NA 032-03-06 AA N 1437

NA 032 DIN-Normenausschuss Gastechnik (NAGas)
NA 032-03-06 AA Arbeitsausschuss Wasserstofftechnologie
E-Mail des Bearbeiters bei DIN: klaas@dvgw.de

ISO DIS 19884 Gaseous hydrogen — Cylinders and tubes for stationary storage

Datum des Dokumentes	2018-02-19
Aktion	Abstimmung
Antworttermin	2018-05-04
Herkunft des Dokumentes	Sekretär ISO/TC 197_J. Ferrero
Pages	73

DRAFT INTERNATIONAL STANDARD
ISO/DIS 19884

ISO/TC **197** Secretariat: **SCC**

Voting begins on: **2018-02-16** Voting terminates on: **2018-05-11**

Gaseous hydrogen — Cylinders and tubes for stationary storage

Hydrogène gazeux — Bouteilles et tubes pour stockage stationnaire

ICS: 71.100.20; 23.020.30

ISO/CEN PARALLEL PROCESSING

Reference number
ISO/DIS 19884:2018(E)

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva, Switzerland
Tel. +41 22 749 01 11
Fax +41 22 749 09 47
copyright@iso.org
www.iso.org

Published in Switzerland

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

In any case, national regulation, if applicable, prevails on standard.

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

ISO 19884 was prepared by Technical Committee ISO/TC 197, *Hydrogen technologies*.

Introduction

As the use of gaseous hydrogen evolves from the chemical industry into various emerging applications, such as fuel for fuel cells and internal combustion engines, and other specialty hydrogen applications, new requirements and usages are foreseen for seamless and composite pressure vessels, including higher number of pressure cycles, and use of transportable storages as stationary vessels.

Requirements covering pressure vessels for stationary storage of compressed gaseous hydrogen are listed in this standard and are mainly intended to maintain or improve the level of safety of this application.

It is to be noted that vessels qualified to ISO 19884 will also need to meet regulations of countries where installed, such as the European PED and building codes that reference ASME. It is a goal of ISO 19884 that qualified vessels will be acceptable to regulators in countries where installed.

Gaseous hydrogen — Cylinders and tubes for stationary storage

1 Scope

This International Standard specifies the requirements for design, manufacture and testing of standalone or manifolded (for some specific tests such as bonfire) cylinders, tubes, and other pressure vessels of steel, stainless steel, aluminium alloys or of non-metallic construction material. These are intended for the stationary storage of gaseous hydrogen of up to a maximum water capacity of 10 000 l and a maximum allowable working pressure not exceeding 110 MPa, of seamless metallic construction (Type 1) or of composite construction (Types 2, 3 and 4), hereafter referred to as pressure vessels. Type 2 and 3 vessels with welded liners are excluded.

For an existing design already qualified for other applications (e.g. transportable applications) follow the requirements of Annex B.

This International Standard is not intended as a specification for pressure vessels used for solid, liquid hydrogen or hybrid cryogenic-high pressure hydrogen storage applications.

This International Standard does not include external piping which can be designed according to a recognized standard (e.g. ISO 15649).

2 Normative references

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

ANSI/CSA CHMC 1-2014 - *Test methods for evaluating material compatibility in compressed hydrogen applications - Metals*

ASME Boiler and Pressure Vessel Code,

ASTM D3170 / D3170M - 14 *Standard Test Method for Chipping Resistance of Coatings*

ASTM E647, *Standard Test Method for Measurement of Fatigue Crack Growth Rates*

CSA PRD 1-2013 - *Pressure relief devices for natural gas vehicle (NGV) fuel containers*

EN 12245, *Transportable gas cylinders. Fully wrapped composite cylinders*

ISO 306, *Plastics — Thermoplastic materials — Determination of Vicat softening temperature (VST)*

ISO 527-2*, Plastics — Determination of tensile properties — Part 2: Test conditions for moulding and extrusion plastics*

ISO 1519, *Paints and varnishes -- Bend test (cylindrical mandrel)*

ISO 2808, *Paints and varnishes — Determination of film thickness*

ISO 2812-1 *Paints and varnishes -- Determination of resistance to liquids -- Part 1: Immersion in liquids other than water*

ISO 4624, *Paints and varnishes — Pull-off test for adhesion*

ISO 6272-2 *Paints and varnishes -- Rapid-deformation (impact resistance) tests -- Part 2: Falling-weight test, small-area indenter*

ISO 6506-1, *Metallic materials — Brinell hardness test — Part 1: Test method*

ISO 7225, *Gas cylinders — Precautionary labels*

ISO 7866, *Gas cylinders — Refillable seamless aluminium alloy gas cylinders — Design, construction and testing*

ISO 9227, *Corrosion tests in artificial atmospheres -- Salt spray tests*

ISO 9809-1, *Gas cylinders — Refillable seamless steel gas cylinders — Design, construction and testing — Part 1: Quenched and tempered steel cylinders with tensile strength less than 1 100* MPa

ISO 9809-3, *Gas cylinders -- Refillable seamless steel gas cylinders -- Design, construction and testing -- Part 3: Normalized steel cylinders*

ISO 9809-4, *Gas cylinders -- Refillable seamless steel gas cylinders -- Design, construction and testing -- Part 4: Stainless steel cylinders with an Rm value of less than 1 100 MPa*

ISO 11114-1 *Gas cylinders — Compatibility of cylinder and valve materials with gas contents — Part 1: Metallic materials*

ISO 11114-2, *Gas cylinders -- Compatibility of cylinder and valve materials with gas contents -- Part 2: Non-metallic materials*

ISO 11114-4, *Transportable gas cylinders — Compatibility of cylinder and valve materials with gas contents — Part 4: Test methods for selecting metallic materials resistant to hydrogen embrittlement*

ISO11119-1, *Gas cylinders -- Refillable composite gas cylinders and tubes -- Design, construction and testing -- Part 1: Hoop wrapped fibre reinforced composite gas cylinders and tubes up to 450 l*

ISO11119-2, *Gas cylinders -- Refillable composite gas cylinders and tubes -- Design, construction and testing -- Part 2: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with load-sharing metal liners*

ISO 11120, *Gas cylinders — Refillable seamless steel tubes for compressed gas transport, of water capacity between 150 l and 3000 l — Design construction and testing*

ISO 11357-2, *Plastics -- Differential scanning calorimetry (DSC) -- Part 2: Determination of glass transition temperature*

ISO 11439*, Gas cylinders -- High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles*

ISO 11507, *Paints and varnishes -- Exposure of coatings to artificial weathering -- Exposure to fluorescent UV lamps and water*

ISO 11623, *Transportable gas cylinders -- Periodic inspection and testing of composite gas cylinders*

ISO 12108, *Metallic materials -- Fatigue testing -- Fatigue crack growth method*

ISO 14130, *Fibre-reinforced plastic composites -- Determination of apparent interlaminar shear strength by short-beam method*

ISO 15500-13, *Road vehicles -- Compressed natural gas (CNG) fuel system components -- Part 13: Pressure relief device (PRD)*

EN 13322-2, *Transportable gas cylinders — Refillable welded steel gas cylinders — Design and construction — Part 2: Stainless steel*

3 Terms, definitions and symbols

3.1 Terms and definitions

3.1.1.
autofrettage
pressure application procedure which strains the metal liner past its yield point sufficient to cause permanent plastic deformation, and results in the liner having compressive stresses and the fibres having tensile stresses when at zero internal gauge pressure

3.1.2.
autofrettage pressure
pressure within the overwrapped composite pressure vessel at which the required distribution of stresses between the liner and the composite overwrap is established

3.1.3.
batch of pressure vessels/liners
set of manufactured finished pressure vessels/liners subject to a manufacturing quality pass / fail criteria based on the results of specified tests performed on a specified number of units from that set

3.1.4.
boss
dome shaped metallic component mounted on one end or on the two ends of a non-metallic liner with a neck providing an opening and/or an external element of mechanical support

3.1.5.
burst pressure
highest pressure reached in a cylinder during a burst test

3.1.6.
composite overwrap
combination of fibres (including steel wire) and matrix

3.1.7.
controlled tension winding
process used in manufacturing composite pressure vessels with metal liners by which compressive stresses in the liner and tensile stresses in the composite overwrap at zero internal pressure are obtained by winding the reinforcing fibres under controlled tension

3.1.8.
cycle amplitude
ratio of pressure increase to maximum pressure in a pressure cycle, expressed in %

3.1.9.
design change
change in the selection of structural materials or dimensional changes exceeding the tolerances as on the design drawings

3.1.10.
exterior coating
layers of material applied to the cylinder (eg for protection)

NOTE The coating may be clear or pigmented.

3.1.11.
finished pressure vessels
pressure vessels, which are ready for use, typical of normal production, complete with identification marks and external coating including integral insulation specified by the manufacturer, but free from non-integral insulation or protection

NOTE In the framework of this standard, a tube or a cylinder is a finished pressure vessel.

3.1.12.
full cycle
cycle of pressure amplitude between not less than MAWP (see 3.1.19) and not more than 10% of the MAWP

3.1.13.
fully wrapped composite pressure vessel
pressure vessel with a composite overwrap taking both circumferential and longitudinal stress

3.1.14.
leakage
release of hydrogen through a crack, pore, or similar defect

NOTE Permeation through the wall of a Type 4 pressure vessel that is less than the rates described in A.14 is not considered leakage.

3.1.15.
liner
inner portion of the composite cylinder, comprising a metallic or non-metallic vessel, whose purpose is both to contain the gas and transmit the gas pressure to the fibres

3.1.16.
load sharing liner
liner that has a burst pressure of at least 5 % of the minimum burst pressure of the finished composite cylinder

3.1.17.
matrix
material that is used to bind and hold the fibres in place

3.1.18.
maximum allowable temperature
maximum temperature of any part of the pressure vessel for which it is designed (or intended to be used if Annex B is followed)

NOTE Different limits may apply for maintenance.

3.1.19.
maximum allowable working pressure (MAWP)
maximum pressure to which the component is designed to be subjected to and which is the basis for determining the strength of the component under consideration (also known as design pressure)

3.1.20.
maximum energy content
maximum energy content is the product of the pressure vessel's water capacity in litres and the MAWP in MPa.

3.1.21.
minimum allowable temperature

minimum temperature of any part of the pressure vessel for which it is designed (or intended to be used if Annex B is followed)

3.1.22.
operator
Entity legally responsible for the use and maintenance of the vessel

3.1.23.
Pressure-activated pressure relief device (PRD)
device designed to release pressure in order to prevent a rise in pressure above a specified value due to emergency or abnormal conditions

NOTE Pressure-activated PRDs may be either re-closing devices (such as valves) or non-re-closing devices (such as rupture disks).

3.1.24.
pressure cycle
pressure variation composed of one period of monotonic pressure increase up to a peak pressure followed by one period of monotonic pressure decrease

3.1.25.
pressure cycle life
maximum number of pressure cycles in hydrogen service that the pressure vessel is designed to withstand in service

3.1.26.
pre-stress
process of applying autofrettage or controlled tension winding

3.1.27.
service life
maximum period (expressed in years) for which the pressure vessel is designed to be in service (based on fatigue life and stress rupture characteristics of composite cylinders)

NOTE service life usually depends on the pressure cycle or other service conditions and requirements from applicable standards. For composite cylinders, life in years is a requirement to address reliability under stress rupture conditions, which is also an underlying basis for the required stress ratios.

3.1.28.
Shallow pressure cycle
Pressure cycle from MAWP to not less than 70 % of MAWP

3.1.29.
shallow pressure cycle life
maximum number of shallow pressure cycles, that the pressure vessel is designed to withstand in hydrogen service

3.1.30.
stationary storage
pressurized storage in a fixed location for a fixed purpose, not transported while pressurized

3.1.31.
stationary test pressure (TP)
required pressure applied during a pressure test for the pressure vessel used in stationary service

NOTE If Annex B is used, this is not to be confused with the test pressure P_h used in e.g. ISO 9809 series for design purposes as transportable gas cylinder.

3.1.32.
stress ratio
stress in fibre at specified minimum burst pressure divided by stress at MAWP

3.1.33.
test pressure
required pressure applied during a pressure test

3.1.34.
thermally activated pressure relief device
device that activates by temperature to release pressure and prevent a pressure vessel from bursting due to fire effects and which will activate regardless of vessel pressure

3.1.35.
thermoplastic materials
plastics capable of being repeatedly softened by increase of temperature and hardened by decrease of temperature

3.1.36.
thermosetting materials
plastics that, when cured by the application of heat or chemical means, harden permanently into a substantially infusible and insoluble product

3.1.37.
Type 1 pressure vessel
an all metal cylindrical pressure vessel

3.1.38.
Type 2 pressure vessel
a hoop wrapped cylindrical pressure vessel with a load sharing metal liner and composite reinforcement on the cylindrical part only

3.1.39.
Type 3 pressure vessel
fully wrapped cylindrical pressure vessel with a load sharing metal liner and composite reinforcement on both the cylindrical part and dome ends

3.1.40.
Type 4 pressure vessel
a fully wrapped cylindrical pressure vessel with a non-load sharing liner and composite reinforcement on both the cylindrical part and the dome ends

3.1.41.
Non-load-sharing liner
a non-load-sharing liner is a liner that has a burst less than 5% of the nominal burst pressure of the finished composite cylinder

3.1.42.
working pressure
settled pressure of a fully filled cylinder at a uniform temperature of 15°C (ISO 11439)

NOTE This term is normally used for transportable cylinders, see Annex B.

3.2 Symbols

ΔP_i : variation of pressure during a given actual pressure cycle (in bar)

ΔP_{max} : variation of pressure during the pressure test specified in the reference standard (in bar)

F : design stress factor (ratio of equivalent wall stress at test pressure P_h to guarantee minimum yield strength)

Fa : Hydrogen Accelerating Factor (see B.2.2.6)

MAWP : maximum allowable working pressure

n_{eq} : number of cycles equivalent to full cycles (guaranteed in a given standard)

n_i : number of pressure cycle corresponding to ΔP_i

P_h : test pressure (in bar)

PW: working pressure (in bar)

4 Specified service conditions

4.1 Maximum allowable working pressure

The maximum allowable working pressure shall be specified by the pressure vessel manufacturer and shall not be less than 15 MPa and shall not exceed 110 MPa.

4.2 Maximum allowable energy content

The maximum allowable energy content of a single pressure vessel shall not exceed 300000 MPa.l.

4.3 Maximum and minimum allowable temperature

The maximum allowable temperature and the minimum allowable temperature shall be specified by the pressure vessel manufacturer and noted on the name plate.

The specified value for the maximum allowable temperature shall not be less than 50°C and shall not exceed 85°C.

The specified value for the minimum allowable temperature shall not exceed -25°C and shall not be less than -50°C.

The manufacturer may specify a distinct maximum temperature not to be exceeded during maintenance (e.g. for painting).

4.4 Pressure cycle life

The pressure cycle life in hydrogen service shall be specified by the pressure vessel manufacturer.

The owner/operator may elect to further restrict to number of cycles allowed.

The pressure cycle life can be calculated according to method described in A.7 or following requirements given in clause 8.1.3.5.

4.5 Shallow pressure cycle life

A shallow pressure cycle life may optionally be specified by the pressure vessel manufacturer or user. In this case, the shallow pressure cycle life shall be at least three times the pressure cycle life.

The shallow pressure cycle life shall be calculated using 4.6.2, 4.6.3, 8.1.3.5 or experimentally determined according to method described in A.7

4.6 Effective pressure cycle count and maximum number of pressure cycles allowed in service

4.6.1 General

One of the following methods shall be used to determine the pressure cycles life of the cylinder.

4.6.2 Pressure Intensity Factor

The cycle life limit is reached when the effective pressure cycle count, which is the pressure cycle count computed with the application of a pressure intensity factor, reaches the specified cycle life.

For all types of vessels, the number of cycles equivalent to full cycles (guaranteed in a given standard) can be calculated according to the formula given in Annex B.

4.6.3 Goodman Diagrams

The cycle life may be determined by the use of a Goodman diagram and Miner’s Rule. The Goodman diagram shall be based on fatigue testing of similar materials and construction as the vessel to be qualified. An example of this approach is provided in Annex F.

4.7 Service life

The service life shall be specified by the pressure vessel manufacturer.

For Type 2, Type 3, and Type 4 designs incorporating aramid or glass fiber, the specified service life shall not exceed 30 years.

The duration of service is also limited by the specified pressure cycle life. The operator is responsible for monitoring the cycles placed on the pressure vessels and removing them from service when their rated life has been reached.

The owner must keep record of the total number of pressure cycles the pressure vessel has been subjected to during its life.

NOTE For example, a pressure vessel specified for 150 000 cycles and subjected to a pressure cycle every hour will need to be removed from service after 17 years.

5 Additional service conditions

5.1 Environmental conditions

The manufacturer shall specify the environmental conditions for which the pressure vessel has been designed as well as any protection to be provided at point of use, such as external protection from extreme solar radiation.

Precautions shall be taken against drop or impact (particularly during installation). If drop or impact does occur, an inspection shall be conducted.

This information shall be included in the statement of service provided by the manufacturer as required by Clause 6.2.

Immersion in fluids, additional coating, protecting layer or medium isolating the cylinders or generating retention of fluids of any kind requires written approval from the manufacturer.

5.2 Fire conditions

The owner / operator shall assess the outcome of a risk analysis to demonstrate that in case of a fire, overall safety will be maintained.

For protection, several solutions can be used (e.g. extinguishing devices, fire retardants, PRD, intumescent paints...).

When regulations or risk analysis require the installation of a pressure relief device, see for information suggested design and test procedures in Annex G.

6 Information to be recorded

6.1 General

The pressure vessel manufacturer shall keep on file the information specified herein. This information shall be retained for the intended life of the pressure vessel.

6.2 Statement of service

A statement of service shall be provided by the manufacturer of the pressure vessel to the user. This statement of service shall include the following:

a) the name and address of the pressure vessel manufacturer;

b) the specified service conditions as specified in Clause 4 and Clause 5, including a warning about the need for measures to prevent specified limitations, such as temperature limits and cycle life, from being exceeded.

c) a statement that the pressure vessel design is suitable for use in the service conditions provided in Clauses 4 and 5;

d) a description of the pressure vessel design, including diameter (mm), length (mm), internal volume (l), empty weight (kg), and port geometry;

e) if applicable, a specification of the pressure relief performance required to prevent violent rupture in case of exposure to fire conditions, as specified in Clause 5.2;

f) a specification for the support methods, external protection, protective coatings and any other items required, but not provided with the pressure vessel;

g) A statement that the number of cycles of operations shall be determined and that the actual number of cycles shall be monitored

h) any other information and instructions necessary to ensure the safe use and inspection of the pressure vessel, including that specified hereafter, where relevant:

- for Type 2, Type 3, and Type 4 designs requiring protection against exposure to UV emissions, instructions shall require that this protection be provided by the installation;
- for Type 4 designs, the manufacturer shall:
  - specify the minimum residual pressure in normal operation (MRP). The specified MRP shall not exceed 15 % of the MAWP
  - specify the maximum depressurization rate during normal operation, which shall be lower than 20 MPa/min
  - provide a procedure for complete depressurization from MRP without liner collapse.

NOTE Annex E provides further typical information on the manufacturer's instructions for handling, use and inspection of pressure vessels.

6.3 Design drawings and information

All pressure vessel drawings and related technical data shall be kept on file by the pressure vessel manufacturer and shall show the following information:

a) title, reference number, date of issue, and revision numbers with dates of issue, if applicable;

b) the MAWP;

c) the operating process temperature range;

d) the specified service conditions, in addition to the MAWP, as specified in Clauses 4 and 5;

e) dimensions complete with tolerances, including details of end closure shapes with minimum thickness and openings;

f) mass, complete with tolerance;

g) material specifications, complete with minimum mechanical and chemical properties and tolerance ranges and, for metal pressure vessels, metal liners and bosses, the specified hardness range and maximum allowable defect size;

h) autofrettage pressure range and duration;

i) test pressure as carried out by the manufacturer;

NOTE Applicable regulation may require a different value.

j) details on exterior protective coating.

6.4 Stress analysis report

The manufacturer shall produce a stress analysis report as required by 8.1.1.1, including a table summarizing the determined stresses. The manufacturer shall keep this report on file.

6.5 Material property data

The manufacturer shall keep the following information on file, as applicable, and make available to regulatory authorities or inspectors on request:

a) detailed description of the materials and tolerances of the material properties used in the design, including test data characterizing the mechanical properties and the suitability of the materials for service under the conditions specified in Clauses 4 and 5

b) published specifications for composite materials, as well as the material manufacturer's recommendations for storage conditions and shelf life

c) the fibre manufacturer's certification that each shipment conforms to the manufacturer's specifications for the product.

6.6 Manufacturing data

Details of all fabrication processes, tolerances, non-destructive examinations, batch tests and production tests shall be specified and kept on file by the manufacturer.

The manufacturer shall specify the minimum burst pressure for the design. In no case shall the minimum specified burst pressure be less than the minimum burst pressure specified in this International Standard in relation to the MAWP.

Surface finish, thread details, acceptance criteria for Non Destructive Examination, and lot sizes for batch tests shall also be specified by the manufacturer and kept on file.

The manufacturing data specified in 8.1.2.5, 8.1.2.6 and 8.1.2.7, along with the results of non-destructive examinations, batch tests, and production tests shall be kept on file by the manufacturer.

6.7 Retention of records

The design and manufacturing data kept on file, as specified in 6.5, 6.6 and 8.1.4.1, shall be retained by the manufacturer for a duration of at least the service life of the pressure vessel plus five years from date of manufacture.

7 Material properties

7.1 Compatibility

The design shall not have incompatible materials in contact with each other. All materials in contact with hydrogen shall be suitable for use in hydrogen. according to the criteria of ISO 11114-1, ISO 11114-2 and ISO 11114-4 as applicable.

NOTE Guidance on hydrogen compatibility can be found in the documents listed in the bibliography.

7.2 Steel

Steels for pressure vessels, seamless liners, and bosses shall either conform to the materials requirements of ISO 9809-1 for pressure vessels of up to 450 l water capacity and of ISO 11120 for pressure vessels of water capacity greater than 450 l and to ISO 11114-1, or be suitable with hydrogen according to ISO 11114-4.

7.3 Stainless steels

Stainless steels for pressure vessels, liners, and bosses shall either conform to the specific materials requirements of ISO 9809-4 for hydrogen service and to ISO 11114-1, or be suitable with hydrogen according to ISO 11114-4.

7.4 Aluminium alloys

Aluminium alloys for pressure vessels, liners, and bosses shall conform to the materials requirements of ISO 7866.

Aluminium alloys not covered by the materials requirements of ISO 7866 may be used for bosses only, provided that that they are suitable for use in hydrogen according to the criteria of ISO 11114-1 and 11114-4.

7.5 Fibre material

Structural reinforcing fibre material types shall be carbon fibre, aramid fibre or glass fibre, or any mixture thereof.

7.6 Resins

The material for impregnation may be thermosetting or thermoplastic resins. Examples of suitable matrix materials are epoxy, modified epoxy, polyester and vinyl-ester thermosetting plastics, as well as polyethylene and polyamide thermoplastic.

The glass transition temperature of the resin material shall be determined in accordance with ISO 11357-2. The glass transition temperature shall be at least 15ºC above the maximum allowable temperature.

7.7 Plastic liner material

The polymeric material used for plastic liners shall be compatible with the service conditions specified in Clauses 4 and 5.

For the thermoplastic materials, the Vicat softening temperature per ISO 306 shall be at least 90°C, and its melting temperature at least 100°C.

8 General design requirements

8.1 Requirements for new design

8.1.1 General considerations

8.1.1.1 Stress analysis

For all designs, a stress analysis shall be performed using finite element analysis or similar validated numerical method that include geometric and material non-linearities as required to establish the minimum design wall thickness and confirm the required stress ratios specified in 8.1.1.2.1 are met. It shall include the determination of the stresses in the liners and fibres of composite designs.

Alternatively, for Type 1, methods described in ISO 9809 series or ISO 11120 can be used. For Type 2 and Type 3 designs, the stresses in the composite and in the liner after pre-stress shall be calculated at zero-gauge pressure, MAWP, test pressure and design burst pressure. The calculations shall take account of non-linear material behaviour of the liner to establish the stress distributions. Calculations shall be transformed into the direction of the fibre for hoop and helically wound layers.

For Type 2 and Type 3, the limits within which the autofrettage pressure shall fall shall be calculated and specified.

For Type 4 designs, the stresses in the composite shall be calculated in the tangential and longitudinal direction of the pressure vessel. The pressures used for these calculations shall be zero gauge pressure, MAWP, test pressure and design burst pressure. The calculations shall establish the stress distribution throughout the pressure vessel. Calculations shall be transformed into the direction of the fibre for hoop and helically wound layers.

Stress calculations shall include:

a) an analysis method with capability for non-linear materials, such as a special purpose computer program or a finite element analysis program;

b) suitable modelling of the elastic-plastic stress-strain curve for the liner material;

c) suitable modelling of the mechanical properties of the composite materials;

d) calculations at autofrettage pressure, zero gauge pressure after autofrettage, MAWP, and minimum burst pressure;

e) pre-stresses from the winding tension;

f) in the case of a hybrid composite overwrap, load share between the different fibres based on the different elastic moduli of the fibres.

8.1.1.2 Burst pressure and fibre stress ratio

8.1.1.2.1 Pressure vessel

The minimum actual burst pressure of the pressure vessel shall not be less than the values given in Table 1. This pressure shall be verified on one unit per manufacturing lot. Test shall be done according to procedure described in A.6

For Type 2, Type 3 and Type 4 designs, the stress ratio in the composite overwrap shall also meet the minimum stress ratio requirements of Table 1. Methods for verifying stress ratios are provided in Annex C.

In a hybrid construction, the applicable stress ratio requirements shall be met in one of the two following ways:

a) If load sharing between the various fibre reinforcing materials is considered a fundamental part of the design, each fibre shall meet the stated stress ratio requirements.

b) If load sharing between fibres is not considered as a fundamental part of the design, then one of the reinforcing fibres shall be capable of meeting the stress ratio requirements even if all other fibre reinforcing materials are removed.

Table 1- Minimum stress ratios and burst pressures

Construction	Minimum stress ratio[(a)]			Minimum actual burst pressure[(b)]			
	Type 2	Type 3	Type 4	Type 1	Type 2	Type 3	Type 4
All-Metal	-	-	-	2	-	-	-
Glass	2.65	3.5	3.5	-	2.4	3.4	3.5
Aramid	2.25	3.0	3.0	-	2.25	2.9	3.0
Carbon	2.25	2.25	2.25	-	2.25	2.25	2.25

(a) Fiber stress at minimum burst pressure divided by fiber stress at MAWP

(b) Burst pressures are expressed as a factor of the MAWP

8.1.1.2.2 Type 2 vessel liner burst pressure

For Type 2 designs, the un-reinforced metal liner shall have a minimum burst pressure of 1,125 times the MAWP, see also Annex B.

8.1.1.3 Test pressure

For all designs, the manufacturer shall specify the test pressure. The test pressure specified shall be at least 1,25 times the MAWP pressure, see also Annex B

The test procedure should be done according to A.18.

NOTE Some regulations require higher test pressures.

8.1.1.4 Maximum defect size in metallic materials

The manufacturer shall specify the maximum allowable defect size in pressure bearing metallic materials (pressure vessel, liner or boss). The method to detect the maximum allowable defect depth shall be specified (e.g. ISO 9809 series) and not be greater than 5 % of wall thickness.

At all times, the wall thickness shall not be less than the minimum design thickness.

Defects larger than the specified maximum size shall be detectable by Non Destructive Examination.

8.1.1.5 Protection of liner and boss against corrosion

As a general requirement, the vessel design is to protect the components from corrosion from the environment it is to be sited in.

In particular, if carbon fibre reinforcement is used, the design shall incorporate means to prevent galvanic corrosion of metallic components of the pressure vessel (e.g. appropriate insulating coating, inner glass fibre….).

An inner glass fibre wound and resin layer may be used for metallic liners. A glass cloth or resin layer may be used between a metallic end nozzle and the laminate.

Steel liners shall be protected against corrosion prior to wrapping for all types of fibres.

8.1.1.6 Resistance to UV emissions

Materials on the outside of the pressure vessel, including paint or polymeric coating, if applied, or the composite if no coating is applied, shall be resistant to UV emissions. The materials shall be subjected to 1000 hours of exposure to UVA radiation per ISO 11507. The gloss loss shall be less than 20 %.

8.1.1.7 Resistance to humidity

Fibre/resin reinforcement shall be resistant to humidity, as measured by short beam shear testing, so that it maintains integrity over its lifetime. Resin system materials shall be tested on a sample test panel representative of the composite overwrap, in accordance with ISO 14130. Following a 24-hour water boil, the composite shall have a minimum shear strength of 13,8 MPa.

8.1.1.8 Protective layer

An optional external layer of laminate may be provided for protection of the structural laminate layer from damage due to impact, ultraviolet radiation or other environmental exposure, fire or abrasive conditions.

This layer shall not be considered in the calculation on the stress levels in the vessel and shall not be applied to the vessel used for the qualification testing.

8.1.2 Construction and workmanship

8.1.2.1 Liner materials

Type 1 designs and Type 2 liners shall be of seamless construction using carbon steel, stainless steel or aluminium alloys that comply with the materials requirements in 7.2, 7.3, or 7.4, as appropriate.

Type 3 liners shall be constructed from aluminium alloys, carbon steel or stainless steels, and shall be seamless. They shall comply with the materials requirements in 7.2, 7.3 or 7.4, as appropriate.

For Type 3 liners subjected to cold-forming or cryo-forming processes, heat treatment of the pre-form component is not required. Liners that have been cold-formed or cryo-formed shall not be subjected to any subsequent heat treatment or to additional heat application, such as welding, or possibly elevated temperature curing of the composite, which degrades the liner properties.

Type 4 liners shall comply with the materials requirements in 7.7, and may be of seamless or welded construction.

8.1.2.2 Openings, neck threads, neck ring, foot ring, attachment for support

Pressure vessels may be designed with one or two openings along the central cylinder axis only

Openings with tapered or parallel threads may be used. Threads shall be clean cut, even, without surface discontinuities, to gauge and conform to International Standards.

When a neck ring, foot ring or attachments for support are provided, it shall be of a material compatible with that of the pressure vessel and shall be securely attached by a method other than welding, brazing or soldering.

8.1.2.3 Forming

The base ends of Type 1 steel pressure vessels and Type 2 steel liners shall be hot formed using either forging, spinning methods, or deep drawing plate techniques.

The base ends of steel pressure vessels that have been closed by hot spinning shall be inspected using Non Destructive Examination or methods in ISO 9809-1 or other equivalent techniques, and shall be checked to confirm there is no leakage.

A hot spinning process, such as fusion welding, shall not be used to fully close and seal the ends for aluminum pressure vessels and liners.

Metals shall not be added in the process of closure of the ends. Manufacturing defects shall not be corrected by addition of material.

Bases of cylinders closed by hot spinning or other closing method shall be leak tested.

The manufacturer shall employ such manufacturing techniques and apply such tests as will demonstrate to the satisfaction of the inspector that the cylinders do not leak. For guidance, see ISO 9809-1 for steel liners, ISO 9809-4 for stainless steel and ISO 7866 for aluminium alloy liners.

Each pressure vessel shall be examined for wall thickness and visual surface defects prior to final assembly. For guidance, see ISO 9809-1 for steel liners, ISO 9809-4 for stainless steel and ISO 7866 for aluminium alloy liners.

After end forming, the pressure vessels shall be heat treated to the hardness range specified for the design. Localised heat treatment shall not be used. For guidance, see ISO 9809-1 for steel liners, ISO 9809-4 for stainless steel and ISO 7866 for aluminium alloy liners.

8.1.2.4 Fibre winding

Type 2, Type 3, and Type 4 pressure vessels shall be fabricated from a liner overwrapped with continuous fibre windings. Fibre winding operations shall be computer or mechanically controlled. The fibres shall be applied under controlled tension during winding.

During winding the significant variables shall be monitored to demonstrate that they remain within specified tolerances. The results shall be documented in a winding record that shall be retained by the pressure vessel manufacturer for the intended life of each batch of pressure vessels. These variables can include but are not limited to:

a) fibre type including sizing;

b) impregnation method;

c) winding tension;

d) winding speed;

e) number of rovings;

f) band width;

g) type of resin and composition;

h) temperature of the resin;

i) temperature of the liner; and

j) winding angle.

8.1.2.5 Curing of thermosetting resins

If a thermosetting resin is used, the resin shall be cured after the fibre winding is complete. Thermosetting resins shall be cured by heating, using a predetermined and controlled time-temperature profile.

During the curing, the curing cycle (i.e. the time-temperature history) shall be documented and retained by the pressure vessel manufacturer for the intended life of each batch of pressure vessels.

The maximum curing time and temperature for pressure vessels with aluminium alloy liners shall not adversely affect metal, resin and fibre properties.

8.1.2.6 Autofrettage

Autofrettage, if used, shall be carried out before the hydraulic test specified in 8.1.4.1 g). The autofrettage pressure shall be within the limits established in 8.1.1.1. The pressure vessel manufacturer shall establish the method to verify that the appropriate pressure is applied.

The manufacturer shall monitor effectiveness of the autofrettage by appropriate measurement technique(s), such as a volumetric expansion test.

Records of autofrettage pressure shall be retained by the pressure vessel manufacturer for the intended life of each batch of pressure vessels.

8.1.2.7 Exterior environmental protection

Exterior protection may be provided by using any of the following:

a) a surface finish giving adequate protection (e.g. metal sprayed on aluminium, anodizing);

b) a suitable fibre and matrix material (e.g. carbon fibre in resin); or

c) a protective coating (e.g. organic coating, paint).

Any coatings applied to pressure vessels shall be such that neither the coating nor the application process adversely affects the mechanical properties of the pressure vessel. The manufacturer shall provide guidance on coating treatment during in-service inspection to ensure the continued integrity of the pressure vessel (e.g. removal of coatings if necessary to carry out inspection method).

8.1.3 Qualification of new designs

8.1.3.1 General

The pressure vessel material, design, manufacturing process and examination shall be proved to be adequate for their intended service by meeting the requirements of the material tests and type tests specified in 8.1.3.2 and 8.1.3.3.

Pressure vessel designs that have been qualified to another standard do not need to repeat tests in this section, but do need to conduct tests that were not included in their prior qualification. See Annex B

for specific requirements.

Material tests and type tests shall be conducted on each new design, on finished pressure vessels that are representative of normal production, complete with identification marks. If more pressure vessels or liners are subjected to the tests than are required, all results shall be documented. All pressure vessels subjected to type tests shall be made unserviceable after the tests.

The pressure vessel manufacturer shall retain the type test results for the intended service life of the pressure vessel design. The test data shall also document the dimensions, wall thickness and weights of each of the tested pressure vessel.

8.1.3.2 Material tests

Unless otherwise permitted by Annex A, Type 1, 2, 3 and 4 designs shall be subjected to the applicable type tests listed in Table 2 and described in Annex A.

Table 2 - Summary of material tests

Test		Number of pressure vessels required for testing	Applicable to type			
			Type 1	Type 2	Type 3	Type 4
8.1.3.2.1to 8.1.3.2.4	Material tests for metallic vessels, liners, and bosses	1 pressure vessel or liner or representative test ring	✓	✓	✓	
8.1.3.2.5	Material tests for plastic liners	1 liner				✓
8.1.3.2.6	Resin properties	composite samples		✓	✓	✓
8.1.3.2.7	Coatings test	Coating systems samples	✓	✓	✓	✓

8.1.3.2.1 Material and hydrogen compatibility tests for vessels, liners, and bosses in steel other than stainless steel

If the pressure vessel, boss, or liner is made of steel, appropriate material tests in accordance with ISO 9809-1 for pressure vessels of up to 450 l capacity or ISO 11120 for pressure vessels of water capacity greater than 450 l, shall be carried out on one vessel, liner, representative test ring, or boss. The tensile strength shall meet the manufacturer’s design specifications. For Type 1 and Type 2 designs the steel elongation shall be at least 14 %. For Type 3 designs the tensile strength and elongation shall meet the manufacturer’s design specifications.

The hydrogen compatibility of steels in contact with hydrogen shall be demonstrated in accordance with A.1. Steels that are exempted from hydrogen compatibility testing in application of ISO 9809-1 or ISO 11120 are exempted from this test.

8.1.3.2.2 Material and hydrogen compatibility tests for aluminium alloy vessels, liners, and bosses

For Type 1 pressure vessels and Type 2 liners using aluminium alloy, corresponding material tests as required in ISO 7866 shall be carried out on one pressure vessel or liner. The materials properties shall meet the manufacturer’s design specifications. The elongation shall be at least 12 %.

For Type 3 liners using aluminium alloy, corresponding materials tests as required in ISO 7866 shall be carried out on one liner. The materials properties, including elongation, shall meet the manufacturer’s design specifications.

The hydrogen compatibility of aluminium alloys in contact with hydrogen shall be demonstrated in accordance with A.1. Aluminium alloys that are exempted from hydrogen compatibility testing in application of ISO 7866 are exempted from this test.

8.1.3.2.3 Material and hydrogen compatibility tests for stainless steel liners, and bosses

Materials used for stainless steel liners or bosses shall conform to ISO 9809-4.

Materials used for welded stainless steel liners for Type 4 pressure vessels shall follow the corresponding requirements of EN 13322-2.

The hydrogen compatibility of stainless steels in contact with hydrogen shall be demonstrated in accordance with A.1.

8.1.3.2.4 Hydrogen sensitivity factor of metallic vessel, liner and boss materials

Metallic materials used for vessels, liners and bosses shall be tested in accordance with A.2 to determine the hydrogen sensitivity factor to be applied in A.7 unless, for type 1 and type 2 cylinders, section 8.1.3.5 is used

8.1.3.2.5 Material tests for polymeric liners

One liner shall be subjected to the following requirements:

a) The tensile yield strength and ultimate elongation shall be determined in accordance with A.3 and shall meet the requirements therein.

b) For thermoplastic materials, the softening temperature shall be determined in accordance with A.4 and shall meet the requirements therein.

8.1.3.2.6 Resin properties tests

For Type 2, Type 3 and Type 4 designs, samples representative of the composite overwrap shall be tested in accordance with A.5. Resin materials shall meet the requirements therein.

8.1.3.2.7 Coating tests

If a protective coating is part of the design, the coatings shall be evaluated using the test methods in A.20.

8.1.3.3 Pressure vessel tests

Unless otherwise permitted by 8.2, Type 1, 2, 3 and 4 designs shall be subjected to the applicable type tests listed in Table 3 and described in Annex A.

Table 3 - Summary of pressure vessel or liner tests

Test		Number of pressure vessels required for testing	Applicable to type			
			Type 1	Type 2	Type 3	Type 4
8.1.3.3.2	Hydrostatic burst pressure	3 plus 1 liner	✓	✓	✓	✓
8.1.3.3.3	Ambient temperature pressure cycling	2 to 10	✓	✓	✓	✓
8.1.3.3.4	Leak-before-break (LBB)	2	✓(1)	✓	✓	✓
8.1.3.3.5	Accelerated stress rupture	1		✓	✓	✓
8.1.3.3.6	Extreme temperature pressure cycling	1		✓	✓	✓
8.1.3.3.7	High strain rate impact	1			✓	✓
8.1.3.3.8	Bonfire	1 or 2	✓(2)	✓(2)	✓(2)	✓(2)
8.1.3.3.9	Impact damage	1, 2 or 3			✓	✓
8.1.3.3.10	Chemical exposure	1		✓	✓	✓
8.1.3.3.11	Permeation	1				✓
8.1.3.3.12	Boss torque	1				✓
8.1.3.3.13	Hydrogen gas cycling	1				✓
8.1.3.3.14	Water soak	1		✓	✓	✓

(1) : LBB is only applicable when using high strength aluminum (ISO 7866) or steel (ISO 9809-2)

(2) If required by risk analysis described in 8.1.3.3.8

8.1.3.3.1 Use of subscale units

Where indicated, tests may be performed on full scale diameter pressure vessels of shorter length; however, the L/D ratio of sub-scale units shall be greater than 2,5. If the full scale cylinder L/D ratio is less than 2,5, a full scale cylinder is required. The winding pattern of the sub-scale unit shall be the same as the full scale pressure vessel.

8.1.3.3.2 Hydrostatic burst pressure test

For Type 2 designs, one liner shall be hydrostatically pressurized to failure in accordance with A.6. The burst pressure shall meet or exceed 1.125 times the MAWP.

For all designs, three pressure vessels shall be hydrostatically pressurized to failure in accordance with A.6. For each pressure vessel, the burst pressure shall exceed the specified minimum burst pressure specified in Table 1. In no case shall the burst pressure be less than the value necessary to meet the stress ratio requirements in Table 1. The average of the burst pressure to fibre strength ratio of the three pressure vessels shall be recorded for future reference.

8.1.3.3.3 Ambient temperature pressure cycling test

For all design Types, two to five pressure vessels shall be pressure cycled at ambient temperature in accordance with A.7.1 and meet the requirements therein.

If a shallow pressure cycle life is specified, two to five additional vessels shall be pressure cycle at ambient temperature in accordance with A.7.2 and meet the requirements therein.

For pressure vessels with an internal volume of at least 450 l, sub-scale units may be used as specified in 8.1.3.3.1 for this test

8.1.3.3.4 Leak-before-break (LBB) test

For all design Types, two pressure vessels shall be tested in accordance with A.8 and shall meet the requirements therein.

For pressure vessels with an internal volume of at least 450 l, sub-scale units may be used as specified in 8.1.3.3.1 for this test

8.1.3.3.5 Accelerated stress rupture test

For Type 2, Type 3 and Type 4 designs, one pressure vessel shall be tested in accordance with A.12 and meet the requirements therein.

For pressure vessels with an internal volume of at least 450 l, sub-scale units may be used as specified below:

Material properties may be demonstrated using a sub-scale unit of a size appropriate to determine stability of the laminate under thermal loading. The stress level and winding pattern of the sub-scale shall be the same as the full scale cylinder. The sub-scale unit shall have an internal volume not smaller than 10 % of the internal volume of the full scale unit and not smaller than 150 l.

8.1.3.3.6 Extreme temperature pressure cycling test

For Type 2, Type 3 and Type 4 designs, one pressure vessel shall be tested in accordance with A.13 and meet the requirements therein.

For pressure vessels with an internal volume of at least 450 l, sub-scale units may be used as specified in 8.1.3.3.1 for this test.

8.1.3.3.7 High rate strain impact test

For Types 3 and 4, one pressure vessel shall be tested in accordance with A.10 and meet the requirements therein.

Sub-scale units may be used as specified in 8.1.3.3.1 for this test

8.1.3.3.8 Bonfire test

For all design Types, if PRD (Pressure Relief Device) are used according to Clause 5.2, one or two pressure vessels as appropriate shall be tested in accordance with A.9 and meet the requirements therein.

Risk analysis should address need for PRD and / or bonfire test, and should consider potential for fire, presence of combustible materials, insulation of tanks and the presence fire abatement systems (fire extinguishers, deluge systems, fire hose, ..)

8.1.3.3.9 Impact damage test

For Type 3 and Type 4 designs having a water capacity of 150 l or less, one or more finished pressure vessels shall be tested in accordance with A.22 and meet the requirements therein.

8.1.3.3.10 Chemical exposure test

For Type 2, Type 3 and Type 4 designs, one pressure vessel shall be tested in accordance with A.11 and meet the requirements therein.

Sub-scale units may be used as specified below:

Material properties may be demonstrated using a sub-scale unit of a size appropriate to determine the environmental resistance of the laminate and/or protective coating. The stress level and winding pattern of the sub-scale shall be the same as the full scale cylinder.

8.1.3.3.11 Permeation test

For Type 4 designs, one pressure vessel shall be tested for permeation in accordance with A.14 and meet the requirements therein.

Sub-scale units may be used as specified in 8.1.3.3.1 for this test

8.1.3.3.12 Boss torque test

For Type 4 designs, one pressure vessel shall be tested in accordance with A.15 and meet the requirements therein.

Sub-scale units may be used as specified in 8.1.3.3.1 for this test

8.1.3.3.13 Hydrogen gas cycling test

Before proceeding with this test, a leak test according to A.19 should be performed.

For Type 4 designs, one pressure vessel shall be tested in accordance with A.16 and meet the requirements therein.

Sub-scale units may be used as specified in 8.1.3.3.1 for this test

8.1.3.3.14 Water soak test

For Type 2, Type 3, and Type 4 designs, one pressure vessel shall be tested in accordance with A.16 and meet the requirements therein.

Sub-scale units may be used as specified in 8.1.3.3.1 for this test

8.1.3.4 Qualification of design changes

Design changes may be qualified through a reduced test program as specified in Table 4. Design changes that exceed the changes defined in Table 4 shall be qualified by a complete test program.

A fibre shall be considered to be of a new fibre type when any of the following conditions apply:

a) the fibre is of a different classification, e.g. glass, aramid, carbon;

b) the fibre is produced from a different precursor (starting material), e.g. polyacrylonitrile (PAN), pitch for carbon;

c) the nominal fibre modulus, specified by the fibre manufacturer, differs by more than ± 5 % from that defined in the prototype tested design;

d) the nominal fibre strength, specified by the fibre manufacturer, differs by more than ± 5 % from that defined in the prototype-tested design.

A design approved by a reduced series of tests (a design change) shall not be used as a basis for a second design change approval with a reduced set of tests (i.e. multiple changes from an approved design are not permitted). If a test has been conducted on a design change (A) that falls within the testing requirements for a second design change (B) then the result for (A) can be applied to the new design change (B) test program. However, design change (A) cannot be used as the reference for determining the testing required for any new design change.

Tests previously exempted remain exempted.

Table 4 - Qualification tests for design changes

		Design change																
Test No.	**Test**	Fibre manufacturer	Materials				Length		Diameter [a]		MAWP [a] ≤ 20 %	Dome shape	Base shape	Opening size	Coating	End boss [b]	Specified pressure relief diameter and hold time	Manufacturer process [c]
			Fibre	Resin	Metal pressure vessel, liner, or boss	Plastic liner	≤ 50 %	> 50 %	≤ 20 %	> 20 %								
8.1.3.3.2	Burst	X	X		X		X[h]	X	X	X	X	X	X	X				X
8.1.3.3.3	Ambient cycle	X	X		X	X	X[h]	X[h]	X	X	X	X	X					X
8.1.3.3.4	LBB	X	X		X [g]				X	X			X					
8.1.3.3.8	Bonfire [i]		X	X	X	X		X		X							X[e]	
8.1.3.3.9	Impact damage		X	X	X				X [d]	X								
8.1.3.3.10	Chemical exposure		X	X	X	X									X			
8.1.3.3.5	Accelerated stress rupture	X	X	X	X													
8.1.3.3.6	Extreme temperature	X	X	X	X	X			X	X								
8.1.3.3.7	High strain rate impact	X	X	X	X				X	X								
8.1.3.3.11	Permeation					X						X[f]				X		
8.1.3.3.12	Boss torque					X						X				X		
8.1.3.3.13	Hydrogen gas					X						X				X		
8.1.3.2.1 / 8.1.3.2.2	Hydrogen compatibility				X													
8.1.3.2.4	Hydrogen sensitivity				X													
8.1.3.2.5 to 8.1.3.2.7	Other materials (as appropriate)	X	X	X	X	X									X			

[a] Only when thickness changes proportional to diameter and/or pressure change, otherwise qualify as a new design.
[b] Test not required if the stresses in the neck are equal to the original or reduced by the design change (e.g. reducing the diameter of internal threads, or changing the boss length), the liner to boss interface is not affected, and the original materials are used for boss, liner and seals.
[c] Any deviation from the manufacturing parameters specified in 6.6 is a change in the manufacturing process.
[d] Required if the diameter decreases.
[e] Required if more time is provided to relieve pressure.
f Required only if boss/liner interface changes.
g Not required for change of boss material.
h Not required for Type 1 and Type 2
i If required by risk analysis described in 8.1.3.3.8

8.1.3.5 Design qualification by fracture mechanics

As an alternative method for new design qualification, fracture mechanics design based approaches can be used. If pressure vessel cycle life is determined in accordance with the rules in 8.1.3.5, 8.1.3.2.4 and annex A.7 shall be ignored.

Fracture mechanics assumes that an initial crack exists in the pressure vessel. Crack propagates due to cyclic internal pressure variation and failure is assumed to occur when a valid fracture mechanics parameter (e.g. elastic stress intensity factor, K) reaches a critical threshold value.

8.1.3.5.1 Fatigue crack growth rate tests

Fatigue crack growth rates shall be measured in accordance with ASTM E647 or ISO 12108 standards with the following exceptions:

- Test frequency shall not be greater than 1 Hz. Higher frequencies may be used provided it is clearly demonstrated that fatigue crack growth rate data are not affected by frequency in the explored ΔK region.

  NOTE This frequency is known to be valid for ferritic steels. Other metallic materials, e.g. austenitic stainless steels or aluminum alloys, may require different test frequencies.

- Waveform shall be either triangular or sinusoidal.

- Stress ratio shall be consistent with stress ratio seen by the pressure vessel during its lifetime. Stress ratio R=0.8 shall be considered as an upper bound for fatigue crack growth rate.

NOTE a single linear relationship in the form da/dN=C*ΔKm may not be obtained since different regions with different parameters exist depending on the applied ΔK level. Use of multiple da/dN=C*ΔKm relationships for calculation of pressure vessels cycle life is allowed.

NOTE the pressure vessel can be subjected to different cyclic ranges. Fatigue crack growth rates may follow the different stress ranges.

A minimum of three tests shall be carried out.

Test pressure shall not be less than the intended service pressure.

Specimens shall be machined with TL orientation, meaning the test specimen has a fracture plane whose normal is in the transverse direction of the pressure vessel and the expected crack propagation direction is in the longitudinal direction of the pressure vessel.

The hydrogen used for testing shall comply with the requirement listed in ISO 11114-4.

8.1.3.5.2 Fracture toughness testing

The test method allows to determine the onset of critical threshold for hydrogen assisted cracking.

Guidance on this test method is given in standard ANSI/CSA CHMC 1-2014.

A minimum of two tests shall be carried out.

Test pressure shall not be less than the intended service pressure.

The lower bound fracture toughness data shall be considered for design purposes.

8.1.3.5.3 Allowable number of cycle

Allowable number of cycles is half the number of cycles to reach the final crack depth defined as the crack size at which stress intensity factor reaches material fracture toughness.

NOTE Art. KD-4 and KD-10 provides guidance for fracture mechanics evaluation

8.1.3.5.4 Material qualification

Tests results from clauses 8.1.3.5.1 and 8.1.3.5.2 only apply to a batch of material from which specimens were extracted.

The purpose of this clause is to qualify a material by testing two heats of material per heat treatment condition.

Specimens for hydrogen tests shall be in the final heat treated condition to be used in the pressure vessels construction and obtained on a minimum of two heats representative of the material specification. Specifically, the maximum tensile strength allowed by the specification shall not exceed 5% of the highest strength heat.

A set of minimum three specimens per heat shall be tested according to clause 8.1.3.5.1, allowing a sufficient ∆K range to be explored. The upper bound fatigue crack growth rate curve, for each of the explored ∆K region, data shall be used for calculation in clause 8.1.3.5.3.

A set of minimum two specimens per heat shall be tested according to clause 8.1.3.5.2. The lower bound fracture toughness data shall be used for calculation in clause 8.1.3.5.3.

The data obtained in a) may be used for other pressure vessels manufactured from the same material and grade, having the same nominal composition and heat treatment condition, provided its tensile strength do not exceed the values of the material used in the qualification tests by more than 5%.

8.1.4 Production and batch tests

8.1.4.1 Production tests

Production verifications and tests shall be carried out as follows on all pressure vessels produced in a batch. All visual testing should be according to ISO 11623, when required.

Each pressure vessel shall be subject to the following verifications during manufacturing or after completion:

a) Non Destructive Examination of all seamless steel metallic pressure vessels and liners in accordance with the corresponding requirements of ISO 9809-1 for pressure vessels of up to 450 l of water capacity or ISO 11120 for pressure vessels of water capacity greater than 450 l, or a demonstrated equivalent method, to confirm that the maximum defect size does not exceed the size specified in the design as determined in accordance with 8.1.1.4. The NDE method shall be capable of detecting the maximum defect size allowed. For aluminium alloy liners, the Non Destructive Examination inspection should be done according to the procedure listed in ISO 10461

b) inspection of plastic liners to confirm that the maximum defect size present is less than the size specified in the design;

c) the verification of critical dimensions and mass of the finished pressure vessels, liners and overwrapping are within design tolerances;

d) verification of conformance to the manufacturer's specified surface finish with special attention to deep drawn surfaces and folds or laps in the neck or shoulder of forged or spun end enclosures or openings;

e) verification of the markings;

f) hardness tests or equivalent tests of metallic pressure vessels and liners in accordance with A.17, carried out after the final heat treatment. The values thus determined shall be in the range specified for the design;

g) hydraulic test of finished pressure vessels in accordance with A.18:

Optionally, for Type 3 and Type 4 designs the manufacturer shall define the appropriate limit of elastic expansion at test pressure for the test pressure used, but in no case shall the elastic expansion of any pressure vessel exceed the average batch value by more than 10 %;

h) leak test on Type 4 pressure vessels or liners in accordance with A.19, except that the pressure used may be less than the MAWP.

i) Inspection of composite surfaces for compliance with requirements for surface defects,

8.1.4.2 Batch tests

8.1.4.2.1 General requirements

Batch tests shall be carried out on each batch of pressure vessels.

Batch tests shall be conducted on finished liners and pressure vessels that are representative of normal production, complete with identification marks. The pressure vessels and liners required for testing shall be randomly selected from each batch for vessel sizes up to 450 l. The first unit of the batch of pressure vessels and liners may be selected for testing for vessel sizes greater than 450 l. If more pressure vessels are subjected to the tests than are required, all results shall be documented.

Batches of pressure vessels shall be proved to be adequate for their intended service by meeting the requirements of the batch tests specified in 8.1.4.2.2. The pressure vessel manufacturer shall retain the batch test results and relevant data for each batch (e.g. cast number) for the intended life of the pressure vessels in the batch. All pressure vessels subjected to batch tests shall be made unserviceable after the tests.

8.1.4.2.2 Batch requirements

a) A batch of Type 3 or Type 4 pressure vessels shall be limited to a quantity of up to 200 finished pressure vessels, plus test units, made on the same or equivalent equipment, equivalent equipment meaning of the same basic design, capability, and control system, and in the same factory.

b) A batch of Type 1 and Type 2 pressure vessels of capacity greater than 450 l shall be limited to a quantity of up to 30 finished pressure vessels, plus test units, made on the same or equivalent equipment, equivalent equipment meaning of the same basic design, capability, and control system, and in the same factory.

c) A batch of Type 1 and Type 2 pressure vessels of capacity smaller than 450 l shall be limited to a quantity of up to 200 finished pressure vessels, plus test units, made on the same or equivalent equipment, equivalent equipment meaning of the same basic design, capability, and control system, and in the same factory.

d) A batch of vessels may be discontinuous, i.e. interrupted by other production or periods of no production, providing that controls are in place to assure that consistency of the vessel manufacture and performance will be maintained within the batch once production is restarted.

e) A batch of finished composite pressure vessels may contain different batches of liners, fibers, and matrix materials, providing that controls are in place to assure that consistency of the vessel manufacture and performance will be maintained within the batch.

f) A batch of finished Type 1, Type 2 or Type 3 pressure vessels shall be formed from one cast of metal.

g) Vessels in the batch shall be of the same nominal diameter, thickness, design, and cure or heat treatment as appropriate; and, of the same nominal length except as noted in h).

h) A batch of Type 1 metal vessels, and Type 2 vessels with hoop reinforcement, may include vessels of different length, providing that controls are in place to assure that consistency of the vessel manufacture and performance will be maintained within the batch and will not be affected by the difference in length.

8.1.4.2.3 Required tests

One pressure vessel shall be subjected to the hydrostatic burst pressure test in accordance with A.6. The pressure vessel burst pressure shall exceed the specified minimum burst pressure and stress ratio requirement specified in Table 1.

One pressure vessel shall be subjected to pressure cycle testing in accordance with the requirements in 8.1.4.2.4. The pressure vessel used for the pressure cycle test in 8.1.4.2.4 may also be used for the burst pressure test.

For Type 1, Type 2 and Type 3 designs, a further pressure vessel, liner, or sample representative of a finished pressure vessel or liner, shall be subjected to the following tests:

a) verification of the critical dimensions of the design;

b) tensile tests for steel pressure vessels or liners, in accordance with the corresponding requirements of ISO 9809-1 for pressure vessels of up to 450 l of water capacity or ISO 11120 for pressure vessels of water capacity greater than 450 l. Tensile tests for aluminium alloy pressure vessels or liners, in accordance with the corresponding requirements of ISO 7866. Tensile tests for stainless steel liners, in accordance with the corresponding the requirements of ISO 9809-4.

c) impact tests for steel pressure vessels or liners, in accordance with the corresponding requirements of ISO 9809-1 for pressure vessels of up to 450 l of water capacity or ISO 11120 for pressure vessels of water capacity greater than 450 l, as appropriate, and meet the requirements therein. Impact tests for stainless steel liners in accordance with the corresponding requirements of ISO 9809-4, and meet the requirements therein.

d) when a protective coating according to 8.1.2.7 is a part of the design, a coating batch test shall be performed in accordance with A.21. Where the coating fails to meet the requirements of A.21, the batch shall be 100 % inspected to remove similarly defectively coated pressure vessels. The coating on all defectively coated pressure vessels shall be stripped using a method that does not affect the integrity of the composite wrapping, and recoated. The coating batch test shall then be repeated.

For Type 4 designs, a further pressure vessel, or liner, or sample representative of a finished pressure vessel, shall be subjected to the following tests:

a) verification of the critical dimensions of the design;

b) yield strength and ultimate elongation of the plastic liner material shall be determined in accordance with A.3 and meet the requirements therein;

c) softening temperature of the plastic liner shall be tested in accordance with A.4, and meet the requirements of the design;

d) when a protective coating according to 8.1.2.7 is a part of the design, a coating batch test shall be performed in accordance with A.21. Where the coating fails to meet the requirements of A.21, the batch shall be 100 % inspected to remove similarly defectively coated pressure vessels. The coating on all defectively coated pressure vessels shall be stripped using a method that does not affect the integrity of the composite wrapping, and recoated. The coating batch test shall then be repeated.

All pressure vessels and liners represented by a batch test that fails to meet the requirements specified shall follow the procedures specified in 8.1.4.3.

8.1.4.2.4 Ambient temperature pressure cycling test

Except for design according to section 8.1.3.5, one pressure vessel per every batch of finished vessels shall be subjected to a fatigue test to the requirements of A.7. All pressure cycles may be at ambient temperature for the production testing. The manufacturer, as a minimum, shall test one pressure vessel per year in accordance with A.7 if production rates are less than 200 vessels per year.

The batch cycling test per A.7 is no longer required on every batch once it has been demonstrated that the pressure vessel design and materials are not sensitive to fatigue cycling by passing the batch cycle testing on a total of 5 pressure vessels with the number of cycles per A.7 and having no leaks either in the first set of “N” cycles, or in the second set of “N” cycles (where a leak would otherwise be allowed but not a rupture), for a total of 5.2 times the design service life when cycling to the nominal working pressure, or an equivalent margin when cycling to elevated pressure per A.7. However, the batch cycle test shall be repeated at least once every three years. If a leak or rupture occurs during a batch test, then batch testing would have to be re-initiated until a new total of 5 pressure vessels pass the cycle requirements per A.7 with no leaks.

8.1.4.3 Failure to meet batch and production test requirements

In the event of failure to meet test requirements, re-testing or re-heat treatment and re-testing shall be carried out as follows:

a) if there is evidence of a fault in carrying out a test, or an error of measurement, a further test of the same kind shall be performed. If the result of this test is satisfactory, the first test shall be ignored;

b) if the test has been carried out in a satisfactory manner, the cause of test failure shall be identified.

   1) If the failure is considered to be due to the applied heat treatment, the manufacturer may subject all the metal pressure vessels or liners implicated by the failure to a further heat treatment, i.e. if the failure is in batch test, the test failure shall require re-heat treatment of all the represented metal pressure vessels or liners prior to re-testing; however if the failure occurs sporadically in a production test, then only those metal pressure vessels or liners which fail the test shall require re-heat treatment and re-testing.

      Only the appropriate batch tests needed to prove the acceptability of the new batch shall be performed again. If one or more tests prove unsatisfactory, all metal pressure vessels or liners of the batch shall be rejected.

   2) If the failure is due to a cause other than the heat treatment applied, all defective metal pressure vessels or liners shall be either rejected or repaired. Repaired metal pressure vessels or liners that pass the test(s) required for the repair shall be treated as a separate new batch.

8.1.5 Markings

On each pressure vessel the manufacturer shall provide clear permanent markings. The font size used on the markings shall be a minimum 5 mm high on pressure vessels with a diameter greater than or equal to 140 mm, and greater than 2,5 mm high on pressure vessels with a diameter of less than 140 mm. Marking shall be to the customary industry standard (e.g. PED, ASME, JSME), or by labels incorporated into resin coatings, labels attached by adhesive, or by low stress stamps used on the thickened ends of Type 1 and Type 2 designs, or any combination of the above. Adhesive labels and their application shall be in accordance with ISO 7225. Multiple labels may be used and should be located such that they are not obscured by mounting brackets.

Each pressure vessel shall be permanently marked with the following information:

a) "H_2 STATIONARY USE ONLY";

b) "DO NOT USE AFTER “YYYY-MM", where YYYY identifies the year and MM the month of expiry;

c) the manufacturer’s identification;

d) the pressure vessel identification (model and the serial number unique for every pressure vessel*)*;

e) the water capacity of the pressure vessel in litres

f) the MAWP in MPa

g) the test pressure in MPa

h) the reference to this International Standard

i) the type of pressure vessel shown as T1 (Type 1), T2 (Type 2), T3 (Type 3) or T4 (Type 4)

j) the minimum allowable temperature in °C

k) the maximum allowable temperature in °C

l) the design cycle life in number of reference cycles

m) the design shallow cycle life, if applicable, in number of reference cycles

n) for Type 3 and 4 vessels, and for Type 1 and Type 2 vessels if PRDs are included in the design by the vessel manufacturer , the following note: "REQUIRES PROTECTION BY A THERMAL RELIEF SYSTEM PROVIDING SPECIFIED PRESSURE RELIEF”

o) the date of manufacture (year in four digits and month in two digits).

if labels are used, there is an additional requirement for a unique identification number and the manufacturer’s identification to be permanently marked on an exposed metal surface in order to permit tracing in the event that the label is destroyed;

The expiry date may be applied to the pressure vessels at the time of dispatch, provided that the pressure vessels have been stored in a dry location without internal pressure. The period between the dispatch date and the expiry date shall not exceed the specified service life.

The markings shall be placed in the listed sequence but the specific arrangement may be varied to match the space available. The following is an acceptable example, .

H_2 ONLY
DO NOT USE AFTER 2042-03
Manufacturer / model / serial number
500 l WC
MAWP 95 MPa – TP 119 MPa
ISO 19884_T3_-40°C **/ 85**°C
DO NOT USE AFTER_15 000 cycles @ 100% MAWP / 100 000 cycles @ 30% MAWP
REQUIRES PROTECTION BY A THERMAL PROTECTION SYSTEM PROVIDING SPECIFIED PRESSURE RELIEF 2012-03

NOTE Attention is drawn to requirements for marking in relevant regulations which might override the requirements of this International Standard

8.1.6 Preparation for dispatch

Prior to dispatch the manufacturer shall ensure that every pressure vessel shall be suitably cleaned to prevent the contamination of the fluid to be contained. The pressure vessel shall be internally cleaned and dried as specified by the owner / operator, sealed, and marked as “cleaned for hydrogen service”.

Pressure vessels not immediately closed by the fitting of a valve and safety devices, if applicable, shall have plugs fitted to all openings to prevent the entry of moisture and protect threads.

Each pressure vessel nameplate shall be checked for appropriate markings.

The manufacturer's statement of service and all necessary information and instructions to ensure the proper handling, use and in-service inspection of the pressure vessel shall be supplied to the owner / operator.

The statement of service shall be in accordance with 6.2.

8.2 Requirements for existing designs

The requirements for existing designs are given in Annex B

Annex A. (normative)

Test methods and acceptance criteria

A.1 Hydrogen compatibility tests

Hydrogen compatibility of the pressure vessel, liner and boss materials made of steel shall be demonstrated in accordance with ISO 11114-4.

A.2 Hydrogen sensitivity tests

A hydrogen sensitivity factor (F_{hs}) shall be determined as follows for the pressure vessel, liner and boss materials, using component material or equivalent material and method 1 or 2.

A.2.1 Test Method 1 - Fatigue testing of tensile specimens

A.2.1.1 Fatigue life tests

This test method is used to evaluate the total fatigue life which includes initiation and crack propagation to failure for metallic materials exposed to gaseous hydrogen environment.

A.2.1.2 Test environment

Tests shall be carried out at the pressure not less than MAWP and results are valid for all equal to or less than the pressure used in the tests.

The hydrogen used for testing shall comply with the requirement listed in ISO 11114-4.

Temperature shall be such that occurrence of hydrogen embrittlement is maximum.

NOTE: for carbon and low alloy steel and aluminium alloys maximum hydrogen embrittlement occurs at room temperature. Other steels (e.g. stainless steels) and metallic materials may require different temperatures to be determined.

A.2.1.3 Specimen preparation

Specimens shall be prepared according to Figure A.1 with TL orientation meaning the test specimen has a fracture plane whose normal is in the transverse direction of the pressure vessel and the expected crack propagation direction is in the longitudinal direction of the pressure vessel.

If the specimen cannot be machined according to Figure A.1 from the pressure vessel wall thickness, lower thicknesses may be allowed provided the specimens have at least 85% of the original pressure vessel wall thickness.

If a TL orientation cannot be obtained, LT orientation is allowed.

NOTE: Electro-discharge machining operation is recommended for notch preparation.

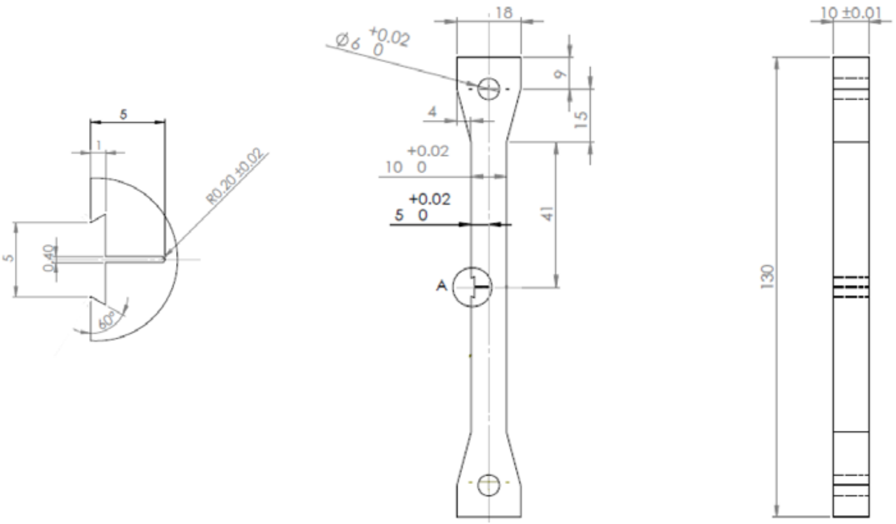

Figure A. 1 - Fatigue test specimens

A.2.1.4 Test procedure

Conduct a minimum of total eight fatigue tests in hydrogen and in air or inert environment.

A minimum of four tests shall be conducted to failure in air or inert environment, applying load amplitudes (maximum force minus minimum force divided by two with a positive stress ratio of 0.1 or less which result in cycles to failure greater than 10^5 cycles.

A minimum of four tests shall be conducted to failure in gaseous hydrogen according to paragraph A.2.1.2, applying the same load amplitudes and stress ratio used for tests in air or inert environment.

For tests in gaseous hydrogen, frequency shall not be greater than 1 Hz.

The hydrogen sensitivity factor, F_{hs}, is the ratio between the average number of cycles to failure in air or inert environment and gaseous hydrogen.

NOTE: The hydrogen sensitivity factor for higher R-ratios, which can reproduce shallow cycles conditions, may be lower than the one obtained at stress ratio equal to 0.1, however, insufficient research on stress ratio effect exists at the present time to confirm quantitatively this trend.

A.2.1.5 Material qualification

Tests results from section A.2.1.4 only apply to a batch of material from which specimens were extracted.

1. The purpose of this clause is to qualify a material by testing two heats of material per heat treatment condition.

   Specimens for hydrogen tests shall be in the final heat treated condition to be used in the pressure vessels construction and obtained on a minimum of two heats representative of the material specification. Specifically, the maximum yield strength allowed by the specification shall not exceed 5% of the highest strength heat.

   The largest hydrogen sensitivity factor determined in all the tests shall be used.

2. The data obtained in 1- may be used for other pressure vessels manufactured from the same material and grade, having the same nominal composition and heat treatment condition, provided its tensile and yield strength do not exceed the values of the material used in the qualification tests by more than 5%.

Material qualification tests for H2 shall be performed when the nominal chemical composition or mechanical characteristics change and when MAWP is increased by more than 100 bar for: Type 1 steel pressure vessels, steel liners for Type 2 and Type 3 composite cylinders, and/or steel bosses.

A.2.2 Method 2 - Fatigue testing of disks

These tests shall be performed using the specimens and apparatus relative to the disk test method described in ISO 11114-4.

Five specimens shall be fatigue tested to failure in nitrogen, applying pressure cycles with a pressure ratio of 0,1 or less and with a maximum pressure equal to 80 % of the pressure leading to burst when performing method A of ISO 111114-4.

Five specimens shall be fatigue tested to failure in hydrogen under a pressure greater than or equal to MAWP, applying differential pressure cycles with a ratio of minimum differential pressure to maximum differential pressure of 0.1 and the same maximum differential pressure as the maximum pressure in the test above, by application of nitrogen backpressure.

The pressure rise in each cycle shall take place over at least 5 s and shall be followed by a hold time of at least 2 s.

The hydrogen used for testing shall comply with the requirement listed in ISO 11114-4.

NOTE It is critical to comply with limitation on oxygen content in the hydrogen used as the effect of hydrogen on the material will not be correctly quantified if this limit is exceeded.

The test pressure in hydrogen may be lower than the MAWP, if it has been established that the fatigue behaviour in hydrogen of the material compared to that in nitrogen at the stress levels considered is not significantly affected by hydrogen pressure, or if it has been established that fatigue performance in hydrogen can be conservatively extrapolated to the MAWP for the type of material considered.

If no shallow pressure cycle life has been specified, the value of the hydrogen sensitivity factor Fhs to be applied for the material is the larger of the two ratios of the number of cycles to failure in nitrogen and in hydrogen respectively determined by applying full amplitude cycles and shallow cycles

If a shallow pressure cycle life is specified, the sensitivity factor determined for full amplitude / shallow cycles respectively shall be applied for determining to how many full amplitude / shallow cycles respectively a pressure vessel shall be tested in relation to desired cycle life, as specified in A.7.1.

NOTE Composition ranges may be so wide that test results may not apply to all the alloys included of the specified grade.

A.3 Tensile properties of plastics

For Type 4 designs, the tensile yield strength and ultimate elongation of plastic liner material shall be determined at – 40 °C in accordance with ISO 527-2.

The test results shall demonstrate the ductile properties of the plastic liner material at temperatures of – 40 °C or lower by meeting the values specified by the manufacturer.

A.4 Softening temperature of plastics

When thermoplastic materials are used, for Type 4 designs, specimens from finished liners shall be tested in accordance with ISO 306. The appropriate method to be applied should be specified by the supplier of the polymeric material.

The softening temperature shall be at least 100 °C.

A.5 Resin properties tests

For Type 2, Type 3, and Type 4 designs, resin shear strength shall be tested on three sample coupons representative of the composite overwrap in accordance with ISO 14130. Following a 24-hour water boil the composite shall have a minimum shear strength of 13.8 MPa.

For Type 2, Type 3, and Type 4 designs, resin glass transition temperature shall be determined in accordance with ISO 11357-2, or equivalent. The test results shall be within the manufacturer's specifications.

A.6 Hydrostatic burst pressure test

The pressure vessel (or metal liner, as appropriate) shall be filled with a fluid such as water and the pressure gradually increased until failure of the pressure vessel. It shall be ensured that the pressure measuring device is monitoring the true pressure vessel pressure, particularly when the pressurization rate exceeds 0,35 MPa/s. Alternatively, there shall be a five second hold at the minimum design burst pressure.

The burst pressure shall be recorded. Unless different burst test criteria are specified for different test methods, the actual pressure vessel burst pressure shall exceed the minimum burst pressure specified in Table 1 for the applicable pressure vessel design. In no case shall the burst pressure be less than the value necessary to meet the stress ratio requirements in Table 1. For Types 1 and 2, rupture shall initiate only in the cylindrical portion of the pressure vessel. For Types 3 and 4, a leak or rupture may occur in either the cylindrical region or the dome region of the pressure vessel.

A.7 Ambient temperature pressure cycling

A.7.1 Full amplitude pressure cycling

Pressure cycling shall be performed in accordance with the following procedure:

a) fill the pressure vessel with a non-corrosive fluid such as oil, inhibited water or glycol;

b) cycle the vessel pressure between not more than 2 MPa and not less than the MAWP at a rate not exceeding 10 cycles per minute. The temperature on the outside surface of the vessel shall not exceed 50°C during the test.

The vessel shall not fail before reaching a number of cycles N_1 calculated as follows. The test shall continue for an additional N_1, cycles, or until the vessel fails whichever is sooner. The vessel shall not fail by burst during this second part of the test.

$N_1 = CL \times K_n \times F_{hs}$

where

CL is the specified pressure cycle life;

K_n is the fatigue life variability margin factor;

F_{hs} is the largest hydrogen sensitivity factor of the metallic materials constituting the pressure vessel and exposed to hydrogen determined as specified by A.2 in accordance with 8.1.3.2.4.

K_n shall be determined as per Table A. 1 based on the number of tested pressure vessels. Alternatively, if the pressure is cycled to MAWP or more, K_n may be determined as per Table A. 2.

Table A. 1— Fatigue life variability margin factor K_n in function of the number of tested pressure vessels

Number of tested pressure vessels	2	3	4	5
K_n	4	3.5	3	2.6

Table A. 2 — Alternative fatigue life variability margin factor Kn in function of the number of tested pressure vessels, applicable when cycling pressure to MAWP

Number of tested pressure vessels	2	3	4	5
K_n	2.1	1.8	1.6	1.3

A.7.2 Partial amplitude pressure cycling

If the manufacturer has specified a shallow pressure cycle life in accordance with 4.5, the test shall be repeated on a new set of pressure vessels in the same conditions except that the pressure vessel shall be cycled between not more than 0,8 times the MAWP and not less than the MAWP at a rate not exceeding 50 cycles per minute. The temperature on the outside surface of the vessel shall not exceed 50 °C during the test.

The pressure vessel shall not fail before N_2 cycles are reached, and shall not fail by burst before an additional N_2 cycles are reached, where N_2 is calculated as follows:

$N_2 = SCL \times K_n \times F_{hs}$

where

SCL is the specified shallow pressure cycle life;

K_n is the fatigue life variability margin factor;

F_{hs} is the largest hydrogen sensitivity factor of the metallic materials constituting the pressure vessel and exposed to hydrogen determined as specified by A.2 in accordance 8.1.3.2.4.

K_n shall be determined as per based on the number of tested pressure vessels. Alternatively, the pressure may be cycled between not more than the MAWP and at least 1,25 times the MAWP, in which case, the values provided by Table A. 2

A.7.3 Alternative tests to A.7.1 and A.7.2

The full amplitude and shallow amplitude pressure cycling test may be performed in combination on a single set of cylinders. In this case the cylinder shall not fail before N_1 full amplitude cycles and N_2 partial amplitude cycles are applied successively, and shall not burst before an additional N_1 full amplitude cycles and N_2 partial amplitude cycles are applied successively.

A.7.4 Alternative pressure cycling conditions

A.7.4.1 Pressure cycling to 1.5 MAWP

The full amplitude pressure cycling test may be performed at 1,5 times the MAWP. In this case the full amplitude pressure cycling test may be performed on only two pressure vessels, and the number of cycles that shall be achieved without failure is limited to N_1'= $CL \times F_{sh}$ for the each of the two testing steps.

The partial amplitude pressure cycling test, when required, may be performed between 1,2 times the MAWP and 1,5 times the MAWP. In this case the partial amplitude pressure cycling test may be performed on only two pressure vessels, and the number of cycles that shall be achieved without failure is limited to N_2'= SCL x K_{sh} for the each of the two testing steps.

Full amplitude and shallow amplitude pressure cycling test may be performed in combination on a single set cylinders as specified in A.7.2.

A.7.4.2 Equivalent pressure cycling

Full amplitude and partial pressure cycling may be combined to reach an equivalent number of full amplitude cycles to which the pressure vessel(s) may be subjected. This equivalence may be established with methods such as Goodman diagrams developed from fatigue life curves (S-N diagrams)

A reduced number of full amplitude cycles, conducted to pressures higher than MAWP, is permitted through the use of e representative fatigue life curve (S-N diagram)

See Annex F for guidance on development of S-N diagrams, Goodman diagrams, and their use in establishing equivalent pressure cycling.

A.7.5 Parameters to be monitored and recorded

The following parameters shall be monitored and recorded:

a) temperature of the vessel;

b) number of cycles achieving upper cyclic pressure;

c) minimum and maximum cyclic pressures;

d) cycle frequency;

e) test medium used;

f) description of the failure and location of the failure initiation.

A.8 Leak-before-break (LBB) test

The pressure vessel shall be filled with a non-corrosive fluid such as oil, inhibited water or glycol, and hydraulically pressure cycled from not more than 2 MPa to not less than 1.25 times the MAWP at a maximum rate of 10 cycles per minute. The pressure vessel shall fail by leakage, or shall exceed the number of filling cycles as specified per 4.4

NOTE This could be made by following the procedure of A.7.4

A.9 Bonfire test

Bonfire test may be required (see Clause 5.2).

Annex G gives examples of bonfire test.

A.10 High strain impact test

A pressure vessel pressurized to the MAWP ± 1 % with nitrogen or hydrogen shall be impacted by an armour piercing bullet with a diameter of 7.62 mm and with an impact speed of at least 850 m/s. The bullet shall impact the sidewall at an approximate angle of 45° to the pressure vessel centreline. The pressure vessel shall not rupture.

If the bullet has not fully perforated the wall, the pressure vessel shall be immediately safely depressurized after impact, and the pressure vessel shall be rendered unserviceable.

A.11 Chemical exposure test

A.11.1 General

The following chemical exposure test procedure shall be performed on a finished pressure vessel, including the coating if applicable.

A.11.2 Pre-conditioning

The upper section of the pressure vessel shall be divided into five distinct areas and marked for pendulum impact preconditioning and fluid exposure (see Figure A. 2). The five areas shall each be nominally 100 mm in diameter. The five areas do not need to be oriented along a single line, but they shall not overlap.

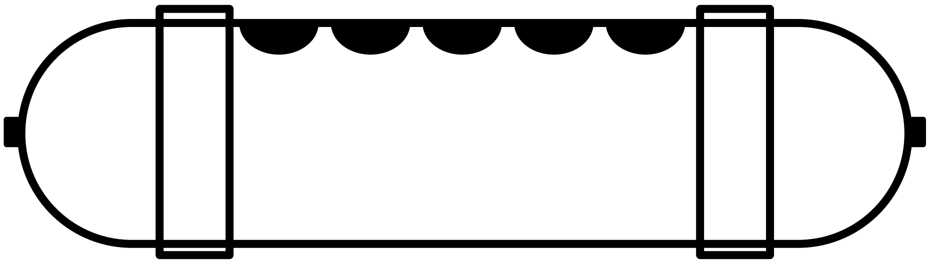

Figure A. 2— Pressure vessel orientation and layout of exposure areas

The approximate centre of each of the five areas shall be preconditioned by the impact of a pendulum body. The steel impact body of the pendulum shall have the shape of a pyramid with equilateral triangle faces and a square base, the summit and the edges being rounded to a radius of 3 mm. The centre of percussion of the pendulum shall coincide with the centre of gravity of the pyramid; its distance from the axis of rotation of the pendulum being 1 m and the total mass of the pendulum referred to its centre of percussion shall be 15 kg. The energy of the pendulum at the moment of impact shall not be less than 30 J. During pendulum impact, the pressure vessel shall be held in position by the end bosses or by the intended mounting brackets. The pressure vessel shall not be under pressure during preconditioning.

A.11.3 Exposure to chemicals

Each of the five preconditioned areas shall be exposed to one of five solutions (each solution shall be used and applied to only one preconditioned area). The five solutions are the following:

— volume fraction of 19 % sulphuric acid in water;

— mass fraction of 25 % sodium hydroxide in water;

— volume fraction of 5 % methanol in gasoline;

— mass fraction of 28 % ammonium nitrate in water;

— volume fraction of 50 % methyl alcohol in water (windshield washer fluid).

During the exposure, orient the test cylinder with the fluid exposure areas on top. Place a pad of glass wool approximately 0,5 mm thick and 100 mm in diameter on each of the five preconditioned exposure areas. Apply an amount of the test fluid to the glass wool sufficient to ensure that the pad is wetted evenly across its surface and through its thickness for the duration of the test.

A.11.4 Pressure cycling

The pressure vessel shall then be filled with a non-corrosive fluid such as oil, inhibited water or glycol, and hydraulically pressure cycled from not more than 2 MPa to not less than MAWP for at least 0,6 times the specified pressure cycle life per 4.4 . After pressure cycling, the pressure vessel shall be pressurized to MAWP, and held at that pressure a minimum of 24 hours.

A.11.5 Acceptance criteria

When burst tested in accordance with A.6, the pressure vessel shall have a burst pressure that exceeds 1.8 times the MAWP.

A.12 Accelerated stress rupture test

The pressure vessel shall be hydrostatically pressurized to 1,25 times the MAWP at 85 °C. The pressure vessel shall be held at this pressure and temperature for 2 000 hours. The pressure vessel shall then be pressured to burst in accordance with the procedure specified in A.6.

A.13 Extreme temperature pressure cycling

The finished pressure vessel, with the composite wrapping free of any protective coating, shall be cycle tested in accordance with the following procedure:

a) Fill with a non-corrosive fluid such as oil, inhibited water or glycol, and condition for 48 hours at a pressure of less than 2 MPa, at not less than 85 °C, and 95 % or greater relative humidity. The intent of this requirement shall be deemed met by spraying with a fine spray or mist of water in a chamber held at 85 °C.

b) Hydrostatically pressurize for 0,5 times the pressure cycle life specified in clause 4.4 between not more than 2 MPa nor less than MAWP at 85 °C or higher as measured on the pressure vessel surface, and 95 % or greater relative humidity.

c) Condition the pressure vessel and fluid at – 40 °C or the minimum allowable temperature, whichever is lower, as measured in the fluid and on the pressure vessel surface.

d) Pressurize from not more than 2 MPa to not less than the MAWP for 0,5 times the number of filling cycles as specified per clause 4.4, at – 40 °C or the minimum allowable temperature, whichever is lower. For Type 4 designs, recording instrumentation shall be provided to ensure the minimum temperature of the fluid is maintained during the low temperature cycling.

The pressure cycling rate of b) shall not exceed 10 cycles per minute. The pressure cycling rate of d) shall not exceed 2 cycles per minute unless a pressure transducer is installed directly within the pressure vessel.

During this pressure cycling, the pressure vessel shall show no evidence of rupture, leakage or fibre unravelling.

Following pressure cycling at extreme temperatures, pressure vessels shall be hydrostatically pressured to failure in accordance with A.6.

A.14 Permeation test

For Type 4 designs, the finished pressure vessel shall be filled with compressed hydrogen to MAWP, placed in a sealed chamber at ambient temperature, and monitored for permeated flow for 500 hours.

The steady state permeation rate for hydrogen gas shall be less than 6 cm^3 of hydrogen per hour per litre of water capacity.

A.15 Boss torque test

The body of the pressure vessel shall be restrained against rotation and a torque specified by the manufacturer shall be applied to each end boss of the pressure vessel. The torque shall be applied first in the direction to tighten a threaded connection, then in the untightening direction, and finally again in the tightening direction.

The pressure vessel shall then be subjected to a leak test in accordance with A.19, followed by a burst test in accordance with A.6.

A.16 Hydrogen gas cycling test

Special consideration shall be given to safety when conducting this test intended for type 4 pressure vessels. Prior to conducting this test, pressure vessels of the same design shall have successfully passed the test requirements of A.6 (hydrostatic burst pressure test), A.7 (ambient temperature pressure cycling) and A.14 (permeation test). The pressure vessel to be used in the test shall have successfully passed the test requirements of A.18 (hydraulic test).

The test procedure comprises the following steps:

a) The finished pressure vessel shall first be pressure cycled using compressed hydrogen gas from 80 % of the minimum residual pressure in operation (MRP) specified by the manufacturer per 8.1.3 to MAWP, at 150 % of the maximum depressurization rate specified by the manufacturer per 6.2 and 8.1.3, with a 24 hour hold time at each minimum cycle pressure as well as each maximum cycle pressure, for 10 cycles.

b) The pressure vessel shall subsequently be fully depressurized according to the depressurisation procedure specified by the manufacturer in accordance with 8.1.3 and visually inspected for absence of liner collapse or blistering.

c) The pressure vessel shall then be pressure cycled using compressed hydrogen gas from 80 % of the MRP to the MAWP, for 1000 cycles. The minimum hold time shall not be less than one hour. Every 100 cycles, there shall be a 24-hour hold period at the MAWP. The pressure vessel shall show no evidence of rupture, leakage or fibre unravelling during pressure cycling.

d) The pressure vessel shall then undergo blowdown from MRP through a 4mm diameter orifice and a venting system releasing the hydrogen to a safe location.

NOTE This flow section provides for an 80 % pressure drop in a period of time expressed in seconds equal to approximately 1/6th of the pressure vessel volume expressed in litres (e.g. 100 s for a 600 l pressure vessel).

e) The pressure shall then be subjected to a leak test in accordance with A.19.

Temperatures during the test shall be monitored using a thermocouple attached to the internal surface of the metal end boss at both ends of the pressure vessel. If only one boss end is exposed, the second temperature shall be obtained by inserting a probe into the pressure vessel to measure the gas temperature at the opposite end. Care shall be taken to ensure that temperatures of the bosses during filling and venting do not exceed the defined service conditions, except during blowdown from MRP.

If the specified maximum filling time of 5 minutes or the maximum cycle time of 1 hour results in boss material temperatures exceeding the specified service conditions, the filling time and/or the cycle time may be relaxed to the extent necessary for not exceeding these limits.

A.17 Hardness test

Hardness tests shall be carried out on the parallel wall at the centre, and at one of the domed ends of each pressure vessel or liner in accordance with ISO 6506-1, or using an equivalent method. The test shall be carried out after the final heat treatment and the hardness values thus determined shall be in the range specified for the design.

A.18 Hydraulic test

Hydraulic test shall be performed in accordance with the following procedure:

a) pressure vessel shall be hydraulically tested to at least 1,25 times the MAWP. In no case shall the test pressure exceed the autofrettage pressure;

b) pressure shall be maintained for 30 seconds or sufficiently longer to ensure complete expansion. If the test pressure cannot be maintained due to failure of the test apparatus, the test shall be repeated at a pressure increased by 0,7 MPa. No more than two such repeat tests shall be performed;

A.19 Leak test

Pressure vessel designs shall be leak tested in accordance with the following procedure:

a) thoroughly dry the pressure vessel;

b) pressurize the pressure vessel to the MAWP with hydrogen, or nitrogen containing a detectable gas such as helium.

Any leakage detected shall be cause for rejection.

NOTE Leakage is the release of gas through a crack, pore, unbound, or similar defect. Permeation through the wall in conformity to A.14 is not considered to be leakage.

A.20 Coating tests

Coatings shall be evaluated in accordance with the following procedure:

a) Adhesion testing in accordance with ISO 4624. A minimum rating of 4 shall be obtained when measured using Method A or B, as appropriate;

b) Flexibility in accordance with ISO 1519, using Test Method B with a 12 mm mandrel at the specified thickness at – 20 °C. Samples for the flexibility test shall be prepared in accordance with ISO 1519. There shall be no visually apparent cracks;

c) Impact resistance in accordance with ISO 6272-2. The coating at room temperature shall pass a forward impact test of 18 J;

d) Chemical resistance in accordance with ISO 2812-1 except as identified in the following. The tests shall be conducted using the open spot test method and 100-hour exposure to a 30 % sulphuric acid solution (battery acid with specific gravity of 1,219). There shall be no evidence of lifting, blistering or softening of the coating. The adhesion shall meet a rating of 3 when tested in accordance with ISO 4624;

e) Light and water exposure using a UVA-340 lamp in accordance with ISO 11507 for a minimum 1 000 hours. There shall be no evidence of blistering, and adhesion shall meet a rating of 3 when tested in accordance with ISO 4624. The maximum gloss loss shall be less than or equal to 20 %;

f) Salt spray exposure in accordance with ISO 9227 for a minimum 500 hours. Undercutting shall not exceed 3 mm at the scribe mark. There shall be no evidence of blistering, and adhesion shall meet a rating of 3 when tested in accordance with ISO 4624;

g) Resistance to chipping at room temperature in accordance with ASTM D3170-14. The coating shall have a rating of 7A or better and there shall be no exposure of the substrate.

A.21 Coating batch tests

A.21.1 Coating thickness

The thickness of the coating shall be measured in accordance with ISO 2808 and shall meet the requirements of the design.

A.21.2 Coating adhesion

The coating adhesion strength shall be measured in accordance with ISO 4624, and shall have a minimum rating of 4 when measured using either test method A or B, as appropriate.

A.22 Impact damage test

One or more finished pressure vessels shall be drop tested at ambient temperature without internal pressurization or attached valves. All drop tests may be performed on one pressure vessel, or individual impacts on a maximum of 3 pressure vessels. A plug may be inserted in the threaded ports to prevent damage to the threads and seal surfaces.

The surface onto which the pressure vessels are dropped shall be a smooth horizontal concrete pad or similar rigid surface. The pressure vessel(s) shall be tested in accordance with the following procedure:

a) drop once from a horizontal position with the bottom 1,8 m above the surface onto which it is dropped;

b) drop once onto each end of the pressure vessel from a vertical position with a potential energy of not less than 488 J, but in no case shall the height of the lower end be greater than 1,8 m;

c) drop once at a 45° angle, and then for non-symmetrical and non-cylindrical pressure vessels rotate the pressure vessel through 90° along its longitudinal axis and drop again at 45°, with its centre of gravity 1,8 m above the impact surface. However, if the bottom is closer to the impact surface than 0,6 m, the drop angle shall be changed to maintain a minimum height of 0,6 m and a centre of gravity of 1,8 m above the impact surface.

No attempt shall be made to prevent the bouncing of pressure vessels, but the pressure vessels may be prevented from falling over during the vertical drop test described in b).

Following the drop impact, the cylinders shall be pressure cycled between 20 bar and the maximum allowable working pressure at ambient temperature for the pressure cycle life.

The cylinder shall not leak or rupture for a number of cycles equal to two years of service, but may fail only by leakage during the remaining pressure cycle life.

All cylinders that complete this test shall be destroyed.

Annex B.
(Normative)

Requirements for existing designs

B.1 Introduction

As indicated in the scope, this Annex specifies alternative solutions for the safe use of cylinders and tubes already qualified for other applications.

The principle of this Annex is to use existing and approved design standards for transportable, fuel vehicle or stationary applications and to determine how to adapt them for use in stationary storage service.

This Annex specifies the requirements for assessing cylinders, tubes, and other pressure vessels. These can be of steel, stainless steel, aluminium alloy or non-metallic construction, designed, manufactured and tested in accordance with existing and approved standards or codes for transportable, fuel vehicles or stationary applications which are intended for the stationary storage of gaseous hydrogen of up to a maximum water capacity of 10 000 L and a maximum allowable working pressure not exceeding 110 MPa. These can be of seamless metallic construction (Type 1) or of composite construction (Types 2, 3 and 4) excluding any non-seamless load sharing metallic components. Hereafter they are referred to as pressure vessels.

B.2 Requirements

B.2.1 General requirements

Before a pressure vessels covered can be assessed in accordance with requirements of this standard, it shall have been designed, manufactured and tested to:

Either an existing and approved ISO standard (listed here below)

  - ISO 9809-1,
  - ISO 9809-2,
  - ISO 9809-3,
  - ISO 9809-4,
  - ISO 11120,
  - ISO 11439,
  - ISO 11119-1,
  - ISO 11119-2,
  - ISO 11119-3,
- or an approved national pressure vessel code. National or regional standards can only be used if it is demonstrated that they have an acceptable equivalent level of safety as the one listed in Clause 2 in the country of use.

Note: Such cylinders and tubes used for stationary storage are normally covered by National Regulations, (e.g. the PED in Europe and the ASME codes in the USA).

Other standards and codes can only be used with the approval of the competent authority.

In addition to the requirements of the above listed standards, the following requirements shall apply.

B.2.2 Specific requirements

B.2.2.1 Maximum allowable working pressure (MAWP)

The MAWP shall not exceed the maximum pressure authorized by the existing and approved standard or by regulation, i.e. for transportable cylinders and tubes the test pressure P_h as defined in transportable cylinder standards. If the pressure vessel is designed to ISO 11439 (fuel vehicle applications) the MAWP shall not exceed 1.3 PW (working pressure) (see also stationary test pressure in B.2.2.4).

B.2.2.2 Maximum allowable working temperature

For type 1 vessels, the maximum allowable working temperature (MAWT) shall not exceed manufacturer's limit as stated on the vessel name plate. In the absence of a stated limit, the MAWT shall not exceed 85°C.

For type 2, 3 and 4 vessels, the maximum allowable working temperature (MAWT) shall not exceed the lesser of 85°C and MAWT at which the cylinders have been previously tested and qualified.

If these temperatures are intended to be exceeded, it shall be demonstrated by appropriate testing that this is safe, e.g. cycling tests at the MAWT to safe margin.

Note: The maximum temperature for the valves and accessories shall also need to be considered.

B.2.2.3 Minimum allowable working temperature

For type 1 vessels, the minimum allowable working temperature shall not be less than manufacturer's limit as stated on the vessel name plate. In the absence of a stated limit, the minimum allowable working temperature shall not be less than -50°C.

For type 2, 3 and 4 vessels, the minimum allowable working temperature shall not be less than -50°C nor less than the temperature at which the cylinders have been tested, whichever is most restrictive.

B.2.2.4 Stationary test pressure (TP)

Some regulations require that pressure vessels for stationary storage be tested at a pressure higher than the MAWP, e.g. PED requires at least 1.43 times the MAWP.

In addition to the any regulatory requirement, when calculating the stationary test pressure it shall be checked that the following values are not exceeded:

a) For Type 1 pressure vessels, $TP \leq 0.95 * \frac{Ph}{F}$ (in order to avoid plastic deformation)

b) For Type 4 pressure vessels, $TP \leq 1.15 * Ph$;

c) For Types 2 and 3 pressure vessels, 95% of the auto-frettage pressure (in order to avoid plastic deformation).

Consequently the value of MAWP may result in a value less than the value specified in B.2.2.1

B.5 gives examples of calculation of MAWP and stationary test pressure;

B.2.2.5 Gas/material compatibility

For hydrogen/material compatibility, the requirements of the reference standard (see B.2.1), and the requirements of ISO 11114-1 and ISO 11114-2 shall be followed depending of the type of materials, as applicable.

ISO 11114-4 can also be used when applicable.

B.2.2.6 Cycle life

Pressure vessels for stationary storage are submitted to many cycles often to shallow pressure cycles

To determine the cycle life of the pressure vessels for stationary storage, either appropriate testing to determine cycle life for shallow cycles shall be performed or the following procedure shall be used to verify the suitability for the intended use.

The user shall specify the predicted maximum number of pressure cycles and the corresponding amplitudes and the pressure cycles that the pressure vessel has already experienced.

Equation 1 enables to recalculate a shallow pressure cycle life.

$$n_{eq} = \sum n_i \left[\frac{\Delta P_i}{\Delta P_{max}}\right]^3 \quad \text{Equation 1}$$

This equation should only be used to calculate a number of equivalent shallow cycles as defined in section 3.1 from a full cycle pressure amplitude, not the opposite.

For pressure vessels designed per ISO 11120 the number of full cycles n_{eq} shall be taken as 12 000 cycles at P_h.

For other standard designs or codes where no pressure cycle requirements exist, cycle tests with full pressure amplitude shall be carried out

A higher exponent than 3 may be applied in the above formula if the manufacturer can demonstrate that this remains conservative for counting pressure cycles having a lower maximum pressure than MAWP, based on the relationship between fatigue performance and stress level (S-N curve) for the materials constituting the pressure vessel.

Pressure variations exclusively due to variations of ambient temperature are not counted as pressure cycles.

NOTE Equation (1) has been checked to be safe for Type 1, 2 and 3 cylinders. For some metallic materials hydrogen accelerates crack initiation and crack propagation during fatigue.

This shall be taken into account when calculating the cycle life as follows

A hydrogen accelerating factor depending on the material shall be used.

This factor (Fa) is as follow:

- Fa = 1 for aluminum alloys and for hydrogen compatible stainless steels (see B.2.2.5)

- Fa = 5 for Cr - Mo quenched and tempered steels

For other materials this factor shall be determined by appropriate testing. See A.1 and A.2

NOTE The design life of composite cylinders is often limited by the reference standard. The shortest of the pressure cycle life and design life shall apply.

B.5 gives an example of calculation of cycle life.

B.2.2.7 Hydraulic pressure test

If the stationary test pressure is higher than the original designed test pressure, the pressure vessels shall be subjected to a pressure test (procedure according to the existing and approved standard) at the stationary test pressure

B.3 Marking

B.3.1 Pressure vessels manufactured specifically for stationary service

They should be marked in accordance with 8.1.5.

NOTE : In case of conflict with the applicable regulation, the applicable regulation takes precedence.

B.3.2 Pressure vessels initially used as a transportable cylinders.

Such pressure vessels shall have additional markings to comply with the applicable regulation for stationary service and they shall at least be specifically marked “ISO 19884 “ and the new MAWP to indicate that they are suitable for stationary service

B.4 Certificate

The certificate shall indicate :

- The reference of the existing standard
- The new MAWP
- The minimum and maximum allowable temperature
- The stationary test pressure
- The fatigue life calculation in relation in relation with the expected cycle llife
- The agreed markings
- The certificate confirming that the hydraulic test has been performed.

B.5 Examples of calculation for MAWP

B.5.1 Type 1 cylinder to ISO 9809 with Pw/Ph of 200/300 bar in Europe

TP max = 300 x 0.95 / 0.77 = 370 bar

MAWP max = 370 / 1.43 = 258 bar

B.5.2 Type 4 cylinder to ISO 11119-3 with P_w/P_h of 200/300 bar in Europe

TP max = 300 X 1.15 = 345 bar

MAWP max = 345 / 1.43 = 241 bar

B.5.3 Type 1 cylinder to ISO 9809 with P_w/P_h of 1 000/1 500 bar in Europe

TP max = 1 500 x 0.95 / 0.77 = 1 850 bar

MAWP max = 1 850 / 1.43 = 1 294 bar

B.5.4 Type 4 cylinder to ISO 11119-3 with P_w/P_h of 1 000/1 500 bar in Europe

TP max = 1 500 X 1.15 = 1 725 bar

MAWP max = 1 725 / 1.43 = 1 206 bar

B.6 Cycle life calculation

For example, a cylinder designed to ISO 9809-1 with PW = 700 bar and P_h = 1 050 bar, used as a stationary buffer for filling hydrogen vehicles. If we assume that this buffer is submitted to pressure cycles between 700 and 900 bar (10 000 cycles per year).

For this cylinder:

ΔPi = 900 – 700 bar= 200 bar

ΔPmax = 1 050 – 5 bar = 1 045 bar

ni = 10 000 cycles/year . For an expected life of 30 years, ni = 300 000 cycles

$$n_{eq} = 300000 \cdot \left(\frac{200}{1045}\right)^3 = 2103$$

Taken into account the accelerating factor Fa = 5 it comes to 10 515 cycles which is less than 12 000 cycles.

Annex C.
(informative)
Verification of stress ratios using strain gauges

The following describes a procedure that may be used to verify stress ratios by using strain gauges.

a) stress-strain relationship for fibres is always elastic, therefore, stress ratios and strain ratios are equal;

b) high elongation strain gauges are required;

c) strain gauges should be orientated in the direction of the fibres on which they are mounted (i.e. with hoop fibre on the outside of the pressure vessel, mount gauges in the hoop direction);

d) Method 1 (applies to pressure vessels that do not use high tension winding):

   1) prior to autofrettage, apply strain gauges and calibrate;

   2) measure strains at autofrettage pressure, zero pressure after autofrettage, MAWP, and minimum burst pressure;

   3) confirm that the strain at minimum burst pressure divided by the strain at the MAWP meets the stress ratio requirements. For hybrid construction, the strain at the MAWP is compared with the rupture strain of pressure vessels reinforced with a single fibre type.

e) Method 2 (applies to all pressure vessels):

   1) at zero pressure after winding and autofrettage, apply strain gauges and calibrate;

   2) measure strains at zero-gauge pressure, MAWP, and minimum burst pressure;

   3) at zero pressure, after strain measurements are taken at MAWP and minimum burst pressure, and with strain gauges monitored, cut the pressure vessel section apart so that the region containing the strain gauge is approximately 125 mm long. Remove the liner without damaging the composite. Measure the strains after the liner is removed;

   4) adjust the strain readings at zero-gauge pressure, MAWP and minimum burst pressure by the amount of strain measured at zero pressure with and without the liner;

   5) confirm that the strain at minimum burst pressure divided by the strain at the MAWP meets the stress ratio requirements. For hybrid construction, the strain at the MAWP is compared with the rupture strain of pressure vessels reinforced with a single fibre type.

Annex D.
(informative)

NDE defect size by flawed pressure vessel cycling

The following procedure can be used to determine the Non Destructive Examination (NDE) defect size for designs.

a) introduce internal and external flaws. Internal flaws may be machined prior to the heat treatment and closing of the end of the pressure vessel;

b) size these artificial defects to exceed the defect length and depth detection capability of the NDE inspection method;

c) pressure cycle three pressure vessels containing these artificial defects to failure in accordance with the test method specified in A.7.

If the pressure vessels do not leak or rupture in less than the specified pressure cycle life specified in 4.4 then the allowable defect size for NDE is equal to or less than the artificial flaw size at that location.

In all cases, the reduction of cycle life due to the effect of hydrogen exposure should be considered.

Annex E.
(informative)

Manufacturer’s instructions for handling, use and inspection of pressure vessels

E.1 General

The primary function of the manufacturer’s instructions is to provide guidance to the pressure vessel purchaser, distributor, installer and owner / operator concerning handling, use and inspection of the pressure vessel over its intended service life.

Installation and periodic inspection of pressure vessels are covered by regulation for the area of use which shall prevail on this annex.

E.2 Distribution

The manufacturer should advise the owner/operator to supply these instructions to all parties involved in the distribution, handling, installation and use of the pressure vessels.

The document may be reproduced to provide sufficient copies for this purpose; however, it should be marked to provide reference to the pressure vessels being delivered.

E.3 Reference to existing codes, standards and regulations

Specific instructions may be stated by reference to national or recognized codes, standards and regulations.

E.4 Pressure vessel handling

Handling procedures should be described which would ensure that the pressure vessels will not suffer unacceptable damage or contamination during handling.

E.5 Installation

Installation instructions should be provided which would ensure that the pressure vessels do not suffer unacceptable damage during installation and during normal operation over the intended service life.

Where the mounting is specified by the manufacturer, the instructions should, where relevant, contain details such as mounting design, the use of resilient gasket materials, the correct tightening torques and avoidance of direct exposure of the pressure vessel to the environment, chemicals and mechanical contacts. Pressure vessel locations and mountings should conform to recognized installation standards.

Where the mounting is not specified by the manufacturer, the manufacturer should draw the owner / operator’s attention to possible long-term impacts of the mounting system, e.g., pressure vessel expansion/contraction associated with from pressure variation.

E.6 Use of pressure vessels

The manufacturer should draw the owner / operator’s attention to the intended service conditions specified in this International Standard, in particular the pressure vessel’s permissible number of pressure cycles, its life in years, the permissible maximum pressures and any other relevant parameter which could limit the life of the pressure vessel (eg purity of the gas).

The manufacturer should draw the owner / operator's attention on the fact that it is of the responsibility of the user to ensure adequacy of the specified cycle life with regards to expected service, and to take the necessary measures for ensuring removal from service before the specified cycle life is exceeded when this could occur before the 30-year service life limit is reached.

E.7 In-service inspection

E.7.1 General

The manufacturer should clearly specify the owner / operator's obligation to observe the required pressure vessel inspection requirements (e.g. re-inspection interval, by authorized personnel). This information should be in agreement with the design approval requirements, and should cover the following aspects.

E.7.2 Periodic re-qualification

Inspection and/or testing is required to be performed in accordance with the relevant regulations of the country(ies) where the pressure vessels are used.

Recommendations for periodic re-qualification by visual inspection or testing during the service life should be provided by the pressure vessel manufacturer on the basis of use under service conditions specified herein. Each pressure vessel should be visually inspected at least every 36 months, and at the time of any re-installation, for external damage and deterioration, including under the support straps. The visual inspection should be performed by a competent agency approved or recognized by the regulatory authority, in accordance with the manufacturer's specifications.

Pressure vessels without labels or stamps containing mandatory information, or with labels or stamps containing mandatory information that is illegible in any way should be removed from service. If the pressure vessel can be positively identified by manufacturer and serial number a replacement label or stamping may be applied, allowing the pressure vessel to remain in service.

E.7.3 Pressure vessels having experienced impact damage

Pressure vessels having experienced impact damage should be re-inspected by an authorized inspection agency or condemned.

Pressure vessels that failed the inspection are not authorized for service. It is recommended that they are decommissioned, removed from service and scrapped in a manner to prevent alternative use.

E.7.4 Pressure vessels involved in fires

Pressure vessels that have been subject to the action of fire should be re-inspected by an authorized inspection agency, or condemned.

Pressure vessels that failed the inspection are not authorized for service. It is recommended that they are decommissioned, removed from service and scrapped in a manner to prevent alternative use.

Annex F.
(Informative)

Fatigue Life Evaluation using Goodman Diagrams

F.1 Purpose

This annex contains background information regarding the development of S-N diagrams and Goodman diagrams for the purpose of evaluating equivalent full pressure cycles at elevated pressure, so that the total number of test cycles be reduced, yet provide assurance that the pressure vessel can meet life requirements with high reliability.

F.2 Developing an S-N diagram

The pressure vessel manufacturer is responsible for developing the S-N diagram based on using the same materials and manufacturing approach used for the pressure vessels to be developed. As this is an S-N diagram to evaluate fatigue characteristics of the composite, the failure must be a failure of the composite, e.g. burst, not liner leakage. The following steps are required:

1. Establish the mean burst pressure of the vessel used to develop the S-N diagram. A minimum of 10 units are required. Plot this point as 100% stress, 1 cycle on the S-N diagram.
2. Cycle a minimum of 4 pressure vessels from no more than 10% of nominal working pressure to a first specified pressure level for which the stress is known. Plot this point on the S-N diagram. The S value will be stress relative to the mean burst, the N value will be either the point of first failure, or the point at which cycling was stopped if there was no failure.
3. Cycle a minimum of 4 pressure vessels from no more than 10% of nominal working pressure to a second specified pressure level for which the stress is known. Plot this point on the S-N diagram as was done for the first specified pressure level.
4. Draw a line from the 100%-1 point (burst) through the fatigue point that gives the lower of lines. This will be the characteristic line. It is recommended that the two fatigue points be at least one decade apart on the diagram.

Figure F. 1, illustrates an S-N diagram based on the above development.

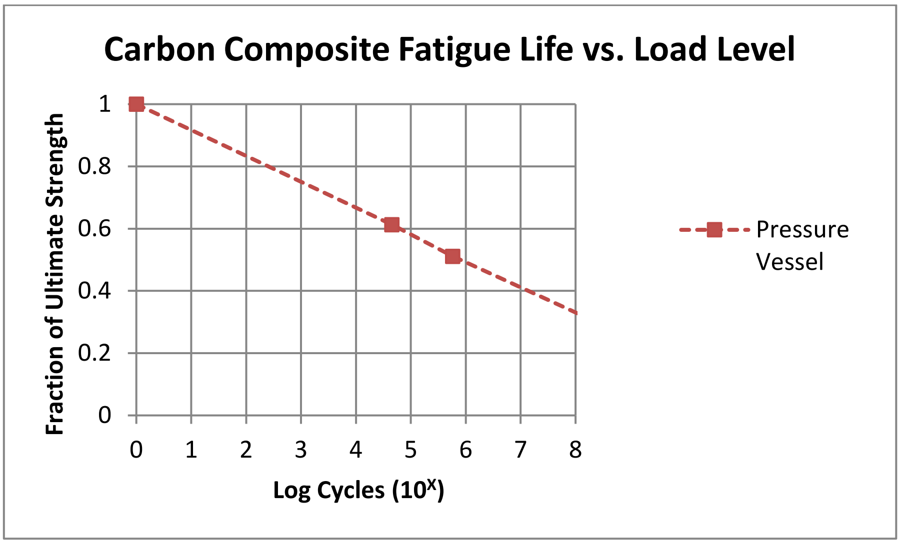

Figure F. 1 - Carbon Composite Fatigue Life vs. Load Level

F.3 Equivalent pressure cycling

The S-N Diagram (Figure F. 1) can be used to specify an alternate pressure to demonstrate fatigue resistance. For example:

- Assume the requirement for full cycles is 10^7 full pressure cycles (10,000,000). The vessel must be designed so the stress is no more than 40% of the mean burst pressure.
- The same vessel can be expected to withstand about 10^2 full pressure cycles (100) at about 80% of the mean burst pressure. If pressure cycles exceed 100 to 80% pressure without failure, the design is qualified.
- If some vessels fail before the required number of cycles, then the failure line would have to be lowered accordingly, and the vessel would need to operate at a correspondingly lower stress level to be certified.

F.4 Developing a Goodman diagram

A Goodman diagram, see Figure F. 1, may developed as given in Table F. 1 , from the S-N diagram (Figure F. 1) as follows:

1. Identify the fatigue levels from the S-N diagram to be used in the Goodman diagram (column 1)
2. Identify the stress level (i.e. at upper cycle pressure) from the S-N diagram that corresponds with that fatigue level (column 2) Note: stress levels are given as a fraction of the ultimate strength.
3. Identify the lower stress level (i.e. at lower cycle pressure) associated with the fatigue level (column 3) Note: Some fatigue testing is done with a lower limit that is as high as 10% of the maximum working pressure, but might be near zero. For purposes of this example, the lower cycle pressure is set at zero.
4. Calculate the average stress level for the pressure cycle (column 4) Note: this is equal to one-half of the upper limit plus the lower limit
5. Calculate the amplitude for pressure cycle (column 5) Note: this is equal to the average stress level minus the lower stress level (equal to one-half of the upper limit minus the lower limit)
6. Enter the coordinates for the second point of each line (column 6, column 7). Since this represents the tensile strength, such as in a burst test, these coordinates will be the same for

all fatigue lines, and will have a normalized value of 1.0 for the upper limit, and a value of 0.0 for the amplitude.

7. From the two sets of (X,Y) coordinates, calculate the slope of the resultant line (column 8), and the intercept of the Y-axis (column 9).

Table F. 1 - Goodman diagram development

Col.1	Col.2	Col.3	Col.4	Col.5	Col.6	Col.7	Col.8	Col.9
Fatigue level	Upper cycle limit	Lower cycle limit	Average stress (X2)	Amplitude (Y2)	Strength (X1)	Amplitude (Y1)	Slope (m)	Intercept (b)
1x10^1	0.92	0.0	0.460	0.460	1.0	0.0	-0.8518	0.85
1x10^2	0.83	0.0	0.415	0.415	1.0	0.0	-0.7094	0.71
1x10^3	0.74	0.0	0.370	0.370	1.0	0.0	-0.5873	0.59
1x10^4	0.66	0.0	0.330	0.330	1.0	0.0	-0.4925	0.49
1x10^5	0.60	0.0	0.300	0.300	1.0	0.0	-0.4286	0.43
1x10^6	0.50	0.0	0.250	0.250	1.0	0.0	-0.3333	0.33
1x10^7	0.40	0.0	0.200	0.200	1.0	0.0	-0.2500	0.25
1x10^8	0.31	0.0	0.155	0.155	1.0	0.0	-0.1834	0.18

The bottom four lines of Table F. 1are shown in Figure F. 2 below. More of the lines could be plotted if needed.

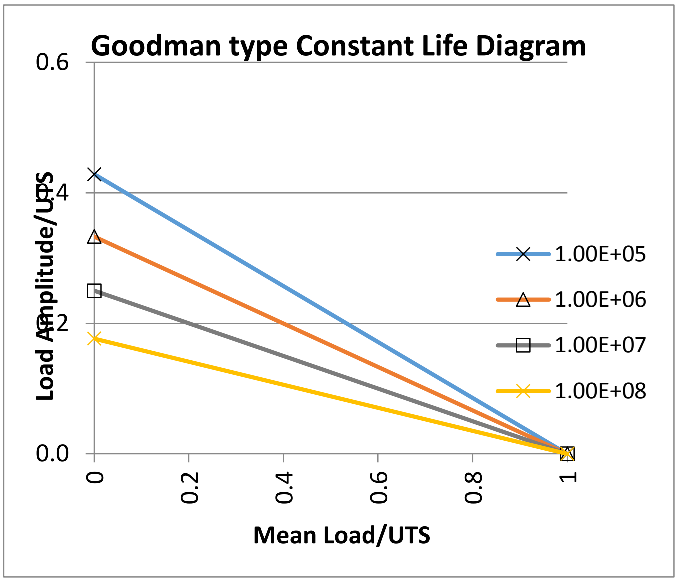

Figure F. 2 - Goodman Type Constant Life Diagram

The manufacturer may, as an alternative to the method of 4.5.1, specify the pressure ranges, and cycles in each pressure range, expected to be seen over the life of the pressure vessel, and show that there is margin on the fatigue life. The analysis may use, if appropriate, a means to equate the pressure ranges to a common reference datum, e.g. a Goodman type Constant Life Diagram, and shall assess the fraction of life used in each pressure range and subsequent summation of expected life, e.g. using Miner's Rule. This analysis must be done for the composite and metallic components of a pressure vessel.

Table F. 2 gives an example of a sample pressure cycle specification. In this example, the burst pressure is 2.25 times the maximum upper pressure (100 x 2.25 = 225). This data can be put into the non-dimensional terms to plot on the Goodman Diagram, as given in Table F. 3, using the approach described above.

Table F. 2- Sample pressure cycle specification

Set No.	Lower Pressure	Upper Pressure	R	No. of Cycles
1	0	100	0	100,000
2	30	70	0.429	400,000
3	70	100	0.7	500,000

Table F. 3- Normalized sample terms

Set No.	Lower limit ratio	Upper limit ratio
1	0.222	0.222
2	0.222	0.0889
773	0.3778	0.0667

The points can be plotted on the Goodman diagram, Figure F. 2. Lines can be plotted similarly to the previous lines. It is also possible to get an equivalent cycle range where the lower pressure limit is 0, by intersecting the “reliability” line with one from the point 0,0 with a slope of 1. It can be seen that data set number 1 lies between the 1x10^6 and 1x10^7 lines, while the other two points lie below the 1x10^8 line. From this information, it is possible to estimate the total fraction of life used, as shown in Table F. 4, Life evaluation. The resultant Factor of Safety can be calculated as FS > 1/0.109 = 9.2.

Table F. 4- Life evaluation

Set No.	Cycles	Life Fraction	= LF
1	100,000	<100,000 / 1E6	< 0.100
2	400,000	<400,000 / 1E8	< 0.004
3	500,000	<500,000 / 1E8	< 0.005
Sum – Miner’s Rule			< 0.109

Annex G. (informative)

Optional Bonfire Test

G.1 General

This bonfire test is designed to demonstrate that finished cylinders, complete with the fire protection system (cylinder valve, pressure relief devices and/or integral thermal insulation) specified in the design, will prevent the rupture of the cylinder when tested under the specified fire conditions.

This test procedure allows the cylinders and PRDs/valves to be tested separately, and results of testing combined for a system evaluation. The testing of the cylinder in a fire establishes the qualification limit envelope. The testing of the PRD in a fire, combined with a venting test of the fuel storage system, establishes the service limit envelope. There should be a positive margin between these two envelopes.

Pressure relief devices should be thermally activated and conform to ISO 15500‑13, CSA PRD1-2013, or equivalent standard.

Precautions should be taken during fire testing in the event that cylinder rupture occurs.

G.2 Cylinder test

G.2.1 Cylinder set-up

The cylinder should be placed horizontally with the cylinder bottom approximately 100 mm above the fire source. A fitting or valve should be installed in one end such that the contents may be released remotely during the test, thereby allowing a controlled decrease in pressure. It is not necessary for the valve to be positioned in the fire. Metallic shielding of a minimum 0,4 mm thickness should be used to prevent direct flame impingement on cylinder valves if they are located in the fire. The metallic shielding should not be in direct contact with the valve.

If the cylinder will be insulated in service, the insulation may be placed on the cylinder during the test.

If the cylinder is longer than 1,15 m, a subscale cylinder of full diameter, and length at least 2,5 times the diameter, may be tested.

G.2.2 Fire source

A uniform fire source of 1,65 m length should provide direct flame impingement on the cylinder surface across its entire diameter width. Any fuel may be used for the fire source provided it supplies uniform heat sufficient to maintain the specified test temperatures until the cylinder is vented. The selection of a fuel should take into consideration pollution concerns. The arrangement of the fire should be recorded in sufficient detail to ensure that the rate of heat input to the cylinder is reproducible.

Any failure or inconsistency of the fire source during a test should invalidate the result.

G.2.3 Temperature and pressure measurements

Surface temperatures should be monitored by at least three thermocouples located along the bottom of the cylinder and spaced not more than 0,75 m apart. Metallic shielding of a minimum 0,4 mm thickness should be used to prevent direct flame impingement on the thermocouples. The metallic shielding should be in contact with the thermocouples. Alternatively, thermocouples may be inserted into blocks of metal measuring less than 25 mm square. Thermocouple temperatures and the cylinder pressure should be recorded at intervals of every 30 s or less during the test.

G.2.4General Test Requirements

The cylinder should be pressurized to working pressure with helium or hydrogen and tested in the horizontal position at working pressure. Wind speed must be less than 2,25 m/s at the start of the test.

The cylinder should be positioned such that one end is in the fire and located 0,5 m from the edge, with the remainder of the cylinder extending further into the fire, and is allowed to extend out of the fire if it is of length greater than 1,15 m.

Immediately following ignition, the fire should produce flame impingement on the surface of the cylinder

along the 1,65 m length of the fire source and across the cylinder diameter width.

Within 5 min of ignition the temperature on at least one thermocouple should indicate a temperature ≥ 590 °C. This minimum temperature should be maintained for the remainder of the test.

G.2.5Test Options

G.2.5.1 Option A – Controlled Release of Pressure

One full scale cylinder is required for this test. Subscale should be considered if cylinder length is higher than 1.65m The cylinder is initially pressurized with hydrogen to the MAWP. The fire is set on 1.65*1.65 m surface. The manufacturer should determine the maximum time in qualified fire before release of contained gas. The pressure is then controlled by starting releasing contents remotely using a valve connected to the cylinder. The timing of the start of the release of contents and the rate of release of the contents is determined by the manufacturer. The pressure vs. time should be recorded.

20% of predetermined time in the qualified fire should be subtracted as a safety margin to get the outer envelope for the pressurized cylinder lifetime in a fire.

G.2.5.2 2.5.2 Option B – Fire Test until Rupture

Four full scale cylinders are required for this test. Subscale should be considered if cylinder length is higher than 1.65m. The four cylinders are initially pressurized, with one cylinder each at 100, 80, 40 and 5 percent of the MAWP. One cylinder at a time is placed in the fire until the cylinder ruptures or the cylinder leaks. The time from commencement of the fire until rupture or leak should be recorded. If there is not burst or leak within 60 minutes of commencement of the fire, the test should be stopped, and a value of 60 minutes used as the test result.

30% of predetermined time in the qualified fire should be subtracted as a safety margin to get the outer envelope for the pressurized cylinder lifetime in a fire.

G.3 PRD test

The PRD should be mounted on a representative cylinder, or alternatively on a steel pipe, on the end of the cylinder or pipe and on the centerline. The setup and fire should be as required in G.2.1 and G.2.2, and the measurement requirements and test conditions should be as given in G.2.3 and G.2.4, except that the fire source should be 0.6m by 0.6m, and the PRD centered in the fire.

A pressure source should be connected to the PRD system such that The PRD system sees pressure on the locations it would see in service. The pressure source should contain at least two litres of compressed gas. The pressure of the source should be 25 percent of the minimum pressure of any cylinder that the PRD is intended to be used on.

The time between the start of the test and the activation of the PRD should be recorded.

G.4 Vent Test

An activated PRD system should be connected to the cylinder(s) it is intended to protect. The flow characteristics of the PRD system, including the flow orifice diameter and the length and diameter of vent tubing, should be representative of the cylinder system to be protected. A valve should be placed between the cylinder and PRD so that the venting is activated at the start of the vent test. The cylinder should be at the rated service pressure.

The pressure of the cylinder vs. time should be recorded from the initiation of the test until the pressure is less than 5 percent of the service pressure.

G.5 System assessment

G.5.1 Qualification Limit Envelope

For cylinders tested under Option A – controlled release of pressure, the recorded pressure vs. time should be the qualification limit envelope.

For cylinders tested under Option B – fire test until rupture, the qualification limit envelope should be developed by plotting the time-to-rupture vs. pressure for the four cylinders testing, and connecting the points.

G.5.2 Service Limit Envelope

The service limit envelope should be developed by first considering the time to activate the PRD from G.3.

The pressure vs. time data recorded from the vent test of G.4 should be appended to the activation time to complete the service limit envelope.

G.5.3 Acceptable results

When plotted together, the service limit envelope should be within the qualification limit envelope. The depressurization portion of the service limit should be offset from that of the qualification limit by a time equal to 20 percent of the point on the qualification limit envelope when pressure decrease begins until the point where only 10 percent of the pressure remains.

G.6 (Informative) Figure 1

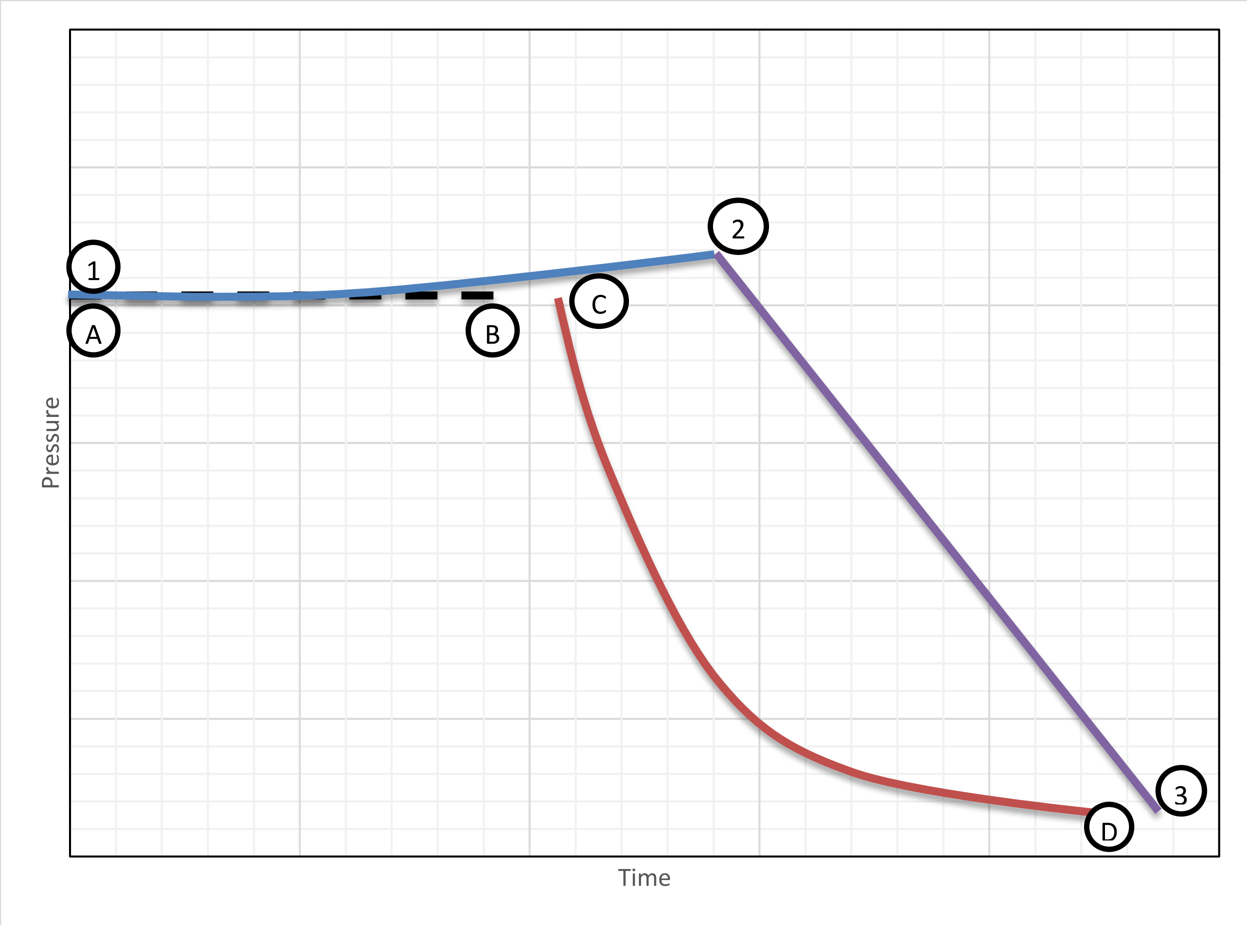

Figure G. 1- Generation of a safety envelope and actual cylinder/PRD performance

(1) The pressurized tank is exposed to the test fire
(1)->(2) Internal pressure increases while the tank is exposed to the fire
(2) The vent valve is opened manually
(2)->(3) Pressure vs. time is established by controlling the vent valve
(3) The tank is vented
(A) The thermally activated PRD is introduced into the test fire
(B) The thermally activated PRD activates in the test fire (A time based safety margin may be added first)
(C) Venting is initiated from the representative pressurized tank or tank assembly through a representative activated PRD and vent tube assembly
(D) The tank/tank assembly is vented
The (A)->(B) and (C)->(D) data is generated separately, then added together
Test requirement: (A)->(B)+(C)->(D) line is entirely within the (1)->(2)->(3) line. (C)->(D) line must offset
from the (2)->(3) line by 20% of the time at point (2).

Reference: ISO/TR 13086-2 Guidance for design of composite cylinders Part 2. Composite Pressure Receptacles in a Fire.

Annex H. (informative) - Information on factor of safety

H.1 Purpose

This annex contains information regarding the development and selection of a Factor of Safety (FS) for carbon fiber reinforced pressure tubes.

H.2 Background

Some ISO standards for transportable cylinders use a higher factor of safety, FS = 3.0 times Working Pressure (Pw), for carbon fiber reinforced pressure containers, than is used for similar cylinders in service as fuel containers, FS = 2.25 x Pw, or permanently mounted transportable containers (cylinders or tubes).

The question has been raised as to what safety factor is appropriate for carbon fiber reinforced pressure tubes.

H.3 Recommended Safety Factor

A factor of safety of 2.25 times Working Pressure is adequate, even conservative, for carbon fiber to address its inherent failure mode, which is stress rupture. However, to have a safe end product, performance based qualification test requirements must be included in a standard to address damage and impact tolerance, fatigue, and environmental resistance.

H.4 Discussion

Glass fiber reinforced composites were introduced in the 1950s, including for use in rocket motor cases. Early applications used a factor of safety similar to that of metals, but unexpected ruptures occurred. Investigation led to a property inherent to glass that led to failure over time when held at load, known as stress rupture or static fatigue.

The nominal factor of safety was increased to a value of 3.5 to deal with the relatively poor stress rupture characteristics of glass fiber. This FS = 3.5 also addressed other performance issues in early pressure vessels, including drop and impact performance, non-shatterability in a gunfire test, and fatigue performance of metal liners.

Aramid fiber was introduced into the market in the 1970s. Carbon fiber was available in the 1970s, but its use in the pressure vessel market increased in the late 1980s as increased strength and reduced cost made it more competitive. These fibers were initially treated similarly as “composite reinforced” products in commercial service rather than looking in greater detail at their properties, particularly as it regards factors of safety.

The aerospace/defense industry became early adopters of the newer aramid and carbon fibers, and conducted stress rupture studies to understand the performance of these fibers, and allow more appropriate safety factors, lower than used in early commercial applications, and still maintain high reliability under stress rupture conditions.

Carbon fiber has significantly better stress rupture characteristics than glass fiber, and can therefore be used at a lower factor of safety and still have an equal or higher level of reliability. The industry has established a target stress rupture reliability of 0.999999 over a lifetime for pressure vessel applications.

A stress ratio, or factor of safety, of 2.25 has been generally established and accepted for carbon fiber reinforced pressure vessels. Stress rupture studies have indicated this stress ratio is conservative, and that a stress ratio of 1.8 would likely give the desired reliability over time in service. This stress ratio of

2.25 has also proven safe over time. It has been used in the aerospace and fuel container applications for over 25 years, with no known stress rupture failures.

Additional performance based qualification testing is required for safe operation of the pressure vessels in service. While the stress ratio addresses stress rupture, the pressure vessel's damage tolerance, fatigue resistance, and environmental resistance must also be considered. While increasing the factor of safety will improve performance in these areas, there are other, more effective means of dealing with performance than simply increasing the factor of safety.

Damage tolerance, for example, can be improved by using hybrid reinforcement, such as combining glass fiber with the carbon fiber when reinforcing the container. This provides greater damage tolerance by increasing wall thickness, and by addition of a less brittle material. Wall thickness also increases with increasing diameter or increasing pressure. Although there is some concern with the added energy content with larger diameters or higher pressures, the impact resistance goes up at an even faster rate.

Fatigue resistance of the composite reinforcement is generally much greater than needed, regardless of the factor of safety. Fatigue issues generally are an issue of metal liners, which are chosen and designed to have a leak-before-break failure mode. Fatigue resistance can be improved by increasing the amount of fiber reinforcement, and therefore the factor of safety, but one can also increase the fatigue life if, for example, the liner is a polymer material, such as high density polyethylene (HDPE).

Environmental resistance of carbon fiber is excellent, regardless of the factor of safety used. It is generally not affected significantly by high or low temperatures, acids, bases, solvents, or other fluids. Other fiber reinforcing materials do have some sensitivity to some of these factors, hence the need for environmental testing.

There is broad world-wide acceptance for using a factor of safety for carbon fiber of 2.25 or even lower. This acceptance is evidenced in various industries and applications as noted in the following paragraphs.

The aerospace and defense industries were the first to use carbon fiber in pressure vessel applications. They began using carbon fiber in the 1970s and 1980s, and have used factors of safety as low as FS = 1.50. Standards in use by these industries include MIL-STD-1522A, AIAA S-081, and ISO 14623.

The automotive industry was also an early adopter of composite reinforced pressure vessels, in the form of high pressure fuel containers for natural gas and hydrogen powered vehicles. Natural gas containers generally operate at 200 and 240 bar (2900 and 3600 psi), while hydrogen containers generally operate at 350 to 700 bar (5000 to 10,000 psi). These vessels have been in use since about 1990, with significant standards released in 1993 and 2000. Factors of Safety are generally FS = 2.25 or FS = 2.35, and are fully accepted world-wide. Applicable standards include ISO 11439, ANSI/CSA NGV2, and ECE R110, and EC 79. Some newer standards for hydrogen fuel tanks are reducing the factor of safety to FS = 2.0.

Marine applications, including ship components and ladings, have used factors of safety of FS=2.25 since about 2003. Standards include DNV OS-C501 and CNG Rules and recommendations in EU-project HyComp. ABS has provided approvals under its Guidance Notes on Review and Approval of Novel Concepts, and specifically under ABSHOU 557163.

Stationary applications using FS = 2.25 developed in the 2000 to 2010 time frame. PED applications were approved around 2000. Amendment M270 to ADR accept 2,25xPw for hydrogen cylinders with NWP of 70MPa. Development of ASME Code began about this time, and was published in 2010 as Section X Appendix 8, for Section X Class III pressure vessels having a FS = 2.25 for carbon fiber reinforced vessels. Approval was given to qualified designs shortly after the Code was approved.

Transportable cylinders and tubes that are permanently mounted gained approval with FS = 2.25 to FS = 2.35 beginning about 2010 and continuing today. The first approval was by ABS under ABSHOU

557163. Over 13 countries have approved use of these vessels, including the United States under DOT Special Permit SP14951 (with a FS = 2.4).

H.5 Conclusions

The use of a factor of safety FS = 2.25 x Pw has been demonstrated safe based on 25 to 40 years of experience in service in a variety of applications. The trend is to reduce the factor of safety to 2.25 x Pw for carbon fiber reinforced vessels, and in some cases to lower factors of safety. No standards have increased the factor of safety to a higher level for carbon fiber reinforced pressure vessels.

H.6 Recommendations

The use of factor of safety FS = 2.25 x Pw has been demonstrated as safe and should be allowed in any application, given that sufficient performance based qualification testing is used for other conditions. A factor of safety FS = 2.35 x Pw may be used for CNG applications due to the higher change in pressure due to change in temperature compared with other gases.

H.7 Further reading:

- ISO/TR 13086-1 Gas cylinders – Guidance for the design of composite cylinders – Part 1: Stress rupture of fibres and burst ratios related to test pressure
- ASME STP-PT-014, Data Supporting Composite Tank Standards Development for Hydrogen infrastructure Applications
- Hycomp deliverables available here : http://www.hycomp.eu/menus-sp/menu-bas/pressroom/power-pointpresentation.html, especially http://www.hycomp.eu/fileadmin/_migrated/content_uploads/HyCOMP_Workshop_Technical_review_WP6_AL.pdf WP6 - Design requirements and testing procedures

Bibliography

[1] ISO/TR 15916, *Basic considerations for the safety of hydrogen systems*

[2] ISO/TR 13086-2 *Guidance for design of composite cylinders Part 2. Composite Pressure Receptacles in a Fire.*

[3] EN 13445-3, *Unfired pressure vessels – Part 3: design*

[4] ANSI/AIAA G-095-2004, *Guide to Safety of Hydrogen and Hydrogen Systems*

[5] Sandia National Laboratories, *Technical Reference for Hydrogen Compatibility of Materials at www.ca.sandia.gov/matlsTechRef/*

[6] Yukitaka MURAKAMI, *Metal Fatigue: Effects of Small Defects and Nonmetallic Inclusions*, Elsevier Science Ltd., Oxford, UK, 2002.

[7] Hervé BARTHELEMY, Alberto AGNOLETTI, *Cylinders and tubes used as buffers in the filling stations*, ICHS 2015