

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

Part 2: Design, fabrication, inspection and testing

The European Standard EN 1251-2:2000 has the status of a
British Standard

ICS 23.020.40

Confirmed March 2008

National foreword

This British Standard was published by BSI. It is the UK implementation of EN 1251-2:2000, incorporating Corrigendum August 2006.

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.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

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

This British Standard, having been prepared under the direction of the Engineering Sector Committee, was published under the authority of the Standards Committee and comes into effect on 15 May 2000

© BSI 2006

ISBN 0 580 32832 5

Amendments issued since publication

Amd. No.	Date	Comments
16822 Corrigendum No. 1	29 December 2006	Replacement of Figures 5, 14, 15, 16, 17, 26 and B.1

English version

Cryogenic vessels - Transportable vacuum insulated vessels of not more than 1 000 litres volume - Part 2: Design, fabrication, inspection and testing

Réipients cryogéniques - Réipients transportables, isolés
sous vide, d'un volume n'excédant pas 1 000 litres -
Partie 2: Conception, fabrication, inspection et essai

Kryo-Behälter - Ortsbewegliche, vakuum-isolierte Behälter
mit einem Fassungsraum von nicht mehr als 1 000 Liter -
Teil 2: Bemessung, Herstellung und Prüfung

This European Standard was approved by CEN on 19 June 1999.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Central Secretariat has the same status as the official versions.

CEN members are the national standards bodies of Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and United Kingdom.



EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

Central Secretariat: rue de Stassart, 36 B-1050 Brussels

Contents

Foreword	3
1 Scope.....	4
2 Normative references	4
3 Definitions and symbols.....	5
3.1 Definitions	5
3.2 Symbols	5
4 Design	7
4.1 Design validation options	7
4.2 Common design requirements	7
4.3 Design validation by calculation	12
4.4 Design validation by experimental method	27
5 Fabrication	59
5.1 General	59
5.2 Cutting	59
5.3 Cold forming	59
5.4 Hot forming	60
5.5 Manufacturing tolerances	60
5.6 Welding	63
5.7 Non-welded joints	63
6 Inspection and testing	64
6.1 Quality	64
6.2 Production control test plates	65
6.3 Non-destructive testing	65
6.4 Rectification	69
6.5 Pressure testing	69
Annex A (normative) Elastic stress analysis	70
A.1 General	70
A.2 Terminology	70
A.3 Limit for longitudinal compressive general membrane stress	72
A.4 Stress categories and stress limits for general application	73
A.5 Specific criteria, stress categories and stress limits for limited application	74
Annex B (informative) Recommended weld details	79
B.1 Scope.....	79
B.2 Weld detail	79
B.3 Oxygen service requirements.....	80
Annex C (normative) Additional requirements for flammable fluids	84
Annex D (normative) Outer jacket relief devices	85
D.1 Scope.....	85
D.2 Definitions	85
D.3 Requirements	85
Bibliography	87

Foreword

This European Standard has been prepared by Technical Committee CEN/TC 268, “Cryogenic vessels”, the secretariat of which is held by AFNOR.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by July 2000, and conflicting national standards shall be withdrawn at the latest by July 2000.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

The standard has been submitted for reference into the RID and/or in the technical annexes of the ADR.

Therefore the standards listed in the normative references and covering basic requirements of the RID/ADR not addressed within the present standard are normative only when the standards themselves are referred to in the RID and/or in the technical annexes of the ADR.

The other parts of EN 1251 are:

- Part 1: Fundamental requirements;
- Part 3: Operational requirements.

The standard covers validation of design by calculation or by an experimental method.

1 Scope

This European Standard is applicable to the design, fabrication, inspection and testing of transportable vacuum insulated cryogenic vessels of not more than 1 000 litres volume and designed for a maximum allowable pressure greater than atmospheric.

This standard applies to transportable vacuum insulated cryogenic vessels for fluids as specified in EN 1251-1 and is not applicable to such vessels designed for toxic fluids.

For details of acceptable materials see clause 8 of EN 1251-1.

Additional requirements for flammable fluids are given in annex C.

2 Normative references

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies.

EN 287-1, *Approval testing of welders - Fusion welding - Part 1: Steels*

EN 287-2, *Approval testing of welders - Fusion welding - Part 2: Aluminium and aluminium alloys*

EN 288-3, *Specification and approval of welding procedures for metallic materials - Part 3: Welding procedure tests for arc welding of steels*

EN 288-4, *Specification and approval of welding procedures for metallic materials - Part 4: Welding procedure tests for arc welding of aluminium and its alloys*

EN 288-8, *Specification and approval of welding procedures for metallic materials - Part 8: Approval by a pre-production welding test*

EN 473, *Qualification and certification of NDT personnel - General principles*

EN 729-2, *Quality requirements for welding - Fusion welding of metallic materials - Part 2: Comprehensive quality requirements*

EN 729-3, *Quality requirements for welding - Fusion welding of metallic materials - Part 3: Standard quality requirements*

EN 895, *Destructive tests on welds in metallic materials - Transverse tensile test*

EN 910, *Destructive tests on welds in metallic materials - Bend tests*

EN 962, *Transportable gas cylinders - Valve protection devices caps and valve guards for industrial and medical gas cylinders - Design, construction and tests*

EN 970, *Non-destructive examination of fusion welds - Visual examination*

EN 1251-1, *Cryogenic vessels - Transportable vacuum insulated vessels of not more than 1 000 litres volume - Part 1: Fundamental requirements*

EN 1251-3, *Cryogenic vessels - Transportable vacuum insulated vessels of not more than 1 000 litres volume - Part 3: Operational requirements*

EN 1252-1, *Cryogenic vessels - Materials - Part 1: Toughness requirements for temperatures below -80 °C*

EN 1418, *Welding personnel - Approval testing of welding operators for fusion welding and resistance weld setters for fully mechanized and automatic welding of metallic materials*

EN 1435, *Non-destructive examination of welds - Radiographic examination of welded joints*

EN 1626, *Cryogenic vessels - Valves for cryogenic service*

EN 1708-1, *Welding - Basic weld joint details in steel - Part 1: Pressurized components*

EN 1797-1, *Cryogenic vessels - Gas/material compatibility - Part 1: Oxygen compatibility*

EN 10045-1, *Metallic materials - Charpy impact test - Part 1: Test method*

EN 10204, *Metallic products - Types of inspection documents*

EN 12213, *Cryogenic vessels - Evaluation methods of thermal insulation performance*

EN 12300, *Cryogenic vessels - Cleanliness for cryogenic service*

EN 22244:1992, *Packaging - Complete, filled transport packages - Horizontal impact tests (horizontal or inclined plane tests - Pendulum test) (ISO 2244:1985)*

prEN ISO 4126-2, *Safety devices for protection against excessive pressure - Part 2: Bursting disc safety devices (ISO/DIS 4126-2:1996)*

EN ISO 6520-1, *Welding and allied processes - Classification of geometric imperfections in metallic materials - Part 1: Fusion welding (ISO 6520-1:1998)*

3 Definitions and symbols

3.1 Definitions

For the purposes of this standard, the following definitions apply in addition to those given in EN 1251-1.

3.1.1

automatic welding

welding in which the parameters are automatically controlled. Some of these parameters may be adjusted to a limited extent, either manually or automatically, during welding to maintain the specified welding conditions

3.1.2

maximum allowable pressure, P_s

the maximum pressure which may be exerted under normal conditions of use

3.1.3

volume of the inner vessel

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

3.2 Symbols

For the purposes of this standard, the following symbols apply:

c allowance for corrosion, in millimetres

d_i internal diameter of tube or nozzle, in millimetres

f	narrow side of rectangular or elliptical plate, in millimetres
l_b	buckling length, in millimetres
n	number
p	design pressure, in bar
p_e	allowable external pressure limited by elastic buckling, in bar
p_p	allowable external pressure limited by plastic deformation, in bar
r	radius, e.g. inside knuckle radius of dished end and cones, in millimetres
s	required wall thickness including allowances, in millimetres
s_e	actual wall thickness, in millimetres
v	factor indicative of the utilization of the permissible design stress in joints or factor allowing for weakening
x	(decay-length zone) distance over which governing stress is assumed to act, in millimetres
A	area, in square millimetres
C, β	design factors
D	shell diameter, in millimetres
D_a	outside diameter, e.g. of a cylindrical shell, in millimetres
D_i	internal diameter, e.g. of a cylindrical shell, in millimetres
E	Young's modulus, in Newtons per square millimetre
I	moment of inertia of stiffening ring, in millimetres ⁴
K	material property used for design, in Newtons per square millimetre
R	radius of curvature, e.g. inside crown radius of dished end, in millimetres
S	safety factor at design pressure
S_k	safety factor against elastic buckling at design pressure
S_p	safety factor against plastic deformation
Z	auxiliary value
ν	Poisson's ratio
u	out of roundness

4 Design

4.1 Design validation options

Each type of vessel shall be subject to validation of the design in accordance with one of the options given in 4.1.1, 4.1.2 or 4.1.3. The manufacturer shall consider the nature of the individual design, particularly the degree of novelty; a method of validation appropriate to that design; and the limitation of that method.

4.1.1 Validation 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 not be less than required by 4.3. Additional calculations are required to validate the design for the operating conditions including an allowance for dynamic loads.

4.1.2 Validation by experimental method

This option requires the pressure retaining capacity and structural integrity to be validated by experiment as detailed in 4.4.

4.1.3 Validation by calculation and experimental method

This option requires validation of the pressure retaining capacity by calculation except that the minimum wall thickness requirements of Tables 1 and 2 do not apply. Structural integrity shall be validated by experiment as detailed in 4.4.

4.2 Common design requirements

4.2.1 General

The requirements of 4.2.2 to 4.2.7 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 allowable pressure;
 - 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);
 - to the fundamental shape;
 - to the decrease in the minimum mechanical properties of the material being used;
 - to 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 validation 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 4.4.4.2 and 4.4.4.3) or the relevant calculations shall be repeated to take account of these changes.

4.2.2 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 used;
- liquid capacity;
- volume of the inner vessel;
- method of handling and securing;
- stacking arrangement.

A design document in the form of drawings and/or written text shall be prepared; it shall contain the information given above plus the following where applicable:

- definition of which components are validated 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;
- type of material test certificates in accordance with EN 10204;
- 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 standard;
- design validation test programme;
- non-destructive testing requirements;
- pressure test requirements;
- piping configuration including type, size and location of all valves and relief devices;
- details of lifting points and lifting procedure.

4.2.3 Design loads

4.2.3.1 General

The transportable cryogenic vessel shall be able to withstand safely the mechanical and thermal loads and the chemical effects encountered during pressure test and normal operation.

4.2.3.2 Inner vessel

With the exception of a) the following loads shall be considered to act in combination where relevant:

- a) pressure test: The following value shall be used for validation purposes:

$$P_T \geq 1,3 (P_s + 1) \text{ bar} \quad (1)$$

where:

P_s is the maximum allowable working pressure, in bar;

The 1 bar is added to allow for the external vacuum.

- b) pressure during operation, P_C , where:

$$P_C = P_s + P_L + 1 \text{ bar}; \quad (2)$$

P_L is the pressure, in bars, exerted by the liquid contents when the vessel is filled to capacity and subject to dynamic load;

- c) reaction at the support points of the inner vessel due to the mass of the inner vessel and its contents when subject to dynamic load;
- d) 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:

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

4.2.3.3 Outer jacket

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

- a) an external pressure of 1 bar;
- 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 4.2.3.2 d);
- 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 4.3.8).

4.2.3.4 Inner vessel supports

The inner vessel supports shall be suitable for the load defined in 4.2.3.2 c) plus loads due to differential thermal movements.

4.2.3.5 Outer jacket supports

The outer jacket supports shall be suitable for the load defined in 4.2.3.3 f).

4.2.3.6 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 4.3.8).

4.2.3.7 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 4.3.8).

4.2.3.8 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.

4.2.3.9 Piping

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 allowable working pressure P_s plus one bar 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 4.2.3.2 d);
- d) dynamic loads;
- e) set pressure of thermal relief devices where applicable;
- f) loads generated during pressure relief discharge.

4.2.4 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.

4.2.5 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 will not occur.

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

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

4.2.6 Pressure relief

4.2.6.1 General

Relief devices for inner vessels shall be in accordance with the appropriate European Standards.

Relief devices for outer jackets shall be in accordance with annex D.

Systems shall be designed to meet the following requirements.

4.2.6.2 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;

NOTE Insulation performance evaluated as described in EN 12213 shall be sufficient to satisfy the holding time requirement of EN 1251-3.

- 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 allowable pressure for condition a) and in excess of the test pressure for condition b) or c).

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

Shut off valves or 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.

4.2.6.3 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 0,5 bar. The discharge area of the pressure relief device shall be not less than 0,34 mm²/l capacity of the inner vessel but not less than 10 mm diameter.

4.2.6.4 Piping

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

4.2.7 Valves

Valves shall be in accordance with EN 1626.

4.3 Design validation by calculation

4.3.1 General

When design validation is by calculation in accordance with 4.1.1 or 4.1.3, the dimensions of the inner vessel and outer jacket shall not be less than that determined in accordance with this sub-clause.

4.3.2 Inner vessel

4.3.2.1 Wall thickness

The following shall be used to determine the pressure part thicknesses in conjunction with the calculation formulae of 4.3.7.

The actual wall thickness shall be not less than shown in Table 1 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 A.

Table 1 — Inner vessel minimum wall thickness

Inner vessel diameter D (mm)	Minimum wall thickness s_0 for reference steel ¹⁾ (mm)
$D \leq 400$	1
$400 < D \leq 1\,800$	$1 + \frac{D - 400}{700}$

¹⁾ Reference steel material is material having a product $R_m A_5$ of 10 000.
For other materials calculate the minimum thickness using the following formula:

$$s = \frac{21,4s_0}{\sqrt[3]{R_m A_5}}$$

where:

R_m is the ultimate tensile strength, in Newtons per square millimetre;

A_5 is the elongation at fracture, in percent.

4.3.2.2 Design pressure p

The internal design pressure p shall be equal to P_T as defined in 4.2.3.2.

The inner vessel need not be designed for external pressure.

4.3.2.3 Material property K at 20 °C

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

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

K shall be the minimum value at 20 °C 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.

For austenitic stainless steel a strength value obtained in work hardened material may be used in the design provided this value and adequate ductility is maintained in the finished component.

4.3.2.4 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 $S_p = 2,1$

$$S_k = 2,6 + 0,0018 R / s$$

- knuckle region $S_p = 1,6$.

4.3.2.5 Weld joint factors v

For internal pressure (pressure on the concave surface) $v = 0,85$ or $1,0$ (see clause 6).

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

4.3.2.6 Allowances c

$$c = 0$$

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

4.3.3 Outer jacket

4.3.3.1 General

The following shall be used to determine the pressure part thicknesses in conjunction with the calculation formulae of 4.3.7.

The actual wall thickness shall be not less than shown in Table 2 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 A.

Table 2 — Outer jacket minimum wall thickness

Outer jacket diameter D (mm)	Minimum wall thickness s_0 for reference steel ¹⁾ (mm)
$D \leq 1\,800$	$0,5 + \frac{D}{1200}$
¹⁾ Reference steel material is material having a product $R_m A_5$ of 10 000. For other materials calculate the minimum thickness using the following formula: $s = \frac{21,4 s_0}{\sqrt[3]{R_m A_5}}$ where: R_m is the ultimate tensile strength, in Newtons per square millimetre; A_5 is the elongation at fracture, in percent.	

4.3.3.2 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 one bar.

4.3.3.3 Material property K at 20 °C

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 4.3.2.3;
- for carbon steel K = yield strength.

NOTE Upper yield strength may be used.

4.3.3.4 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 $S_p = 1,6$

$$S_k = 2,0 + 0,0014 R / s$$

— knuckle region $S_p = 1,2.$

4.3.3.5 Weld joint factors v

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

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

4.3.3.6 Allowances 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.

4.3.4 Supports, lifting points and frame

The supports and frame shall be designed for the loads defined in 4.2, 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.

4.3.5 Protective guards

External fittings shall be protected by a guard designed for the loads specified in 4.2.3.8. 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.

Some damage and deformation of the guard is acceptable provided that the integrity of the transportable cryogenic vessel and its safety systems is maintained with no leakage of fluid except for small quantities escaping from the safety devices protecting the inner vessel.

4.3.6 Piping

Piping shall be designed for the loads defined in 4.2.3.9 using established piping design methods and safety factors.

4.3.7 Calculation formulae

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

4.3.7.1.1 Scope

Cylindrical shells and spheres where

$$D_a / D_i \leq 1,2.$$

4.3.7.1.2 Openings

For weakening factor v due to openings see 4.3.7.7.

4.3.7.1.3 Calculation

The required minimum wall thickness s is

— for cylindrical shells

$$s = \frac{D_a p}{\frac{20Kv}{S} + p} + c \quad (3)$$

— for spherical shells

$$s = \frac{D_a p}{\frac{40Kv}{S} + p} + c \quad (4)$$

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

4.3.7.2.1 Scope

Cylindrical shells where

$$D_a / D_i \leq 1,2.$$

4.3.7.2.2 Openings

Openings shall be calculated in accordance with 4.3.7.7 using the external pressure as an internal pressure.

4.3.7.2.3 Calculation

Calculations shall be performed for elastic buckling and for plastic deformation. The lowest calculated pressure p_e or p_p shall not be less than the external design pressure.

The buckling length l_b is the length of the unsupported cylindrical shell (see Figures 1 and 2). Other forms of stiffening section may be used.

For vessels with dished ends, the buckling length starts at the junction of the cylinder and the knuckle region of the dished end (see Figure 3).

4.3.7.2.4 Plastic buckling

Calculations are performed using the following formula:

$$p_e = \frac{E}{S_k} \left(\frac{20}{(n^2 - 1) \left[1 + \left(\frac{n}{Z} \right)^2 \right]^2} \times \frac{s - c}{D_a} + \frac{80}{12(1 - \nu^2)} \left[n^2 - 1 + \frac{2n^2 - 1 - \nu}{1 + \left(\frac{n}{Z} \right)^2} \left[\frac{s - c}{D_a} \right]^3 \right] \right) \quad (5)$$

where $Z = 0,5\pi D_a / l_b$ and n is an integer equal to or greater than two and greater than Z , so determined that the value for p_e is a minimum. n denotes the number of lobes produced by the buckling process which

may occur at the circumference in the event of failure. The number of lobes can be estimated using the following approximation equation:

$$n = 1,63 \sqrt[4]{\frac{D_a^3}{l_b^2 (s - c)}} \quad (6)$$

For tubes and pipes, calculations may be performed using the following simplified formula:

$$p_e = \frac{E}{S_k} \times \frac{20}{1 - \nu^2} \left(\frac{s - c}{D_a} \right)^3 \quad (7)$$

4.3.7.2.5 Plastic deformation

When $D_a / l_b \leq 5$

$$p_p = \frac{20K}{S_p} \times \frac{s - c}{D_a} \times \frac{1}{1 + \frac{u(1 - 0,2 D_a / l_b) D_a}{100 (s - c)}} \quad (8)$$

When $D_a / l_b > 5$ the higher pressure obtained using equations (9) and (10) shall not be less than the external design pressure:

$$p_p = \frac{20K}{S_p} \times \frac{(s - c)}{D_a} \quad (9)$$

$$p_p = \frac{30K}{S_p} \left(\frac{s - c}{l_b} \right)^2 \quad (10)$$

4.3.7.2.6 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. The stiffening rings welded to the shell shall satisfy the following conditions:

$$I \geq \frac{0,124 p D_a^3}{10E} \sqrt{D_a (s - c)} \quad (11)$$

$$A \geq \frac{0,75 p D_a}{10K} \sqrt{D_a (s - c)} \quad (12)$$

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 must cover at least one third of the shell circumference and the number of weld discontinuities must be at least $2n$. The number of buckling lobes n is obtained as indicated in 4.3.7.2.4.

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

Spherical shells subject to external pressure shall be evaluated in accordance with 4.3.7.4.4.

4.3.7.4 Dished ends subject to internal or external pressure

4.3.7.4.1 Scope

Hemispherical ends where $D_a / D_i \leq 1,2$.

10 % torispherical ends where $R = 0,8D_a$ and $r = 0,1D_a$ and

2:1 torispherical ends where $R = 0,8D_a$ and $r = 0,154D_a$.

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

Other torispherical head shapes may be used provided suitable calculations are carried out in accordance with 4.3.8.

4.3.7.4.2 Straight flange

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

- for 10 % torispherical ends, 3,5 s
- for 2:1 torispherical ends, 3,0 s.

The straight flange may be shorter providing 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.

4.3.7.4.3 Internal pressure calculation (pressure on concave surface)

a) Crown and hemisphere thickness:

The wall thickness of the crown region of dished ends and of hemispherical ends shall be determined using 4.3.7.1.3 for spherical shells with $D_a = 2(R + s)$.

Openings within the crown area of $0,6D_a$ of torispherical ends and in hemispherical ends shall be reinforced in accordance with 4.3.7.7. When pad type reinforcement is used the edge of the pad shall not extend beyond the area of $0,8D_a$ for 10 % torispherical ends or $0,7D_a$ for 2:1 torispherical ends.

b) Torispherical end knuckle thickness and hemispherical end to shell junction thickness:

The required thickness of the knuckle region and hemispherical end junction shall be:

$$s = \frac{D_a p \beta}{40K_v} + c. \quad (13)$$

β is taken from Figure 6a for 10 % torispherical ends and from Figure 6b 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.

When there are opening outside the are $0,6D_a$ the required thickness is found from Figures 6a and 6b using the appropriate curve for the relevant value of d_i / D_a .

The lower curves of Figure 6a and 6b apply when there are no openings outside the area $0,6D_a$.

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

For hemispherical ends, a β value of 1,1 shall be applied within the distance x from the tangent line joining the end to the cylinder, regardless of the ratio, $(s-c)/D_a$, where

$$x = 0,5\sqrt{R(s-c)}.$$

4.3.7.4.4 External pressure calculations (pressure on the convex surface)

a) Elastic buckling:

There is adequate resistance to elastic buckling when:

$$p \geq 3,66 \frac{E}{S_k} \left(\frac{s-c}{R} \right)^2. \quad (14)$$

b) Plastic deformation:

Resistance to plastic deformation is determined by using 4.3.7.1 with the appropriate safety factor S_p defined in 4.3.2.4 and 4.3.3.4.

4.3.7.5 Cones subject to internal or external pressure

4.3.7.5.1 Symbols and units

For the purposes of 4.3.7.5, the following symbols apply in addition to those given in 3.2:

A	area of reinforcing ring, in square millimetres
D_{a1}	outside diameter of connected cylinder (Figure 7), in millimetres
D_{a2}	outside diameter at effective stiffening (Figure 9), in millimetres
D_k	design diameter (Figure 7), in millimetres
D_s	shell diameter at nozzle (Figure 8), in millimetres
I	moment of inertia about the axis parallel to the shell, in millimetres ⁴
l	cone length between effective stiffenings (Figure 9), in millimetres
s_g	required wall thickness outside corner area, in millimetres
s_l	required wall thickness within corner area, in millimetres
x_i	characteristic lengths ($i = 1,2,3$) to define corner area (Figure 11 and 4.3.7.5.5), in millimetres
φ	cone angle, in degrees

Cones according to Figure 7 where:

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

and

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

For external pressure $\varphi \leq 70^\circ$. Small ends with a knuckle can be safely assessed and verified as a small end with a corner joint.

4.3.7.5.3 Openings

Openings outside of the corner area (Figure 8) shall be designed as follows.

If $\varphi < 70^\circ$ design according to 4.3.7.7 using an equivalent cylinder diameter of

$$D_i = \frac{D_s + d_i \sin \varphi}{\cos \varphi}. \quad (15)$$

If $\varphi \geq 70^\circ$ design according to 4.3.7.6.

4.3.7.5.4 Non-destructive testing

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

4.3.7.5.5 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 7a and 7b by x_1 , x_2 , x_3 calculated from the following equations:

$$x_1 = \sqrt{D_{a1} (s_1 - c)} \quad (16)$$

$$x_2 = 0,7 \sqrt{\frac{D_{a1} (s_1 - c)}{\cos \varphi}} \quad (17)$$

$$x_3 = 0,5x_1. \quad (18)$$

4.3.7.5.6 Internal pressure calculation $\varphi \leq 70^\circ$ (pressure on concave surface)

a) Within corner area:

The required wall thickness (s_1) within the corner area as calculated from Figures 10.1 to 10.7 for the large end and Figure 10.8 for the small end of a cone using the following variables:

$$\varphi, \frac{pS}{15K_v} \text{ and } \frac{r}{D_{a1}}$$

shall be not less than the required wall thickness, s_g , outside the corner area as calculated in formula (19).

For a corner joint use the curve for $r / D_{a1} = 0$.

For intermediate cone angles (φ) use linear interpolation.

For intermediate values of r / D_{a1} the relevant interpolation equation stated in Figures 10.1 to 10.8 shall be used.

The wall thickness s_1 in the corner area shall not be less than the required thickness s_g outside of the corner area as calculated in formula (19).

b) Outside corner area:

The required wall thickness s_g outside the corner area is calculated from

$$s_g = \frac{D_k p}{20 \frac{K}{s} v - p} \times \frac{1}{\cos \varphi} + c \quad (19)$$

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 .

4.3.7.5.7 Internal pressure calculation $\varphi > 70^\circ$ (pressure on the concave surface)

If $r \geq 0,01 D_{a1}$ the required wall thickness is

$$s_1 = s_g = 0,3(D_{a1} - r) \times \frac{\varphi}{90} \sqrt{\frac{p}{10 \frac{K}{S} v}} + c \quad (20)$$

4.3.7.5.8 External pressure calculation (pressure on the convex surface)

Stability against elastic buckling and plastic deformation shall be verified using 4.3.7.2 and an equivalent cylinder.

For the example shown in Figure 9 the equivalent cylinder diameter between the knuckle and the stiffener is

$$D_a = \frac{D_{a1} + D_{a2}}{2 \cos \varphi} \quad (21)$$

and the equivalent cylinder length is

$$l = \frac{D_{a1} - D_{a2}}{2 \sin \varphi} \quad (22)$$

Depending on the relevant boundary conditions the equivalent length between two effective stiffening sections shall be reliably estimated within the meaning of 4.3.7.2.

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 φ or a stiffener shall be fitted with the following properties:

$$I \geq S_k \frac{p D_{a1}^4}{960E} \tan \varphi \quad (23)$$

$$A \geq S_k \frac{p D_{a1}^2}{80K} \tan \varphi \quad (24)$$

where:

S_k is the safety factor to prevent elastic buckling from 4.3.2.4 or 4.3.3.4;

D_{a1} is the diameter in accordance with Figure 7b.

The shell over a width of $0,5\sqrt{D_{a1}s_l}$ 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 4.3.7.5.6 above and the safety factors S from 4.3.2.4 or 4.3.3.4 increased by 20 %. For thicknesses in the corner area v shall be the value applicable for internal pressure.

4.3.7.6 Flat ends

4.3.7.6.1 Symbols and units

For the purposes of 4.3.7.6, the following symbols apply in addition to those given in 3.2:

d_1 , d_2 , etc., opening diameters in millimetres;

D_1 , D_2 , etc., flat end diameters in millimetres.

4.3.7.6.2 Scope

Welded or solid flat ends where:

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

and

$$\frac{(s-c)}{D} \leq \frac{1}{3}$$

and Poisson's ratio is approximately 0,3.

4.3.7.6.3 Openings

Openings are calculated in accordance with 4.3.7.6.4 but with the C factor multiplied by C_A . C_A is given in Figure 11.

4.3.7.6.4 Calculation

The required minimum wall thickness of a circular flat end is

$$s = CD_1 \sqrt{\frac{0,1pS}{K}} + c. \quad (25)$$

C and D_1 are taken from Figure 12.

The required minimum wall thickness of a rectangular or elliptical flat end is

$$s = CC_E f \sqrt{\frac{0,1pS}{K}} + c. \quad (26)$$

C_E is taken from Figure 13.

4.3.7.7 Openings in cylinders, spheres and cones

4.3.7.7.1 Symbols and units

For the purposes of 4.3.7.7, the following symbols apply in addition to those given in 3.2:

b	width of pad, ring or shell reinforcement, in millimetres
h	thickness of pad reinforcement, in millimetres
l	ligament (web) between two nozzles, in millimetres
l_s	length of nozzle reinforcement, in millimetres
m	protruding length, in millimetres
s_A	required wall thickness at opening edge, in millimetres
s_S	wall thickness of nozzle, in millimetres
t	in this context: centre-to-centre distance between two nozzles, in millimetres
v_A	compensation factor for the weakening effect of openings

4.3.7.7.2 Scope

Round openings and the reinforcement of round openings of unlimited diameter in cylindrical and spherical shells within the following limits:

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

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

NOTE 1 These rules only apply to cones if the wall thickness is determined by the circumferential stress.

NOTE 2 Additional external forces and moments are not covered by this section and need to be considered separately where necessary.

NOTE 3 These design rules permit plastic deformations of up to 1 % at highly stressed local areas during pressure test. Openings must therefore be carefully designed to avoid abrupt changes in geometry.

4.3.7.7.3 Reinforcement methods

Openings may be reinforced by one or more of the following methods:

- increase of shell thickness, see Figures 14 and 15;
- set in or set on ring reinforcement, see Figures 16 and 17;
- pad reinforcement, see Figure 18;
- increase of nozzle thickness, see Figures 19 and 20;
- pad and nozzle reinforcement, see Figure 21.

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

4.3.7.7.4 Design of openings

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

The critical dimensions 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 e) 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.

4.3.7.7.5 Calculation

a) The weakening factor v_A for nozzles perpendicular to the shell can be read with sufficient accuracy from Figures 22. The wall thickness s_A in these figures is the required wall thickness. s_A has to be determined by iteration.

Where the material property K of the reinforcement is lower than that of the shell the cross section of pad reinforcement and the thickness of nozzle reinforcement shall be reduced by the ratio of K values before determining the factor v_A .

When $v_A < v$ the value obtained from Figures 22 for individual nozzles or from formula (35) for multiple nozzles shall be used in place of v to determine the wall thickness s_A at the edge of the opening. v_A does not affect the required wall thickness away from the opening.

b) Openings can also be reinforced according to the following relationship:

$$\frac{p}{10} \left(\frac{A_p}{A_\sigma} + \frac{1}{2} \right) \leq \frac{K}{S} \quad (27)$$

which is based on equilibrium between the pressurized area A_p and the load bearing cross sectional area A_σ . The wall thickness obtained from this relationship must not be less than the thickness of the unpierced shell.

The pressurized area A_p and the load bearing cross sectional area A_σ , which equals $A_{\sigma 0} + A_{\sigma 1} + A_{\sigma 2}$, are obtained from Figures 23 to 26.

The maximum extent of the load bearing cross sectional area shall be not more than b as defined in formula (29) for shells and l_s as defined in formula (31) or (32) for nozzles.

The protrusion of a nozzle may be included as load bearing cross sectional area up to a maximum length of

$$l'_s = 0,5l_s.$$

The restrictions of 4.3.7.7.7 and 4.3.7.7.8 below shall be observed.

If the material property K_1 , K_2 , etc., of the reinforcing material is lower than that of the shell, the dimensions shall comply with

$$\left(\frac{K}{S} - \frac{p}{20}\right) A\sigma + \left(\frac{K_1}{S} - \frac{p}{20}\right) A\sigma_1 + \left(\frac{K_2}{S} - \frac{p}{20}\right) A\sigma_2 \leq \frac{p}{10} A_p. \quad (28)$$

The calculation method selected, i.e. a) or b), shall be indicated in the design documents.

4.3.7.7.6 Reinforcement by increased shell thickness

The weakening factor v_A of openings to Figures 14 and 15 shall be taken from the lower curve of Figures 22.

4.3.7.7.7 Ring or pad reinforcement

If the actual wall thickness of the cylinder or sphere is less than the required thickness s_A at the opening, the opening is adequately reinforced if the wall thickness s_A is available round the opening over a width of

$$b = \sqrt{(D_i + s_A - c)(s_A - c)} \quad (29)$$

with a minimum of $3s_A$, see Figures 16, 17 and 18.

The thickness of pad reinforcement to Figure 18 shall not be more than the actual wall thickness to which the pad is attached.

Internal pad reinforcement is not allowed.

For calculation purposes s_A shall be limited to not more than twice the actual wall thickness.

The width of the pad reinforcement may be reduced to b_1 provided the pad thickness is increased to h_1 according to

$$b_1 h_1 \geq b h \quad (30)$$

and the limits given above are observed.

4.3.7.7.8 Reinforcement by increased nozzle thickness

For reinforcement in accordance with Figures 19 and 20 the weakening factor v_A shall be taken from Figures 22 for the wall thickness ratio

$$\frac{s_S - c}{s_A - c}.$$

The wall thickness of protruding nozzles according to Figure 19 type (c) may be reduced by 20 % if the nozzle protrusion $m \geq s_S$.

The wall thickness ratio shall satisfy $\frac{s_S - c}{s_A - c}$.