t = \frac{PD_0}{2S_m + 0.8P} \quad (3.4.1a)$$

where

D₀: Outer diameter of the piping

3.4.1.2 Thickness of spherical shell plate

This applies to a spherical shell with the minimum thickness of the shell plate being equal to or less than 0.178 of the inner diameter of the shell.

$$t = \frac{PD}{4S_m - 0.4P} \quad (3.4.2)$$

3.4.1.3 Thickness of conical shell plate

$$t = \frac{PD}{2\cos\theta(S_m - 0.6P)} \quad (3.4.3)$$

where

D: Inner diameters of the parts used to calculate the minimum thickness of the shell plate, measured perpendicularly to the cone axis

θ : One half of vertical angle of the cone [°]

3.4.1.4 Thickness of torispherical head plate or total hemispherical head plate

$$t = \frac{PRW}{2S_m - 0.2P} \quad (3.4.4)$$

where

R: Internal radius of the central part of a torispherical head or total hemispherical head

W: Coefficient relating to a torispherical shape, obtained by the following equation (for a total hemispherical shape, W is 1)

$$W = \frac{1}{4} \left[3 + \sqrt{\frac{R}{r_1}} \right]$$

where

r_1 : Internal radius of the round corner of a torispherical head

3.4.1.5 Thickness of semi-ellipsoidal head plate

$$t = \frac{PDK}{2S_m - 0.2P} \quad (3.4.5)$$

where

D: Major axis of ellipsoid inside of head

K: Coefficient determined by head shape, obtained by the following equation

$$K = \frac{1}{6} \left[2 + \left[\frac{D}{2h} \right]^2 \right]$$

where

h : Half of minor axis of ellipsoid inside of head

3.4.1.6 Thickness of conical head plate

- (1) For a conical part of head with vertical angle equal to or less than 140 degrees

$$t = \frac{PD}{2\cos\theta(S_m - 0.6P)} \quad (3.4.6a)$$

where

D: Inner diameter of the parts used to calculate the minimum thickness of a head, measured perpendicularly to the cone axis

θ : One half of the apical angle of the cone [$^\circ$]

- (2) For a conical part of head with vertical angle exceeding 140 degrees

Use the minimum thickness which is smaller value obtained either by the equation (3.4.6a) above or by the equation below.

$$t = 0.5(D_0 - r_2) \frac{\theta}{90} \sqrt{\frac{P}{S_m}} \quad (3.4.6b)$$

where

D_0 : Outer diameter at the end of conical head

r_2 : Internal radius of the round part connecting to the end of conical head

3.4.2 Calculation of plate thickness of launch vehicle propellant tank

Plate thickness shall be calculated according to the loading conditions during flight. Calculated plate thickness shall be verified for flight and ground handling according to detailed analysis described in paragraph 3.5.

Calculate plate thickness according to the following equations. If other equations are used, provide the rationale and source.

3.4.2.1 Cylindrical shell

Plate thickness of cylindrical shell may vary according to the magnitude of load in the vehicle axis direction. However, in any vehicle axis directions, plate thickness shall not be thinner than the thickness calculated based on the circumferential stress and the thickness calculated based on load in the vehicle axis direction.

When waffle or isogrid is used in plate structure, equivalent thickness which is calculated with the effect of rib/flange reinforced flat plate can be used. (Note 1)

Note1: Figure 3.4.2-1 shows the equivalent thickness of the isogrid flat plate as reference.

(1) Calculation of plate thickness for circumferential stress

Calculate plate thickness for circumferential stress according to equation (3.4.1) in paragraph 3.4.1.

For the thickness, equivalent thickness may be used for isogrid reinforced flat plate. (See Figure 3.4.2-1)

(2) Calculation of plate thickness for the stress in the vehicle axis direction

The stress in the vehicle axis direction in the cylindrical shell of a launch vehicle propellant tank has tensile and compressive components due to the bending moment during flight. Therefore, calculate thickness for each case as described below. For the compressive stress, thickness shall be calculated in terms of both compressive strength and buckling strength.

For the tensile stress generated by the bending moment

–Calculate thickness in terms of strength according to a. below.

For the compressive stress generated by the bending moment

–Calculate thickness in terms of strength according to b. below.

–Calculate thickness in terms of buckling strength according to c. below.

Thickness need not be calculated when (1) the equivalent tensile force in the vehicle axis direction $(F_{eq})_a$ is determined to be compressive in case a, and (2) the equivalent compressive force in the vehicle axis direction $(F_{eq})_b$ is determined to be tensile in case b.

a. Calculation of plate thickness for the stress of the tension component generated

by the bending moment during flight

$$t = \frac{(F_{eq})_a}{\pi D S_m} \quad (3.4.7)$$

$$(F_{eq})_a = -F + \frac{4M}{D} + \frac{\pi D^2 P}{4}$$

where

$(F_{eq})_a$: Maximum value of equivalent tensile force in the vehicle axis direction with pressure load in load history

t : Plate thickness. Equivalent plate thickness can be used for isogrid reinforced flat plate. (See Figure 3.4.2-1)

D : Inner diameter

F : Compressive force in the vehicle axis direction

M : Bending moment

P : Pressure

S_m : Design stress intensity

$$S_m = \text{Small value among} \left[\begin{array}{c} \frac{\text{Material Yield Stress } (\sigma_y)^*}{\text{Safety Factor for Yield Stress}^{**}} \\ \text{and} \\ \frac{\text{Material Tensile Strength } (\sigma_u)^*}{\text{Safety Factor for Tensile Strength}^{**}} \end{array} \right]$$

* Use the value specified at the design temperature. For materials used at cryogenic temperature, yield stress or tensile strength at normal temperature may be used if cryogenic yield stress or tensile strength at cryogenic temperature exceeds those at normal temperature. For welding part, the increased weld thickness described in 4.2.1 (2).

** Use the value which is specified in Table 3.1.3-1 and is actually used

b. Calculation of plate thickness for the stress of the compression component generated by the bending moment during flight

$$t = \frac{(F_{ed})_b}{\pi D S_m} \quad (3.4.8)$$

$$(F_{eq})_b = F + \frac{4M}{D} - \frac{\pi D^2 P_{min}}{4}$$

where

$(F_{eq})_b$: Maximum equivalent compressive force in the vehicle axis direction

with pressure load in load history

- t : Plate thickness. Equivalent plate thickness can be used for isogrid reinforced flat plate. (See Figure 3.4.2-1)
- D: Inner diameter
- F: Compressive force in the vehicle axis direction
- M: Bending moment
- P: Pressure
- S_m: Design stress intensity

c. Calculating thickness for buckling during flight

$$t_b = \frac{(F_{eq})_b}{\pi D S_b} \quad (3.4.9)$$

$$S_b = \frac{\sigma_{cr}}{\text{Safety Factor}^*}$$

$$\sigma_{cr} = \frac{\gamma}{\{3(1-\nu^2)\}^{1/2}} E \frac{2t}{D}$$

where

- t_b : Plate thickness for buckling during flight
- (F_{eq})_b: Maximum equivalent compressive force in the vehicle axis direction with pressure load in load history (The same equation as used in (b) above.)
- P: Pressure
- S_b : Buckling strength
- t : Plate thickness. Equivalent plate thickness can be used for isogrid reinforced flat plate. If equivalent stiffness thickness is used, equivalent longitudinal elastic modulus shall be used at the same time. (See Figure 3.4.2-1)
- σ_{cr}: Buckling stress
- D: Inner diameter
- ν: Poisson ratio
- E: Longitudinal elastic modulus. Equivalent longitudinal elastic modulus can be used for isogrid reinforced flat plate. When equivalent longitudinal elastic modulus is used, thickness of

equivalent stiffness shall be used at the same time.

γ : Correction factor to reduction in buckling stress below the theoretical value due to initial fabrication irregularity, and residual stress ($\gamma < 1$). Set this correction factor based on the test result, analysis result, or documented evidence and clarify the source.

* Safety factor for buckling as specified in paragraph 3.1.3.3.

3.4.2.2 Head (Dome part)

Calculate plate thickness for the head to withstand internal loads during flight. Plate thickness of the head shall not be less than the calculated thickness. Conduct detailed analyses described in paragraph 3.5 to confirm strength (including buckling) when the payload load is applied to the head or when the back pressure is applied to the common bulkhead.

(1) Torispherical head and total hemispherical head

Calculation of thickness for torispherical head shall be applied to the central part of torispherical head. Detail analysis shall be conducted according to paragraph 3.5 to confirm the strength of the part of round corners of torispherical head.

$$t = \frac{PR}{2S_m - 0.2P} \quad (3.4.10)$$

where

P: Limit pressure

t : Minimum plate thickness

R: Radius of the central part of torispherical head, or internal radius of total hemispherical head

S_m : Design stress intensity

$$S_m = \text{Small value among} \left[\begin{array}{c} \frac{\text{Material Yield Stress } (\sigma_y)^*}{\text{Safety Factor for Yield Stress}^{**}} \\ \text{and} \\ \frac{\text{Material Tensile Strength } (\sigma_u)^*}{\text{Safety Factor for Ultimate}^{**}} \end{array} \right]$$

* Use the value specified at the design temperature. For materials used at cryogenic temperature, yield stress or tensile strength at normal temperature can be used when yield stress or tensile strength at cryogenic temperature exceeds yield stress or tensile strength at normal temperature. For weld parts, consider the increased weld thickness as shown in (2) of paragraph 4.2.1.

** Use the value which is specified in Table 3.1.3-1 and is actually used

(2) Ellipsoidal head

$$t = \left[\text{great value among } \frac{N_{\phi}}{S_m} \text{ and } \frac{N_{\theta}}{S_m} \right] \quad (3.4.11)$$

$$\frac{N_{\phi}}{aP} = \frac{a}{2b} \left[1 - \left(\frac{R}{a} \right)^2 \left\{ 1 - \left(\frac{b}{a} \right)^2 \right\} \right]^{\frac{1}{2}}$$

$$\frac{N_{\theta}}{aP} = \frac{N_{\phi}}{aP} \left[2 - \frac{1}{1 - \left(\frac{R}{a} \right)^2 \left\{ 1 - \left(\frac{b}{a} \right)^2 \right\}} \right]$$

Figure 3.4.2-2 illustrates the parameters of a, b, R, P in above equations.

where

t : Plate thickness

N_{ϕ} : Load in the radial direction per unit length

N_{θ} : Load in the circumferential direction per unit length

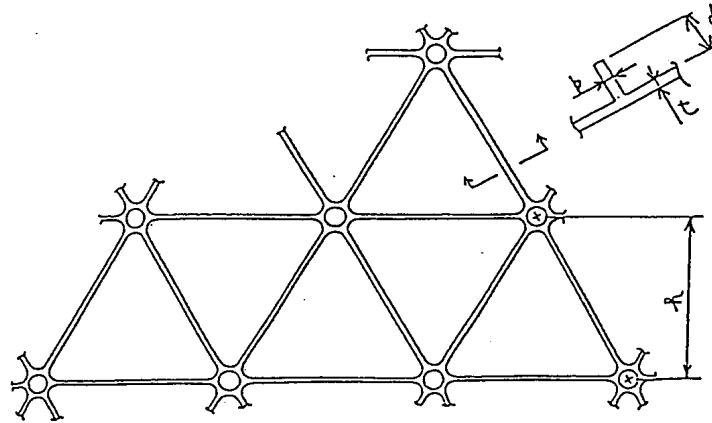
a: Semi-major axis of ellipsoid

b: Semi-minor axis of ellipsoid

R: Distance from the central axis

P: Limit pressure

S_m : Design stress intensity (The same as in (1) above shall apply.)



Non-dimensional parameter

$$\alpha = \frac{bd}{th}$$

$$\delta = \frac{d}{t}$$

$$\beta = \left[3\alpha(1+\delta)^2 + (1+\alpha)(1+\alpha\delta^2) \right]^{1/2}$$

Equivalent plate thickness

$$t_{\text{eff}} = t(1+\alpha)$$

Equivalent stiffness thickness / Equivalent longitudinal elastic modulus

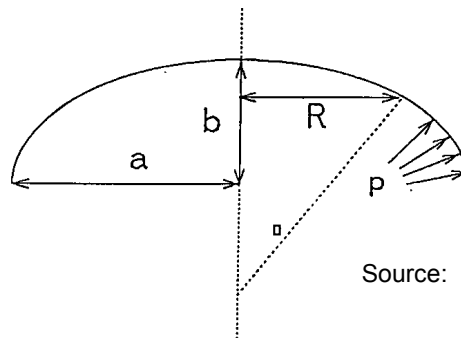
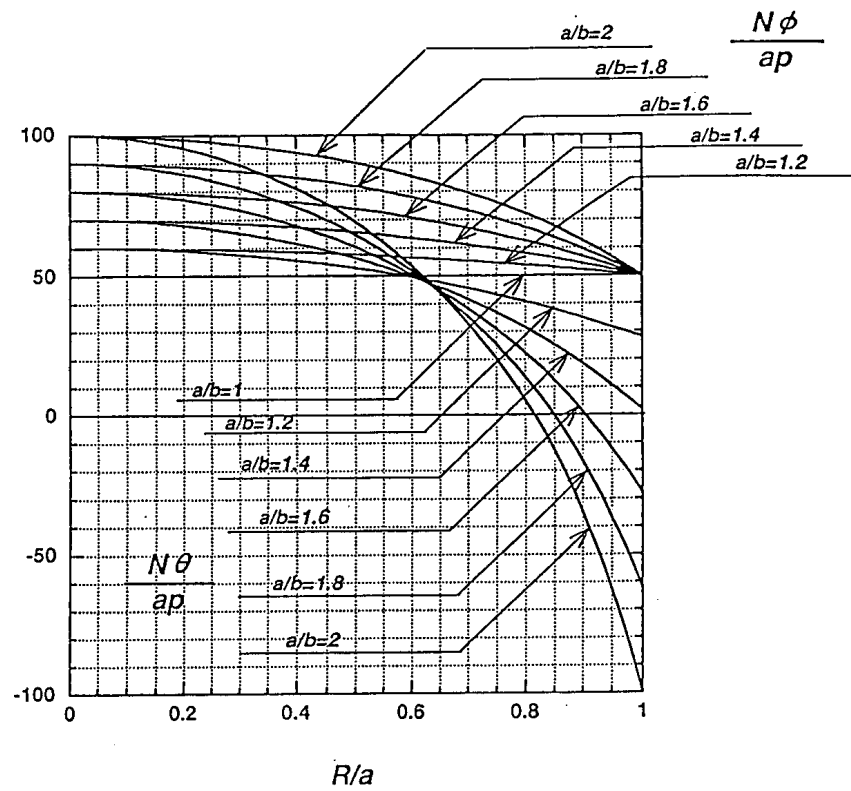
$$t^* = t \frac{\beta}{1+\alpha}$$

$$E^* = E_0 \frac{(1+\alpha)^2}{\beta}$$

Source: NASA-CR-124075

ISOGRID DESIGN HANDBOOK

Figure 3.4.2-1 Equivalent Plate Thickness of Isogrid Reinforced Flat Plate (Reference)



Source: NASA-CR 912

SHELL ANALYSIS MANUAL

Figure 3.4.2-2 Ellipsoidal Head Load Distribution by Internal Pressure

3.4.3 Calculation of plate thickness of COPV

Figure 3.4.3-1 illustrates the flow for calculating plate thickness of COPV. Make clear the formula used to calculate plate thickness. An example of calculation of plate thickness for COPV with a metallic liner is shown below.

3.4.3.1 Calculation of plate thickness

3.4.3.1.1 Spherical COPV

Equation to calculate plate thickness when composite material of spherical COPV is assumed to be pseudo isotropy material. (Effect of the poisson ratio is ignored.)

$$t_c = \frac{(1-k_m)P_B \cdot R}{E_c \cdot \epsilon_B} \quad (3.4.12)$$

where

t_c : Composite material thickness when pseudo isotropy is assumed

k_m : Sharing pressure ratio for metallic liner

P_B : Design burst pressure

R : Radius of vessel

E_c : Elastic modulus in the direction of the fiber of composite material

ϵ_B : Strain in the direction of the fiber at design burst pressure (breaking strain)

Next, calculate the thickness of the metallic liner using the following equation.

$$t_m = \frac{k_m \cdot P_B \cdot R}{2 \cdot S_{my}} \quad (3.4.13)$$

where

t_m : Metallic liner thickness

S_{my} : Metallic liner yield stress

3.4.3.1.2 Cylindrical COPV (excepting hoop-wrap constructions)

(1) When approach to begin with shell thickness calculation

This paragraph describes an example of calculating the shell thickness before determining the head thickness.

a. Shell thickness

First, determine a winding angle θ for the helical winding layer (or in-plane winding layer) after determining the winding pattern based on vessel shape. Applying the

following equations, calculate the thickness of the helical winding layer (or in-plane winding layer), and metallic liner.

$$k = \frac{\varepsilon_{LP\theta}}{\varepsilon_{my}} = \frac{E_m \varepsilon_{LP\theta}}{(1 - \nu_m) S_{my}} \quad (3.4.14)$$

$$t_\theta = \frac{(P_B - P_P) D}{4 E_L \cos^2 \theta (\varepsilon_{LB\theta} - k \varepsilon_{my})} \quad (3.4.15)$$

$$t_m = \frac{(P_B \varepsilon_{LP\theta} - P_P \varepsilon_{LB\theta}) D}{4 (\varepsilon_{LP\theta} - \varepsilon_{LB\theta}) S_{my}} \quad (3.4.16)$$

where

- k : Ratio of strain in the fiber (fiber strain during plastic deformation processing) and metallic liner at autofrettage and yield strain of the metallic liner (This depends on material properties of the metallic liner and a fiber. e.g., k = 2 to 3) E
- P_B: Design burst pressure
- P_P: Autofrettage pressure
- D: Vessel diameter
- S_{my}: Metallic liner yield stress
- t_m: Metallic liner thickness
- t_θ: Thickness of the helical winding layer (or in-plane winding layer)
- E_L: Modulus of elasticity in the direction of the fiber of the composite material
- E_m: Modulus of longitudinal elasticity of the metallic liner
- ν_m: Poisson ratio of the metallic liner
- ε_{LBθ}: Strain of the composite material in the helical winding layer (or in-plane winding layer) in the direction of the fiber at design burst pressure
- ε_{LPθ}: Strain of the composite material in the helical winding layer (or in-plane winding layer) in the direction of the fiber at autofrettage pressure
- ε_{my}: Yield strain of a metallic liner
- θ : Angle of the helical winding layer (or in-plane winding layer)

For the hoop winding layer, calculate thickness of using the following equations.

$$t_h = \frac{\frac{P_B D}{2} - S_{my} t_m - E_L \varepsilon_{LB\theta} t_\theta \sin^2 \theta}{E_L \varepsilon_{LBh}} \quad (3.4.17)$$

$$\varepsilon_{LPh} = \frac{\frac{P_p D}{2} - S_{my} t_m - E_L \varepsilon_{LP\theta} t_\theta \sin^2 \theta}{E_L t_h} \quad (3.4.18)$$

where

ε_{LBh} : Strain of the composite material in hoop winding layer in the direction of the fiber at design burst pressure

ε_{LPh} : Strain of the composite material in the hoop winding layer in the direction of the fiber at autofrettage pressure

t_h : Thickness of the hoop winding layer

b. Head thickness

Determine the distribution of the thickness of the composite material and the distribution of crossing angles of the fiber based on the thickness of the shell determined in a. above. Assume that the thickness of the metallic liner at the head is consistent. The shape of a head can be determined with equation (3.4.19) below. (Source: NASA-CR-72124)

$$\ddot{\rho} = \frac{2(\dot{\rho}^2 + 1)^{\frac{1}{2}}}{\rho} \left[-\frac{k_m}{2\rho} (\tan^2 \theta - 1) + (\dot{\rho}^2 + 1)^{\frac{1}{2}} \left(\frac{1}{2} \tan^2 \theta - 1 \right) \right] \quad (3.4.19)$$

where

$$\tan^2 \theta = \frac{\rho_0^2}{\rho^2 - (\rho_0)^2} \quad (\text{At an even tension curved surface}) \quad (3.4.20a)$$

$$\tan^2 \theta = \frac{[\rho \tan \gamma - (\zeta \tan \gamma + \rho_e) \dot{\rho}]^2}{(1 + \dot{\rho}^2)[\rho^2 - (\zeta \tan \gamma + \rho_e)^2]} \quad (\text{When in-plane winding is used}) \quad (3.4.20b)$$

Symbols r and z represent coordinates in Figure 3.4.3-2. ρ and ζ are non-dimensional coordinates of r and z . R is the radius of the shell.

k_m : Ratio of pressure fraction sustained by the liner
(When design burst pressure is applied)

$$\rho = \frac{r}{R} \quad \dot{\rho} = \frac{dp}{d\zeta}$$

$$\zeta = \frac{z}{R} \quad \ddot{\rho} = \frac{d^2\rho}{d\zeta^2}$$

γ : In-plane angle

ρ_e : In-plane parameter

ρ_0 : Aperture ratio

γ , ρ_e , and ρ_0 are shown in Figure 3.4.3-3.

Since equation (3.4.19) is an ordinary differential equation of the second order, the head shape is determined by numerical calculations such as Runge-Kutta method. The boundary conditions are assumed as the following at the joint of the head and the shell.

$$\rho(\zeta = 0) = 1, \quad \dot{\rho}(\zeta = 0) = 0$$

When the head shape is determined, calculate the distribution of thickness of the composite material of the head using the following equation:

$$t_{\theta d} = \frac{\cos\theta_0}{\rho\cos\theta} t_\theta \quad (3.4.21)$$

where

$t_{\theta d}$: Thickness of the composite material of the head

θ_0 : Winding angle at the joint of the head and the shell

(2) Approach starting with head thickness calculation

This paragraph describes an example of determining the head thickness before determining the shell thickness.

a. Head thickness determination

First, determine winding angle θ for the helical winding layer (or in-plane winding layer) after determining the winding pattern based on vessel shape. Applying the following equations, calculate the thickness of the helical winding layer (or in-plane winding layer) and metallic liner.

$$t_\theta = (1 - k_m) \frac{P_B D}{4E_L \varepsilon_{LB\theta} \cos^2\theta} \quad (3.4.22)$$

$$t_m = \frac{k_m P_B D}{4S_{my}} \quad (3.4.23)$$

where

k_m : Ratio of pressure fraction sustained by the head liner when the design burst pressure is applied

Determine the head shape and the distribution of the crossing angles of the fiber using equations (3.4.19) and (3.4.20) and determine the distribution of the thickness of the head using equation (3.4.21).

b. Shell thickness determination

Determine the thickness of a hoop winding layer of the shell using the following equation:

$$t_h = \frac{1}{E_L \varepsilon_{LBh}} \left(\frac{P_B D}{2} - S_{my} t_m - E_L \varepsilon_{LB\theta} t_\theta \sin^2 \theta \right) \quad (3.4.24)$$

Using the thickness determined in paragraphs a and b above, calculate the strains of the helical winding layer and the hoop winding layer under autofrettage pressure.

$$\varepsilon_{LP\theta} = \frac{1}{E_L t_\theta \cos^2 \theta} \left(\frac{P_p D}{4} - S_{my} t_m \right) \quad (3.4.25)$$

$$\varepsilon_{LP_h} = \frac{1}{E_L t_h} \left(\frac{P_p D}{2} - S_{my} t_m - E_L \varepsilon_{LP\theta} t_\theta \sin^2 \theta \right) \quad (3.4.26)$$

3.4.3.2 Confirming compressive strength of a metallic liner

When using a metallic liner, calculate the compressive stress of the unpressurized liner after autofrettage and confirm that the liner will not yield due to compression.

$$S_{m0} < S'_{my}$$

where

S_{m0} : Stress of the liner under unpressurization after autofrettage

S'_{my} : Yield stress of materials

When adopting a design method that allows for the metallic liner to yield, evaluate its compressive strength according to the strength analysis described in paragraph 3.5.1.

3.4.3.3 Confirming buckling strength of the metallic liner

When using a metallic liner, calculate the compressive stress of the pressurized liner after autofrettage and confirm that the liner does not buckle due to compression.

$$S_{m0} < S_{cr}$$

For stress in the circumferential direction of a cylindrical COPV (Source: NASA-CR-72753)

$$\frac{S_{cr}}{E_m} = 106,000 \left(\frac{t_m}{D} \right)^3 \quad (3.4.27)$$

For the head of a spherical and a cylindrical COPV (Source: NASA-CR-72753)

$$\frac{S_{cr}}{E_m} = 21,200 (1 - \nu_m^2) \left(\frac{t_m}{D} \right)^2 \quad (3.4.28)$$

where

S_{m0} : Stress of the metallic liner under no pressurization after autofrettage

S_{cr} : Buckling stress

E_m : Modulus of longitudinal elasticity of the material of the metallic liner
(Second modulus when the metallic liner is in yield range)

t_m : Metallic liner sheet thickness

D : Metallic liner diameter

ν_m : Poisson ratio of the metallic liner

3.4.3.4 Drawing pressure-strain diagram

Calculate the ratio of pressure fractions to internal pressure for the metallic liner and composite material based on the determined thickness and the shape of the vessel and draw the pressure-strain diagram (see example in Figure 3.4.3-4).

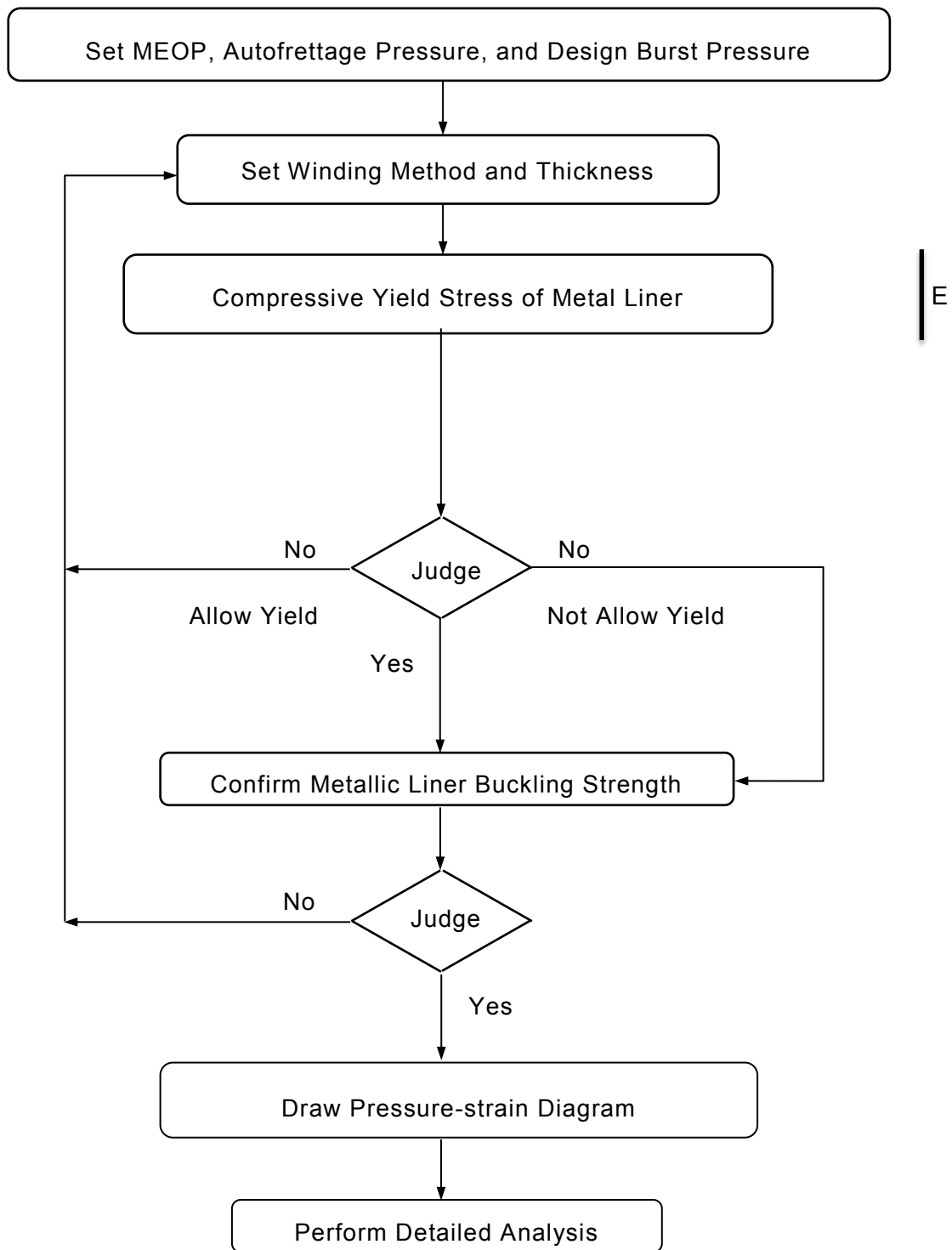


Figure 3.4.3-1 Thickness Determination Flow

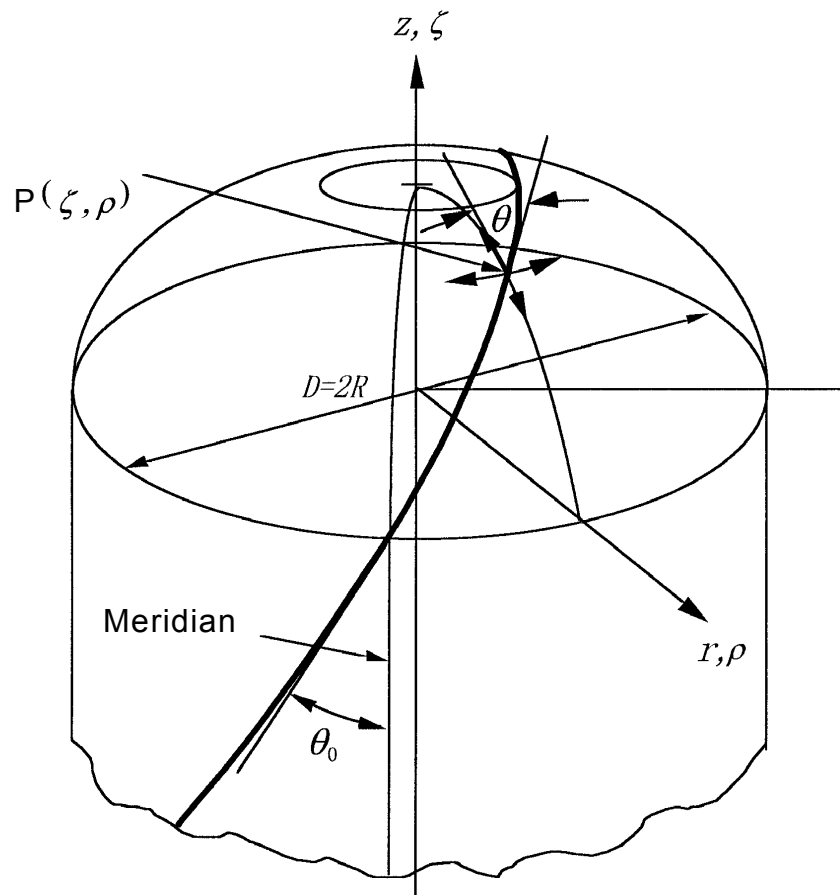


Figure 3.4.3-2 Symbols and Coordinates (1)

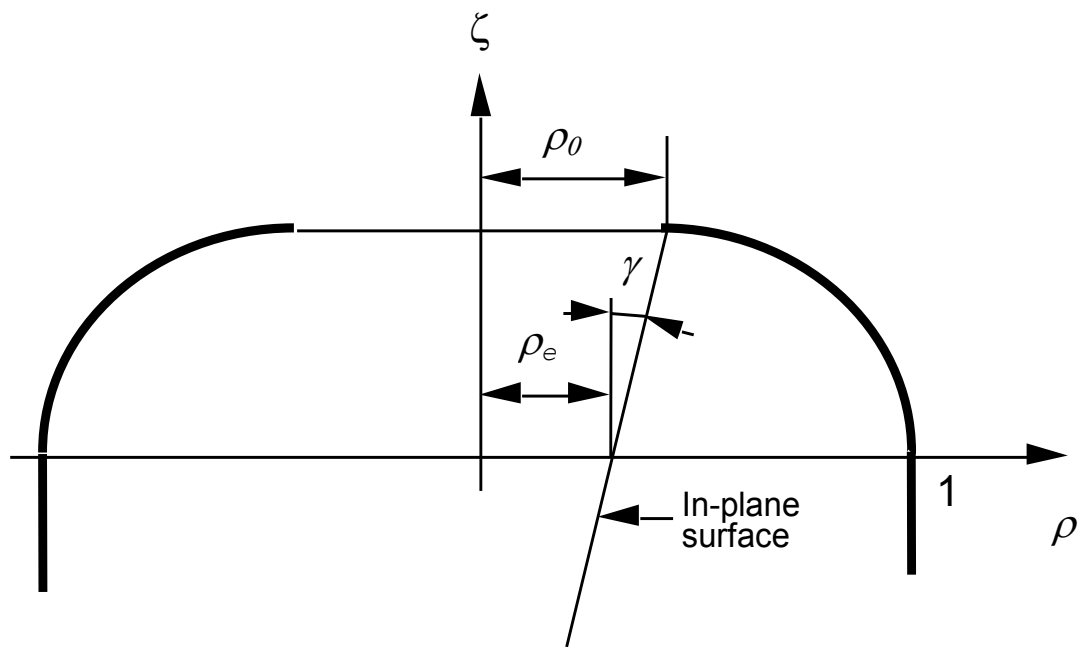
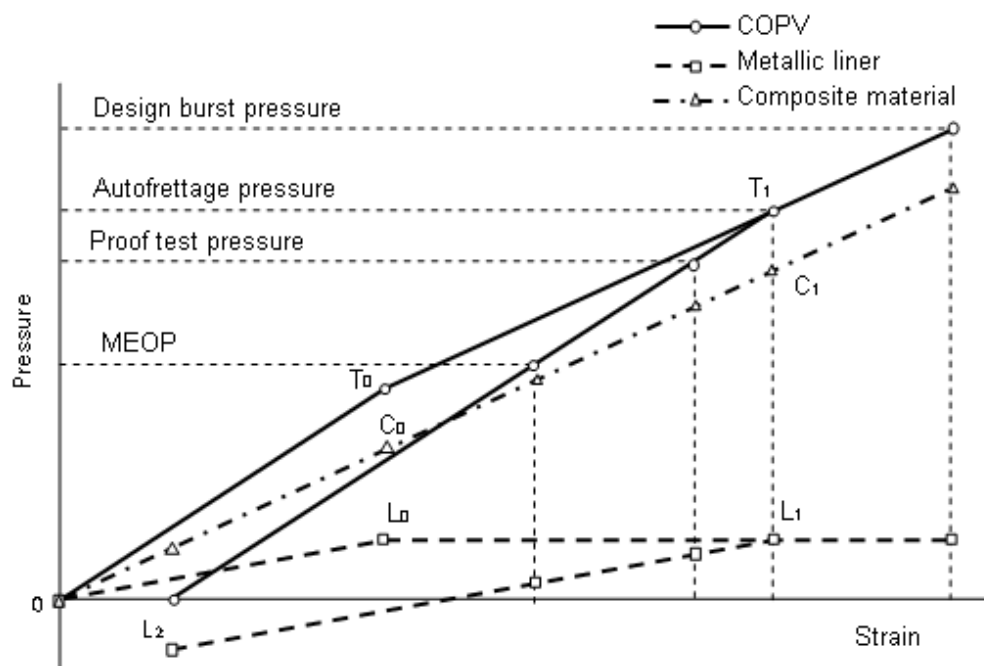
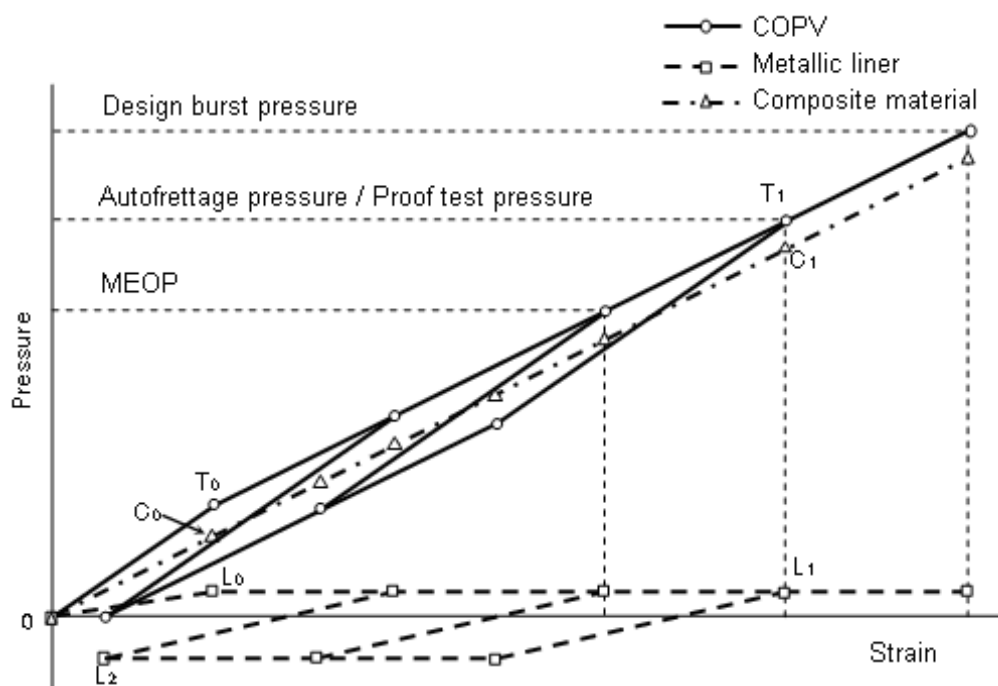


Figure 3.4.3-3 Symbols and Coordinates (2)



(Metallic liner does not yield when used)



(Metallic liner yields when used.)

Figure 3.4.3-4 Pressure-strain diagram (Representative examples)

3.5 Detailed Analysis

Design of the high-pressure gas equipment shall be verified by stress analysis, verification of Leak-Before-Burst (LBB) occurrence, fatigue damage analysis or flaw growth analysis, acceptance test, and qualification test as shown in Figure 3.5-1. Select appropriate procedures depending on the results of the LBB verification described below.

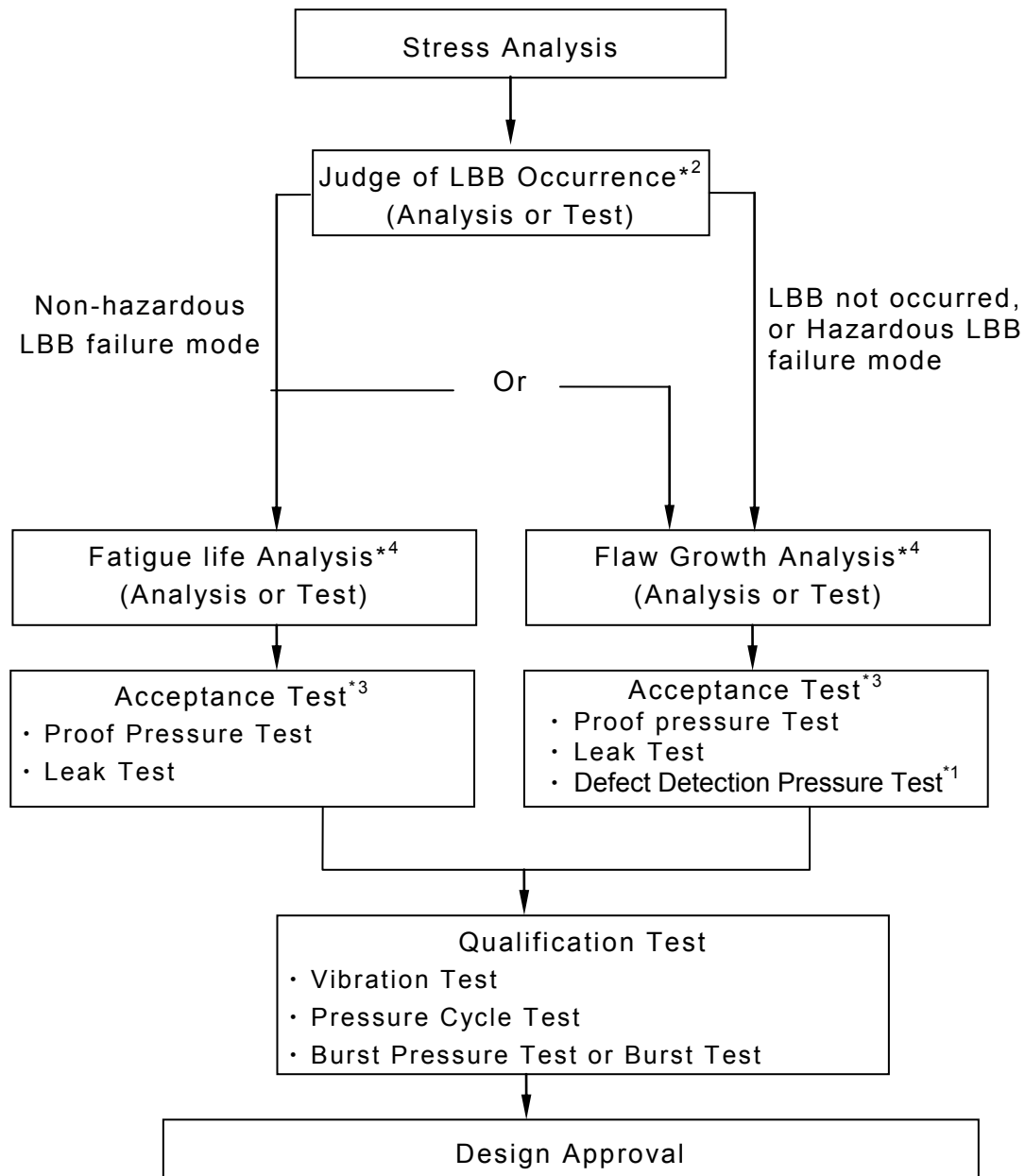
- (1) LBB occurs and non-hazardous leakage
- (2) LBB does not occur, or LBB occurs and hazardous leakage

The design shall be verified by the general procedure described below.

- 1) Perform stress analysis to ensure the safety of the equipment according to the methods described in paragraph 3.5.1. Analysis of pressure vessels other than launch vehicle propellant tanks shall follow paragraph 3.5.1.1, "Pressure load analyses," and paragraph 3.5.1.2, "Analysis for flight." Analysis of launch vehicle propellant tanks shall follow paragraph 3.5.1.2 "Analysis for flight" and paragraph 3.5.1.3 "Analysis for ground handling."
- 2) LBB occurrence shall be judged by the following paragraph 3.5.2.
- 3) When LBB occurs and non-hazardous leakage is verified, perform fatigue damage analysis to verify that the fatigue does not lead to burst, according to paragraph 3.5.3. For composite material and metallic liner that yields due to pressurization or depressurization at MEOP of COPV, fatigue damage analysis shall be performed regardless of LBB occurrence.
- 4) When LBB does not occur, or LBB occurs and hazardous leakage is verified, perform flaw growth analysis according to paragraph 3.5.4.
- 5) Perform the pressure test and leak test as acceptance test according to paragraph 4.7.5.

When LBB does not occur, or LBB occurs and hazardous leakage is verified (or when the flaw growth analysis is performed even when LBB occurs and non-hazardous leakage is verified), the proof test (defect detection pressure test) may be performed after pressure loading for the pressure test.

- 6) Qualification test shall be conducted according to paragraph 5.2.



*1 Perform defect detection pressure test when the initial flaw size is not set at nondestructive inspection.

*2 When LBB occurrence is not judged, it is assumed that LBB does not occur.

*3 Test items of acceptance test may be performed as a part of qualification test.

*4 Fatigue damage analysis shall be performed for composite material and yielding metal liner of COPV whenever LBB occurs or LBB does not occur.

Figure 3.5-1 Method of Design Verification

3.5.1 Stress analysis

Conduct the following analyses to demonstrate that the thickness determined according to paragraph 3.4 possesses appropriate strength (including buckling). The analyses described in this section are the minimum required. Conduct other analyses if considered necessary.

Determine the material properties and other mechanical or physical properties used for stress analysis as below.

For metallic materials, select the appropriate values from the following documents or material standards used (such as MIL, AMS, and FS standards).

- (1) MMPDS-01 Metallic Materials and Elements for Aerospace Vehicle Structure
- (2) AFML-TR-68-115 Aerospace Structural Metals Handbook

If a material not described in these official documents is to be used, conduct the material basic test specified in paragraph 5.1.1 and use its evaluation data. Note that the material strength used as judgment criteria shall be equivalent to "A" value in MMPDS-01.

This technical standard does not consider material creep since the equipment will not be used at high temperatures as specified in paragraph 3.1.2.4, "Temperature conditions." For metal liners in composite pressure vessels, the yield stress of the metal liner material used for analysis of plastic deformation treatments can be analyzed using the average value in a mill sheet for a similar commercially available material.

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Conduct material basic test specified in paragraph 5.1.1 to obtain the evaluation data on material properties and other mechanical or physical properties. Use the obtained evaluation data for composite material stress analysis.

The data shall be properly converted considering the volume fraction of fiber (V_f) of composite materials. The tensile strength in the direction of the fiber shall be the minimum value of the test data at 95% reliability and 1% destruction probability. The modulus of elasticity in the direction of the fiber may be the fiber-producer-provided value with V_f conversion applied, if the materials are a curing type and have no distinct non-linearity.

For material properties of a non-metallic liner, conduct a material basic test specified in paragraph 5.1.1, as necessary, and use the obtained evaluation data.

3.5.1.1 Pressure analysis

(1) Purpose

These analyses confirm that thickness determined in paragraph 3.4 provide appropriate strength (including buckling) for pressurization tasks including the

following fabrication and launch preparation tasks.

- a. Fabrication process
- b. Qualification testing
- c. Acceptance testing
- d. Leak tests during launch preparation
- e. System tests of a launch vehicle and payloads
- f. Prelaunch pressurization

These analyses apply to metallic pressure vessels, COPV and piping, fittings and other components which do not satisfy the safety factors shown in Table 3.1.3-1. They do not apply to launch vehicle propellant tanks because paragraph 3.5.1.3 “Analysis for ground handling” covers pressure load analysis.

(2) Methods and conditions

- a. Perform stress analysis of the thickness and shape determined in paragraph 3.4 using the Finite Element Method (FEM) analysis. Establish analysis conditions properly (including model development) and clarify these conditions.
- a. If required, perform buckling analysis of the thickness and shape determined in paragraph 3.4 in addition to stress analysis. Establish analysis conditions properly (including model development) and clarify these conditions.
- b. Perform FEM analysis primarily for elastic analysis. Consider geometric non-linearity (form non-linearity) as necessary for COPV. Perform elasto-plasticity analysis for plastic deformation and cases in which the metallic liner yields due to pressurization to MEOP and depressurization. Properly develop appropriate models based on the necessary assumptions to ensure safety. For the metallic liner thickness, use the minimum design metallic liner thickness for general parts and weld parts. Also consider appropriate deformations such as weld deformations (particularly, angular deformations) and mis-match. For structural discontinuities including uneven surfaces and notches, determine the maximum value of the local peak stress. If reliable analysis or experiment results are available for the stress concentration factor, use the result for peak stress. When the stress concentration factor is not identified, use 4.
- d. For buckling analysis, use the minimum design thickness. Consider a correction factor for decrease in the buckling limit load caused by initial fabrication irregularities and residual stress.
- e. Establish boundary conditions including the spring constants based on the necessary assumptions to ensure safety as in model development.
- f. Consider MEOP for loading for a metallic pressure vessel.

- g. Perform buckling analysis when applying vacuum to load propellants and the internal pressure of the vessel becomes negative with respect to the external pressure.
- h. For loading conditions for COPV, perform the analysis considering all phases from fabrication to operations and in the specified order for the vessels under the following conditions.
 - 1) When autofrettage is performed (only when autofrettage is performed).
 - 2) When the vessel is not pressurized after autofrettage (only when autofrettage is performed).
 - 3) When proof pressure test is performed
 - 4) When MEOP is being applied
 - 5) When design burst pressure is applied
- i. When analyzing the part where structure is discontinuous such place as near the joint of head and cylinder of COPV, near the opening of head, where liner thickness changes, or where pressure vessel is supported, pay particular attention to mesh division and similar occurrences.
- j. For COPV, pay particular attention to where high stress and strain is applied, draw a pressure-strain diagram and analyze the case when a liner evaluated by Mises equivalent stress does not yield in any of the following cases and the case when a liner yields.
 - 1) When no pressure is applied after autofrettage
 - 2) When the proof test pressure is applied
 - 3) When no pressure is applied after the proof test pressure is applied
 - 4) When MEOP is applied
 - 5) When no pressure is applied after MEOP is applied.
- k. For COPV, note that twisting or crossing of fiber caused by filament winding reduces the composite material strength. Develop a model for FEM analysis for resin cracking, which is unique to COPV with filament windings by performing analysis with modulus of elasticity perpendicular to the fiber (E_T , ν_{LT}) reduced to within a range that will not disturb analysis at the elements whose stress perpendicular to the fiber and strain seemed to exceed material strength. Note that the model may developed by performing alternative analysis with modulus of elasticity perpendicular to the fiber reduced at all elements for convenience.
- l. When external pressure is applied to metallic liner in COPV subjected to autofrettage, perform buckling analysis. In this case, perform elasto-plasticity

analysis.

(3) Judgment criteria

Judgment shall follow paragraph 3.5.1.4.

3.5.1.2 Analyses for flight

(1) Purpose

These analyses confirm that the thickness determined in paragraph 3.4 provide appropriate strength (including buckling) for pressure loads and flight loads applied to the equipment from launch to flight to the orbit (including return for the reusable equipment).

The analyses shall apply to metallic pressure vessels, launch vehicle propellant tanks and COPV. They shall also apply to piping, fittings, and other components which cannot satisfy safety factors described in Table 3.1.3-1.

(2) Methods and conditions

- a. Perform stress analysis of the thickness and shape determined in paragraph 3.4 using FEM analysis. Establish analysis conditions properly (including model development) and clarify these conditions.
- b. When buckling analysis of the thickness and shape determined in paragraph 3.4 is required, perform it separately from stress analysis. Establish analysis conditions properly (including model development) and clarify these conditions.
- c. Perform FEM analysis primarily for elastic analysis. Perform elasto-plasticity analysis when a metallic liner of a COPV yields due to pressurization to MEOP. Develop appropriate models based on the necessary assumptions to ensure safety. For the thickness, use the minimum design thickness for general parts and weld parts. Also consider appropriate deformations such as weld deformations (particularly, angular deformations) and mis-match. For structural discontinuities including uneven surfaces and notches, determine the maximum value of the local peak stress. If reliable analysis or experiment results are available for the stress concentration factor, use the result for peak stress. When the stress concentration factor is not identified, use 4.
- d. For buckling analysis, use the minimum sheet thickness in the schematic. Also, consider that initial irregularities and residual stress at the time of fabrication will reduce the buckling load to below the theoretical value. However, for buckling analysis of rocket propellant tanks, use the nominal design value as the plate thickness.
- e. Establish boundary conditions including spring constants based on the necessary assumptions to ensure safety as in model development.

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- f. Each component shall be analyzed under the maximum stress condition during flight sequence.
- g. Calculate stress by numerical analyses including FEM when analyzing stress of structurally discontinuous parts such as joints of cylindrical shells and heads, flanges and the like shown in Figure 3.5.1-1 and when analyzing stress of parts simultaneously subject to flight load, pressure load, and thermal stress due to the temperature distribution.
- h. Conduct buckling analysis for the following cases.
 - 1) When axial compressive force due to flight load and bending moment are applied to the cylindrical shell.
 - 2) When the payload load is applied to the head (dome). (See Figure 3.2-2.)
 - 3) When back pressure is applied to the common bulkhead. (See Figure 3.2-2.)

(3) Judgment criteria

Judgment criteria shall be followed by paragraph 3.5.1.4.

3.5.1.3 Analyses for ground handling

(1) Purpose

These analyses confirm that the launch vehicle propellant tank thickness determined in paragraph 3.4.2 provides appropriate strength (including buckling) for pressure loads during ground handling and ground handling loads.

(2) Methods and conditions

- a. Calculate stress by numerical analyses including FEM when analyzing stress of structurally discontinuous parts such as joints of cylindrical shells and heads, flanges and the like shown in Figure 3.5.1-1 and when analyzing stress of parts simultaneously subject to ground handling loads, pressure loads, and thermal stress due to the temperature distribution.
- b. When buckling analysis of the thickness and shape calculated in paragraph 3.4 is required, perform buckling analysis separately from stress analysis. Set analysis conditions properly (including model development) and clarify these conditions.
- c. Perform FEM analysis primarily for elastic analysis. Develop appropriate models based on the necessary assumptions to ensure safety. For thickness, use the minimum design metallic liner thickness for general parts and weld parts. Also consider appropriate deformations such as weld deformations (particularly, angular deformations) and miss-match. For structural discontinuities including uneven surfaces and notches, determine the maximum value of the local peak stress. If reliable analysis or experiment

results are available for the stress concentration factor, use the result for the peak stress. When the stress concentration factor is not identified, use 4.

- d. When performing buckling analysis, use the nominal design thickness as the thickness for calculating stress. Also, consider that initial irregularities and residual stress at the time of fabrication will reduce the buckling stress to below the theoretical value.
- e. Establish boundary conditions including spring constants based on the necessary assumptions to ensure safety as in model development.
- f. For ground handling loads, consider special factor (see paragraph 3.1.3.4).
- g. Each component shall be analyzed under the maximum stress condition during ground operations.
- h. Conduct buckling analysis for the following cases.
 - 1) When an axial compressive force due to the ground handling load and bending moment are applied to the cylindrical shell.
 - 2) When the payload load is applied to the head (dome) (See Figure 3.2-2.).
 - 3) When back pressure is applied to the common bulkhead (See Figure 3.2-2.).

(3) Judgment Criteria

Judgment criteria shall be followed by paragraph 3.5.1.4.

3.5.1.4 Judgment criteria

The following are the judgment criteria for “Pressure load analyses” in paragraph 3.5.1.1, “Analyses for flight” in paragraph 3.5.1.2 and for “Analyses for ground handling” in paragraph 3.5.1.3.

3.5.1.4.1 Judgment criteria for stress analysis for metallic pressure vessel and launch vehicle propellant tank

- (1) Judgment criteria for strength analysis for metallic pressure vessels and launch vehicle propellant tanks

- a. Primary general membrane stress, primary general membrane stress plus bending stress, or primary local membrane stress plus bending stress

Stress intensity at any cross-section or parts to which pressure and external loads such as vibration are applied shall be as illustrated in Figure 3.5.1-2.

Figure 3.5.1-2 is a graphic representation of the following equation.

$$\frac{P_m + P_b}{S_m} \leq \frac{5}{3} - \frac{3}{2} \left[\frac{1}{3} - \frac{P_m}{S_m} \right]^2 \quad (3.5.1)$$

$$\frac{P_m}{S_m} \leq 1 \quad (3.5.2)$$

In the above equation, $P_m + P_b$ stands for general primary membrane stress plus bending stress. $P_L + P_b$ shall be used to calculate local primary membrane stress plus bending stress,

where

P_m : Stress intensity of general primary membrane stress generated by pressure analysis, analysis for flight and analysis for ground handling.

$$P_m = \text{Max}\{|\sigma_1 - \sigma_2|, |\sigma_2 - \sigma_3|, |\sigma_3 - \sigma_1|\}$$

$\sigma_1, \sigma_2, \sigma_3$: Principal stresses

P_b : Stress intensity of bending stress generated by pressure analysis, analysis for flight, and analysis for ground handling

P_L : Stress intensity of local primary membrane stress generated by pressure analysis, analysis for flight, and analysis for ground handling

S_m : Design stress intensity

$$S_m = \text{Small value among} \left[\begin{array}{c} \frac{\text{Material Yield Stress } (\sigma_y)^*}{\text{Safety Factor for Yield Stress}^{**}} \\ \text{and} \\ \frac{\text{Material Tensile Strength } (\sigma_u)^*}{\text{Safety Factor for Ultimate}^{**}} \end{array} \right]$$

* Use the value specified at the design temperature. For materials used at cryogenic temperatures, if the yield stress or tensile strength at cryogenic temperatures exceeds the yield stress or tensile strength at normal temperature, the yield stress or tensile strength at normal temperature may be used.

** Use the value which is specified in Table 3.1.3-1 for pressure analysis, and the value which is specified in Table 3.1.3-3 for analysis for flight. Consider special factor shown in paragraph 3.1.3.4 and use the value specified in Table 3.1.3-1 for analysis for ground handling.

b. Shakedown (Primary stress plus secondary stress)

One of the following conditions shall be satisfied at any cross-sections or parts

to which pressure and external loads such as vibration are applied.

$$P_L + P_b + Q \leq 2\sigma_y \quad (3.5.3a)$$

or

$$P_m + P_b + Q \leq 2\sigma_y \quad (3.5.3b)$$

where

Q: Secondary stress, excluding local stress concentration

σ_y : Yield stress of material

(2) Judgment criteria for buckling analysis of metallic pressure vessels and launch vehicle propellant tanks

Based on the buckling analysis result, judge buckling using the following equations.

$$\frac{P}{S_b} \leq 1 \quad (3.5.4)$$

$$S_b = \frac{P_{cr}}{\text{Safety Factor}^*}$$

* Use the safety factor which is specified in paragraph 3.1.3.3 and is actually used.

where

S_b : Load display buckling strength

P: Compressive load applied to the structure described above.

P_{cr} : Buckling limit load applied to the structure

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3.5.1.4.2 Judgment criteria for stress analysis of COPV

(1) Judgment criteria for strength analysis of COPV

a. Judgment criteria for pressure analysis

The following are judgment criteria for composite materials, metallic liners and non-metallic liners subjected to design burst pressure and proof test pressure defined below.

(Design burst pressure)=(MEOP) x (Safety factor for design burst pressure described in Table 3.1.3-2)

(Proof test pressure)=(MEOP) x (Proof test pressure factor described in Table 4.4-1)

1) Composite materials

- When design burst pressure is applied : $S_{cb} < S_{cu}$

where

S_{cb} : Maximum stress generated in composite material in the direction of the fiber due to design burst pressure.

S_{cu} : Tensile strength of composite material in the direction of the fiber.

$$S_{cu} = S_{ca} \times R_{fw}$$

S_{ca} : Minimum value of tensile strength of a composite material

R_{fw} : The ratio at which strength of a composite material is reduced by overlap of fibers and other causes

When fatigue damage analysis (stress rupture analysis) shown in paragraph 3.5.3.1 is conducted for the reusable type high-pressure gas equipment using glass fiber or other material, the following equation should be used:

- When design burst pressure is applied : $S_{cb} < S_{cu} \times 0.625$

2) Metallic liners

When a metallic liner does not yield

- When proof test pressure is applied : $S_{mp} < S_{my}$

- Design burst pressure is applied : $\epsilon_{mb} < \epsilon_{mu}$

where

S_{mp} : Mises equivalent stress generated in a metallic liner by proof test pressure

S_{my} : Yield stress in a metallic liner

ϵ_{mb} : Maximum strain generated in a metallic liner by design burst pressure

ϵ_{mu} : Breaking strain in a metallic liner

When a metallic liner yields

- When design burst pressure is applied: $\epsilon_{mb} < \epsilon_{mu}$

Perform fatigue damage analysis and confirm that the strain generated in the metallic liner by MEOP described in the pressure-strain diagram will not destroy the metallic liner by fatigue after being subjected to four times the number of pressurization cycles for the required life.

3) Non-metallic liners

- When design burst pressure is applied: $\epsilon_{rb} < \epsilon_{ru}$

where

ε_{rb} : Maximum strain generated in a non-metallic liner by design burst pressure

ε_{ru} : Breaking strain in a non-metallic liner

b. Judgment criteria for analysis for flight

1) Composite materials

$$(S_{cm} + S_{cd}) \times (\text{Safety factor for ultimate load specified in Table 3.1.3-4}) < S_{cu}$$

where

$S_{cm} + S_{cd}$: Maximum stress generated in a composite material in the direction of the fiber by a combination of MEOP and dynamic load.

S_{cu} : Tensile strength of a composite material in the direction of the fiber

When fatigue damage analysis (stress rupture analysis) is conducted pursuant to paragraph 3.5.3.1 for expendable high-pressure gas equipment using glass fiber or other material, the following equation should be used:

$$(S_{cm} + S_{cd}) \times (\text{Safety factor for ultimate load specified in Table 3.1.3-4}) < S_{cu} \times 0.625$$

2) Metallic liners

$$(S_{mm} + S_{md}) \times (\text{Safety factor for yield stress (metallic liner) specified in Table 3.1.3-4}) < S_{my}$$

$$(\varepsilon_{mm} + \varepsilon_{md}) \times (\text{Safety factor for ultimate load specified in Table 3.1.3-4}) < \varepsilon_{mu}$$

where

$S_{mm} + S_{md}$: Mises equivalent stress generated in a metallic liner by a combination of MEOP and dynamic load

S_{my} : Yield stress in a metallic liner

ε_{mm} : Maximum strain generated in a metallic liner by the MEOP

ε_{md} : Maximum strain generated in a metallic liner by dynamic loads

ε_{mu} : Breaking strain of a metallic liner

When adopting a design method that allows yielding of the metallic liner, confirm only that the following strain conditions are satisfied:

$$(\varepsilon_{mm} + \varepsilon_{md}) \times (\text{Safety factor for ultimate load specified in Table 3.1.3-4}) < \varepsilon_{mu}$$

3) Non-metallic liners

$$(\epsilon_{cm} + \epsilon_{cd}) \times (\text{Safety factor for ultimate load specified in Table 3.1.3-4}) < \epsilon_{cu}$$

where

$\epsilon_{cm} + \epsilon_{cd}$: Maximum strain generated in a non-metallic liner by a combination of MEOP and dynamic load

ϵ_{cu} : Breaking strain in a non-metallic liner

(2) Judgment criteria for buckling analysis of COPV.

Judgment criteria shall be followed by paragraph 3.4.3.3.

(3) Judgment criteria for compressive yield stress in composite pressure vessels | E

Judgment criteria shall be followed by paragraph 3.4.3.2. However, when design method which allows yielding of metallic liner is adopted, this paragraph can be exempted.

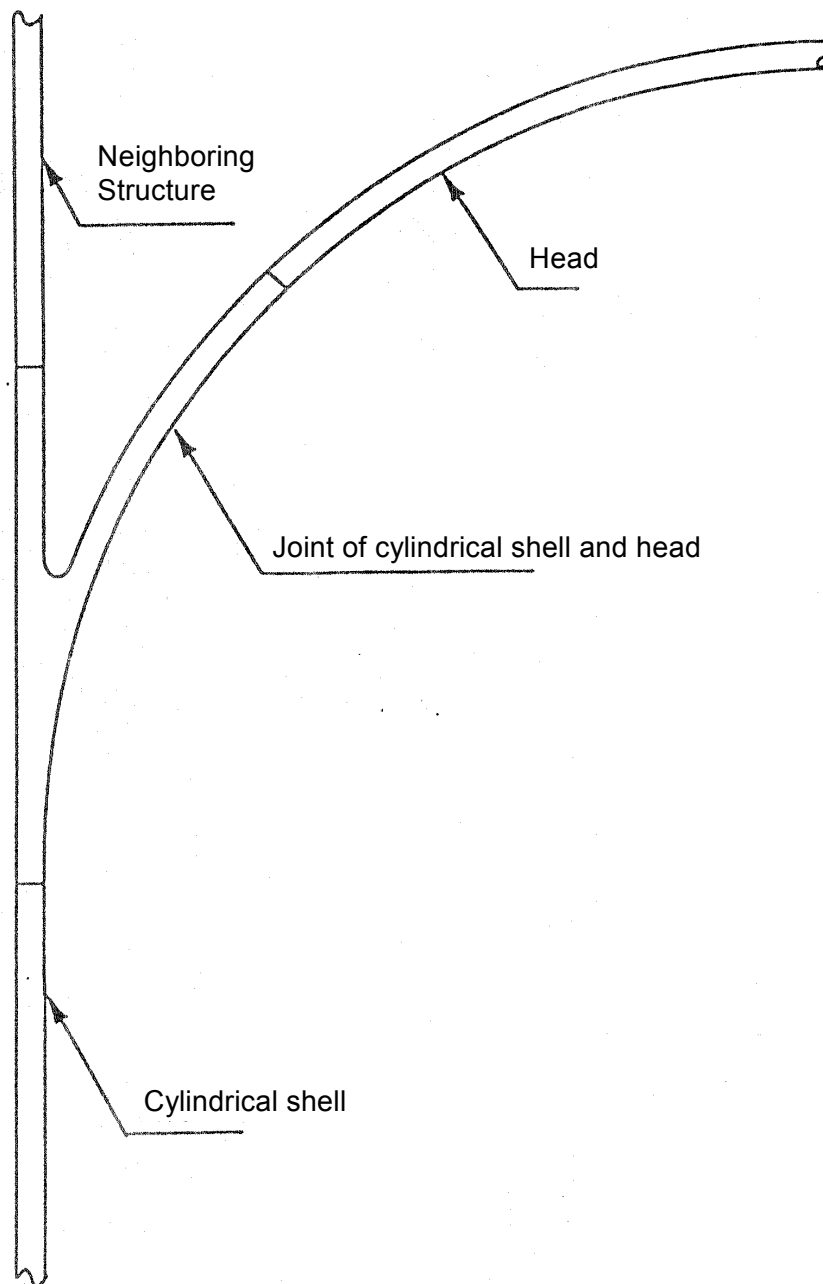


Figure 3.5.1-1 Joint Part of Cylindrical Shell and Head (Example)

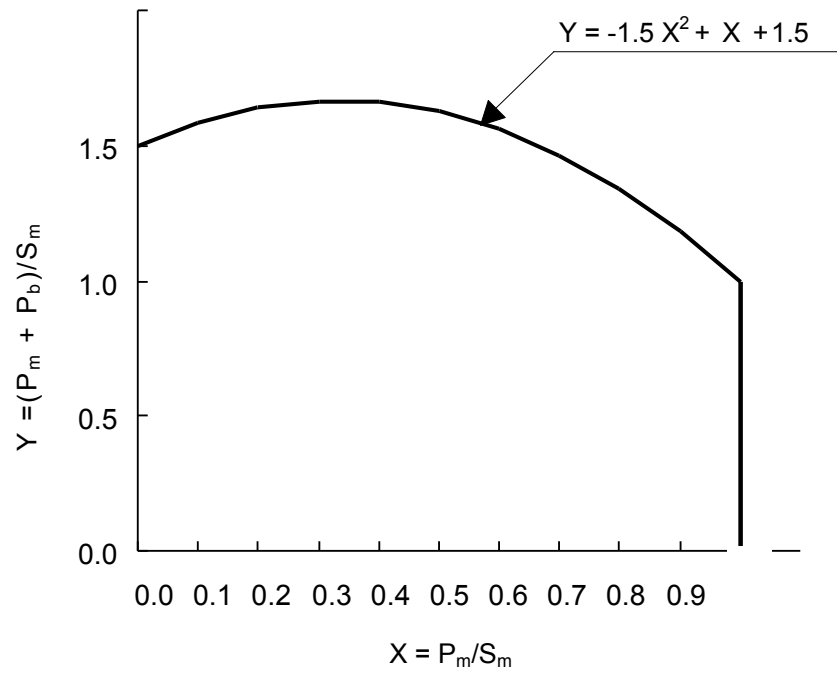


Figure 3.5.1-2 Allowable range of primary general membrane stress, primary general membrane stress plus bending stress, or primary local membrane stress plus bending stress

3.5.2 Judgment of LBB occurrence (Analysis and testing)

Judge by the following equations considering fracture toughness and plastic collapse pressure or testing to determine whether LBB occurs due to cyclic loading of the MEOP. The analysis shall be conducted for a part of high-pressure gas equipment to which large stress is applied.

The analysis shall be performed for pressure vessels and launch vehicle propellant tanks. Additionally, the analysis shall be conducted for piping, fitting, and other components which do not satisfy the safety factor requirements specified in Table 3.1.3-1.

3.5.2.1 Judgment of LBB occurrence by analysis

3.5.2.1.1 Metallic pressure vessel and launch vehicle propellant tank

Perform flaw growth analysis to estimate the surface flaw shape immediately before penetration, or through-flaw dimensions immediately after penetration. Evaluate the burst condition for either of the estimates following the steps below. Flaw growth analysis may be substituted by evaluation using a wide range of surface flaw shapes or through flaw dimensions.

- 1) Analyze the burst condition (K_r) in (1).
- 2) When the material has a noticeable burst resistance curve (R curve), analyze burst condition (K_R) in (2) instead of burst condition (K_r) in (1).
- 3) Analyze plastic collapse condition (L_r) in (3).
- 4) Judge LBB occurrence in either of the following cases:
 - Judgment 1: When $K_r < 1$ and $L_r < 1$, LBB occurrence is applied. In other cases, LBB occurrence is not applied.
 - Judgment 2: Judge by burst evaluation curve (Figure 3.5.2-1) considering mutual influence between burst condition (K_r) and plastic collapse condition (L_r).

The following are the details of LBB judgment equation.

(1) Burst conditions (K_r)

LBB occurrence is applied: $K_r < 1$

LBB occurrence is not applied: $K_r \geq 1$

$$K_r = \frac{K}{K_C}$$

K: Stress intensity factor

K_c : Fracture toughness at material's design temperature

The value of K_c shall be established based on highly reliable data obtained under appropriate test conditions. If the data reliability can be ensured, the mean value of the data may be used.

The value of K should be calculated from (3.5.7) to (3.5.17). In case of using other equations are used, the reference or the sources should be indicated clearly.

a. Surface flaw

$$K = \sqrt{\pi a} (\sigma_m f_m + \sigma_b f_b) \quad (3.5.7)$$

$$\sigma = \sigma_m + \sigma_b \left(1 - \frac{2z}{t}\right) \quad (3.5.8)$$

$$f_m^A = \frac{1}{\sqrt{Q}} \left[1.13 - 0.18 \frac{a}{2c} + \left(-0.54 + \frac{0.89}{0.2 + \frac{a}{c}} \right) \left(\frac{a}{t} \right)^2 + \left(0.5 - \frac{1}{0.65 + \frac{a}{c}} + 14 \left(1 - \frac{a}{c} \right)^{24} \right) \left(\frac{a}{t} \right)^4 \right] \quad (3.5.9)$$

$$Q = \phi^2 - 0.212 \left[\frac{\sigma}{\sigma_y} \right]^2 \quad (3.5.10)$$

$$\phi^2 = 1 + 4.595 \left[\frac{a}{2c} \right]^{1.65} \quad (3.5.11)$$

$$f_m^B = \left[\left(1.1 + 0.35 \left(\frac{a}{t} \right)^2 \right) \left(\frac{a}{c} \right)^{0.5} \right] f_m^A \quad (3.5.12)$$

$$f_b^A = \left[1 + \left(-1.22 - 0.24 \frac{a}{2c} \right) \frac{a}{2c} + \left\{ 0.55 - 1.05 \left(\frac{a}{c} \right)^{0.75} + 0.47 \left(\frac{a}{c} \right)^{1.5} \right\} \left(\frac{a}{t} \right)^2 \right] f_m^A \quad (3.5.13)$$

$$f_b^B = \left[1 - 0.34 \frac{a}{t} - 0.22 \left(\frac{a}{t} \right) \left(\frac{a}{2c} \right) \right] f_m^B \quad (3.5.14)$$

1) Internal pressure of a cylindrical vessel (Flaw along axis)

$$\sigma_m = \frac{PR}{t}, \quad \sigma_b = 0$$

2) Internal pressure of a spherical vessel

$$\sigma_m = \frac{PR}{2t}, \sigma_b = 0$$

where

σ : Linear stress distribution for thickness direction

σ_m : Tensile stress

σ_b : Bending stress

σ_y : Yield stress at material set temperature

f_m : Correction factor of tensile stress

f_b : Correction factor of bending stress

f_m^A : f_m at point A (deepest point)

f_b^A : f_b at point A (deepest point)

f_m^B : f_m at point B (Surface point)

f_b^B : f_b at point B (surface point)

Q: Shape parameter of a flaw corrected for plastic region

ϕ : Shape parameter of a flaw

2W: Sheet width

a: Flaw depth

c: One half of flaw length

t: Thickness

z: Distance for thickness direction from inside (flaw side)

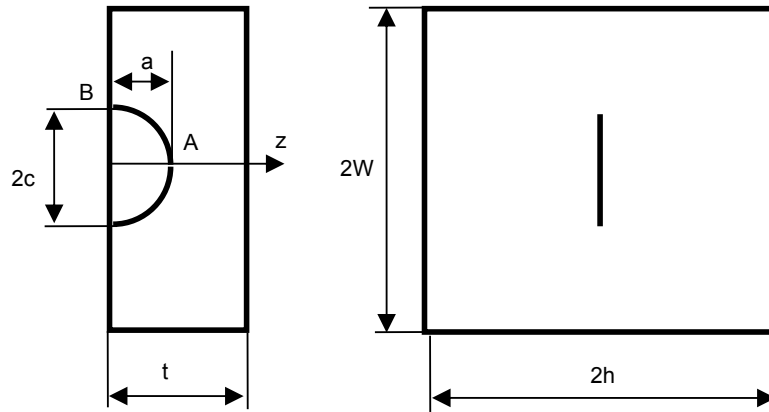
2h: Sheet length

P: Internal pressure

R: Internal radius

These equations shall be applied within the following range.

$$\frac{a}{t} \leq 0.8, \quad \frac{a}{2c} \leq 0.5, \quad \frac{2c}{W} \leq 0.3, \quad \frac{2c}{h} \leq 0.3$$



b. Through-thickness flaw

$$K = \sigma_m \sqrt{\pi a} F \quad (3.5.15)$$

$$F = 1 + 7.2449 \times 10^{-2} \lambda + 0.64856 \lambda^2 - 0.2327 \lambda^3 + 3.8154 \times 10^{-2} \lambda^4 - 2.3487 \times 10^{-3} \lambda^5 \quad (3.5.16)$$

$$\lambda = \frac{a}{\sqrt{Rt}} \quad (3.5.17)$$

where “a” is one half of the flaw length. The shape of a through-thickness flaw is obtained by replacing the surface flaw that has penetrated thickness (flaw depth $a=t$, flaw length $2c$) with the through-thickness flaw (flaw length $2c=2a$).

1) Internal pressure of a cylindrical vessel (Flaw in the axis direction)

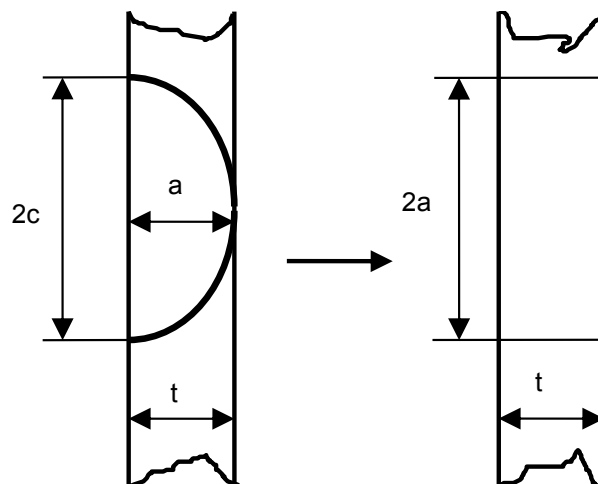
$$\sigma_m = \frac{PR}{t}$$

2) Internal pressure of a spherical vessel

$$\sigma_m = \frac{PR}{2t}$$

These equations shall be applied within the following range.

$$0 \leq \lambda \leq 5$$



(2) Burst condition (K_R)

When the material has a noticeable burst resistance curve (R curve), the following equations shall be applied.

LBB occurrence is applied

$$\frac{\partial K}{\partial a} < \frac{dK_R}{da} \quad \text{at } K = K_R$$

LBB occurrence is not applied

$$\frac{\partial K}{\partial a} \geq \frac{dK_R}{da} \quad \text{at } K = K_R$$

K_R : Burst resistance at material's design temperature

(3) Plastic collapse conditions

LBB occurrence is applied

$$L_r(\text{local}) < 1, \quad L_r(\text{total}) < 1$$

or,

$$L_r(\text{local}) \geq 1, \quad L_r(\text{total}) < 1$$

LBB occurrence is not applied

$$L_r(\text{total}) \geq 1$$

$$L_r = \frac{P}{P_c}$$

P : Internal pressure

P_c : Plastic collapse pressure at design temperature

The value of P_c should be calculated from (3.5.18) to (3.5.31). In case of using other equations are used, the reference or the sources should be indicated clearly.

a. Surface flaw

Local collapse

$$P_c = P_0 \frac{\eta}{1 - \frac{1 - \eta}{m}} \quad (3.5.18)$$

$$\eta = 1 - \frac{a}{t} \quad (3.5.19)$$

$$m = \left[1 + \frac{1.61(1-\eta)c^2}{Rt} \right]^{0.5} \quad (3.5.20)$$

Total collapse

$$P_c = P_0 \left(\eta + \frac{1-\eta}{m'} \right) \quad (3.5.21)$$

$$m' = \left[1 + \frac{1.61c^2}{Rt} \right]^{0.5} \quad (3.5.22)$$

1) Internal pressure of cylindrical vessel (Flaw in the axis direction)

$$P_0 = \frac{\sigma_y t}{R}$$

2) Internal pressure of spherical vessel

$$P_0 = \frac{2\sigma_y t}{R}$$

where

P_0 : Plastic collapse pressure without a flaw

σ_y : Yield stress at material's design temperature

b. Through thickness flaw

Total collapse

1) Internal pressure of a cylindrical vessel (Flaw in the axis direction)

$$P_c = \frac{P_0}{m} \quad (3.5.23)$$

$$P_0 = \frac{\sigma_y t}{R} \quad (3.5.24)$$

$$m = \left(1 + 1.2987\lambda^2 - 0.026905\lambda^4 + 5.3549 \times 10^{-4}\lambda^6 \right)^{0.5} \quad (3.5.25)$$

$$\lambda = \frac{a}{\sqrt{Rt}} \quad (3.5.26)$$

where “a” is one half of the flaw length. The shape of a through-thickness flaw is obtained by replacing the surface flaw that has penetrated thickness (flaw depth $a=t$, flaw length $2c$) with the through-thickness flaw (flaw length $2c=2a$).

These equations apply for the following.

$$0 \leq \lambda \leq 5$$

2) Internal pressure of spherical vessel

$$P_c = P_0 \frac{2}{\left(1 + \frac{8\rho^2}{\cos^2\phi}\right)^{0.5}} \quad (3.5.27)$$

$$P_0 = \frac{2\sigma_y t}{R} \quad (3.5.28)$$

$$\rho = \frac{a}{\sqrt{Rt}} \quad (3.5.29)$$

$$\phi = \frac{a}{R} \quad (3.5.30)$$

where “a” is one half of the flaw length. The shape of a through-thickness flaw is obtained by replacing the surface flaw that has penetrated thickness (flaw depth $a=t$, and flaw length $2c$) with the through-thickness flaw (flaw length $2a=2c$).

These equations apply for the following.

$$\frac{t}{R} \leq 0.1 \quad (3.5.31)$$

(4) Burst evaluation curve

LBB occurrence is applied

Inside the burst evaluation curve.

LBB occurrence is not applied

Outside the burst evaluation curve.

The burst evaluation curve is expressed by the following equations.

$$K_r = (1 - 0.14(L_r)^2) [0.3 + 0.7 \exp(-0.65(L_r)^6)] \quad (3.5.32)$$

$$L_r = L_r^{\max} \quad (3.5.33)$$

$$L_r^{\max} = \frac{\sigma_{\text{eff},y}}{\sigma_y} \quad (3.5.34)$$

$$\sigma_{\text{eff},y} = \frac{\sigma_y + \sigma_u}{2} \quad (3.5.35)$$

where

σ_u : Tensile strength at material's design temperature

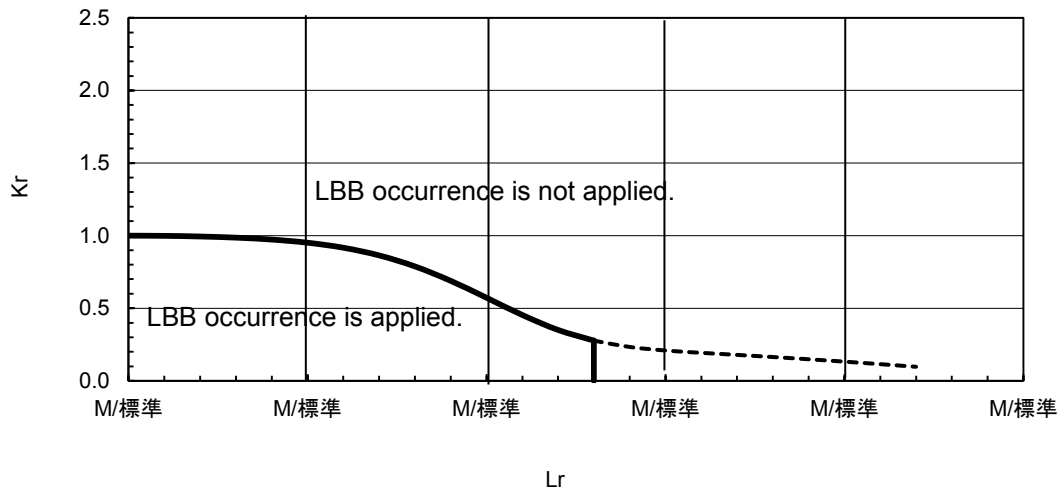


Figure 3.5.2-1 Burst Evaluation Curve

3.5.2.1.2 COPV

(1) COPV with metallic liners

Evaluate burst condition (K_r) and plastic collapse condition (L_r) of a metallic liner with the same method as described in paragraph 3.5.2.1.1 “Metallic pressure vessels and launch vehicle propellant tanks.”

Verify the LBB occurrence for COPV according to 1) or 2) depending on whether the bursting of the metallic liner will cause the pressure vessel to burst or not:

1) $K_r < 1$, L_r = random: LBB occurrence is applied.

$K_r \geq 1$, L_r = random: LBB occurrence is not applied.

2) Inside the burst evaluation curve: LBB occurrence is applied.

Outside the burst evaluation curve: LBB occurrence is not applied.

(2) COPV with non-metallic liners

All pressure fractions are shared by composite materials because a non-metallic liner does not share pressure fractions. Ensure that composite material parts do not burst due to fatigue damage analysis. For COPV, the LBB occurrence is assumed to be applied because bursting of the non-metallic liner does not induce burst of the pressure vessel.

3.5.2.2 Judgment of LBB occurrence by test

3.5.2.2.1 Metallic pressure vessel (including launch vehicle propellant tank)

There are two methods to judge LBB occurrence by testing. Basically, the method should be selected using the flight model. In individual development project, however, the verification method may be selected by using test piece or equivalent as shown below, if test piece or partial model which has the same thickness as the flight model can generate stress or strain equivalent to that of flight model.

(1) Verification test using the flight model

a. Test article

A vessel of the same structure as that for the flight model shall be fabricated in the same manner.

Initial crack shall be determined by either of 1) or 2) below, with the crack width being 0.3mm or less:

1) When flaw growth analysis is performed

The initial crack shall be the limit detectable in nondestructive inspection or larger, and the shape of the initial crack ($a/2c$) shall be determined using either the surface flaw shape immediately before the through thickness is reached or the flaw dimension immediately after the through thickness is reached, as estimated by flaw growth analysis.

2) When flaw growth analysis is not performed

The shape of the initial crack ($a/2c = 0.1 \sim 0.5$) shall be determined to cover a larger range of through thickness flaw dimensions.

b. Test method

To verify LBB occurrence by making an initial crack determined according to 1) or 2) in item a. above and applying a repeated load at MEOP.

c. Judgment criteria

Flaw shall be stable when the initial crack reaches through thickness.

(2) Verification test using test piece

a. Test piece

Test piece shall be fabricated, welded, and applied heat treatment similarly to flight model and has the same thickness as specified in applicable drawing. An example of the shape of the test article is shown in Fig.3.5.2-2.

Initial crack shape shall be set by either of 1) or 2) in item a. of (1) verification test using flight model, with the crack width of 0.3mm or less:

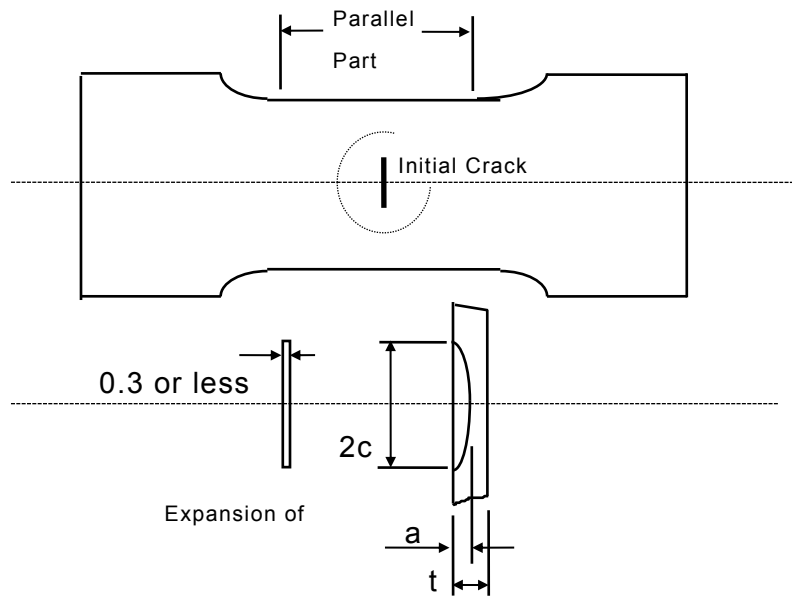


Figure.3.5.2-2 Shape of Test Article

b. Test method

Verify LBB occurrence by making initial crack set according to 1) or 2) in item a. of (1) Verification test using the flight model and applying repeated stress or strain equivalent at MEOP.

c. Judgment criteria

Flaw shall be stable when the initial crack reaches through thickness.

3.5.2.2.2 COPV

There are three methods to judge LBB occurrence by testing. Basically, it is desirable to select the method using the flight model. In individual development project, however, the verification method using partial model or test piece as shown below, can be selected if partial model or test piece which has the same thickness as flight model can generate stress or strain equivalent to that of flight model.

(1) COPV with metallic liners

a. The verification test using the flight model

1) Test article

The vessel of the structure same as flight model shall be fabricated by the same process. Initial crack shall be set by either of 1) or 2) in item a. of (1) Verification test using flight model for metallic pressure vessel, with the crack

width of 0.3mm or less:

2) Test method

To verify LBB occurrence by making initial crack set according to 1) or 2) in item a. of (1) Verification test using flight model for metallic pressure vessel and applying repeated pressure at MEOP.

3) Judgment criteria

Flaw shall be stable when initial crack reaches through thickness.

b. The verification test using partial model

1) Test article

Test article shall be partial model which simulates flight model in terms of structure.

Partial model of liner shall be fabricated, welded, and applied heat treatment similarly to flight model and has the same thickness as specified in applicable drawing. If the stress equivalent to Mises stress which is generated in flight operation exceeds yield stress, strain cycle in flight operation shall be applied, including the plastic zone for each of the tensile and compressive sides. An example of the shape of partial model is shown in Figure 3.5.2-3.

Initial crack shall be set by either of 1) or 2) in item a. of (1) Verification test using flight model for metallic pressure vessel, with the crack width of 0.3 mm or less:

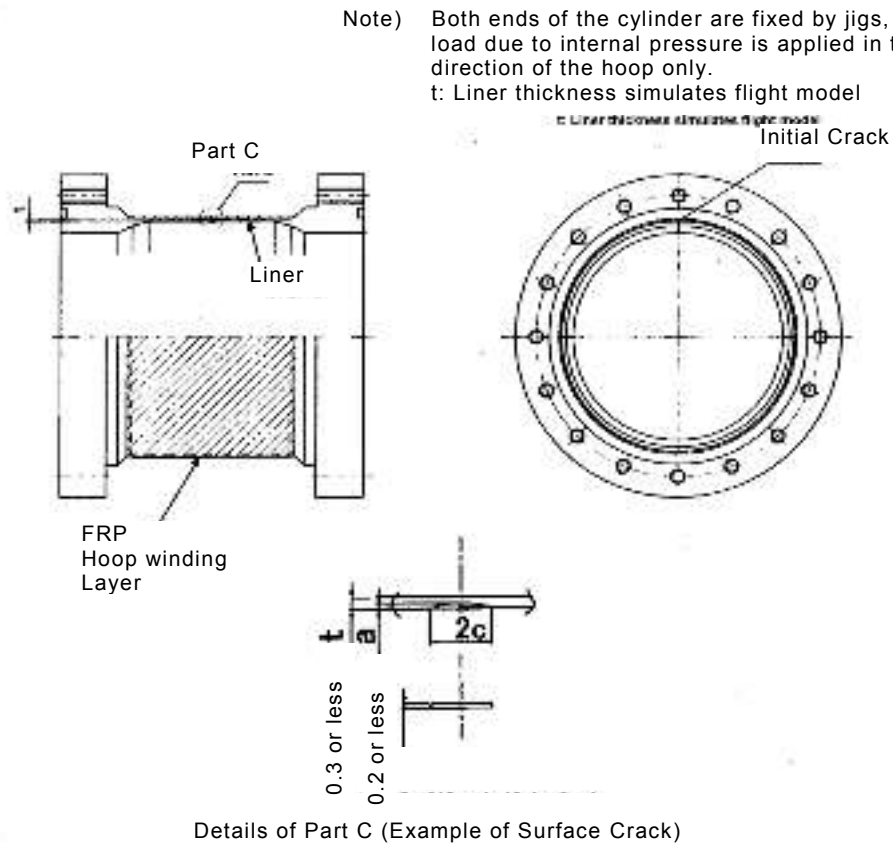


Figure.3.5.2-3 An Example of a Test Article for a Partial Model

2) Test method

LBB occurrence shall be verified by applying a repeated load (pressure) to a partial model having an initial crack set as illustrated in Figure 3.5.2-3. Pressure shall be set at the level where strain cycle in flight operation, including the plastic region for each of tensile and compressive sides, is equivalent to that of flight model. If strain is applied in the single axis direction for partial model, magnitude of the applied strain is converted by the following equation.

Conversion equation:

$$\varepsilon' = ((\varepsilon_1)^2 + (\varepsilon_2)^2)^{0.5}$$

ε' : Strain to be applied to the partial model

$\varepsilon_1, \varepsilon_2$: Strain to be generated in the flight model

3) Judgment criteria

Flaw shall be stable when the initial crack reaches through thickness.

c. Verification test using test piece

The verification test using test piece as specified in item (2) for metallic pressure vessels shall be applied. If Mises equivalent stress which is generated in flight operation exceeds yield stress, test shall be conducted by strain control rather than stress control. Stress shall be set at the level where a strain cycle in flight operation, including the plastic zone for each of the tensile and compressive sides, is equivalent to that of flight model.

(2) COPV with non-metallic liners

Test for COPV with non-metallic liners is not required because LBB occurrence for these COPV is basically considered to be LBB occurrence is applied.

3.5.3 Fatigue damage analysis and test

Verify that high-pressure gas equipment has sufficient fatigue strength and stress rupture characteristics by analysis or test.

3.5.3.1 Fatigue damage analysis

(1) Purpose

Perform fatigue damage analysis for high-pressure gas equipment under cyclic loads, especially for the portions exposed to high stress, to analytically prove that the pressure cycle life requirement in (2) of paragraph 3.1.5 is satisfied.

This analysis shall be applied to pressure vessels and bellows (safety factor for material strength is specified in Table 3.1.3-1). Also, this analysis shall be applied to pressure piping and fittings and other components which do not satisfy the safety factor requirements specified in Table 3.1.3-1.

(2) Methods and conditions

- a. The analysis shall confirm with Minor's Law that the pressure cycle life requirement is satisfied by comparing the cyclic stress range for peak stress and the number of loading cycles, which are calculated based on the equipment's duty cycle, with the material's design fatigue curve.
- b. When the cyclic stress is beyond the elastic range, evaluate cyclic strain (total strain range) and calculate the value of the virtual elastic stress range at design temperature by multiplying the cyclic strain by the modulus of longitudinal elasticity at design temperature.
- c. When modulus of longitudinal elasticity shown in the material design fatigue curve is different from the modulus of longitudinal elasticity at material design temperature, correct the cyclic stress range or virtual elastic stress range by the ratio of longitudinal elasticity.
- d. When the vibration stress which is generated by fluid pressure cycle and mechanical vibration is superimposed, the vibration stress shall be converted to equivalent stress range by using modified Goodman chart (equation 3.5.38). Fatigue by pressure cycle and fatigue by vibration shall be loaded independently. Each fatigue is accumulated by Miner's rule (equation 3.5.39).

(3) Design fatigue curve of metallic materials

a. JIS method

Apply the design fatigue curve of JIS B 8266 Appendix 8 for the materials specified in this curve. This design fatigue curve considers the effect of mean stress and the safety factor of fatigue strength for a given endurance [2] and safety factor of fatigue life [20].

b. Nominal fatigue life performance value method

Use nominal values for materials to which nominal fatigue life performance values specified in reliable materials standards (such as MMPDS-01) issued by public organizations are applicable. When applying the nominal value, consider finishing conditions including stress concentration and surface roughness resulting from the shapes of corners, notches, holes and joints, and the like.

Also consider effects of environmental conditions such as mean stress, strain, heat treatment, temperature at use, and atmosphere. Nominal fatigue life performance value is usually shown as the optimum fatigue curve. When the conditions above are satisfied, the safety factor of [5] can be used for fatigue life.

c. Manson-Coffin equation method

Apply the following Manson-Coffin equation to draw design fatigue curve for low-cycle fatigue with less than 1000 loading cycles.

$$\Delta = 0.0266(\varepsilon_f)^{0.155} \left[\frac{\sigma_u}{E} \right]^{-0.53} (N_f)^{-0.56} + 1.17 \left[\frac{\sigma_u}{E} \right]^{0.832} (N_f)^{-0.09} \quad (3.5.36)$$

$$\Delta\sigma = E\Delta\varepsilon_t \quad (3.5.37)$$

where

$\Delta\varepsilon_t$: Total strain range

$\Delta\sigma$: Virtual elastic stress range

N_f : LBB fatigue life

E : Modulus of the longitudinal elasticity at design temperature

σ_u : Tensile stress at design temperature

ε_f : Breaking strain at design temperature (true strain of fracture)

E , σ_u , and ε are determined by the material basic test specified in (1) of paragraph 5.1 of this technical standard. Draw the design fatigue curve so as to envelop the lower of the two curves obtained by incorporating the safety factors of fatigue strength for a given endurance [2] and of fatigue life [20] into the above equation. This equation is obtained by the strain-controlled alternating fatigue test (with 0 mean stress), but is to be applied regardless of the mean stress value.

d. Design fatigue curve development

Apply the Manson-Coffin equation in paragraph c. above to draw design

fatigue curves for low-cycle fatigue with not less than 1000 cyclic loads and for high-cycle fatigue. In addition, confirm compatibility with the Manson-Coffin equation by conducting the strain-controlled alternating fatigue test using more than five test articles having different cyclic stress ranges. If compatibility is not ensured, determine the optimum fatigue curve by performing the strain-controlled alternating fatigue test using many test articles. Draw the design fatigue curve so as to envelop the lower of the two curves obtained by incorporating the safety factors of fatigue strength at a given endurance [2] and of fatigue life [20] into the above equation. If mean stress is applicable, convert it into the equivalent stress range in the equation below using the modified Goodman chart.

$$\Delta\sigma_{eq} = \frac{\Delta\sigma}{1 - \sigma_m/\sigma_u} \quad (3.5.38)$$

where

$\Delta\sigma_{eq}$: Equivalent stress range when mean stress is applicable

$\Delta\sigma$: Stress range

σ_m : Mean stress ($\sigma_m = 0$ for compression)

σ_u : Tensile strength at design temperature

(4) Composite Materials

a. Carbon fiber

Fatigue damage analysis (stress rupture analysis) is not required for carbon fiber.

b. Glass fiber and other

For glass fiber and similar materials, fatigue damage analysis (stress rupture analysis) shall be performed and a material satisfying the following requirement shall be selected:

$$\frac{\text{Stress rupture strength of the flight operation period stress}}{\text{Tensile strength of the fiber of a COPV}(S_{cu})} > 0.625$$

If glass fiber or other type of fiber, is demonstrated to have stress rupture characteristics equivalent to carbon fiber, then it can be treated as equivalent to carbon fiber.

(5) Judgment Criteria

The following Miner's equation shall be satisfied.

$$\sum \frac{n_i}{N_i} \leq 1.0 \quad (3.5.39)$$

where

N_i: Allowable loading cycles corresponding to the cyclic stress range $\Delta\sigma_i$ on the design fatigue curve. The stress intensity of the peak stress for determining the cyclic stress range shall be as follows.

$$P_L + P_b + Q + F$$

or

$$P_m + P_b + Q + F$$

where

F: Includes increases in stress added to primary stress or secondary stress (peak stress) arising from stress concentrations due to structural discontinuities such as steps or notches and increases in stress due to angular deformation and misalignment of welds.

E

n_i: Number of cycles in the above stress range

3.5.3.2 Fatigue damage test

Fabricate a test article (pressure vessel) geometrically similar to the flight vessel subject to the test which contains a part to which cyclic load is applied and its neighboring part which affects stress applied to the part. Conduct tests for four times the number of required pressure cycles described in (2) of paragraph 3.1.5 to ensure bursting from fatigue will not occur during the required life. Correct the loading level considering the geometrical similarity between the flight vessel and the test article.

JIS B 8266 Annex 8, "6. Experimental stress analysis", ASME Section VIII Division 2 Appendix 6, etc., may be referred to regarding testing methods.

E

3.5.4 Flaw growth analysis and test

Conduct the following analyses or tests to confirm that the high-pressure gas equipment, with a part to which high stress and cyclic load are applied, will last for four or more times the required life specified in paragraph 3.1.5 “Life Requirements”.

3.5.4.1 Flaw growth analysis

3.5.4.1.1 Purpose

Flaw growth analysis should analytically confirm that small flaws generated during fabrication of high-pressure gas equipment will not grow to a size which causes the equipment to fracture during the life specified in “Life requirements for pressure cycle” in (2) of paragraph 3.1.5. This analysis shall apply to pressure vessels and to piping, fittings and other components which do not satisfy the safety factor shown in Table 3.3-1. For COPV, this analysis shall apply only to metallic liners.

3.5.4.1.2 Methods and conditions

When conducting the analysis, clearly specify its analytical basis and scope. The size of the initial flaw used for the analysis shall be determined as one of the following:

1) Part on which nondestructive inspection is performed

The flaw size is detectable by nondestructive inspections, but minimum limit is $2c = 0.25$ [mm].

2) Part on which nondestructive inspection cannot be performed

The flaw size is ensured by proof test (defect detection pressure test), but minimum limit is $2c = 0.25$ [mm].

where the pressure used for defect detection pressure test shall be the pressure to multiply proof factor by MEOP. Relation of the initial flaw size and proof factor is expressed as follows.

$$a_i = \frac{a_{cr}}{(P.F.)^2} \quad (3.5.40)$$

where

P.F: Proof factor

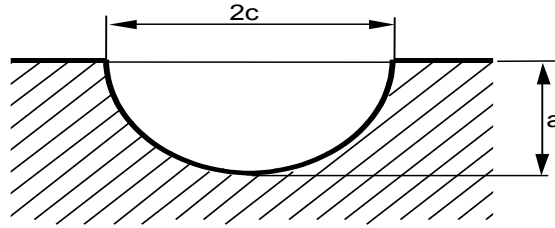
a_{cr} : Critical flaw size (depth) that results in destruction or through-thickness penetration of high-pressure gas equipment when the MEOP is applied.

a_i : Size (depth) of initial flaw ensured by the proof test (defect

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detection pressure test)

The flaw shape is defined in the following figure for calculating a_{cr} and a_i .



where a/c is determined by the fabrication process, loading conditions, etc. ($0.2 \leq a/c \leq 1$) Conduct flaw growth analysis using the initial flaw size determined above.

(1) Flaw growth rate equations

Flaw growth rate may be determined by Paris's Law or Forman's Law listed below. If other equations are employed, clearly state their sources.

Material coefficients (C_1 , C_2 , m_1 , and m_2) shall be the values at normal temperature. Fracture toughness (K_c) shall be the value at design temperature.

$$\frac{da}{dN} = C_1 (\Delta K)^{m_1} \quad (\text{Paris}) \quad (3.5.41a)$$

$$\frac{da}{dN} = \frac{C_2 (\Delta K)^{m_2}}{(1-R_1) K_c - \Delta K} \quad (\text{Forman}) \quad (3.5.41b)$$

where

a : Flaw depth

N : Number of loading cycles

ΔK : Fluctuation range of the stress intensity factor

$\Delta K = K_{\max} - K_{\min}$, However, $\Delta K = K_{\max}$, when K_{\min} is negative.

C_1 , C_2 : Material coefficients at normal temperature

m_1 , m_2 : Material coefficients at normal temperature

R_1 : Stress ratio ($R_1 = K_{\min}/K_{\max}$)

K_c : Fracture toughness at design temperature

Choose the values for C , m and K_c for the above equations based on highly reliable data obtained under appropriate test conditions. If data reliability is ensured, the mean of the data may be used.

(2) Stress intensity factor

Obtain stress intensity factors for calculating a_{cr} , a_i and the flaw growth rate with the following equations. The following are the equations for the stress intensity factor of a flat plate to which tensile and bending stress is applied (in paragraph a. below) and the equations for the stress intensity factor of a cylindrical vessel (in paragraph b. below). These equations can also be used for the stress intensity factor of a spherical vessel.

a. Stress intensity factor for a semi-ellipsoidal surface flaw on a flat plate

The stress intensity factor of a semi-ellipsoidal surface flaw on a flat plate, K_I , is calculated with the equations (3.5.7) to (3.5.14).

These equations consider plastic correction factors and can also be used when small-scale yielding conditions are not met.

b. Stress intensity factor in the axis direction for a semi-ellipsoidal surface flaw of a cylindrical vessel.

The stress intensity factor in the axis direction for a semi-ellipsoidal surface flaw of a cylindrical vessel, K_I , is calculated with the following equations.

Internal pressure

Deepest point

$$K_I = \sigma_h \sqrt{\pi t f} \quad (3.5.42)$$

$$\sigma_h = p \frac{(R_o)^2 + (R_i)^2}{(R_o)^2 - (R_i)^2} \quad (3.5.43)$$

$$f = 0.25 + \frac{0.4759\alpha + 0.1262\alpha^2}{\left[0.102 \left[\frac{R_i}{t} \right] - 0.02 \right]} \quad (3.5.44)$$

$$\alpha = \frac{\frac{a}{t}}{\left(\frac{a}{c} \right)^{0.58}} \quad (3.5.45)$$

Surface point

$$K_I = \sigma_h \sqrt{\pi t} f_s \quad (3.5.46)$$

$$f_s = f \left[1.06 + 0.28 \left(\frac{a}{t} \right)^2 \right] \left(\frac{a}{c} \right)^{0.41} \quad (3.5.47)$$

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Random distribution stress

Deepest point

$$K_I = \sqrt{\pi t} \left[\sum_{i=0}^3 \sigma_i g_i \right] \quad (3.5.48)$$

$$\sigma = \sigma_0 + \sigma_1 \left[\frac{z}{t} \right] + \sigma_2 \left[\frac{z}{t} \right]^2 + \sigma_3 \left[\frac{z}{t} \right]^3 \quad (3.5.49)$$

$$g_i = A_0 + \frac{[A_1 \alpha_i + A_2 (\alpha_i)^2 + A_3 (\alpha_i)^3 + A_4 (\alpha_i)^4 + A_5 (\alpha_i)^5]}{\left[0.102 \left(\frac{R_i}{t} \right) - 0.02 \right]} \quad (3.5.50)$$

$$\alpha_i = \frac{\frac{a}{t}}{\left(\frac{a}{c} \right)^\beta} \quad (3.5.51)$$

i	A ₀	A ₁	A ₂	A ₃	A ₄	A ₅	β
0	0.00	1.7767	-2.5975	2.7520	-1.3237	0.2363	0.58
0*	0.20	0.5000	0.0962	0.000	0.000	0.000	0.58
1	0.00	0.1045	0.4189	0.000	0.000	0.000	0.22
2	0.00	0.02038	-0.00397	0.42126	0.000	0.000	0.10
3	0.00	0.07283	-0.36006	0.66883	0.000	0.000	0.05

*Applicable range $a/c < 0.2$, $\alpha > 2$

Surface point

$$K_I = \sqrt{\pi t} \left[\sum_{i=0}^3 \sigma_i g_{si} \right] \quad (3.5.52)$$

$$g_{si} = g_i \left[A_6 + A_7 \left[\frac{a}{t} \right]^2 \right] \left[\frac{a}{c} \right]^\gamma \quad (3.5.53)$$

i	A_6	A_7	γ
0	1.06	0.28	0.41
1	0.25	0.20	0.26
2	0.07	0.16	0.06
3	0.085	0.02	0.00

where

A_{0-7} : Constant for correction factor

f : Correction factor at the deepest point (pressure)

f_s : Correction factor at a surface point (pressure)

g_i : Correction factor at the deepest point (random distribution stress)
($i = 0$ to 3)

g_{si} : Correction factor at a surface point (random distribution stress) ($i = 0$ to 3)

K_I : Stress intensity factor

P : Pressure

R_i : Internal radius of a cylinder

R_o : Outer radius of a cylinder

t : Plate thickness of a cylinder

z : Distance from inside (flaw side) in thickness direction

σ : Non-linear stress distribution to the thickness direction
(approximation of polynomial equations)

σ_h : Maximum value of hoop stress (circumferential stress)

σ_i : Stress distribution with approximation of polynomial equations ($i = 0$ to 3)

α : Parameter for flaw size ratio (internal pressure)

α_i : Parameter for flaw size ratio (random distribution stress) ($i=0-3$)

β : Constant of parameter for flaw size ratio (random distribution stress)

γ : Constant for correction factor at a surface point (random distribution stress)

These equations are applicable within the following ranges.

Internal pressure

$$0.05 \leq a/t \leq 0.85$$

$$0.1 \leq a/c \leq 1$$

$$0.2 \leq \alpha$$

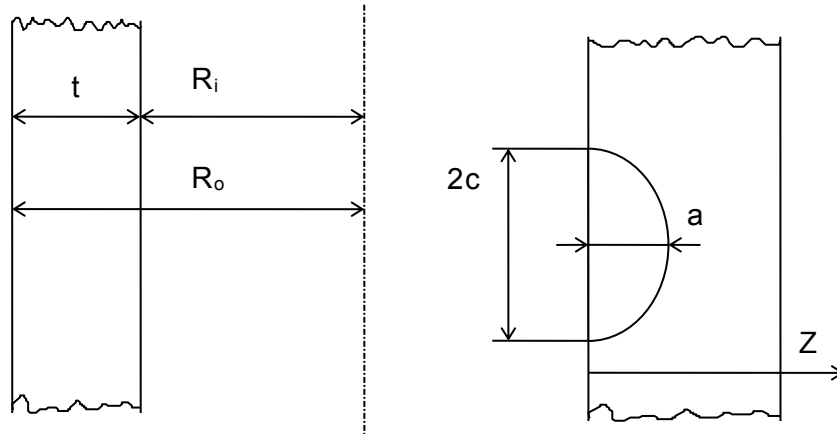
$$1 \leq R_i/t \leq 10$$

Random distribution stress

$$0.05 \leq a/t \leq 0.85$$

$$0.1 \leq a/c \leq 1$$

$$1 \leq R_i/t \leq 10$$



To apply these equations, the following condition for small-scale yielding must be satisfied.

$$a, t - a \geq 2.5 \left(\frac{K_I}{\sigma_y} \right)^2 \quad (3.5.54)$$

When the above equation is not satisfied, consider plastic region correction for the stress intensity factor. Determine the plastic region correction either by solving the following equation or by performing an iterative calculation.

$$K_I^* = f \left[\sigma, a + \frac{1}{2\pi} \left[\frac{K_I^*}{\lambda \sigma_y} \right]^2 \right] \quad (3.5.55)$$

where

K_I^* : Stress intensity factor corrected for the plastic region correction

- $f[]$: Stress intensity factor equation (functional equation)
- σ : Stress
- a : Flaw size (flaw depth "a" or flaw length "c")
- σ_y : Yield stress
- λ : Plastic constraint factor (deepest point $\lambda=1.68$, surface point $\lambda=1$)

3.5.4.1.3 Judgment criteria

The following equation shall be satisfied.

$$S.F_1 \times N < N_D \quad (3.5.56)$$

where

- $S.F_1$: Safety factor ($S.F_1 = 4$)
- N : Number of loading cycles
- N_D : Number of loading cycles until thru- thickness penetration or unstable fracture of equipment results

3.5.4.2 Flaw growth test

(1) Purpose

Perform test to confirm that the high-pressure gas equipment satisfies the life requirement by applying a cyclic stress equivalent to the stress described in (2) of paragraph 3.1.5, "Life requirements for pressure cycle," applied to the test article simulating the flaw generated during fabrication.

(2) Methods and conditions

- a. The initial flaw size shall exceed the detectable limit in the nondestructive inspection, but the minimum size is $2c = 0.25$ [mm]. The tip of the flaw shall have fatigue damage.
- b. Notch the test article on the surface. Ensure that the thickness of the test article is that of the part subjected to the test as defined in the drawing. Simulate processing, welding and heat treatment of a flight model.
- c. The surface notch shape shall be $0.2 \leq a/c \leq 1$.
- d. Apply stress generated by the pressure cycle established in paragraph 3.1.5, "Life Requirements."
- e. Conduct the test at the design temperature established in paragraph 3.1.2.4, "Temperature conditions."
- f. Ensure that at least three test articles are available. Determine the number of

test articles based on the availability of the existing data, the test methods, etc.

(3) Judgment criteria

The tested item shall demonstrate four or more times the required life specified in paragraph (2) of 3.1.5, "Life requirements for pressure cycle."

3.5.5 Stiffness analysis and test

Some properties of high-pressure gas equipment such as stiffness, mass, natural frequency, sloshing behavior and so on are determined by analysis or testing and are provided to space system design for hazardous interaction control between space system structure and high-pressure gas equipment. Confirmation of all properties are under the tolerance required by space system may be alternative to the presentation of analysis results.

3.5.6 Bellows analysis

3.5.6.1 Stress analysis and judgment criteria

Confirm that the stress values at MEOP and maximum displacement for all parts are under allowable stress by computer analysis according to JIS B 8277 or finite element method or equivalent methods. Analysis method and judging criteria for buckling stress and torsional stress shall be EJMA 8th Edition for Unreinforced Bellows or equivalent and time-prove method for reinforced bellows such as the Braid equations. The material strength property evaluated with work-hardening which is used in the analysis needs that supporting evidences.

3.5.6.2 Life analysis and judgment criteria

Bellows shown in table 3.1.3-1 No.5 shall be regarded as high pressure vessel. Analysis method and judging criteria for the bellows shall be referred to JIS B 8277 or paragraph 3.5.3.1. Pressure cycle and displacement cycle shall be considered in the analysis. Additionally, if vibration such as flow induced vibration, mechanical vibration and so on are overlapped on the bellows operations, paragraph 3.5.3.1.(3)d of this standard shall be applied.

Analysis shall be performed using design fatigue curve without work hardening effect, but can be performed using design fatigue curve with work hardening effect if reliable fatigue strength data of work hardening material are available.

3.5.6.3 Fluid vibration

Evaluate the possibility of fluid vibration induced inner flow of bellows by computer analysis or flow testing. Prove that control capability of no resonance by computer analysis in case of generating fluid vibration in bellows.

3.5.6.4 Restriction of Bellows

(1) Requirement

Bellows can deform flexibly within a limit of operation, but shall be restricted to prevent harmful deformation.

(2) Analysis method

Bellows shall be analyzed geometrically, kinematically, and mechanically.

(3) Judgment criteria

Bellows shall be restricted mechanically in the system. Failure prevention measures such as bellows thrust compensation, prevention of deformation over the limit, prevention of excessive reaction (including moment), prevention of excessive friction force at joint bearing, pressure change compensation of volume change at expansion/compression, prevention of contamination and break down of straitening liner, and prevention of adherence caused by gas and the liquid freezing shall be taken.

3.6 Damage Control Requirements for COPV

COPV damage prevention control or damage tolerant design, or both shall be implemented for the expected type of damage. This provision covers three types of damages, namely impact damage, surface cut and abrasion.

Damage prevention control is an act of ensuring soundness and reliability of a product by taking appropriate measures to prevent conceivable damage and performing inspection to check the damage of product.

Damage tolerant design is an act of ensuring soundness and reliability of a product by designing the product which does not lose functional requirements due to conceivable damage.

In designing a pressure vessel, the type(s) of damage shall be identified and adequate damage control technique shall be decided.

Damage control is required for COPV with the safety factor for fracture of less than 4.0 or thickness of less than 6.35mm.

3.6.1 Damage prevention control

Damage prevention control of pressure vessel consists of development of damage prevention control plan, compliance with the plan, and record of damage prevention control.

3.6.1.1 Development of damage prevention control plan

To form an organization to implement damage prevention control and prepare damage prevention control plan including the following:

- 1) To identify all activities that may cause impact damage, surface cut, and abrasion in each process from acceptance inspection in 4.7.4 or reuse inspection in 6.1 to completion of the launch preparation work;
- 2) To define damage prevention measures for any activity or work that may cause damage;
- 3) To define an effective method for protection of pressure vessels;
- 4) Damage prevention control process flow

Determine the timing and procedures according to the process flow of figure 3.6.1-1 for COPV damage inspection. Confirm damage by visual inspection, ultrasonic inspection, and acoustic emission (AE) measurements.

a. Visual inspections

Always perform visual inspections. Table 4.7.4-1 shows targets for visual inspections.

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b. Ultrasonic inspections

If visual inspection uncovers any damage, perform ultrasonic inspection and confirm any significant signals. In this case, demonstrate appropriate defect detection capability and flaw detection procedures.

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c. AE measurement

It is desirable to acquire AE data as much as possible in this flow. It is necessary to show the correctness of AE measurement procedures.

3.6.1.2 Compliance with the damage prevention control plan and record of damage prevention control

Conduct damage prevention control activities in compliance with the damage prevention control plan and record the damage prevention control.

Troubleshooting and other activities not included in the damage prevention control plan shall be planned and conducted on the basis of evaluation of each activity and its interface with the damage prevention control plan.

3.6.1.3 Detection and judgment of damage

When damage is detected, it shall be inspected and inspection results shall be recorded, starting the nature of damage and circumstances surrounding the damage in detail.

Based on the results of analysis or testing to assess the extent and degree of damage, it shall be decided whether the product can be used.

3.6.2 Damage tolerant design

Damage tolerant design, according to the type of damage, shall be specified with verification of its validity.

Validity of damage tolerant design shall be verified by analysis or testing. Pressure vessel shall be designed and fabricated according to the identical specifications applied to the flight model, shall be subjected to the severest level of damage in the most sensitive position that is expected, and to a destructive test by applying pressure, in order to check if it meets performance requirements.

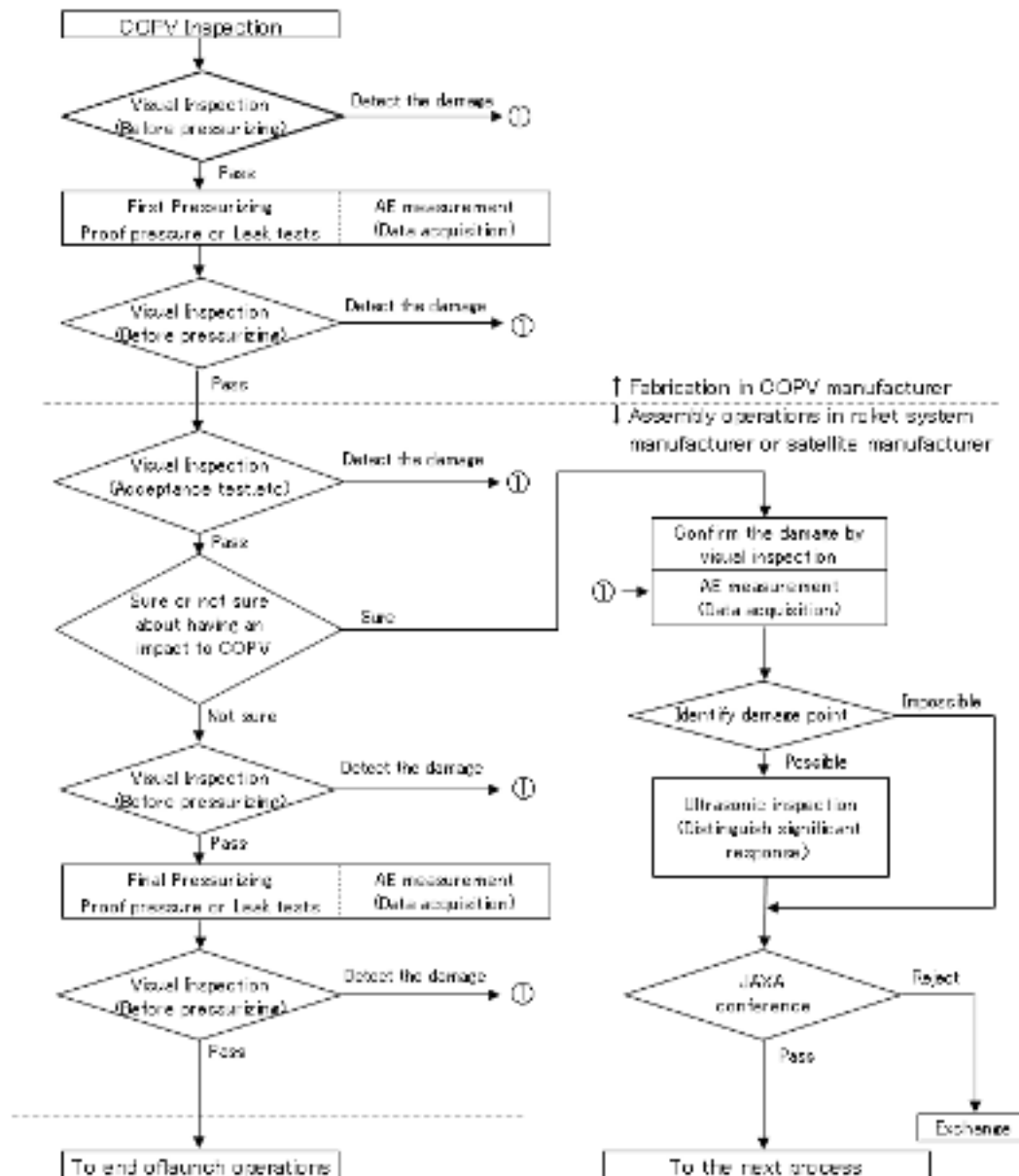


Figure 3.6.1-1 Damage prevent control process flow

3.6.3 Consideration to damage control

For the damage prevention control and the damage tolerant design, the following items shall be considered in the design.

- a. Inclusion of protective layers.
- b. Ensuring sufficient strength margins in design standard parts within ranges allowed by the host system.
- c. To provide design consideration to ensure that the standard design part does not become a part susceptible to damage
(Ex: When the CFRP hoop layer is the design standard, ensure that the outermost layer does not become the hoop layer in the design.)

d. When thermal insulation is installed outside the container, consider design sizes, thicknesses, ranges, etc., for the case of becoming a protective component. | E

4. Fabrication

Fabrication process of high-pressure gas equipment shall be assessed to be suitable through the trade-offs among reliability, work efficiency, costs, and others. Mechanical processing, plate processing, welding, heat treatment, and ultrasonic cleansing shall not degrade the mechanical and physical properties of material to the allowable limit. The manufacturing process shall guarantee the property of material used for design and analysis when high-pressure gas equipment is manufactured.

Verify integrity of the following manufacturing methods by qualification test. Integrity can be verified by development test, if development test is performed. However, verify quality of flight model is assured in fabrication when material, fabrication method, or fabrication facility is modified

Typical fabrication flows for high pressure equipment are shown in Figure 4-1 (Metallic high-pressure gas equipment), Figure 4-2 (Composite pressure vessel) and Figure 4-3 (Piping assembly and propellant subsystem assembly).

4.1 Fabrication and Forming

Fabrication method and forming method of high-pressure gas equipment influence the mechanical properties of materials. Manage these methods according to the criteria and provisions established by qualification test data.

4.2 Welding

For welding, select the appropriate welding methods, joint shapes, and filler materials. Welding joints shall possess the specified mechanical properties.

4.2.1 General requirements

(1) Locations, shapes, and dimensions of weld joints

Determine the appropriate locations, shapes, and dimensions of weld joints considering strength deterioration in weld joints, scope of heat effect, stress concentration, welding methods, etc.

(2) Increased weld thickness

When the strength of weld joints becomes lower than that of the base material, consider reducing the strength of weld parts. If necessary, increase the thickness of the weld joints as shown in Figure 4.2-1.

(3) Welders

Welders shall be certified as specified in AWS D17.1 or shall possess equivalent qualifications.

(4) Inspection of welding machines

Periodically inspect each different model of the welding machines to maintain welding performance. Based on the inspection, judge the welding machines' performance and stability.

(5) Groove shape

Grooves for high-pressure gas equipment shall conform to proven shapes unless specifically instructed otherwise. A representative set of the groove shapes is shown in Figure 4.2-2.

(6) Repair welding

When performing repair welding, generally weld the same weld part once or twice.

4.2.2 Welding control

Control welding by preparing the welding procedural document. Pay particular attention to the following items which affect strength.

(1) Welding Conditions

Ensure the welding conditions satisfy paragraph 5.1.2, "Welding method selection and verification." Document the actual welding conditions. Control atmosphere and welding machines during actual welding and maintain reproducibility of the above conditions.

(2) Grooves

Confirm the cleanliness of the grooves before welding to ensure removal of grease or rust which affects weld strength.

(3) Preventing welding deformation and unevenness

Minimize welding deformations (particularly angular deformation) and mis-match by setting welding joints on the appropriate welding jigs.

(4) Weld beads and penetration beads

Establish the welding conditions so that weld beads and penetration beads become smooth to avoid stress concentration. When penetration beads cannot be identified, confirm them by conducting a development test or qualification test.

(5) Preventing missing targets

Weld correctly on the targeted weld lines.

(6) Weld defects

Establish the welding conditions so that surface and internal defects of the weld parts are within the specified values.

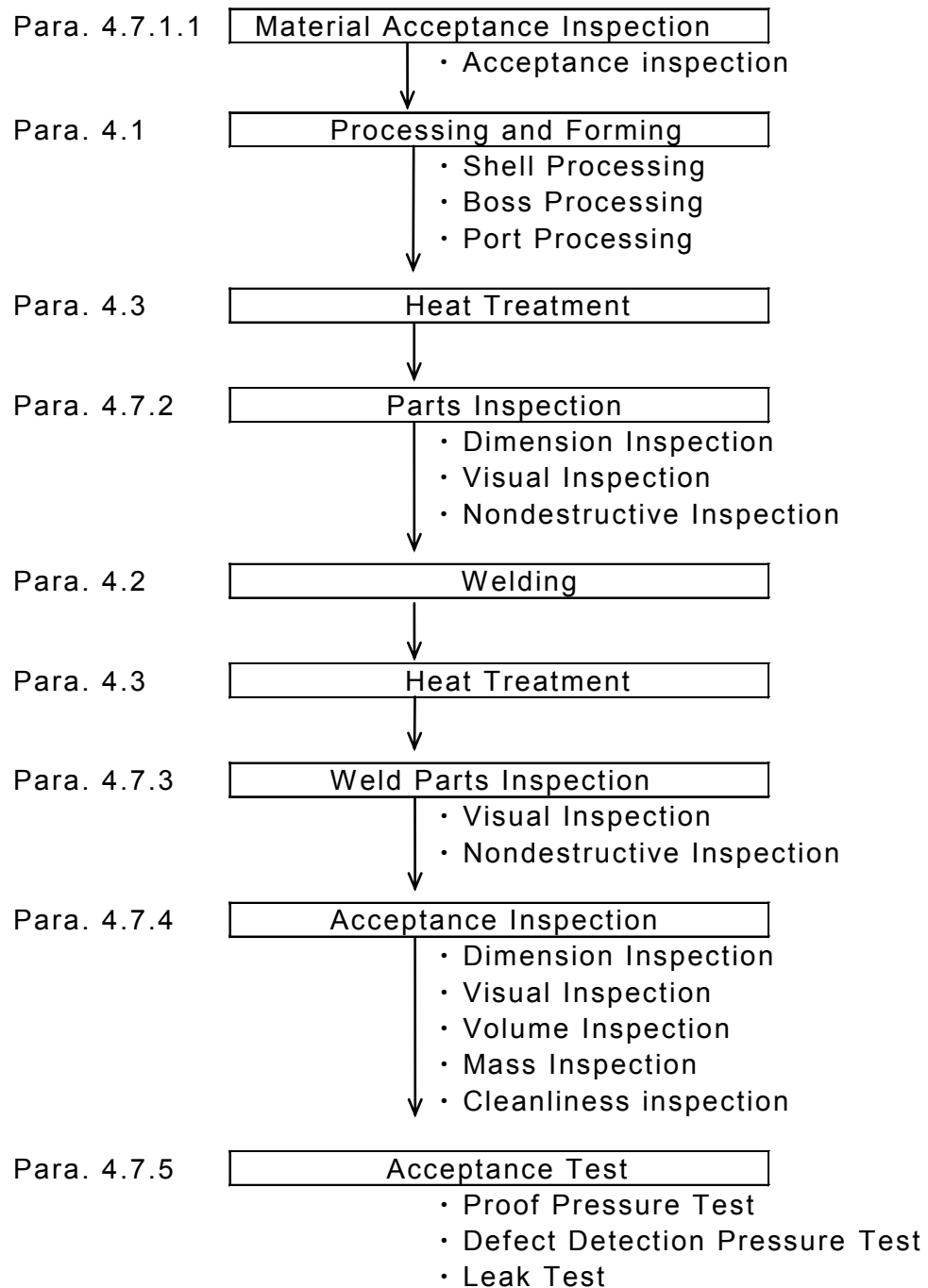


Figure 4-1 Metallic High-pressure Vessel Fabrication Flow
(Typical Example)

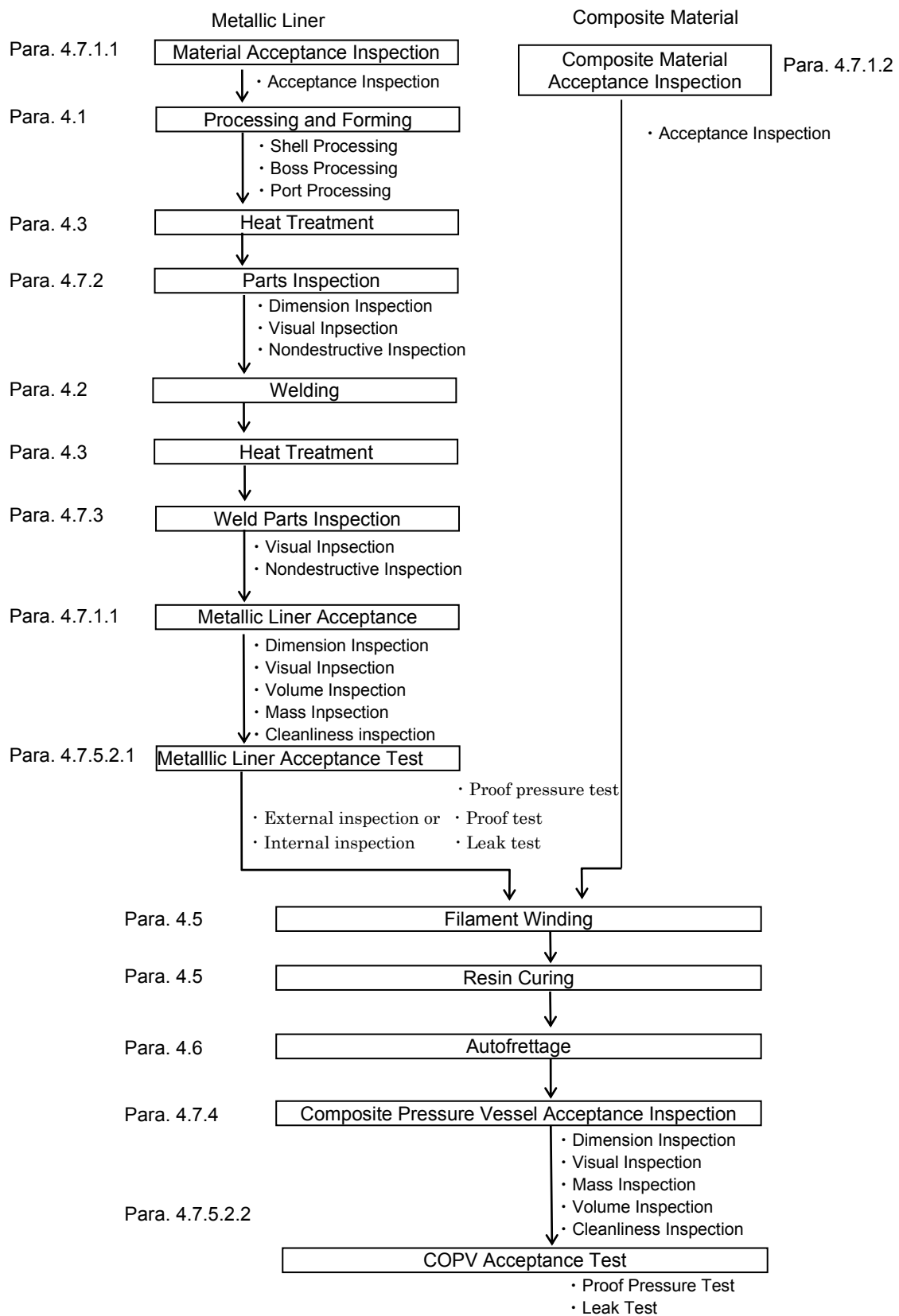


Figure 4-2 (1/2) COPV Fabrication flow (Typical Flow for Vessels with Metallic Liners)

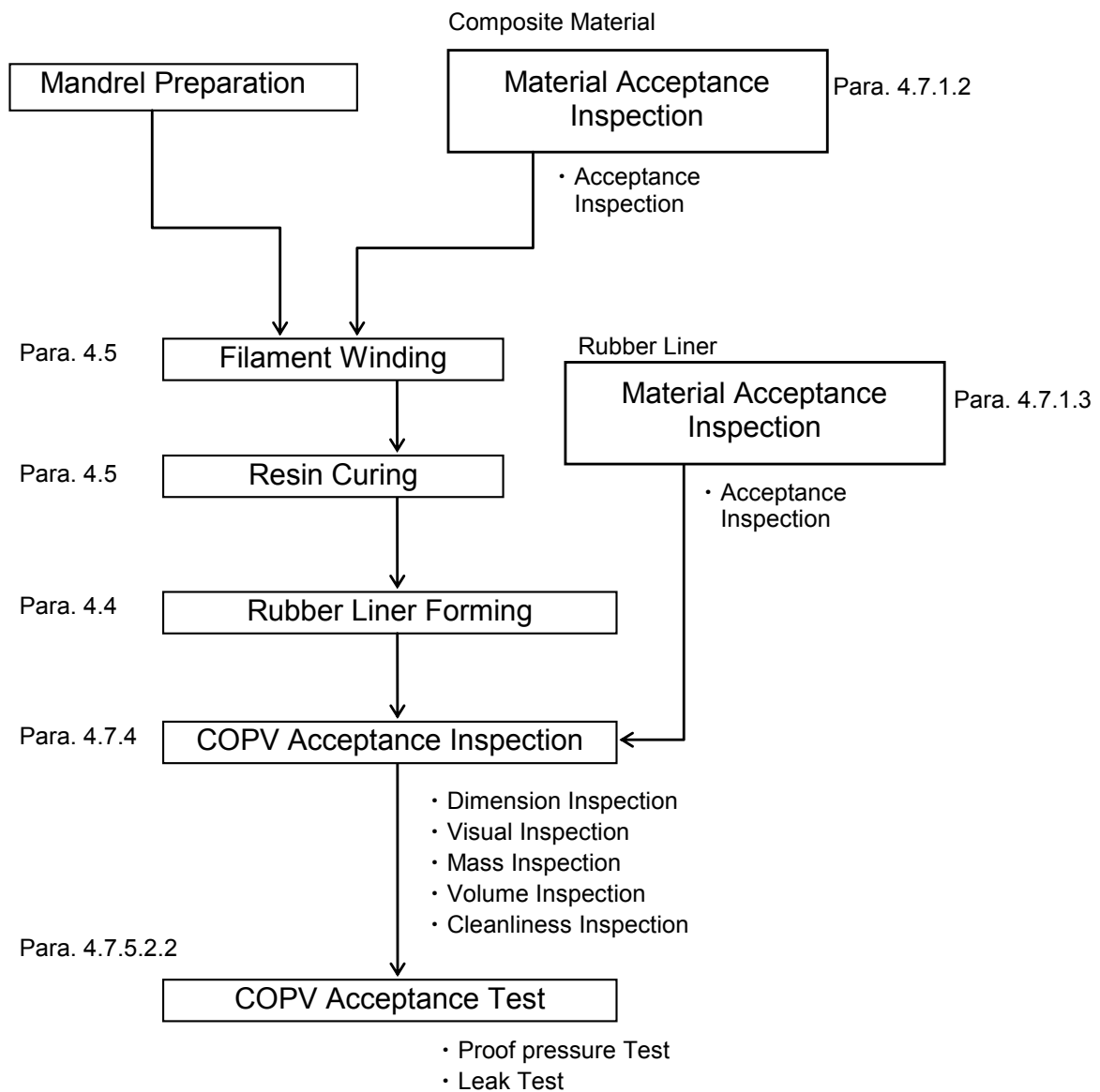


Figure 4-2 (2/2) COPV Fabrication Flow (Typical Flow for Vessels with Rubber Liners)

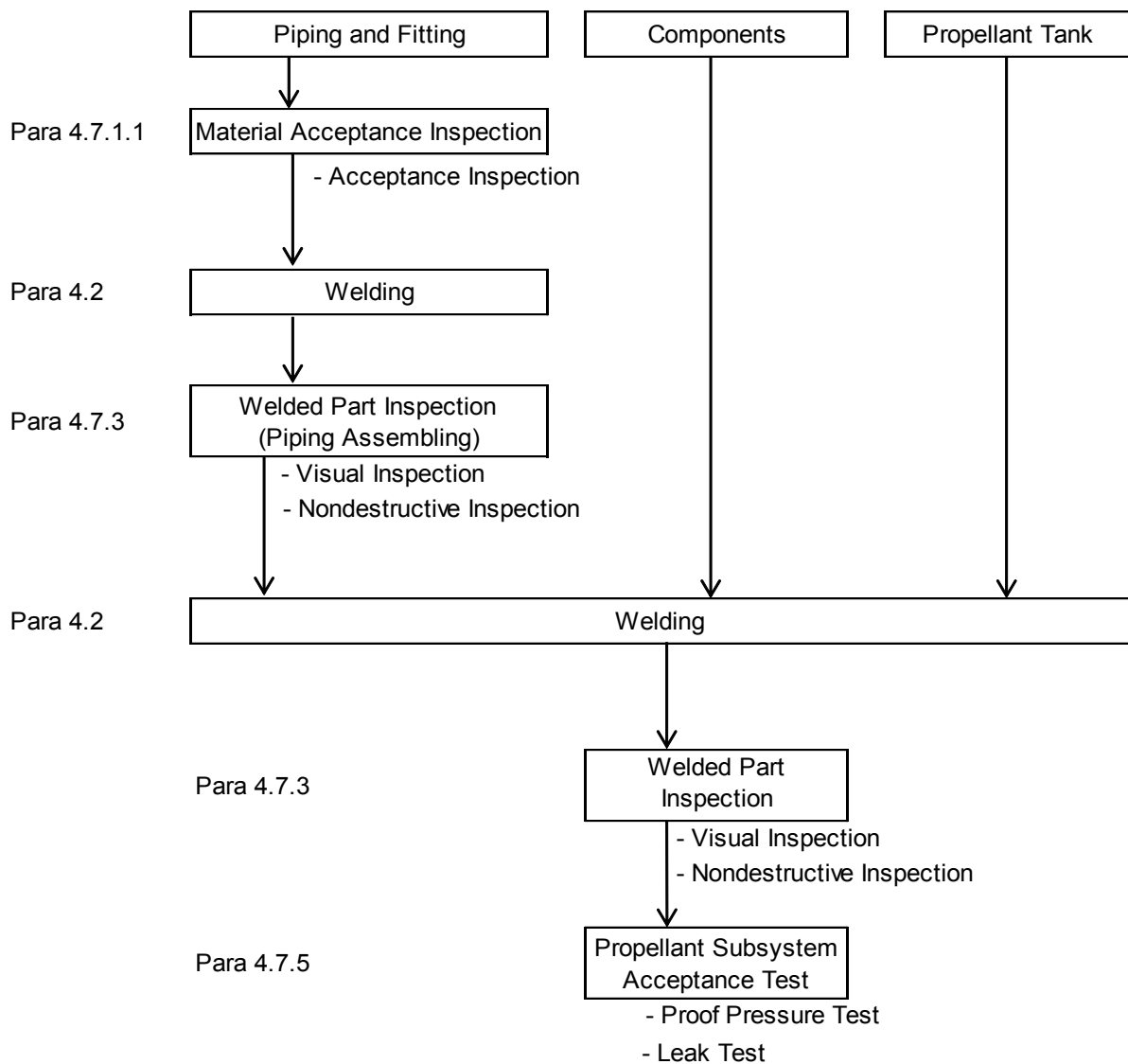
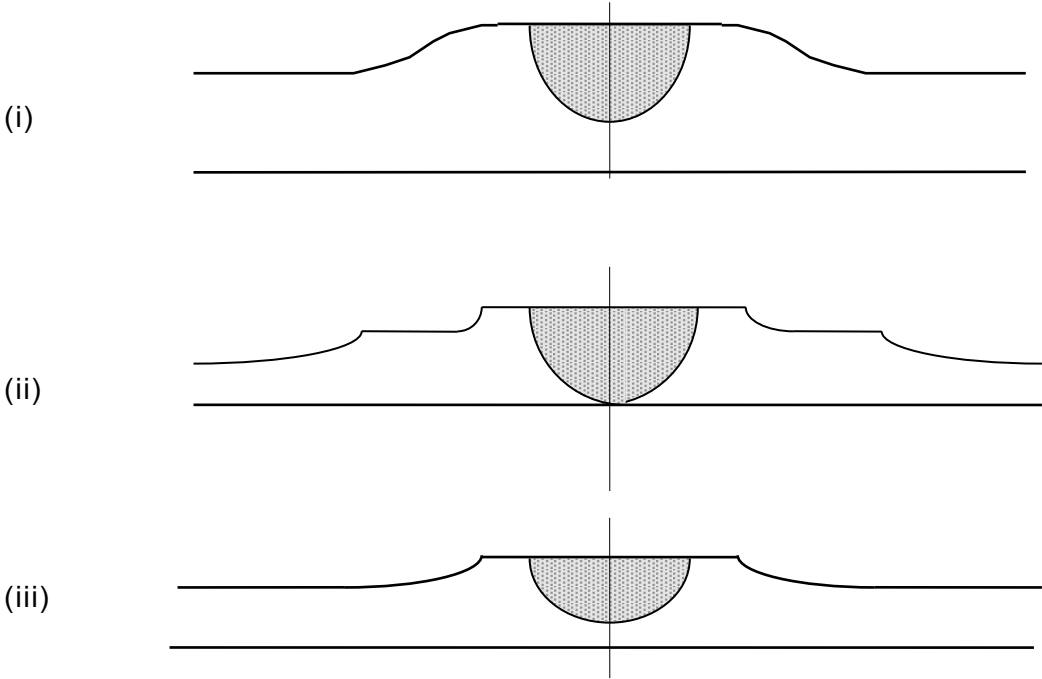


Figure 4-3 Piping Assembly and Propellant Subsystem fabrication Flow
(Typical Example)

For Metallic Pressure Vessels



For COPV

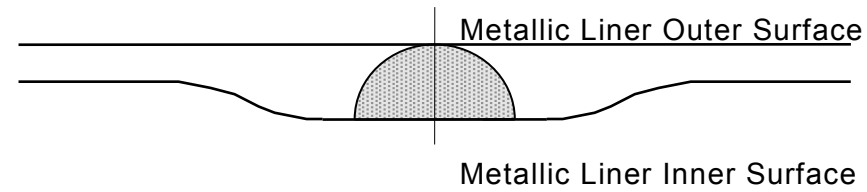
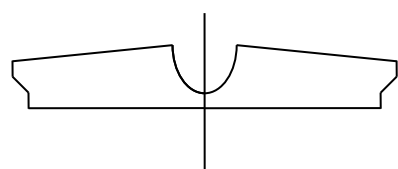
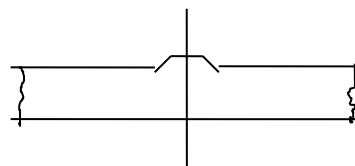


Figure 4.2-1 Typical forms of welded joint thickening (reference)

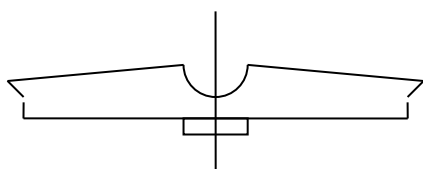
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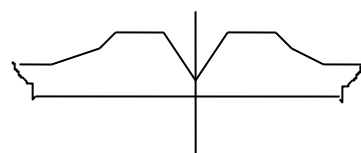
U Shape



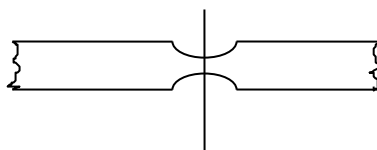
Butt Joint
(Without Filler Material)



U Shape with Backing



V Shape



H Shape

Figure 4.2-2 Representative Set of Groove Shapes for High-Pressure Gas Equipment (Reference)

4.3 Heat Treatment

Apply appropriate heat treatments such as annealing, post-welding heat treatment, solution heat treatment, and aging during the high-pressure gas equipment fabrication process except when heat treatment is expected to deform the structure, as in weld joints of thin vessels and heat treatment is considered inappropriate.

4.4 Non-metallic Liner Forming

Control the following items appropriately when non-metallic liner is formed.

- a. Useful life of raw materials
- b. Useful life of adhesive, if adhesive is used
- c. Formulation ingredients ratio of adhesive, if adhesive is used
- d. Temperature and pressure profiles of autoclave, if heat curing is performed

4.5 Filament Winding

When performing filament winding using composite material, control the following items according to the criterion which are specified in paragraph 5.1.3, "Prototype Test."

(1) For winding processes

- a. Control of useful life of fibers and matrix resins
- b. Winding angles of fibers in each layer
- c. Number of windings or weight of fibers used
- d. Fiber tension during winding
- e. Matrix resin formulation ingredients ratio (when two or more resins are mixed)
- f. Matrix resin temperature during winding
- g. Volume fraction of fiber (V_f)
- h. Winding speed

(2) For curing processes

- a. Temperature and pressure profiles of autoclave if heat curing is performed
- b. Time for curing if performed

4.6 Autofrettage

When autofrettage is performed on a metallic liner by applying internal pressure after composite materials are formed, ensure the following requirements for

determining processing pressure are satisfied.

- a. Perform autofrettage at around 100 to 110% of the proof test pressure established for COPV. (Using Figure 3.4.3-4 as an example, perform pressurization following the line connecting 0, T0, and T1.)
- b. Fluids used for autofrettage should be incompressible.
- c. Confirm buckling of a metallic liner by evaluating appearance, capacity, dimensions, and other inspection results.
- d. When performing autofrettage, observe safety standards applied to proof pressure tests on incompressible fluids.

4.7 Inspection and Test

Inspections and tests for high-pressure gas equipment shall be highly reliable and suitable for the inspection or test purpose and inspection or test targets. The processes and methods should not degrade equipment quality.

During the high-pressure gas equipment fabrication, conduct the following inspections and tests and document their results.

4.7.1 Material acceptance inspection

4.7.1.1 Metallic material acceptance inspection

Confirm that the properties of accepted materials satisfy the specifications by using mill sheets, etc.

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4.7.1.2 Composite material acceptance inspection

Confirm that the following properties of accepted composite materials satisfy the requirements based on the inspection records and other related matters.

(1) Fibers

- a. Fiber brand names
- b. Tensile strength as a fiber
- c. Modulus of elasticity as a fiber
- d. Breaking strain
- e. Usage expiration date
- f. Other properties required for their design and fabrication

(2) Matrix resin (when accepted alone)

- a. Resin brand name

- b. Components
- c. Viscosity
- d. Usage expiration date
- e. Other properties required for their design and fabrication

(3) Matrix resin (when accepted as pre-preg)

- a. Resin brand name
- b. Glass transition temperature
- c. Resin content
- d. Gel time
- e. Resin run-off
- f. Usage expiration date
- g. Other properties required for their design and fabrication

4.7.1.3 Non-metallic liner acceptance inspection

Confirm that the following properties of accepted non-metallic liners satisfy the requirements based on the inspection records and other related matters.

(1) Unvulcanized rubber

- a. Appearance
- b. Dimensions

(2) During and after vulcanization

- a. Density
- b. Viscosity during vulcanization
- c. Hardness after vulcanization
- d. Breaking strain after vulcanization
- e. Other properties required for their design and fabrication

(3) Adhesives (when used)

- a. Adhesive brand names
- b. Other properties required for their design and fabrication

4.7.2 Parts inspection (Metallic material)

(1) Dimension inspections

Confirm that drawing requirements are satisfied.

(2) Visual inspections

Confirm that no harmful processing damage, dents, or corrosion exist.

(3) Nondestructive inspections

Perform penetrant testing, eddy current testing, or ultrasonic inspection to confirm that there are no harmful defects. The defect detection capability specified for these penetrant inspections means the size of the defects detectable by nondestructive inspection defined in 1) of paragraph 3.5.4.1.2.

a. Penetrant testing

When performing penetrant testing, adhere to the testing standards specified in AMS-2645, ASTM-E1417, or the equivalent.

b. Eddy current testing

When performing eddy current testing, demonstrate appropriate defect detection capabilities and flaw detection procedures.

c. Ultrasonic testing

When performing ultrasonic inspection, demonstrate appropriate defect detection capabilities and flaw detection procedures.

If the above nondestructive inspections are not applicable due to item shape, then select and implement an appropriate alternative method with sufficient defect detection capabilities.

4.7.3 Welded part inspection

4.7.3.1 Welding condition

Confirm that welding is performed according to the conditions specified by paragraph 4.2.

4.7.3.2 Visual inspection

Confirm that welding locations are as specified in the drawings. Confirm also that weld reinforcement shape and such are appropriate.

4.7.3.3 Welding deformation and mis-match

Confirm that welding deformation and mis-match are within drawing requirements.

4.7.3.4 Welding bead and penetration bead

Confirm that the shapes of welding beads and penetration beads are within drawing requirements.

In general, check back-bead welding by visual inspections.

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4.7.3.5 Weld defect

(1) For surfaces

Perform penetrant testing, eddy current testing, or ultrasonic inspection in consideration of item form, workability, etc. The defect detection capability specified for these penetrant inspections means the size of the defects detectable by nondestructive inspection defined in 1) of paragraph 3.5.4.1.2. If this inspection does not reveal harmful defects, a proof test may be omitted.

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a. Penetrant testing

Perform penetrant testing in adherence to the testing standards specified in AMS-2645, ASTM-E1417, or the equivalent to confirm there are no harmful defects.

b. Eddy current testing

Perform eddy current testing to confirm there are no harmful defects. When applying eddy current testing, demonstrate that defect detection capabilities and test procedures are appropriate.

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c. Ultrasonic inspection

Perform ultrasonic inspection to confirm there are no harmful defects. When applying ultrasonic inspection, demonstrate that defect detection capabilities and test procedures are appropriate.

(2) For inside

Conduct radiographic testing or ultrasonic flaw detection testing in consideration of item shape, etc.

a. Radiographic testing

Perform radiographic testing in adherence to ASTM-E1742 or equivalent standards to confirm the absence of harmful unwelded areas, cracks, porosity, and poor fusion. When performing radiographic testing, imaging plates (IP) can be used.

The criterion for determining the size of a single porosity shall be determined with sufficient design consideration, taking the least of the following as the maximum limit:

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- The smaller of $1/3 \times t$ (thickness) or 1.5 mm, as defined in AWS D17.1 CLASS A or NAS 1514 CLASS III.
- Maximum design tolerance for defect size.

For multiple porosities, one of the following must be satisfied:

- The sum of the maximum dimensions of welded parts per 76-mm length is the smaller of $1.33 \times t$ (mm) or 6 mm or less, in compliance with AWS D17.1 CLASS A.
- The total area per 25-mm length of the weld is $1.25 \times t$ (mm²) or less, in compliance with NAS 1514 CLASS III.

Note that t may be the actual weld thickness.

b. Ultrasonic testing

Perform ultrasonic inspection in adherence to ASTM-E164 or equivalent standards to confirm there are no harmful unwelded areas, cracks, porosity, or poor fusion.

The criterion for determining the size of a single porosity shall be determined with sufficient design consideration, taking the least of the following as the maximum limit:

- The smaller of $1/3 \times t$ (thickness) or 1.5 mm, as defined in AWS D17.1 CLASS A or NAS 1514 CLASS III.
- Maximum design tolerance for defect size.

For multiple porosities, the sum of the maximum dimensions of welded parts per 76-mm length is the smaller of $1.33 \times t$ (mm) or 6 mm or less, in compliance with AWS D17.1 CLASS A.

Note that t may be the actual weld thickness.

If ultrasonic inspection detects and measures porosity, demonstrate the flaw detection procedure, detection capabilities, and capabilities for dimensional measurements.

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4.7.4 Acceptance inspection

(1) Dimension inspection

Confirm that drawing requirements are satisfied.

(2) Visual inspection

Make clear the acceptance criteria. Perform visual inspection items 1–6 listed in Table 4.7.4-1 for metal pressure vessels, and items 1–12 for COPV, satisfying all criteria. Confirm that the requirements for COPV as shown table 4.7-1 No.1 to No.12 are satisfied by performing visual inspections. The inspection scope shall be classified macro inspection by direct visual inspection from micro inspection using microscope.

Table 4.7.4-1 Visual inspection items

General inspection items for metallic pressure vessel and COPV	
1	Machining print
2	Impact print/Pressed print
3	Friction defect
4	Abnormal color tone
5	Corrosion
6	Scaffolding
Additional inspection items for COPV	
7	Exfoliation
8	Breaking of fiber
9	Abnormal order of fiber/Pucker
10	Resin crack
11	Resin absence/Resin excess
12	Contamination/Bubble

Notice: Inspector's eyesight and lightning condition for inspection shall be complied with NDIS 3414" Standard of visual testing" established by the Japanese Society for Non-Destructive Inspection.

(3) Volume inspection

Confirm that the requirements are satisfied by performing volume inspection as necessary.

(4) Mass inspection

Confirm that the requirements are satisfied by performing mass inspections as necessary.

(5) Cleanliness inspection

Confirm that the requirements are satisfied by performing cleanliness inspection for space system specification.

4.7.5 Acceptance test

4.7.5.1 Metallic high-pressure gas equipment acceptance test

Conduct the following tests on metallic high-pressure gas equipment whose fabrication has been completed.

(1) Proof pressure test

a. Proof pressure testing pressure is that obtained by multiplying the maximum expected operating pressure (limit pressure) by the coefficient in Table 4.4-1. In principle, the range for stress intensity during proof pressure testing must be within the range shown in Figure 4.4-1.

b. When conducting proof pressure testing at room temperature, in principle, correct the testing pressure according to the ratio between the material yield stress at the design temperature and the yield stress at room temperature.

(Proof test pressure at normal temperature) =

$$(\text{Proof test pressure at design temperature}) \times \frac{(\text{Yield stress at normal temperature})}{(\text{Yield stress at design temperature})}$$

c. Figure 4.4-1 graphically represents the following equation.

$$\frac{P_m + P_b}{\sigma_y} = \frac{5}{3} - \frac{3}{2} \left[\frac{1}{3} - \frac{P_m}{S_m} \right]^2 \quad (4.7.1)$$

$$\frac{P_m}{\sigma_y} = 1 \quad (4.7.2)$$

In the above equation, $P_m + P_b$ stands for general primary membrane stress plus bending stress. Calculate local primary membrane stress plus bending stress using $P_L + P_b$,

where

P_m : Stress intensity of general primary membrane stress

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P_L : Stress intensity of local primary membrane stress

P_b : Stress intensity of bending stress

σ_y : Yield stress of material

Stress strength at the time of proof pressure testing on launch vehicle propellant tanks shall satisfy the following shakedown requirements for any cross section or part, in addition to equations 4.7.1 and 4.7.2:

$$P_L + P_b + Q \leq 2\sigma_y$$

or

$$P_m + P_b + Q \leq 2\sigma_y$$

where

Q : Secondary stress, excluding local stress concentration

σ_y : Yield stress of the material

- d. Fluids used for the proof test should be incompressible fluids. However, compressible fluids may be used when incompressible fluids are judged inappropriate due to the properties of high-pressure gas equipment.
- e. After testing, perform visual inspections of the exterior and confirm there are no harmful deformations, cracking, or other abnormalities.
- f. In separate testing of high-pressure gas equipment, except for rocket propellant tanks, after proof pressure testing, in principle perform one of a. penetrant testing, b. eddy current testing, or c. ultrasonic inspection in paragraph 4.7.3.5(1) on welded parts and ensure there are no harmful defects.
- g. To verify prescribed pressure was loaded.
- h. In principle, measure cylindrical part diameters before and after proof pressure testing, and confirm that residual deformation is 0.2% or less.
- i. (Deleted)
- j. If components are installed on the equipment with gasket, the blank flange and the dummy gasket which is robuster than the actual one could be installed instead of the actual components for the proof pressure test.

Note that there are exceptions to the principles in items a, b, f, and h, including piping to which exemption item 2.2.1 applies and purchased goods to which item 2.2.3 applies.

(2) Leak tests

- a. Complete proof pressure tests prior to leak tests.

- b. For a leak test, use a pressure with gas at the MEOP or higher. For launch vehicle propellant tanks, apply the equation below for leak test.

(Leak test pressure at normal temperature) $\leq 1/4 \times$ (Design burst pressure at design temperature) \times (Tensile strength at normal temperature) / (Tensile strength at design temperature)

- c. Gas used for a leak test shall not degrade performance of pressure vessels.
- d. Determine the time for pressurization to suit the individual leak test method.
- e. Leakage shall be within the specified values.

(3) Defect detection pressure tests

Perform assurance testing for areas where the nondestructive inspections described in 3.5.4.1.2 cannot be performed as follows.

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- a. For pressure for defect detection pressure test, use the MEOP multiplied by proof factors obtained according to paragraph 3.5.4.1.2. The range of stress strength at the time of defect detection pressure test shall be as specified in (1) of paragraph 4.7.5.1, "Proof pressure tests."
- b. A defect detection pressure test may be conducted immediately following a proof pressure test.
- c. A defect detection pressure test should be conducted using incompressible fluids. Try to hold the pressure for 5 seconds or less and try to depressurize to the proof test pressure level within 15 seconds or less after pressure is achieved (see Figure 4.7-2).
- d. After testing, perform visual inspections of the exterior and confirm there are that no harmful deformations, cracking, or other abnormalities.
- e. After assurance testing (defect detection pressure testing), perform one of a. penetrant testing, b. eddy current testing, or c. ultrasonic inspection in paragraph 4.7.3.5(1) on welded parts and ensure there are no harmful defects.
- f. When the same pressure is used for the proof test and the defect detection pressure test and the two tests are conducted simultaneously, verify prescribed pressure was loaded.
- g. For additional information on the defect detection pressure test, refer to NASA SP-8040.

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4.7.5.2 COPV acceptance test

4.7.5.2.1 Metallic liner acceptance test

For the metal liner in full-wrap containers and the straight body in hoop-wrap containers, confirm that there are no harmful defects on the outer or inner surfaces

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before filament winding.

Alternatively, perform (1) proof pressure testing, (2) airtightness testing, and (3) assurance testing (if required) in paragraph 4.7.5.1 on individual liners. Here, the proof pressure testing pressure and airtightness testing pressure should be the pressure set for the metal liner alone.

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4.7.5.2.2 COPV acceptance test

(1) Proof pressure test

Conduct proof pressure tests according to (1) of paragraph 4.7.5.1. However, paragraphs b, c and f shall not apply.

Proof pressure tests may be conducted simultaneously with pressurization specified in paragraph 4.6, "Autofrettage."

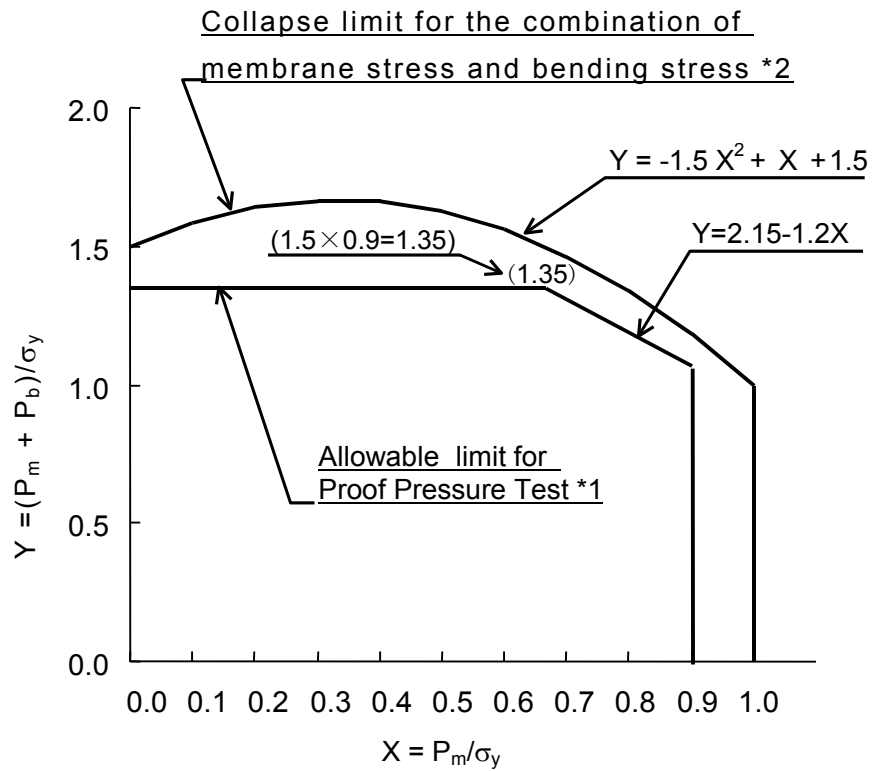
(2) Leak test

Conduct leak tests according to (2) of paragraph 4.7.5.1.

Table 4.7-2 Factors Used to Multiply MEOP to Obtain Proof Test Pressure

No. (Note 1)	Structural Category	Factor
1	Metallic Pressure Vessels and COPV (Approach allowed)	1.5 or more
2	Metallic Pressure Vessels (Approach prohibited)	$\frac{1 + (\text{safety factor for tensile strength})}{2}$ or more
	COPV (Approach prohibited)	$\frac{1 + (\text{safety factor for burst pressure})}{2}$ or more
3	Piping and Fittings (Diameter 38.1mm or more)	1.5 or more
4	Piping and Fittings (Diameter less than 38.1mm)	1.5 or more
5	Bellows	1.0 or more
6	Bellows	1.5 or more
7	Other Components	1.5 or more
8	Launch Vehicle Propellant Tanks	1.0 or more

Note 1 When selecting a coefficient from this table, match the number in this table and the numbers in Table 3.1.3-1 and Table 3.1.3-2 and select a coefficient allowing the approach of personnel.



*1: Allowable limit of metallic pressure vessels during proof pressure test.

*2: Allowable limit of launch vehicle propellant tank during proof pressure test.

Figure 4.7-1 Stress Intensity Allowable Limit during Proof Pressure Test

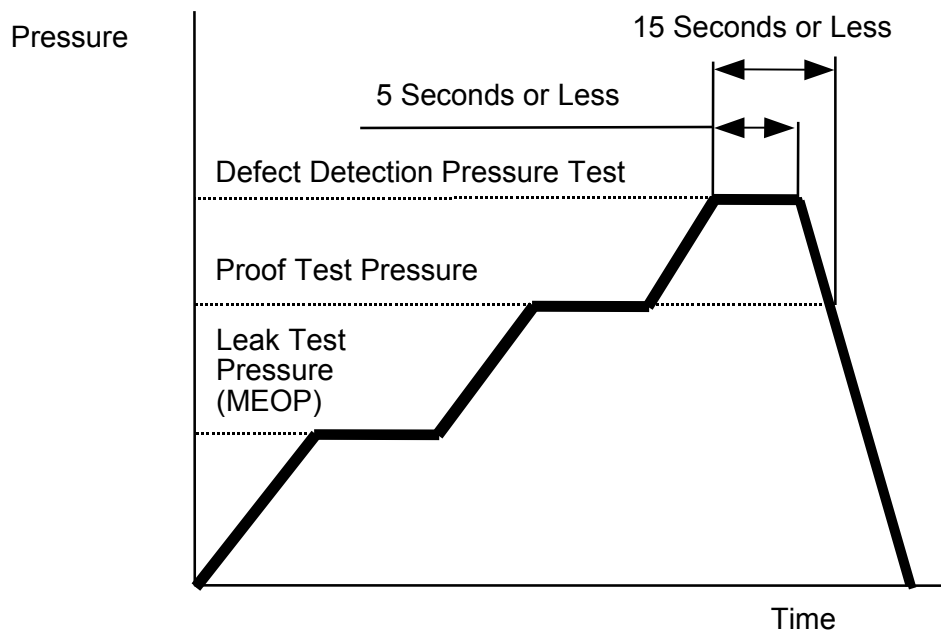


Figure 4.7-2 Defect Detection Pressure Test Time Constraints

5. Development Test and Qualification Test

5.1 Development Test

5.1.1 Material basic test

(1) Metals

- a. When fabricating high-pressure gas equipment with a safety factor below 3.5 using non-AMS, MIL, or FS standard materials, or when manufacturing high-pressure gas equipment using a newly developed processing method, test as necessary and obtain the following material data:
 - Chemical composition
 - Macro/micro metallographic structure
 - Tensile strength, yielding stress, and elongation (including weld parts)
 - Fracture toughness
 - Fatigue properties
- b. Test article shapes shall meet JIS or ASTM standards. If test article shapes do not satisfy JIS and ASTM, clearly state the shapes.
- c. Evaluate the obtained data according to MMPDS-01.

(2) Non-metals and composite materials

- a. When a non-metallic liner is fabricated, conduct a tensile test as necessary to obtain material data including breaking strain (ϵ). For vulcanized rubber, conduct a tensile test according to JIS-K6251, "Rubber, vulcanized or thermoplastics-Determination of tensile stress-strain properties". If the test is conducted according to other standard, clearly describe the test method.
- b. Data of tensile strength in the direction of fiber must be acquired. The test method and test piece shape shall satisfy ASTM D2290, ASTM D3039. If the test piece shape does not satisfy ASTM standard, clarify the test piece shape and validity of the acquired data. The test piece must be fabricated in the same process as the final product fabrication process.
- c. Test the following properties as necessary to obtain the material data.
 - Elasticity factor (Obtain material data for the elasticity factor in the direction of fibers according to paragraph 3.5.1.)
 - Stress rupture characteristics
 - Ionized radiation susceptibility
- d. Materials for which sufficient data has already been acquired need not be conducted material basic test.

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5.1.2 Welding method selection and verification

Select the welding method which ensures the weld quality required in paragraph 4.2, and verify the selected method. When selecting a welding method to be used, clarify the following and ensure reproducibility.

- a. Welding methods
- b. Welding materials (chemical composition, trade name, diameter of welding rods, etc.)
- c. Welding conditions (electrode, welding current, arc voltage, welding speed, welding position, welding rod manipulation method, welding heat input, gas shielding, etc.)
- d. Backing
- e. Preheating
- f. Post welding heat treatment

Verify the welding method according to paragraph 4.4.3.

5.1.3 Prototype test

Prototype test should be conducted during the development phase.

Fabricate test article to evaluate design and prove the validity of analysis result, and conduct the following tests as necessary.

- a. Proof pressure test
- b. Leak test
- c. Pressure cycle test
- d. Loading test for flight (only for launch vehicle propellant tanks)
- e. Burst pressure test (*1) or burst test (*1)
- f. Negative pressure test (*2)

*1 Measure the strain when pressurized (except for components including valves).

*2 Conduct this test only when internal pressure is expected to become negative with respect to external pressure during the period from fabrication to completion of the number of planned flights.

Judgment criteria for prototype tests are as follows:

- a. Proof pressure test

Follow (1) of paragraph 4.7.5.1.

b. Leak test

Follow (2) of paragraph 4.7.5.1.

c. Pressure cycle test

Follow (1) of paragraph 5.2.

d. Loading test for flight

The test article should not buckle or burst.

e. Burst pressure test (*1) or Burst test (*1)

Follow (2) of paragraph 5.2.

f. Negative pressure test (*2)

The test article should not buckle when negative pressure is applied to it.

5.2 Qualification Test

Qualification test which incorporate actual environmental conditions shall be conducted during the last phase of high-pressure gas equipment development to verify the validity of the design, fabrication, and inspection processes.

Qualification tests may be omitted when qualified high-pressure gas equipment or those with small alternation are used.

In qualification test, use test articles fabricated following the same fabrication and inspection processes as the flight model. After passing the inspection and the test specified in paragraph 4.7, the test article shall undergo the following tests.

Test pressures for the proof pressure testing in paragraph 4.7.5.1(1) should in principle be corrected for the difference between the measured minimum thickness of the test specimen and the design minimum thickness, simulating the case where the test piece is fabricated at the minimum design thickness.

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(1) Pressure cycle test

a. Conduct a pressure cycle test according to vessel construction.

For metallic pressure vessels, pressure cycle testing according to either of the following:

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1) Twice the number of cycles of the required life at the MEOP, applying pressure 1.5 times of the MEOP.

2) Four times the number of cycles of the required life at the MEOP, applying the MEOP.

Note: When multiple proof pressure tests are to be conducted during flight model operations, add the additional number of pressure cycles

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required to the pressure cycles of either 1) or 2).

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For COPV, Pressure cycle test according to either of the following:

- 1) Four times the number of the planned proof pressure tests at test pressure (if two or more tests are conducted for operation of the flight model, add pressurization required for proof pressure testing) and four times the number of proof pressure tests required at MEOP.
- 2) Four times the number of the planned pressure cycles in the applicable sequence of pressurization and depressurization (applicable only when a peak operating pressure generates tensile stress that exceeds an initial compressive stress value for metallic liners as given by autofrettage)

Note: The planned pressure cycle means a series of pressure cycles such as the number of times required for proof pressure tests, airtight tests, and MEOP applications.

- b. After testing, perform external appearance inspections and confirm there are no harmful deformations, cracking, or other abnormalities.
- c. The bellows as shown in Table 3.1.3-1 No. 5 is needed the pressure cycle test as required to pressure vessel. Both pressure cycle and displacement cycle shall be considered in the pressure cycle test.
- d. The pressure cycle test may be omitted if the test is too difficult to conduct for launch vehicle propellant tanks.

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(2) Burst pressure test

- a. Burst pressure testing is in principle performed at the design burst pressure and at a temperature corrected for the material strength, and at a pressure corrected for the difference between the minimum measured plate thickness and the design minimum plate thickness of the specimen. Ensure that the specimen does not break at below the corrected pressure.

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For COPV, the pressure retaining period is longer than 30s.

- b. The burst test following above burst pressure test is recommended.

For the burst test, pressurize the test article beyond the design burst pressure until the test article bursts and confirm the equipment's strength margin.

- c. For the burst test of metallic pressure vessels, compare the actual burst pressure with the predicted pressure calculated from the flow stress equations as shown below.

Flow stress equations

- 1) Cylindrical shell

$$P_B = \frac{2}{\sqrt{3}} \left(\frac{\sigma_y + \sigma_u}{2} \right) \frac{t}{R_i}$$

2) Spherical shell

$$P_B = 2 \left(\frac{\sigma_y + \sigma_u}{2} \right) \frac{t}{R_i}$$

P_B : Burst pressure

σ_y : Material yield stress

σ_u : Material tensile strength

R_i : Inner diameter

t : Thickness

Notice: Actual values of the property of the burst tested metallic pressure vessel are used in above equations.

(3) Vibration test

- a. In the vibration test, conduct random vibration test, sinusoidal wave vibration test, and acoustic test.
- b. When the qualification test specified in (1) or (2) above could not cover the vibration requirement by the environment specified in paragraph 3.1.2.2, conduct the vibration test.
- c. Specify the test conditions including the vibration levels and loading time as vibration test requirements.
- d. Launch vehicle propellant tank is not required to conduct vibration test.

(4) Ground handling load test

The launch vehicle propellant tank shall be loaded ground handling load as needed (*1) and confirm validity of design analysis according to paragraph 3.5.1.3 (the special factor shown in paragraph 3.1.2.3 and the safety factor shown in paragraph 3.1.3.4 are assured).

*1 In the case when ground handling load is the most severe load for the shell thickness calculation.

(5) Operational cycle test and displacement cycle test

The high-pressure gas equipment having moving mechanism such as electromagnetic valve, fill and drain valve and so on shall be qualified by operational cycle test. The cycle number is set by the multiple of the cycle number from paragraph 3.1.5 (3) and safety factor given from space system. For the bellows the displacement cycle test shall be done instead of operational

cycle test. However, the bellows which is defined in table 3.1.3-1 No.5 shall be qualified by the pressure cycle test according to paragraph 5.2.(1) c.

(6) Interlaminar shear testing

Except for carbon fiber-reinforced epoxy composites, the resin-impregnated fiber layer of the COPV must pass interlaminar shear testing using equivalent test materials as follows:

- a. Perform testing on five test pieces in accordance with ASTM-D2344, JIS K 7078, or JIS K 7057.
- b. If a test piece breaks as a result of testing in a form other than horizontal interlaminar shear failure, invalidate the test results, collect a replacement test piece, and repeat the test.
- c. Perform testing at the design temperature.
- d. The test is passed if the shear stress value for each test piece is 35 N/mm^2 or higher.

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6. Reuse

When reusing reusable high-pressure gas equipment, define the degradation factors during the mission, ground operations and storage. Ensure safety by analyzing or testing for the degradation factors. Major degradation factors are mechanical factors such as pressure, vibration, acceleration, and shock; environmental factors such as cosmic radiation and heat; chemical factors such as corrosion caused by propellant or pressurizing gas.

Figure 6-1 shows the task flow for reuse.

6.1 Reuse Inspection

6.1.1 Visual inspection

Confirm that no abnormalities such as harmful flaws, deformations, dents or corrosion exist.

6.1.2 Nondestructive inspection

Conduct the following nondestructive inspection as required ensuring that no defects harmful to the high-pressure gas equipment exist. When visual inspection reveals a defect or when a repair is performed, select and perform an appropriate test method from among the following:

(1) Penetrant testing

Perform penetrant testing on base metals and the surface of welded parts in adherence to the testing standards specified in AMS-2645, ASTM-E1417, or the equivalent. Judgment criteria are according to paragraphs 4.7.2 and 4.7.3. The eddy current testing or ultrasonic inspection described in paragraphs 4.7.2(3) and 4.7.3.5(1) may be performed in place of penetrant testing.

(2) Radiographic testing

Perform radiographic testing in adherence to ASTM-E1742 or an equivalent standard on welded part interiors. Judgment criteria are as per paragraph 4.7.3.

(3) Ultrasonic testing

Perform ultrasonic inspection in adherence to ASTM-E164 or an equivalent standard on welded part interiors. Judgment criteria are as per paragraph 4.7.3.

6.1.3 Dimension inspection

Perform dimension inspection of the high-pressure gas equipment for which dimension change will affect strength during mission operation or for which dimension is changed due to the repair specified in paragraph 6.3, and ensure that the dimension satisfy the drawing requirement.

6.2 Reuse Test

(1) Proof pressure test

For reuse test, conduct the proof pressure test to confirm structural integrity for the following cases. Sufficiently examine whether the proof pressure test is performed or not, because the proof pressure test could reduce the life of high-pressure gas equipment.

- a. When repaired
- b. When reuse high-pressure gas equipment which is suspected to have been stored for a long period under conditions not satisfying the requirements specified in (2) to (4) of paragraph 8.
- c. When the proof pressure test is considered to be necessary.

The proof pressure test, if conducted, shall comply with (1) of paragraph 4.7.5.1 and (1) of paragraph 4.7.5.2.2, "Proof pressure test."

(2) Leak test

Perform the leak test as specified in (2) of paragraph 4.7.5.1 and (2) of paragraph 4.7.5.2.2, "Leak test."

6.3 Repair

When structural damage or a defect exceeding allowable level is found in reuse inspection, or when the equipment is rejected by reuse test, appropriately repair the high-pressure gas equipment. If the repair is not feasible, re-fabricate and replace such high-pressure gas equipment.

Repair so as to maintain the material characteristics and repair within the dimensional tolerance. When the repair deviates from the dimensional tolerance, ensure that problem does not occur by conducting additional analysis or test.

Because the repair could reduce strength, determine the need to repair damage or defects considering the result of flaw growth analysis described in paragraph 3.5.4.1.

When high-pressure gas equipment is repaired, conduct the proof pressure test in the reuse test. Determine to repair with enough consideration because it will affect the number of pressurization cycle which are estimated by planned number of flight.

Repair which does not affect the strength (e.g., replacement of seals for leakage found in the leak test) does not require the proof pressure test in the reuse test.

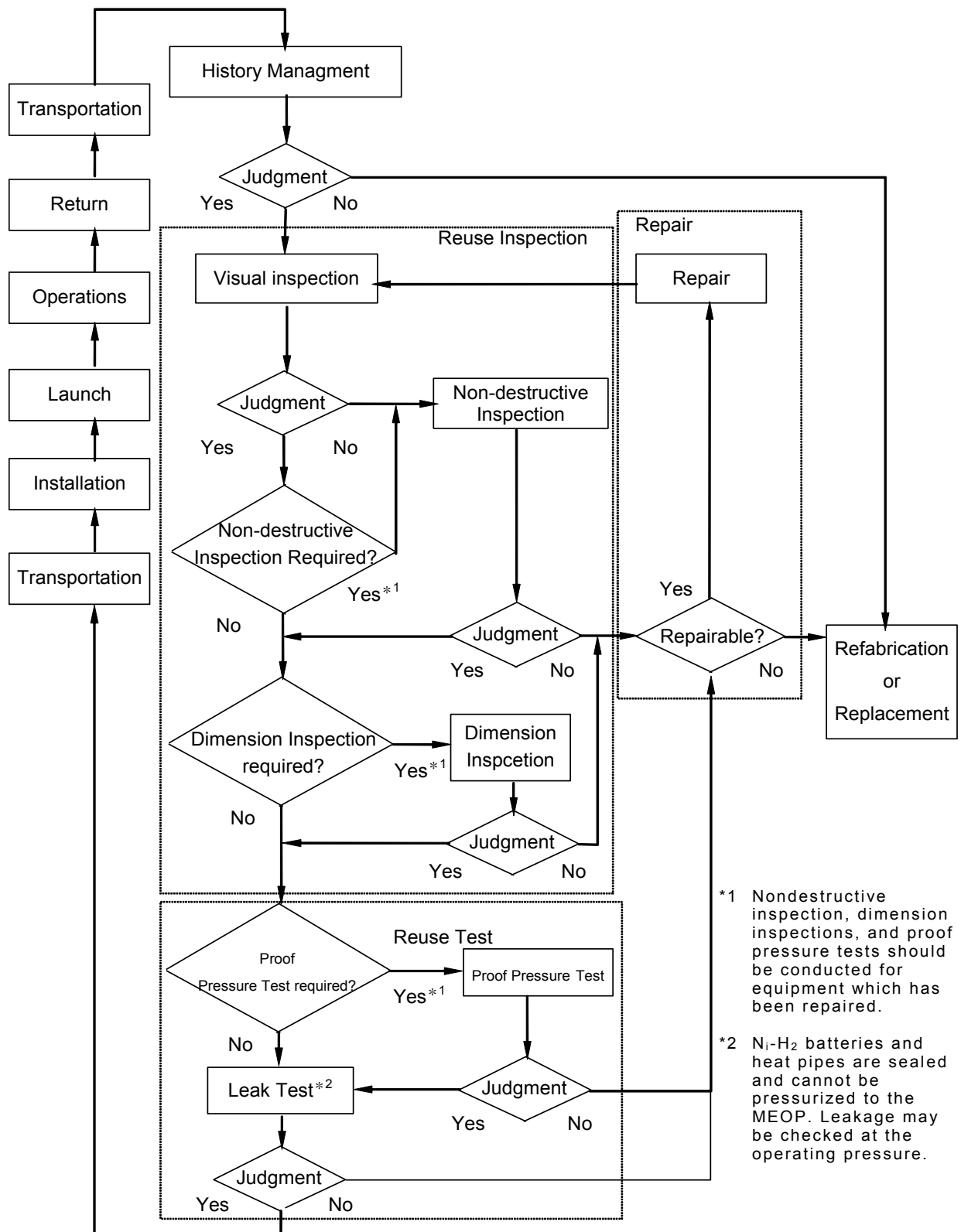


Figure 6-1 Task Flow for Reusing Reusable High-Pressure Gas Equipment

7. Safety Assurance During Pressurization

Observe the following rules to assure safety of testing personnel when pressurizing the high-pressure gas equipment in the leak test, proof pressure test or pressure gas loading at the launch site.

- (1) Pressure relief valve or equivalent function (hereinafter referred to as safety device) should be installed to the test equipment to prevent excessive pressurization. In some case where safety device cannot be installed to the test equipment, safety device may be installed to the ground support equipment.

Pressure settings for safety valves, etc., are as follows, with pressure corresponding to the blow start pressure.

- For leak test: Airtightness test pressure + Positive test pressure tolerance

- For filling: MEOP

When taking the blow pressure as the pressure setting, it should be less than 1.1 times the blow start pressure. The tolerance is according to JIS B 8210.

- (2) Pressurizing/Depressurizing shall be operated remotely or operated manually from protected place.
- (3) Facility shall be furnished to exhaust a pressurized fluid urgently.
- (4) Pressurize after judging whether personnel can approach the high-pressure gas equipment according to the requirements or not in Tables 3.1.3-1 and 3.1.3-2.

- (5) If the COPV capacity is 500 L or less and tensile testing is performed on the base material of liners (excluding nonmetal liners) or welded parts during certification testing, use the following pressures. For other high-pressure gas equipment, when applying pressures more than 1/4 the design burst pressure, perform pressurization and depressurization from beyond an appropriate distance for safe operations or while using an appropriate protective barrier.

Carbon fiber composite pressure vessels: more than 1/2.25 of design burst pressure

Aramid fiber composite pressure vessel: more than 1/3 of design burst pressure

Glass fiber composite pressure vessel: more than 1/3.5 of design burst pressure

- (6) When personnel must approach vessels at the pressures described in item (5), observe pressure changes after pressurization is completed, and confirm that pressure has stabilized before approaching.

- (7) When the pressure applied to the pressure vessel exceeds the MEOP, conduct such pressurization in a pit or equivalent structure.
- (8) Safety control personnel shall be present at the test.

Note: Although safety needs to be ensured for N_i - H_2 batteries or heatpipes that are pressurized or depressurized in normal operations, portions of items (1) to (3), (7) and (8) above may be omitted when it is considered to be impracticable.

8. Handling

- (1) To confirm that high-pressure gas equipment can be operated normally, perform historical management for the number of flight, the required life for pressure cycle, operating cycle, displacement cycle, inspection result at acceptance and operation, and repair record according to paragraph 3.1.5.
- (2) Do not use fluids, gases, inspection solutions, or other auxiliary materials for high-pressure gas equipment fabrication and inspection if such materials will corrode or embrittle the materials for high-pressure gas equipment or may lead to destruction, leakage, or contamination of the high-pressure gas equipment.
- (3) Purge high-pressure gas equipment with low-pressure, clean, dry inert gas or maintain dry air that has passed through desiccants before handling and storage to prevent internal contamination due to dust, deformation due to creep or self-weight, and corrosion.
- (4) Store high-pressure gas equipment in temperature and humidity-controlled rooms to prevent degradation during storage due to external environments. High-pressure gas equipment should be stored in containers to protect it from unnecessary external forces.
- (5) During ground handling and transportation, avoid excessive loads on high-pressure gas equipment by limiting handling methods, reinforcement with jigs, and protection by containers.
- (6) Comply with the damage prevention control plan according to 3.6.1.2.

9. Measures for Revisions

When these technical standards are revised, the revised version is effective immediately after issuance, but conformance assessments based on these technical standards will be implemented as follows.

(1) Conformance assessments in the pre-revision edition are in principle limited to six months following issuance of the revised edition.

(2) When applying for a fabrication conformity review according to a revised edition for a device issued conformity certification by design conformity review under a pre-revision edition, ensure that all revised items conform to the design conformity review, and carry out special treatment if they do not. In such cases, conformity certification based on the design conformity examination under the pre-revision edition is valid for future devices having the same design.

(3) In the case of equipment for which conformity certification was issued by a design conformity review under the pre-revision edition, if there are items among the revised items not matching the design conformity review, and if special treatment could not be completed, conformity certification by production conformity inspection will be issued if the fabrication results all conform with the revised version.

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APPENDIX

The symbols used in this technical standard are defined below. Please note that these definitions apply to the representative examples. If the symbols are used for the definitions other than those specified below, the applicable definitions are explained in appropriate paragraphs.

a	Flaw size (flaw depth "a" or flaw length "c").
a _{cr}	Critical flaw size (depth) that results in destruction or through thickness of high-pressure gas equipment under the MEOP.
a _i	Size (depth) of initial flaw guaranteed by the flaw detection pressure test.
D	Major axis of ellipsoid inside of head.
D ₀	Outer diameter of the large opening of a conical head.
d _o	Outer diameter.
d _i	Internal diameter.
E	Modulus of longitudinal elasticity.
F	Increment of stress to primary and secondary stresses due to stress concentration generated by structural discontinuities, such as uneven surfaces or notches (peak stress) Includes incremental stress due to angular deformation and unevenness at weld joints.
h	One half of the minor axis of ellipsoid inside of head.
K	Stress intensity factor.
K _C	Fracture toughness.
K _R	Fracture resistance.
ΔK	Fluctuation range of stress intensity factor, K.
L _r	Internal pressure: P divided by plastic collapse pressure: P _c
N _D	Number of loading cycles until thru-thickness penetration or unstable fracture of high-pressure gas equipment results.
N _f	Fatigue life.
N _i	Number of loading cycle.
n _i	Number of cycle in the stress range.
P	MEOP.
P ₀	Plastic collapse pressure.
P _B	Burst pressure.
P _b	Stress intensity of bending stress.
P _c	Plastic collapse pressure at design temperature
P _L	Stress intensity of local primary membrane stress.

P_m	Stress intensity of general primary membrane stress generated by the MEOP.
P.F	Proof factor.
Q	Secondary stress.
R	Internal radius of the central part of a torispherical head or total hemispherical head.
R_1	Stress ratio ($R_1 = K_{MIN}/K_{MAX}$).
R_i	Internal radius of a cylinder.
R_o	Outer radius of a cylinder.
r_1	Internal radius of the round corner of a torispherical head.
r_2	Internal radius of the round part continuing to the large opening of a conical shell.
S_m	Design stress intensity.
S.F ₁	Safety factor (S.F ₁ =4).
t	Minimum thickness
t_c	Thickness of composite material when artificial isotropy is assumed.
t_m	Thickness of a metallic liner.
t_θ	Helical winding layer.
t_h	Thickness of hoop winding.
u	Distance toward plate width from internal surface (flaw side).
W	Coefficient relating to a torispherical shape.
z	Distance of thickness direction from internal surface (flaw side).
ε_f	Breaking elongation (true strain of fracture).
$\Delta\varepsilon_t$	Total strain range.
θ	One half of the apical angle of the cone.
λ	Plastic constraint factor (deepest point $\lambda = 1.68$ and surface point $\lambda = 1$)
ν	Poisson ratio
σ	Stress.
σ_b	Nominal (maximum) bending stress.
σ_h	Maximum value of hoop stress (circumferential stress).
σ_i	Stress distribution with approximation of polynomial equations ($i = 0$ to 3).
σ_m	Mean stress.
σ_u	Tensile strength of material
σ_y	Yield stress of material or 0.2% proof stress.

$\Delta\sigma$ Virtual elastic stress range.