



BSI Standards Publication

Cryogenic vessels — Transportable vacuum insulated vessels of not more than 1 000 litres volume

Part 1: Design, fabrication, inspection and tests

National foreword

This British Standard is the UK implementation of ISO 21029-1:2018+A1:2019. It supersedes [BS ISO 21029-1:2018](#), which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee PVE/18, Cryogenic vessels.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

© The British Standards Institution 2019
Published by BSI Standards Limited 2019

ISBN 978 0 539 02422 7

ICS 23.020.40

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 March 2018.

Amendments/corrigenda issued since publication

Date	Text affected
31 May 2019	Implementation of ISO amendment A1:2019: Figure F.5 replaced

INTERNATIONAL STANDARD

ISO 21029-1

Second edition
2018-02-28

AMENDMENT 1
2019-05

Cryogenic vessels — Transportable vacuum insulated vessels of not more than 1 000 litres volume —

Part 1: Design, fabrication, inspection and tests

*Réipients cryogéniques — Réipients transportables, isolés sous vide,
d'un volume n'excédant pas 1 000 litres —*

Partie 1: Conception, fabrication, inspection et essais



Reference number
ISO 21029-1:2018(E)

AVA Documents
Document Sharing Hub
© ISO 2018



COPYRIGHT PROTECTED DOCUMENT

© ISO 2018, Published in Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized otherwise in any form or by any means, electronic or mechanical, including photocopying, or posting on the internet or an intranet, without prior written permission. Permission can be requested from either ISO at the address below or ISO's member body in the country of the requester.

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

Contents

Page

Foreword	v
1 Scope	1
2 Normative references	1
3 Terms and definitions	2
4 Symbols	5
5 General requirements	6
6 Mechanical loads	7
6.1 General	7
6.2 Load during the pressure test	7
6.3 Other mechanical loads	7
7 Chemical effects	8
8 Thermal conditions	8
9 Material	8
9.1 General	8
9.2 Material properties	8
9.3 Inspection certificate	9
9.4 Materials for outer jackets and equipment	9
10 Design	9
10.1 Design options	9
10.1.1 General	9
10.1.2 Design by calculation	9
10.1.3 Design by calculation and supplemented with experimental methods	10
10.2 Common design requirements	11
10.2.1 General	11
10.2.2 Design specification	11
10.2.3 Design loads	12
10.2.4 Inspection openings	14
10.2.5 Pressure relief	14
10.2.6 Piping, valves and equipment	15
10.2.7 Degree of filling	16
10.3 Design by calculation	16
10.3.1 General	16
10.3.2 Inner vessel	16
10.3.3 Outer jacket	17
10.3.4 Supports, lifting points and frame	18
10.3.5 Protective guards	18
10.3.6 Piping	19
10.3.7 Calculation formulae	19
10.3.8 Calculations for operating loads	49
10.4 Design validation by experimental method	50
10.4.1 General	50
10.4.2 Procedure for experimental test programme	50
10.4.3 Tests for pressure integrity	50
10.4.4 Tests for structural integrity	50
10.4.5 Test conditions	52
11 Fabrication	53
11.1 General	53
11.2 Cutting	53
11.3 Cold forming	53
11.3.1 Austenitic stainless steel	53

11.3.2	Ferritic steel	54
11.3.3	Aluminium or aluminium alloys	54
11.4	Hot forming	54
11.4.1	General	54
11.4.2	Austenitic stainless steel	54
11.4.3	Aluminium or aluminium alloys	54
11.5	Manufacturing tolerances	54
11.5.1	Plate alignment	54
11.5.2	Thickness	55
11.5.3	Dished ends	55
11.5.4	Cylinders	55
11.6	Welding	56
11.6.1	General	56
11.6.2	Qualification	56
11.6.3	Temporary attachments	56
11.6.4	Welded joints	57
11.7	Non-welded joints	57
12	Initial inspection and testing	58
12.1	Quality plan	58
12.1.1	General	58
12.1.2	Inspection stages during manufacture of an inner vessel	58
12.1.3	Additional inspection stages during manufacture of a transportable cryogenic vessel	58
12.2	Production control test plates	59
12.2.1	Number of tests required	59
12.2.2	Testing	59
12.3	Non-destructive testing	59
12.3.1	General	59
12.3.2	Extent of examination for surface imperfections	59
12.3.3	Extent of examination for volumetric imperfections	60
12.3.4	Acceptance criteria for surface and volumetric imperfections as classified in ISO 6520-1	61
12.4	Rectification	62
12.4.1	General	62
12.4.2	Manually welded seams	62
12.4.3	Seams produced using automatic welding processes	62
12.5	Pressure testing	62
13	Marking and labelling	63
14	Documentation	63
	Annex A (informative) Base materials	64
	Annex B (normative) Outer jacket relief devices	67
	Annex C (normative) Elastic stress analysis	68
	Annex D (normative) Components subject to external pressure (pressure on the convex surface) — Calculation	77
	Annex E (informative) Marking and labelling information	82
	Annex F (informative) Specific weld details	84
	Annex G (informative) Design validation as part of type approvals	88
	Bibliography	90

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).

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).

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

For an explanation on 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 the following URL: www.iso.org/iso/foreword.html.

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

This second edition cancels and replaces the first edition (ISO 21029-1:2004), which has been technically revised. The main changes compared to the previous edition are as follows:

- amendments were made in order to increase consistency with the UN model regulations;
- the partial exchange of calculation methods by experimental methods is explained in detail in order to improve clarity;
- subclauses [10.2](#) and [12.3](#) were technically revised, [Annex A](#) has been integrated in the main text.

A list of all parts in the ISO 21029 series can be found on the ISO website.

This page deliberately left blank

Cryogenic vessels — Transportable vacuum insulated vessels of not more than 1 000 litres volume —

Part 1: Design, fabrication, inspection and tests

1 Scope

This document specifies requirements for the design, fabrication, type test and initial inspection and test of transportable vacuum-insulated cryogenic pressure vessels of not more than 1 000 l volume. This document applies to transportable vacuum-insulated cryogenic vessels for fluids as specified in [3.1](#) and [Table 1](#) and does not apply to such vessels designed for toxic fluids.

NOTE 1 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 land and marine vehicles, see [ISO 13985](#).

NOTE 2 Specific requirements for open top dewards are not covered by this document.

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 148-1](#), *Metallic materials — Charpy pendulum impact test — Part 1: Test method*

[ISO 2244](#), *Packaging — Complete, filled transport packages and unit loads — Horizontal impact tests*

[ISO 3834-2](#), *Quality requirements for fusion welding of metallic materials — Part 2: Comprehensive quality requirements*

[ISO 4126-1](#), *Safety devices for protection against excessive pressure — Part 1: Safety valves*

[ISO 4126-2](#), *Safety devices for protection against excessive pressure — Part 2: Bursting disc safety devices*

[ISO 4136](#), *Destructive tests on welds in metallic materials — Transverse tensile test*

[ISO 5173](#), *Destructive tests on welds in metallic materials — Bend tests*

[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 10474:2013](#), *Steel and steel products — Inspection documents*

[ISO 10042](#), *Welding — Arc-welded joints in aluminium and its alloys — Quality levels for imperfections*

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

[ISO 10675-2](#), *Non-destructive testing of welds — Acceptance levels for radiographic testing — Part 2: Aluminium and its alloys*

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

[ISO 15607](#), *Specification and qualification of welding procedures for metallic materials — General rules*

[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 17635:2016, *Non-destructive testing of welds — General rules for metallic materials*

[ISO 17636-1](#), *Non-destructive testing of welds — Radiographic testing — Part 1: X- and gamma-ray techniques with film*

[ISO 17636-2](#), *Non-destructive testing of welds — Radiographic testing — Part 2: X- and gamma-ray techniques with digital detectors*

[ISO 17637](#), *Non-destructive testing of welds — Visual testing of fusion-welded joints*

[ISO 21011](#), *Cryogenic vessels — Valves for cryogenic service*

[ISO 21013-1](#), *Cryogenic vessels — Pressure-relief accessories for cryogenic service — Part 1: Reclosable pressure-relief valves*

[ISO 21013-2](#), *Cryogenic vessels — Pressure-relief accessories for cryogenic service — Part 2: Non-reclosable pressure-relief devices*

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

[ISO 21014](#), *Cryogenic vessels — Cryogenic insulation performance*

[ISO 21028-1](#), *Cryogenic vessels — Toughness requirements for materials at cryogenic temperature — Part 1: Temperatures below -80 °C*

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

ISO 21029-2, *Cryogenic vessels — Transportable vacuum insulated vessels of not more than 1 000 litres volume — Part 2: Operational requirements*

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

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:

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

3.1

cryogenic fluid

refrigerated liquefied gas

gas which is partially liquid because of its low temperature

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

Note 2 to entry: This includes totally evaporated liquids and supercritical fluids.

Table 1 — Refrigerated but non-toxic gases

UN No. ^a	Proper shipping name and description ^a
Asphyxiant gases	
1913	neon, refrigerated liquid
1951	argon, refrigerated liquid
1963	helium, refrigerated liquid
1970	krypton, refrigerated liquid
1977	nitrogen, refrigerated liquid
2187	carbon dioxide, refrigerated liquid
2591	xenon, refrigerated liquid
3136	trifluoromethane, refrigerated liquid
3158	gas, refrigerated liquid, N.O.S ^b
Oxidizing gases	
1003	air, refrigerated liquid
1073	oxygen, refrigerated liquid
2201	nitrous oxide, refrigerated liquid
3311	gas, refrigerated liquid, oxidizing, N.O.S ^b
Flammable gases	
1038	ethylene, refrigerated liquid
1961	ethane, refrigerated liquid
1966	hydrogen, refrigerated liquid
1972	methane, refrigerated liquid or natural gas, refrigerated liquid, with high methane content
3138	ethylene, acetylene and propylene mixture, refrigerated liquid, containing at least 71,5 % ethylene with not more than 22,5 % acetylene and not more than 6 % propylene
3312	gas, refrigerated liquid, flammable, N.O.S ^b
^a U.N. No. and proper shipping name according to UN Recommendations.	
^b N.O.S. = not otherwise specified.	

3.2

transportable cryogenic vessel

thermally insulated vessel comprising a complete assembly ready for service, consisting of an inner vessel, an outer jacket, all of the valves and equipment together with any additional framework, intended for the transport of one or more cryogenic fluids

3.3

thermal insulation

vacuum interspace between the inner vessel and the outer jacket

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

vessel intended to contain the cryogenic fluid

3.5

outer jacket

gas-tight enclosure that contains the inner vessel and enables the vacuum to be established

3.6

normal operation

intended operation of the vessel at maximum permissible pressure including the handling loads defined in [3.7](#)

3.7

handling loads

loads exerted on the transportable cryogenic vessel in all normal conditions of transport including loading, unloading, moving by hand or by fork-lift truck

3.8

piping system

all pipes and piping components which can come in contact with cryogenic fluids including valves, fittings, pressure relief devices and their supports

3.9

equipment

devices that have a safety-related function with respect to pressure containment and/or control (e.g. protective or limiting devices, regulating and monitoring devices, valves, indicators)

3.10

manufacturer of the transportable cryogenic vessel

company that carries out the final assembly of the transportable cryogenic vessel

3.11

gross volume of the inner vessel

volume of the inner vessel, excluding nozzles, pipes etc. determined at minimum design temperature and atmospheric pressure

3.12

tare mass

mass of the empty transportable cryogenic vessel

3.13

net mass

maximum permissible mass of the cryogenic fluid which may be filled

Note 1 to entry: The maximum permissible mass is equal to the mass of the cryogenic fluid occupying 98 % of the net volume of the inner vessel 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.

3.14

gross mass

sum of tare mass plus net mass

3.15

pressure

pressure relative to atmospheric pressure, i.e. gauge pressure

3.16

automatic welding

welding in which all operations are performed without welding operator intervention during the process

Note 1 to entry: Manual adjustment of welding variables by the welding operator during welding is not possible.

[SOURCE: ISO 14732:2013, 3.1]

3.17

maximum allowable working pressure

MAWP

p_s

maximum effective gauge pressure permissible at the top of the vessel in its normal operating position including the highest effective pressure during filling and discharge

Note 1 to entry: Adapted from UN Model Regulations, Rev.19, Vol. II, 6.2.1.3.6.5.

3.18

net volume of the inner vessel

volume of the shell, below the inlet to the relief devices, excluding nozzles, pipes, etc. determined at minimum design temperature and atmospheric pressure

3.19

type approval

vessel type, which was successfully subjected to the design calculation and/or the experimental type test, as issued by the responsible authority or its delegate

Note 1 to entry: Vessel type is as defined by [10.2.2](#).

Note 2 to entry: If it can be proven that the calculation and the experimental tests also cover variants of the prototype these variants may be included in the type approval. If the type includes variants it might also be called "family".

3.20

relief plate/plug

plate or plug retained by atmospheric pressure but which allows relief of excess internal pressure

3.21

bursting disc device

non-reclosing pressure relief device ruptured by differential pressure

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

4 Symbols

Symbol	Designation	Unit
A	cross sectional area of reinforcing element	mm ²
C, β	design factors	1
c	allowance for corrosion	mm
D	shell diameter	mm
D_a	external diameter e.g. of a cylindrical shell	mm
D_i	internal diameter e.g. of a cylindrical shell	mm
d_a	external diameter of tube or nozzle	mm
d_i	diameter of opening	mm
E	Young's modulus	N/mm ²
f	narrow side of rectangular or elliptical plate	mm

Symbol	Designation	Unit
I	moment of inertia of reinforcing element	mm ⁴
K	material property used for design	N/mm ²
K_T (e.g. K20 for material property at 20 °C)	material property at temperature T expressed in °C	N/mm ²
l_b, l'_b	buckling length	mm
n	number of lobes	1
p	design pressure as defined in 10.2.3.1.1	bar (MPa)
p_e	permissible external pressure limited by elastic buckling	bar (MPa)
p_k	strengthening pressure	bar (MPa)
p_p	permissible external pressure limited by plastic deformation	bar (MPa)
p_s	maximum permissible pressure	bar (MPa)
p_t	test pressure (see 10.2.3.1.2)	bar (MPa)
R	radius of curvature e.g. inside crown radius of dished end	mm
R_e (1 % proof stress for austenitic steel)	minimum guaranteed yield stress or 0,2 % proof stress	N/mm ²
R_m	minimum guaranteed tensile strength (actual or guaranteed)	N/mm ²
r	radius, e.g. inside knuckle radius of dished end and cones	mm
S	safety factor at design pressure, with respect to R_e	1
S_k	safety factor against elastic buckling at design pressure	1
S_p	safety factor against plastic deformation	1
s	minimum thickness	mm
s_e	actual wall thickness	mm
u	out of roundness (see 11.5.4.2)	1
v	factor indicative of the utilization of the permissible design stress in joints or factor allowing for weakenings	1
χ_i	(decay-length zone) distance over which governing stress is assumed to act	mm
Z	auxiliary value	1
ν	Poisson's ratio	1

5 General requirements

5.1 Applicable regulations may require conformity assessment.

5.2 The transportable cryogenic vessel shall safely withstand the mechanical and thermal loads and the chemical effects encountered during pressure testing and normal operation. These requirements are deemed to be satisfied if [Clauses 6](#) to [11](#) are fulfilled. The vessel shall be marked in accordance with [Clause 13](#), tested in accordance with [Clause 12](#) and operated in accordance with ISO 21029-2.

5.3 Transportable cryogenic vessels shall be equipped with valves and pressure relief devices configured and installed in such a way that the vessel can be operated safely.

The inner vessel, the outer jacket and any section of pipework containing cryogenic fluid which can be trapped, shall be protected against over pressurization.

5.4 The transportable cryogenic vessel shall be cleaned for the intended service in accordance with ISO 23208 or an equivalent standard (e.g. [EN 12300](#)).

5.5 For transportable cryogenic vessel intended for service with flammable cryogenic fluids, all metallic components of the vessel shall be electrically continuous. The vessel shall be provided with a means of attachment to an earthing device(s) so that the resistance to earth is less than 10 Ω.

5.6 The manufacturer shall retain the documentation defined in [Clause 14](#) for a period required by regulations (e.g. product liability). In addition, the manufacturer shall retain all supporting and background documentation issued by his subcontractors (if any) which establishes that the vessel conforms to this document.

6 Mechanical loads

6.1 General

The transportable cryogenic vessel shall resist the mechanical loads without suffering deformation which could affect safety and which could lead to leakage. This requirement can be validated by:

- calculation ([10.2.1](#));
- experimental method ([10.4](#));
- calculation and experimental method ([10.1.3](#)).

The mechanical loads to be considered are given in [6.2](#) and [6.3](#).

6.2 Load during the pressure test

The load exerted during the pressure test is given by:

$$p_t \geq 1,3(p_s + 1) \text{ in bar or } [p_t \geq 1,3 + (p_s + 0,1) \text{ in MPa}]$$

where

- p_t is the test pressure, in bar;
- p_s is the maximum permissible pressure (= relief device set pressure), bar (+0,1 MPa);
- +1 is the allowance for external vacuum.

6.3 Other mechanical loads

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

- a) a pressure equal to the maximum permissible pressure in the inner vessel and pipework;
- b) the pressure exerted by the liquid when the vessel is filled to capacity;
- c) loads produced by the thermal movement of the inner vessel, outer jacket and interspace piping;
- d) loads imposed in lifting and handling fixtures (at the vessel);
- e) full vacuum in the outer jacket;
- f) a pressure in the outer jacket equal to the set pressure of the relief device protecting the outer jacket;
- g) load due to dynamic effects, when the vessel is filled to capacity, giving consideration to:
 - 1) the inner vessel support system including attachments to the inner vessel and outer jacket;

- 2) the interspace and external piping;
- 3) the outer jacket supports and, where applicable, the supporting frame.

6.3.2 Dynamic loads during normal operation, equal to twice the mass of the inner vessel when filled to the capacity shown on the data plate exerted by the inner vessel both horizontally and vertically, shall be considered.

6.3.3 If the vessel has a volume of more than 100 l or a gross mass of more than 150 kg or if the height of the centre of gravity of the fully loaded vessel is less than twice the smallest horizontal dimension at its base, the vertically upwards acting reference load may be reduced to equal the gross mass.

7 Chemical effects

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

Also, 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.

8 Thermal conditions

The following thermal conditions shall be taken into account:

- a) for the inner vessel and its associated equipment the full range of temperature expected;
- b) for the outer jacket and equipment thereof [other than equipment covered by a)]:
 - 1) a minimum working temperature of $-20\text{ }^{\circ}\text{C}$;
 - 2) a maximum working temperature of $50\text{ }^{\circ}\text{C}$.

9 Material

9.1 General

For the materials used to manufacture the transportable cryogenic vessels, the following requirements shall be met.

9.2 Material properties

9.2.1 All materials that will, or might, be in contact with cryogenic fluids shall be in accordance with the relevant standards for compatibility for the specific cryogenic fluid(s) that they might be in contact with.

Particular consideration shall be given to material compatibility with cryogenic fluids that are either flammable or oxidants.

Material compatibility and cleanliness requirements for vessels intended for service in oxygen or other oxidising liquids are described in [ISO 21010](#) and ISO 23208 (or in equivalent standard such as [EN 12300](#)).

For liquid hydrogen vessels, consideration shall be given to the possible presence of oxygen enriched air due to condensation on uninsulated cold parts. See also [ISO 21010](#).

9.2.2 Materials used at low temperatures shall follow the toughness requirements of the relevant standard. For temperatures below $-80\text{ }^{\circ}\text{C}$, see [ISO 21028-1](#). For non-metallic materials low temperature suitability shall be demonstrated by providing sufficient test data.

9.2.3 The base materials, listed in [Annex A](#), subject to meeting the extra requirements given in the main body of this document, are suitable for and may be used in the manufacture of the cryogenic vessels conforming to this document.

9.3 Inspection certificate

9.3.1 The material shall be declared by an inspection certificate 3.1 in accordance with [ISO 10474](#).

9.3.2 The material manufactured to a recognized International Standard shall meet the testing requirements of [ISO 21028-1](#) and ISO 21028-2 and shall be certified by inspection certificate 3.1 in accordance with [ISO 10474](#).

9.3.3 The delivery of material which is not manufactured to a recognized standard shall be certified by inspection certificate 3.1 in accordance with [ISO 10474](#) confirming that the material fulfils the requirements listed in [9.2](#). The material manufacturer shall follow a recognized standard for processing and establishing the guaranteed material properties.

9.4 Materials for outer jackets and equipment

The outer jacket and the equipment not subjected to cryogenic 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](#) or [10.1.3](#).

NOTE For design validation as part of type approvals see [Annex G](#).

10.1.2 Design by calculation

This option requires calculation of all pressure and load-bearing components. The pressure part thicknesses of the inner vessel and outer jacket shall be not less than the requirements given in [10.3](#). Additional calculations are required to ensure the design is satisfactory for the operating conditions including an allowance for dynamic loads.

Fatigue life calculation shall be conducted according to [EN 13445-3](#), ASME VIII-2 or equivalent standards/codes, if the pressure loading is exceeding the limit of predominantly non-cyclic nature defined by the applied standard/code.

The fatigue life calculation shall be conducted for unlimited lifetime.

Alternatively, the fatigue life of the vessel may be specified. The user of the vessel shall estimate the operational fatigue load regime during the expected lifetime. Then the designer can take into account the operational load regime in the fatigue life calculation.

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](#).

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.

10.1.3 Design by calculation and supplemented with experimental methods

This option requires validation of the pressure-retaining capacity by calculation except that the minimum wall thickness requirements of [Tables 2](#) and [3](#) do not apply. Structural integrity shall be validated by experiment as described in [10.4](#).

The pressure-retaining capacity may be validated by experimental methods:

- if no design formulae are available for shape or material, or
- for vessels with a (p/V) lower than 1 000 bar/l (100 MPa/l).

Table 2 — Inner vessel minimum wall thickness

Inner vessel diameter, D (mm)	Minimum wall thickness s_0 for reference steel ^a (mm)
$D \leq 400$	1
$400 < D \leq 1\,800$	$0,5 + \frac{D}{1\,200}$
^a Reference steel material is material having a product $R_m \times A_5$ of 10 000. For other steels calculate the minimum thickness using the following formula: $s = \frac{21,4 s_0}{\sqrt[3]{R_m \times A_5}}$ where R_m is the ultimate tensile strength, in newtons per square millimetre; A_5 is the elongation at fracture, in per cent.	

Table 3 — Outer jacket minimum wall thickness

Outer vessel diameter, D (mm)	Minimum wall thickness s_0 for reference steel ^a (mm)
$D \leq 1\,800$	$0,5 + \frac{D}{1\,200}$
^a Reference steel material is material having a product $R_m \times A_5$ of 10 000. For other steels calculate the minimum thickness using the following formula: $s = \frac{21,4 s_0}{\sqrt[3]{R_m \times A_5}}$ where R_m is the ultimate tensile strength, in newtons per square millimetre; A_5 is the elongation at fracture, in per cent.	

10.2 Common design requirements

10.2.1 General

The requirements of [10.2.2](#) to [10.2.6](#) are applicable to all vessels irrespective of the design validation option used. In the event of an increase in at least one of the following parameters:

- maximum permissible 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;

or, in the event of any change relative to:

- the type of material or grade (e.g. stainless steel to aluminium or change of stainless steels grades);
- 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;
- the initial design programme shall be repeated to take account of these modifications.

In addition, if any changes affect the handling method or the stacking condition, the appropriate tests (complying respectively with [10.4.4.2](#) and [10.4.4.3](#)) or the relevant calculations, shall be repeated to take account of these changes.

10.2.2 Design specification

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

- maximum permissible pressure;
- fluids to be used;
- liquid capacity;
- volume of the inner vessel;
- method of handling and securing;
- stacking arrangement;
- range of ambient temperatures.

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

- definition of which components are designed by calculation and which are validated 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 compliance with 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 and other accessories if applicable;
- details of lifting points and lifting procedure.

10.2.3 Design loads

10.2.3.1 Inner vessel

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

- a) Design pressure, p given in [Formula \(1\)](#);

$$p = p_s + p_l + 1 \text{ bar or } (p = p_s + p_l + 0,1 \text{ MPa}) \quad (1)$$

where p_l is the pressure, in bars, exerted by the liquid contents when the vessel is filled to capacity and subject to dynamic loading;

- b) loads imposed on the inner vessel due to the mass of the inner vessel and its contents when subject to dynamic loading;
- c) load imposed by the piping due to the differential thermal movement of the inner vessel, the piping and the outer jacket;

The following cases shall be considered:

- 1) cooldown (inner vessel warm – piping cold);
 - 2) filling and withdrawal (inner vessel cold – piping cold);
 - 3) transshipment and storage (inner vessel cold – piping warm);
- d) load imposed on the inner vessel at its support points when cooling from ambient to operating temperature and during operation.

10.2.3.1.2 The design shall be evaluated for the following condition.

Pressure test: the following value, defined with [Formula \(2\)](#) shall be used for validation purposes:

$$p_t \geq 1,3(p_s + 1) \text{ bar or } [p_t \geq 1,3(p_s + 0,1) \text{ MPa}] \quad (2)$$

where p_s is the maximum permissible pressure.

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

For cryogenic vessels with a capacity above 450 l, the minimum test pressure shall be 3 bar (or 0,3 MPa). This requirement does not apply to heating or cooling systems and related service equipment.

10.2.3.2 Outer jacket

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

- a) an external pressure of 1 bar (or 0,1 MPa);
- 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 dynamic load;
- d) load imposed by piping as defined in [10.2.3.1.1 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 support points due to the mass of the transportable cryogenic vessel and its contents when filled to capacity and subject to dynamic load (see [10.3.8](#)).

10.2.3.3 Inner vessel supports

The inner vessel supports shall be suitable for the load defined in [10.2.3.1.1 c\)](#) plus loads due to differential thermal movements.

10.2.3.4 Outer jacket supports

The outer jacket supports shall be suitable for the load defined in [10.2.3.2 f\)](#).

10.2.3.5 Lifting points

Lifting points shall be suitable for lifting the transportable cryogenic vessel when filled to capacity and subject to vertical dynamic load, when lifted in accordance with the specified procedure (see [10.3.8](#)).

10.2.3.6 Frame

Where a frame is part of the transportable cryogenic vessel it shall be suitable for the static and dynamic loads imposed during storage, lifting and transport. This shall include loads due to stacking vessels where applicable (see [10.3.8](#)).

10.2.3.7 Protective guards

Guards fitted for the protection of fittings and external pipework shall be designed to withstand a load equal to the mass of the transportable cryogenic vessel filled to capacity applied in the horizontal or vertical direction.

The load shall be equal to twice the total mass if any of the following conditions is met:

- capacity less than 100 l;
- total mass less than 150 kg;
- the height of the centre of gravity of the transportable cryogenic vessel, when filled to capacity, including any framework elements, is more than twice the smaller horizontal dimension of its base.

10.2.3.8 Piping and valves

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

- a) pressure test: not less than the permissible working pressure p_s plus 1 bar (or 0,1 MPa) for piping that is 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 [10.2.3.1.1](#) c);
- d) dynamic loads;
- e) set pressure of thermal relief devices where applicable;
- f) loads generated during pressure relief discharge.

10.2.4 Inspection openings

Inspection openings are not required in the inner vessel or the outer jacket.

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.

NOTE 3 The elimination of inspection openings also assists in maintaining the integrity of the vacuum in the interspace.

10.2.5 Pressure relief

10.2.5.1 General

Relief devices for inner vessels shall be in accordance with [ISO 21013-1](#) and [ISO 21013-2](#) as appropriate, with the exception that, for flammable gases, non-reclosable pressure-relief devices shall not be used.

Relief devices for inner vessels shall be sized in accordance with [ISO 21013-3](#), taking into consideration the conditions stipulated in [10.2.5.2](#) and [10.2.5.3](#).

In sizing pressure relief devices the calculations shall take into account the back pressure developed by equipment that may be installed downstream of the outlet of the relief device, such as venting systems, and, in the case of flammable gas relief devices, flame arrestors.

Relief devices for outer jackets shall be in accordance with [Annex B](#).

Systems shall be designed to meet the requirements given in [10.2.5.2](#) and [10.2.5.3](#).

10.2.5.2 Inner vessel

The inner vessel shall be provided with at least two pressure relief devices to protect the vessel against excess pressure due to the following:

- a) normal heat leak. Insulation performance evaluated as described in [ISO 21014](#) shall be sufficient to satisfy the holding time requirement;
- b) heat leak with loss of vacuum;
- c) failure in the open position of a pressure build-up system.

Excess pressure means a pressure in excess of 110 % of the maximum permissible pressure for condition a) and in excess of the test pressure for condition b) or c).

An exception is made for vessels of less than 450 l capacity where at least one pressure relief device shall be provided.

Shut-off valves or the equivalent may be installed upstream of pressure relief devices, provided that additional devices and interlocks are fitted to ensure that the vessel has sufficient relief capacity at all times.

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

All pressure relief devices that can release flammable cryogenic fluid to the atmosphere shall be connected to a venting system that discharges the contents safely.

10.2.5.3 Outer jacket

A pressure relief device shall be fitted to the outer jacket. The device shall be set to open at a pressure of not more than 1,7 bar (or 0,17 MPa). The discharge area of the pressure relief device shall be not less than 0,171 mm²/l capacity of the inner vessel but not less than 6 mm in diameter.

For calculating the resistance of the inner vessel and the outer vessel to the pressure, the maximum actual set values shall be considered.

10.2.5.4 Piping

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

10.2.6 Piping, valves and equipment

10.2.6.1 All piping, valves and equipment shall be suitable for use with the specific cryogenic fluid(s) for which the vessel may be used. Particular consideration shall be given to the suitability of components to be used with cryogenic fluids that are flammables or oxidants.

10.2.6.2 Because of the risk of fire and explosion with vessels used for flammable cryogenic fluids, the design of the piping shall provide for:

- a) upward venting;
- b) leak-tightness;
- c) the vessel and piping to be purged with a non-flammable/non-oxidizing gas when required for the safe operation and maintenance of the vessel.

All lines that can release flammable cryogenic fluid to the atmosphere, such as filling lines and vent lines, shall be connected to a venting system that discharges the contents safely. Lines to atmosphere that are only used occasionally, such as purge lines used in relation to maintenance activities, need only be connected to the venting system when in use but shall have double isolation, in accordance with [10.2.6.3](#), at all other times.

10.2.6.3 Valves shall be conform to [ISO 21011](#) and to [ISO 4126-1](#).

For safety critical valves on vessels for flammable gas, depending of the material used (body, seals), consideration should be given to the use of valves certified as fire-safe in accordance with a standard such as API 607 or [ISO 10497](#).

On vessels that are to be used for flammable cryogenic fluids, all lines that can be open to the atmosphere, such as filling lines and vent lines, shall be provided with two means of isolation, with the exception of relief devices which shall not have two means of isolation.

The main means of isolation shall be an isolation valve, located close to the vessel and easily accessible in an emergency. The secondary means of isolation shall be placed between the main isolation valve and atmosphere.

The secondary means of isolation may be an isolation valve, a non-return valve, a cap or a plug, as appropriate, with the exception of the secondary isolation for the liquid fill line which shall be either a non-return valve or a fail-closed automatic shut-off valve.

10.2.7 Degree of filling

The degree of filling of large transportable vacuum-insulated vessels intended for the carriage of flammable gases shall remain below the level at which, if the contents were raised to the temperature at which the vapour pressure equalled the opening pressure of the safety valve, the volume of the liquid would reach 98 % of the vessel's net volume at that temperature. The degree of filling for helium may be 100 % of net volume. Pre-trip inspection shall ensure that the above limits are not exceeded. The degree of filling shall be calculated or determined or put on the tank plate.

All vessels to be used for flammable cryogenic fluids shall be equipped with safety devices to protect against overfilling (level limiters).

10.3 Design by calculation

10.3.1 General

When design validation is by calculation in accordance with [10.1.2](#) or [10.1.3](#) the dimensions of the inner vessel and outer jacket shall be not less than that determined in accordance with this sub-clause.

10.3.2 Inner vessel

10.3.2.1 Wall thickness

The information given in [10.3.2.2](#) to [10.3.2.6](#), in conjunction with the calculation formulae of [10.3.7](#), shall be used to determine the pressure part thicknesses.

The actual wall thickness shall be not less than as shown in [Table 3](#) unless either:

- a) the design has been validated by experiment, or
- b) a stress analysis has been carried out, and assessed in accordance with [Annex C](#).

10.3.2.2 Design pressure, p

The internal design pressure p shall be as defined in [10.2.3.1](#).

The minimum design pressure shall be 2,31 bar (or 0,231 MPa).

The inner vessel shall be designed for a minimum external pressure equal to the set pressure of the outer jacket pressure relief device.

10.3.2.3 Material property, K_{20}

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

- for austenitic stainless steel, 1 % proof strength;
- for aluminium and aluminium alloys, 0,2 % proof strength.

K shall be the minimum value at 20 °C as taken from the material standard. In the case of austenitic stainless steels the specified minimum value may be exceeded by up to 15 % provided this higher value is attested in the inspection certificate.

Higher values of K may be used provided that 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 rolled plate or coil of the material to be delivered;

- the increased properties shall be attested in the inspection certificate;
- the welding procedures shall be suitably qualified.

For austenitic steel higher stress values due to work-hardening may be considered in the design only, if their presence in the component has been proved, the material (including welding seam) has sufficient residual elongation of rupture and still sufficient impact energy as minimum required.

If allowed by the applicable authorities where the vessel is to be operated.

10.3.2.4 Safety factors S , S_p and S_k

The safety factors to be used are as follows:

- internal pressure (pressure on the concave surface): $S = 1,33$;
- 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 see applicable method in [Annex D](#);
 - knuckle region, $S_p = 1,6$.

10.3.2.5 Weld joint factors, v

For internal pressure (pressure on the concave surface), $v = 0,85$ or $1,0$ (see [Clause 12](#)).

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

10.3.2.6 Corrosion allowances, c

$c = 0$

NOTE No corrosion allowance is required for austenitic stainless steel, aluminium and aluminium alloys.

10.3.3 Outer jacket

10.3.3.1 General

The following, in conjunction with the calculation formulae of [10.3.7](#), shall be used to determine the pressure part thicknesses.

The actual wall thickness shall be not less than as shown in [Table 3](#) unless either

- a) the design has been validated by experiment, or
- b) a stress analysis has been carried out and assessed in accordance with [Annex C](#).

10.3.3.2 Design pressure, p

The internal design pressure, p , shall be equal to the set pressure of the outer jacket pressure relief device.

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

10.3.3.3 Material property, K_{20}

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

- for austenitic stainless steel, aluminium and aluminium alloys, material property values shall be as defined in [10.3.2.3](#);
- for carbon steel, K = yield strength.

NOTE Upper yield strength can be used.

10.3.3.4 Safety factors S , S_p and S_k

The safety factors to be used are as follows:

- internal pressure (pressure on the concave surface): $S = 1,1$;
- external pressure (pressure on the convex surface):
 - cylindrical shells, $S_p = 1,1$, $S_k = 2,0$;
 - spherical region, $S_p = 1,6$, $S_k = 2,0 + 0,001\ 4\ R/s$;
 - knuckle region, $S_p = 1,2$.

10.3.3.5 Plastic deformation

Resistance to plastic deformation is determined by using [Annex C](#) 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, v

For internal pressure (pressure on the concave surface), $v = 0,7$.

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

10.3.3.7 Corrosion allowance, c

For austenitic stainless steel, $c = 0$.

For aluminium and aluminium alloys, $c = 0$.

For carbon steel, $c = 1,0\text{ mm}$.

c may be reduced to zero if the external surface is adequately protected against corrosion.

10.3.4 Supports, lifting points and frame

The supports and frame shall be designed for the loads defined in [10.2.3](#), using established structural design methods and safety factors.

When designing the inner vessel support system the temperature and corresponding mechanical properties to be used may be those of the component in question when the inner vessel is filled to capacity with cryogenic fluid.

10.3.5 Protective guards

External fittings shall be protected by a guard designed for the loads specified in [10.2.3.7](#). The requirements are satisfied if the fittings to be protected are either:

- within a guard which is permanently attached to the transportable cryogenic vessel, or

- located within the outline of the transportable cryogenic vessel, e.g. within an end which is domed inwards.

10.3.6 Piping

Piping shall be designed for the loads defined in [10.2.3.8](#) using established piping design methods and safety factors.

10.3.7 Calculation formulae

10.3.7.1 Cylindrical shells and spheres subject to internal pressure (pressure on the concave surface) (In case of using pressure unit in MPa, conversion shall be considered)

10.3.7.1.1 Field of application

Cylindrical shells and spheres where $D_a/D_i \leq 1,2$.

10.3.7.1.2 Openings

For reinforcement of openings see [10.3.7.7](#).

10.3.7.1.3 Calculation

The required minimum wall thickness, s , is

- for cylindrical shells, as per [Formula \(3\)](#):

$$s = \frac{D_a p}{20 \left(\frac{K_{20}}{S} \right) v + p} + c \quad (3)$$

- for spherical shells, as per [Formula \(4\)](#):

$$s = \frac{D_a p}{40 \left(\frac{K_{20}}{S} \right) v + p} + c \quad (4)$$

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

10.3.7.2.1 Field of application

Cylindrical shells where $D_a/D_i \leq 1,2$

10.3.7.2.2 Openings

Inner vessel openings shall be calculated in accordance with [10.3.7.7](#) using the external pressure as an internal pressure.

10.3.7.2.3 Calculation

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

10.3.7.2.4 Stiffening rings

In addition to the ends, effective reinforcing elements may be regarded as including the types of element illustrated in [Figures 1](#) and [2](#).

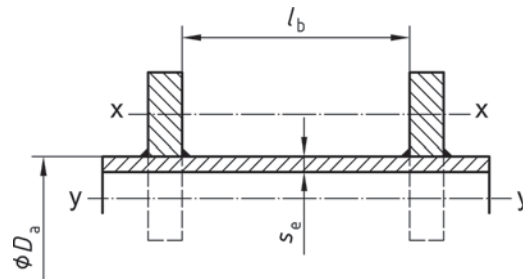


Figure 1 — Stiffening rings

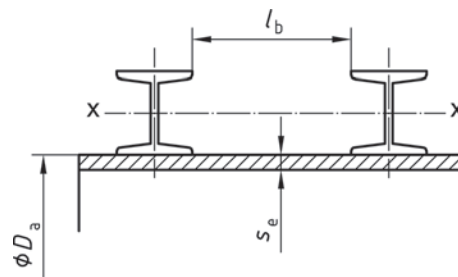


Figure 2 — Sectional material stiffeners

The stiffening rings welded to the shell shall satisfy the conditions in [Formulae \(5\)](#) and [\(6\)](#).

$$I \geq \frac{0,124 p D_a^3}{10 E} \sqrt{D_a (s - c)} \quad (5)$$

$$A \geq \frac{0,75 p D_a}{10 K} \sqrt{D_a (s - c)} \quad (6)$$

The moment of inertia I is relative to the neutral axis of the reinforcing elements cross-section parallel to the shell axis (see axis x – x in [Figures 1](#) and [2](#)). Narrow and high reinforcing elements of the kind shown in [Figure 1](#) may undergo severe buckling. Where the height of the element is greater than eight times its width, a more accurate calculation shall be made.

Where stiffening rings are joined to the shell by means of intermittent welds, the fillet welds at each side shall cover at least one third of the shell circumference and the number of weld discontinuities shall be at least $2n$. The number of buckling lobes, n , is obtained as indicated in [D.3.1.2.5](#).

10.3.7.3 Spheres subject to external pressure (pressure on the convex surface)

Spherical shells subject to external pressure shall be evaluated in accordance with [10.3.7.4.4](#).

10.3.7.4 Dished ends subject to internal or external pressure

See [Figures 3](#), [4](#) and [5](#).

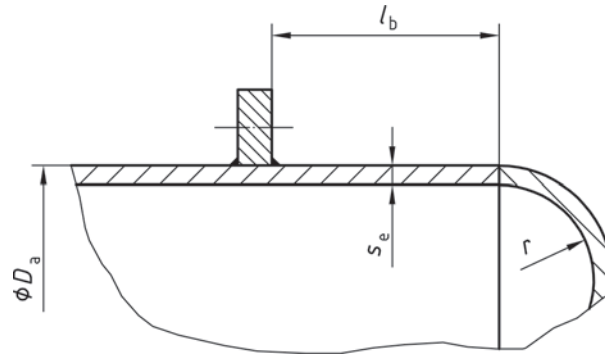


Figure 3 — Dished ends

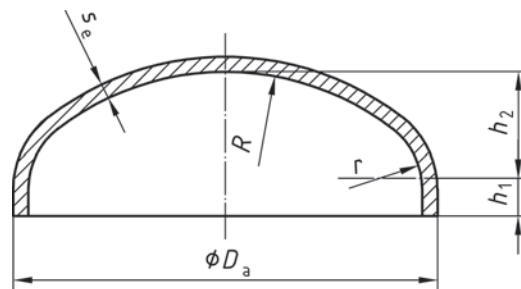


Figure 4 — Unpierced dished end

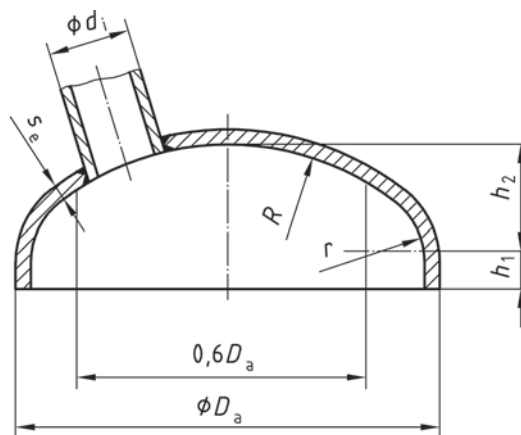


Figure 5 — Dished end with nozzle

10.3.7.4.1 Field of application

The following dish ends may be utilized:

- a) hemispherical ends where $D_a/D_i \leq 1,2$;
- b) 10 % torispherical ends where $R = 0,8 D_a$ and $r = 0,1 D_a$;
- c) 2:1 torispherical ends where $R = 0,8 D_a$ and $r = 0,154 D_a$;

NOTE In the case of torispherical ends $0,002 \leq (s - c)/D_a \leq 0,1$.

- d) 2:1 elliptical ends where $R = 0,9 D_a$ and $r = 0,170 D_a$;

NOTE In the case of elliptical ends $0,002 \leq (s - c)/D_a \leq 0,1$.

- e) other torispherical head shapes may be used provided suitable calculations are carried out in accordance with [10.3.8](#).

10.3.7.4.2 Straight flange

The straight flange length h_1 (see [Figures 4](#) and [5](#)) shall be not less than:

- for 10 % torispherical ends, 3,5 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.

10.3.7.4.3 Internal pressure calculation (pressure on concave surface)

10.3.7.4.3.1 Crown and hemisphere thickness

The wall thickness of the crown region of dished ends and of hemispherical ends shall be determined using [10.3.7.1.3](#) for spherical shells with $D_a = 2(R + s)$.

Openings within the crown area of 0,6 D_a of torispherical ends and in hemispherical ends shall be reinforced in accordance with [10.3.7.7](#). When pad type reinforcement is used, the edge of the pad shall not extend beyond the area of 0,8 D_a for 10 % torispherical ends or 0,7 D_a for 2:1 torispherical ends.

10.3.7.4.3.2 Torispherical end knuckle thickness and hemispherical end to shell junction thickness

The required thickness of the knuckle region and hemispherical end junction shall be as per [Formula \(7\)](#).

$$s = \frac{D_a p \beta}{40 \left(\frac{K_{20}}{S} \right)^v} + c \quad (7)$$

β is taken from [Figure 6 a\)](#) for 10 % torispherical ends and from [Figure 6 b\)](#) for 2:1 torispherical ends as a function of $(s - c)/D_a$. Iteration is necessary. D_a is the diameter of the end as shown in [Figures 4](#) and [5](#).