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**Cryogenic vessels — Large  
transportable vacuum-insulated  
vessels —**

**Part 1:  
Design, fabrication, inspection and  
testing**

*Réipients cryogéniques — Réipients transportables isolés sous vide  
de grande contenance —*

*Partie 1: Conception, fabrication, inspection et essais*



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## 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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see [www.iso.org/directives](http://www.iso.org/directives)).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see [www.iso.org/patents](http://www.iso.org/patents)).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see [www.iso.org/iso/foreword.html](http://www.iso.org/iso/foreword.html).

This document was prepared by Technical Committee ISO/TC 220, *Cryogenic vessels*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at [www.iso.org/members.html](http://www.iso.org/members.html).

This second edition cancels and replaces the first edition (ISO 20421-1:2006), which has been technically revised. It also incorporates ISO 20421-1:2006/Cor 1:2007. The main changes compared to the previous edition are as follows:

- Subclause [12.3](#) has been revised;
- [Annex D](#) has been revised;
- Chinese materials have been added in [Annex G](#).

A list of all parts in the ISO 20421 series can be found on the ISO website.

## Introduction

This document has been written so that it is suitable to be referenced in the UN Model Regulations<sup>[1]</sup>.

This document does not include the general vehicle requirements, e.g. running gear, brakes, lighting, etc., for which the relevant standards/regulations apply.

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# Cryogenic vessels — Large transportable vacuum-insulated vessels —

## Part 1: Design, fabrication, inspection and testing

### 1 Scope

This document specifies requirements for the design, fabrication, inspection and testing of large transportable vacuum-insulated cryogenic vessels of more than 450 l volume, which are permanently (fixed tanks) or not permanently (demountable tanks and portable tanks) attached to a means of transport, for one or more modes of transport.

This document applies to large transportable vacuum-insulated cryogenic vessels for fluids specified in [3.1](#) and does not apply to vessels designed for toxic fluids.

This document does not include the general vehicle requirements, e.g. running gear, brakes, lighting, etc.

NOTE 1 This document does not cover specific requirements for refillable liquid-hydrogen tanks that are primarily dedicated as fuel tanks in vehicles. For fuel tanks used in land vehicles, see ISO 13985.

NOTE 2 This document does not cover specific requirements for refillable liquid hydrogen and LNG tanks that are primarily dedicated as fuel tanks in vehicles. For fuel tanks used in vehicles, see ISO 13985.

### 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 3834-2, *Quality requirements for fusion welding of metallic materials — Part 2: Comprehensive quality requirements*

ISO 4126-2, *Safety devices for protection against excessive pressure — Part 2: Bursting disc safety devices*

ISO 5817, *Welding — Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) — Quality levels for imperfections*

ISO 9606-1, *Qualification testing of welders — Fusion welding — Part 1: Steels*

ISO 9606-2, *Qualification test of welders — Fusion welding — Part 2: Aluminium and aluminium alloys*

ISO 9712, *Non-destructive testing — Qualification and certification of NDT personnel*

ISO 10042, *Welding — Arc-welded joints in aluminium and its alloys — Quality levels for imperfections*

ISO 10474:2013, *Steel and steel products — Inspection documents*

ISO 10675-1, *Non-destructive testing of welds — Acceptance levels for radiographic testing — Part 1: Steel, nickel, titanium and their alloys*

ISO 14732, *Welding personnel — Qualification testing of welding operators and weld setters for mechanized and automatic welding of metallic materials*

ISO 15613, *Specification and qualification of welding procedures for metallic materials — Qualification based on pre-production welding test*

ISO 15614-1, *Specification and qualification of welding procedures for metallic materials — Welding procedure test — Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys*

ISO 15614-2, *Specification and qualification of welding procedures for metallic materials — Welding procedure test — Part 2: Arc welding of aluminium and its alloys*

ISO 17635, *Non-destructive testing of welds — General rules for metallic materials*

ISO 17637, *Non-destructive testing of welds — Visual testing of fusion-welded joints*

ISO 20421-2, *Cryogenic vessels — Large transportable vacuum-insulated vessels — Part 2: Operational requirements*

ISO 21010, *Cryogenic vessels — Gas/material compatibility*

ISO 21011, *Cryogenic vessels — Valves for cryogenic service*

ISO 21028-1, *Cryogenic vessels — Toughness requirements for materials at cryogenic temperature — Part 1: Temperatures below -80 degrees C*

ISO 21028-2, *Cryogenic vessels — Toughness requirements for materials at cryogenic temperature — Part 2: Temperatures between -80 degrees C and -20 degrees C*

ISO 21013-3, *Cryogenic vessels — Pressure-relief accessories for cryogenic service — Part 3: Sizing and capacity determination*

ISO 23208, *Cryogenic vessels — Cleanliness for cryogenic service*

ASME VIII-2, *Rules for construction of pressure vessels, Division 2, Alternative Rules*

EN 13445-3, *Unfired pressure vessels — Part 3: Design*

### 3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

#### 3.1

##### **cryogenic fluid** **refrigerated liquefied gas**

gas which is partially liquid because of its low temperature (see [Table K.1](#))

Note 1 to entry: This includes totally evaporated liquids and supercritical fluids.

Note 2 to entry: In the context of this document, the refrigerated but non-toxic gases and gas mixtures given in [Table K.1](#) are referred to as cryogenic fluids.

#### 3.2

##### **large transportable cryogenic vessel** **tank**

thermally insulated vessel of more than 450 l intended for the transport of one or more *cryogenic fluids* ([3.1](#)), consisting of an *inner vessel* ([3.4](#)), an *outer jacket* ([3.5](#)), all of the valves and *service equipment* ([3.9](#)) together with the structural parts

Note 1 to entry: The large transportable cryogenic vessel comprises a complete assembly that is ready for service.

### 3.3 insulation

vacuum interspace between the *inner vessel* (3.4) and the *outer jacket* (3.5)

Note 1 to entry: The space may or may not be filled with material to reduce the heat transfer between the inner vessel and the outer jacket.

### 3.4 inner vessel

*pressure* (3.16) vessel intended to contain the *cryogenic fluid* (3.1) to be transported

### 3.5 outer jacket

gas-tight enclosure which contains the *inner vessel* (3.4) and enables the vacuum to be established

### 3.6 normal operation

intended operation of the vessel at a *pressure* (3.16) not greater than the maximum allowable working pressure including the *handling loads* (3.7)

### 3.7 handling load

load exerted on the transportable cryogenic vessel in all normal conditions of transport including loading, unloading, moving and lifting

### 3.8 piping system

all pipes, tubes and associated components which can come in contact with *cryogenic fluids* (3.1) including valves, fittings, pressure-relief devices and their supports

### 3.9 service equipment

measuring instruments and filling, discharge, venting, safety, heating, cooling and insulating devices including any equipment for storing cooling fluids

### 3.10 manufacturer

<large transportable cryogenic vessel> company that carries out the final assembly, including the final acceptance test, of the *large transportable cryogenic vessel* (3.2)

### 3.11 gross volume

<of the inner vessel> internal volume of the *inner vessel* (3.4), excluding nozzles, pipes, etc., determined at minimum design temperature and atmospheric *pressure* (3.16)

### 3.12 tare mass

mass of the empty *large transportable cryogenic vessel* (3.2)

### 3.13 net volume

volume of the *inner vessel* (3.4), below the inlet to the relief devices, excluding nozzles, pipes, etc., determined at minimum design temperature and atmospheric *pressure* (3.16)

### 3.14 net mass

maximum allowable mass of the *cryogenic fluid* (3.1) which may be filled

Note 1 to entry: The maximum allowable mass is equal to the mass of the cryogenic liquid occupying 98 % of the *net volume* (3.13) of the *inner vessel* (3.4) under conditions of incipient opening of the relief device with the vessel in a level attitude and the mass of the gas at the same conditions in the remaining volume of the inner vessel.

Note 2 to entry: Cryogenic liquid helium can occupy 100 % of the volume of the inner vessel at any *pressure* (3.16).

**3.15**

**gross mass**

sum of *tare mass* (3.12) plus *net mass* (3.14)

**3.16**

**pressure**

**gauge pressure**

pressure relative to atmospheric pressure

**3.17**

**fixed tank**

**tank vehicle**

large transportable vessel permanently attached to a vehicle or to units of running gear

**3.18**

**demountable tank**

large transportable vessel non-permanently attached to a vehicle

Note 1 to entry: When attached to the carrier vehicle, the demountable tank meets the requirements prescribed for a fixed tank. It is designed to be lifted only when empty.

**3.19**

**portable tank**

a thermally insulated tank having a capacity of more than 450 litres fitted with *service equipment* (3.9) and structural equipment necessary for the transport of refrigerated liquefied gases

Note 1 to entry: It can be lifted full and loaded and discharged without removal of structural element.

Note 2 to entry: The list of the refrigerated liquefied gases is available in [Annex K](#).

**3.20**

**maximum allowable working pressure**

*ps*

maximum gauge *pressure* (3.16) permissible at the top of the vessel in its normal operating position

**3.21**

**relief plate**

**relief plug**

plate or plug retained by atmospheric *pressure* (3.16) which allows relief of excess internal pressure, generally from the vacuum jacket

**3.22**

**bursting disc device**

non-reclosing pressure-relief device ruptured by differential *pressure* (3.16)

Note 1 to entry: It is the complete assembly of installed components including the bursting disc holder, where appropriate.

**3.23**

**pressure-strengthened vessel**

*pressure* (3.16) vessel which has been subjected to a calculated and controlled internal pressure (strengthening pressure) after completion, the wall thickness of which is calculated on the basis of the stress at the strengthening pressure and not on the basis of the conventional design stress value of the material used

Note 1 to entry: *Pressure* (3.16) vessels made from solution heat-treated material are subject to a controlled plastic deformation during the strengthening operation as its yield point is raised. Pressure vessels made from work-hardened material are subject to little or no plastic deformation.

**3.24****residual elongation**

original elongation of the steel minus the elongation created by the cold-forming deformation

**3.25****leakproofness test**

test using gas subjecting the shell and its *service equipment* (3.9), to an effective internal *pressure* (3.16) not less than 90 % of the MAWP but not greater than the design pressure

**4 Symbols**

| Symbol      | Definition                                                                | Unit         |
|-------------|---------------------------------------------------------------------------|--------------|
| $b$         | width of pad, ring or shell reinforcement                                 | mm           |
| $c$         | allowance for corrosion                                                   | mm           |
| $d_i$       | diameter of opening                                                       | mm           |
| $d_a$       | outside diameter of tube or nozzle                                        | mm           |
| $f$         | narrow side of rectangular or elliptical plate                            | mm           |
| $h$         | thickness of pad reinforcement                                            | mm           |
| $l_c$       | cone length between effective stiffenings (see <a href="#">Figure 5</a> ) | mm           |
| $l$         | ligament (web) between two nozzles                                        | mm           |
| $l_b, l'_b$ | buckling length                                                           | mm           |
| $l_s$       | length of nozzle reinforcement outstanding                                | mm           |
| $n$         | number of lobes                                                           | —            |
| $p$         | design pressure as defined in <a href="#">10.3.2.2</a>                    | —            |
| $p_c$       | calculation pressure as defined in <a href="#">10.2.3.1 a)</a>            | bar (or MPa) |
| $p_e$       | allowable external pressure limited by elastic buckling                   | bar (or MPa) |
| $p_k$       | strengthening pressure                                                    | bar (or MPa) |
| $p_L$       | liquid pressure                                                           | bar (or MPa) |
| $p_p$       | allowable external pressure limited by plastic deformation                | bar (or MPa) |
| $p_s$       | maximum allowable gauge pressure                                          | bar (or MPa) |
| $p_T$       | test pressure (see <a href="#">6.2</a> )                                  | bar (or MPa) |
| $r$         | radius, e.g. inside knuckle radius of dished end and cones                | mm           |
| $s$         | minimum thickness                                                         | mm           |
| $s_A$       | required wall thickness at opening edge                                   | mm           |
| $s_e$       | actual wall thickness                                                     | mm           |
| $s_g$       | required wall thickness outside corner area                               | mm           |

|            |                                                                                                                   |                   |
|------------|-------------------------------------------------------------------------------------------------------------------|-------------------|
| $s_n$      | length of nozzle reinforcement in stand                                                                           | mm                |
| $s_s$      | wall thickness of nozzle                                                                                          | mm                |
| $s_1$      | required wall thickness within corner area                                                                        | mm                |
| $t$        | in this context, centre-to-centre distance between two nozzles                                                    | mm                |
| $x$        | (decay-length zone) distance over which governing stress is assumed to act                                        | mm                |
| $x_i$      | characteristic lengths ( $i = 1, 2, 3$ ) to define corner area [Figure 7 a) and Figure 7 b) and 10.3.6.5.4]       | mm                |
| $\eta$     | factor indicative of the utilization of the permissible design stress in joints or factor allowing for weakenings | —                 |
| $A$        | cross-sectional area of reinforcing element                                                                       | mm <sup>2</sup>   |
| $C, \beta$ | design factors                                                                                                    | —                 |
| $D$        | shell diameter                                                                                                    | mm                |
| $D_a$      | outside diameter, e.g. of a cylindrical shell                                                                     | mm                |
| $D_{a1}$   | outside diameter of connected cylinder (see Figure 7)                                                             | mm                |
| $D_{a2}$   | outside diameter at effective stiffening (see Figure 9)                                                           | mm                |
| $D_i$      | internal diameter, e.g. of a cylindrical shell                                                                    | mm                |
| $D_k$      | design diameter (see Figure 7)                                                                                    | mm                |
| $D_s$      | shell diameter at nozzle (see Figure 8)                                                                           | mm                |
| $E$        | Young's modulus                                                                                                   | N/mm <sup>2</sup> |
| $I$        | moment of inertia of reinforcing element                                                                          | mm <sup>4</sup>   |
| $R_e$      | minimum guaranteed yield stress or 0,2 % proof stress at 20 °C (1 % proof stress for austenitic steel)            | N/mm <sup>2</sup> |
| $R_m$      | minimum guaranteed tensile strength at 20 °C                                                                      | N/mm <sup>2</sup> |
| $K$        | material property used for design (see 10.3.2.3)                                                                  | N/mm <sup>2</sup> |
| $K_T$      | material property at temperature $T$ in °C (e.g. $K_{20}$ for material property at 20 °C (see 10.3.2.3.2))        | N/mm <sup>2</sup> |
| $R$        | radius of curvature, e.g. inside crown radius of dished end                                                       | mm                |
| $S$        | safety factor at design pressure, in relation with $R_e$                                                          | —                 |
| $S_k$      | safety factor against elastic buckling at design pressure                                                         | —                 |
| $S_p$      | safety factor against plastic deformation                                                                         | —                 |
| $Z$        | auxiliary value                                                                                                   | —                 |

|           |                                                  |   |
|-----------|--------------------------------------------------|---|
| $\nu$     | Poisson's ratio                                  | — |
| $u$       | out of roundness (see <a href="#">11.5.5.2</a> ) | — |
| $\varphi$ | cone angle                                       | ° |

## 5 General requirements

**5.1** The large transportable cryogenic vessel shall safely withstand the mechanical and thermal loads and the chemical effects encountered during pressure test and normal operation. These requirements are deemed to be satisfied if [Clauses 6](#) to [12](#) are fulfilled. The vessel shall be marked in accordance with [Clause 13](#), tested in accordance with [Clause 14](#) and operated in accordance with ISO 20421-2.

**5.2** Large transportable cryogenic vessels shall be equipped with valves, pressure-relief devices, etc., configured and installed in such a way that the vessel can be operated safely. The number of openings in the inner vessel for this equipment shall be kept to a minimum.

**5.3** The large transportable cryogenic vessel shall be clean for the intended service in accordance with ISO 23208.

**5.4** The manufacturer shall retain the documents referred to in [Clause 16](#), and all supporting documentation (including that from his subcontractors, if any), for a required period (e.g. product liability). In addition, the manufacturer shall retain all supporting and background documentation (including that from his subcontractors, if any) which establishes that the vessel conforms to this document.

## 6 Mechanical loads

### 6.1 General

The large transportable cryogenic vessel shall resist the mechanical loads mentioned in [10.2.3](#) without such deformation which can affect safety and which can lead to leakage. This requirement can be validated by:

- the calculation;
- the calculation and pressure-strengthening method, if allowed;
- the calculation and experimental method.

### 6.2 Load during the pressure test

The load exerted during the pressure test shall be calculated with [Formula \(1\)](#):

$$p_T \geq 1,3(p_S + 1) \text{ bar or } [p_T \geq 1,3(p_S + 0,1) \text{ MPa}] \quad (1)$$

where

- $p_T$  is the test pressure (in bar);
- $p_S$  is the maximum allowable pressure (in bar);
- +1 is the allowance for external vacuum (in bar).
- +0,1 is the allowance for external vacuum (in MPa).

## 7 Chemical effects

Due to operating temperatures and the materials of construction, the possibility of chemical action on the inner surfaces in contact with the cryogenic fluids can be neglected.

Due to the fact that the inner vessel is inside an evacuated outer jacket, neither external corrosion of the inner vessel, nor corrosion on the inner surfaces of the outer jacket will occur. Therefore, inspection openings are not required in the inner vessel or the outer jacket.

Corrosion allowance is also not required on surfaces in contact with the operating fluid or exposed to the vacuum interspace between the inner vessel and the outer jacket.

The material and the protection for the surfaces exposed to the atmosphere shall be suitable for intended use (e.g. resistant to industrial and marine atmospheres).

## 8 Thermal conditions

The following thermal conditions shall be taken into account:

For the inner vessel and its associated equipment the full range of temperature expected.

For the outer jacket and equipment thereof (other than equipment covered in [Clause 7](#)):

- a minimum working temperature of  $-20\text{ }^{\circ}\text{C}$ ;
- a maximum working temperature of  $50\text{ }^{\circ}\text{C}$ .

NOTE 1 Some locations require lower minimum working temperature e.g.  $-40\text{ }^{\circ}\text{C}$  and/or higher maximum working temperature, e.g.  $+65\text{ }^{\circ}\text{C}$ .

NOTE 2 This does not apply if the jacket is designed for a lower temperature to be marked on the nameplate.

## 9 Materials

### 9.1 Selection of materials

**9.1.1** Materials which are, or can be, in contact with cryogenic fluids shall be in accordance with ISO 21010.

**9.1.2** Materials used at low temperatures shall follow the requirements of the relevant parts of ISO 21028-1 and ISO 21028-2; for non-metallic materials, low-temperature suitability shall be validated by an experimental method, taking into account operating temperatures.

**9.1.3** The base materials, listed in [Annex G](#), subject to meeting the extra requirements given in [Clauses 5](#) to [16](#), are suitable for and may be employed in the manufacture of the cryogenic vessels, in conformance with this document.

### 9.2 Inspection documentation

**9.2.1** The material according to ISO 21028-1 and ISO 21028-2 shall be declared by an inspection certificate 3.1 in accordance with ISO 10474:2013, 5.1.

**9.2.2** The material manufactured to a recognized International Standard shall meet the testing requirements of ISO 21028-1 and ISO 21028-2 and shall be declared by an inspection certificate 3.1 in accordance with ISO 10474:2013, 5.1.

**9.2.3** The delivery of material which is not manufactured to a recognized International Standard shall be guaranteed by an inspection certificate 3.2 in accordance with ISO 10474:2013, 5.2 confirming that the material fulfils the requirements in [9.1](#). The material manufacturer shall follow a recognized International Standard for processing and establishing the guaranteed material properties.

**9.2.4** The outer jacket and the equipment not subjected to low temperature shall be manufactured from material suitable for the intended service.

## 10 Design

### 10.1 Design options

#### 10.1.1 General

The design shall be carried out in accordance with one of the options given in [10.1.2](#), [10.1.3](#) or [10.1.4](#).

Metallic materials used at cryogenic temperatures shall meet the requirements of the relevant clauses of ISO 21028-1 and ISO 21028-2.

In the case of 9 % Ni steel, the additional requirements in [Annex C](#) shall be satisfied.

#### 10.1.2 Design by calculation

Calculation of all pressure- and load-bearing components shall be carried out. The pressure part thicknesses of the inner vessel and outer jacket shall not be less than required by [10.3](#). Additional calculations may be required to ensure the design is satisfactory for the operating conditions including an allowance for dynamic loads.

#### 10.1.3 Design by calculation and pressure strengthening

The pressure-retaining capability of inner vessels manufactured from austenitic stainless steel, strengthened by pressure, shall be calculated in accordance with [Annex D](#).

#### 10.1.4 Design of components by calculation supplemented with experimental methods

Where it is not possible to design non-inner vessel components by calculation alone, planned and controlled experimental means may be used provided that the results confirm the safety factors required in [10.3](#). An example is the application of strain gauges to assess stress levels.

### 10.2 Common design requirements

#### 10.2.1 General

The requirements of [10.2.2](#) to [10.2.7](#) are applicable to all vessels irrespective of the design option used.

In the event of an increase in at least one of the following parameters, the initial design process shall be repeated to take account of these modifications:

- maximum allowable pressure;
- specific mass (density) of the densest gas for which the vessel is designed;
- maximum tare weight of the inner vessel;
- nominal length and/or diameter of the inner shell.

The initial design process shall be repeated also in the event of any change relative to:

- the type of material or grade (e.g. stainless steel to aluminium);
- the fundamental shape;
- the decrease in the minimum mechanical properties of the material being used;
- the modification of the design of an assembly method concerning any part under stress, particularly as far as the support systems between the inner vessel and the outer jacket or the inner vessel itself or the protective frame, if any, are concerned.

### 10.2.2 Design specification

To enable the design to be prepared, the following information which defines a vessel type shall be available:

- maximum allowable pressure;
- fluids intended to be contained;
- gross volume of the inner vessel;
- dimensions and allowable weight, taking into account characteristics of the vehicle;
- location of fastening points and loads allowable on these points;
- filling and emptying rate;
- range of ambient temperature, if different from [Clause 8](#);
- transportation mode (see [Tables 2](#) and [3](#)).

A design document in the form of drawings with text, if any, shall be prepared. It shall contain the information given above plus the following where applicable:

- definition of which components are designed by calculation, by pressure strengthening, by experiment;
- drawings with dimensions and thicknesses of load-bearing components;
- specification of all load-bearing materials including grade, class, temper, testing, etc., as relevant;
- applicable material test certificates;
- location and details of welds and other joints, welding and other joining procedures, filler, joining materials, etc., as relevant;
- calculations to verify conformance to this document;
- design test programme;
- non-destructive testing requirements;
- pressure test requirements;
- piping configuration, including type, size and location of all valves and relief devices;
- details of fastenings.

### 10.2.3 Design loads

#### 10.2.3.1 General

**10.2.3.1.1** The large transportable cryogenic vessel shall be able to withstand safely the mechanical and thermal loads encountered during a pressure test and normal operation. The static forces used shall be obtained as required in [10.2.3.1.2](#) and [10.2.3.1.3](#).

**10.2.3.1.2** The inner vessel, its fastenings and supports shall be designed for the static forces obtained by multiplying the load factors applicable for the transportation modes given in [Table 1](#) with the maximum weight imposed on the inner vessel. The maximum weight imposed on the inner vessel shall include the weights of the inner vessel, its fastenings and supports, maximum permissible content, piping, insulation and any other item supported on the inner vessel. Each load case shall be considered separately, but all forces in a load case shall be considered acting simultaneously. The static forces obtained are equivalent to the dynamic loads experienced during normal operation of the transport vessel. The load factors for assessment of fatigue life are given in [Table 2](#).

**10.2.3.1.3** The outer jacket, its fastenings and supports shall be designed for the static forces obtained by multiplying the load factors applicable for the transportation modes given in [Table 1](#) with the maximum weight imposed on the outer jacket. The maximum weight imposed on the outer jacket shall include the weights of the outer jacket, with all its enclosures including inner vessel filled to the maximum permissible capacity and the weights of all items fastened to or supported from/to the outer jacket such as piping, controls, cabinets, etc. Each load case shall be considered separately, but all forces in a load case shall be considered acting simultaneously. The static forces obtained are equivalent to the dynamic loads experienced during normal operation of the transport vessel. The load factors for assessment of fatigue life are given in [Table 2](#).

**10.2.3.1.4** Fatigue life calculation shall be conducted according to EN 13445-3, ASME VIII-2 or equivalent standards/codes under consideration of the imperfections under [11.5](#), and shall be conducted for the highest number of expected cycles of all relevant loads during the life time with consideration of the following criteria.

The life time of the vessel may be specified and marked on the nameplate.

In fatigue evaluation of any item designed to withstand more than one load case, the maximum loadings in each direction from all applicable load cases shall be considered to act simultaneously in determining the magnitude of alternating stresses. The usage factor shall not exceed 0,5 for the inner tank, and 1,00 nor for the outer tank.

**NOTE** Fatigue analysis as stated above can be satisfied for existing designs through documented evidence of previous long term satisfactory service under the same operating conditions.

**Table 1 — Design load factors in specified transportation modes**

| Transportation modes | Load case      | Load factors |          |     |      |         |
|----------------------|----------------|--------------|----------|-----|------|---------|
|                      |                | Forward      | Backward | Up  | Down | Lateral |
| Road and water       | 1              | 2,0          |          |     | 1,0  |         |
|                      | 2              |              | 2,0      |     | 1,0  |         |
|                      | 3              |              |          | 1,0 |      |         |
|                      | 4              |              |          |     | 2,0  |         |
|                      | 5 <sup>a</sup> |              |          |     | 1,0  | 1,0     |

**NOTE** For mixed transportation modes, the higher appropriate design factor applies.

<sup>a</sup> Load case 5A should be considered instead of load case 5 if the direction of the travel is not known.

<sup>b</sup> The cushioning devices should be tested to demonstrate their ability to limit forces transmitted from the coupler to the tank is less than twice the weight of the tank filled to its rated capacity at a 16 kilometre per hour impact.

Table 1 (continued)

| Transportation modes                         | Load case       | Load factors |          |     |      |         |
|----------------------------------------------|-----------------|--------------|----------|-----|------|---------|
|                                              |                 | Forward      | Backward | Up  | Down | Lateral |
|                                              | 5A <sup>a</sup> |              |          |     | 1,0  | 2,0     |
| Rail with cushioning devices <sup>b</sup>    | 1               | 2,0          |          |     | 1,0  |         |
|                                              | 2               |              | 2,0      |     | 1,0  |         |
|                                              | 3               |              |          | 2,0 |      |         |
|                                              | 4               |              |          |     | 2,0  |         |
|                                              | 5               |              |          |     | 1,0  | 2,0     |
| Rail without cushioning devices <sup>b</sup> | 1               | 4,0          |          |     | 1,0  |         |
|                                              | 2               |              | 4,0      |     | 1,0  |         |
|                                              | 3               |              |          | 2,0 |      |         |
|                                              | 4               |              |          |     | 2,0  |         |
|                                              | 5 <sup>a</sup>  |              |          |     | 1,0  | 2,0     |
|                                              | 5A <sup>a</sup> |              |          |     | 1,0  | 4,0     |

NOTE For mixed transportation modes, the higher appropriate design factor applies.

<sup>a</sup> Load case 5A should be considered instead of load case 5 if the direction of the travel is not known.

<sup>b</sup> The cushioning devices should be tested to demonstrate their ability to limit forces transmitted from the coupler to the tank is less than twice the weight of the tank filled to its rated capacity at a 16 kilometre per hour impact.

Table 2 — Load factors for normal operation for fatigue analysis in specified transportation modes

| Transportation modes                         | Load case       | Load factors |          |        |        |        |         |
|----------------------------------------------|-----------------|--------------|----------|--------|--------|--------|---------|
|                                              |                 | Forward      | Backward | Up     | Down   |        | Lateral |
|                                              |                 | cyclic       | cyclic   | cyclic | cyclic | steady | cyclic  |
| Road and water                               | 1               | 0,7          |          |        |        | 1,0    |         |
|                                              | 2               |              | 0,7      |        |        | 1,0    |         |
|                                              | 3               |              |          | 1,0    |        |        |         |
|                                              | 4               |              |          |        | 1,0    | 1,0    |         |
|                                              | 5               |              |          |        |        | 1,0    | 0,7     |
| Rail with cushioning devices <sup>b</sup>    | 1               | 2,0          |          |        |        | 1,0    |         |
|                                              | 2               |              | 2,0      |        |        | 1,0    |         |
|                                              | 3               |              |          | 1,0    |        |        |         |
|                                              | 4               |              |          |        | 1,0    | 1,0    |         |
|                                              | 5 <sup>a</sup>  |              |          |        |        | 1,0    | 1,0     |
|                                              | 5A <sup>a</sup> |              |          |        |        | 1,0    | 2,0     |
| Rail without cushioning devices <sup>b</sup> | 1               | 4,0          |          |        |        | 1,0    |         |
|                                              | 2               |              | 4,0      |        |        | 1,0    |         |
|                                              | 3               |              |          | 1,0    |        |        |         |
|                                              | 4               |              |          |        | 1,0    | 1,0    |         |
|                                              | 5 <sup>a</sup>  |              |          |        |        | 1,0    | 1,0     |
|                                              | 5A <sup>a</sup> |              |          |        |        | 1,0    | 4,0     |

<sup>a</sup> Load case 5A should be considered instead of load case 5 if the direction of the travel is not known.

<sup>b</sup> The cushioning devices should be tested to demonstrate their ability to limit forces transmitted from the coupler to the tank is less than twice the weight of the tank filled to its rated capacity at a 16 kilometre per hour impact.

### 10.2.3.2 Inner vessel

**10.2.3.2.1** The following loads shall be considered to act in combination where relevant:

- a) calculation pressure,  $p$ , with [Formula \(2\)](#):

$$p = p_S + p_L + 1 \text{ bar or } (p = p_S + p_L + 0,1 \text{ MPa}) p_c \quad (2)$$

where  $p_L$  is the pressure, in bar, exerted by the mass of the liquid contents when the vessel is filled to capacity and subject to each load defined in [10.2.3.1](#), with either:

- 1) boiling liquid at atmospheric pressure; or
  - 2) cryogenic fluid at its equilibrium triple point or melting-point temperature at atmospheric pressure;
- b) loads imposed on the inner vessel due to the mass of the inner vessel and its contents when subject to each of the loads defined in [10.2.3.1](#);
- c) loads imposed by the piping due to the differential thermal movement of the inner vessel, the piping and the outer jacket, in which the following cases shall be considered:
- cool down (inner vessel warm/piping cold);
  - filling and withdrawal (inner vessel cold/piping cold); and
  - transport and storage (inner vessel cold/piping warm);
- d) reactions at the support points of the inner vessel during operation when the vessel contains cryogenic liquid product. The reactions shall be determined as described in [10.2.3.1.1](#);
- e) reactions at the support points of the inner vessel during operation when the vessel contains only gaseous product at 20 °C. The reactions shall be determined as described in [10.2.3.1.1](#).

**10.2.3.2.2** The design shall be evaluated for the following conditions:

Pressure test: the value used for validation purposes shall be considered for each element of the vessel, e.g. shell courses, head, etc., [see [Formula \(3\)](#)]:

$$p_T \geq 1,3(p_S + 1) \text{ bar or } [p_T \geq 1,3(p_S + 0,1) \text{ MPa}] \quad (3)$$

where  $p_S$  is the maximum allowable pressure.

The 1 bar (0,1 MPa) is added to allow for the external vacuum. The primary membrane stress at test pressure shall not exceed the prescribed value but in no case the yield stress of the material.

The minimum test pressure of the inner vessel shall be 3 bar (0,3 MPa). This requirement does not apply to heating or cooling systems including cooling fluid reservoirs, and related service equipment.

### 10.2.3.3 Outer jacket

The following loads shall be considered to act in combination where relevant:

- a) an external pressure of 1 bar (0,1MPa);
- b) an internal pressure equal to the set pressure of the outer-jacket pressure relief device;
- c) load imposed by the inner-vessel and its contents at the support points in the outer jacket when subject to the forces specified in [10.2.3.1.1](#) and [10.2.3.1.2](#) and [Tables 2](#) and [3](#);

- d) load imposed by piping as defined in [10.2.3.2.1 c\)](#);
- e) load imposed at the inner-vessel support points in the outer jacket when the inner vessel cools from ambient to operating temperature and during operation;
- f) reactions at the outer-jacket fastening points when subject to the forces specified in [10.2.3.1.2](#) and [Tables 2](#) and [3](#).

#### 10.2.3.4 Self-supporting vessels

In the case of vehicles in which the inner vessel and possibly the outer jacket constitute stressed self-supporting members of the vehicle, these shall be designed to withstand the stresses thus imposed in addition to stresses from other sources [see [10.2.3.2.1 c\)](#) and [10.2.3.3 f\)](#)].

#### 10.2.3.5 Inner-vessel supports

The inner-vessel supports shall be designed for the loads specified in [10.2.3.1](#) and [10.2.3.2](#) to a maximum allowable stress value equal to  $\frac{2}{3}K_{20}$ .

Hardening effects where guaranteed can be considered in the allowable stress.

#### 10.2.3.6 Surge plates

The inner-vessel shall be divided by surge plates to provide stability and limit dynamic loads to the requirements of [10.2.3](#), unless it is to be filled equal to or more than 80 % of its capacity or nominally empty. The cross-sectional area of the surge plate shall be at least 70 % of the cross-section of the vessel.

The volume between surge plates shall not exceed  $\frac{10500}{s_g}$  litres where  $s_g$  is the specific gravity of the cryogenic fluid at 1 bar (0,1 MPa) saturation.

Surge plates and their attachments to the shell shall be designed to resist the stresses caused by a pressure evenly distributed across the area of the surge plate. The pressure is calculated by considering the mass of liquid between the plates decelerating at  $2g$  ([10.2.3](#)).

#### 10.2.3.7 Outer-jacket supports

The outer-jacket supports shall be suitable for the load defined in [10.2.3.3](#).

#### 10.2.3.8 Fastening points

Fastening points shall be suitable for fastening the large transportable cryogenic vessel to the vehicle when filled to capacity and subject to each of the loads defined in [10.2.3](#).

#### 10.2.3.9 Protection of upper fittings

The fittings and accessories mounted on the upper part of the vessel shall be protected in such a way that damage caused by overturning cannot impair operational integrity. This protection may take the form of cylindrical profile of the vessel, of strengthening rings, protective canopies or transverse or longitudinal members so shaped that effective protection is given (e.g. structures of frame such as in ISO 1496-3). External stiffening rings shall not be used on vacuum jacket of tanks for flammable fluids.

#### 10.2.3.10 Stability

The overall width of the ground-level bearing surface (distance between the outer points of contact with the ground of the right-hand tyre and the left-hand tyre of the same axle) shall be at least equal to 90 % of the height of the centre of gravity of the fully laden tank vehicle. In an articulated vehicle, the

mass on the axles of the load-carrying unit of the laden semitrailer shall not exceed 60 % of the nominal total laden mass of the complete articulated vehicle.

#### 10.2.3.11 Piping and valves

Piping including valves, fittings and supports shall withstand the following loads. With the exception of a), the loads shall be considered to act in combination where relevant.

- a) Pneumatic pressure test: not less than the allowable working pressure  $p_s$  plus 1 bar (0,1 MPa) for piping inside the vacuum jacket.
- b) Pressure during operation: not less than the set pressure of the system pressure-relief device.
- c) Thermal loads defined in [10.2.3.2.1 d\)](#).
- d) Dynamic loads.
- e) Set pressure of thermal-relief devices where applicable.
- f) Loads generated during pressure-relief discharge.

Piping and accessories shall be designed such that their lowest natural frequency is equal to or higher than 30 cycles per second.

This equipment shall be protected or positioned so as to be protected against the risk of being wrenched off or damaged during transport.

In the particular case of liquid with a boiling temperature colder than that of liquid nitrogen, the possibility of air condensing on uninsulated parts shall be considered.

The leakproofness of this equipment shall be ensured in the event of overturning of the vehicle. The gaskets shall be made of a material compatible with the fluid carried, in accordance with ISO 21010.

Each bottom-filling or bottom-discharge opening shall be provided with at least two independent shut-off devices in series, the first being a stop valve situated as close as possible to the outer jacket and provided with protection against mechanical damage at least equal to that afforded by the outer jacket.

For flammable fluids only, in order to prevent leaks of flammable fluids, the first stop valve shall be a quick-closing safety device which closes automatically in the event of an unintended movement of the vehicle or of fire during the filling/emptying operation. It shall also be possible to operate the closing device by remote control. All vent pipes, including pressure-relief devices and purge valves, shall be connected to a vent pipe allowing safe discharge. The control cabinet shall be vented so that flammable gas cannot accumulate inside.

#### 10.2.4 Fatigue

The design shall take into account the effect of cyclic stress on the inner vessel, outer jacket and their attachments during normal conditions of operation, as listed in [Table 2](#), including pressure cycles.

When considering the case of fatigue, the common requirement of designing with loads according to [10.2.3](#) is such as to accommodate the effects of fatigue. It can be necessary to pay particular attention to specific details in the supports and piping systems to avoid stress raisers.

#### 10.2.5 Corrosion allowance

Corrosion allowance is not required on surfaces in contact with the operating fluid. Corrosion allowance is not required on other surfaces if they are adequately protected against corrosion.

NOTE 1 Due to the combination of materials of construction and operating fluids, internal corrosion cannot occur.

NOTE 2 The inner vessel is inside the evacuated outer jacket and, hence, external corrosion of the inner vessel cannot occur.

### 10.2.6 Inspection openings

Inspection openings are not required in the inner vessel or the outer jacket, provided that the requirements of ISO 20421-2 are followed.

NOTE The elimination of inspection openings also assists in maintaining the integrity of the vacuum in the interspace.

### 10.2.7 Pressure relief

#### 10.2.7.1 General

Relief systems shall be designed to meet the requirements given in [10.2.7.2](#) to [10.2.7.4](#).

#### 10.2.7.2 Inner vessel

**10.2.7.2.1** Every shell shall be provided with not less than two independent spring-loaded pressure relief devices set at pressures not exceeding the maximum allowable pressure of the tank. The pressure relief devices shall open automatically at pressures not less than the set pressure of the device and be fully open at a pressure equal to 110 % of the set pressure. These devices shall, after discharge, close at a pressure not lower than 10 % below the pressure at which discharge starts and shall remain closed at all lower pressures. The pressure relief devices shall be of the type that will resist dynamic forces including surge.

**10.2.7.2.2** In the case of the loss of vacuum, an additional reclosing pressure-relief device, set at no more than 110 % of the maximum allowable pressure, may be used, and the combined capacity of all pressure-relief devices installed shall be sufficient, so that the pressure (including accumulation) inside the vessel does not exceed 120 % of the maximum allowable pressure, in accordance with this document. For non-flammable refrigerated liquefied gases (except oxygen) and hydrogen, this capacity may be achieved by the use of bursting discs in parallel with the required safety relief devices. Bursting discs shall rupture at nominal pressure equal to the test pressure.

**10.2.7.2.3** Under the circumstances described in [10.2.7.2.1](#) and [10.2.7.2.2](#), together with complete fire engulfment, the combined capacity of all pressure-relief devices shall be sufficient to limit the pressure in the vessel to the test pressure, providing the piping capacity and effects of back pressures are properly accounted for.

**10.2.7.2.4** Relief devices for inner vessels shall be in accordance with ISO 21013-1 and ISO 21013-2.

**10.2.7.2.5** The required capacity of the relief devices shall be calculated in accordance with ISO 21013-3.

The pressure-relief system shall be sized so that the pressure drop during discharge does not cause the valve to reseal instantly.

#### 10.2.7.3 Outer jacket

Relief devices for the outer jacket shall be in accordance with [Annex F](#).

A pressure-relief device shall be fitted to the outer jacket. The device shall be set to open at a pressure which prevents collapse of the inner vessel and is not more than 0,5 bar (0,05 MPa). The total discharge area of the pressure relief device(s) should not be less than 0,34 mm<sup>2</sup>/l capacity of the inner vessel.

#### 10.2.7.4 Piping

Any section of pipework containing cryogenic fluid which can be isolated shall be protected by a relief valve or other suitable relief device.

#### 10.2.8 Valves

Valves shall conform to ISO 21011.

#### 10.2.9 Insulation

For oxygen or gases having a boiling point below  $-182\text{ }^{\circ}\text{C}$  at atmospheric pressure, the insulation installed on the tank shall be in accordance with ISO 21010.

Heat shields cooled by non-flammable, non-toxic fluid being transported of a different fluid carried separately or both and is vented to atmosphere may be used in UN portable tanks for refrigerated liquefied gases to reduce the heat flow into the fluid being carried. The vented fluid shall be in gaseous state and the venting shall be done in an environmentally friendly manner with temperature of the venting gas not less than  $40\text{ }^{\circ}\text{C}$  below the ambient temperature and pressure of the venting gas not higher than 0,75 bar.

#### 10.2.10 Degree of filling

The degree of filling of large transportable vacuum-insulated vessels shall remain below the level at which, if the contents were raised to the temperature at which the vapour pressure equalled to opening pressure of the lowest set pressure relief valve on stream, the volume of the liquid would reach 98 % of the vessel's net volume. Degree of filling for helium may be 100 % of the net volume. Pre-trip inspection shall ensure that the above limits are not exceeded.

In some countries, same degree of filling, without taking into account liquid expansion, is allowed when the intended duration of carriage is considerably shorter than the holding time.

#### 10.2.11 Electrical continuity

All metallic components of large transportable vacuum-insulated vessels intended for the carriage of flammable gases shall be electrically continuous. The electrical resistance, as measured by an ohmmeter, between the inner vessel and/or related metallic components to the vehicle chassis shall not exceed 10 ohms.

### 10.3 Design by calculation

#### 10.3.1 General

The dimensions of the inner vessel and outer jacket shall not be less than that determined in accordance with this subclause.

#### 10.3.2 Inner vessel

##### 10.3.2.1 General

The minimum thickness of the inner vessel shall be the larger of the thickness value from [Table 3](#) or [10.3.6](#).

Table 3 — Inner-vessel minimum wall thickness

Dimensions in millimetres

| Inner vessel diameter<br>$D$                                                                                                                                                                                                                                                      | Minimum wall thickness for reference material <sup>a</sup><br>$s_r$ |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------|
| $D \leq 1\,800$                                                                                                                                                                                                                                                                   | 3                                                                   |
| $D > 1\,800$                                                                                                                                                                                                                                                                      | 4                                                                   |
| <sup>a</sup> Reference material is material having a product $R_m \times A_5$ of approximately 10 000, which yields $(R_m \times A_5)^{1/3} = 21,4$ .<br>For other materials, the required minimum thickness of the metal used shall be calculated from <a href="#">Annex J</a> . |                                                                     |

The  $R_m$  and  $A_5$  values at a temperature not lower than the saturation temperature of the fluid at pressure  $p_s$  shall be determined from the appropriate material standard or shall be guaranteed by the material manufacturer.

### 10.3.2.2 Design pressure, $p$

The internal design pressure,  $p$ , shall be the greater of  $p_T$  as defined in [10.2.3.2.1 a\)](#), or  $p_C$  as defined in [10.2.3.2.2](#), corrected for operating conditions (i.e. multiplied by  $\frac{K_{20}}{K_T}$ ) to take into account the cold properties of the material used. It follows that shall  $K_{20}$  be used in the subsequent formulae where  $p$  is shown as the design pressure. The inner vessel shall be designed for an external pressure equal to the set pressure of the outer jacket pressure relief device.

### 10.3.2.3 Material properties, $K$

#### 10.3.2.3.1 General

The material property,  $K$ , to be used in the calculations shall be as follows:

- for austenitic stainless steels,  $R_{e\,1,0}$  proof strength;
- for carbon steels, aluminium and aluminium alloys,  $R_e$  = yield strength and, if not available,  $R_{e\,0,2}$  proof strength.

For calculation purposes the material property,  $K$ , of the inner vessel shall be limited to  $0,75 R_e$  or  $0,5 R_m$  (the minimum guaranteed tensile strength), whichever is the most stringent.

#### 10.3.2.3.2 $K_{20}$

$R_e$  and  $R_m$  shall be the minimum guaranteed values at 20 °C taken from the material standard.

In the case of austenitic stainless steels, the specified minimum values may be exceeded by up to 15 % for carrying all loads listed in [10.2.3.2](#), except for the design pressure,  $p$ , specified under [10.2.3.2.1 a\)](#).

The 15 % higher values of  $K_{20}$  may be used provided this higher value is attested in the inspection certificate and the following conditions are met:

- the material manufacturer shall guarantee compliance with this higher value, in writing, when accepting the order;
- the increased properties shall be verified by testing each cast (production lot);
- the welding procedure shall be suitably qualified.

Values of  $R_e$  and  $R_m$  used for design calculations shall be the minimum specified values of  $R_e$  and  $R_m$  in the material inspection certificate except that the value of  $R_e$  used shall not exceed  $0,85 R_m$ .

### 10.3.2.3.3 $K_t$

The permissible values of  $R_e$  and  $R_m$  shall be determined for the material at the operating temperature corresponding to a temperature not lower than the saturation temperature of the fluid at pressure,  $p_s$ . The values of  $R_e$ ,  $R_m$  and  $E$  shall be determined from the appropriate material standard or shall be guaranteed by the material manufacturer.

### 10.3.2.3.4 Brittleness

The material shall not be subject to brittle fracture at its minimum operating temperature (see ISO 21028-1 and ISO 21028-2).

### 10.3.2.3.5 Elongation

For steel, the elongation at fracture in % shall be not less than [Formula \(4\)](#) at 20 °C:

$$\frac{10000}{S_D} \text{ at } 20^\circ\text{C} \quad (4)$$

where  $S_D$  is the determined tensile strength in N/mm<sup>2</sup>.

In any case, it shall be not less than 16 % for fine grained steels and not less than 20 % for other steels. For aluminium and aluminium alloys the elongation at fracture shall not be less than 12 %.

Elongation and determined tensile strengths are the actual values indicated in the material certificates.

### 10.3.2.4 Safety factors $S$ , $S_p$ and $S_k$

Safety factors are the ratio of material property  $R$ ,  $K_{20}$ , or  $K_t$  over the maximum allowable stress.

a) Internal pressure (pressure on the concave surface):  $S = 1,33$ .

b) External pressure (pressure on the convex surface):

- cylindrical shells:  $S_p = 1,4$ ;  
 $S_k = 2,6$ ;
- spherical region:  $S_p = 2,1$ ;  
 $S_k = 2,6 + 0,0018 R/s_e$ ;
- knuckle region:  $S_p = 1,6$ .

### 10.3.2.5 Weld joint factor, $\eta$

$\eta = 1$  for all butt double-welded joints and single-welded butt joints with removable backing strips with complete penetration and full fusion and circumferential seams with permanent backing strip and circumferential joggle joints.

### 10.3.2.6 Corrosion allowances, $c$

$c = 0$

No corrosion allowance is required.

### 10.3.3 Outer jacket

#### 10.3.3.1 General

The following shall be used to determine the pressure part thickness in conjunction with [Formulae \(6\)](#) and [\(7\)](#).

The reference material equivalent thickness of the outer jacket shall be determined using [Annex J](#).

The aggregate reference material equivalent thickness of the outer-jacket wall and inner-vessel wall shall be not less than 5 mm if the diameter of the inner vessel is not more than 1 800 mm, and not less than 6 mm if this diameter is more than 1 800 mm. The minimum thickness in reference steel of outer jacket of tanks for flammable fluids shall be 6 mm.

#### 10.3.3.2 Calculation pressure, $p$

The internal calculation pressure,  $p$ , shall be not less than the set pressure of the outer jacket pressure, relief device.

The external calculation pressure shall be 1 bar (0,1 MPa).

#### 10.3.3.3 $K_{20}$

See [10.3.2.3.2](#).

#### 10.3.3.4 Safety factors $S$ , $S_p$ and $S_k$ in relation to $K$ , $K_{20}$ or $K_T$

- a) Internal pressure (pressure on the concave surface):  $S = 1,73$  may be reduced to 1,5 for road transportation mode, if allowed.
- b) External pressure (pressure on the convex surface):
  - cylindrical shells:  $S_p = 1,1$ ;  
 $S_k = 2,0$ ;
  - spherical region:  $S_p = 1,6$ ;  
 $S_k$  (see applicable method in [Annex H](#));
  - knuckle region:  $S_k = 1,2$ .

#### 10.3.3.5 Plastic deformation

Resistance to plastic deformation is determined by using [10.3.6.1.3](#) with the appropriate safety factor,  $S_p$ , defined in [10.3.2.4](#) and [10.3.3.4](#).

#### 10.3.3.6 Weld joint factor, $\eta$

For internal pressure (pressure on the concave surface),  $\eta = 0,85$ .

For external pressure (pressure on the convex surface),  $\eta = 1,0$ .

#### 10.3.3.7 Corrosion allowances, $c$

For austenitic stainless steel,  $c = 0$ .

For aluminium alloys,  $c = 0$ .

For carbon steel,  $c = 1,0$  mm.

NOTE  $c$  can be reduced to zero if the external surface is adequately protected against corrosion.

#### 10.3.4 Attachments

For those items attached to the inner vessel wall, other than the inner-vessel supports (see [10.2.3.4](#)), the allowable stress shall not exceed the  $0,75 K_{20}$  or  $0,75 K_T$  as applicable. Other attachments to the jacket shall be designed for the loads defined in [10.2.3.1](#) using established design methods and allowable stress not exceeding  $0,75 K_{20}$ . See also [Annex B](#) for an acceptable method.

When the inner vessel is being designed, the temperature and corresponding mechanical properties of the structural attachment attached to the inner vessel may be those of the component in question when the inner vessel is filled to capacity with cryogenic fluid at a temperature not lower than the saturation temperature at pressure  $p_s$ . However, it shall be checked whether the stresses are acceptable in warm conditions (vessel empty).

#### 10.3.5 Piping and accessories

Piping shall be designed for the loads defined in [10.2.3.11](#) using established piping design methods and safety factors. However, the overall safety factor used on the material property,  $K$ , shall not be less than the values given in [10.3.2.3](#).

#### 10.3.6 Calculation formula

##### 10.3.6.1 Cylindrical shells and spheres subject to internal pressure (pressure on the concave surface)

###### 10.3.6.1.1 Field of application

The field of application for cylindrical shells and spheres is [Formula \(5\)](#):

$$D_a/D_i \leq 1,2 \quad (5)$$

###### 10.3.6.1.2 Openings

For reinforcement of openings, see [10.3.6.7](#).

###### 10.3.6.1.3 Calculation

The required minimum wall thickness,  $s$ , for cylindrical shells is [Formula \(6\)](#):

$$s = \frac{D_a p}{20 \frac{K_{20}}{S} \eta + p} + c \quad (6)$$

The required minimum wall thickness,  $s$ , for spherical shells is [Formula \(7\)](#):

$$s = \frac{D_a p}{40 \frac{K_{20}}{S} \eta + p} + c \quad (7)$$

In case of  $p$  in MPa, conversion shall be considered.

### 10.3.6.2 Cylindrical shells subject to external pressure (pressure on the convex surface)

#### 10.3.6.2.1 Field of application

The field of application for cylindrical shells is [Formula \(8\)](#):

$$D_a/D_i \leq 1,2 \quad (8)$$

#### 10.3.6.2.2 Openings

Openings shall be calculated in accordance with [10.3.6.7](#) using the external pressure as an internal pressure.

#### 10.3.6.2.3 Calculation

[Annex H](#) gives two alternative calculation methods. Both methods give comparable results and shall be equally accepted.

### 10.3.6.3 Spheres subject to external pressure (pressure on the convex surface)

See [Annex H](#).

### 10.3.6.4 Dished ends

#### 10.3.6.4.1 Field of application

The following dish ends may be used:

- a) hemispherical ends where  $D_a/D_i \leq 1,2$ ;
- b) torispherical ends where  $0,5 D_a \leq R \leq D_a$  and  $0,5 D_a \geq r \geq 0,06 D_a$ ;
- c) 2:1 elliptical ends where  $R = 0,9 D_a$  and  $r = 0,170 D_a$ .

NOTE In the case of elliptical ends,  $0,001 \leq (s - c)/D_a \leq 0,1$ .

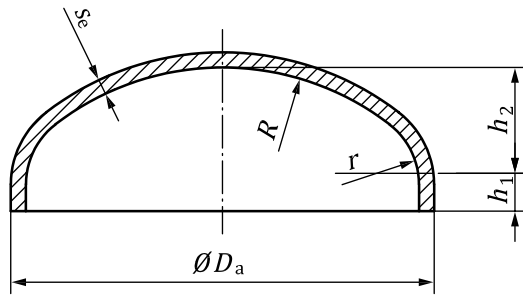
Dished ends of vacuum jackets are not required to meet the above restrictions on  $R$  and  $r$ , when  $r$  is greater than or equal to  $3 s$ .

#### 10.3.6.4.2 Straight flange

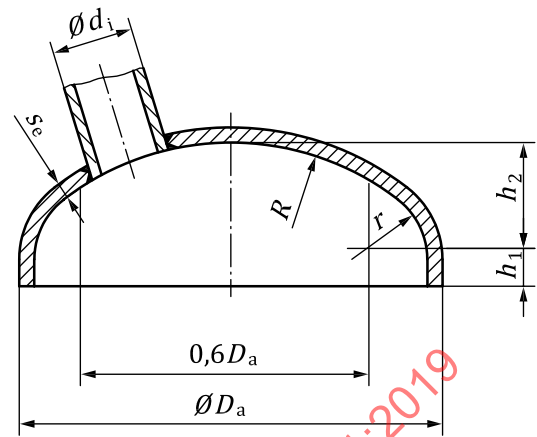
The straight flange length,  $h_1$  [[Figure 1](#) a) and b)], shall not be less than:

- for 10 % torispherical ends:  $3,0 s$ ;
- for 2:1 torispherical ends:  $3,0 s$ ;
- for 2:1 elliptical ends:  $3,0 s$ .

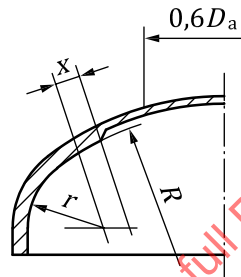
The straight flange may be shorter provided that in the case of inner vessels, the circumferential joint between the dished end and the cylinder is non-destructively tested as required for a weld joint factor of 1,0.



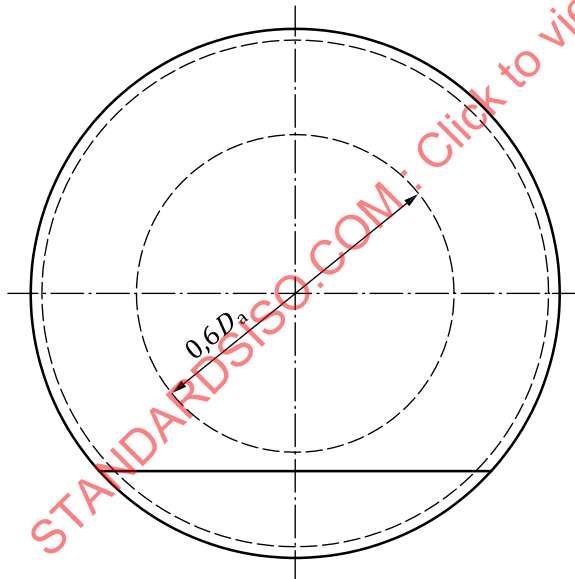
a) Unpierced dished end



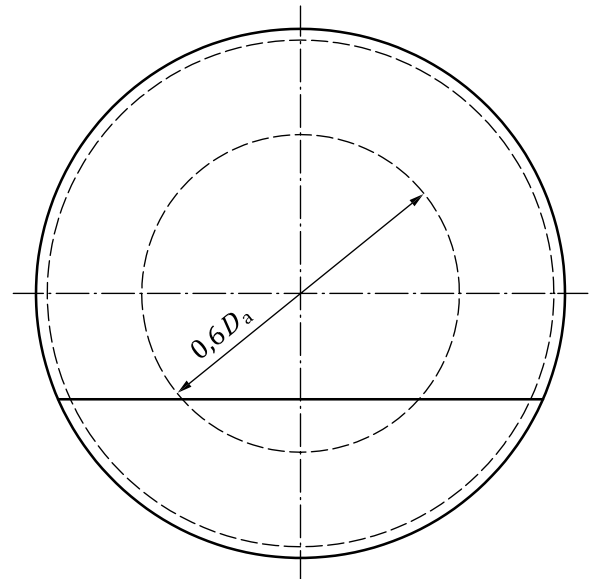
b) Dished end with nozzle



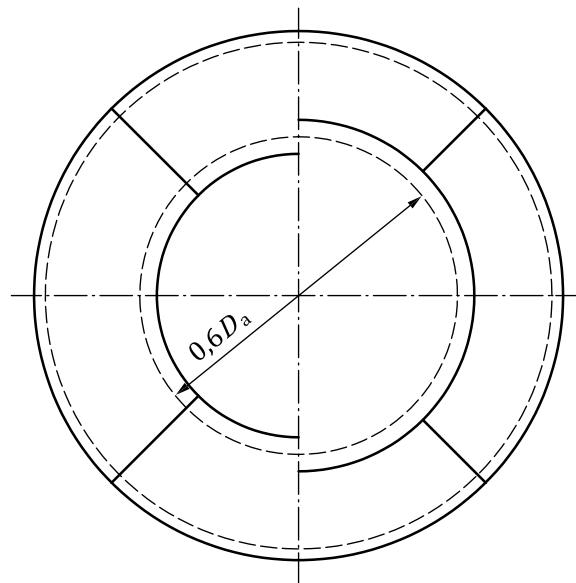
c) End with knuckle and crown of unequal wall thickness



d) Weld outside  $0,6 D_a$



e) Weld inside  $0,6 D_a$



$$\eta = 1,0 \quad \eta = 0,85 \text{ or } 1,0$$

**f) End welded together from round plate and segments**

**Figure 1 — Examples of dished ends**

**10.3.6.4.3 Internal-pressure calculation (pressure on concave surface)**

**10.3.6.4.3.1 Crown and hemisphere thickness**

The wall thickness of the crown region of dished ends and of hemispherical ends shall be determined using [10.3.6.1.3](#) for spherical shells with  $D_a = 2(R + s)$ .

The opening within the crown area of  $0,6 D_a$  of torispherical ends and in hemispherical ends shall be reinforced in accordance with [10.3.6.7](#). When pad-type reinforcement is used, the edge of the pad shall not extend beyond the area of  $0,8 D_a$ .

**10.3.6.4.3.2 Torispherical end knuckle thickness and hemispherical end to shell junction thickness**

The required thickness of the knuckle region or hemispherical end junction shall be [Formula \(9\)](#):

$$s = \frac{pRM}{20 \frac{K_{20}\eta}{S} - 0,2p} \quad (9)$$

where

$$M = 0,25 \left( 3 + \sqrt{\frac{R}{r}} \right);$$

$R$  is the inside crown radius;

$r$  is the inside knuckle radius.

In case of  $p$  in MPa, conversion shall be considered.

Dished ends designed for normal operation under internal pressure (pressure on concave side) shall have  $R \leq D_a$  and  $r \geq 0,06 D_a$ , but in no case less than 3 s. Dished ends of vacuum jackets are not required to meet the above restrictions on  $R$  and  $r$  except  $r \geq 3 s$ .

#### 10.3.6.4.3.3 Elliptical ends

The required thickness at the thinnest point after forming of elliptical ends under pressure on the concave side shall be determined by [Formula \(10\)](#):

$$s = \frac{p D_i B}{20 \frac{K_{20} \eta}{S} - 0,2 p} \quad (10)$$

where

$$B = \frac{1}{6} \left[ 2 + \left( \frac{D_i}{2h} \right)^2 \right];$$

$h$  is one-half of the length of the minor axis of the ellipsoidal end, or the inside depth of the ellipsoidal end measured from the tangent line (end-bend line), in mm.

In case of  $p$  in MPa, conversion shall be considered.

**10.3.6.4.3.4** If a dished end is welded together from crown and knuckle components, the joint shall be at a sufficient distance,  $x$ , from the knuckle.

$x$  shall be the larger of the following:

- 100 mm;
- $0,78 \sqrt{R(s)}$  if the crown and knuckle are of different thickness, where  $s$  is the thickness of the knuckle component;
- 3,5 s.

$\eta = 1,0$  may be used if the scope of testing corresponds to that specified for a design stress level equal to the permissible design stress level or in the case of one-piece ends.

**10.3.6.4.3.5** If the ligament on the connecting line between adjacent openings is not entirely within the  $0,6 D_a$  region, the ligament shall not be less than half the sum of the opening diameters.

#### 10.3.6.5 Cones subject to internal or external pressure

##### 10.3.6.5.1 Field of application

The field of application for cones is according to [Figure 2](#), where  $0,001 \leq \frac{s_g - c}{D_{a1}} \leq 0,1$  and

$$0,001 \leq \frac{s_1 - c}{D_{a1}} \leq 0,1.$$

Small ends with a knuckle can be safely assessed and verified as a small end with a corner joint.

For external pressure,  $|\varphi| \leq 70^\circ$ .

Other cone angles may be used providing suitable calculations are carried out.

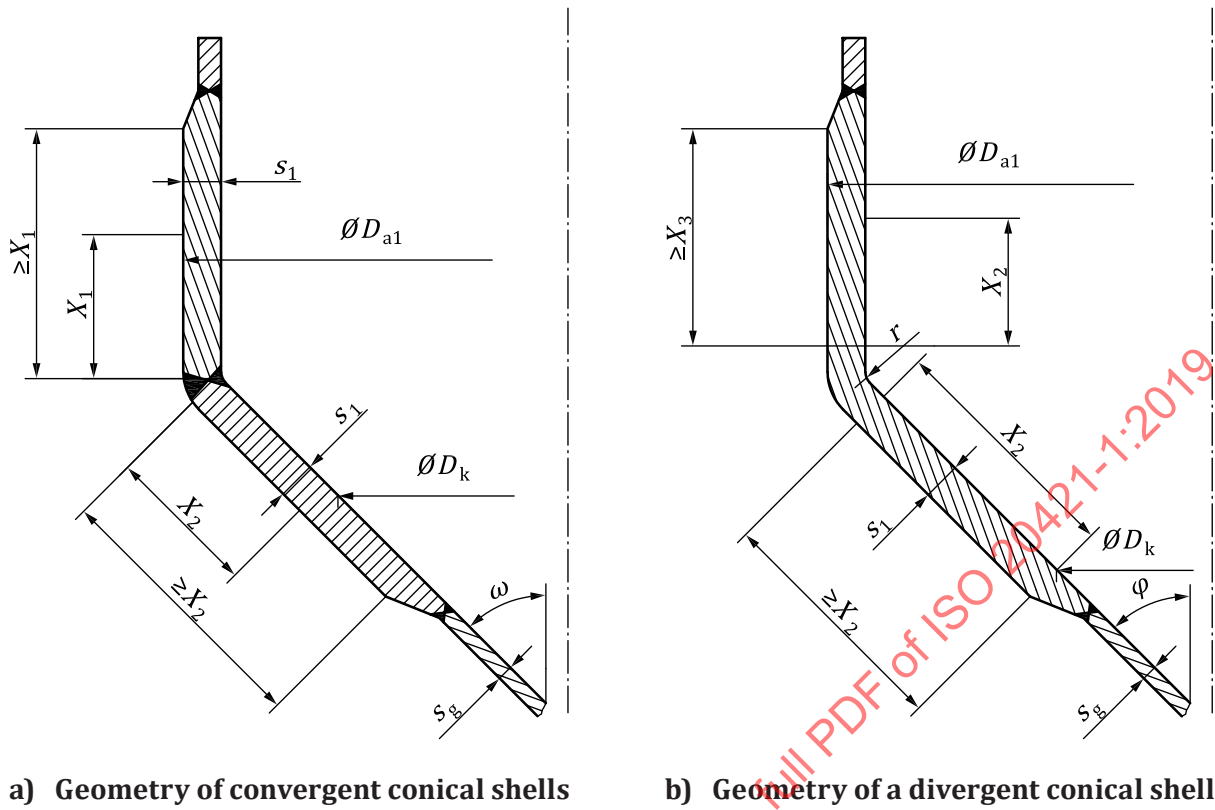


Figure 2 — Examples of cones

### 10.3.6.5.2 Openings

Openings outside of the corner area (Figure 3) shall be designed as follows:

- if  $|\phi| < 70^\circ$ , design according to 10.3.6.5.5 using an equivalent cylinder diameter as per Formula (11):

$$D_i = \frac{D_s + d_i |\sin \phi|}{\cos \phi} \quad (11)$$

- if  $|\phi| \geq 70^\circ$  design according to 10.3.6.5.5.

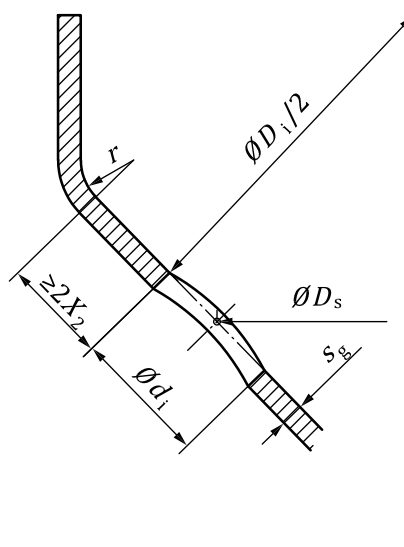


Figure 3 — Geometry of a cone opening

#### 10.3.6.5.3 Non-destructive testing

All corner joints shall be subject to the examination required for a weld joint factor of 1,0.

#### 10.3.6.5.4 Corner area

The corner area is that part of the cone where the dominant stresses are bending stresses in the longitudinal direction.

The corner area is defined in Figures 2 a) and 2 b) by  $X_1$ ,  $X_2$ ,  $X_3$  calculated from Formulae (12) to (14):

$$X_1 = \sqrt{D_{a1}(s_1 - c)} \quad (12)$$

$$X_2 = 0,7 \sqrt{\frac{D_{a1}(s_1 - c)}{\cos \varphi}} \quad (13)$$

$$X_3 = 0,5X_1 \quad (14)$$

#### 10.3.6.5.5 Internal-pressure calculation (pressure on concave surface) $|\varphi| \leq 70^\circ$

##### a) Within corner area

The required wall thickness ( $s_1$ ) within the corner area is calculated from Figures 4 a) to 4 g) for the large end and Figure 4 h) for the small end of a cone using Formula (15):

$$\varphi, \frac{p_s}{15K_v} \text{ and } \frac{r}{D_{a1}} \quad (15)$$

For a corner joint, the curve for  $\frac{r}{D_{a1}} = 0$  shall be used.

For intermediate cone angles, linear interpolation shall be used.

b) Outside corner area

The wall thickness,  $s_1$ , in the corner area shall not be less than the required thickness,  $s_g$ , outside the corner area.

The required wall thickness,  $s_g$ , outside the corner area, is calculated from [Formula \(16\)](#):

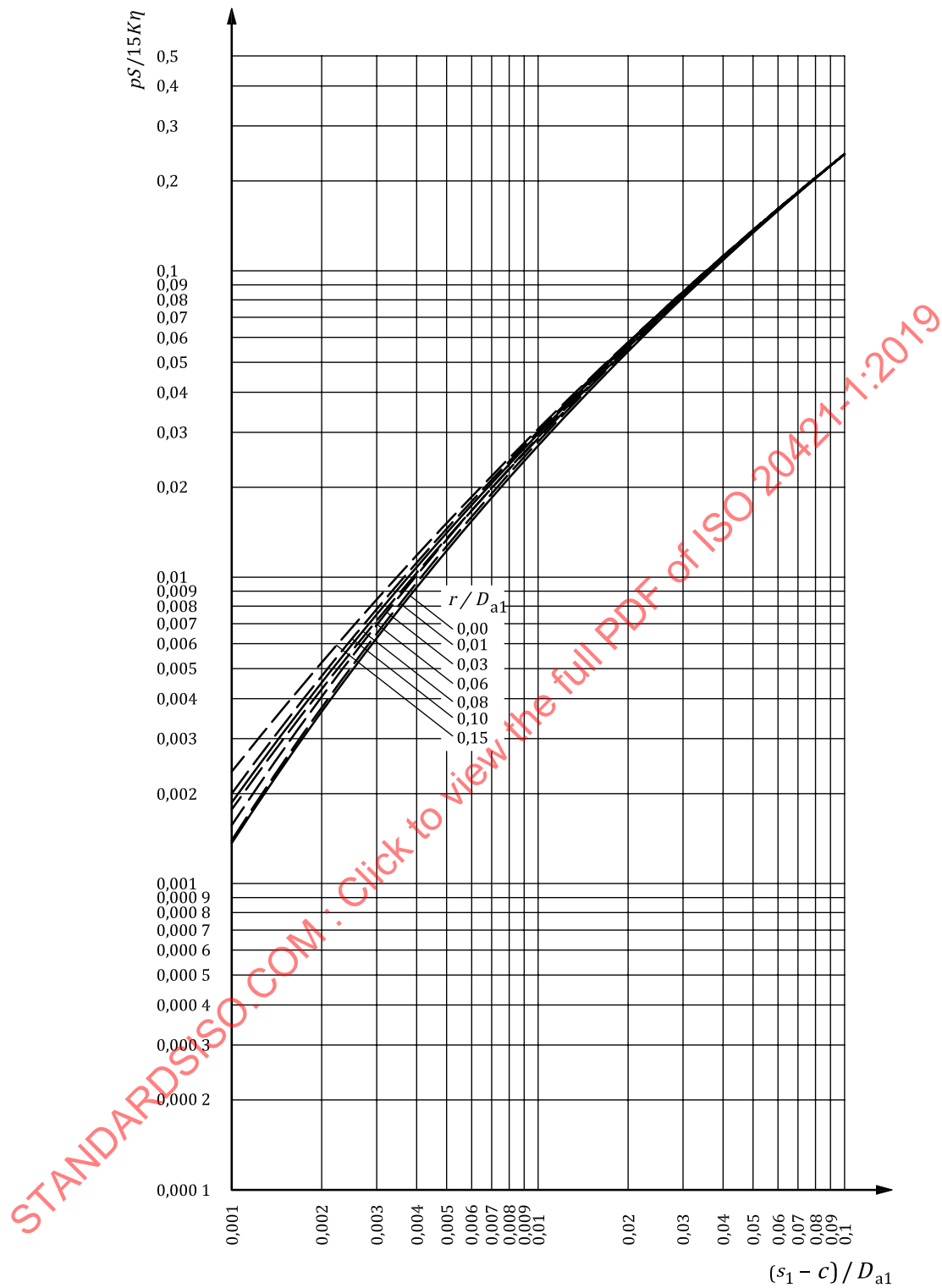
$$s_g = \frac{D_k p}{\left(20 \frac{K}{S} \eta\right) - p} \times \frac{1}{\cos \varphi} + c \quad (16)$$

where

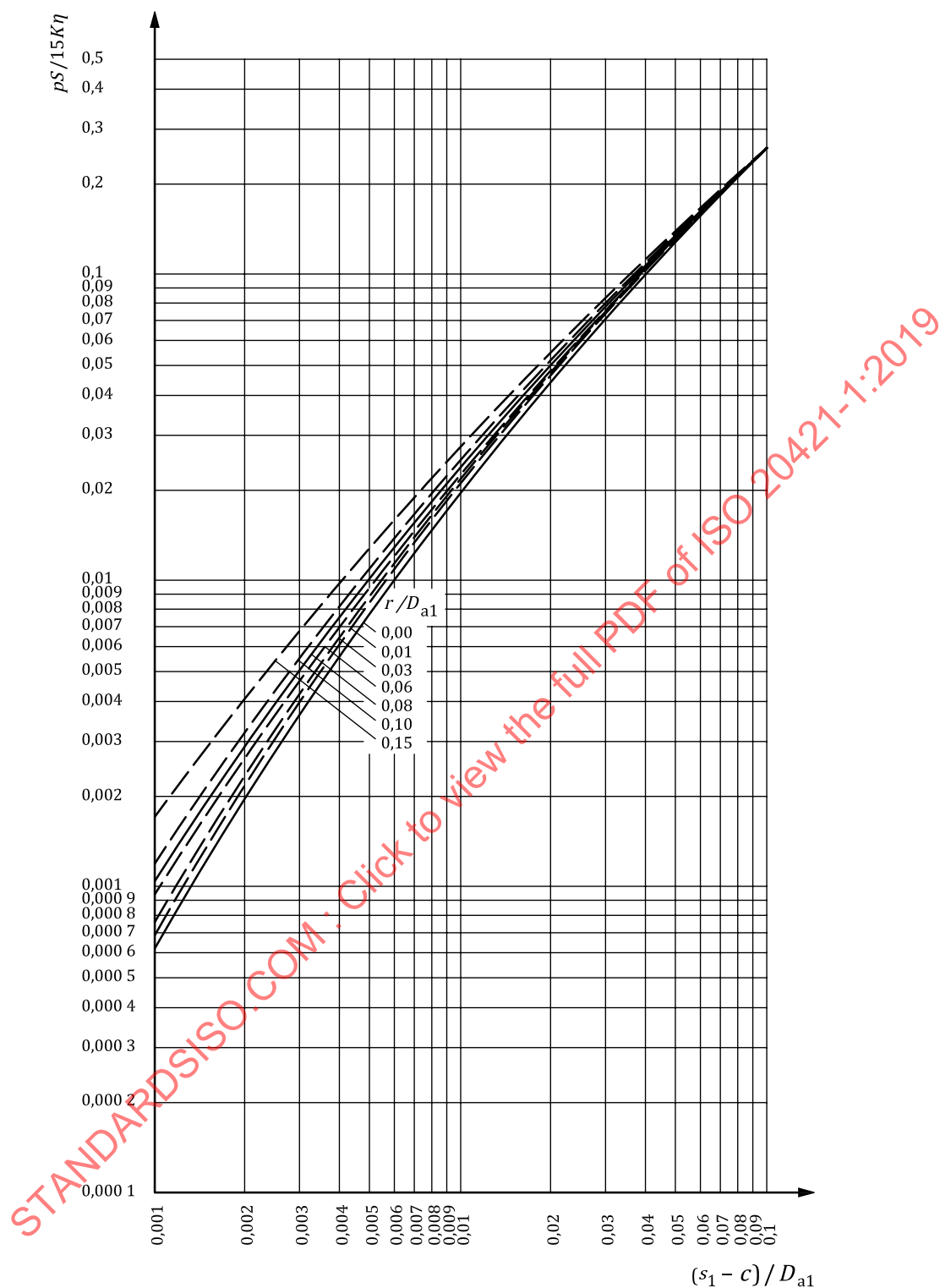
for the large end,  $D_k = D_{a1} - 2 [s_1 + r(1 - \cos \varphi) + x_2 \sin \varphi]$ ;

for the small end,  $D_k$  is the maximum diameter of the cone, where the wall thickness is  $s_g$ .

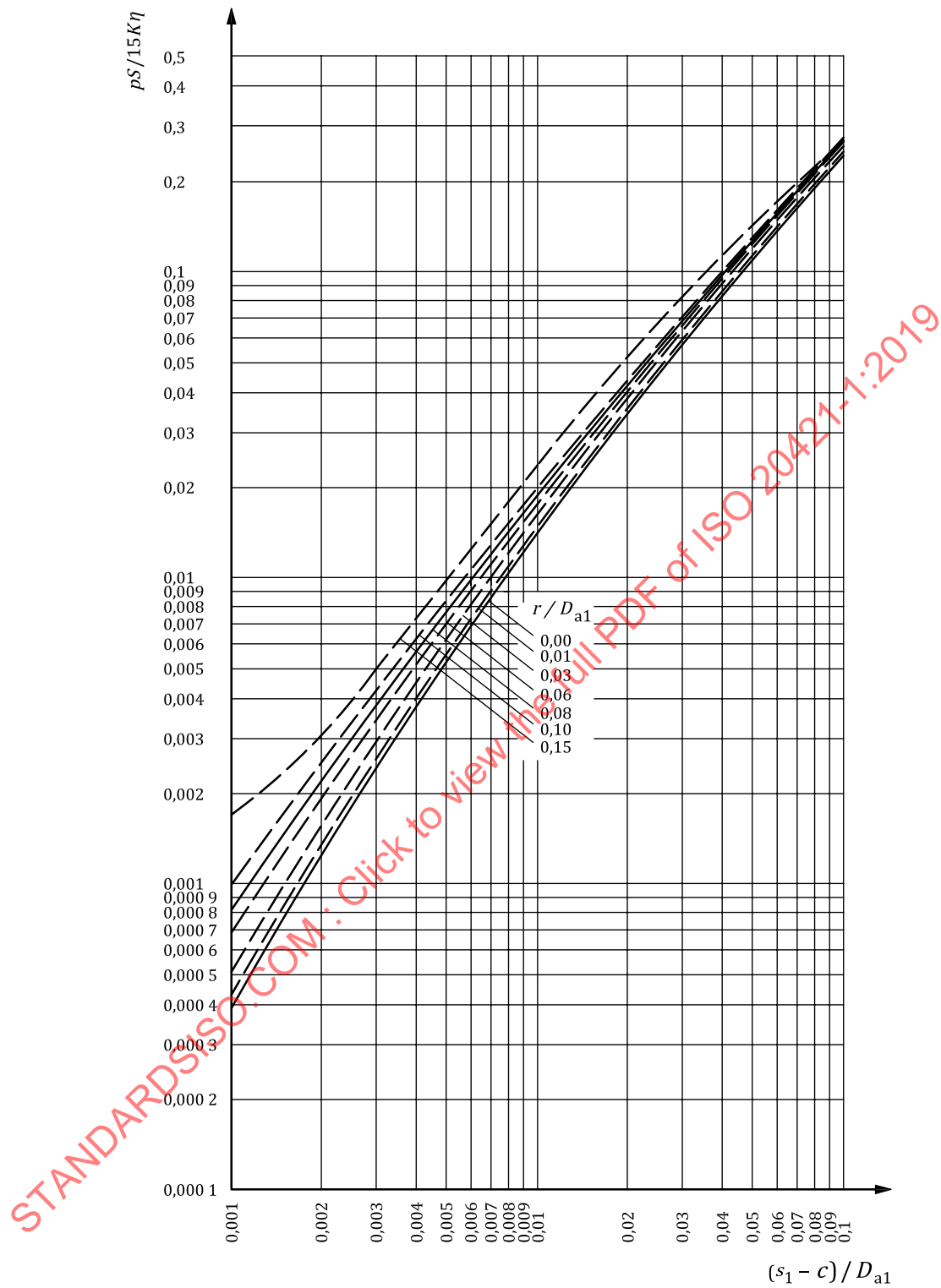
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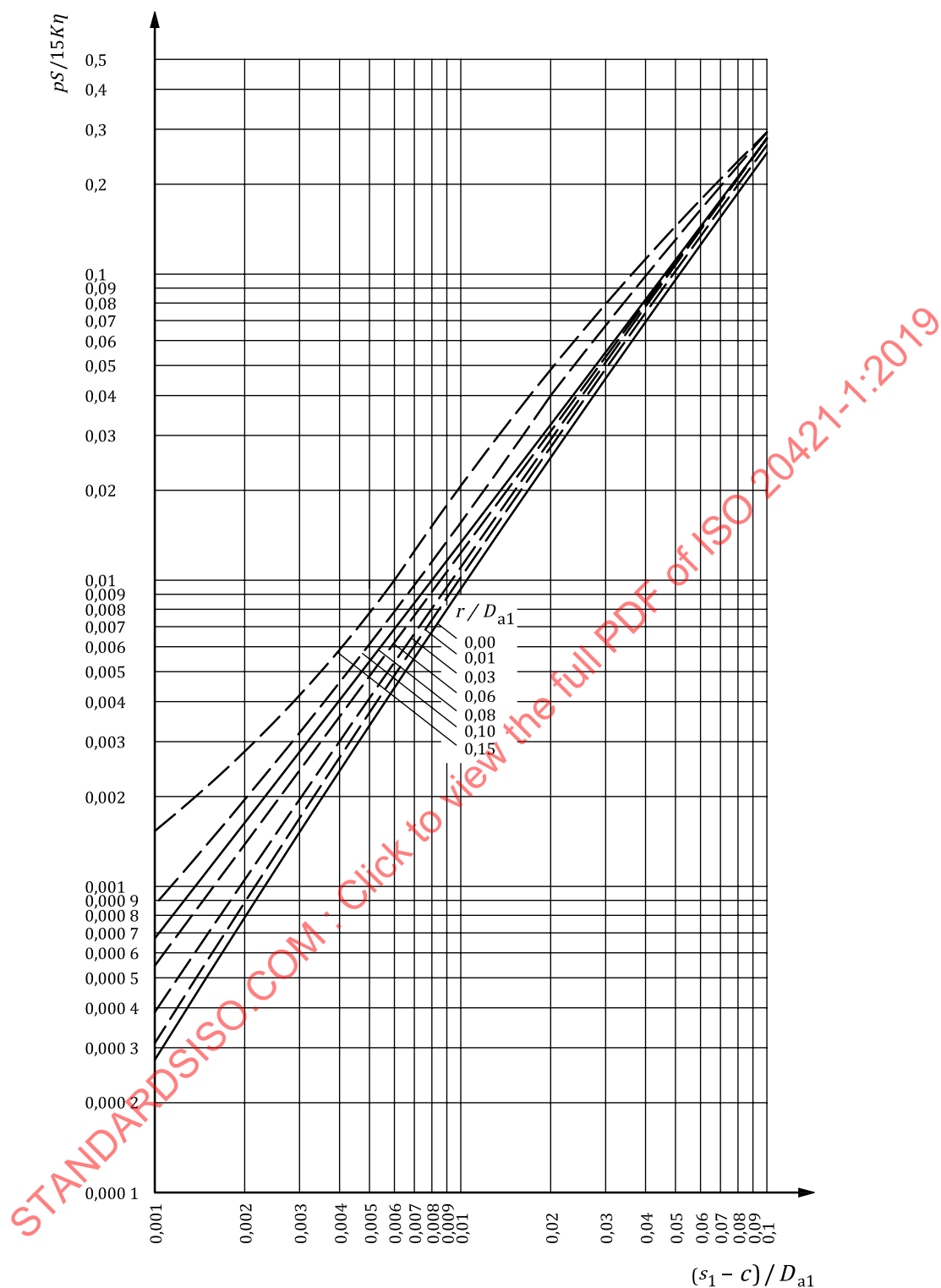
a) Permissible value  $\frac{p_S}{15K\eta}$  for convergent cone with an opening angle  $\varphi = 10^\circ$



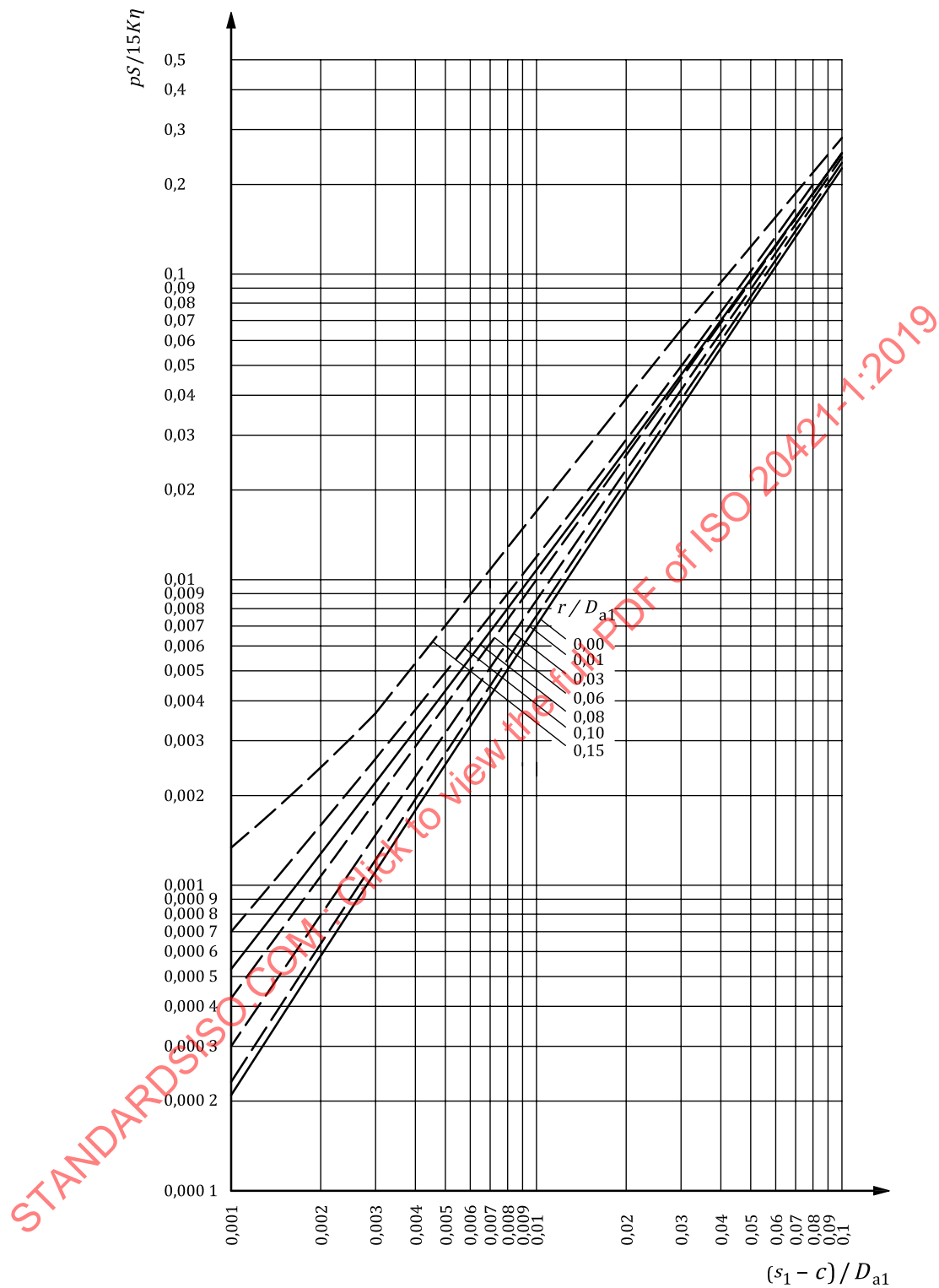
b) Permissible value  $\frac{p_S}{15K\eta}$  for convergent cone with an opening angle  $\varphi = 20^\circ$



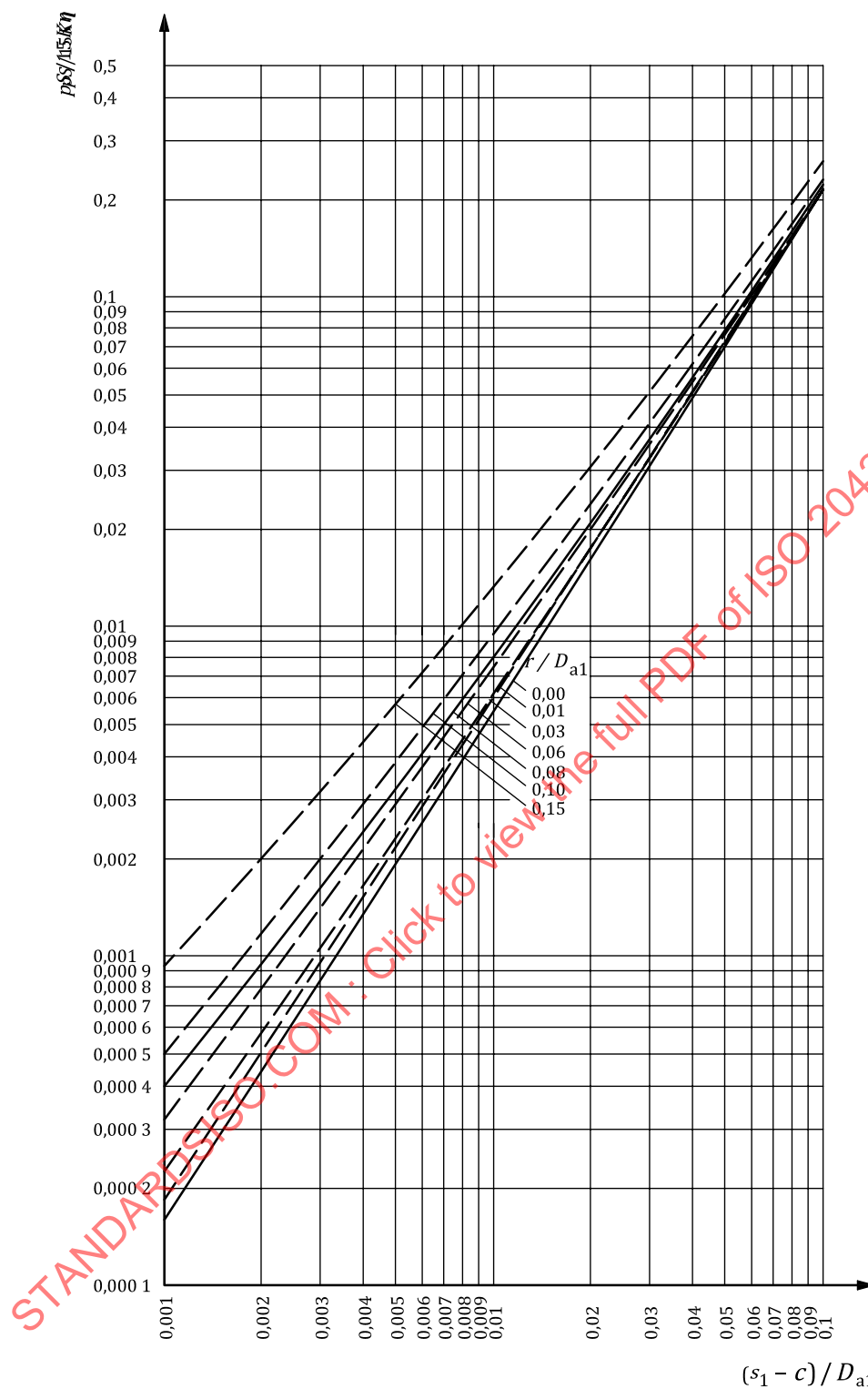
c) Permissible value  $\frac{p_s}{15K\eta}$  for convergent cone with an opening angle  $\varphi = 30^\circ$



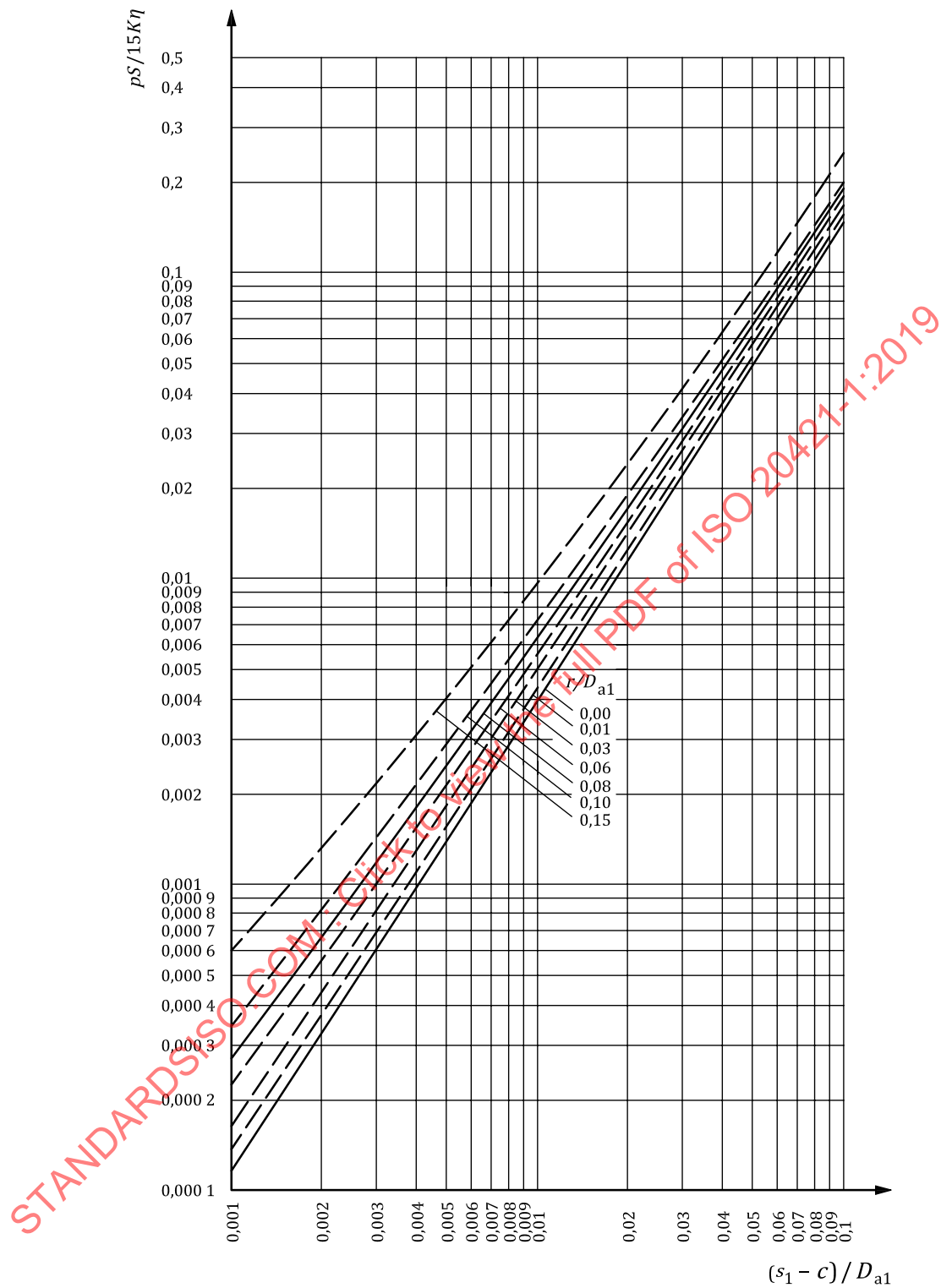
d) Permissible value  $\frac{p_s}{15K\eta}$  for convergent cone with an opening angle  $\varphi = 40^\circ$

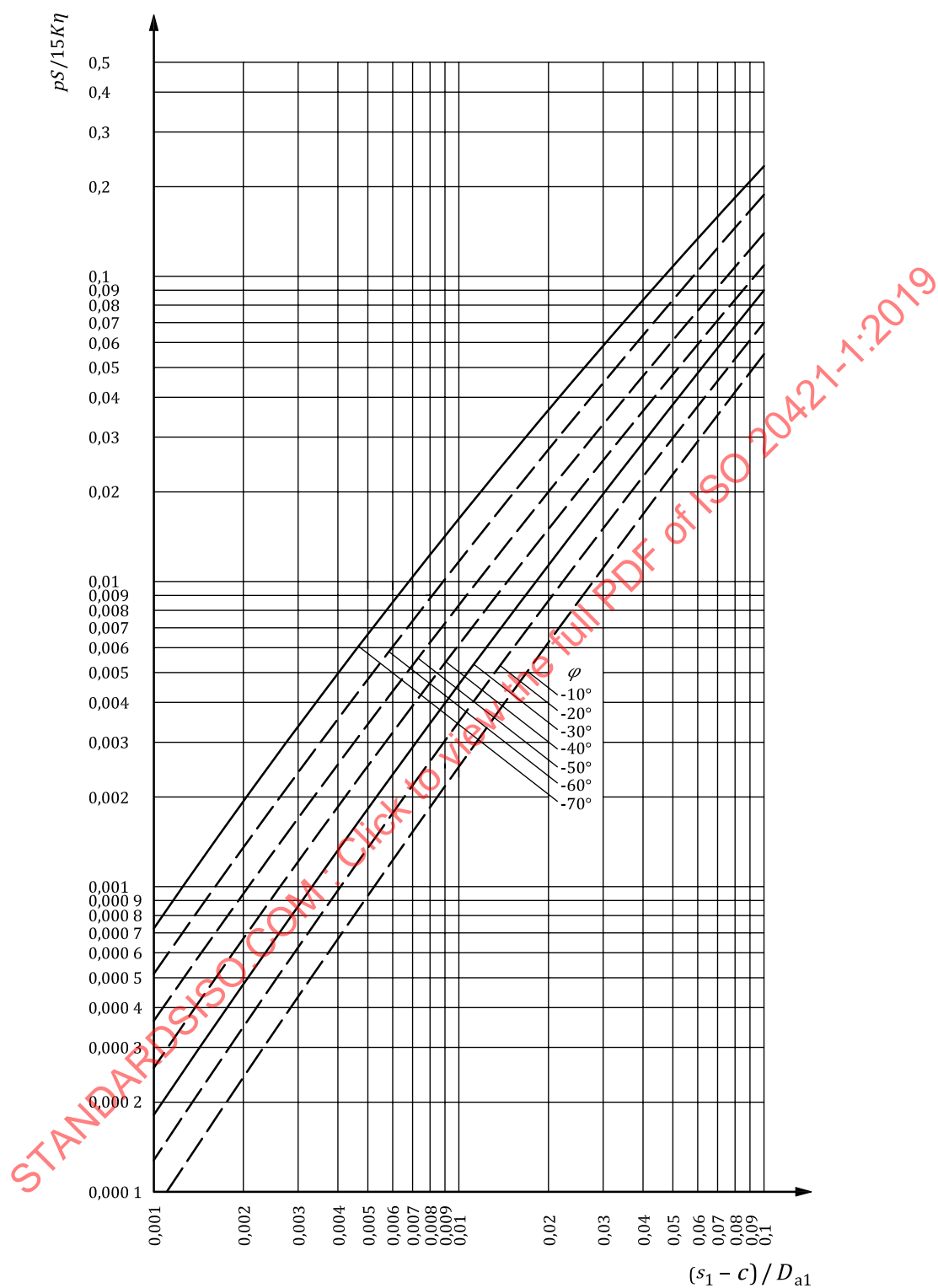


e) Permissible value  $\frac{p_s}{15K\eta}$  for convergent cone with an opening angle  $\varphi = 50^\circ$



f) Permissible value  $\frac{p_S}{15K\eta}$  for convergent cone with an opening angle  $\varphi = 60^\circ$





h) Permissible value  $\frac{p_s}{15K\eta}$  for divergent cone (corner joint) with an opening angle  $\varphi = 10^\circ$  to  $70^\circ$

**Key**

$$X \quad \ln[(s_1 - c)/D_{a1}] \quad Z = \sum_{i=1}^4 \sum_{j=1}^2 A_{ij} \cdot X^{i-1} \cdot Y^{j-1}$$

$$Y \quad Y = r/D_{a1} \quad \frac{p_s}{15 K_\eta} = e^Z$$

**Figure 4 — Wall thickness (s1) within the corner area****10.3.6.5.6 Internal-pressure calculation (pressure on the concave surface)  $|\varphi| > 70^\circ$** 

If  $r \geq 0,01 D_{a1}$ , the required wall thickness is [Formula \(17\)](#):

$$s_1 = s_g = 0,3(D_{a1} - r) \times \frac{|\varphi|}{90} \times \sqrt{\frac{p}{10 \left( \frac{K}{S} \right) \eta}} + c \quad (17)$$

**10.3.6.5.7 External-pressure calculation (pressure on the convex surface)**

Stability against elastic buckling and plastic deformation shall be verified using [10.3.6.2](#) and an equivalent cylinder.

For the example shown in [Figure 5](#) the equivalent cylinder diameter between the knuckle and the stiffener is [Formula \(18\)](#):

$$D_a = \frac{D_{a1} + D_{a2}}{2 \cos|\varphi|} \quad (18)$$

and the equivalent cylinder length is [Formula \(19\)](#):

$$l = \frac{D_{a1} - D_{a2}}{2 \sin|\varphi|} \quad (19)$$

Depending on the relevant boundary conditions, the equivalent length between two effective stiffening sections shall be reliably estimated within the meaning of [10.3.6.2](#).

When  $\varphi \geq 10^\circ$ , the corner area of a large end can be considered as effective stiffening.

For small ends, the thickness in the corner area shall not be less than 2,5 times the required thickness of the conical shell with the same angle  $|\varphi|$  or a stiffener shall be fitted with [Formulae \(20\)](#) and [\(21\)](#):

$$l \geq 0,010 \, 4 S_k \frac{p(D_{a1})^4}{10E} \tan|\varphi| \quad (20)$$

$$A \geq 0,125 S_p \frac{p(D_{a1})^2}{10K} \tan|\varphi| \quad (21)$$

where

$S_k$  (cylinder) is the safety factor to prevent elastic buckling from [10.3.2.4](#) or [10.3.3.4](#);

$S_p$  (cylinder) is the safety factor to prevent plastic deformation from [10.3.2.4](#) or [10.3.3.4](#);

$D_{a1}$  is the diameter according to [Figure 7 b](#)).

The shell over a width of  $0,5\sqrt{D_{a1}s_1}$  can be used to calculate the moment of inertia and the area.

In addition, the corner joint should not be regarded as a classical boundary condition, i.e. the overall length should be formed from the individual meridional length of the cone and cylinder.

In addition, the cone shall be verified using [10.3.6.5.6](#) and the safety factors,  $S_p$ , for cylinders from [10.3.2.4](#) or [10.3.3.4](#) increased by 20 %. For thickness calculations in the corner area,  $v$  shall be the value applicable for internal pressure.

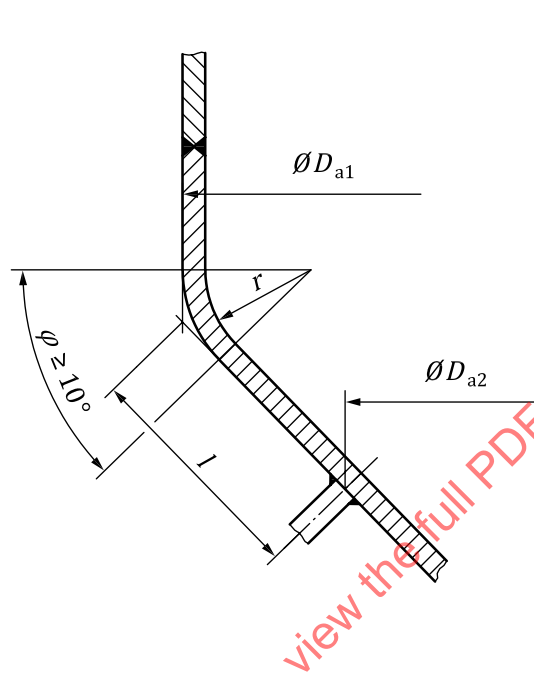


Figure 5 — Geometrical quantities in the case of loading by external pressure

### 10.3.6.6 Flat ends

#### 10.3.6.6.1 Symbols and units

For the purposes of [10.3.6.6](#), the following symbols apply in addition to those given in [Clause 4](#):

- $d_1, d_2$ , etc., opening diameters, in mm;
- $D_1$ , flat-end diameters, in mm.  $A_s$  is shown in [Figure 6](#).

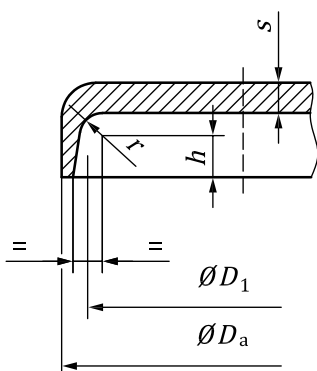
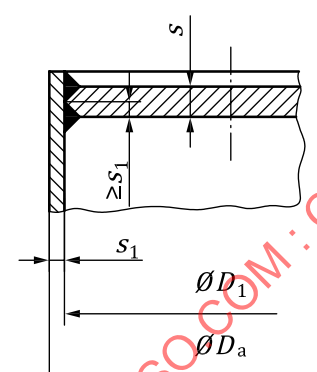
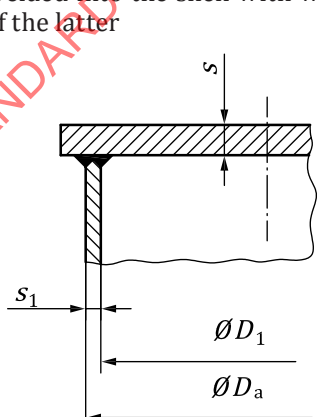
#### 10.3.6.6.2 Field of application

The field of application includes welded or solid flat ends where Poisson's ratio is approximately 0,3, and [Formula \(22\)](#) and [\(23\)](#):

$$\frac{(s-c)}{D} \geq 4 \sqrt{\frac{0,0087p}{E}} \quad (22)$$

$$3 \frac{(s_e - c)}{D_1} \leq 1 \quad (23)$$

| Type of flat-end design (principle only) | Conditions          | Design factor $C$ |
|------------------------------------------|---------------------|-------------------|
| a) Flat end                              | 1. Knuckle radius : | 0,3               |

| Type of flat-end design (principle only)                                                                                                                     | Conditions                                                                                                                                                                                                                                                                                                                                                                                                        | Design factor C |            |           |    |                      |    |                        |    |                        |    |            |    |  |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|------------|-----------|----|----------------------|----|------------------------|----|------------------------|----|------------|----|--|
|                                                                                                                                                              | <table><tr><th><math>D_a</math></th><th><math>r_{\min}</math></th></tr><tr><td>up to 500</td><td>30</td></tr><tr><td>over 500 up to 1 400</td><td>35</td></tr><tr><td>over 1 400 up to 1 600</td><td>40</td></tr><tr><td>over 1 600 up to 1 900</td><td>45</td></tr><tr><td>over 1 900</td><td>50</td></tr></table> <p>and <math>r \geq 1,3s</math><br/>2. cylindrical part: <math>h \geq 3,5 \times s</math></p> | $D_a$           | $r_{\min}$ | up to 500 | 30 | over 500 up to 1 400 | 35 | over 1 400 up to 1 600 | 40 | over 1 600 up to 1 900 | 45 | over 1 900 | 50 |  |
| $D_a$                                                                                                                                                        | $r_{\min}$                                                                                                                                                                                                                                                                                                                                                                                                        |                 |            |           |    |                      |    |                        |    |                        |    |            |    |  |
| up to 500                                                                                                                                                    | 30                                                                                                                                                                                                                                                                                                                                                                                                                |                 |            |           |    |                      |    |                        |    |                        |    |            |    |  |
| over 500 up to 1 400                                                                                                                                         | 35                                                                                                                                                                                                                                                                                                                                                                                                                |                 |            |           |    |                      |    |                        |    |                        |    |            |    |  |
| over 1 400 up to 1 600                                                                                                                                       | 40                                                                                                                                                                                                                                                                                                                                                                                                                |                 |            |           |    |                      |    |                        |    |                        |    |            |    |  |
| over 1 600 up to 1 900                                                                                                                                       | 45                                                                                                                                                                                                                                                                                                                                                                                                                |                 |            |           |    |                      |    |                        |    |                        |    |            |    |  |
| over 1 900                                                                                                                                                   | 50                                                                                                                                                                                                                                                                                                                                                                                                                |                 |            |           |    |                      |    |                        |    |                        |    |            |    |  |
| b) Forged or pressed flat end<br>                                          | 1. Knuckle radius:<br>$r \geq \frac{s}{3}$ , however at least 8 mm<br>2. Cylindrical part: $h \geq s$                                                                                                                                                                                                                                                                                                             | 0,35            |            |           |    |                      |    |                        |    |                        |    |            |    |  |
| c) Flat plate welded into the shell from both sides<br>                   | Plate thickness:<br>$s \leq 3s_1$<br>$s > 3s_1$                                                                                                                                                                                                                                                                                                                                                                   | 0,35; 0,40      |            |           |    |                      |    |                        |    |                        |    |            |    |  |
| d) Plate welded into the shell with welds at both sides of the latter<br> | Plate thickness:<br>$s \leq 3s_1$<br>$s > 3s_1$<br>Only killed steels may be utilized.<br>When plate material is employed over an area of at least $3s_1$ in the weld zone there shall be no evidence of material discontinuities in the plate.                                                                                                                                                                   | 0,40; 0,45      |            |           |    |                      |    |                        |    |                        |    |            |    |  |

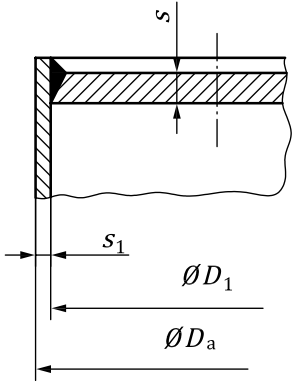
| Type of flat-end design (principle only)                                                                                                                       | Conditions                                      | Design factor <i>C</i> |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|------------------------|
| <div>e) Flat plate welded into the shell from one side only</div> <div></div> | Plate thickness:<br>$s \leq 3s_1$<br>$s > 3s_1$ | 0,45;0,50              |

Figure 6 — Design factors for unstayed circular flat ends and plates

10.3.6.6.3 Openings

Openings are calculated in accordance with 10.3.6.6.4 but with the *C* factor multiplied by *C<sub>A</sub>*, where *C<sub>A</sub>* is given in Figure 7.

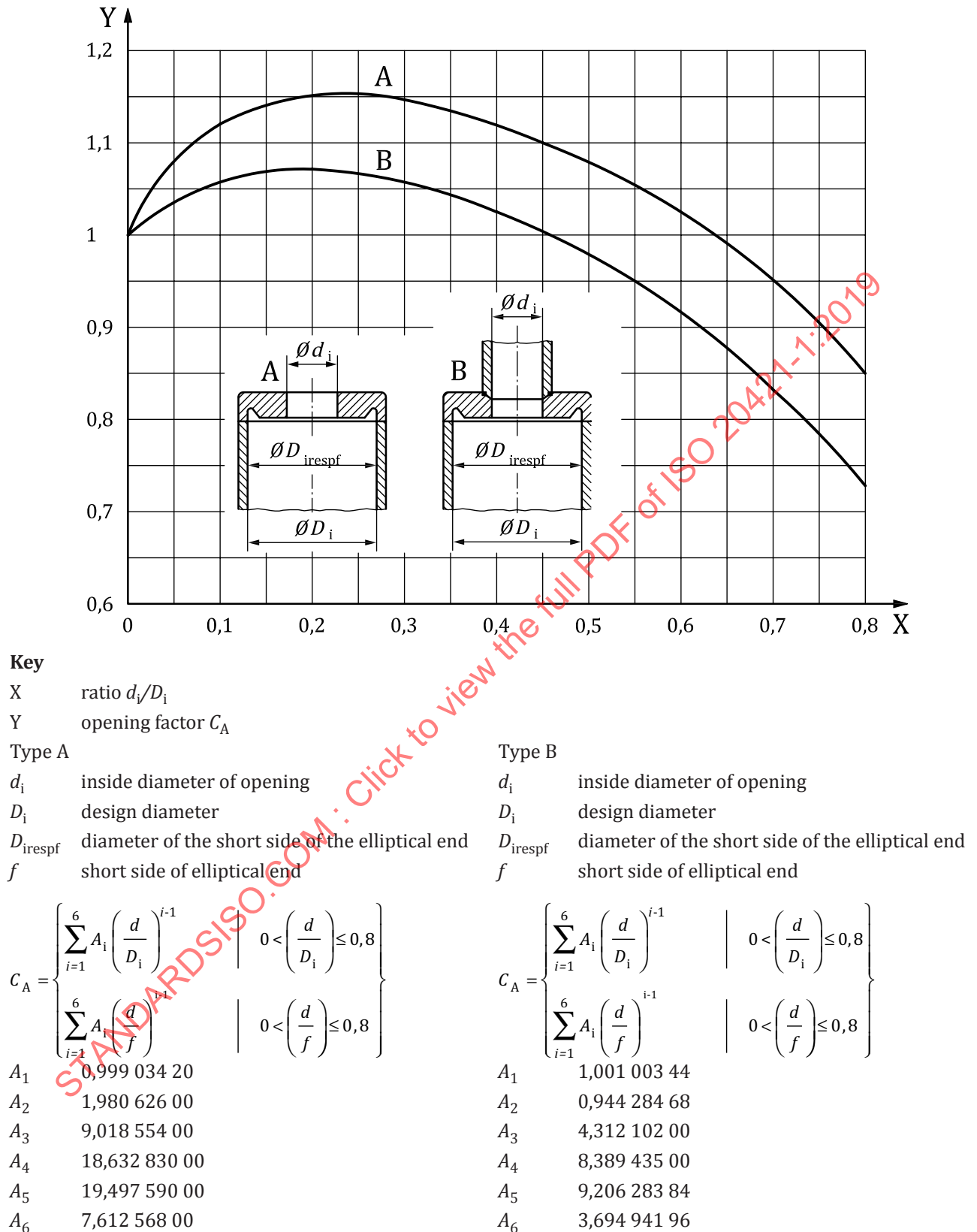


Figure 7 — Opening factor,  $C_A$ , for flat ends and plates without additional marginal moment

#### 10.3.6.6.4 Calculation

The required minimum wall thickness of a circular flat end is [Formula \(24\)](#):

$$s = CD_1 \sqrt{\frac{0,1pS}{K}} + c \quad (24)$$

where  $C$  and  $D_1$  are taken from [Figure 6](#).

The required minimum wall thickness of a rectangular or elliptical flat end is [Formula \(25\)](#):

$$s = CC_e \sqrt{\frac{0,1pS}{K}} + c \quad (25)$$

where  $C_e$  is taken from [Figure 8](#).

#### 10.3.6.7 Openings in cylinders, spheres and cones

##### 10.3.6.7.1 Field of application

Round openings and the reinforcement of round openings in cylinders, spheres and cones within the limits of [Formulae \(26\)](#) and [\(27\)](#):

$$0,002 \leq \frac{(s-c)}{D_a} \leq 0,1 \quad (26)$$

$$\frac{(s-c)}{D_a} < 0,002 \text{ is acceptable if } \frac{d_i}{D_a} \leq \frac{1}{3} \quad (27)$$

These rules only apply to cones if the wall thickness is determined by the circumferential stress.

Additional external forces and moments are not covered by this subclause and should be considered separately where necessary.

These design rules permit plastic deformations of up to 1 % at highly stressed local areas during pressure test. Openings should therefore be carefully designed to avoid abrupt changes in geometry.

The design rules for non-perpendicular nozzles shall be based on a perpendicular nozzle, using the dimension of the major elliptical axis.

##### 10.3.6.7.2 Reinforcement methods

Openings may be reinforced by one or more of the following typical but not exclusive methods:

- increase of shell thickness;
- set-in or set-on ring reinforcement;
- pad reinforcement (see [Figure 9](#));
- increase of nozzle thickness (see [Figures 10](#) and [11](#));
- pad and nozzle reinforcement.

Where ring or pad reinforcement is used on the inner vessel, the space between the two fillet welds shall be vented into the vacuum interspace.

### 10.3.6.7.3 Design of openings

All nozzles shall be attached to the vessel wall with a full penetration weld unless the attachment weld is maintained at atmospheric temperatures at all times or the weld is not subjected to thermal cycling.

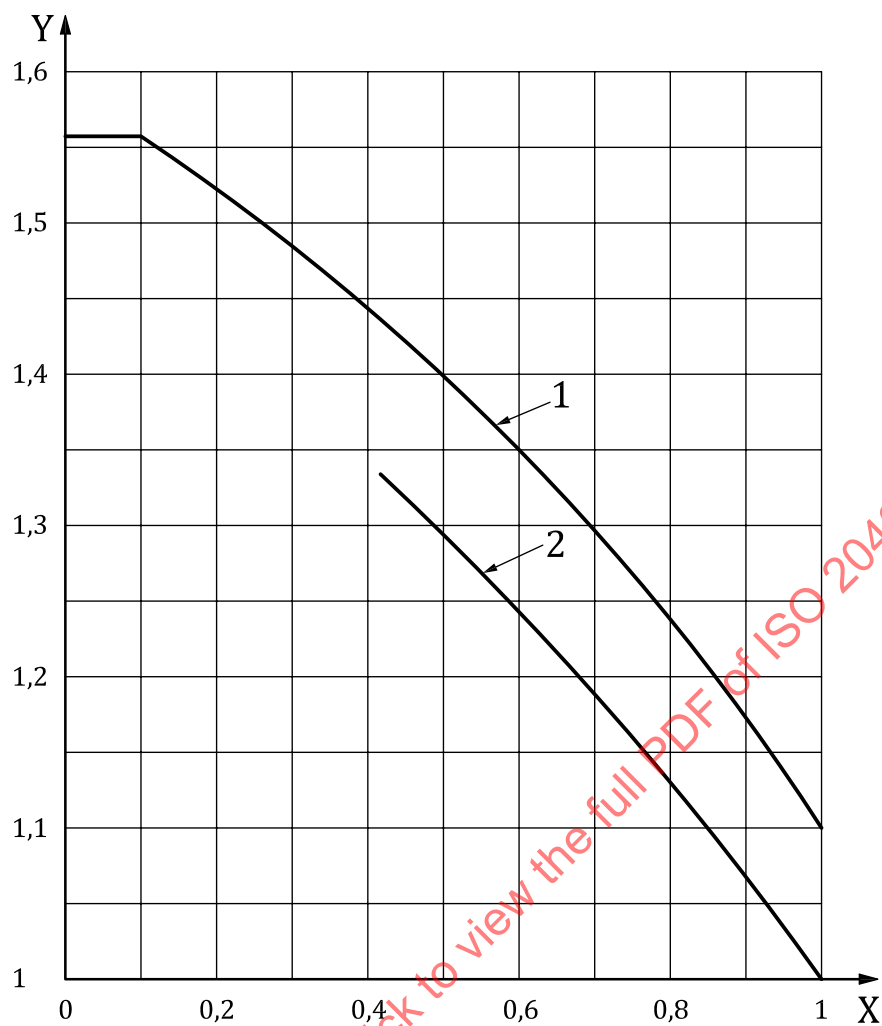
The fillet weld on a reinforcing pad shall have a minimum throat thickness of half of the pad thickness.

The throat thickness of a fillet weld of each nozzle to shell weld shall be not less than the required thickness of the thinner part.

Where the strength of the reinforcing material is lower than the strength of the shell material, an allowance in accordance with [10.3.6.7.4](#) shall be made in the design calculations. If the strength of the reinforcing material is higher than the strength of the shell material, no allowance for the increased strength is permitted.

### 10.3.6.7.4 Calculation

[Annex I](#) gives two alternative calculation methods. Both methods give comparable results and shall be equally accepted.



Key

- 1 rectangular plate
- 2 elliptical plate

Rectangular plates

$f$  short side of the rectangular plate  
 $e$  long side of the rectangular plate

$$C_e = \begin{cases} \sum_{i=1}^4 A_i \left(\frac{f}{e}\right)^{i-1} & \left| \quad 0,1 < \left(\frac{f}{e}\right) \leq 1,0 \right. \\ 1,562 & \left| \quad 0 < \left(\frac{f}{e}\right) \leq 0,1 \right. \end{cases}$$

- $A_1$  1,589 146 00
- $A_2$  -0,239 349 90
- $A_3$  -0,335 179 80
- $A_4$  0,085 211 76

Elliptical plates

$f$  short side of the elliptical plate  
 $e$  long side of the elliptical plate

$$C_e = \begin{cases} \sum_{i=1}^4 A_i \left(\frac{f}{e}\right)^{i-1} & \left| \quad 0,43 < \left(\frac{f}{e}\right) \leq 1,0 \right. \end{cases}$$

- $A_1$  1,489 146 00
- $A_2$  -0,239 349 90
- $A_3$  -0,335 179 80
- $A_4$  0,085 211 76

Figure 8 — Design factor,  $C_e$ , for rectangular or elliptical flat plates

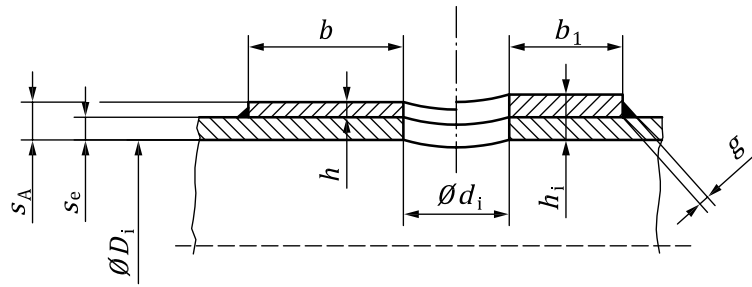


Figure 9 — Pad reinforcement

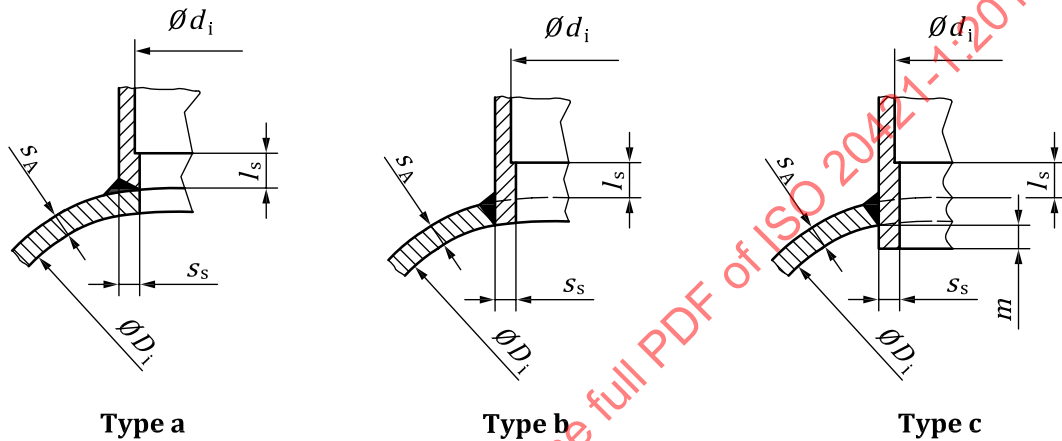


Figure 10 — Nozzle reinforcement

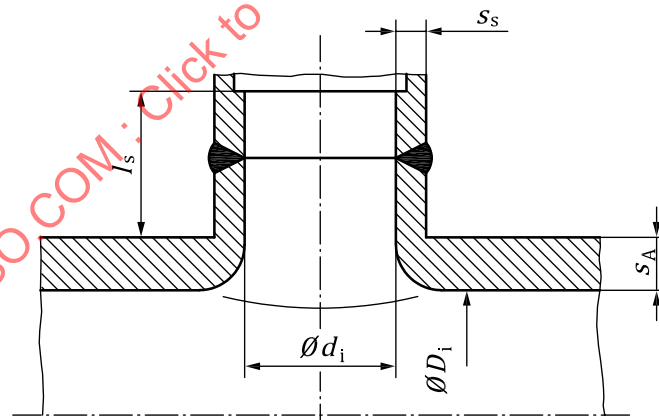


Figure 11 — Necked-out opening

### 10.3.7 Calculations for operating loads

Unless the design has been validated by experiment, calculations in addition to those in 10.3.6 may be required to ensure that stresses due to operating loads are within acceptable limits. All load conditions expected during service shall be considered (see 10.2.3).

In these calculations, equivalent static loads shall be substituted for static plus dynamic loads.

The analysis shall take account of gross structural discontinuities.

Annex B or ASME VIII-2 provides terminology and acceptable stress limits when an elastic stress analysis is performed.

Acceptable calculation methods include:

- finite element;
- finite difference;
- boundary element;
- recognized text books, codes and standards.

Planned and controlled experimental means may be used in order to confirm these calculations, for example by application of strain gauges to verify stress levels.

## 11 Fabrication

### 11.1 General

**11.1.1** The manufacturer, or his or her subcontractor, shall have equipment available to ensure manufacture and testing in accordance with the design.

**11.1.2** The manufacturer shall maintain:

- a system of material traceability for pressure-bearing parts used in the construction of the inner vessel;
- design dimensions within specified tolerances;
- necessary cleanliness of the inner vessel, associated piping and other equipment which can come in contact with the cryogenic fluid.

### 11.2 Cutting

Material may be cut to size and shape by thermal cutting, machining, cold shearing or other appropriate method. Thermally cut material shall be dressed back by machining or grinding.

### 11.3 Cold forming

#### 11.3.1 Austenitic stainless steel

Heat treatment after cold forming is not required in any of the following cases:

- a) for operating temperatures down to  $-196\text{ }^{\circ}\text{C}$ :
  - 1) the test certificate for the base material shows an elongation at fracture  $A_5$  of not less than 30 %; and
  - 2) the cold-forming deformation is not more than 15 % or it is demonstrable that the residual elongation is not less than 15 %;

Cold forming deformation may be calculated according to [Formula \(28\)](#):

$$F = 100 \ln \frac{D_{b(x)}}{D_e - 2e} \quad (28)$$

where

$e$  is the thickness of the initial product;

$D_{b(x)}$  is the diameter of the initial product;

$D_e$  is the external diameter of the final product;

$\ln$  is the natural logarithm (addition of the formula to conform with ISO 21009-1).

- b) for operating temperatures below  $-196\text{ }^{\circ}\text{C}$ : the cold-forming deformation is less than or equal to 15 % and it is demonstrated that the residual elongation is not less than 15 %;
- c) for cold formed heads, the test certificate for the base material shows an elongation at fracture  $A_5$ :
  - not less than 30 % in the case of wall thicknesses not more than 15 mm at design temperatures down to  $-196\text{ }^{\circ}\text{C}$ ;
  - not less than 35 % in the case of wall thicknesses more than 15 mm at design temperatures down to  $-196\text{ }^{\circ}\text{C}$ ;
  - not less than 40 % at design temperatures below  $-196\text{ }^{\circ}\text{C}$ .

Where heat treatment is required, this shall be carried out in accordance with the material standard.

Heat treatment of cold formed heads should be performed for liquid hydrogen service or for cryogenic gases containing unacceptable levels of  $\text{H}_2\text{S}$ . ( see ISO 11114-1).

### 11.3.2 Ferritic steel

The following requirements for post-forming heat treatment shall be observed:

- a) material for the outer jacket, including cold-formed ends with or without jogged joints, does not require post-forming heat treatment;
- b) 9 % Ni steel requires post-forming heat treatment where cold-forming deformation exceeds 5 %. Fully certified quenched and tempered or double normalized and tempered 9 % Ni steel shall be stress relieved at  $560\text{ }^{\circ}\text{C}$  to  $580\text{ }^{\circ}\text{C}$ . Forming and stress relieving may be performed in several stages. A test piece taken from the parent material that accompanies the formed part through all stages of heat treatment shall be tested after all heat treatment is complete to demonstrate that the material mechanical properties conform to the requirements of the material standard;
- c) for the following ferritic steels used for the inner vessel, post-forming heat treatment is not required where the forming deformation is not more than 5 %:
  - 1) nickel-alloyed steels, suitable for low-temperature use;
  - 2) carbon and carbon-manganese steels:
    - where  $R_m \leq 530\text{ N/mm}^2$ ;
    - or where  $530 < R_m \leq 650\text{ N/mm}^2$  and  $R_{0,002} \leq 360\text{ N/mm}^2$ .

When heat treatment is required, suitable heat treatments after cold forming are normalizing, normalizing (double) plus tempering, quenching plus tempering or solution annealing.

Parameters given by the base-material manufacturer in the test certificate shall be taken as an indication or recommendation for heat treatments except that other heat treatments may be applied if the procedure is qualified and the product or a test piece representing the product is tested after forming and heat treatment.

### 11.3.3 Aluminium or aluminium alloy

Cold-formed ends made from aluminium or aluminium alloy do not normally require post-forming heat treatment, unless there is a risk of stress corrosion in service. Treatment shall be carried out in accordance with the material standard.

## 11.4 Hot forming

### 11.4.1 General

Forming shall be carried out in accordance with a written qualified procedure. The forming procedure shall specify the heating rate, the holding temperature, the temperature range and time for which the forming takes place and shall give details of any heat treatment to be given to the formed part.

### 11.4.2 Austenitic stainless steel

Material shall be heated uniformly in an appropriate atmosphere without flame impingement, to a temperature not exceeding the recommended hot-forming temperature of the material. When forming is carried out after the temperature of the material has fallen below 900 °C the requirements of [11.3.1](#) shall be complied with.

### 11.4.3 Ferritic steel

The following requirements for post-forming heat treatment shall be observed:

- a) 9 % Ni steel that is hot formed shall be double normalized and tempered, or quenched and tempered in accordance with the material standard to establish the material properties specified therein. Test piece(s) shall be provided and tested in accordance with the material standard;
- b) ferritic steel that is hot formed shall be heat treated in accordance with the material standard to establish the material properties specified therein:
  - air-quenched steels shall be tempered subsequently;
  - test pieces shall be provided and tested in accordance with the material standard;
  - for normalized steels a post-forming heat treatment is not necessary if the hot forming is done within the specified temperature range, specified in the material standards; further test pieces are not required.

### 11.4.4 Aluminium or aluminium alloy

Post-forming heat treatment may be omitted if evidence in the form of a procedure qualification can be provided showing that the elongation at fracture  $A_5$  of the formed material is not less than 10 %.

## 11.5 Manufacturing tolerances

### 11.5.1 General

The recommendations in this subclause are suitable for vessels subjected to predominantly static loads. For fatigue loads, the manufacturing tolerances shall meet the recommendations of the applied design codes/standards.

To avoid fatigue damage in case of cyclic loading, more severe fabrication, inspection and testing requirements are needed for critical areas of the pressure vessels, see also [12.3.4.2](#). For cyclic loaded vessels the absence of surface imperfections and the necessity of smooth transitions are essential. Only smooth transitions are allowed. Similarly, shape imperfections such as peaking are absolutely critical and the maximum permissible peaking of the applied standard/code, or the value permitted in the fatigue analysis, shall not be exceeded

### 11.5.2 Plate alignment

Except where a tapered transition is provided, misalignment of the surfaces of adjacent plates at welded seams shall be for longitudinal and circumferential seams, not more than 25 % of the thickness of the thinner plate up to a maximum of 3 mm.

Where a taper is provided between the surfaces, this shall have a slope of not more than  $18,4^\circ$ . The taper may include the width of the weld, the lower surface being built-up with added weld metal if necessary. Where material is removed from a plate to provide a taper, the thickness of either plate shall not be reduced below that required for the design.

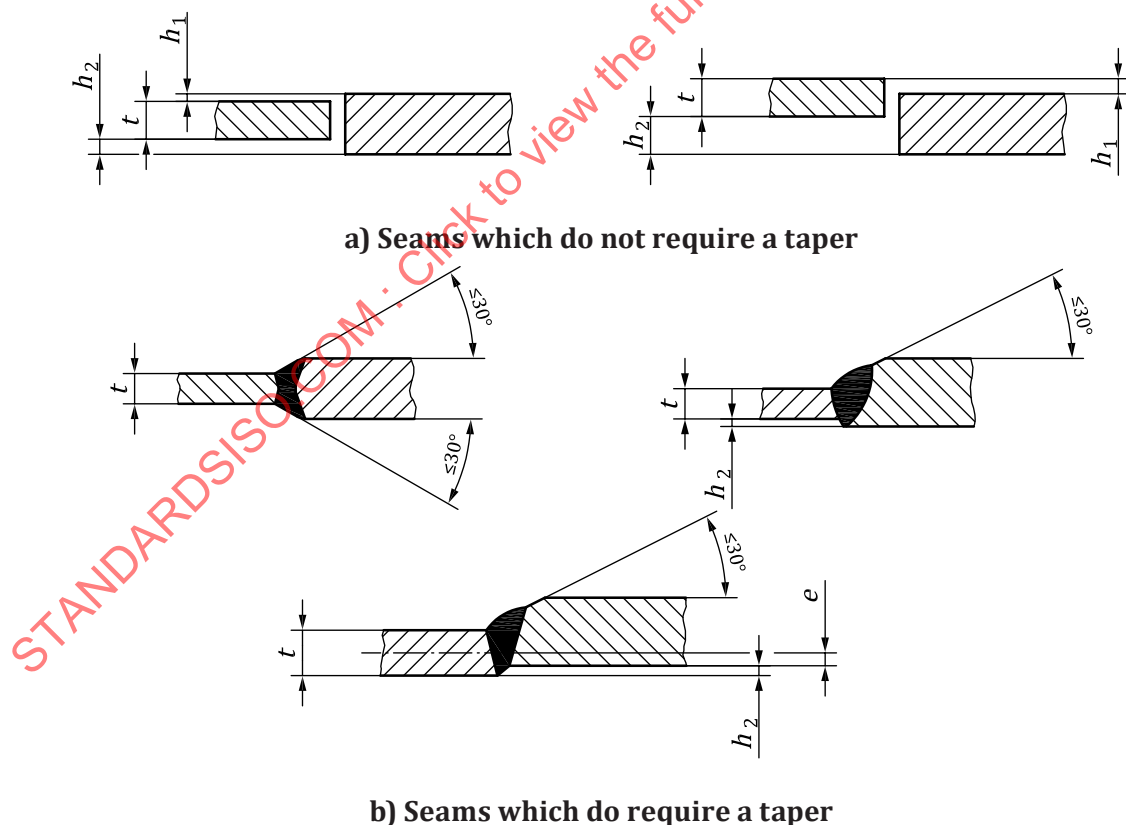
The distance between either surface of the thicker plate and the centre line of the thinner plate of tapered seams shall be for longitudinal and circumferential seams, not less than 35 % of the thickness of the thinner plate.

In no case shall the surface of any plate lie between the centre lines of the two plates.

These requirements are illustrated in [Figure 12](#).

The following nomenclature applies:

- $h, h_1, h_2$ : surface misalignments;
- $t$ : thickness of the thinner plate;
- $e$ : distance from the surface of the thicker plate to the centre line of the thinner plate.



NOTE 1 For longitudinal and circumferential seams which do not require a taper:  $h_1 \leq 0,25t$  and  $h_2 \leq 0,25t$ .

NOTE 2 For longitudinal and circumferential seams which require a taper:  $e = \frac{t}{2} - h_2 \geq 0,35t$ .

**Figure 12 — Plate alignment**

### 11.5.3 Thickness

The thickness of the vessel shall not be less than the design thickness. This shall be taken as the thickness of the vessel after manufacture, and any variations in thickness shall be gradual.

### 11.5.4 Dished ends

The knuckle radius shall not be less than specified and any variation of crown radius shall not be abrupt but shall adhere to the following tolerances:  $\begin{matrix} +0,625 \\ -1,25 \end{matrix} \%$ .

### 11.5.5 Cylinders

**11.5.5.1** The actual circumference shall not deviate from the circumference calculated from the specified diameter by more than 1,5 %.

**11.5.5.2** The out of roundness,  $u$ , calculated from [Formula \(29\)](#):

$$u = \frac{200(D_{\max} - D_{\min})}{D_{\max} + D_{\min}} \% \quad (29)$$

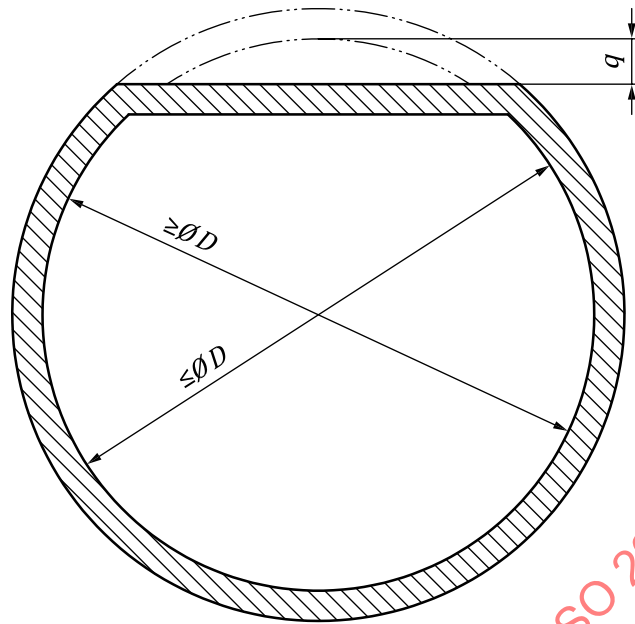
shall be not more than the values shown in [Table 4](#).

**Table 4 — Permitted out of roundness**

| Wall thickness to diameter ratio | Permitted out of roundness for |                   |
|----------------------------------|--------------------------------|-------------------|
|                                  | internal pressure              | external pressure |
| $s/D = 0,01$                     | 2,0 %                          | 1,5 %             |
| $s/D > 0,01$                     | 1,5 %                          | 1,5 %             |

The determination of the out of roundness need not consider the elastic deformation due to the dead weight of the pressure vessel. At nozzle positions, a greater out of roundness may be permitted if it can be justified by calculation or strain gauge measurement. Single dents or knuckles shall be within the tolerances. Dents shall be smooth and their depth which is the deviation from the generatrix of the shell shall not exceed 1 % of their length or 2 % of their width respectively. Greater dents and knuckles are permissible provided they have been proven admissible by calculation or by strain measurements.

Irregularities in profile (checked by a 20° gauge) shall not exceed 2 % of the gauge length. This maximum value may be increased by 25 % if the length of the irregularities does not exceed one-quarter of the length of the shell part between two circumferential seams with a maximum of 1 m. Greater irregularities require proof by calculation or strain gauge measurement that the stresses are permissible (see [Figure 13](#)).



NOTE Definitions:

$u$  equivalent to  $\frac{4}{D_a} \times q \times 100$

Limitations:

$u \leq 15 \%$

$q \leq 0,003\,75D_a$

**Figure 13 — Allowable shape imperfections**

Furthermore, where irregularity in the profile occurs at the welded seam and is associated with “flats” adjacent to the weld the irregularity in profile or “peaking” shall not exceed the values given in [Table 5](#).

A conservative method of measurement (covering peaking and ovality) shall be by means of a 20° profile gauge (or template).

The use of such a profile gauge is illustrated in [Figure 14](#). Two readings shall be taken,  $P_1$  and  $P_2$ , on each side of the seam, at any particular location. The maximum peaking is taken as being equivalent to  $0,25 (P_1 + P_2)$ .

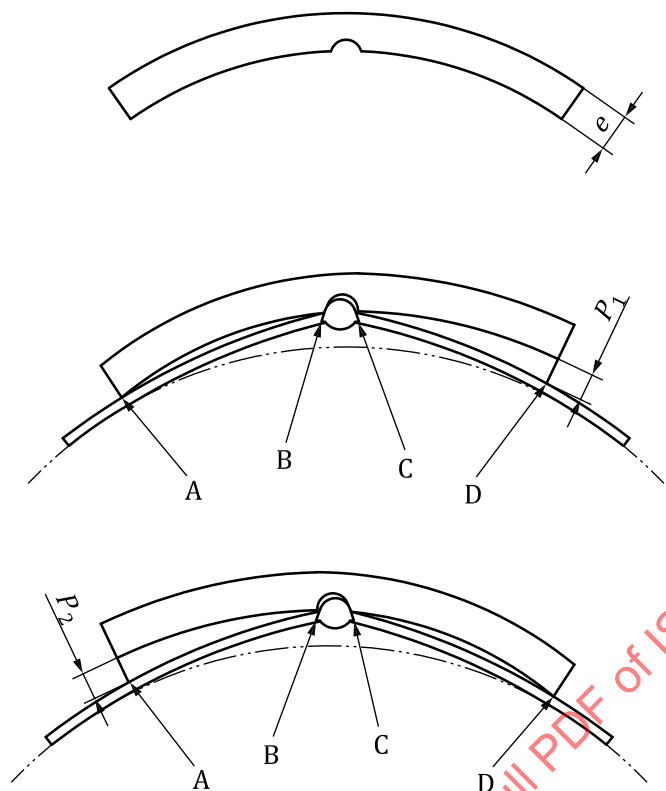


Figure 14 — Gauge details

Measurements should be taken at approximately 250 mm intervals on longitudinal seams to determine the location with the maximum peaking value. Use of other types of gauges such as bridge gauges or needle gauges are not prohibited. The maximum peaking value permitted is given in [Table 5](#).

Table 5 — Maximum permitted peaking

Dimensions in millimetres

| Vessel ratio wall thickness $s$ to diameter $D$ | Maximum permitted peaking |
|-------------------------------------------------|---------------------------|
| $s/D \leq 0,025$                                | 5                         |
| $s/D > 0,025$                                   | 10                        |

For all ratios, a maximum permitted peaking is  $e$ .

For cylinders subject to external pressure and where the circumference has a flattened portion, it shall be demonstrated that the shell has sufficient strength to avoid plastic deformation where the depth of flattening is more than 0,4 % of the outside diameter of the cylinder. The depth of flattening shall be measured as a deviation from the normal curvature or from the line of the cylindrical shell. Adequate strength may be determined by calculation in accordance with [Formula \(14\)](#), using a value of  $u$  determined with [Formula \(30\)](#):

$$u = \frac{400}{D_a} \times q \tag{30}$$

where

- $q$  is the depth of flattening, in mm;
- $D_a$  is the external diameter of the cylinder, in mm.

**11.5.5.3** Departure of the cylinder axis from a straight line shall be not more than 0,5 % of the cylindrical length, except where required by the design.

## 11.6 Welding

### 11.6.1 General

The manufacturer shall fulfil the requirements of ISO 3834-2 or equivalent.

The welding method shall be appropriate and shall be carried out by qualified welders and/or operators, the materials shall be compatible, and there shall be verification by a welding procedure test.

### 11.6.2 Qualification

Welding procedures shall be approved in accordance with ISO 15614-1, ISO 15614-2, ISO 15613 or ISO 14732 as applicable, or with equivalent standards. Welders and welding operators shall be qualified in accordance with ISO 9606-1 or ISO 9606-2 or with ISO 14732 as applicable or with equivalent standards.

### 11.6.3 Temporary attachments

Temporary attachments welded to pressure-bearing parts shall be kept to a practical minimum.

Temporary attachments welded directly to pressure-bearing parts shall be compatible with the immediately adjacent material.

It is permissible to weld dissimilar metal attachments to intermediate components, such as pads, which are connected permanently to the pressure-containing part. Compatible welding materials shall be used for dissimilar metal joints.

Temporary attachments shall be removed from the inner vessel prior to the first pressurization. The removal technique shall avoid impairing the integrity of the inner vessel and shall be by chipping or grinding. Any rectification necessary by welding of damaged regions shall be undertaken in accordance with an approved welding procedure.

The area of the inner vessel from where the temporary attachments have been removed shall be dressed smooth and examined by appropriate non-destructive testing.

Any attachments on the outer jackets may be removed by thermal cutting as well as by the methods described above.

### 11.6.4 Welded joints

**11.6.4.1** Some specific weld details appropriate to vessels conforming to this document are given in [Annex E](#). These details show sound and currently accepted practice. It is not intended that these be mandatory, nor should they restrict the development of welding technology in any way.

The manufacturer, in selecting an appropriate weld detail, shall consider:

- the method of manufacture;
- the service conditions;
- the ability to carry out necessary non-destructive testing.

Weld details may be used provided their suitability is proven by procedure approval according to ISO 15614-1, ISO 15614-2 or ISO 15613 as applicable.

To avoid sub-standard welding of ferritic steels, excess residual magnetism shall be avoided.

**11.6.4.2** Where any part of a vessel is made in two or more courses, the longitudinal weld seams of adjacent courses shall be staggered. A minimum of 100 mm is recommended. Joggled joints may be used in stainless steels for circumferential welds only and plate thickness up to 8 mm. Backing strips may be used for circumferential welds only with no thickness restriction. When forming the joggled joints, reduction in toughness shall be considered for low temperature.

**11.6.4.3** As the mechanical characteristics of work-hardened austenitic stainless steels can be adversely affected if the material is not welded properly, the additional requirements below shall be applied:

- the heat input during welding shall be not more than 1,5 kJ/mm per bead to be verified in the procedure qualification test;
- the material shall cool to a temperature of not more than 200 °C between passes;
- the material shall not be heat treated after welding.

See also [C.2.7](#), [C.2.8](#), [C.2.9](#), and [C.2.10](#).

## 11.7 Non-welded joints

Where non-welded pressure-retaining joints are made between metallic materials and/or non-metallic materials, procedures shall be established in a manner similar to that used in establishing welding procedures, and these procedures shall be followed for all such joints. Similarly, operators shall be qualified in such procedures, and only qualified personnel shall then carry out these procedures.

## 12 Inspection and testing

### 12.1 Quality plan

#### 12.1.1 General

A quality plan forming part of the quality system shall include, as a minimum, the inspection and testing stages listed in [12.1.2](#).

#### 12.1.2 Inspection stages during manufacture of an inner vessel

The following inspection stages shall be conducted during the manufacture of an inner vessel:

- verification of material test certificates and correlation with materials;
- approval of weld procedure qualification records;
- approval of welders' qualification records;
- examination of material cut edges;
- examination of setup of seams for welding including dimensional check;
- examination of weld preparations, tack welds;
- visual examination of welds;
- verification of non-destructive testing;
- testing production control test plates for welds and, where required, for formed parts after heat treatment;
- verification of cleaning of inside surface of vessel;
- examination of completed vessel including dimensional check;

- pressure test.

If cold stretching is used, inspection scope and requirements should be adapted as specified in [D.5.5](#).

### 12.1.3 Additional inspection stages during manufacture of a large transportable cryogenic vessel

The following inspection stages shall be conducted during the manufacture of a large transportable cryogenic vessel:

- verification of cleanliness and dryness of the cryogenic vessel (see ISO 23208);
- visual examination of welds not covered by [12.1.2](#);
- leakproofness tests ensuring the integrity of vacuum, and leak testing of external piping when it is connected to the inner vessel;
- leak test of external piping;
- check of documentation and installation of pressure-relief device(s);
- check of installation of vacuum-space relief device;
- check of nameplate and any other specified markings;
- examination of completed vessel including dimensional check.

## 12.2 Production control test plates

### 12.2.1 Requirements

Production control test plates shall be produced and tested for the inner vessel as follows:

- one test plate per vessel shall be used for each welding procedure on longitudinal joints except as specified in b);
- after 10 sequential test plates to the same procedure have successfully passed the tests, testing may be reduced to one test plate per 50 m of longitudinal joint for 9 % Ni and ferritic steels and to one test plate per 100 m for other metals, one test plate per 130 m for other metals, provided the joints are made within any three-month period.

Production control test plates are not required for the outer jacket.

The results of the tests shall be as follows:

- weld tensile test ( $T$ ):  $R_{\text{et}}$ ,  $R_m$  and  $A_5$  of the test specimens shall normally not be less than the corresponding specified minimum values for the parent metal, or the agreed values of the welding procedure approved;
- impact test (IW, IH): this test shall be performed in accordance with ISO 21028-1 and ISO 21028-2;
- bend test (BF, BR, BS): the testing and the test requirements shall comply with ISO 15614-1 for steels and with ISO 15614-2 for aluminium and its alloys;
- macro etch (Ma): the macro etch shall show sound build-up of beads and sound penetration.

### 12.2.2 Extent of testing

The number and type of test specimens to be taken from the test plate is dependent on material and thickness, and shall be in accordance with the requirements in [Tables 7](#) and [8](#) for the particular material and thickness applicable.

NOTE The symbols for [Tables 7](#) and [8](#) are given in [Table 6](#).

The test plate shall be of sufficient size to allow for the required specimens including an allowance for retests.

Prior to cutting the test piece, non-destructive testing of the test plate may be applied in order that the test specimens are taken from sound areas.

**Table 6 — Test specimens**

| Designation                           | Symbol |
|---------------------------------------|--------|
| Face bend test to ISO 5173            | BF     |
| Root bend test to ISO 5173            | BR     |
| Side bend test to ISO 5173            | BS     |
| Tensile test to ISO 4136              | T      |
| Impact test: weld deposit to ISO 9016 | IW     |
| Impact test: HAZ to ISO 9016          | IH     |
| Macro etch                            | Ma     |

**Table 7 — Testing of production test plates for steels**

| Group                                                       | se<br>in mm       | Test specimens        |
|-------------------------------------------------------------|-------------------|-----------------------|
| Fine-grain steels normalized or thermo-mechanically treated | $se \leq 12$      | 1 BF, 1 BR, 1 T, 1 Ma |
|                                                             | $12 < se \leq 35$ | 3 IW, 3 IH, 1 T, 1 Ma |
| Ni steels up to 9 % Ni                                      | $se \leq 12$      | 1 BF, 1 BR, 1 T, 1 Ma |
|                                                             | $12 < se$         | 3 IW, 3 IH, 1 T, 1 Ma |
| Austenitic stainless steels                                 | $se \leq 12$      | 1 BF, 1 BR, 1 T, 1 Ma |
|                                                             | $12 < se$         | 3 IW, 1 T, 1 Ma       |
| Impact test requirement for steels used below 77 K          | $se > 2,5$        | 3 IW, 1 T, 1 Ma       |

**Table 8 — Testing of production test plates for aluminium**

| Group                                                                     | se<br>in mm       | Test specimens        |
|---------------------------------------------------------------------------|-------------------|-----------------------|
| Pure aluminium and aluminium with up to 1,5 % impurities or alloy content | $se \leq 12$      | 1 BF, 1 BR, 1 T, 1 Ma |
|                                                                           | $12 < se \leq 35$ | 2 BS, 1 T, 1 Ma       |

## 12.3 Non-destructive testing

### 12.3.1 General

Non-destructive testing personnel shall be qualified for the duties in accordance with ISO 9712.

Non-destructive testing shall be performed according to ISO 17635, ISO 5817 and ISO 10042, specifying general rules and standards to be applied to the different types of testing, for either the methodology or the acceptance level for metallic materials.

Non-destructive testing for volumetric imperfections is not required on the outer jacket of transportable cryogenic vessels.

### 12.3.2 Extent of examination for surface imperfections

All welds shall be visually examined in accordance with ISO 17637 and ISO 5817 or ISO 10042. If any doubt arises, this examination shall be supplemented by surface-crack detection, e.g. penetrant testing

according to ISO 3452-1 and ISO 23277. Areas from which temporary attachments have been removed shall be ground smooth and subjected to surface crack detection.

### 12.3.3 Extent of examination for inner-vessel weld seams

Examination of the inner vessel for inner-vessel weld seams shall be carried out by radiographic examination in accordance with ISO 17636-1 and ISO 10675-1 or ISO 10675-2.

A special case is made:

- to use radiographic techniques with digital detectors and processing according to ISO 17636-2;
- to justify ultrasonic testing in accordance with ISO 17640 and ISO 11666 (and ISO 22852 for austenitic steels), or other methods.

The extent of radiographic examination of main seams on the inner vessel shall be in accordance with Table 9. See 12.3.4 for acceptance criteria.

When hemispherical ends without a straight flange are welded together or to a cylinder, the weld shall be tested as a longitudinal weld. Any welds within a hemispherical end shall also be tested as longitudinal welds.

**Table 9 — Extent of radiographic examination for welded seams of the inner vessel**

| Longitudinal seams                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | T junctions <sup>a</sup> | Circumferential seams <sup>a</sup> |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|------------------------------------|
| 100 %                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 100 %                    | 100 %                              |
| <sup>a</sup> Unless the following conditions are met, in which case no radiographic examination is required, but a weld joint factor of 0,7 shall be used for the circumferential seam: <ol style="list-style-type: none"> <li>1) Circumferential seam is not a butt joint.</li> <li>2) Length of the vessel is less than 1 500 mm.</li> <li>3) Design pressure of the vessel is less than 2 bar (0,2 MPa).</li> <li>4) The vessel is not to carry flammable or toxic fluids.</li> </ol> NOTE 1 For additional requirements for 9 % Ni steel, see Annex B.<br>NOTE 2 Additional examination can be required when pneumatic proof testing is used. |                          |                                    |

### 12.3.4 Acceptance criteria for surface and volumetric imperfections as classified in ISO 6520-1

#### 12.3.4.1 Acceptance levels for predominantly static loaded vessels

The results of the weld checks and inspections shall meet quality level C of ISO 5817 or ISO 10042 and the corresponding ISO standards for testing classes and acceptance levels, as defined in ISO 17635:2016, Annex A.

| NDT method                                                                                                                                | Testing techniques and levels in accordance with | Acceptance levels in accordance with                                               |
|-------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|------------------------------------------------------------------------------------|
| Visual testing (VT)                                                                                                                       | ISO 17637                                        | ISO 5817 Level C (for steel welds)<br>ISO 10042 Level C (for aluminium welds)      |
| Radiographic testing (RT)                                                                                                                 | ISO 17636-1 class B <sup>a</sup>                 | ISO 10675-1 Level 2 (for steel welds)<br>ISO 10675-2 Level 2 (for aluminium welds) |
| Penetrant testing (PT)                                                                                                                    | ISO 3452-1                                       | ISO 23277 Level 2X                                                                 |
| <sup>a</sup> The minimum number of exposures for circumferential weld testing may correspond to the requirements of ISO 17636-1, class A. |                                                  |                                                                                    |

Additional requirements for the following imperfections:

- stray arc (601) – removal plus 100 % penetrant testing to ensure no imperfection;
- spatter (602) – weld spatter shall be removed from all pressure parts and load carrying attachment welds;
- torn surface (603), grinding mark (604), chipping mark (605) shall be ground to provide a smooth transition;
- underflushing (606) shall not be permitted. Any local underflushing shall be related to design characteristics.

#### 12.3.4.2 Acceptance criteria for fatigue loaded vessels

The results of the weld checks and inspections shall meet quality level B of ISO 5817 or ISO 10042 and the corresponding ISO standards for testing classes and acceptance levels as defined in ISO 17635:2016, Annex A.

| NDT method                                                                                                                                | Testing techniques and levels in accordance with | Acceptance levels in accordance with                                               |
|-------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|------------------------------------------------------------------------------------|
| Visual testing (VT)                                                                                                                       | ISO 17637                                        | ISO 5817 Level B (for steel welds)<br>ISO 10042 Level B (for aluminium welds)      |
| Radiographic testing (RT)                                                                                                                 | ISO 17636-1 class B <sup>a</sup>                 | ISO 10675-1 Level 1 (for steel welds)<br>ISO 10675-2 Level 1 (for aluminium welds) |
| Penetrant testing (PT)                                                                                                                    | ISO 3452-1                                       | ISO 23277 Level 2X                                                                 |
| <sup>a</sup> The minimum number of exposures for circumferential weld testing may correspond to the requirements of ISO 17636-1, class A. |                                                  |                                                                                    |

Additional requirements for the following imperfections:

- stray arc (601) – removal plus 100 % penetrant testing to ensure no imperfection;
- spatter (602) – weld spatter shall be removed from all pressure parts and load carrying attachment welds.
- torn surface (603), grinding mark (604), chipping mark (605) shall be ground to provide a smooth transition;
- underflushing (606) shall not be permitted. Any local underflushing shall be related to design characteristics.

#### 12.3.4.3 Extent of examination of non-welded joints

Where non-welded joints are used between metallic materials and/or non-metallic materials, the quality plan referred to in 12.1 shall include reference to an adequate specification. This technical specification shall include the description of the requirements for inspection and testing, together with the criteria necessary to allow for the repair of any imperfections.

### 12.4 Rectification

The weld or surface imperfections may be repaired by removing the imperfections and/or rewelding, 100 % of all repaired welds shall be examined and tested to the original acceptance standards.

## 12.5 Pressure testing

**12.5.1** Every inner vessel shall be subjected to a pressure test and its leak tightness shall be demonstrated. This leak tightness may be demonstrated during the establishment of the vacuum or by a separate leak test at pressures up to the design pressure **but not less than 90 % of the maximum allowable working pressure**.

The test pressure for the inner vessel shall not be less than the highest of:

- $1,3 (p_S + 1)$  bar [ $1,3 (p_S + 0,1)$  MPa] if not surrounded by vacuum; and
- $1,3 (p_S + 1) - 1$  bar [ $1,3 (p_S + 0,1) - 0,1$  MPa] if surrounded by vacuum;

considered for each element of the vessel, e.g. shell courses, head, etc.

Where the test is carried out hydraulically, the pressure shall be raised gradually to the test pressure holding it there for 30 min. Then the pressure shall be reduced to the design pressure so that a visual examination of all surfaces and joints can be made. The vessel shall show no gross plastic deformation or leakage (except as in [Annex D](#)). The test may be carried out pneumatically on a similar basis. As pneumatic testing employs substantially greater stored energy than hydraulic testing, it shall normally only be carried out where adequate facilities and procedures are employed to assure the safety of inspectors, employees and the public.

**12.5.2** Vessels which have been repaired subsequent to the pressure test shall be re-subjected to the specified pressure test after completion of the repairs.

Cosmetic grinding on the base material which does not affect the required minimum thickness may be done after pressure test without doing another pressure test.

**12.5.3** Where austenitic stainless steel comes into contact with water, the chloride content of the water and time of exposure shall be controlled so as to avoid stress corrosion cracking.

**12.5.4** The piping system shall be subjected to a pressure test at a pressure in accordance with [10.2.3.11](#). It is not necessary to strength test mechanical joints and fittings that have demonstrated satisfactory in-service experience.

**12.5.5** Leakproofness tests (see [12.1.2](#)).

## 13 Marking and labelling

The large transportable cryogenic vessel shall bear the required markings and labellings. Examples of tank plates (of the complete tank and of the inner vessel) for fixed tanks (tank vehicles), demountable tanks, tank containers and tank swap bodies are given for information in [Annex A](#).

At a minimum, the labelling shall include the size limitations, if any, for operation and transportation mode.

Marking shall be on a corrosion-resistant metal plate, permanently attached to the outer jacket of the cryogenic vessel, in a conspicuous place quickly accessible for inspection.

## 14 Final acceptance test

The first date and stamp of the expert (marks 14, 16 — see [A.1](#)) after the final acceptance test on the large transportable cryogenic vessel confirms that the marking and labelling, and that the vessel itself, meets the requirements of this document. These marks also confirm that the large transportable cryogenic vessel is ready for putting into service provided that the requirements of ISO 20421-2 are met.

## 15 Periodic inspection

The large transportable cryogenic vessel shall be inspected periodically with the applicable standard. By affixing the mark of the inspector and the date on the data plate, the inspector confirms the successfully completed periodic inspection.

The periodic inspection shall be done in accordance with ISO 20421-2.

## 16 Documentation

Technical documents delivered by the manufacturer to the owner consisting of:

- all documentation establishing the conformity with this document (e.g. material, pressure test, cleanliness, safety devices);
- a short description of the vessel (including characteristic data, etc.);
- a list of fluids and their net mass for which the cryogenic vessel is designed;
- an operating manual (for the user) which consists of:
  - a short description of the vessel (including characteristic data, etc.);
  - a statement that the vessel is in conformance with this document;
  - the instructions for normal operation.

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## Annex A (informative)

### Examples of tank plates

#### A.1 Example 1: Tank plate (of the complete tank) for fixed tanks of road tankers (tank vehicles), demountable tanks, tank containers and tank swap bodies

|    |                                                                                               |               |    |                                                   |
|----|-----------------------------------------------------------------------------------------------|---------------|----|---------------------------------------------------|
| 1  | Manufacturer                                                                                  |               |    |                                                   |
| 2  | Approval number                                                                               |               | 2a | Conformity mark                                   |
| 3  | Manufacturer's serial number                                                                  |               | 4  | Year of manufacture                               |
| 5  | Tank code                                                                                     |               | 6  | Test pressure                                     |
| 7  | Capacity of the tank                                                                          | litres        | 8  | Design temperature                                |
| 9  | Material and materials standards of                                                           | inner vessel: |    | Bar (or MPa)                                      |
|    |                                                                                               | outer jacket: |    | °C                                                |
| 10 | Insulation                                                                                    |               |    | vacuum-insulated or thermally insulated by vacuum |
| 11 | Maximum allowable working pressure                                                            |               |    | Bar (or MPa)                                      |
| 12 | The proper shipping name of the gas(es), for whose transport in the portable tank is approved |               |    |                                                   |
| 13 | Minimum filling temperature for each gas                                                      | °C            | °C | °C                                                |
| 14 | Maximum permissible load mass for each gas                                                    | kg            | kg | kg                                                |
| 15 | Date (month and year) of initial test and most recent periodic test                           |               |    |                                                   |
| 16 | Stamp of the expert who carried out the tests                                                 |               |    |                                                   |
| 17 | Name of owner or operator                                                                     |               |    |                                                   |
| 18 | Maximum permissible mass                                                                      |               |    | kg                                                |
| 19 | Unladen mass                                                                                  |               |    | kg                                                |

**Figure A.1 — Tank plate for the complete tank**

The markings of [Figure A.1](#) are explained in [Table A.1](#).

**Table A.1 — Explanation of the marking of the tank plate (complete tank)**

| No. | Content/explanation                                                                                                               |
|-----|-----------------------------------------------------------------------------------------------------------------------------------|
| 1   | Manufacturer's name or mark of the complete tank.                                                                                 |
| 2   | Approval number given by the competent authority or body designated by this authority.                                            |
| 2a  | Conformity mark (e.g. π) according to applicable code, accompanied by the identification number of the notified or approved body. |

**Table A.1** (continued)

| No. | Content/explanation                                                                                                                                                                                                                                                                                                                                                                    |
|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 3   | Serial or production number issued by the manufacturer.                                                                                                                                                                                                                                                                                                                                |
| 4   | Year of manufacture.                                                                                                                                                                                                                                                                                                                                                                   |
| 5   | Tank code according to the certificate.                                                                                                                                                                                                                                                                                                                                                |
| 6   | Test pressure (gauge) of the shell, in MPa or bar.                                                                                                                                                                                                                                                                                                                                     |
| 7   | Water capacity, in litres.                                                                                                                                                                                                                                                                                                                                                             |
| 8   | Design temperature, in °C.                                                                                                                                                                                                                                                                                                                                                             |
| 9   | Materials of the shell (and of the ends if different) of the inner vessel and reference to materials standards, if available and materials of the shell (and of the ends if different) of the outer jacket and reference to materials standards, if available.                                                                                                                         |
| 10  | Type of insulation of the tank in words, e.g. "thermally insulated" or "thermally insulated by vacuum", if applicable, in an official language of the country of registration and also, if that language is not English, French or German, in English, French or German, unless any agreements concluded between the countries concerned in the transport operation provide otherwise. |
| 11  | Maximum (allowable) working pressure (gauge), in bar or MPa.                                                                                                                                                                                                                                                                                                                           |
| 12  | The name(s) in full of the gas(es), and, in addition for gases classified under an n.o.s. entry, the technical name of the gases, for which the tank is approved,                                                                                                                                                                                                                      |
| 13  | Minimum filling temperature for each gas.                                                                                                                                                                                                                                                                                                                                              |
| 14  | Maximum allowable (net) mass of each gas according to mark 12, in kg.                                                                                                                                                                                                                                                                                                                  |
| 15  | Month and year of the initial inspection and of each subsequent periodic inspection.                                                                                                                                                                                                                                                                                                   |
| 16  | Stamp of the inspector (notified or approved body) who carried out the inspection(s) of mark 14 accompanied by the identification number of the notified or approved body.                                                                                                                                                                                                             |
| 17  | Name of owner or operator.                                                                                                                                                                                                                                                                                                                                                             |
| 18  | Maximum permissible mass (gross mass of the road tanker (tank vehicle), demountable tank, tank container and tank swap body).                                                                                                                                                                                                                                                          |
| 19  | Unladen mass (tare mass of the road tanker (tank vehicle), demountable tank, tank container and tank swap body).                                                                                                                                                                                                                                                                       |

## A.2 Example 2 :Tank plate for the inner vessel of fixed tanks of road tankers (tank vehicles), demountable tanks, tank containers and tank swap bodies

**Table A.2 — Explanation of the marking of the tank plate for the inner vessel**

| No. | Content/explanation                                                                                                           |
|-----|-------------------------------------------------------------------------------------------------------------------------------|
| 1   | Manufacturer's name or mark of the inner vessel.                                                                              |
| 2   | Approval number given by the competent authority or body designated by this authority                                         |
| 3   | Serial or production number issued by the manufacturer.                                                                       |
| 4   | Year of manufacture.                                                                                                          |
| 5   | To be dropped.                                                                                                                |
| 6   | Test pressure (gauge) of the inner vessel, in MPa or bar.                                                                     |
| 7   | Water capacity, in litres.                                                                                                    |
| 8   | Design temperature, in °C.                                                                                                    |
| 9   | Materials of the shell (and of the ends if different) of the inner vessel and reference to materials standards, if available. |
| 10  | To be dropped.                                                                                                                |
| 11  | Maximum (allowable) working pressure (gauge), in bar or MPa.                                                                  |

**Table A.2** *(continued)*

| No. | Content/explanation                                     |
|-----|---------------------------------------------------------|
| 12  | To be dropped.                                          |
| 13  |                                                         |
| 14  |                                                         |
| 15  | Month and year of the pressure test of the inner vessel |
| 16  | Stamp of the inspector who witnessed the pressure test  |
| 17  | To be dropped.                                          |
| 18  |                                                         |
| 19  |                                                         |

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## Annex B (informative)

### Elastic stress analysis

#### B.1 General

This annex provides rules to be followed if an elastic stress analysis is used to evaluate components of a large vacuum-insulated transportable cryogenic vessel for operating conditions. The loads to be considered are those defined in [10.2.3](#).

[B.4](#) and [B.5](#) give alternative criteria for demonstrating the acceptability of design on the basis of elastic analysis. The criteria in [B.5](#) apply only to local stresses in the vicinity of attachments, supports, nozzles, etc.

The calculated stresses in the area under consideration are grouped into the following stress categories:

- general primary membrane stress;
- local primary membrane stress;
- primary bending stress;
- secondary stress.

Stress intensities  $f_m$ ,  $f_L$ ,  $f_b$  and  $f_g$  can be determined from the principal stresses  $f_1$ ,  $f_2$  and  $f_3$  in each category, using the maximum shear stress theory of failure (see [B.2.1](#)).

The stress intensities determined in this way shall be less than the allowable values given in [B.3](#), [B.4](#) or [B.5](#).

If [Annex D](#) is applied, see [D.4.1.6](#), to consider the different orientation of material hardening

[Figure B.1](#) and [Table B.1](#) have been included as guidance, where [B.4](#) is used for evaluation, in establishing stress categories for some typical cases and stress intensity limits for combinations of stress categories. There will be instances when references to definitions of stresses will be necessary to classify a specific stress condition to a stress category. [B.4.5](#) explains the reason for separating them into two categories, “general” and “secondary” in the case of thermal stresses.

#### B.2 Terminology

##### B.2.1 Stress intensity

The stress intensity is twice the maximum shear stress, i.e. the difference between the algebraically largest principal stress and the algebraically smallest principal stress at a given point. Tension stresses are considered positive and compression stresses are considered negative.

The principal stresses  $f_1$  and  $f_2$  acting tangentially to the surface at the point under consideration should be calculated from [Formulae \(B.1\)](#) and [\(B.2\)](#):

$$f_1 = 0,5 \times \left( \sigma_1 + \sigma_2 + \sqrt{(\sigma_1 - \sigma_2)^2 + 4 \times \tau^2} \right) \quad (\text{B.1})$$

$$f_2 = 0,5 \times \left( \sigma_1 + \sigma_2 - \sqrt{(\sigma_1 - \sigma_2)^2 + 4 \times \tau^2} \right) \quad (\text{B.2})$$

where

- $\sigma_1$  is the circumferential stress;
- $\sigma_2$  is the meridional stress (longitudinal in a cylindrical shell);
- $\tau$  is the shear stress.

## B.2.2 Gross structural discontinuity

A gross structural discontinuity is a source of stress or strain intensification that affects a relatively large portion of a structure and has a significant effect on the overall stress or strain pattern or on the structure as a whole.

Examples of gross structural discontinuities are:

- EXAMPLE 1 End to shell junctions.
- EXAMPLE 2 Junctions between shells of different diameters or thicknesses.
- EXAMPLE 3 Nozzles.

## B.2.3 Local structural discontinuity

A local structural discontinuity is a source of stress or strain intensification that affects a relatively small volume of material and does not have a significant effect on the overall stress or strain pattern or on the structure as a whole.

- EXAMPLE 1 Small fillet radii.
- EXAMPLE 2 Small attachments.
- EXAMPLE 3 Partial penetration welds.

## B.2.4 Normal stress

The normal stress is the component of stress normal to the plane of reference; this is also referred to as direct stress.

Usually the distribution of normal stress is not uniform through the thickness of a part, so this stress is considered to be made up in turn of two components, one of which is uniformly distributed and equal to the average value of stress across the thickness of the section under consideration, and the other of which varies with the location across the thickness.

## B.2.5 Shear stress

The shear stress is the component of stress acting in the plane of reference.

## B.2.6 Membrane stress

The membrane stress is the component of stress that is uniformly distributed and equal to the average value of stress across the thickness of the section under consideration.

## B.2.7 Primary stress

A primary stress is a stress produced by mechanical loadings only and so distributed in the structure that no redistribution of load occurs as a result of yielding. A normal stress, or a shear stress developed by the imposed loading, is necessary to satisfy the simple laws of equilibrium of external and internal

forces and moments. The basic characteristic of this stress is that it is not self-limiting. Primary stresses that considerably exceed the yield strength will result in failure, or at least in gross distortion. A thermal stress is not classified as a primary stress. Primary stress is divided into “general” and “local” categories. The local primary stress is defined in [B.2.8](#).

Examples of general primary stress are:

EXAMPLE 1 The stress in a cylindrical or a spherical shell due to internal pressure or to distributed live loads.

EXAMPLE 2 The bending stress in the central portion of a flat head due to pressure.

### B.2.8 Primary local membrane stress

Cases arise in which a membrane stress produced by pressure or other mechanical loading and associated with a primary and/or a discontinuity effect produces excessive distortion in the transfer of load to other portions of the structure.

Conservatism requires that such a stress be classified as a primary local membrane stress even though it has some characteristics of a secondary stress. A stressed region may be considered as local if the distance over which the stress intensity exceeds 110 % of the allowable general primary membrane stress does not extend in the meridional direction more than  $0,5\sqrt{Rs}$  and if it is not closer in the meridional direction than  $2,5\sqrt{Rs}$  to another region where the limits of general primary membrane stress are exceeded, where  $R$  and  $s$  are respectively the radius and thickness of the component.

An example of a primary local stress is the membrane stress in a shell produced by external load and moment at a permanent support or at a nozzle connection.

### B.2.9 Secondary stress

A secondary stress is a normal stress or a shear stress developed by the constraint of adjacent parts or by self-constraint of a structure. The basic characteristic of a secondary stress is that it is self-limiting. Local yielding and minor distortions can satisfy the conditions that cause the stress to occur and failure from one application of the stress is not to be expected.

An example of secondary stress is the bending stress at a gross structural discontinuity.

#### B.2.9.1 Peak stress

The basic characteristic of a peak stress is that it does not cause any noticeable distortion and is objectionable only as a possible source of a fatigue crack. A stress that is not highly localized falls into this category if it is of a type that cannot cause noticeable distortion.

EXAMPLE 1 The surface stresses in the wall of a vessel or pipe produced by thermal shock.

EXAMPLE 2 The stress at a local structural discontinuity.

### B.3 Limit for longitudinal compressive general membrane stress

The longitudinal compressive stress shall not exceed  $0,93\Delta K$  for ferritic steels and  $0,73 \Delta K$  for austenitic stainless steel and aluminium alloys, where  $\Delta$  is obtained from [Figure B.2](#) or [B.3](#) in terms of  $P_e/P_{yss}$  and where:

$$P_e = \frac{1,21Es^2}{R^2};$$

$$P_{yss} = \frac{1,86Ks}{R} \text{ for ferritic steel; and}$$

$$P_{yss} = \frac{1,46Ks}{R} \text{ for austenitic stainless steel and aluminium alloys.}$$

## B.4 Stress categories and stress limits for general application

### B.4.1 General

A calculated stress depending upon the type of loading and/or the distribution of such stress will fall within one of the five basic stress categories defined in B.4.2 to B.4.6. For each category, a stress intensity value is derived for a specific condition of design. To satisfy the analysis, this stress intensity shall fall within the limit detailed for each category.

### B.4.2 General primary membrane stress category

The stresses falling within the general primary membrane stress category are those defined as general primary stresses in B.2.7, and are produced by pressure and other mechanical loads, but excluding all secondary and peak stresses. The value of the membrane stress intensity is obtained by averaging these stresses across the thickness of the section under consideration. The limiting value of this stress intensity  $f_m$  is the allowable stress value  $2K/3$ .

### B.4.3 Local primary membrane stress category

The stresses falling within the local primary membrane stress category are those defined in B.2.8 and are produced by pressure and other mechanical loads, but excluding all thermal and peak stresses. The stress intensity  $f_L$  is the average value of these stresses across the thickness of the section under consideration and is limited to  $K$ .

### B.4.4 General or local primary membrane plus primary bending stress category

The stresses falling within the general or local primary membrane plus primary bending stress category are those defined in B.2.7, but the stress intensity value  $f_b$ ,  $(f_m + f_b)$  or  $(f_L + f_b)$  is the highest value of those stresses acting across the section under consideration, excluding secondary and peak stresses.  $f_b$  is the primary bending stress intensity, which means the component of primary stress proportional to the distance from centroid of solid section. The stress intensity  $f_b$ ,  $(f_m + f_b)$  or  $(f_L + f_b)$  is not to exceed  $K$ .

### B.4.5 Primary plus secondary stress category

The stresses falling within the primary plus secondary stress category are those defined in B.2.7 plus those of B.2.9 produced by pressure, other mechanical loads and general thermal effects. The effects of gross structural discontinuities, but not of local structural discontinuities (stress concentrations), should be included. The stress intensity value  $(f_m + f_b + f_g)$  or  $(f_L + f_b + f_g)$  is the highest value of these stresses acting across the section under consideration and shall be limited to  $2K$ .

### B.4.6 Thermal stress

Thermal stress is a self-balancing stress produced by a non-uniform distribution of temperature or by differing thermal coefficients of expansion. Thermal stress is developed in a solid body whenever a volume of material is prevented from assuming the size and shape that it normally should under a change in temperature.

For the purpose of establishing allowable stresses, the following two types of thermal stress are recognized, depending on the volume or area in which distortion takes place:

- a) general thermal stress is associated with distortion of the structure in which it occurs. If a stress of this type, neglecting stress concentrations, exceeds  $2K$ , the elastic analysis may be invalid and

successive thermal cycles may produce incremental distortion. This type is therefore classified as secondary stress in [Table B.1](#) and [Figure B.1](#).

Examples of general thermal stress are:

EXAMPLE 1 The stress produced by an axial thermal gradient in a cylindrical shell.

EXAMPLE 2 The stress produced by the temperature difference between a nozzle and the shell to which it is attached.

- b) Local thermal stress is associated with almost complete suppression of the differential expansion and thus produces no significant distortion. Such stresses are only considered from the fatigue standpoint.

EXAMPLE A small cold spot in a vessel wall.

## B.5 Specific criteria, stress categories and stress limits for limited application

### B.5.1 General

The criteria and stress limits for particular stress categories for elastically calculated stresses adjacent to attachments and supports and to nozzles and openings which are subject to the combined effects of pressure and externally applied loads are specified in [B.5.2](#) to [B.5.4](#).

The minimum separation between adjacent loaded attachments, pads, nozzles or openings or other stress concentrating features shall not be less than  $2,5\sqrt{Rs}$ .

$R$  and  $s$  are respectively the radius and thickness of the component. The criteria of [B.2.8](#) are not applicable to this section.

If design acceptability is demonstrated by [B.5](#), then the use of [B.4](#) is not required.

### B.5.2 Attachments and supports

The dimension in the circumferential direction of the loaded area shall not exceed one-third of the shell circumference. The stresses adjacent to the loaded area due to pressure acting in the shell may be taken as the shell pressure stresses without any concentrating effects due to the attachment.

Under the design combined load, the following stress limits apply:

- the primary membrane stress intensity should not exceed  $0,6K$  or  $0,3R_m$ ;
- the stress intensity due to the sum of primary membrane and primary bending stresses shall not exceed  $4K/3$ ;
- the stress intensity due to the sum of primary membrane stresses, primary bending stresses and thermal stresses shall not exceed  $2K$ .

### B.5.3 Nozzles and openings

The nozzle or opening shall be reinforced in accordance with [10.3.6.7](#).

Under the design combined load, the following stress limits apply:

- the primary membrane stress intensity should not exceed  $0,8K$ ;
- the stress intensity due to the sum of primary membrane stresses and primary bending stresses shall not exceed  $1,5K$ ;
- the stress intensity due to the sum of primary membrane stresses, primary bending stresses and thermal stresses shall not exceed  $2K$ .

### B.5.4 Additional stress limits

Where significant compressive membrane stresses are present, the possibility of buckling shall be investigated and the design modified if necessary (see B.3). In cases where the external load is highly concentrated, an acceptable procedure would be to limit the sum of membrane and bending stresses (total compressive stress) in any direction at the point to  $0,9K$ .

Where shear stress is present alone, it shall not exceed  $K/3$ . The maximum permissible bearing stresses should not exceed  $K$ .

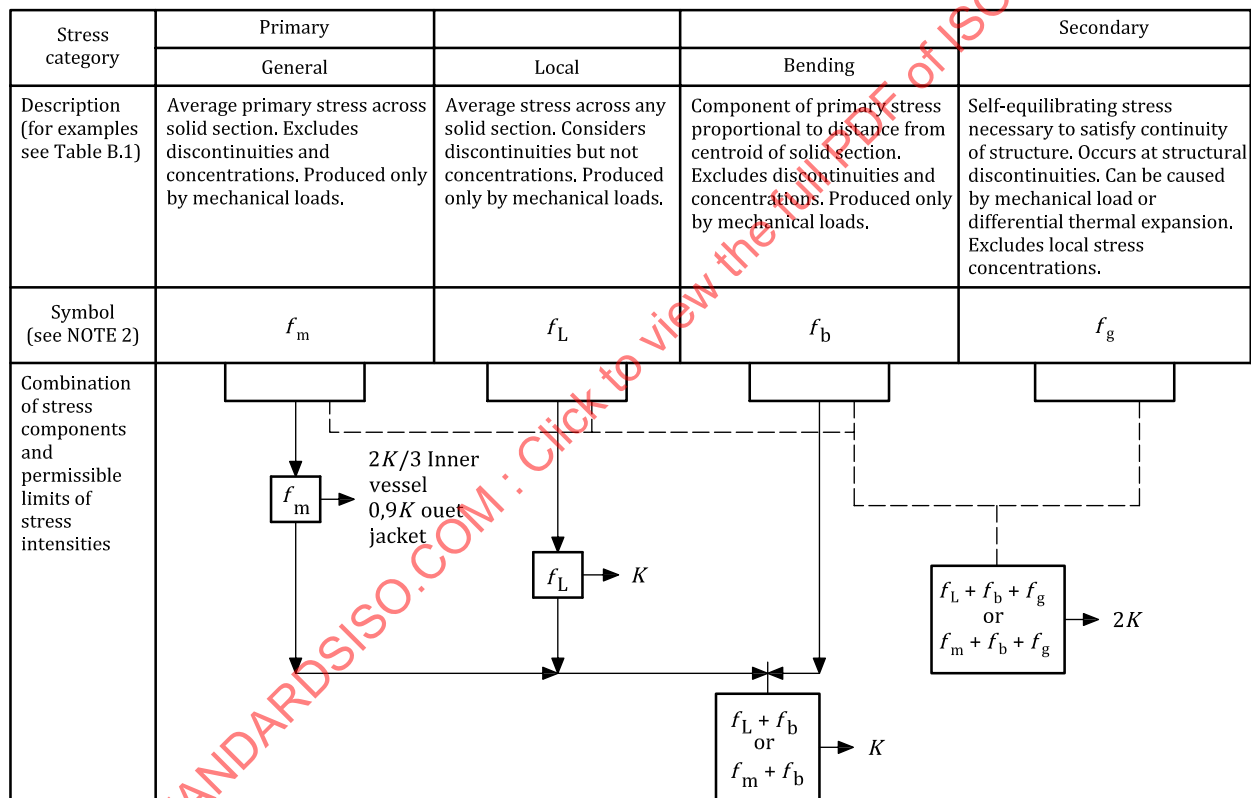
**Table B.1 — Classification of stresses for some typical cases**

| Vessel component               | Location                                                                                                                                       | Origin of stress                              | Type of stress                                                                                 | Classification |       |
|--------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------|------------------------------------------------------------------------------------------------|----------------|-------|
| Cylindrical or spherical shell | Shell plate remote from discontinuities                                                                                                        | Internal pressure                             | General membrane                                                                               | $f_m$          |       |
|                                |                                                                                                                                                |                                               | Gradient through plate thickness                                                               | $f_g$          |       |
|                                |                                                                                                                                                | Axial thermal gradient                        | Membrane                                                                                       | $f_g$          |       |
|                                |                                                                                                                                                |                                               | Bending                                                                                        | $f_g$          |       |
|                                | Junction with head                                                                                                                             | Internal pressure                             | Membrane                                                                                       | $f_L$          |       |
|                                |                                                                                                                                                |                                               | Bending                                                                                        | $f_g$          |       |
| Any shell or end               | Any section across entire vessel                                                                                                               | External load or moment, or internal pressure | General membrane averaged across full section, stress component perpendicular to cross-section | $f_m$          |       |
|                                |                                                                                                                                                | External load or moment                       | Bending across full section, stress component perpendicular to cross-section                   | $f_m$          |       |
|                                | Near nozzle or other opening                                                                                                                   | External load or moment, or internal pressure | Local membrane                                                                                 | $f_L$          |       |
|                                |                                                                                                                                                |                                               | Bending                                                                                        | $f_g$          |       |
|                                | Any location                                                                                                                                   | Temperature difference between shell and end  | Membrane                                                                                       | $f_g$          |       |
|                                |                                                                                                                                                |                                               | Bending                                                                                        | $f_g$          |       |
|                                | Dished end or conical end                                                                                                                      | Crown                                         | Internal pressure                                                                              | Membrane       | $f_m$ |
|                                |                                                                                                                                                |                                               |                                                                                                | Bending        | $f_b$ |
| Knuckle or junction to shell   |                                                                                                                                                | Internal pressure                             | Membrane                                                                                       | $f_L$          |       |
|                                |                                                                                                                                                |                                               | Bending                                                                                        | $f_g$          |       |
| Flat end                       | Centre region                                                                                                                                  | Internal pressure                             | Membrane                                                                                       | $f_m$          |       |
|                                |                                                                                                                                                |                                               | Bending                                                                                        | $f_b$          |       |
|                                | Junction to shell                                                                                                                              | Internal pressure                             | Membrane                                                                                       | $f_L$          |       |
|                                |                                                                                                                                                |                                               | Bending                                                                                        | $f_g$          |       |
| Perforated end or shell        | Typical ligament in a uniform pattern                                                                                                          | Pressure                                      | Membrane (average through cross section)                                                       | $f_m$          |       |
|                                |                                                                                                                                                |                                               | Bending (average through width of ligament, but gradient through plate)                        | $f_b$          |       |
|                                | Isolated or atypical ligament                                                                                                                  | Pressure                                      | Membrane                                                                                       | $f_g$          |       |
|                                |                                                                                                                                                |                                               | Bending                                                                                        | $f_g$          |       |
|                                | Consideration should also be given to the possibility of buckling and excessive deformation in vessels with large diameter-to-thickness ratio. |                                               |                                                                                                |                |       |

Table B.1 (continued)

| Vessel component | Location                                   | Origin of stress                             | Type of stress                                                                             | Classification |
|------------------|--------------------------------------------|----------------------------------------------|--------------------------------------------------------------------------------------------|----------------|
| Nozzle           | Cross section perpendicular to nozzle axis | Internal pressure or external load or moment | General membrane (average across full section), stress component perpendicular to section) | $f_m$          |
|                  |                                            | External load or moment                      | Bending across nozzle section                                                              | $f_m$          |
|                  | Nozzle wall                                | Internal pressure                            | General membrane                                                                           | $f_m$          |
|                  |                                            |                                              | Local membrane                                                                             | $f_L$          |
|                  |                                            |                                              | Bending                                                                                    | $f_g$          |
|                  |                                            | Differential expansion                       | Membrane                                                                                   | $f_g$          |
|                  |                                            |                                              | Bending                                                                                    | $f_g$          |

Consideration should also be given to the possibility of buckling and excessive deformation in vessels with large diameter-to-thickness ratio.



NOTE The symbols  $f_m$ ,  $f_L$ ,  $f_b$  and  $f_g$  do not represent single quantities but rather sets of six quantities representing the six stress components.

Figure B.1 — Stress categories and limits of stress intensity

The stresses in category  $f_g$  are those parts of the total stress which are produced by thermal gradients, structural discontinuities, etc., and do not include primary stresses which can also exist at the same point. It should be noted, however, that a detailed stress analysis frequently gives the combination of primary and secondary stresses directly and, when appropriate, this calculated value represents the total of  $f_m$  (or  $f_L$ ) +  $f_b$  +  $f_g$  and not  $f_g$  alone.

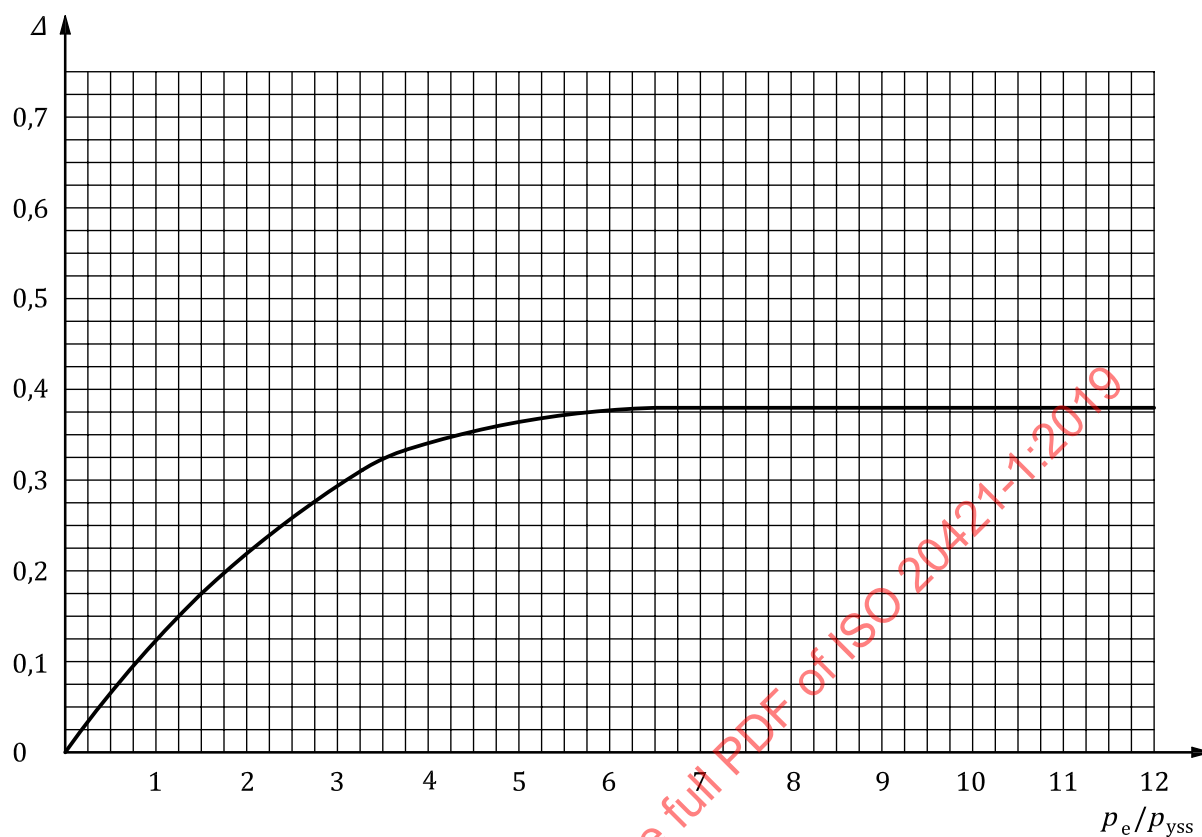


Figure B.2 — For vessels subject to external pressure

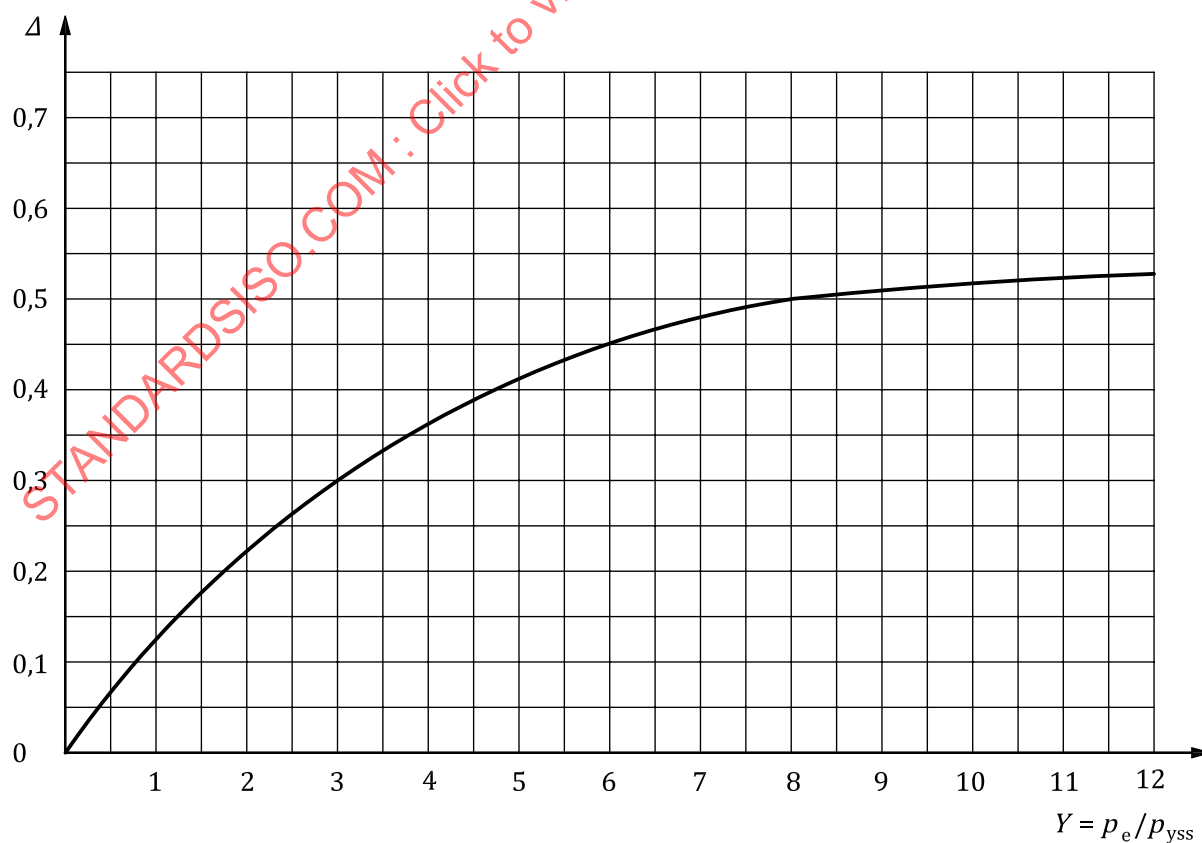


Figure B.3 — For vessels not subject to external pressure

## Annex C (normative)

### Additional requirements for 9 % Ni steel

#### C.1 General

Vessels constructed of 9 % Ni steels are normally welded using an austenitic or modified austenitic consumable. The 1 % or 0,2 % proof strength of the parent plate material normally exceeds that of an all-weld metal sample. These weld metals exhibit excellent ductility and work-hardening characteristics. After work hardening, the enhanced proof strength of the weld metal is maintained within an entirely elastic regime.

The value of  $K$  to be adopted in the calculation formula of [Table 7](#) is that of the parent 9 % Ni steel material.

During the first proof pressure test after fabrication, the welds plastically strain by a small, but sufficient amount such that their strength increases to create equilibrium with the applied loads. Thereafter, the vessel behaves elastically when subjected to the maximum allowable working pressure.

#### C.2 Specific requirements

**C.2.1** The minimum design temperature of vessels constructed of 9 % Ni steel shall not be less than  $-196\text{ }^{\circ}\text{C}$ .

**C.2.2** The maximum design temperature shall not exceed  $50\text{ }^{\circ}\text{C}$ , when defrosting or drying the vessel at low pressure.

**C.2.3** The maximum thickness of the vessel at the weld edge preparation shall not exceed 30 mm. A high-nickel austenitic weld wire shall be used when the thickness of the vessel at the weld edge preparation exceeds 20 mm.

**C.2.4** The full length of all branch attachment welds shall be examined by dye penetrant before the first proof pressure test.

**C.2.5** Imperfections that are unacceptable according to this document shall be repaired and re-examined to demonstrate compliance.

**C.2.6** The vessel and all welds shall be examined visually after the proof pressure test to ensure that there is no evidence of gross deformation.

**C.2.7** The weld procedure qualification and production control transverse tensile test specimens shall:

- show no gross deformation when subjected to a tensile stress equal to the minimum specified material property  $K$  of the parent plate. Some small reduction in area is acceptable due to the expected plastic deformation associated with strain hardening. The measured 1 % proof stress of the transverse tensile test piece when using a 50 mm gauge length shall not be less than the minimum specified material property " $K$ " of the parent plate;
- demonstrate a rupture strength not less than the minimum specified ultimate strength of the parent plate.

NOTE These items also apply to work-hardened austenitic stainless steel.

**C.2.8** Longitudinal bend tests shall be used rather than side bend tests as permitted by ISO 15607 when qualifying weld procedures or testing production control test plates.

**C.2.9** The heat-affected zone at the weld fusion boundary shall be demonstrated to attain an ISO V-notch impact strength of 50 joules or 0,38 mm for lateral expansion at  $-196\text{ }^{\circ}\text{C}$ , as an average of three test pieces, during weld procedure qualification and production control plate testing. These tests shall be performed in accordance with ISO 21028-1 and ISO 21028-2.

**C.2.10** Openings shall not be located with their centre lines closer to principal seams than twice their diameter.

NOTE These items also apply to work-hardened austenitic stainless steel.

**C.2.11** Butt welds shall not be located where they are subject to high bending stresses which can result in plastic cycling and incremental collapse.

**C.2.12** 9 % Ni vessels may be fitted with nozzles of stainless steel. Where the outside diameter of the nozzle exceeds 75 mm, the stresses in the shell and nozzle, due to pressure, mechanical loads and thermal expansion, shall be assessed and shown to comply with the requirements of [Annex A](#) and to provide an adequate fatigue life for the intended application of the vessel.

**C.2.13** Filler wires shall be selected from austenitic, modified austenitic or high-nickel austenitic materials.

**C.2.14** 9 % Ni material conforming to ISO 9328-4 is suitable for the construction of cryogenic vessels conforming to this document. Other materials may be suitable provided sufficient test data is made available to demonstrate the suitability of the material.

## Annex D (normative)

### Pressure strengthening of vessels from austenitic stainless steels

#### D.1 General

Austenitic stainless steel exhibits stress/strain characteristics [Figure D.1 b)], different from that of carbon steel (Figure D.1), that enable stainless steel to accept strain as a means of increasing its proof strength. Plastic deformation of 10 % is possible with steels having an elongation at fracture of at least 35 % in the solution heat-treated condition.

Austenitic stainless steel that has been strained to a higher proof strength will retain and even increase its enhanced strength advantage at cryogenic temperatures.

For instance, when austenitic stainless steel is loaded in tension to a stress  $\sigma_k$  above its proof strength and then unloaded, a permanent plastic elongation will result. When this steel is loaded again, it will remain elastic up to this higher stress which is then the new proof strength; only when the stress exceeds  $\sigma_k$  will the deformation be plastic, and it will then follow the original stress/strain curve.

When the strengthening stress  $\sigma_k$  has been chosen, the minimum wall thickness of parts of the vessel can be calculated from the design stress to be equal to or less than three-quarters of  $\sigma_k$  (which is equal to the new proof strength). In practice, the strengthening is produced by pressurizing the finished vessel to a pressure  $p_k$  known to produce the required stress, which in turn gives the required amount of plastic deformation to withstand the pressure load.

This technology primarily applies to vessels (or parts of vessels) of non-complex “balloon-type” design, i.e. structures where the pressure-induced membrane stresses are dominant. Other parts of the vessel are normally designed based on conventional design stress values in D.4 and the relevant annexes of this document.

**NOTE** This method is also known as “cold-stretching”. However, using the word “cold” in connection with cryogenic vessels can be misleading since the strengthening pressure is applied at room temperature. Also, the “stretching” is slight if any when using shell material in the work-hardened condition. On the other hand, applying a pressure in excess of the normal test pressure effectively demonstrates the strength and pressure-bearing capability of all parts of the complete vessel.

#### D.2 Application of this annex

This annex applies to cryogenic pressure vessels made from austenitic stainless steel of a wall thickness of not more than 30 mm, strengthened by pressurization at room temperature after being completed and intended for a maximum operating temperature of less than 50 °C.

#### D.3 Materials

**D.3.1** Accepted materials of construction that have already been proven suitable for pressure strengthening for operating temperatures of not less than –196 °C are the austenitic stainless steels specified in Table D.1. Requirements regarding these materials are found in ISO 9328-7.

When material is delivered in a work-hardened condition, the material shall have an elongation at fracture  $A_5$  of not less than 35 %.

**Table D.1 — Austenitic stainless steels accepted for pressure strengthening of cryogenic vessels for operating temperatures of not less than –196 °C**

| Steel designation |         | Solution heat-treated material          |                                         | Pressure-strengthened vessel            |
|-------------------|---------|-----------------------------------------|-----------------------------------------|-----------------------------------------|
| Name              | Number  | $R_{p0,2}$<br>N/mm <sup>2</sup><br>min. | $R_{p1,0}$<br>N/mm <sup>2</sup><br>min. | $\sigma_k$<br>N/mm <sup>2</sup><br>max. |
| X5CrNi18-10       | 1.4301  | 210                                     | 250                                     | 410                                     |
| X2CrNi19-11       | 1.4306  | 200                                     | 240                                     | 400                                     |
| X2CrNi18-10       | 1.4311  | 270                                     | 310                                     | 470                                     |
| X6CrNiTi18-10     | 1.4541  | 200                                     | 240                                     | 400                                     |
| X6CrNiNb18-10     | 1.4550  | 200                                     | 240                                     | 400                                     |
| X5CrNi19-09       | 1.4315  | 270                                     | 310                                     | 470                                     |
| SA/A-240 340      | S 30400 | —                                       | —                                       | 410                                     |
| SA/A-240 304L     | S 30403 | —                                       | —                                       | 385                                     |
| SA/A-240 304N     | S 30451 | —                                       | —                                       | 470                                     |
| SA/A-240 316      | S 31600 | —                                       | —                                       | 410                                     |
| SA/A-240 316L     | S 31603 | —                                       | —                                       | 385                                     |
| SA/A-240 316N     | S 31651 | —                                       | —                                       | 470                                     |
| SA/A-240 316LN    | S 31653 | —                                       | —                                       | 410                                     |

**D.3.2** In case stable or metastable austenitic steels (when the strengthening strain exceeds 5 %) according to [Clause 9](#), other than those listed in [Table D.1](#), are to be qualified for pressure strengthening, or the vessel operating temperature will be below –196 °C, steel quality and welding procedure shall be validated by the type approval test detailed below. This test shall be carried out in addition to the tests required by [9.1](#) and [11.6.1](#).

A welded test plate shall be pre-stretched to an elongation of 15 % (in one direction).

From this test plate, specimens shall be tested as per [Table D.2](#).

**Table D.2 — Testing of pre-stretched production test plates for steels**

| Group                              | Test specimens                    |
|------------------------------------|-----------------------------------|
| Austenitic stainless steels ≤12 mm | 1 BF, 1 BR, 1 TT, 1TW, 1 Ma       |
| Austenitic stainless steels >12 mm | 1 BF, 1 BR, 1 TT, 1TW, 1 Ma, 3 IW |

- base material: two tensile tests along the direction of the applied stress and one set of impact tests across the direction of the applied stress;
- weld: two tensile tests across the weld and one set of impact tests of the weld metal according to ISO 21028-1 and ISO 21028-2.

One tensile test and the impact tests shall be carried out at the lowest operating temperature. The other tensile test shall be carried out at 20 °C. The impact value shall not be less than 0,53 mm lateral expansion.

The base material and the weld shall follow [Formulae \(D.1\)](#) to (D.3):

$$R_{p0,2} \geq \sigma_k \quad (D.1)$$

$$A_5 \geq 25 \% \quad (D.2)$$

$$\alpha_{k \text{ ISO-V}} \geq 48 \text{ J/cm}^2 \quad (\text{D.3})$$

**D.3.3** The welded test plate shall be pre-stretched (on one direction) to an elongation of 15 % before working out the specimen for destructive testing.

## D.4 Design

### D.4.1 General

**D.4.1.1** Wall thicknesses calculated according to [D.4.3](#) refers to thicknesses before strengthening.

**D.4.1.2** Nominal diameters may be used in the design calculations. No allowance is necessary for the possible increase in diameter due to strengthening.

**D.4.1.3** Maximum design stress value is limited to 200 N/mm<sup>2</sup> above  $R_{p0,2}$  for the material in the solution heat-treated condition.

**D.4.1.4** The weld joint factor 1,0 may be used for the calculation of all pressure strengthened parts of the vessel (longitudinal welds in cylinder, cone or end).

**D.4.1.5** Pressure strengthening applies to vessels (or part of vessels) where the pressure-induced membrane stresses are dominant. Other parts of the vessel shall be designed in accordance with [Clause 10](#) and the relevant annexes of this document. This requirement shall not preclude utilization of the strengthening process, provided the manufacturer can show that it does not cause deformations that impair the integrity of the vessel.

**D.4.1.6** Fastenings and supports should be preferably attached in non-cold stretched areas otherwise for the simultaneously acting pressure and additional loads the different orientation of material hardening (anisotropic hardening) has been taken into account.

### D.4.2 Design for internal pressure

#### D.4.2.1 Design stress values

The design stress value  $\sigma_k$  at 20 °C can be selected freely up to the highest allowable design stress value  $\sigma_{kmax}$  according to [Table D.1](#). This highest allowable design stress value is the same whether the material used is in the solution heat-treated or work-hardened condition.

#### D.4.2.2 Calculation of the strengthening pressure

The required strengthening pressure  $p_k$  is calculated according to [Formula \(D.4\)](#):

$$p_k \geq 1,33p_T \quad (\text{D.4})$$

**NOTE** Strained material is also known to increase its strength when cooled to cryogenic temperatures. However, the effect on strengthening pressure (analogous to the effect on test pressure as in [10.3.2.3.3](#)) is not taken into account in this Annex.

#### D.4.2.3 Calculation of wall thicknesses

##### D.4.2.3.1 General

The wall thickness of the various parts of the pressure vessel shall be calculated according to applicable subclauses of this document with the modifications shown in [Table D.3](#).

**Table D.3 — Modification of formula for the design of pressure-strengthened vessels**

| Subclause                             |                                                                                                                                                                                                                                                                                             | Modification, see subclause in this annex              |
|---------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------|
| <a href="#">10.3.6.1</a>              | Cylinders and spheres subject to internal pressure                                                                                                                                                                                                                                          | <a href="#">D.4.2.3.3</a>                              |
| <a href="#">10.3.6.4</a>              | Dished ends subject to internal or external pressure, <a href="#">10.3.6.4.3</a> — Internal pressure calculation (pressure on the concave surface)                                                                                                                                          | <a href="#">D.4.2.3.4</a>                              |
| <a href="#">10.3.6.5.5/10.3.6.5.6</a> | Cones subject to internal or external pressure <a href="#">10.3.6.5.5</a> — Internal-pressure calculation (pressure on the concave surface) $ \varphi  \leq 70^\circ$ , <a href="#">10.3.6.5.6</a> — Internal-pressure calculation (pressure on the concave surface) $ \varphi  > 70^\circ$ | <a href="#">D.4.2.3.4</a><br><a href="#">D.4.2.3.2</a> |
| <a href="#">10.3.6.6</a>              | Flat ends                                                                                                                                                                                                                                                                                   | <a href="#">D.4.2.3.2</a>                              |
| <a href="#">10.3.6.7</a>              | Openings in cylinders, spheres and cones                                                                                                                                                                                                                                                    | <a href="#">D.4.2.3.2</a><br><a href="#">D.4.2.3.5</a> |

**D.4.2.3.2** Parts where bending stresses are dominant and large deformations cannot be accepted, like flat cones according to [10.3.6.5.6](#) and flat ends according to [10.3.6.6](#), shall be calculated in the normal way using the design pressure  $p$  and design stress values according to [10.3.2.3](#). That is, the effect of the strengthening may not be used in such designs.

Additionally, the capability to pass the strengthening without plastic deformation shall be checked by repeating the calculations using the strengthening pressure (taking the mass of contents into account) for the test pressure  $p_T$  and the design stress value at 20 °C from [10.3.2.3](#).

**D.4.2.3.3** When designing parts according to [10.3.6.1](#), insert into the applicable formula the following:

- design stress value  $\sigma_k$ ;
- weld joint factor 1,0.

**D.4.2.3.4** Parts shall be designed with the same modifications as in [D.4.2.3.3](#). Additionally the shape factor  $\beta$  for dished ends may be reduced to:

- for 10 % torispherical ends, 2,93;
- for 2:1 elliptical ends, 1,91.

However, it shall be demonstrated by calculation or experiment that the strain during strengthening will not cause excessive deformation in regions subject to bending stresses. In cases where the deformation will lead to a better shape (e.g. deeply dished ends turning hemispherical) the method may be used even with large bending stresses.

Also, the risk of buckling in regions where compressive stresses occur (i.e. the knuckle of dished ends and corner area of cones) shall be paid special attention. However, since buckling is heavily dependent on initial imperfections and work-hardening of the material before pressurization, there is no substitute for experience. However, the stretching process in itself will reveal any such tendencies (see [D.5.1](#)).

**D.4.2.3.5** For reinforcements of openings, the stiffness of the attachment shall be considered so that over-dimensioned reinforcements are avoided. Preferably, openings without reinforcement should be used. Unreinforced openings in this context include openings having reinforcement not complying with [10.3.6.7.4](#).

For openings, where the hole diameter exceeds that given below, calculation of the reinforcement shall be made according to [10.3.6.7](#) with the same modifications as in [D.4.2.3.3](#).

When using external plate reinforcement or other kinds of reinforcements that are not welded with full penetration, the risk of overloading of the welds during strengthening shall be observed.

When ligament efficiency is less than 1, stresses due to strengthening shall be analysed according to [10.3.6.7](#).

#### D.4.2.3.6 Largest allowed opening of unreinforced single holes.

In the case of holes joining a nozzle, etc. to the shell, the inside diameter of the nozzle shall not exceed  $d_{\max}$ .

- $d_{\max}$  = diameter of largest allowed opening (major axis for oval holes), in mm;
- $D_y$  = outside diameter of shell, in mm;
- $R$  = inside crown radius of end, in mm;
- $s_0$  = wall thickness of unpierced shell, in mm;
- $s$  = true wall thickness of shell, in mm;
- $\mu = s_0/s$ ;
- $C = 60\sqrt{2(1-\mu)}$  with a maximum of 60 mm.

$$d_{\max} = 0,4\sqrt{D_y \times s + C} \quad (\text{D.5})$$

The value of  $d_{\max}$  calculated according to [Formula \(D.5\)](#) may be rounded up to the nearest higher even 10 mm.  $d_{\max}$ , however, shall meet the conditions in [Formulae \(D.6\)](#) and [\(D.7\)](#):

$$d_{\max} \leq 150 \text{ mm} \quad (\text{D.6})$$

$$d_{\max} \leq 0,2D_y \quad (\text{D.7})$$

The wall thickness of an unpierced cylinder is calculated from [Formula \(D.8\)](#):

$$s_0 = \frac{pD_y}{20 \frac{\sigma_k}{1,33} + 2p} \quad (\text{D.8})$$

The wall thickness of the crown region of an unpierced dished end is calculated from [Formula \(D.9\)](#):

$$s_0 = \frac{pR}{20 \frac{\sigma_k}{1,33}} \quad (\text{D.9})$$

### D.4.3 Design for external pressure

**D.4.3.1** If a pressure strengthened vessel normally operating under internal pressure can be subject to external pressure, the vessel shall also be designed to withstand external pressure according to the applicable subclauses of [Clause 10](#).

By these calculations, the design stress value shall be taken from [10.3.2.3](#). If the pressure-strengthened vessel is made from solution heat, treated material the safety factors  $S_k$  given in [10.3.2.4](#) may be replaced by  $S_k/1,5$ .

**NOTE** This modification is a consequence of the improved shape of the pressure vessel produced by the straining so that a lower factor of safety can be accepted.

In the case of vessels having large nozzles in the shell or when this improvement of the shape is otherwise doubtful, the above modification may be used only if measurements after strengthening show that the vessel is not significantly out of round.

**D.4.3.2** If a vessel is shaped such that it is subject to an external pressure during the strengthening operation, it shall be calculated using the strengthening pressure (taking the mass of contents into account) as a test pressure  $p_T$  and the material properties at 20 °C from [10.3.2.3](#).

## D.5 Manufacturing and inspection

### D.5.1 Strengthening procedure

**D.5.1.1** The strengthening operation, which is a step in the production of the finished vessel, shall be made following written procedures. These procedures shall include the steps described in [D.5.1.2](#) to [D.5.1.6](#).

The procedure shall be monitored and verified on a prototype or a demonstration vessel.

When vessels under pressure require inspection and measurement, adequate facilities and procedures shall be employed to assure the safety of inspectors, employees and the public.

**D.5.1.2** The vessel is filled with liquid. Before the vessel is closed, there should be a wait of at least 15 min to let any air dissolved in the liquid escape. The vessel is then topped up and sealed.

**D.5.1.3** The circumference of all courses shall be measured (e.g. with steel tapes) where the largest increase in cross-section is expected. The strain rate during the strengthening operation shall be calculated over the full circumference.

**D.5.1.4** The strengthening shall be carried out as follows. The pressure is raised to the strengthening pressure and maintained until the strain rate has dropped to less than 0,1 %/h. The time under pressure shall be not less than one hour (see however [D.5.1.5](#)). The strain rate shall be checked by repeated measurements of the circumference according to [D.5.1.3](#). The requirement of 0,1 %/h shall be met during the last half hour.

NOTE The total time under pressure can be long. This can be reduced if a 5 % higher pressure is applied during the first 30 min to 1 h of the operation.

**D.5.1.5** For pressure vessels having a diameter not more than 2 000 mm, the time under pressure may be reduced to 30 min and the requirement of 0,1 %/h be met during the last 15 min.

**D.5.1.6** The strengthening operation replaces the initial pressure testing of the vessel. Should later pressure testing be required, only the normal test pressure shall be used. If the vessel needs to be repaired, this repair and pressure testing or possibly renewed strengthening shall be carried out in accordance with [D.5.3](#).

### D.5.2 Procedure record

There shall be a written record of the operation, containing at least the following information:

- pressurizing sequence specifying pressure readings and time;
- circumference measurements before, during and after pressurization;
- strain rate calculations from circumference measurements according to [D.5.1.4](#);
- any significant changes of shape and size relevant to the functioning of the vessel;
- any requirement for renewed strengthening (according to [D.5.1.6](#) and [D.5.3](#));
- The material sheets shall be placed so that the direction of rolling is in the same direction as the vessel's circumference. The difference between the metal sheets used for the vessel shell shall not exceed the criteria of [Formula \(D.10\)](#):

$$\left(k_{p0,2(\text{certificate})} \times S_{(\text{measured value } e)}\right)_{\max} / \left(k_{p0,2(\text{certificate})} \times S_{(\text{measured value } e)}\right)_{\min} \leq 1,2 \quad (\text{D.10})$$

### D.5.3 Welding

The strengthening method presumes high-quality welding. The same rules apply as for conventionally produced cryogenic vessels, except that production control test plates need not be taken.

Irregularities shall be inside of the limits according to ISO 5817 evaluation group B.

### D.5.4 Pressure-vessel drawing

**D.5.4.1** In addition to the information required by [10.2.2](#), the drawing shall bear the following text:

- the vessel is manufactured according to [Annex D](#);
- strengthening pressure, in bars or in MPa;
- thicknesses and diameters shown apply before strengthening.

**D.5.4.2** Details to be welded in place after the strengthening shall be marked on the drawing.

### D.5.5 Inspection and testing

**D.5.5.1** For testing production control, on a regular basis the welded test plates shall be pre-stretched (in one direction) to an elongation of 15% before working out the specimen for destructive testing.

**D.5.5.2** Non-destructive testing

**D.5.5.2.1** Non-destructive testing shall be carried out before the strengthening to the extent stipulated in [12.3](#) for the weld joint factor 1,0.

Irregularities shall be inside of the limits according to ISO 5817 evaluation group B.

**D.5.5.2.2** After the strengthening operation and reducing the pressure to the ambient pressure, welds shall be visually examined externally for their full lengths. Where high local stress and strain concentrations can be expected during the strengthening operation, examination with liquid penetrant shall also be carried out, e.g. at changes in wall thickness or at welded nozzles. Places which have been examined with liquid penetrant according to [D.5.5.2.1](#) shall also if possible be tested at random using a volumetric method (preferably by radiographic examination).

**D.5.5.2.3** Renewed strengthening shall be carried out if pressure-strengthened parts of the vessel have been significantly affected by post-strengthening welding. Exceptions are permitted for tack-welding of attachments carrying low loads only (e.g. insulation supports) and welding of nozzles not more than 10 % of the vessel inner diameter (with a maximum of 100 mm) or minor weld repairs with comparable effect on the construction. Such welds shall be examined according to [D.5.5.2.1](#) and [D.5.5.2.2](#).

Unless renewed pressure strengthening is carried out, there shall be a normal pressure test as required by [12.5.2](#) after all welding on pressure-retaining parts.

**D.5.5.2.4** Repairing pressure strengthening vessels

To ensure good repairs, these should be performed exclusively by the manufacture. Only repairs to cold stretched components are given below. In case of repair, a hydrostatic pressure test shall be carried out

at stretching pressure ( $p_k$ ), and then a radiographic examination and liquid penetration test shall be performed. The repairs and the subsequent test shall be documented.

a) Repairing weld

Defective points in welds metal shall be machined. Welding qualification is required for repairing the weld. The repair weld has to be tested by means of radiographic examination and liquid penetration test. Strength shall be verified by an extended hydrostatic pressure test with a Pressure acc. to  $P_k$  (see. D.

b) Extension of radiographic examination

When defects except tolerances are revealed during the RX sounding, one or several supplementary films (200 mm mini) will be realized in the continuation of one or several defects, whether it is before hydraulic test or after hydraulic test.

See [12.4](#)

c) Installation of none-strain hardening material

In case plates are inserted in the shell of pressure vessel, as a matter of principle, the same material shall be used. The strength of these plates shall be suitable for their place of installation in the cold stretched vessels.

The welds have to be subjected to a visual examination.

## D.5.6 Data plate

The data plate shall, in addition to the information in [Clause 14](#), bear the text "PRESSURE STRENGTHENED".

## D.6 Comments

### D.6.1 Strengthening theory

Austenitic stainless steels exhibit considerable work hardening upon deformation while retaining the characteristics of the material. The stress required for further deformation increases continuously as the deformation increases. Thus, a stress/strain curve for austenitic steel does not have the flow region typical of carbon and low-alloy steels. Compare the stress/strain curves in [Figure D.1](#) a) and b).

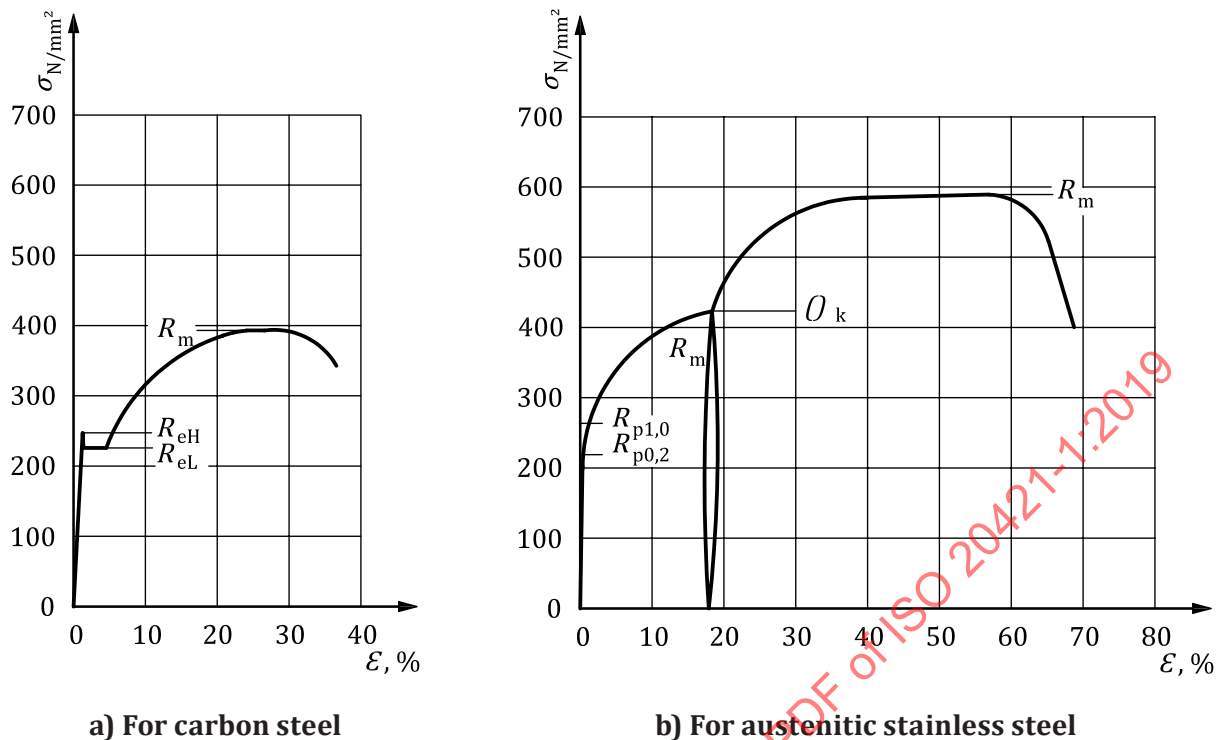


Figure D.1 — Stress/strain curve for carbon and austenitic stainless steel

If a tensile test piece of solution heat-treated austenitic stainless steel is loaded to a strengthening stress  $\sigma_k$  and then unloaded, a permanent plastic elongation will be found. When the same test piece is loaded again, the deformation will remain elastic up to a higher stress level than before. Only when the stress  $\sigma_k$  is exceeded will the plastic deformation continue along the original curve.

A test piece which has been loaded to the strengthening stress  $\sigma_k$  can be regarded as a new test piece with [Formula \(D.11\)](#):

$$R_{p0,2} = \sigma_k \quad (\text{D.11})$$

An austenitic stainless steel that has been stretched at room temperature to a higher proof strength also exhibits higher proof-strength stress at all other temperatures.

The toughness of the material after stretching to 10 % (nominal strain) will still be satisfactory, since austenitic steels in the solution heat-treated condition have an elongation at fracture not less than 35 %.

The plastic deformation required is achieved by subjecting the finished pressure vessel to a strengthening pressure,  $p_k$ . This pressure is calculated so that there is sufficient safety margin with respect to plastic deformation from stresses caused by a pressure equal to the design pressure,  $p$ .

Minimum wall thicknesses for the different parts of the vessel are calculated after establishing a suitable design stress value,  $\sigma_k$ .

During the strengthening of the finished vessel, the material reaches a strengthening stress,  $\sigma_k$ , that is at least 1,33 times the design stress,  $p$ , and 1,73 times the stress at maximum allowable pressure,  $p_s$ .

## D.6.2 Work-hardened material

**D.6.2.1** The term “work-hardened material” shall be applied to material that has had its proof strength raised through cold rolling, roll straightening, uniaxial stretching in a stretching machine or other types of cold work.

**D.6.2.2** Work-hardened material can be used in order to reduce or eliminate the deformation due to strengthening of the pressure vessel. It is primarily used in cylinders for internal pressure.

**D.6.2.3** The increase in the proof strength of a work-hardened material is about the same in all directions. The proof strength of work-hardened plate shall be determined on samples taken across the direction of rolling or stretching, respectively.

**D.6.2.4** The structure of work-hardened material differs from solution heat-treated material only in that the number of dislocations is higher. Material that has been subject to a homogeneous deformation is free from residual stresses. Work hardening does not significantly affect the resistance to general corrosion.

Welding of work-hardened material gives rise to a heat-affected zone (HAZ), the width of which depends on the welding method. In arc welding with coated electrodes, the width of the zone is about equal to the thickness of the material.

The proof strength in the zone may be reduced, but the subsequent strengthening restores it to about the same level as that of the surrounding material.

Impact toughness and corrosion resistance in the zone depend primarily on the initial material condition (analysis, well-annealed structure) and the welding method (extent of heating) but only slightly on the degree of strengthening.

Strengthening of a pressure vessel generally decreases local residual stresses introduced into the vessel during the manufacturing process.

### D.6.3 Derivation of formula

**D.6.3.1** Consider a cylinder of middle diameter  $D$  and design pressure  $p$ , which has been strengthened to a design stress value  $\sigma_k$ . Its wall thickness should comply with [Formula \(9\)](#), see [Formula \(D.12\)](#):

$$s = \frac{pDs_F}{20\sigma_k z} \quad (\text{D.12})$$

NOTE To simplify the formula, the middle diameter is used and the possible (corrosion) allowance is discarded.

The strengthening shall be carried out in such a way that the shell is subjected to the stress  $\sigma_k$ . The stress in a cylinder is as per [Formula \(D.13\)](#):

$$\sigma = \frac{pD}{20s} \quad (\text{D.13})$$

and the strengthening pressure,  $p_k$ , is therefore as per [Formula \(D.14\)](#):

$$p_k = \frac{20s\sigma_k}{D} \quad (\text{D.14})$$

If  $s$  according to [Formula \(D.5\)](#) is substituted as per [Formula \(D.15\)](#):

$$p_k = p \frac{S_F}{z} \quad (\text{D.15})$$

Since  $S_F = 1,33$  and  $\eta = 1,0$ , this corresponds to [Formula \(D.4\)](#). Obviously, cylinders can be calculated from the formula in [D.6.1](#)  $\sigma_k$  is inserted as the design stress value and 1,0 as the weld joint factor.

If a weld joint factor less than 1,0 is applied to any single main seam, an increase in strengthening pressure is required according to [Formula \(D.8\)](#). To sustain this higher pressure, the thickness of all parts of the vessel would then need to be increased.

**D.6.3.2** If a shell consists of several courses and one of them is made thicker than the others, it will have a lower  $\sigma_k$  than the other courses after strengthening.

The thicker course then needs a higher strengthening pressure than the others. Since this is impossible, this course will fail to satisfy [Formula \(D.12\)](#) (not “strengthened enough”), as the anticipated proof strength  $\sigma_k$  will not be reached.

In order to achieve the full theoretical effect throughout the vessel, it would be necessary to decrease the thickness of the thicker course. Since this would hardly increase the safety of the vessel, it is allowed to use greater thickness in some parts, e.g. where required by external loads, even if this is not theoretically correct.

Correspondingly, constant wall thickness is allowed in conical ends, even though the strengthening theory strictly speaking requires the thickness to be decreased in proportion to the radius. Similarly, the spherical part of a dished end will in some cases be “insufficiently pressure strengthened”.

**D.6.3.3** The derivation of the formula in [D.6.3.1](#) applies to parts free from bending stresses, i.e. cylinders, spheres and hemispherical ends.

Use of the strengthening effect is generally not permitted for parts subject to primary bending stresses. For such parts, it is necessary to investigate the stresses during strengthening (see [D.4.2.3.2](#)) and normal operation.

Certain pressure-vessel parts, such as dished and conical ends, contain so-called secondary bending stresses (see [Annex A](#)). It is permissible to use the strengthening effect in such parts, but the magnitude of the secondary bending stresses shall be investigated and should normally not exceed  $2\sigma_k$ .

Excepted from this, requirement of investigation are 2:1 torispherical ends, where experience has shown the bending stresses to be moderate.

**D.6.3.4** Experience has shown that it is possible to use design stress values for pressure-strengthened material when dimensioning reinforcement pads according to [10.3.6.7](#).

**D.6.3.5** This Annex does not preclude the use of the strengthening effect, provided that the manufacturer can show it does not cause harmful deformation or other problems.

## D.6.4 Deformations at strengthening

**D.6.4.1** The highest allowable design stress value  $\sigma_{k\max}$  for the different steels has consistently been set 200 N/mm<sup>2</sup> higher than  $R_{p0,2}$  for the solution heat-treated material.

In conventional tensile testing, this maximum stress produces less than 10 % elongation.

**D.6.4.2** The strengthening process can be simulated in tensile testing by allowing extra time under load. This increases the elongation under maximum stress by another 1 % to 2 %.

After simulated strengthening, the proof strength,  $R_{p0,2}$ , of the material (calculated on basis of the cross-sectional area before the strengthening) is about 30 N/mm<sup>2</sup> higher than the strengthening stress  $\sigma_k$  used.

**D.6.4.3** A multi-axial stress state results in other elongation values than tensile testing. These elongation values can be assessed according to a graph of the deformation hardening of the material as applied to the effective values of stress  $\sigma$  and elongation  $\varepsilon$  [see [Formulae \(D.16\)](#) and [\(D.17\)](#)]:

$$\sigma = \sqrt{\frac{1}{2} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]} \quad (\text{D.16})$$

$$\varepsilon = \sqrt{\frac{2}{9} \left[ (\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2 \right]} \quad (\text{D.17})$$

If the effective values are set = 1, the principal stresses and elongations obtained for the simplest stress conditions are given in [Table D.4](#).

**Table D.4 — Stresses and elongations for different load cases**

|              | True stress |            |            |          | True elongation |                 |                 |               |
|--------------|-------------|------------|------------|----------|-----------------|-----------------|-----------------|---------------|
|              | $\sigma_1$  | $\sigma_2$ | $\sigma_3$ | $\sigma$ | $\varepsilon_1$ | $\varepsilon_2$ | $\varepsilon_3$ | $\varepsilon$ |
| Tensile test | 1           | 0          | 0          | 1        | 1               | -0,5            | -0,5            | 1             |
| Cylinder     | 1,15        | 0,58       | 0          | 1        | 0,87            | 0               | -0,87           | 1             |
| Sphere       | 1           | 1          | 0          | 1        | 0,5             | 0,5             | -1              | 1             |

Among other things, [Table D.4](#) expresses the fact that a tensile test sample contracts in two dimensions, while a cylinder decreases only in thickness by an amount corresponding to the increased circumference.

[Table D.4](#) shows that a certain effective stress,  $\sigma$ , produces different elongations in the principal stress direction  $\varepsilon_1$  for the different load cases. The same effective stress that produces a strain of 10 % in a tensile test ( $\varepsilon_1 = 1,0$ ) produces a circumferential strain 8,7 % ( $\varepsilon_1 = 0,87$ ) in a cylinder shell and 5 % ( $\varepsilon_1 = 0,5$ ) in a sphere.

The true stresses  $\sigma_1$ ,  $\sigma_2$ ,  $\sigma_3$  and  $\sigma$  are calculated on basis of the cross-sectional area of the material after deformation. If instead the nominal stresses are used, calculated on the basis of the original cross-sectional area of the material, the comparison of strains will be different.

The following example gives an indication of the difference.

**EXAMPLE** Values from a typical deformation-hardening curve of austenitic stainless steel are used, i.e. 0,2 %/280 N/mm<sup>2</sup> and 10 %/420 N/mm<sup>2</sup>. If equal nominal principal stresses,  $\sigma_{1\text{nom}}$ , are applied to this material, the principal strain  $\varepsilon_1$  for the cylinder is altered from 0,87 to 0,66 and for the sphere from 0,5 to 0,58.

The strain at bursting pressure is half of the maximum homogeneous strain at tensile testing for a cylinder and one-third for a sphere.

**D.6.4.4** In practice, the maximum circumferential strain of cylinders is usually 3 % to 5 % when using a solution heat-treated plate, less in the spherical part of the ends. The following factors contribute to the measured values being lower than the theoretically calculated maximum value:

- the proof strength  $R_{p0,2}$  is higher than the specified minimum for the material;
- the plate thickness is greater than nominal;
- there are reinforcing effects of ends, nozzles, and  $D$ .

**D.6.4.5** It should be observed that strengthening of pressure vessels of solution heat-treated material can affect the position, direction and roundness of nozzles. This does not entail any reduction of the safety of the vessel, but can in certain cases be a nuisance to the user.

NOTE One way to minimize these changes is to weld the nozzles in place after the strengthening, where the vessel can require renewed strengthening (see [D.5.3](#)). This second strengthening generally leads to much smaller deformations.

**D.6.4.6** When a welded tube is used for nozzles in a cylinder (or cone), the longitudinal weld of the tube should be located in the direction where the stresses are lowest, i.e. in a plane perpendicular to the longitudinal axis of the cylinder (or cone).

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## Annex E (informative)

### Specific weld details

#### E.1 Field of application

Specific weld details given in [E.2](#) are currently in common usage in cryogenic vessels and are appropriate to this service.

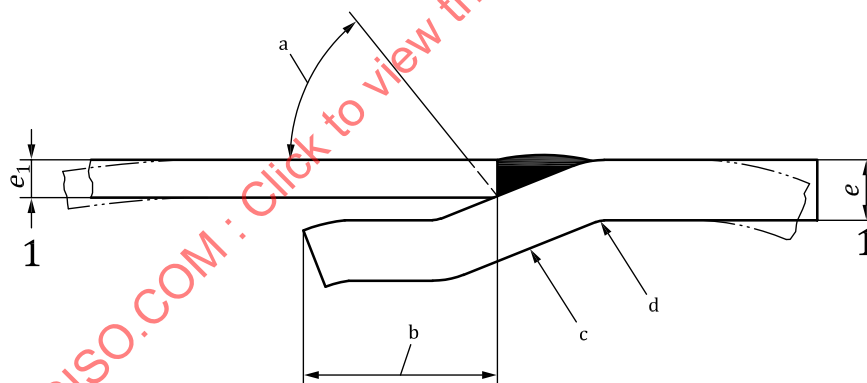
#### E.2 Weld detail

In general, the welds are to be adequate to carry the expected loads and do not need to be designed on the basis of joint wall thickness.

##### E.2.1 Joggle joint

The joggle joint is not allowed if [Annex D](#) applied. For fatigue evaluation, it is recommended to see the restrictions of the applied standard.

See [Figure E.1](#).



#### Key

- a Bevel optional.
- b As desired.
- c Depth of offset =  $e_1$ .
- d Avoid sharp break.

**Figure E.1 — Joggle joint**

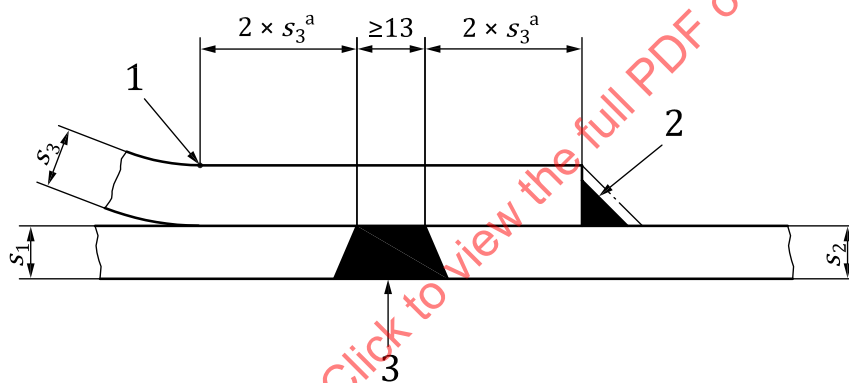
This joint may be used for cylinder to cylinder and end to cylinder (excluding cone to cylinder) connections provided that:

- a) when the flanged section of a dished end is joggled, the joggle is sufficiently clear of the knuckle radius to ensure that the edge of the circumferential seam is at least 12 mm clear of the knuckle (see [10.3.6.4.2](#) for the dimensions);

- b) when a cylinder with a longitudinal seam (butt welded) is joggled to make a circumferential weld:
  - 1) the welds are ground flush internally and externally for a distance of approximately 50 mm prior to joggling with no reduction of plate thickness below the required minimum; and
  - 2) on completion of joggling, the area of the weld is subjected to dye-penetrant examination and is proven to be free of cracks;
- c) the offset section which forms the weld backing is a close fit within its mating section at the weld round the entire circumference;
- d) the profile of the offset is a smooth radius without sharp corners;
- e) on completion of welding, the weld fills the groove smoothly to the full thickness of the plate edges being joined;
- f) the junction of the longitudinal and circumferential seams are examined radiographically and found to be free from significant imperfections.

### E.2.2 Intermediate ends

See [Figure E.2](#) and [10.3.6.4.3](#).



#### Key

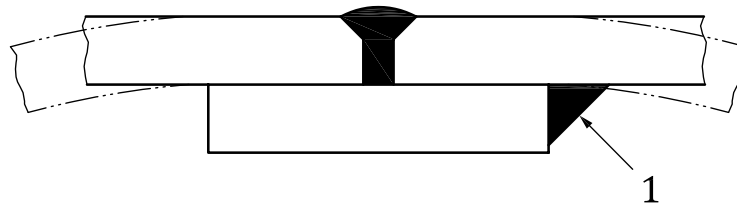
- 1 tangent point
- 2 continuous fillet weld
- 3 butt weld
- $s_1$  cylinder thickness
- $s_2$  cylinder thickness
- $s_3$  end thickness
- <sup>a</sup> Not to exceed 25 mm.

NOTE  $s_1$  and  $s_2$  cannot be equal.

Figure E.2 — Intermediate end

### E.2.3 Backing strip

See [Figure E.3](#).

**Key**

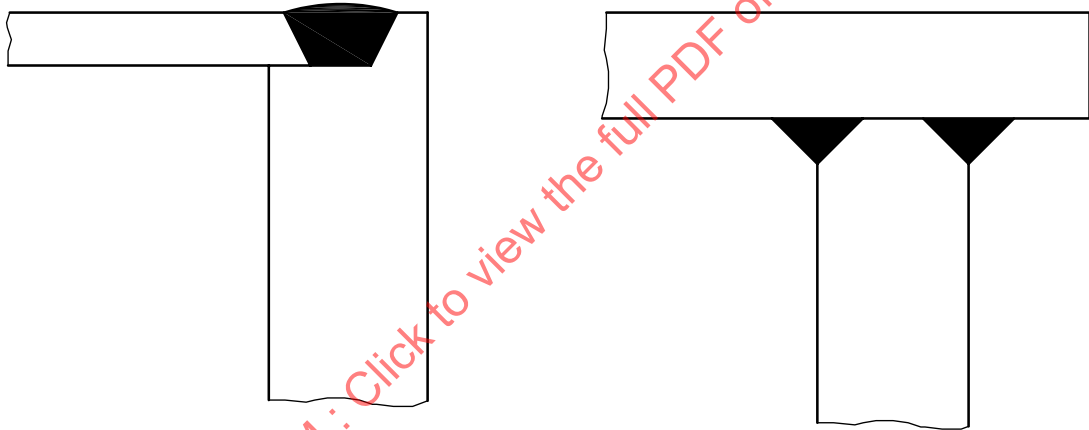
- 1 intermittent or continuous fillet weld

**Figure E.3 — Backing strip**

The backing strip may be used only for circumferential seams in cylinders, ends, nozzles and interspace pipes, when the second side is inaccessible for welding and provided that non-destructive testing can be satisfactorily carried out where applicable.

**E.2.4 End plate closure**

See [Figure E.4](#) for two examples of the many ways of welding flat plates. See also [Figure 6](#).

**Figure E.4 — End plate closure (examples)****E.2.5 Nozzle weld**

See [Figure E.5](#).

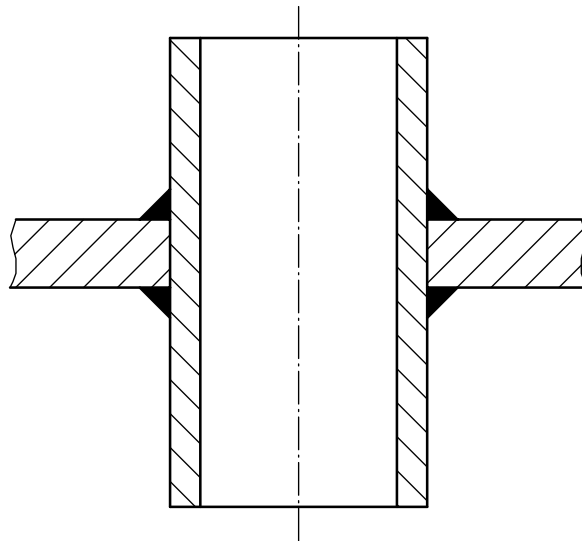


**Figure E.5 — Non-full penetration nozzle welds.**

Special care shall be taken for welding nozzles used for filling or emptying cryogenic vessels (with flow) due to the thermal gradient between the nozzle and the vessel.

Full penetrated welding seams shall be used for nozzle connections where thermal conditions according to [Clause 8](#) are relevant or if [Annex D](#) is applied, where significant plastic deformation/strain during cold stretching.

### **E.2.6 Non-continuous fillet weld on attachments**

Non-continuous fillet welds on attachments may be used for all attachments to main pressure components provided that the following criteria are met:

- strength is adequate for design loadings;
- crevices between attached component and main pressure envelope can be demonstrated not to conflict with [E.3](#).

## **E.3 Oxygen service requirements**

The need for cleanliness of equipment in liquid oxygen and other oxidizing liquid service is described in ISO 21010 and ISO 23208.

The internal weld details shall be such that debris, contaminants, hydrocarbons or degreasants cannot accumulate so as to cause a fire risk in future operation.

## Annex F (normative)

### Outer-jacket relief devices

#### F.1 Field of application

This annex covers the requirements for design, manufacture and testing of pressure-protection devices required on outer jackets of vacuum-insulated cryogenic vessels in order to reduce any accidental accumulation of pressure.

#### F.2 Requirements

##### F.2.1 General

The device shall be either a relief plate/plug or a bursting disc.

Bursting disc devices shall be in accordance with ISO 4126-2.

##### F.2.2 Design

The pressure-protection device shall be capable of withstanding full vacuum and all demands of normal vessel operation, including its own mass acceleration during transportation.

The set pressure and the open relieving area are specified in [10.2.7.2](#). Consideration shall be given to prevention of blocking of the device by insulation materials during operation.

The plate or plug of a relief plate/plug type device shall be designed and installed such that it cannot harm personnel when ejected.

##### F.2.3 Materials

The pressure-protection devices shall be resistant to normal atmospheric corrosion. The materials of construction shall be suitable for the range of ambient temperatures expected in service.

##### F.2.4 Testing

Relief plate/plug type relieving devices shall not require testing other than a prototype test to verify the set pressure.

Bursting disc assemblies shall be tested in accordance with ISO 4126-2.

##### F.2.5 Inspection

Relief plate/plug type devices shall be subjected to an inspection programme that ensures compliance with the drawings or specification.

Bursting discs shall be inspected in accordance with ISO 4126-2.

##### F.2.6 Marking

Bursting discs shall be certified and marked in accordance with ISO 4126-2.

Other pressure-protection devices shall be marked in accordance with this document.

## Annex G (informative)

### Base materials

See Tables G.1 and G.2.

**Table G.1 — Pressure vessels**

| Specification No. | Material grade     | Material number | Material Group<br>ISO/TR 15608:2017 |
|-------------------|--------------------|-----------------|-------------------------------------|
| EN 10028-3        | P275NL1            | 1.0488          | 1.1                                 |
| EN 10028-3        | P275NL2            | 1.1104          | 1.1                                 |
| EN 10028-3        | P355NL1            | 1.0566          | 1.2                                 |
| EN 10028-3        | P355NL2            | 1.1106          | 1.2                                 |
| EN 10028-3        | P460NL1            | 1.8915          | 1.3                                 |
| EN 10028-3        | P460NL2            | 1.8916          | 1.3                                 |
| EN 10028-4        | X8Ni9              | 1.5662          | 9.3                                 |
| EN 10028-5        | P355ML1            | 1.8832          | 1.2                                 |
| EN 10028-5        | P355ML2            | 1.8833          | 1.2                                 |
| EN 10028-5        | P420ML1            | 1.8835          | 2.1                                 |
| EN 10028-5        | P420ML2            | 1.8828          | 2.1                                 |
| EN 10028-5        | P460ML1            | 1.8837          | 2.1                                 |
| EN 10028-5        | P460ML2            | 1.8831          | 2.1                                 |
| EN 10028-7        | X2CrNi18-9         | 1.4307          | 8.1                                 |
| EN 10028-7        | X2CrNi19-11        | 1.4306          | 8.1                                 |
| EN 10028-7        | X2CrNi18-10        | 1.4311          | 8.1                                 |
| EN 10028-7        | X5CrNi19-9         | 1.4315          | 8.1                                 |
| EN 10028-7        | X5CrNi18-10        | 1.4301          | 8.1                                 |
| EN 10028-7        | X2CrMnNiN21-5-1    | 1.4162          | 10.3                                |
| EN 10028-7        | X2CrNiN23-4        | 1.4362          | 10.1                                |
| EN 10028-7        | X3CrNiMo17-12-2    | 1.4401          | 8.1                                 |
| EN 10028-7        | X2CrNiMo17-12-2    | 1.4404          | 8.1                                 |
| EN 10028-7        | X2CrNiMoN17-11-2   | 1.4406          | 8.1                                 |
| EN 10028-7        | X2CrNiMoN17-13-3   | 1.4429          | 8.1                                 |
| EN 10028-7        | X2CrNiMoN22-5-3    | 1.4462          | 10.1                                |
| EN 10028-7        | X2CrNiMoCuN25-6-3  | 1.4507          | 10.2                                |
| EN 10028-7        | X2CrNiMoN25-7-4    | 1.4410          | 10.2                                |
| EN 10028-7        | X2CrNiMoCuWN25-7-4 | 1.4501          | 10.2                                |
| EN 10222-3        | X8Ni9              | 1.5662          | 9.3                                 |
| EN 10222-5        | X2CrNi18-9         | 1.4307          | 8.1                                 |
| EN 10222-5        | X5CrNi18-10        | 1.4301          | 8.1                                 |
| EN 10222-5        | X5CrNiMo17-12-2    | 1.4401          | 8.1                                 |
| EN 10222-5        | X2CrNiMo17-12-2    | 1.4404          | 8.1                                 |
| EN 10088-3        | X2CrNi19-11        | 1.4306          | 8.1                                 |

Table G.1 (continued)

| Specification No. | Material grade   | Material number   | Material Group<br>ISO/TR 15608:2017 |
|-------------------|------------------|-------------------|-------------------------------------|
| EN 10088-3        | X2CrNi18-10      | 1.4311            | 8.1                                 |
| EN 10088-3        | X5CrNi18-10      | 1.4301            | 8.1                                 |
| EN 10088-3        | X5CrNiMo17-12-2  | 1.4401            | 8.1                                 |
| EN 10088-3        | X2CrNiMo17-13-2  | 1.4404            | 8.1                                 |
| EN 10088-3        | X2CrNiMoN17-12-2 | 1.4406            | 8.1                                 |
| EN 10088-3        | X2CrNiMo17-13-3  | 1.4429            | 8.1                                 |
| EN 14286          | AlMg3            | EN AW 5754 O H111 | 22.3                                |
| EN 14286          | AlMg3Mn          | EN AW 5454 O H111 | 22.3                                |
| EN 14286          | AlMg5,5MnZnZr    | EN AW 5059 O H111 | 22.4                                |
| EN 14286          | AlMg4,5Mn0,4     | EN AW 5182 O H111 | 22.4                                |
| EN 14286          | AlMg4Mn0,4       | EN AW 5088 O H111 | 22.4                                |
| EN 14286          | AlMg4,5Mn0,7     | EN AW 5083 O H111 | 22.4                                |
| EN 14286          | AlMg4,5Mn0,9     | EN AW 5383 O H111 | 22.4                                |
| EN 14286          | AlMg4            | EN AW 5086 O H111 | 22.4                                |
| EN 14286          | AlMg4Mn0,4       | EN AW 5186 O H111 | 22.4                                |
| VDTUEV WB 521     | Elongal          | EN AW 5186 O H111 | 22.4                                |
| JIS G 3127        | SL9N520          | 1.5662            | 9.3                                 |
| JIS G 4303-4305   | SUS304           | 1.4301            | 8.1                                 |
| JIS G 4303-4305   | SUS304L          | 1.4307            | 8.1                                 |
| JIS G 4303-4305   | SUS316           | 1.4401            | 8.1                                 |
| JIS G 4303-4305   | SUS316L          | 1.4404            | 8.1                                 |
| JIS G 4317-4320   | SUS321           | 1.4541            | 8.1                                 |
| JIS G 4317-4320   | SUS347           | 1.4550            | 8.1                                 |
| JIS G 4317-4320   | SUS316           | 1.4401            | 8.1                                 |
| JIS G 4317-4320   | SUS316L          | 1.4404            | 8.1                                 |
| JIS G 4317-4320   | SUS317L          | 1.4439            | 8.1                                 |
| JIS G 4313-4315   | SUS304           | 1.4301            | 8.1                                 |
| JIS G 4313-4315   | SUS304L          | 1.4307            | 8.1                                 |
| JIS G 4313-4315   | SUS304N1         | 1.4406            | 8.1                                 |
| JIS G 4313-4315   | SUS304LN         | 1.4311            | 8.1                                 |
| JIS G 4317-4320   | SUS316L          | 1.4406            | 8.1                                 |
| JIS G 4315-4315   | SUS316LN         | 1.4429            | 8.1                                 |
| SA/A-240          | 304LN            | S 30453           | 8.1                                 |
| SA/A-240          | 304N             | S 30451           | 8.1                                 |
| SA/A-240          | 316LN            | S 31653           | 8.1                                 |
| SA/A-240          | 316N             | S 31651           | 8.1                                 |
| SA/A-240          | 201LN            | S 20153           | 8.3                                 |
| SA/A-240          | 201-1            | S 20100           | 8.3                                 |
| SA/A-666          | 201-1            | S 20100           | 8.3                                 |
| SA/A-240          | 201-2            | S 20100           | 8.3                                 |
| SA/A-666          | 201-2            | S 20100           | 8.3                                 |
| SA/A-240          | 201L             | S 20103           | 8.3                                 |
| SA/A-666          | 201L             | S 20103           | 8.3                                 |

Table G.1 (continued)

| Specification No. | Material grade | Material number | Material Group<br>ISO/TR 15608:2017 |
|-------------------|----------------|-----------------|-------------------------------------|
| SA/A-479          | 316LN          | S 31653         | 8.1                                 |
| SA/A-479          | 316N           | S 31651         | 8.1                                 |
| SA/A-240          | XM-29          | S 24000         | 8.3                                 |
| SA/A-479          | XM-29          | S 24000         | 8.3                                 |
| SA/A-479          | 304            | S 30400         | 8.1                                 |
| SA/A-479          | 304L           | S 30403         | 8.1                                 |
| SA/A-240          | 304            | S 30400         | 8.1                                 |
| SA/A-240          | 304L           | S 30403         | 8.1                                 |
| SA/A-479          | 304LN          | S 30453         | 8.1                                 |
| SA/A-479          | 304N           | S 30451         | 8.1                                 |
| SA/A-240          | XM-19          | S 20910         | 8.3                                 |
| SA/A-479          | XM-19          | S 20910         | 8.3                                 |
| SA/A-479          | —              | S 21800         | 8.1                                 |
| SA/A-353          | —              | K 81340         | 9.3                                 |
| SA/A-553          | I              | K 81340         | 9.3                                 |
| SA/A-522          | I              | K 81340         | 9.3                                 |
| SA/A-553          | 2              | K 71340         | 9.3                                 |
| SA/A-351          | —              | —               | 45                                  |
| SA/A-516          | 55             | K 01800         | 1.1                                 |
| SA/A-516          | 60             | K 02100         | 1.1                                 |
| SA/A-516          | 65             | K 02403         | 1.1                                 |
| SA/A-516          | 70             | K 02700         | 11.1                                |
| SA/A-517          | E              | K 21604         | 3.1                                 |
| SA/A-517          | F              | K 11576         | 3.1                                 |
| SA/A-612          | —              | K 02900         | 1.3                                 |
| A-276             | 201LN          | S 20153         | 8.3                                 |
| A-276             | 304            | S 30400         | 8.1                                 |
| A-276             | 304L           | S 30403         | 8.1                                 |
| A-276             | 304LN          | S 30453         | 8.1                                 |
| A-276             | 304N           | S 30451         | 8.1                                 |
| A-276             | 316            | S 31600         | 8.1                                 |
| A-276             | 316L           | S 31603         | 8.1                                 |
| A-276             | 316LN          | S 31653         | 8.1                                 |
| A-276             | 316N           | S 31651         | 8.1                                 |
| A-276             | 201            | S 20100         | 8.3                                 |
| A-276             | XM-29          | S 24000         | 8.3                                 |
| A-276             | XM-19          | S 20910         | 8.3                                 |
| A-276             | —              | S 21800         | 8.1                                 |
| SB/B-209          | 5083           | A 95083         | 22.4                                |
| SB/B-221          | 5083           | A 95083         | 22.4                                |
| SB/B-209          | 6061           | A 96061         | 23.1                                |
| SB/B-221          | 6061           | A 96061         | 23.1                                |
| SB/B-211          | 6061           | A 96061         | 23.1                                |

Table G.1 (continued)

| Specification No. | Material grade | Material number | Material Group<br>ISO/TR 15608:2017 |
|-------------------|----------------|-----------------|-------------------------------------|
| SB/B-308          | 6061           | A 96061         | 23.1                                |
| SB/B-209          | 3003           | A 93003         | 22.1                                |
| SB/B-209          | 5052           | A 95052         | 22.3                                |
| SB/B-211          | 3003           | A 93003         | 22.1                                |
| SB/B-221          | 3003           | A 93003         | 22.1                                |
| B-221             | 6063           | A 96063         | 23.1                                |
| B-187             | —              | —               | 37                                  |
| B-16              | —              | —               | 32                                  |
| GB 3531           | 16MnDR         | —               | 1.2                                 |
| GB 3531           | 15MnNiDR       | —               | 9.1                                 |
| GB 3531           | 09MnNiDR       | —               | 9.1                                 |
| GB 150.2          | 08Ni3DR        | —               | 9.2                                 |
| GB 150.2          | 06Ni9DR        | —               | 9.3                                 |
| GB 24511          | 06Cr19Ni10     | S30408          | 8.1                                 |
| GB 24511          | 022Cr19Ni10    | S30403          | 8.1                                 |
| GB 24511          | 06Cr17Ni12Mo2  | S31608          | 8.1                                 |
| GB 24511          | 022Cr17Ni12Mo2 | S31603          | 8.1                                 |

NOTE SA/SB prefix to specification number refers to ASME specifications. A/B prefix to specification number refers to ASTM specifications. When materials to ASME specifications are unavailable, materials to the same specification number with a prefix of A/B (ASTM) may be used. All ASME/ASTM specification numbers listed are equally acceptable with a suffix M.

Table G.2 — Piping and pipe fittings

| Specification No. | Material grade    | Material number | Material Group<br>ISO/TR 15608:2017 |
|-------------------|-------------------|-----------------|-------------------------------------|
| EN 10216-5-       | X5CrNi18-10       | 1.4301          | 8.1                                 |
| EN 10216-5        | X2CrNi19-11       | 1.4306          | 8.1                                 |
| EN 10216-5        | X2CrNi18-9        | 1.4307          | 8.1                                 |
| EN 10216-5        | X5CrNiMo17-12-2   | 1.4401          | 8.1                                 |
| EN 10216-5        | X2CrNiMo17-12-2   | 1.4404          | 8.1                                 |
| EN 10216-5        | X6CrNiTi18-10     | 1.4541          | 8.1                                 |
| EN 10216-5        | X6CrNiMoTi17-12-2 | 1.4571          | 8.1                                 |
| EN 10217-7        | X5CrNi18-10       | 1.4301          | 8.1                                 |
| EN 10217-7        | X2CrNi19-11       | 1.4306          | 8.1                                 |
| EN 10217-7        | X2CrNi18-9        | 1.4307          | 8.1                                 |
| EN 10217-7        | X5CrNiMo17-12-2   | 1.4401          | 8.1                                 |
| EN 10217-7        | X2CrNiMo17-12-2   | 1.4404          | 8.1                                 |
| EN 10217-7        | X6CrNiTi18-10     | 1.4541          | 8.1                                 |
| EN 10217-7        | X6CrNiMoTi17-12-2 | 1.4571          | 8.1                                 |
| EN 10253-4        | X5CrNi18-10       | 1.4301          | 8.1                                 |
| EN 10253-4        | X2CrNi19-11       | 1.4306          | 8.1                                 |
| EN 10253-4        | X2CrNi18-9        | 1.4307          | 8.1                                 |
| EN 10253-4        | X5CrNiMo17-12-2   | 1.4401          | 8.1                                 |

Table G.2 (continued)

| Specification No. | Material grade  | Material number | Material Group<br>ISO/TR 15608:2017 |
|-------------------|-----------------|-----------------|-------------------------------------|
| EN 10253-4        | X2CrNiMo17-12-2 | 1.4404          | 8.1                                 |
| EN 10253-4        | X6CrNiTi18-10   | 1.4541          | 8.1                                 |
| EN 10253-4        | X6CrNiTi18-10   | 1.4571          | 8.1                                 |
| SA/A-312          | TP 316L         | S 31603         | 8.1                                 |
| SA/A-358          | TP 316L         | S 31603         | 8.1                                 |
| SA/A-249          | TP 316L         | S 31603         | 8.1                                 |
| SA/A-409          | TP 316L         | S 31603         | 8.1                                 |
| SA/A-688          | TP 316L         | S 31603         | 8.1                                 |
| SA/A-813          | TP 316L         | S 31603         | 8.1                                 |
| SA/A-814          | TP 316L         | S 31603         | 8.1                                 |
| SA/A-249          | TP 316          | S 31600         | 8.1                                 |
| SA/A-312          | TP 316          | S 31600         | 8.1                                 |
| SA/A-358          | TP 316          | S 31600         | 8.1                                 |
| SA/A-409          | TP 316          | S 31600         | 8.1                                 |
| SA/A-688          | TP 316          | S 31600         | 8.1                                 |
| SA/A-813          | TP 316          | S 31600         | 8.1                                 |
| SA/A-814          | TP 316          | S 31600         | 8.1                                 |
| SA/A-249          | TP 316LN        | S 31653         | 8.1                                 |
| SA/A-312          | TP 316LN        | S 31653         | 8.1                                 |
| SA/A-358          | TP 316LN        | S 31653         | 8.1                                 |
| SA/A-688          | TP 316LN        | S 31653         | 8.1                                 |
| SA/A-249          | TP 316N         | S 31651         | 8.1                                 |
| SA/A-312          | TP 316N         | S 31651         | 8.1                                 |
| SA/A-358          | TP 316N         | S 31651         | 8.1                                 |
| SA/A-688          | TP 316N         | S 31651         | 8.1                                 |
| SA/A-813          | TP 316N         | S 31651         | 8.1                                 |
| SA/A-814          | TP 316N         | S 31651         | 8.1                                 |
| SA/A-249          | TPXM-29         | S 24000         | 8.3                                 |
| SA/A-312          | TPXM-29         | S 24000         | 8.3                                 |
| SA/A-688          | TPXM-29         | S 24000         | 8.3                                 |
| SA/A-249          | TP 304L         | S 30403         | 8.1                                 |
| SA/A-312          | TP 304L         | S 30403         | 8.1                                 |
| SA/A-358          | TP 304L         | S 30403         | 8.1                                 |
| SA/A-409          | TP 304L         | S 30403         | 8.1                                 |
| SA/A-688          | TP 304L         | S 30403         | 8.1                                 |
| SA/A-813          | TP 304L         | S 30403         | 8.1                                 |
| SA/A-814          | TP 304L         | S 30403         | 8.1                                 |
| SA/A-249          | TP 304          | S 30400         | 8.1                                 |
| SA/A-334          | 8               | K 81340         | 9.3                                 |
| SA/A-333          | 8               | K 81340         | 9.3                                 |
| SA/A-312          | TP 304          | S 30400         | 8.1                                 |
| SA/A-358          | TP 304          | S 30400         | 8.1                                 |
| SA/A-409          | TP 304          | S 30400         | 8.1                                 |

Table G.2 (continued)

| Specification No. | Material grade | Material number | Material Group<br>ISO/TR 15608:2017 |
|-------------------|----------------|-----------------|-------------------------------------|
| SA/A-688          | TP 304         | S 30400         | 8.1                                 |
| SA/A-813          | TP 304         | S 30400         | 8.1                                 |
| SA/A-814          | TP 304         | S 30400         | 8.1                                 |
| SA/A-249          | TP 304LN       | S 30453         | 8.1                                 |
| SA/A-312          | TP 304LN       | S 30453         | 8.1                                 |
| SA/A-358          | TP 304LN       | S 30453         | 8.1                                 |
| SA/A-688          | TP 304LN       | S 30453         | 8.1                                 |
| SA/A-813          | TP 304LN       | S 30453         | 8.1                                 |
| SA/A-814          | TP 304LN       | S 30453         | 8.1                                 |
| SA/A-249          | TP 304N        | S 30451         | 8.1                                 |
| SA/A-312          | TP 304N        | S 30451         | 8.1                                 |
| SA/A-358          | TP 304N        | S 30451         | 8.1                                 |
| SA/A-688          | TP 304N        | S 30451         | 8.1                                 |
| SA/A-813          | TP 304N        | S 30451         | 8.1                                 |
| SA/A-814          | TP 304N        | S 30451         | 8.1                                 |
| SA/A-312          | TP 321         | S 32100         | 8.1                                 |
| SA/A-249          | TP 321         | S 32100         | 8.1                                 |
| SA/A-358          | TP 321         | S 32100         | 8.1                                 |
| SA/A-409          | TP 321         | S 32100         | 8.1                                 |
| SA/A-813          | TP 321         | S 32100         | 8.1                                 |
| SA/A-814          | TP 321         | S 32100         | 8.1                                 |
| SA/A-213          | TP 316L        | S 31603         | 8.1                                 |
| SA/A-312          | TP 316L        | S 31603         | 8.1                                 |
| SA/A-430          | FP 316         | S 31600         | 8.1                                 |
| SA/A-213          | TP 316         | S 31600         | 8.1                                 |
| SA/A-312          | TP 316         | S 31600         | 8.1                                 |
| SA/A-376          | TP 316         | S 31600         | 8.1                                 |
| SA/A-213          | TP 316LN       | S 31653         | 8.1                                 |
| SA/A-312          | TP 316LN       | S 31653         | 8.1                                 |
| SA/A-376          | TP 316LN       | S 31653         | 8.1                                 |
| SA/A-430          | FP 316N        | S 31651         | 8.1                                 |
| SA/A-213          | TP 316N        | S 31651         | 8.1                                 |
| SA/A-312          | TP 316N        | S 31651         | 8.1                                 |
| SA/A-376          | TP 316N        | S 31651         | 8.1                                 |
| SA/A-182          | F 316L         | S 31603         | 8.1                                 |
| SA/A-336          | F 316L         | S 31603         | 8.1                                 |
| SA/A-403          | 316L           | S 31603         | 8.1                                 |
| SA/A-182          | F 316          | S 31600         | 8.1                                 |
| SA/A-336          | F 316L         | S 31600         | 8.1                                 |
| SA/A-403          | 316            | S 31600         | 8.1                                 |
| SA/A-182          | F 316LN        | S 31653         | 8.1                                 |
| SA/A-336          | F 316LN        | S 31653         | 8.1                                 |
| SA/A-403          | 316LN          | S 31653         | 8.1                                 |

Table G.2 (continued)

| Specification No. | Material grade | Material number | Material Group<br>ISO/TR 15608:2017 |
|-------------------|----------------|-----------------|-------------------------------------|
| SA/A-182          | F 316N         | S 31651         | 8.1                                 |
| SA/A-336          | F 316N         | S 31651         | 8.1                                 |
| SA/A-403          | 316N           | S 31651         | 8.1                                 |
| SA/A-182          | F 304L         | S 30403         | 8.1                                 |
| SA/A-336          | F 304L         | S 30403         | 8.1                                 |
| SA/A-403          | 304L           | S 30403         | 8.1                                 |
| SA/A-182          | F 304          | S 30400         | 8.1                                 |
| SA/A-336          | F 304          | S 30400         | 8.1                                 |
| SA/A-403          | 304            | S 30400         | 8.1                                 |
| SA/A-182          | F 304LN        | S 30453         | 8.1                                 |
| SA/A-336          | F 304LN        | S 30453         | 8.1                                 |
| SA/A-403          | 304LN          | S 30453         | 8.1                                 |
| SA/A-182          | F 304N         | S 30451         | 8.1                                 |
| SA/A-336          | F 304N         | S 30451         | 8.1                                 |
| SA/A-403          | 304N           | S 30451         | 8.1                                 |
| SA/A-552          | I              | K 81340         | 9.3                                 |
| SA/A-420          | WPL8           | K 81340         | 9.3                                 |
| SA/A-213          | TP 304L        | S 30403         | 8.1                                 |
| SA/A-213          | TP 304         | S 30400         | 8.1                                 |
| SA/A-213          | TP 304LN       | S 30453         | 8.1                                 |
| SA/A-213          | TP 304N        | S 30451         | 8.1                                 |
| SA/A-430          | FP 304         | S 30400         | 8.1                                 |
| SA/A-430          | FP 304N        | S 30451         | 8.1                                 |
| SA/A-376          | TP 304LN       | S 30453         | 8.1                                 |
| SA/A-376          | TP 304         | S 30400         | 8.1                                 |
| SA/A-376          | TP 304N        | S 30451         | 8.1                                 |
| SA/A-376          | TP 316LN       | S 31653         | 8.1                                 |
| SA/A-376          | TP 316         | S 31600         | 8.1                                 |
| SA/A-376          | TP 316N        | S 31651         | 8.1                                 |
| SA/A-213          | TP 321         | S 32100         | 8.1                                 |
| SA/A-333          | 1              | K 03008         | 11.1                                |
| SA/A-333          | 2              | —               | —                                   |
| SA/A-333          | 3              | K 31918         | 9.2                                 |
| SA/A-333          | 4              | K 11267         | 4.1                                 |
| SA/A-333          | 5              | —               | —                                   |
| SA/A-333          | 6              | K 03006         | 11.1                                |
| SA/A-333          | 7              | K 21903         | 9.1                                 |
| SA/A-333          | 8              | K 81340         | 9.3                                 |
| SA/A-333          | 9              | K 22035         | 9.1                                 |
| SA/A-333          | 10             | —               | 1.3                                 |
| SA/A-333          | 11             | —               | 48                                  |
| SA/A-105          |                | K 03504         | 11.1                                |
| SA/A-350          | LF-1           | K 03504         | 11.1                                |

Table G.2 (continued)

| Specification No. | Material grade | Material number | Material Group<br>ISO/TR 15608:2017 |
|-------------------|----------------|-----------------|-------------------------------------|
| SA/A-350          | LF 2           | K 03009         | 11.1                                |
| SA/A-350          | LF 3           | K 03011         | 9.2                                 |
| SA/A-350          | LF 5           | K 13050         | 9.1                                 |
| SA/A-350          | LF 6           | —               | 1.3                                 |
| SA/A-350          | LF 9           | K 22036         | 9.1                                 |
| SA/A-350          | LF 787         | —               | 9.1                                 |
| SA/A-106          | A              | K 02501         | 11.1                                |
| SA/A-106          | B              | K 03006         | 11.1                                |
| SA/A-106          | C              | K 03501         | 11.1                                |
| SB/B-247          | 5083           | A 95083         | 22.4                                |
| SB/B-247          | 6061           | A 96061         | 23.1                                |
| SB/B-241          | 5083           | A 95083         | 22.2                                |
| SB/B-241          | 6061           | A 96061         | 23.1                                |
| SB/B-210          | 6061           | A 96061         | 23.1                                |
| SB/B-241          | 3003           | A 93003         | 22.1                                |
| SB/B-75           | —              | —               | 31                                  |
| A-511             | TP 304         | S 30400         | 8.1                                 |
| A-511             | TP 304L        | S 30403         | 8.1                                 |
| A-511             | TP 316L        | S 31603         | 8.1                                 |
| A-511             | TP 316         | S 31600         | 8.1                                 |
| A-511             | TP 321         | S 32100         | 8.1                                 |
| A-351             | 304            | S 30400         | 8.1                                 |
| A-351             | 316            | S 31600         | 8.1                                 |
| A-351             | 304L           | S 30403         | 8.1                                 |
| A-351             | 316L           | S 31603         | 8.1                                 |
| A-269             | TP 316L        | S 31603         | 8.1                                 |
| A-269             | TP 316         | S 31600         | 8.1                                 |
| A-269             | TP 316LN       | S 31653         | 8.1                                 |
| A-269             | TP 316 N       | S 31651         | 8.1                                 |
| A-269             | TP 304L        | S 30403         | 8.1                                 |
| A-269             | TP 304         | S 30400         | 8.1                                 |
| A-269             | TP 304LN       | S 30453         | 8.1                                 |
| A-269             | TP 304N        | S 30451         | 8.1                                 |
| A-269             | TP 321         | S 32100         | 8.1                                 |
| A-269             | TPXM 29        | S 24000         | 8.1                                 |
| A-632             | TP 304L        | S 30403         | 8.1                                 |
| A-632             | TP 304         | S 30400         | 8.1                                 |
| A-632             | TP 316L        | S 31603         | 8.1                                 |
| A-632             | TP 316         | S 31600         | 8.1                                 |
| A-632             | TP 321         | S 32100         | 8.1                                 |
| A-733             | TP 304L        | S 30403         | 8.1                                 |
| A-733             | TP 304         | S 30400         | 8.1                                 |
| A-733             | TP 316L        | S 31603         | 8.1                                 |