Cryogenic vessels —
Large transportable non-vacuum insulated vessels —

Part 2: Design, fabrication, inspection and testing

The European Standard EN 14398-2:2003 has the status of a British Standard
National foreword

This British Standard was published by BSI. It is the UK implementation of EN 14398-2:2003, incorporating Corrigendum August 2006.

The start and finish of text introduced or altered by CEN corrigendum August 2006 is indicated in the text by tags \[ \text{[correction]} \].

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.

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

Amendments issued since publication

<table>
<thead>
<tr>
<th>Amd. No.</th>
<th>Date</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>16821</td>
<td>29 December 2006</td>
<td>See national foreword</td>
</tr>
<tr>
<td>Corrigendum No. 1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

© BSI 2006

ISBN 0 580 42564 9
Cryogenic vessels - Large transportable non-vacuum insulated vessels - Part 2: Design, fabrication, inspection and testing

This European Standard was approved by CEN on 10 July 2003.

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 Management Centre 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 Management Centre 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, Hungary, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Slovakia, Spain, Sweden, Switzerland and United Kingdom.
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreword</td>
<td>5</td>
</tr>
<tr>
<td>1 Scope</td>
<td>6</td>
</tr>
<tr>
<td>2 Normative references</td>
<td>6</td>
</tr>
<tr>
<td>3 Terms, definitions and symbols</td>
<td>7</td>
</tr>
<tr>
<td>3.1 Terms and definitions</td>
<td>7</td>
</tr>
<tr>
<td>3.2 Symbols</td>
<td>8</td>
</tr>
<tr>
<td>4 Design</td>
<td>9</td>
</tr>
<tr>
<td>4.1 Design options</td>
<td>9</td>
</tr>
<tr>
<td>4.1.1 General</td>
<td>9</td>
</tr>
<tr>
<td>4.1.2 Design by calculation</td>
<td>9</td>
</tr>
<tr>
<td>4.1.3 Design by calculation and pressure strengthening</td>
<td>9</td>
</tr>
<tr>
<td>4.1.4 Design by calculation supplemented with experimental methods</td>
<td>9</td>
</tr>
<tr>
<td>4.2 Common design requirements</td>
<td>10</td>
</tr>
<tr>
<td>4.2.1 General</td>
<td>10</td>
</tr>
<tr>
<td>4.2.2 Design specification</td>
<td>10</td>
</tr>
<tr>
<td>4.2.3 Design loads</td>
<td>11</td>
</tr>
<tr>
<td>4.2.4 Fatigue</td>
<td>13</td>
</tr>
<tr>
<td>4.2.5 Corrosion allowance</td>
<td>13</td>
</tr>
<tr>
<td>4.2.6 Inspection openings</td>
<td>13</td>
</tr>
<tr>
<td>4.2.7 Pressure relief</td>
<td>14</td>
</tr>
<tr>
<td>4.2.8 Valves</td>
<td>14</td>
</tr>
<tr>
<td>4.2.9 Insulation</td>
<td>14</td>
</tr>
<tr>
<td>4.2.10 Degree of filling</td>
<td>14</td>
</tr>
<tr>
<td>4.2.11 Electrical continuity</td>
<td>14</td>
</tr>
<tr>
<td>4.3 Design by calculation</td>
<td>15</td>
</tr>
<tr>
<td>4.3.1 General</td>
<td>15</td>
</tr>
<tr>
<td>4.3.2 Vessel</td>
<td>15</td>
</tr>
<tr>
<td>4.3.3 Attachments</td>
<td>17</td>
</tr>
<tr>
<td>4.3.4 Piping and accessories</td>
<td>18</td>
</tr>
<tr>
<td>4.3.5 Calculation formulae</td>
<td>18</td>
</tr>
<tr>
<td>4.3.6 Calculations for operating loads</td>
<td>26</td>
</tr>
<tr>
<td>5 Fabrication</td>
<td>52</td>
</tr>
<tr>
<td>5.1 General</td>
<td>52</td>
</tr>
<tr>
<td>5.2 Cutting</td>
<td>52</td>
</tr>
<tr>
<td>5.3 Cold forming</td>
<td>52</td>
</tr>
<tr>
<td>5.3.1 Austenitic stainless steel</td>
<td>52</td>
</tr>
<tr>
<td>5.3.2 Ferritic steel</td>
<td>52</td>
</tr>
<tr>
<td>5.4 Hot forming</td>
<td>53</td>
</tr>
<tr>
<td>5.4.1 General</td>
<td>53</td>
</tr>
<tr>
<td>5.4.2 Austenitic stainless steel</td>
<td>53</td>
</tr>
<tr>
<td>5.4.3 Ferritic steel</td>
<td>53</td>
</tr>
<tr>
<td>5.5 Manufacturing tolerances</td>
<td>53</td>
</tr>
<tr>
<td>5.5.1 Plate alignment</td>
<td>53</td>
</tr>
<tr>
<td>5.5.2 Thickness</td>
<td>55</td>
</tr>
<tr>
<td>5.5.3 Dished ends</td>
<td>55</td>
</tr>
<tr>
<td>5.5.4 Cylinders</td>
<td>55</td>
</tr>
<tr>
<td>5.6 Welding</td>
<td>58</td>
</tr>
<tr>
<td>5.6.1 General</td>
<td>58</td>
</tr>
<tr>
<td>5.6.2 Qualification</td>
<td>58</td>
</tr>
<tr>
<td>5.6.3 Temporary attachments</td>
<td>58</td>
</tr>
<tr>
<td>5.6.4 Welded joints</td>
<td>58</td>
</tr>
<tr>
<td>5.7 Non-welded joints</td>
<td>59</td>
</tr>
</tbody>
</table>
6 Inspection and testing
6.1 Quality plan
6.1.1 Inspection stages during manufacture of a vessel
6.1.2 Additional inspection stages during manufacture of a large transportable cryogenic vessel
6.2 Production control test plates
6.2.1 Requirements
6.2.2 Extent of testing
6.3 Non-destructive testing
6.3.1 General
6.3.2 Extent of examination for surface imperfections
6.3.3 Extent of examination for volumetric imperfections
6.3.4 Acceptance levels
6.4 Rectification
6.5 Pressure testing

Annex A (informative) Elastic stress analysis
A.1 General
A.2 Terminology
A.2.1 Stress intensity
A.2.2 Gross structural discontinuity
A.2.3 Local structural discontinuity
A.2.4 Normal stress
A.2.5 Shear stress
A.2.6 Membrane stress
A.2.7 Primary stress
A.2.8 Primary local membrane stress
A.2.9 Secondary stress
A.2.10 Peak stress
A.3 Limit for longitudinal compressive general membrane stress
A.4 Stress categories and stress limits for general application
A.4.1 General
A.4.2 General primary membrane stress category
A.4.3 Local primary membrane stress category
A.4.4 General or local primary membrane plus primary bending stress category
A.4.5 Primary plus secondary stress category
A.4.6 Thermal stress
A.5 Specific criteria, stress categories and stress limits for limited application
A.5.1 General
A.5.2 Attachments and supports
A.5.3 Nozzles and openings
A.5.4 Additional stress limits

Annex B (normative) Additional requirements for 9 % Ni steel
B.1 Introduction
B.2 Specific requirements

Annex C (normative) Pressure strengthening of vessels from austenitic stainless steels
C.1 Introduction
C.2 Scope
C.3 Definitions and units of measurement
C.4 Materials
C.5 Design
C.5.1 General
C.5.2 Design for internal pressure
C.6 Manufacturing and inspection
C.6.1 Strengthening procedure
C.6.2 Procedure record
C.6.3 Welding
C.6.4 Pressure vessel drawing
C.6.5 Data plate
C.7 Comments
C.7.1 Strengthening theory
C.7.2 Work-hardened material
C.7.3 Derivation of formulae
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.7.4 Deformations at strengthening</td>
<td>85</td>
</tr>
<tr>
<td>Annex D (informative) Specific weld details</td>
<td>88</td>
</tr>
<tr>
<td>D.1 Field of application</td>
<td>88</td>
</tr>
<tr>
<td>D.2 Weld detail</td>
<td>88</td>
</tr>
<tr>
<td>D.2.1 Joggle joint</td>
<td>88</td>
</tr>
<tr>
<td>D.2.2 Intermediate ends</td>
<td>88</td>
</tr>
<tr>
<td>D.2.3 Backing strip</td>
<td>89</td>
</tr>
<tr>
<td>D.2.4 End plate closure</td>
<td>89</td>
</tr>
<tr>
<td>D.2.5 Non full penetration nozzle weld</td>
<td>89</td>
</tr>
<tr>
<td>D.2.6 Non continuous fillet weld on attachments</td>
<td>89</td>
</tr>
<tr>
<td>D.3 Oxygen service requirements</td>
<td>89</td>
</tr>
<tr>
<td>Annex E (normative) Increased material property for austenitic stainless steel</td>
<td>92</td>
</tr>
<tr>
<td>Bibliography</td>
<td>93</td>
</tr>
</tbody>
</table>
Foreword

This document (EN 14398-2:2003) 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 February 2004, and conflicting national standards shall be withdrawn at the latest by February 2004.

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association, and supports the objectives of the framework Directives on Transport of Dangerous Goods.

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.

EN 14398 consists of the following parts under the general title, Cryogenic vessels – Large transportable non-vacuum insulated vessels:

– Part 1: Fundamental requirements
– Part 2: Design, fabrication, inspection and testing
– Part 3: Operational requirements

Annexes A, D and E are informative. Annexes B and C are normative.

This document includes a Bibliography.

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, Hungary, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom.
1 Scope

This European Standard specifies requirements for the design, fabrication, inspection and testing of large transportable non vacuum insulated cryogenic vessels of more than 1000 l volume, which are permanently (fixed tanks) or not permanently (demountable tanks) attached to a vehicle, for carriage by road. However, it can be used for other mode of transport providing the specific regulations/requirements are complied with.

This European Standard applies to large transportable non vacuum insulated cryogenic vessels for fluids specified in EN 14398-1 and does not apply to vessels designed for toxic fluids.

This European Standard does not include the general vehicle requirements e.g. running gear, brakes, lighting etc. that shall be in accordance with the relevant standards/regulations.

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 (including amendments).

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

EN 473, Non destructive testing - Qualification and certification of NDT personnel - General principles.

EN 875, Destructive tests on welds in metallic materials - Impact tests - Test specimen location, notch orientation and examination.

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

EN 910, Destructive tests on welds in metallic materials – Bend tests.


EN 1418, Welding personnel – Approval testing of welding operators for fusion welding and resistance weld setters for fully mechanised 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 1797, Cryogenic vessels - Gas/material compatibility.

EN 10028-4, Flat products made of steels for pressure purposes – Part 4 : Nickel alloy steels with specified low temperature properties.
EN 10028-7:2000, Flat products made of steels for pressure purposes - Part 7: Stainless steels.

EN 13068-3, Non-destructive testing – Radioscopic testing – Part 3: General principles of radioscopic testing of metallic materials by X- and gamma rays.

EN 13445-3, Unfired pressure vessels – Part 3: Design.

EN 13648-3, Cryogenic vessels - Safety devices for protection against excessive pressure - Part 3: Determination of required discharge - Capacity and sizing.

EN 14398-1:2003, Cryogenic vessels - Large transportable non-vacuum insulated vessels - Part 1: Fundamental requirements.

EN 14398-3, Cryogenic vessels – Large Transportable non-vacuum insulated vessels – Part 3 Operational requirements.


ISO 1106-1, Recommended practice for radiographic examination of fusion welded joints - Part 1: Fusion welded butt joints in steel plates up to 50 mm thick.

3 Terms, definitions and symbols

For the purposes of this European Standard, the following terms, definitions and symbols apply.

3.1 Terms and definitions

For the purposes of this European Standard, the terms and definitions given in EN 14398-1:2003 and the following apply.

3.1.1 large transportable non vacuum insulated vessel
vessel of more than 1000 l volume intended for one or more cryogenic fluids, consisting of an inner vessel, an insulation, all of the valves and accessories and additional framework

3.1.2 fixed tank (tank vehicle)
large transportable vessel permanently attached to a vehicle or to units of running gear used in its stead

3.1.3 demountable tank
large transportable vessel non permanently attached to a vehicle. When attached to the carrier vehicle, the demountable tank meets the requirements prescribed for a fixed tank. It is designed to be lifted only when empty

3.1.4 inner vessel
pressure vessel proper intended to contain the cryogenic fluid

3.1.5 insulation
to protect the vessel against heat transfer from the outside atmospheric temperature

3.1.6 automatic welding
welding in which the parameters are automatically controlled. Some of these parameters can be adjusted to a limited extent, either manually or automatically, during welding to maintain the specified welding conditions
3.1.7 maximum allowable pressure, \( p_s \)
maximum pressure for which the equipment is designed, as specified by the manufacturer, defined at a location specified by the manufacturer, being the location of connection of protecting or limited devices or the top of the equipment.

3.1.8 relief plate/plug
plate or plug retained by atmospheric pressure only which allows relief of excess internal pressure.

3.1.9 bursting disc device
non-reclosing pressure relief device ruptured by differential pressure. It is the complete assembly of installed components including where appropriate the bursting disc holder.

3.2 Symbols
For the purposes of this European Standard, the following symbols apply.

- \( c \): allowance for corrosion (mm)
- \( d_i \): diameter of opening (mm)
- \( d_a \): outside diameter of tube or nozzle (mm)
- \( f \): narrow side of rectangular or elliptical plate (mm)
- \( l_b, l'_b \): buckling length (mm)
- \( n \): number of lobes (-)
- \( p \): design pressure as defined in 4.3.2.2 (bar)
- \( p_e \): allowable external pressure limited by elastic buckling (bar)
- \( p_s \): strengthening pressure (bar)
- \( p_o \): allowable external pressure limited by plastic deformation (bar)
- \( p_T \): pressure test (see 4.2.3.2) (bar)
- \( r \): radius e.g. inside knuckle radius of dished end and cones (mm)
- \( s \): minimum thickness (mm)
- \( s_e \): actual wall thickness (mm)
- \( v \): factor indicative of the utilisation of the permissible design stress in joints or factor allowing for weakenings (-)
- \( x \): (decay-length zone) distance over which governing stress is assumed to act (mm)
- \( A \): cross sectional area of reinforcing element (mm\(^2\))
- \( C, \beta \): design factors (-)
- \( D \): shell diameter (mm)
- \( D_a \): outside diameter e.g. of a cylindrical shell (mm)
4 Design

4.1 Design options

4.1.1 General

The design shall be carried out in accordance with one of the options given in 4.1.2, 4.1.3 or 4.1.4.

Metallic materials used at cryogenic temperatures shall meet the requirements of the relevant sections of EN 1252-1 or EN 1252-2.

In the case of 9 % Ni steel, the additional requirements of annex B shall be satisfied.

For carbon and low alloy steels the requirements of EN 1252-2 shall be satisfied.

4.1.2 Design by calculation

Calculation of all pressure and load bearing components shall be carried out. The pressure part thicknesses of the vessel shall not be less than required by 4.3. Additional calculations may be required to ensure the design is satisfactory for the operating conditions including an allowance for dynamic loads.

4.1.3 Design by calculation and pressure strengthening

The pressure retaining capability of vessels manufactured from austenitic stainless steel, strengthened by pressure, shall be calculated in accordance with annex C.

4.1.4 Design by calculation supplemented with experimental methods

Where it is not possible to design by calculation alone planned and controlled experimental means may be used providing that the results confirm the safety factors required in 4.3. An example would be the application of strain gauges to assess stress levels.

---

$D_i$  internal diameter e.g. of a cylindrical shell  mm

$E$  Young's modulus  N/mm$^2$

$I$  moment of inertia of reinforcing element  mm$^4$

$R_e$  apparent yield stress or 0.2 % proof stress (1 % proof stress for austenitic steel)  N/mm$^2$

$R_m$  minimum tensile strength (actual or guaranteed)  N/mm$^2$

$K$  material property used for design  N/mm$^2$

$R$  radius of curvature e.g. inside crown radius of dished end  mm

$S$  safety factor at design pressure, in relation with $R_e$

$S_k$  safety factor against elastic buckling at design pressure

$S_p$  safety factor against plastic deformation

$Z$  auxiliary value

$v$  Poisson's ratio

$u$  out of roundness
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 option used.

In the event of an increase in at least one of the following parameters:

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

or, in the event of any change relative:

- to the type of material or grade (e.g. stainless steel to aluminium);
- 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 insulation or the vessel itself or the protective frame, if any, are concerned;

the initial design programme shall be repeated to take account of these modifications.

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;
- dimensions and allowable weight, taking characteristics of the vehicle into account;
- location of fastening points and loads allowable on these points;
- filling and emptying rate;
- range of ambient temperature, if differing from 7.2 of EN 14398-1:2003.

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

- definition of which components are designed by calculation, by pressure strengthening, by experiment and by satisfactory in service experience;
- 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;
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 test programme;
- non destructive testing requirements;
- pressure test requirements;
- piping configuration including type, size and location of all valves and relief devices;
- details of fastenings.

4.2.3 Design loads

4.2.3.1 General

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

In considering design loads during transport, static loads shall be substituted for static plus dynamic loads. The static loads used shall be as follows:

- in the direction of travel: twice the total mass;
- at right angles to the direction of travel: the total mass;
- vertically upwards: the total mass;
- vertically downwards: twice the total mass.

Each of these loads is considered to act in isolation and includes the mass of the component under consideration.

4.2.3.2 Vessel

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

a) test pressure: the value used for validation purposes shall be:

\[ p_t \geq 1.3 p_s \text{ bar} \]  \hspace{1cm} (1)

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

\( p_s \) is the maximum allowable pressure, in bar.

The vessel shall be capable of holding the pressure test fluid without plastic deformation.

b) pressure during operation, \( p_C \), where:

\[ p_C = p_s + p_L \]  \hspace{1cm} (2)

\( p_L \) is the pressure, in bars, exerted by the mass of the liquid contents when the vessel is filled to capacity and subject to each load defined in 4.2.3.1, with either:

1) boiling liquid at minimum allowable temperature
2) cryogenic fluid at its equilibrium triple point or melting point temperature;
c) reaction at the support points of the vessel due to the mass of the vessel and its contents when subject to each of the loads defined in 4.2.3.1;

d) load imposed by the piping due to the differential thermal movement of the vessel, the piping and the insulation.

The following cases shall be considered:

- cooldown (vessel warm - piping cold);
- filling and withdrawal (vessel cold - piping cold); and
- transport and storage (vessel cold - piping warm);

e) load imposed on the vessel at its support points when cooling from ambient to operating temperature and during operation.

4.2.3.3 Self supporting vessels

In the case of vehicles in which the vessel constitute stressed self-supporting members of the vehicle, these shall be designed to withstand the stresses thus imposed in addition to stresses from other sources, (see 4.2.3.2 c).

4.2.3.4 Vessel supports

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

4.2.3.5 Surge plates

The vessel shall be divided by surge plates to provide stability and limit dynamic loads to the requirements of 4.2.3, unless it is to be filled equal to or more than 80% of its capacity or nominally empty. The cross sectional area of the surge plate shall be at least 70% of that of the vessel.

Current experience with surge plates limiting the capacity to 7500 l has been shown to meet these requirements.

Surge plates and their attachments to the shell shall be designed to resist the stresses caused by a pressure evenly distributed across the area of the surge plate. The pressure is calculated by considering the mass of liquid between the plates decelerating at 2 g (4.2.3).

4.2.3.6 Fastening points

Fastening points shall be suitable for fastening the large transportable cryogenic vessel to the vehicle when filled to capacity and subject to each of the loads defined in 4.2.3.

4.2.3.7 Protection of upper fittings

The fittings and accessories mounted on the upper part of the vessel shall be protected in such a way that damage caused by overturning cannot impair operational integrity. This protection may take the form of strengthening rings, protective canopies or transverse or longitudinal members so shaped that effective protection is given.
4.2.3.8 Stability

The overall width of the ground-level bearing surface (distance between the outer points of contact with the ground of the right-hand tyre and the left-hand tyre of the same axle) shall be at least equal to 90 % of the height of the centre of gravity of the fully laden tank-vehicle. In an articulated vehicle the mass on the axles of the load-carrying unit of the laden semi-trailer shall not exceed 60 % of the nominal total laden mass of the complete articulated vehicle.

4.2.3.9 Piping and valves

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

a) pneumatic pressure test : not less than the allowable working pressure \( p_s \);
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.

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

The leakproofness of this equipment shall be ensured in the event of overturning of the vehicle. The gaskets shall be made of a material compatible with the fluid carried, in accordance with EN 1797.

Each bottom-filling or bottom-discharge opening shall be provided with at least two independent shut-off devices in series, the first being a stop valve provided with protection against mechanical damage.

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

4.2.4 Fatigue

The design shall take into account the effect of cyclic stress on the inner vessel, outer jacket and their attachments during normal conditions of operation.

When considering the case of fatigue, the common requirement of dimensioning with loads according to 4.2.3 will be such as to accommodate the effects of fatigue. Particular attention may be necessary to specific details in the supports and piping systems to avoid stress raisers.

4.2.5 Corrosion allowance

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

4.2.6 Inspection openings

Inspection openings are not required in the vessel, providing the requirements of EN 14398–3 are followed.

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

Relief systems shall be designed to meet the requirements given in 4.2.7.1 and 4.2.7.2.

4.2.7.1 Vessel

The vessel shall be provided with not less than two independent pressure relief devices at least one of which shall be a relief valve, and shall open at no more than $p_s$. The devices may be mounted on a common line.

A device shall protect the vessel against excess pressure due to:

a) normal heat leak,

and the devices acting together shall protect the vessel against excess pressure due to:

b) heat leak with loss of insulation

c) heat leak, without loss of insulation, and the pressure build up system being in the open position.

d) recycling of any possible combination of pumps

Excess pressure means a pressure in excess of 110% of the maximum allowable pressure for condition a) + d) and in excess of the test pressure for condition b) and in excess of the test pressure for condition c).

Relief devices for the vessel shall be in accordance with EN 13648-3 for calculation of sizing.

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

4.2.7.2 Piping

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

4.2.8 Valves

Valves shall conform to EN 1626.

4.2.9 Insulation

To protect the vessel against heat transfer from the outside atmospheric temperature. The insulation consists of a material with low heat transfer values of a certain thickness, which protects the cold liquid content of the vessel from quick increase of the pressure.

The insulation shall be covered by an outside cladding, to protect the insulation against collection of humidity or water and against damage.

The insulation material can be polyurethane foam (injected or moulded as formed plates), etc.

4.2.10 Degree of filling

The degree of filling of large transportable non 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 95% of the vessel’s capacity at that temperature. Large transportable non vacuum insulated vessels may be filled with non-flammable gases to 98% of its total volume at the loading temperature and the loading pressure.

Means shall be provided to ensure that the above limits are not exceeded.
4.2.11 Electrical continuity

All metallic components of large transportable non vacuum insulated vessels intended for the carriage of flammable gases shall be electrically continuous. The large transportable non vacuum insulated vessels shall be provided with the means of attachment to earthing devices so that the resistance to the earthing connection is less than 5 ohms. Any metal contact capable of causing electrochemical corrosion shall be avoided.

4.3 Design by calculation

4.3.1 General

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

4.3.2 Vessel

4.3.2.1 General

The information in 4.3.2.2 to 4.3.2.6 shall be used to determine the pressure part thicknesses in conjunction with the calculation formulae of 4.3.5.

The actual wall thickness shall be not less than shown in Table 1.
Table 1 —vessel minimum wall thickness

<table>
<thead>
<tr>
<th>Diameter D, in millimetres</th>
<th>Minimum wall thickness ( s_0 ), in millimetres for reference steel (^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D \leq 1800 )</td>
<td>3</td>
</tr>
<tr>
<td>( 1800 &lt; D )</td>
<td>4</td>
</tr>
</tbody>
</table>

\(^a\) Reference steel means a steel with a tensile strength of 370 N/mm\(^2\) and an elongation at fracture of 27 %.

For other materials calculate the minimum thickness using the following formula:

\[
S = \frac{464 \times s_0}{\sqrt[3]{(R_m \times A_s)^2}}
\]

where

- \( R_m \) is the minimum tensile strength of the metal chosen, in Newtons per square millimetre at a temperature not lower than the saturation temperature of the fluid at pressure \( p_s \);
- \( A_s \) is the elongation at fracture of the metal chosen, in per cent at the same temperature.

The minimum thickness shall however not be less than the minimum wall thickness defined in chapter 6.8 of the technical annexes of the ADR when other materials are used.

Under these conditions, the reference steel equivalent thickness of the vessel can be determined as follows:

\[
s = s_e \frac{\sqrt[3]{(R_m \times A_s)^2}}{464}
\]

where

\( s_e \) is the actual wall thickness of the inner vessel.

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

### 4.3.2.2 Design pressure \( p \)

The internal design pressure \( p \) shall be the greater of \( p_T \) as defined in 4.2.3.2 a) or \( p_C \) as defined in 4.2.3.2 b) corrected for operating conditions (i.e. times \( K_{20} \)) to take into account the cold properties of the material used. It follows that \( K_{20} \) shall be used in the subsequent formulae where \( p \) is shown as the design pressure.

The vessel shall be able to withstand, without permanent deformation, an external pressure of not less than 40 kPa (0.4 bar) above the internal pressure.

### 4.3.2.3 Material properties \( K \)

#### 4.3.2.3.1 General

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

- for austenitic stainless steels, \( R_e = 1 \) % proof strength ;
- for carbon steels aluminium and aluminium alloys, \( R_e = \) yield strength and if not available 0.2 % proof strength ;
- for carbon steels the upper yield strength may be used.
For calculation purposes the material property $K$ of the inner vessel shall be limited to 2/3 of $R_m$ the minimum guaranteed tensile strength.

4.3.2.3 $K_{20}$

$R_e$ and $R_m$ shall be the minimum guaranteed values at 20 °C taken from the material standard (see annex E).

Ratios of $R_e/R_m$ exceeding 0.85 are not allowed for steels in the construction of welded tanks. In determining the ratio $R_e/R_m$, the minimum specified value of $R_e$ and $R_m$ in the material inspection certificate shall be used.

4.3.2.3.3 $K_t$

The permissible values of $R_e$ and $R_m$ shall be determined for the material at the operating temperature corresponding to a temperature not lower than the saturation temperature of the fluid at pressure $p_s$. The values of $R_e$, $R_m$ and $E$ shall be determined from the appropriate material standard (see EN 10028-7:2000 annex F for austenitic stainless steels) or shall be guaranteed by the material manufacturer.

4.3.2.3.4 Brittleness

The material shall not be subject to brittle fracture at its minimum operating temperature, see EN 1252-1 and EN 1252-2.

4.3.2.3.5 Elongation

For steel, the elongation at fracture in % shall be not less than

$$\frac{10000}{\text{determined tensile strength in N/mm}^2} \text{ at } 20 \ °C$$

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

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

4.3.2.4 Safety factors $S$, $S_p$ and $S_k$

Safety factors are the ratio of material property $K$ over the maximum allowable stress.

$$S = 1.33$$

4.3.2.5 Weld joint factor $v$

In all cases $v = 1$ shall be used including circumferential seams with permanent backing strip and circumferential joggle joint.

4.3.2.6 Corrosion allowances $c$

$$c = 0$$

No corrosion allowance is required.

4.3.3 Attachments

For those items attached to the vessel, the allowable stress shall not exceed the lower of 0.75 $R_e$ or 0.5 $R_m$.

When designing the vessel systems, the temperature and corresponding mechanical properties to be used may be those of the component in question when the vessel is filled to capacity with cryogenic fluid at a temperature not lower than the saturation temperature at pressure $p_s$. 
4.3.4 Piping and accessories

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

4.3.5 Calculation formulae

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

4.3.5.1.1 Field of application

Cylindrical shells and spheres where:

\[ \frac{D_a}{D_i} \leq 1.2 \]

4.3.5.1.2 Openings

For reinforcement of openings, see 4.3.5.5.

4.3.5.1.3 Calculation

The required minimum wall thickness \( s \) is:

- for cylindrical shells:

\[
s = \frac{D_a p}{20 \frac{K}{S} v + p} + c \tag{5}
\]

- for spherical shells:

\[
s = \frac{D_a p}{40 \frac{K}{S} v + p} + c \tag{6}
\]

4.3.5.2 Dished ends subject to internal pressure

4.3.5.2.1 Field of application

Following calculations the thickness of the dished ends shall not be less than the thickness of the cylindrical shell.

Hemispherical ends where

\[ \frac{D_a}{D_i} \leq 1.2 \]

10 % torispherical ends where

\[ R = D_a \text{ and } r = 0.1 D_a \]

and

2:1 torispherical ends where

\[ R = 0.8 D_a \text{ and } r = 0.154 D_a \]

In the case of torispherical ends

\[ 0.001 \leq (s-c)/D_a \leq 0.1 \]

NOTE Other end shapes can be used provided suitable calculations are carried out.
4.3.5.2.2 Internal pressure calculation (pressure on concave surface)

4.3.5.2.2.1 Crown and hemisphere thickness

The wall thickness of the crown region of dished ends and of hemispherical ends shall be determined using 4.3.5.1.3 for spherical shells with \( D_a = 2 (R + s) \).

Opening within the crown area of 0.6 \( D_a \) of torispherical ends and in hemispherical ends shall be reinforced in accordance with 4.3.5.5. 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.

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

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

- for the vessel:
  \[
  s = \frac{D_a p \beta}{40 \frac{K_{20}}{S} v} \quad (7)
  \]

\( \beta \) is taken from Figure 5 for 10 % torispherical ends and from Figure 6 for 2:1 torispherical ends as a function of \((s-c)/D_a\). Iteration is necessary.

For hemispherical ends a \( \beta \) 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 \( x = 0.5 \sqrt{R (s-c)} \)

\( D_a \) is the diameter of the end as shown in Figure 4 a) and 4 b).

When there are openings outside the area 0.6 \( D_a \) the required thickness is found from Figures 5 and 6 using the appropriate curve for the relevant value of \( d_i/D_a \).

The lower curves of Figures 5 and 6 apply when there are no openings outside the area 0.6 \( D_a \).

4.3.5.2.2.3 If a dished end is welded together from crown and knuckle components, the joint shall be at a sufficient distance \( x \) from the knuckle. The distance regarded as sufficient is as follows, but with a minimum, however, of at least 100 mm (see Figure 4 c)):

- crown and knuckle are of different wall thickness:
  \[
  x = 0.5 \sqrt{R (s-c)} \quad (8)
  \]
  where \( s \) is the required wall thickness of the knuckle:

- the crown and knuckle are of equal wall thickness:
  - for 10 % torispherical ends \( x = 3.5 s \);
  - for 2:1 torispherical ends \( x = 3.0 s \).

\( v = 1.0 \) may be applied, if the scope of testing corresponds to that specified for a design stress level equal to the permissible design stress level or in the case of one-piece ends.

\( v = 1.0 \) may also be applied in the case of welded domed ends - except hemispherical ends - regardless of the scope of testing provided the weld intersects the crown area of 0.6 \( D_a \), see Figures 4 e) and 4 f) (left-hand side).
4.3.5.2.2.4 If the ligament on the connecting line between adjacent openings is not entirely within the 0,6 \( D_a \) region the ligament shall not be less than half the sum of the opening diameters. See also 4.3.5.5.9.

4.3.5.3 Cones subject to internal pressure

4.3.5.3.1 Symbols and units

For the purposes of 4.3.5.3, the following symbols apply in addition to those given in 3.2:

- \( A \) : area of reinforcing ring \( \text{mm}^2 \)
- \( D_{a1} \) : outside diameter of connected cylinder (see Figure 7) \( \text{mm} \)
- \( D_{a2} \) : outside diameter at effective stiffening (see Figure 9) \( \text{mm} \)
- \( D_k \) : design diameter (see Figure 7) \( \text{mm} \)
- \( D_S \) : shell diameter at nozzle (see Figure 8) \( \text{mm} \)
- \( I \) : moment of inertia about the axis parallel to the shell \( \text{mm}^4 \)
- \( l \) : cone length between effective stiffenings (see Figure 9) \( \text{mm} \)
- \( s_g \) : required wall thickness outside corner area \( \text{mm} \)
- \( s_i \) : required wall thickness within corner area \( \text{mm} \)
- \( x_i \) : characteristic lengths \((i=1,2,3)\) to define corner area (Figures 7 a) and 7 b) and 4.3.5.3.5) \( \text{mm} \)
- \( \varphi \) : cone angle \( \circ \)
- \( r \) : inside radius of knuckle \( \text{mm} \)

4.3.5.3.2 Field of application

Cones according to Figure 7 where:

\[
0,001 \leq \frac{s_g - \ell}{D_{a1}} \leq 0,1
\]

and

\[
0,001 \leq \frac{s_i - \ell}{D_{a1}} \leq 0,1
\]

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

For external pressure \(|\varphi| \leq 70^\circ\).

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

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

- if $|\varphi| < 70^\circ$ design according to 4.3.5.5 using an equivalent cylinder diameter of:

$$D_s = \frac{D_s + d_1 |\sin \varphi|}{\cos \varphi}$$  \hspace{1cm} (9)

- if $|\varphi| \geq 70^\circ$ design according to 4.3.5.4.

4.3.5.3.4 Non destructive testing

All corner joints shall be subject to the examination required for a weld joint factor of 1.0, see Table 6.

4.3.5.3.5 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:

$$x_1 = \sqrt{D_{a1}(s_1 - c)}$$  \hspace{1cm} (10)

$$x_2 = 0.7 \sqrt{\frac{D_{a1}(s_1 - c)}{\cos \varphi}}$$  \hspace{1cm} (11)

$$x_3 = 0.5 x_1$$  \hspace{1cm} (12)

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

a) within corner area

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

$$\varphi, \quad \frac{p s}{15K \nu} \quad \text{and} \quad \frac{r}{D_{a1}}$$

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

For intermediate cone angles use linear interpolation.

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 follows:

b) outside corner area

The required wall thickness, $s_g$, outside the corner area is calculated from:
EN 14398-2:2003 (E)

\[ s_g = \frac{D_k p}{20K_s v - p} \times \frac{1}{\cos \varphi} + c \]  
(13)

where

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

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

**4.3.5.3.7 Internal pressure calculation (pressure on the concave surface) \(|\varphi| > 70^\circ\)**

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

\[ s_i = s_g = 0,3(D_{a1} - r) \times \frac{|\varphi|}{90} \times \sqrt{\frac{p}{10(\frac{K}{S})v}} + c \]  
(14)

**4.3.5.4 Flat ends**

**4.3.5.4.1 Symbols and units**

For the purposes of 4.3.5.4, the following symbols apply in addition to those given in 3.2:

- \( d_1, d_2 \) etc. opening diameters in mm;
- \( D_1 \), flat end diameters in mm. As shown in Figure 12.

**4.3.5.4.2 Field of application**

Welded or solid flat ends where Poisson's ratio is approximately 0,3, and:

\( \left( \frac{s-e}{D_1} \right) \leq \sqrt{\frac{0,0087p}{E}} \)

and

\( 3 \left( \frac{s_e - c}{D_1} \right) \leq 1 \)

**4.3.5.4.3 Openings**

Openings are calculated in accordance with 4.3.5.4.4 but with the \( C \) factor multiplied by \( C_A \), where \( C_A \) is given in Figure 11.

**4.3.5.4.4 Calculation**

The required minimum wall thickness of a circular flat end is:

\[ s = CD_1 \sqrt{\frac{0,1pS}{K} + c} \]  
(15)

\( C \) and \( D_1 \) are taken from Figure 12.
The required minimum wall thickness of a rectangular or elliptical flat end is:

\[ s = C_E \sqrt{\frac{0.1pS}{K}} + c \] (16)

where \( C_E \) is taken from Figure 13.

### 4.3.5.5 Openings in cylinders, spheres and cones

#### 4.3.5.5.1 Symbols and units

For the purposes of 4.3.5.5, the following symbols apply in addition to those given in 3.2:

- \( b \): width of pad, ring or shell reinforcement, mm
- \( h \): thickness of pad-reinforcement, mm
- \( l \): ligament (web) between two nozzles, mm
- \( l_s \): length of nozzle reinforcement outstandings, mm
- \( s \): length of nozzle reinforcement instand, mm
- \( s_A \): required wall thickness at opening edge, mm
- \( s_S \): wall thickness of nozzle, mm
- \( t \): in this context: centre-to-centre distance between two nozzles, mm

#### 4.3.5.5.2 Field of application

Round openings and the reinforcement of round openings in cylinders, spheres and cones within the following limits:

\[ 0.002 \leq \frac{(s - c)}{D_a} \leq 0.1 \]

\[ \frac{(s - c)}{D_a} < 0.002 \text{ is acceptable if } \frac{d_i}{D_a} \leq \frac{1}{3} \]

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

**NOTE 1** Additional external forces and moments are not covered by this subclause and should be considered separately where necessary.

**NOTE 2** These design rules permit plastic deformations of up to 1% at highly stressed local areas during pressure test. Openings should therefore be carefully designed to avoid abrupt changes in geometry.

The design rules for non perpendicular nozzles shall be based on a perpendicular nozzle, using the dimension of the major elliptical axis or shall be calculated in accordance with EN 13445-3.

#### 4.3.5.5.3 Reinforcement methods

Openings may be reinforced by one or more of the following typical but not exclusive 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 the space between the two fillet welds shall be vented to the outside of the vessel.

### 4.3.5.5.4 Design of openings

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

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

Where the strength of the reinforcing material is lower than the strength of the shell material an allowance in accordance with 4.3.5.5.5 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.

### 4.3.5.5.5 Calculation

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 $\frac{A_p}{A_\sigma}$.

In the case of a shell subjected only to internal pressure, with a row of nozzles joined to the shell by fully penetrating welds, it is not necessary to calculate the individual reinforcement required for each nozzle. However the thickness of the shell to resist internal pressure shall be calculated using the least value of weakening factor of either $\frac{A_p}{A_\sigma}$ obtained from equation (34) or $v$.

Openings shall also be reinforced according to the following relationship:

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

which is based on equilibrium between the pressurised area $A_p$ and the load bearing cross sectional area $A_\sigma$. The wall thickness obtained from this relationship shall be not less than the thickness of the unpierced shell.

The pressurized area $A_p$ and the load bearing cross sectional area $A_\sigma$ which equals $A_{\sigma_0} + A_{\sigma_1} + A_{\sigma_2}$ are obtained from Figures 22 to 25.

The maximum extent of the load bearing cross sectional area shall be not more than $b$ as defined in formula (20) for shells and $l_s$ as defined in formulae (22) or (23) for nozzles, as appropriate.

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

$$l_s' = 0.5 l_s$$

The restrictions of 4.3.5.5.7 and 4.3.5.5.8 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:

$$\left( \frac{K}{S} - \frac{p}{20} \right) A_{\sigma_0} + \left( \frac{K_1}{S} - \frac{p}{20} \right) A_{\sigma_1} + \left( \frac{K_2}{S} - \frac{p}{20} \right) A_{\sigma_2} \geq \frac{p}{10} A_p$$
4.3.5.5.6 Ring or pad reinforcement or increased shell thickness

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:

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

(20)

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

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

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

Internal pad reinforcement is not allowed.

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

$$b_1 \times h_1 \geq b \times h$$

(21)

and the limits given above are observed.

4.3.5.5.7 Reinforcement by increased nozzle thickness

For calculation purposes $s_S$ shall be not more than twice $s_A$.

The thickness of the nozzle $s_S$ should be not greater than twice $s_A$.

The wall thickness $s_A$ at the opening shall extend over a width $b$ in accordance with formula (20) with a minimum of $3 s_A$.

The limits of reinforcement normal to the vessel well are:

- for cylinders and cones, $l_s = 1.25 \sqrt{(d_i + s_s - c)(s_s - c)}$

(22)

- for spheres, $l_s = \sqrt{(d_i + s_s - c)(s_s - c)}$

(23)

The length $l_s$ may be reduced to $l_{s1}$ provided that the thickness $s_s$ is increased to $s_{s1}$ according to the following:

$$l_{s1} \times s_{s1} \geq l_s \times s_s$$

(24)

and the limits given above are observed.

4.3.5.5.8 Reinforcement by a combination of increased shell and nozzle thicknesses

Shell and nozzle thicknesses may be increased in combination for the reinforcement of openings (Figure 21). For the calculation of reinforcement 4.3.5.5.6 and 4.3.5.5.7 shall be applied together. The increase in shell thickness may be achieved by an actual increase in shell thickness or the addition of a pad.

4.3.5.5.9 Multiple openings

Multiple openings are regarded as single openings provided the distance $l$ between two adjacent openings, Figures 24 and 26, complies with:
If \( l \) is less than required by formula (25) a check shall be made to determine whether the cross section between openings is able to withstand the load acting on it. Adequate reinforcement is available if the requirement of formula (17) or (19), as appropriate is met.

Where adjacent openings in a cylinder are arranged intermediately between the longitudinal and circumferential direction the calculation scheme for the longitudinal direction (Figure 24) shall be applied, but the part of the pressure loaded area corresponding to the unpierced cylinder \( \left( \frac{D_i}{2} \right) \) may be reduced with an arrangement factor \(-0.5 \left(1 + \cos^2 \varphi \right)\).

See Figure 25) for angle \( \varphi \).

Nozzles joined to the shell in line by full penetration welds with the wall thickness calculated for internal pressure only may be designed with a weakening factor

\[
\nu_A = \frac{(t-d_i)}{2}
\]

If the nozzles are not attached by full penetration welds, \( d_i \) shall be used in formula (26).

4.3.6 Calculations for operating loads

Unless the design has been validated by experiment, calculations in addition to those in 4.3.5 may be required to ensure that stresses due to operating loads are within acceptable limits. All load conditions expected during service shall be considered (see 4.2.3).

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

The analysis shall take account of gross structural discontinuities, but need not consider local stress concentrations.

Annex A provides terminology and acceptable stress limits when an elastic stress analysis is performed.

Acceptable calculation methods include:

- finite element;
- finite difference;
- boundary element;
- recognised text books, published papers, codes and standards.

Planned and controlled experimental means may be used in order to confirm these calculations, for example, by application of strain gauges to verify stress levels.
- For design of cylindrical shell:
  \[ l_b = \text{maximum of } l_{b1}, l_{b2}, l_{b3}, l_{b4}. \]

- For design of reinforcing elements:
  \[ l'_b = \frac{l_{b1} + l_{b2}}{2} \]

**Figure 1** — Example of joining stiffening ring to shell

**Figure 2** — Determination of buckling length
\[ h/e_a \leq 16 \]

\[ h/e_a \leq 50 \]
\[ b \leq e_a + \frac{0.55 \sqrt{D_a \cdot e_s}}{} \]
\[ b \leq e_a + 16 \cdot e_s \]

**Figure 3a)**

**Figure 3b)**

**Figure 3c)**

**Figure 3d)**
\[ \frac{h}{e_a} \leq 50 \]
\[ b \leq 1.1 \sqrt{D_a \cdot e_s} \]
\[ b \leq 1.1 \sqrt{D_a \,(s - c)} \]

Figure 3e)

\[ x_1 \leq \min \left\{ 0.55 \sqrt{D_a \,(s - c)} \, ; \, \frac{l_{b1}}{2} \right\} \]
\[ x_2 \leq \min \left\{ 0.55 \sqrt{D_a \,(s - c)} \, ; \, \frac{l_{b2}}{2} \right\} \]

\textit{L} is the portion of the shell which acts as part of the reinforcing element and contribute to its effective moment of inertia.

Figure 3 — Determination of reinforcing elements
Figure 4a) — Unpierced dished end

Figure 4b) — Dished end with nozzle

Figure 4c) — End with knuckle and crown of unequal wall thickness
Figure 4d) — Weld outside 0.6 \( D_a \)

Figure 4e) — Weld inside 0.6 \( D_a \)

Figure 4f) — End welded together from round plate and segments

Figure 4
Figure 5 — Design factors $\beta$ for 10% torispherical dished ends

Figure 6 — Design factors $\beta$ for 2:1 torispherical dished ends
Figure 7a) — Geometry of convergent conical shells

Figure 7b) — Geometry of a divergent conical shell

Figure 7
Figure 8 — Geometry of a cone opening

Figure 9 — Geometrical quantities in the case of loading by external pressure
Figure 10.1 — Permissible value $\frac{pS}{15\,kV}$ for convergent cone with an opening angle $\varphi = 10^\circ$
Figure 10.2 — Permissible value $\frac{pS}{15kV}$ for convergent cone with an opening angle $\varphi = 20^\circ$
Figure 10.3 — Permissible value $\frac{pS}{15Kv}$ for convergent cone with an opening angle $\varphi = 30^\circ$
Figure 10.4 — Permissible value \( \frac{pS}{15kV} \) for convergent cone with an opening angle \( \varphi = 40^\circ \)
Figure 10.5 — Permissible value $v_{15} K$ for convergent cone with an opening angle $\varphi = 50^\circ$
Figure 10.6 — Permissible value $\frac{pS}{15\,kV}$ for convergent cone with an opening angle $\varphi = 60^\circ$. 

\begin{align*}
A_{11} &= +1.8694396440 \\
A_{21} &= +1.3659163860 \\
A_{31} &= -0.0648173574 \\
A_{41} &= -0.0057345617 \\
A_{12} &= +0.0553080284 \\
A_{22} &= -0.0511260440 \\
A_{32} &= +0.3015922949 \\
A_{42} &= +0.0090201886
\end{align*}
Figure 10.7 — Permissible value \( \frac{pS}{15Kv} \) for convergent cone with an opening angle \( \varphi = 70^\circ \)
Figure 10.8 — Permissible value $\frac{pS}{15KV}$ for convergent cone (corner joint) with an opening angle $\varphi = 10^\circ$ to $70^\circ$
Key
1 Opening factor $C_A$
2 Ratio $d_i/D_i$ resp. $d_i/f$

**Type A**
- $d =$ inside diameter of opening
- $D_i =$ design diameter
- $f =$ short side of elliptical end

$$C_A = \begin{cases} 
\sum_{i=1}^{6} A_i \left( \frac{d_i}{D_i} \right)^{-1} & 0 < \left( \frac{d_i}{D_i} \right) \leq 0.8 \\
\sum_{i=1}^{6} A_i \left( \frac{d_i}{f} \right)^{-1} & 0 < \left( \frac{d_i}{f} \right) \leq 0.8 
\end{cases}$$

$A_1 = 0.999\,034\,20$
$A_2 = 1.980\,626\,00$
$A_3 = 9.018\,554\,00$
$A_4 = 18.632\,830\,00$
$A_5 = 19.497\,590\,00$
$A_6 = 7.612\,568\,00$

**Type B**
- $d =$ inside diameter of opening
- $D_i =$ design diameter
- $f =$ short side of elliptical end

$$C_A = \begin{cases} 
\sum_{i=1}^{6} A_i \left( \frac{d_i}{D_i} \right)^{-1} & 0 < \left( \frac{d_i}{D_i} \right) \leq 0.8 \\
\sum_{i=1}^{6} A_i \left( \frac{d_i}{f} \right)^{-1} & 0 < \left( \frac{d_i}{f} \right) \leq 0.8 
\end{cases}$$

$A_1 = 1.001\,003\,44$
$A_2 = 0.944\,284\,68$
$A_3 = 4.312\,102\,00$
$A_4 = 8.389\,435\,00$
$A_5 = 9.206\,283\,84$
$A_6 = 3.694\,941\,96$

**Figure 11** — Opening factor $CA$ for flat ends and plates without additional marginal moment
### Type of flat end design (principle only)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Design factor C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a) flat end</td>
</tr>
<tr>
<td>1. knuckle radius:</td>
<td>$D_a$</td>
</tr>
<tr>
<td>$r_{min}$</td>
<td>up to 500</td>
</tr>
<tr>
<td></td>
<td>over 500 up to 1400</td>
</tr>
<tr>
<td></td>
<td>over 1400 up to 1600</td>
</tr>
<tr>
<td></td>
<td>over 1600 up to 1900</td>
</tr>
<tr>
<td></td>
<td>over 1900</td>
</tr>
<tr>
<td>and $r \geq 1.3 \ s$</td>
<td></td>
</tr>
<tr>
<td>2. cylindrical part:</td>
<td>$h \geq 3.5 \times \ s$</td>
</tr>
<tr>
<td></td>
<td>b) forged or pressed flat end</td>
</tr>
<tr>
<td>1. knuckle radius:</td>
<td>$\frac{r}{3}$, however at least 8 mm</td>
</tr>
<tr>
<td>2. cylindrical part:</td>
<td>$h \geq s$</td>
</tr>
<tr>
<td></td>
<td>c) flat plate welded into the shell from one side only</td>
</tr>
<tr>
<td>plate thickness:</td>
<td>$s \leq 3 \ s_1$</td>
</tr>
<tr>
<td></td>
<td>$s &gt; 3 \ s_1$</td>
</tr>
<tr>
<td></td>
<td>d) plate welded into the shell with welds at both sides of the latter</td>
</tr>
<tr>
<td>plate thickness:</td>
<td>$s \leq 3 \ s_1$</td>
</tr>
<tr>
<td></td>
<td>$s &gt; 3 \ s_1$</td>
</tr>
<tr>
<td>Only killed steels may be utilised. When plate material is employed, over an area of at least $3 \ s_1$ in the weld zone there shall be no evidence of material discontinuities in the plate.</td>
<td></td>
</tr>
</tbody>
</table>
Figure 12 — Design factors for unstayed circular flat ends and plates
Key
1 Rectangle
2 Ellipse
Y Design factor $C_e$
X Ratio $f/e$

Rectangular plates
$f = \text{short side of the rectangular plate}$
$e = \text{long side of the rectangular plate}$

Elliptical plates
$f = \text{short side of the elliptical plate}$
$e = \text{long side of the elliptical plate}$

$$C_e = \begin{cases} 
\sum_{i=1}^{4} A_i \left( \frac{f}{e} \right)^{i-1} & 0 < \left( \frac{f}{e} \right) \leq 0.1 \\
1.562 & 0.1 < \left( \frac{f}{e} \right) \leq 1.0 
\end{cases}$$

$$C_e = \begin{cases} 
\sum_{i=1}^{4} A_i \left( \frac{f}{e} \right)^{i-1} & 0.43 < \left( \frac{f}{e} \right) \leq 1.0 
\end{cases}$$

$A_1 = 1.589 \ 146 \ 00$
$A_2 = -0.239 \ 349 \ 90$
$A_3 = -0.335 \ 179 \ 80$
$A_4 = 0.085 \ 211 \ 76$

Figure 13 — Design factor $C_e$ for rectangular or elliptical flat plates
Figure 14 — Increased thickness of a cylindrical shell

Figure 15 — Increased thickness of a conical shell

Figure 16 — Set-on reinforcement ring

Figure 17 — Set-in reinforcement ring

Figure 18 — Pad reinforcement
Figure 19 — Nozzle reinforcement

Figure 20 — Necked out opening
Figure 21 — Pad

Type a) Type b)

Figure 22 — Calculation scheme for cylindrical shells
Figure 23 — Calculation scheme for spherical shells

Figure 24 — Calculation scheme for adjacent nozzles in a sphere or in a longitudinal direction of a cylinder
Key
1 Longitudinal direction
2 Circumferential direction

Figure 25 — Openings between longitudinal and circumferential direction

Figure 26 — Calculation scheme for adjacent nozzles in a sphere or in a circumferential direction of a cylinder
5 Fabrication

5.1 General

5.1.1 The manufacturer or his or her sub-contractor, shall have equipment available to ensure manufacture and testing in accordance with the design.

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

5.2 Cutting

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

5.3 Cold forming

5.3.1 Austenitic stainless steel

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

a) for operating temperatures down to –196 °C: the test certificate for the base material shows an elongation at fracture $A_5$ of not less than 30 % and the cold forming deformation is not more than 15 % or it is demonstrable that the residual elongation is not less than 15 %;

b) for operating temperatures below –196 °C: the cold forming deformation is greater than or equal to 15 % and it is demonstrated that the residual elongation is not less than 15 %;

c) for formed heads, the test certificate for the base material shows an elongation at fracture $A_5$:
- not less than 40 % in the case of wall thicknesses not more than 15 mm at design temperatures down to –196 °C;
- not less than 45 % in the case of wall thicknesses more than 15 mm at design temperatures down to –196 °C;
- not less than 50 % at design temperatures below –196 °C.

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

Cold forming deformation can be calculated according to EN 13445-4.

5.3.2 Ferritic steel

Requirements for post forming heat treatment are:

a) 9 % Ni steel requires post forming heat treatment where cold forming deformation exceeds 5 %. Fully certified quenched and tempered or double normalised and tempered 9 % Ni steel shall be stress relieved at 560 °C to 580 °C. Forming and stress relieving may be performed in several stages. A test piece taken from the parent material that accompanies the formed part through all stages of heat treatment shall be tested after all heat treatment is complete to demonstrate that the material mechanical properties conform to the requirements of the material standard;
b) for the following ferritic steels used for the inner vessel, post forming heat treatment is not required where the forming deformation is not more than 5%:

1) nickel alloyed steels, suitable for low temperature use;

2) carbon and carbon-manganese steels:
   - where \( R_m \leq 530 \text{ N/mm}^2 \)
   - or where \( 530 < R_m \leq 650 \text{ N/mm}^2 \) and \( R_{0.002} \leq 360 \text{ N/mm}^2 \)

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

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

5.4 Hot forming

5.4.1 General

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

5.4.2 Austenitic stainless steel

Material shall be heated uniformly in an appropriate atmosphere without flame impingement, to a temperature not exceeding the recommended hot forming temperature of the material. When forming is carried out after the temperature of the material has fallen below 900 °C the requirements of 5.3.1 shall be complied with.

5.4.3 Ferritic steel

Requirements for post forming heat treatment are:

a) 9 % Ni steel that is hot formed shall be double normalised and tempered or quenched and tempered in accordance with the material standard to establish the material properties specified therein. Test piece(s) shall be provided and tested in accordance with the material standard;

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

5.5 Manufacturing tolerances

5.5.1 Plate alignment

Except where a tapered transition is provided, misalignment of the surfaces of adjacent plates at welded seams shall be:
— for longitudinal seams, not more than 15 % of the thickness of the thinner plate up to a maximum of 3 mm;
— for circumferential seams, not more than 25 % of the thickness of the thinner plate up to a maximum of 5 mm.

Where a taper is provided between the surfaces, this shall have a slope of not more than 30°. The taper may include the width of the weld, the lower surface being built up with added weld metal if necessary. Where material is removed from a plate to provide a taper, the thickness of either plate shall not be reduced below that required for the design.

The distance between either surface of the thicker plate and the centre line of the thinner plate of tapered seams shall be:
— for longitudinal seams, not less than 35 % of the thickness of the thinner plate;
— for circumferential seams, not less than 25 % of the thickness of the thinner plate.

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

These requirements are illustrated in Figure 27.

Nomenclature

\[ h, h_1, h_2 = \text{surface misalignments} \]
\[ t = \text{thickness of the thinner plate} \]
\[ e = \text{distance from the surface of the thicker plate to the centreline of the thinner plate} \]

For longitudinal seams: \( h_1 \leq 0,15 \ t \) and \( h_2 \leq 0,15 \ t \)

For circumferential seams: \( h_1 \leq 0,25 \ t \) and \( h_2 \leq 0,25 \ t \)

**Figure 27a** — Seam which do not require a taper
For longitudinal seams:

\[ h \leq 0.15 \, t \text{ and } e = \frac{t}{2} - h \geq 0.35 \, t \]

For circumferential seams:

\[ h \leq 0.25 \, t \text{ and } e = \frac{t}{2} - h \geq 0.25 \, t \]

Figure 27b) — Seams which do require a taper

Figure 27 — Plate alignment

5.5.2 Thickness

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

5.5.3 Dished ends

The depth of the dishing, excluding the straight flange, shall not be less than the theoretical depth. The knuckle radius shall not be less than specified and the crown radius shall not be greater than specified. Any variation of the profile shall not be abrupt but shall merge gradually into the specified shape.

5.5.4 Cylinders

5.5.4.1 The actual circumference shall not deviate from the circumference calculated from the specified diameter by more than \( \pm 1.5 \% \).

5.5.4.2 The out of roundness \( u \) calculated from the expression:

\[
\text{out of roundness } u = \frac{200(D_{\text{max}} - D_{\text{min}})}{D_{\text{max}} + D_{\text{min}}} \%
\]  (27)
shall be not more than the values shown in Table 2.

### Table 2 — Permitted out of roundness

<table>
<thead>
<tr>
<th>Wall thickness to diameter ratio</th>
<th>Permitted out of roundness for</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>internal pressure</td>
</tr>
<tr>
<td>$s/D = 0.01$</td>
<td>2.0 %</td>
</tr>
<tr>
<td>$s/D &gt; 0.01$</td>
<td>1.5 %</td>
</tr>
</tbody>
</table>

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

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

Definitions:

\[ u = 2 \times \left( \frac{D_{\text{max}} - D_{\text{min}}}{D_{\text{max}} + D_{\text{min}}} \right) \times 100 \]

\[ u \text{ equivalent to } \frac{4}{D_a} \times q \times 100 \]

Limitations:

\[ u \leq 15 \% \]

\[ q \leq 0.00375 \ D_a \]

**Figure 28 — Allowable shape imperfections**

Furthermore, where irregularity in the profile occurs at the welded seam and is associated with “flats” adjacent to the weld the irregularity in profile or “peaking” shall not exceed the values given in Table 3.
A conservative method of measurement (covering peaking and ovality) shall be by means of a 20° profile gauge (or template).

The use of such a profile gauge is illustrated in Figure 29. Two readings shall be taken, \( P_1 \) and \( P_2 \) on each side of the seam, at any particular location, the maximum peaking is taken as being equivalent to \( 0.25(P_1 + P_2) \).

![Figure 29 — Gauge details](image_url)

Measurements should be taken at approximately 250 mm intervals on longitudinal seams to determine the location with the maximum peaking value. Use of other types of gauges such as bridge gauges or needle gauges are not prohibited. The maximum peaking value permitted is given in Table 3.
Table 3 — Maximum permitted peaking

<table>
<thead>
<tr>
<th>Vessel ratio wall thickness $s/D$ to diameter $D$</th>
<th>Maximum permitted peaking</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s/D \leq 0.025$</td>
<td>5</td>
</tr>
<tr>
<td>$s/D &gt; 0.025$</td>
<td>10</td>
</tr>
</tbody>
</table>

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

5.5.4.3 Departure of the cylinder axis from a straight line shall be not more than 0.5 % of the cylindrical length, except where required by the design.

5.6 Welding

5.6.1 General

This European Standard requires that the welding method be appropriate and be carried out by qualified welders and/or operators, that the materials be compatible and that there is verification by a welding procedure test.

5.6.2 Qualification

Welding procedures shall be approved in accordance with EN 288-4, EN 288-8 or with EN 1418 as applicable.

Welders and welding operators shall be qualified accordance with EN 287-1 or EN 287-2 or to EN 1418 as applicable.

5.6.3 Temporary attachments

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

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

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

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

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

5.6.4 Welded joints

5.6.4.1 Some specific weld details appropriate to vessels conforming to EN 14398 are given in annex D. These details show sound and currently accepted practice. It is not intended that these are mandatory nor should they restrict the development of welding technology in any way.

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

- the method of manufacture;
- the service conditions;
- the ability to carry out necessary non-destructive testing.
Weld details may be used provided their suitability is proven by procedure approval according to EN 288-3, EN 288-4 or EN 288-8 as applicable.

5.6.4.2 Where any part of a vessel is made in two or more courses, the longitudinal weld seams of adjacent courses shall be staggered. A minimum of 100 mm is recommended. Joggle joints and backing strips may be used for circumferencial welds only plate thickness up to 8 mm.

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

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

See also B.2.7, B.2.8, B.2.10 and B.2.11.

5.7 Non-welded joints

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

6 Inspection and testing

6.1 Quality plan

A quality plan forming part of the quality system referred to in 5.1.1 shall include as a minimum, the inspection and testing stages listed in 6.1.1.

6.1.1 Inspection stages during manufacture of a vessel

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

- verification of material test certificates and correlation with materials;
- approval of weld procedure qualification records;
- approval of welders qualification records;
- examination of material cut edges;
- examination of set up of seams for welding including dimensional check;
- examination of weld preparations, tack welds;
- visual examination of welds;
- verification of non-destructive testing;
- testing production control test plates for welds and, where required, for formed parts after heat treatment;
- verification of cleaning of inside surface of vessel;
6.1.2 Additional inspection stages during manufacture of a large transportable cryogenic vessel

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

- verification of cleanliness and dryness of the cryogenic vessel (see EN 12300);
- visual examination of welds not covered by 6.1.1;
- check name plate and any other specified markings;
- examination of completed vessel including dimensional check.

6.2 Production control test plates

6.2.1 Requirements

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

a) one test plate per vessel for each welding procedure on longitudinal joints;

b) after 10 sequential test plates to the same procedure have successfully passed the tests, testing may be reduced to one test plate per 50 m of longitudinal joint for 9 % Ni and ferritic steels and to one test plate per 100 m for other metals.

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

The results of the tests shall be as follows:

- weld tensile test \((T)\) : \(R_{e,t}, R_m, \text{and } A_5\) of the test specimens shall normally not be less than the corresponding specified minimum values for the parent metal, or the agreed values of the welding procedure approved;
- impact test \((IW, IH)\) : this test shall be performed in accordance with EN 1252-1 or EN 1252-2;
- bend test \((BF, BR, BS)\) : the testing and the test requirements shall comply with 7.4.2 of EN 288-3:1992 for steels;
- macro etch \((Ma)\) : the macro etch shall show sound build-up of beads and sound penetration.

6.2.2 Extent of testing

The number and type of test specimens to be taken from the test plate is dependent on material and thickness and shall be in accordance with the requirements in Tables 5 and 6 for the particular material and thickness applicable.

NOTE The symbols for Table 5 are given in Table 4.

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

Prior to cutting the test piece non destructive testing of the test plate may be applied in order that the test specimens are taken from sound areas.
### Table 4 — Test specimens

<table>
<thead>
<tr>
<th>Designation</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face bend test to EN 910</td>
<td>BF</td>
</tr>
<tr>
<td>Root bend test to EN 910</td>
<td>BR</td>
</tr>
<tr>
<td>Side bend test to EN 910</td>
<td>BS</td>
</tr>
<tr>
<td>Tensile test to EN 895</td>
<td>T</td>
</tr>
<tr>
<td>Impact test; weld deposit to EN 875</td>
<td>IW</td>
</tr>
<tr>
<td>Impact test; HAZ to EN 875</td>
<td>IH</td>
</tr>
<tr>
<td>Macro etch</td>
<td>Ma</td>
</tr>
</tbody>
</table>

### Table 5 — Testing of production test plates for steels

<table>
<thead>
<tr>
<th>Group</th>
<th>$\varepsilon$ in mm</th>
<th>Test specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine grain steels normalised or thermo mechanically treated</td>
<td>$\varepsilon \leq 12$</td>
<td>1 BF, 1 BR, 1 T, 1 Ma</td>
</tr>
<tr>
<td></td>
<td>$12 &lt; \varepsilon \leq 35$</td>
<td>3 IW, 3 IH, 1 T, 1 Ma</td>
</tr>
<tr>
<td>Ni steels up to 9% Ni</td>
<td>$\varepsilon \leq 12$</td>
<td>1 BF, 1 BR, 1 T, 1 Ma</td>
</tr>
<tr>
<td></td>
<td>$12 &lt; \varepsilon$</td>
<td>3 IW, 3 IH, 1 T, 1 Ma</td>
</tr>
<tr>
<td>Austenitic stainless steels</td>
<td>$\varepsilon \leq 12$</td>
<td>1 BF, 1 BR, 1 T, 1 Ma</td>
</tr>
<tr>
<td></td>
<td>$12 &lt; \varepsilon$</td>
<td>3 IW, 1 T, 1 Ma</td>
</tr>
</tbody>
</table>

### 6.3 Non-destructive testing

#### 6.3.1 General

Non-destructive testing personnel shall be qualified for the duties according to EN 473.

X-ray examination shall be carried out in accordance with EN 1435 or ISO 1106-1. Radioscopy may also be used and shall be carried out in accordance with EN 13068-3.

#### 6.3.2 Extent of examination for surface imperfections

Visual examination (if necessary aided by x 5 lens) shall be carried out on all weld deposits. See Table 8 for acceptance levels. If any doubt arises, this examination shall be supplemented by surface crack detection.

Arc strike contact points and areas from which temporary attachments have been removed shall be ground smooth and subjected to surface crack detection.

#### 6.3.3 Extent of examination for volumetric imperfections

Examination of the vessel for volumetric imperfections shall be by radiographic examination unless a special case is made to justify ultra-sonic or other methods. The extent of examination of main seams on the inner vessel shall be in accordance with Table 6. See Table 8 for acceptance levels.

When hemispherical ends without a straight flange are welded together or to a cylinder, the weld shall be tested as a longitudinal weld. Any welds within an hemispherical end shall also be tested as longitudinal welds.
Table 6 — Extent of radiographic examination for welded seams of the inner vessel

<table>
<thead>
<tr>
<th>Longitudinal seams</th>
<th>T junctions</th>
<th>Circumferential seams</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 %</td>
<td>100 %</td>
<td>100 %</td>
</tr>
</tbody>
</table>

NOTE 1 For additional requirements for 9 % Ni steel use annex B.
NOTE 2 Additional testing can be required when pneumatic proof testing is used.

6.3.4 Acceptance levels

6.3.4.1 Acceptance levels for surface imperfections

Table 7 shows the acceptance criteria for surface imperfections.

Table 7 — Acceptance levels for surface imperfections

<table>
<thead>
<tr>
<th>Imperfection</th>
<th>EN ISO 6520-1 reference</th>
<th>Limit for acceptable imperfection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of penetration</td>
<td>402</td>
<td>Not permitted</td>
</tr>
</tbody>
</table>
| Undercut                     | 5011                     | Where the thickness is less than 3 mm no visible undercut is permitted.  
                               |                          | Where the thickness is not less than 3 mm, slight and intermittent undercut is acceptable, provided that it is not sharp and is not more than 0.5 mm. |
| Shrinkage groove             | 5013                     | As undercut                       |
| Root concavity               | 515                      | As undercut                       |
| Excessive penetration        | 504                      | Where the thickness is less than 5 mm, excessive penetration shall be not more than 2 mm.  
                               |                          | Where the thickness is not less than 5 mm, excessive penetration shall not be more than 3 mm. |
| Excess weld material         | 502                      | Where the thickness is less than 5 mm, excess weld metal shall not be greater than 2 mm and the weld shall blend smoothly.  
                               |                          | Where the thickness is 5 mm or greater, the maximum excess weld metal shall not exceed 3 mm and the weld shall blend smoothly. |
| Irregular surface            | 514                      | Reinforcement to be of continuous and regular shape with complete filling of groove. |
| Sagging                      | 509                      |                                  |
| Incompletely filled groove   | 511                      |                                  |
| Irregular width              | 513                      |                                  |
| Poor restart                 | 517                      |                                  |
| Overlap                      | 506                      | Not permitted                     |
| Linear misalignment          | 507                      | See 5.5.1                         |
| Arc strike                   | 601                      | Grind smooth, acceptable subject to thickness measurement and surface crack detection test. |
| Spatter                      | 602                      |                                  |
| Tungsten spatter             | 6021                     |                                  |
| Torn surface                 | 603                      |                                  |
| Grinding mark                | 604                      |                                  |
| Chipping mark                | 605                      |                                  |
| Surface cracks               |                          | Not permitted                     |
6.3.4.2 Acceptance levels for internal volumetric imperfections

Table 8 shows the acceptance criteria for internal volumetric imperfections detected by radiographic examination.

<table>
<thead>
<tr>
<th>Imperfection</th>
<th>EN ISO 6520-1 reference</th>
<th>Limit for acceptable imperfection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracks and lack of sidewall fusion</td>
<td>4011</td>
<td>Not permitted</td>
</tr>
<tr>
<td>Incomplete root fusion</td>
<td>4013</td>
<td>Not permitted</td>
</tr>
<tr>
<td>Flat root concavity</td>
<td>4009</td>
<td>Acceptable if full weld depth is at least equal to the wall thickness and the depth of the concavity is less than 10 % of the wall thickness.</td>
</tr>
<tr>
<td>Inclusions (including oxide in aluminium welds). Strings of pores, worm holes parallel to the surface and strings of tungsten.</td>
<td>303, 304, 2014, 2015</td>
<td>30 % of thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The maximum length shall be the greater of 7 mm or 2/3 t.</td>
</tr>
<tr>
<td>Intermixed fusion defects and root defects in multipass weld</td>
<td>4012</td>
<td>As inclusions</td>
</tr>
<tr>
<td>Multiple in-line inclusions</td>
<td></td>
<td>Collectively the total length shall not be greater than the thickness in any length of 6 times the thickness. The gap between inclusions shall be greater than twice the length of the larger inclusion.</td>
</tr>
<tr>
<td>Area of general porosity visible on a film</td>
<td>2011</td>
<td>Acceptable if less than 2 % of projected area of weld</td>
</tr>
<tr>
<td>Individual pores</td>
<td>2011</td>
<td>Acceptable if diameter is less than 25 % of the thickness with a maximum of 4 mm</td>
</tr>
<tr>
<td>Worm holes perpendicular to the surface</td>
<td>2021</td>
<td>Where the thickness is less than 10 mm, worm holes are not permitted.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where the thickness is not less than 10 mm, isolated examples are acceptable provided the depth is estimated to be not more than 30 % of the thickness.</td>
</tr>
<tr>
<td>Tungsten inclusions</td>
<td>3041</td>
<td>Where the thickness is less than 12 mm, tungsten inclusions are acceptable provided the length is not more than 3 mm.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where the thickness is not less than 12 mm, tungsten inclusions are acceptable provided the length is not more than 25 % of the thickness.</td>
</tr>
</tbody>
</table>

6.3.4.3 Extent of examination of non-welded joints

Where non-welded joints are used between metallic materials and/or non-metallic materials, the quality plan referred to in 6.1 shall include reference to an adequate technical specification.

This technical specification shall include the description of the requirements for inspection and testing, together with the criteria necessary to allow for the repair of any imperfections.

6.4 Rectification

Although unacceptable volumetric or surface imperfections may be repaired by removing the imperfections and rewelding, 100 % of all repaired welds shall be examined to the original acceptance standards.
6.5 Pressure testing

6.5.1 Every vessel shall be subjected to a pressure test and its leak tightness shall be demonstrated. This leak tightness may be demonstrated during the establishment of the vacuum or by a separate leak test at pressures up to the design pressure.

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

\[ p_s \]

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

Where the test is carried out hydraulically the pressure shall be raised gradually to the test pressure holding it there for 30 min. Then the pressure shall be reduced to the design pressure so that a visual examination of all surfaces and joints can be made. The vessel shall not show any sign of gross plastic deformation or leakage. The test may be carried out pneumatically on a similar basis. As pneumatic testing employs substantially greater stored energy than hydraulic testing, it shall normally only be carried out where adequate facilities and procedures are employed to assure the safety of inspectors, employees and the public.

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

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

6.5.4 The piping system shall be subjected to a pressure test at a pressure in accordance with 4.2.3.9. It is not necessary to strength test mechanical joints and fittings that have demonstrated satisfactory in-service experience.
Annex A
(informative)

Elastic stress analysis

A.1 General

This annex provides rules to be followed if an elastic stress analysis is used to evaluate components of a large vacuum insulated transportable cryogenic vessel for operating conditions. The loads to be considered are those defined in 4.2.3.

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

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

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

Stress intensities $f_m$, $f_L$, $f_b$, and $f_g$ can be determined from the principle stresses $f_1$, $f_2$ and $f_3$ in each category using the maximum shear stress theory of failure, see A.2.1.

The stress intensities determined in this way should be less than the allowable values given in A.3 and A.4 or A.5.

Peak stresses need not be considered as they are only relevant when evaluating designs for cyclic service. Large vacuum insulated transportable cryogenic vessels within the scope of this standard are not considered to be in cyclic service.

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

A.2 Terminology

A.2.1 Stress intensity

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

The principal stresses $f_1$ and $f_2$ acting tangentially to the surface at the point under consideration should be calculated from the following equations:

$$f_1 = 0.5 \times \left( \sigma_1 + \sigma_2 + \sqrt{(\sigma_1 - \sigma_2)^2 + 4 \times \tau^2} \right)$$
EN 14398-2:2003 (E)

\[ f_2 = 0.5 \left( \sigma_1 + \sigma_2 - \sqrt{(\sigma_1 - \sigma_2)^2 + 4 \times \tau^2} \right) \]

where:

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

### A.2.2 Gross structural discontinuity

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

Examples of gross structural discontinuities are:

- **EXAMPLE 1** end to shell junctions.
- **EXAMPLE 2** junctions between shells of different diameters or thicknesses.
- **EXAMPLE 3** nozzles.

### A.2.3 Local structural discontinuity

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

Examples of local structural discontinuities are:

- **EXAMPLE 1** small fillet radii.
- **EXAMPLE 2** small attachments.
- **EXAMPLE 3** partial penetration welds.

### A.2.4 Normal stress

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

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

### A.2.5 Shear stress

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

### A.2.6 Membrane stress

The membrane stress is the component of stress that is uniformly distributed and equal to the average value of stress across the thickness of the section under consideration.
A.2.7 Primary stress

A primary stress is a stress produced by mechanical loadings only and so distributed in the structure that no redistribution of load occurs as a result of yielding. A normal stress, or a shear stress developed by the imposed loading, is necessary to satisfy the simple laws of equilibrium of external and internal forces and moments. The basic characteristic of this stress is that it is not self-limiting. Primary stresses that considerably exceed the yield strength will result in failure, or at least in gross distortion. A thermal stress is not classified as a primary stress. Primary stress is divided into "general" and "local" categories. The local primary stress is defined in A.2.8.

Examples of general primary stress are:

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

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

A.2.8 Primary local membrane stress

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

Conservatism requires that such a stress be classified as a primary local membrane stress even though it has some characteristics of a secondary stress. A stressed region can be considered as local if the distance over which the stress intensity exceeds 110% of the allowable general primary membrane stress does not extend in the meridional direction more than \(0.5 \sqrt{R_s}\) and if it is not closer in the meridional direction than \(2.5 \sqrt{R_s}\) to another region where the limits of general primary membrane stress are exceeded, where \(R\) and \(s\) are respectively the radius and thickness of the component.

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

A.2.9 Secondary stress

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

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

A.2.10 Peak stress

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

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

EXAMPLE 2 The stress at a local structural discontinuity.

A.3 Limit for longitudinal compressive general membrane stress

The longitudinal compressive stress should not exceed \(0.93 \Delta K\) for ferritic steels and \(0.73 \Delta K\) for austenitic stainless steel and aluminium alloys. Where \(\Delta\) is obtained from Figure A.2 in terms of \(p_e / p_{ys}\) and where:
A.4 Stress categories and stress limits for general application

A.4.1 General

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

A.4.2 General primary membrane stress category

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

A.4.3 Local primary membrane stress category

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

A.4.4 General or local primary membrane plus primary bending stress category

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

A.4.5 Primary plus secondary stress category

The stresses falling within the primary plus secondary stress category are those defined in A.2.7 plus those of A.2.9 produced by pressure, other mechanical loads and general thermal effects. The effects of gross structural discontinuities, but not of local structural discontinuities (stress concentrations), should be included. The stress intensity value \( (f_m + f_p) \) or \( (f_L + f_p) \) is the highest value of these stresses acting across the section under consideration and should be limited to \( 2K \).
A.4.6 Thermal stress

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

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

a) general thermal stress is associated with distortion of the structure in which it occurs. If a stress of this type neglecting stress concentrations, exceeds $2 \sigma$ the elastic analysis can be invalid and successive thermal cycles can produce incremental distortion. This type is therefore classified as secondary stress in Table A.1 and Figure A.1.

Examples of general thermal stress are:

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

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

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

EXAMPLE A small cold spot in a vessel wall.

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

A.5.1 General

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

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

$R$ and $s$ are respectively the radius and thickness of the component. The criteria of A.2.8 are not applicable to this section.

If design acceptability is demonstrated by A.5 then the use of A.4 is not required.

A.5.2 Attachments and supports

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

Under the design combined load the following stress limits apply:

— the primary membrane stress intensity should not exceed $0,8 \sigma$;

— the stress intensity due to the sum of primary membrane and primary bending stresses should not exceed $4 \sigma/3$;

— the stress intensity due to the sum of primary membrane stresses, primary bending stresses and thermal stresses should not exceed $2 \sigma$. 
A.5.3 Nozzles and openings

The nozzle or opening should be reinforced in accordance with 4.3.5.5.

Under the design combined load the following stress limits apply:

- the primary membrane stress intensity should not exceed $0.8 \, K$;
- the stress intensity due to the sum of primary membrane stresses and primary bending stresses should not exceed $1.5 \, K$;
- the stress intensity due to the sum of primary membrane stresses, primary bending stresses and thermal stresses should not exceed $2 \, K$.

A.5.4 Additional stress limits

Where significant compressive membrane stresses are present the possibility of buckling should be investigated and the design modified if necessary (see A.3). In cases where the external load is highly concentrated, an acceptable procedure would be to limit the sum of membrane and bending stresses (total compressive stress) in any direction at the point to $0.9 \, K$.

Where shear stress is present alone, it should not exceed $K/3$. The maximum permissible bearing stresses should not exceed $K$. 
### Table A.1 — Classification of stresses for some typical cases

<table>
<thead>
<tr>
<th>Vessel component</th>
<th>Location</th>
<th>Origin of stress</th>
<th>Type of stress</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical or spherical shell</td>
<td>Shell plate remote from discontinuities</td>
<td>Internal pressure</td>
<td>General membrane</td>
<td>$f_m$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gradient through plate thickness</td>
<td>$f_m$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Axial thermal gradient</td>
<td>$f_g$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Membrane</td>
<td>$f_g$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bending</td>
<td>$f_g$</td>
</tr>
<tr>
<td></td>
<td>Junction with head</td>
<td>Internal pressure</td>
<td>Membrane</td>
<td>$f_L$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bending</td>
<td>$f_g$</td>
</tr>
<tr>
<td>Any shell or end</td>
<td>Any section across entire vessel</td>
<td>External load or moment, or internal pressure</td>
<td>General membrane averaged across full section. Stress component perpendicular to cross section</td>
<td>$f_m$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>External load or moment</td>
<td>$f_m$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bending across full section. Stress component perpendicular to cross section</td>
<td>$f_m$</td>
</tr>
<tr>
<td></td>
<td>Near nozzle or other opening</td>
<td>External load or moment, or internal pressure</td>
<td>Local membrane</td>
<td>$f_L$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bending</td>
<td>$f_g$</td>
</tr>
<tr>
<td></td>
<td>Any location</td>
<td>Temperature difference between shell and end</td>
<td>Membrane</td>
<td>$f_g$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bending</td>
<td>$f_g$</td>
</tr>
<tr>
<td>Dished end or conical end</td>
<td>Crown</td>
<td>Internal pressure</td>
<td>Membrane</td>
<td>$f_m$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bending</td>
<td>$f_b$</td>
</tr>
<tr>
<td></td>
<td>Knuckle or junction to shell</td>
<td>Internal pressure</td>
<td>Membrane</td>
<td>$f_L$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bending</td>
<td>$f_g$</td>
</tr>
<tr>
<td>Flat end</td>
<td>Centre region</td>
<td>Internal pressure</td>
<td>Membrane</td>
<td>$f_m$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bending</td>
<td>$f_b$</td>
</tr>
<tr>
<td></td>
<td>Junction to shell</td>
<td>Internal pressure</td>
<td>Membrane</td>
<td>$f_L$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bending</td>
<td>$f_g$</td>
</tr>
<tr>
<td>Perforated end or shell</td>
<td>Typical ligament in a uniform pattern</td>
<td>Pressure</td>
<td>Membrane (average through cross section)</td>
<td>$f_m$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bending (average through width of ligament, but gradient through plate)</td>
<td>$f_b$</td>
</tr>
<tr>
<td></td>
<td>Isolated or atypical ligament</td>
<td>Pressure</td>
<td>Membrane</td>
<td>$f_g$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bending</td>
<td>$f_g$</td>
</tr>
<tr>
<td>Nozzle</td>
<td>Cross section perpendicular to nozzle axis</td>
<td>Internal pressure load or moment</td>
<td>General membrane (average across full section). Stress component perpendicular to section)</td>
<td>$f_m$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>External load or moment</td>
<td>$f_m$</td>
</tr>
<tr>
<td>Nozzle wall</td>
<td>Internal pressure</td>
<td>General membrane</td>
<td>$f_m$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Local membrane</td>
<td>$f_L$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bending</td>
<td>$f_g$</td>
</tr>
<tr>
<td></td>
<td>Differential expansion</td>
<td>Membrane</td>
<td>$f_g$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bending</td>
<td>$f_g$</td>
</tr>
</tbody>
</table>

*a* Consideration should also be given to the possibility of buckling and excessive deformation in vessels with large diameter-to-thickness ratio.
### Table A.1 — Stress categories and limits of stress intensity

<table>
<thead>
<tr>
<th>Stress Category</th>
<th>Primary</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
<td>General</td>
<td>Local</td>
</tr>
<tr>
<td><strong>Description</strong></td>
<td>Average primary stress across solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads</td>
<td>Average stress across any solid section. Consider discontinuities but not concentrations. Produced only by mechanical loads</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol (see NOTE 2)</th>
<th>( f_m )</th>
<th>( f_L )</th>
<th>( f_b )</th>
<th>( f_g )</th>
</tr>
</thead>
</table>

### Figure A.1 — Stress categories and limits of stress intensity

**NOTE 1** The stresses in category \( f_g \) are those parts of the total stress which are produced by thermal gradients, structural discontinuities, etc., and do not include primary stresses which may also exist at the same point. It should be noted, however, that a detailed stress analysis frequently gives the combination of primary and secondary stresses directly and, when appropriate, this calculated value represents the total of \( f_m \) (or \( f_L \)) + \( f_b \) + \( f_g \) and not \( f_g \) alone.

**NOTE 2** The symbols \( f_m \), \( f_L \), \( f_b \) and \( f_g \) do not represent single quantities but rather sets of six quantities representing the six stress components.
Figure A.2 — For vessels not subject to external pressure

Key
1
1
$Y \leq 8\quad \Lambda = 0.5 \left[ 1 - (1 - 0.125 Y)^2 \right]$
$24 \geq Y \geq 8\quad \Lambda = 0.45 + 0.00625 Y$
$Y \leq 24\quad \Lambda = 0.6$
Annex B
(normative)

Additional requirements for 9 % Ni steel

B.1 Introduction

Vessels constructed of 9 % Ni steels are normally welded using an austenitic or modified austenitic consumable. The 1 % or 0.2 % proof strength of the parent plate material normally exceeds that of an all weld metal sample. These weld metals exhibit excellent ductility and work hardening characteristics. After work hardening, the enhanced proof strength of the weld metal is maintained within an entirely elastic regime.

The value of $K$ to be adopted in the calculation formula of 4.3.6 is that of the parent 9 % Ni shell material.

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

B.2 Specific requirements

B.2.1 The minimum design temperature of vessels constructed of 9 % Ni steel shall not be less than -196 °C.

B.2.2 The maximum design temperature shall not exceed 50°C, when defrosting or drying the vessel at low pressure.

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

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

B.2.5 Imperfections that are unacceptable to this standard shall be repaired and re-examined to demonstrate compliance.

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

1) B.2.7 The weld procedure qualification and production control transverse tensile test specimens shall:

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

- demonstrate a rupture strength not less than the minimum specified ultimate strength of the parent plate.

1) These items also apply to work hardened austenitic stainless steel.
1) **B.2.8** Longitudinal bend tests shall be used rather than side bend tests as, permitted by EN 288 when qualifying weld procedures or testing production control test plates.

**B.2.9** The heat affected zone at the weld fusion boundary shall be demonstrated to attain an ISO V-notch impact strength of 50 joules at -196 °C, as an average of 3 test pieces, during weld procedure qualification and production control plate testing. These tests shall be performed in accordance with EN 1252-1.

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

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

**B.2.12** 9 % Ni vessels may be fitted with nozzles of stainless steel. Where the outside diameter of the nozzle exceeds 75 mm, the stresses in the shell and nozzle due to pressure, mechanical loads and thermal expansion are assessed and shown to be consistent with annex A and to provide an adequate fatigue life for the intended application of the vessel.

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

**B.2.14** 9 % Ni material conforming to EN 10028-4 is suitable for the construction of cryogenic vessels conforming to this standard. Other materials may be suitable.

2) These items also apply to work hardened austenitic stainless steel.
C.1 Introduction

Austenitic stainless steel exhibits stress/strain characteristics (Figure C.2), different from that of carbon steel (Figure C.1), that enable stainless steel to accept strain as a means of increasing its proof strength. Plastic deformation of 10% is possible with steels having an elongation at fracture of at least 35% in the solution heat treated condition.

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

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

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

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

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

C.2 Scope

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

C.3 Definitions and units of measurement

Definitions, symbols and units of measurement given in 3.1 apply to this annex, with the following addition:
**pressure strengthened vessel**

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

**NOTE** Pressure vessels made from solution heat treated material will be subject to a controlled plastic deformation during the strengthening operation as its yield point is raised. Pressure vessels made from work-hardened material will be subject to little or no plastic deformation.

### C.4 Materials

**C.4.1** Accepted materials of construction that have already been proven suitable for pressure strengthening for operating temperatures of not less than -196 °C are the austenitic stainless steels specified in Table C.1. Requirements regarding these materials are found in EN 10028-7.

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

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

<table>
<thead>
<tr>
<th>Steel designation</th>
<th>Solution heat treated material</th>
<th>Pressure strengthened vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Number</td>
<td>$R_{p0,2}$ N/mm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>min</td>
</tr>
<tr>
<td>X5CrNi18-10</td>
<td>1.4301</td>
<td>210</td>
</tr>
<tr>
<td>X2CrNi19-11</td>
<td>1.4306</td>
<td>200</td>
</tr>
<tr>
<td>X2CrNiN18-10</td>
<td>1.4311</td>
<td>270</td>
</tr>
<tr>
<td>X6CrNiTi18-10</td>
<td>1.4541</td>
<td>200</td>
</tr>
<tr>
<td>X6CrNiNb18-10</td>
<td>1.4550</td>
<td>200</td>
</tr>
<tr>
<td>X5CrNi19-09</td>
<td>1.4315</td>
<td>270</td>
</tr>
</tbody>
</table>

**C.4.2** In case stable or metastable austenitic steels according to clause 8 of EN 14398-1:2003 other than those listed in Table C.1 are to be qualified for pressure strengthening, or the vessel operating temperature will be below -196 °C, steel quality and welding procedure shall be validated by the type approval test detailed below. This test shall be carried out in addition to the tests required by 8.1 of EN 14398-1:2003 and 5.6.1 of this standard.

A welded test plate shall be subjected to a tensile stress across the weld equal to the anticipated value of $\sigma_k$. From this test plate specimens shall be tested as follows:

- to test the base material: two tensile tests along the direction of the applied stress and one set of impact tests across the direction of the applied stress;
- to test the weld: two tensile tests across the weld and one set of impact tests of the weld metal according to 3.4 of EN 1252-1:1998.

One tensile test and the impact tests shall be carried out at the lowest operating temperature, the other tensile test shall be carried out at 20 °C.
The base material and the weld shall comply with:

\[ R_{p0.2} \geq \sigma_k \; ; \quad A_5 \geq 25 \% ; \quad a_k \text{ISO-V} \geq 50 \text{ J/cm}^2 \]

C.5 Design

C.5.1 General

C.5.1.1 Wall thicknesses calculated according to C.5.2 refer to thicknesses before strengthening.

C.5.1.2 Nominal diameters may be used in the design calculations. No allowance is necessary for the possible increase in diameter due to strengthening.

C.5.1.3 Maximum design stress value is limited to 200 N/mm\(^2\) above \( R_{p0.2} \) for the material in the solution heat treated condition.

C.5.1.4 The weld joint factor 1.0 may be used for the calculation of all pressure strengthened parts of the vessel (longitudinal welds in cylinder, cone or end).

C.5.1.5 Pressure strengthening applies to vessels (or part of vessels) where the pressure induced membrane stresses are dominant. Other parts of the vessel shall be designed in accordance with clause 4 and the relevant annexes of this standard. This requirement shall not preclude utilisation of the strengthening process, provided that the manufacturer can show that it does not cause deformations that impair the integrity of the vessel.

C.5.2 Design for internal pressure

C.5.2.1 Design stress values

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

C.5.2.2 Calculation of the strengthening pressure

The required strengthening pressure \( P_k \) is calculated according to the formula:

\[ P_k = 1.33 \, p \]  \hspace{1cm} (C.1)

NOTE Strained material is also known to increase its strength when cooled to cryogenic temperatures. However, the effect on strengthening pressure (analogous to the effect on test pressure as in 4.3.2.3.3 of this document) is not taken into account in this annex.

C.5.2.3 Calculation of wall thicknesses

C.5.2.3.1 General

The wall thickness of the various parts of the pressure vessel shall be calculated according to applicable sub-clauses of this standard with the modifications shown in Table C.2.
C.5.2.3.2 Parts where bending stresses are dominant and large deformations cannot be accepted, like flat cones according to 4.3.5.3.7 and flat ends according to 4.3.5.3, shall be calculated in the normal way using the design pressure $p$ and design stress values according to 4.3.2.3. That is, the effect of the strengthening may not be utilised in such designs.

Additionally, the capability to pass the strengthening without plastic deformation shall be checked by repeating the calculations using the strengthening pressure (taking the mass of contents into account) for the test pressure $p_T$ and the design stress value at 20 °C from 4.3.2.3.

C.5.2.3.3 When designing parts according to 4.3.5.1 insert into the applicable formulae the following:

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

C.5.2.3.4 Parts according to 4.3.5.2.2.2 and 4.3.5.2.2.3 of this standard shall be designed with the same modifications as in C.5.2.3.3. Additionally the shape factor $\beta$ for dished ends may be reduced to:

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

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

Also the risk of buckling in regions where compressive stresses occur (i.e. the knuckle of dished ends and corner area of cones) shall be paid special attention. But, since buckling is heavily dependent on initial imperfections and work-hardening of the material before pressurisation, there is no substitute for experience. However, the stretching process in itself will reveal any such tendencies (see C.6.1).

C.5.2.3.5 For reinforcements of openings the stiffness of the attachment shall be considered so that overdimensioned reinforcements are avoided. Preferably openings without reinforcement should be used. Unreinforced openings in this context includes openings having reinforcement not complying with 4.3.5.5.5 of this standard.
For openings, where the hole diameter exceeds that given below, calculation of the reinforcement shall be made according to 4.3.5.5 of this standard with the same modifications as in C.5.2.3.3.

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

When ligament efficiency is less than 1, stresses due to strengthening shall be analysed according to 4.3.5.5 of this standard.

Largest allowed opening of unreinforced single holes

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

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

\[
d_{\text{max}} = 0.4 \sqrt{D_y s + C}
\]  
(C.2)

The value of $d_{\text{max}}$ calculated according to formula (C.2) may be rounded up to the nearest higher even 10 mm. $d_{\text{max}}$ shall however meet the conditions:

\[
\begin{align*}
  d_{\text{max}} &\leq 150 \text{ mm} \quad \text{(C.3)} \\
  d_{\text{max}} &\leq 0.2 D_y \quad \text{(C.4)}
\end{align*}
\]

The wall thickness of an unpierced cylinder is calculated from:

\[
s_0 = \frac{pD_y}{20 \sigma_k/1.33 + 2 p}
\]  
(C.5)

The wall thickness of the crown region of an unpierced dished end is calculated from:

\[
s_0 = \frac{pR}{20 \sigma_k/1.33}
\]  
(C.6)
C.6 Manufacturing and inspection

C.6.1 Strengthening procedure

C.6.1.1 The strengthening operation, which is a step in the production of the finished vessel, shall be made following written instructions. These instructions shall include the steps described in C.6.1.2 to C.6.1.6.

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

C.6.1.2 The vessel is filled with liquid. Before the vessel is closed there should be a wait for at least 15 min to let any air dissolved in the liquid escape. The vessel is then topped up and sealed.

C.6.1.3 The circumference of all courses shall be measured (e.g. with steel tapes) where the largest increase in cross-section is expected. The strain rate during the strengthening operation shall be calculated over the full circumference.

C.6.1.4 The strengthening shall be carried out as follows: the pressure is raised to the strengthening pressure and maintained until the strain rate has dropped to less than 0,1 %/h. The time under pressure shall be not less than one hour (see however C.6.1.5). The strain rate shall be checked by repeated measurements of the circumference according to C.6.1.2. The requirement of 0,1 %/h shall be met during the last half hour.

NOTE The total time under pressure can be long. This can be reduced if a 5 % higher pressure is applied during the first 0,5 h to 1 h of the operation.

C.6.1.5 For pressure vessels having a diameter not more than 2 000 mm the time under pressure may be reduced to 30 min and the requirement of 0,1 %/h be met during the last 15 min.

C.6.1.6 The strengthening operation replaces the initial pressure testing of the vessel. Should later pressure testing be required, only the normal test pressure shall be used. If the vessel requires to be repaired, this repair and pressure testing or possibly renewed strengthening shall be carried out in accordance with C.6.3.4.

C.6.2 Procedure record

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

— pressurising sequence specifying pressure readings and time;
— circumference measurements before, during and after pressurisation;
— strain rate calculations from circumference measurements;
— any significant changes of shape and size relevant to the functioning of the vessel;
— any requirement for renewed strengthening (according to C.6.1.6 and C.6.3.4).

C.6.3 Welding

C.6.3.1 The strengthening method presumes high quality welding. The same rules apply as for conventionally produced cryogenic vessels, except that production control test plates need not be taken.

C.6.3.2 Non-destructive testing shall be carried out before the strengthening to the extent stipulated in 6.3. Where high local stress and strain concentrations can be expected during the strengthening operation, examination with liquid penetrant shall also be carried out e.g. at changes in wall-thickness or at welded nozzles.
C.6.3.3 After the strengthening operation and reducing the pressure to the design pressure welds shall be visually examined externally for their full lengths. Places which have been examined with liquid penetrant according to C.6.3.2 shall also if possible be tested at random using a volumetric method (preferably by radiographic examination).

C.6.3.4 Renewed strengthening shall be carried out if pressure strengthened parts of the vessel have been significantly affected by post strengthening welding. Exceptions are permitted for tack-welding of attachments carrying low loads only (e.g. insulation supports) and welding of nozzles not more than 10 % of the vessel inner diameter (with a maximum of 100 mm) or minor weld repairs with comparable effect on the construction. Such welds shall be examined according to C.6.3.2 and C.6.3.3.

Unless renewed pressure strengthening is carried out there shall be a normal pressure test as required by 6.6.2 after all welding on pressure retaining parts.

C.6.4 Pressure vessel drawing

C.6.4.1 In addition to the information required by 4.2.2, the drawing shall bear the following text:

- the vessel is manufactured according to annex C;
- strengthening pressure in bar;
- thicknesses and diameters shown apply before strengthening.

C.6.4.2 Details to be welded in place after the strengthening shall be marked on the drawing.

C.6.5 Data plate

The data plate shall in addition to the information according to clause 10 of EN 14398-1:2003 bear the text “PRESSURE STRENGTHENED”.

C.7 Comments

C.7.1 Strengthening theory

Austenitic stainless steels exhibit considerable work-hardening upon deformation while retaining the characteristics of the material. The stress required for further deformation increases continuously as the deformation increases. Thus, a stress/strain curve for austenitic steel does not have the flow region typical of carbon and low-alloy steels. Compare the stress/strain curves in Figure C.1 and C.2.
Figure C.1 — Stress/strain curve for carbon steel

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

A test piece which has been loaded to the strengthening stress $\sigma_k$ can be regarded as a new test piece with:

$$R_{p0.2} = \sigma_k$$  \hspace{1cm} (C.7)

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

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

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

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

During the strengthening of the finished vessel, the material reaches a strengthening stress ($\sigma_k$) that is at least -1.33 times the design stress, $p$, and 1.73 times the stress at maximum allowable pressure, $p_s$.

C.7.2 Work-hardened material

C.7.2.1 The term work-hardened material shall be applied to material that has had its proof strength raised through cold rolling, roll straightening, uniaxial stretching in a stretching machine or other types of cold work.
C.7.2.2 Work-hardened material can be used in order to reduce or eliminate the deformation due to strengthening of the pressure vessel. It is primarily used in cylinders for internal pressure.

C.7.2.3 The increase in the proof strength of a work-hardened material is about the same in all directions. The proof strength of work-hardened plate shall be determined on samples taken across the direction of rolling or stretching respectively.

C.7.2.4 The structure of work-hardened material differs from solution heat treated material only in that the number of dislocations is higher. Material that has been subject to a homogeneous deformation is free from residual stresses. Work-hardening does not significantly affect the resistance to general corrosion.

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

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

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

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

C.7.3 Derivation of formulae

C.7.3.1 Consider a cylinder of middle diameter $D$ and design pressure $p$, which has been strengthened to a design stress value $\sigma_k$. Its wall thickness should comply with the formula for cylinders in 4.3.5.1.3 of this standard:

$$s = \frac{pDs_F}{20\sigma_k z}$$

(C.8)

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

The strengthening shall be carried out in such a way that the shell is subjected to the stress $\sigma_k$. The stress in a cylinder is:

$$\sigma = \frac{pD}{20s}$$

(C.9)

and the strengthening pressure $p_k$ will therefore be:

$$p_k = \frac{20s\sigma_k}{D}$$

(C.10)

If $s$ according to formula (C.8) is substituted:

$$p_k = \frac{pS_F}{z}$$

(C.11)

Since $S_F = 1.33$ and $z = 1.0$ this corresponds to formula (C.1). Obviously cylinders can be calculated from the formula in 4.3.5.1.3 if $\sigma_k$ is inserted as the design stress value and 1.0 as the weld joint factor.
NOTE If a weld joint factor \( z \) less than 1.0 is applied to any single main seam an increase in strengthening pressure is required according to formula (C.5). To sustain this higher pressure the thickness of all parts of the vessel would then need to be increased.

C.7.3.2 If a shell consists of several courses and one of them is made thicker than the others, it will have a lower \( \sigma_k \) than the other courses after strengthening.

The thicker course then needs a higher strengthening pressure than the others. Since this is impossible, this course will fail to satisfy formula (C.8) (not "strengthened enough"), as the anticipated proof strength \( \sigma_k \) will not be reached.

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

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

C.7.3.3 The derivation of formulae in C.7.3.1 applies to parts free from bending stresses, i.e. cylinders, spheres and hemispherical ends.

Utilisation of the strengthening effect is generally not permitted for parts subject to primary bending stresses. For such parts, it is necessary to investigate the stresses during strengthening (see C.5.2.3.2) and normal operation.

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

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

C.7.3.4 Experience has shown that it is possible to use design stress values for pressure strengthened material when dimensioning reinforcement pads according to 4.3.5.5.

C.7.3.5 This annex does not preclude utilisation of the strengthening effect, provided that the manufacturer can show that it does not cause harmful deformation or other problems.

C.7.4 Deformations at strengthening

C.7.4.1 The highest allowable design stress value \( \sigma_{k_{\text{max}}} \) for the different steels has consistently been set 200 N/mm\(^2\) higher than \( R_{p0,2} \) for the solution heat treated material.

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

C.7.4.2 The strengthening process can be simulated in tensile testing by allowing extra time under load. This increases the elongation under maximum stress by another 1 % to 2 %.

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

C.7.4.3 A multi-axial stress state result in other elongation values than tensile testing. These elongation values can be assessed according to a graph of the deformation hardening of the material as applied to the effective values of stress \( \sigma \) and elongation \( \varepsilon \).
EN 14398-2:2003 (E)

\[
\sigma = \sqrt{\frac{1}{2}\left[\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_1 - \sigma_3\right)^2\right]} \\
\varepsilon = \sqrt{\frac{2}{9}\left[\left(\varepsilon_1 - \varepsilon_2\right)^2 + \left(\varepsilon_2 - \varepsilon_3\right)^2 + \left(\varepsilon_1 - \varepsilon_3\right)^2\right]}
\]

If the effective values are set = 1, the principal stresses and elongations obtained for the simplest stress conditions are given in Table C.3.

### Table C.3 — Stresses and elongations for different load cases

<table>
<thead>
<tr>
<th></th>
<th>True stress</th>
<th>True elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\sigma_1)</td>
<td>(\varepsilon_1)</td>
</tr>
<tr>
<td>Tensile test</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Cylinder</td>
<td>1.15</td>
<td>0.87</td>
</tr>
<tr>
<td>Sphere</td>
<td>1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Among other things, Table C.3 expresses the fact that a tensile test sample contracts in two dimensions, while a cylinder decreases only in thickness by an amount corresponding to the increased circumference.

Table C.3 shows that a certain effective stress \(\sigma\) produces different elongation in the principal stress direction \(\varepsilon_1\) for the different load cases. The same effective stress that produces a strain of 10 % in a tensile test \((\varepsilon_1 = 1.0)\) produces a circumferential strain 8.7 % \((\varepsilon_1 = 0.87)\) in a cylinder shell and 5 % \((\varepsilon_1 = 0.5)\) in a sphere.

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

The following example gives an indication of the difference.

EXAMPLE Values from a typical deformation hardening curve of austenitic stainless steel are used, i.e. 0.2 %/280 N/mm\(^2\) and 10 %/420 N/mm\(^2\). If equal nominal principal stresses \(\sigma_1\)\(_{\text{nom}}\) are applied to this material, the principal strain \(\varepsilon_1\) for the cylinder is altered from 0.87 to 0.66 and for the sphere from 0.5 to 0.58.

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

**C.7.4.4** In practice, the maximum circumferential strain of cylinders is usually 3 % to 5 % when using solution heat treated plate, less in the spherical part of the ends. The following factors contribute to the measured values being lower than the theoretically calculated maximum value:

- the proof strength \(R_{p0.2}\) is higher than the specified minimum for the material;
- the plate thickness is greater than nominal;
- there are reinforcing effects of ends, nozzles, etc.
C.7.4.5 It should be observed that strengthening of pressure vessels of solution heat treated material can affect the position, direction and roundness of nozzles. This does not entail any reduction of the safety of the vessel, but may in certain cases be a nuisance to the user.

NOTE One way to minimise these changes is to weld the nozzles in place after the strengthening, whereupon the vessel may require renewed strengthening (see C.6.3.4). This second strengthening generally leads to much smaller deformations.

C.7.4.6 When a welded tube is used for nozzles in a cylinder (or cone), the longitudinal weld of the tube should be located in the direction where the stresses are lowest, i.e. in a plane perpendicular to the longitudinal axis of the cylinder (or cone).
Annex D
(informative)

Specific weld details

D.1 Field of application

Specific weld details given in D.2 are currently in common usage in cryogenic vessels and are appropriate to this service. Although the scope of EN 1708-1:1999, does not specifically consider the application of weld details to cryogenic vessels, the manufacturer can consult it for guidance.

D.2 Weld detail

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

D.2.1 Joggle joint

See Figure D.1.

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

a) when the flanged section of a dished end is joggled, the joggle is sufficiently clear of the knuckle radius to ensure that the edge of the circumferential seam is at least 12 mm clear of the knuckle (see 4.3.5.2.2 for the dimensions);

b) when a cylinder with a longitudinal seam is joggled:

1) the welds are ground flush internally and externally for a distance of approximately 50 mm prior to joggling with no reduction of plate thickness below the required minimum; and

2) on completion of joggling, the area of the weld is subjected to dye penetrant examination and is proven to be free of cracks;

c) the offset section which forms the weld backing is a close fit within its mating section at the weld round the entire circumference;

d) the profile of the offset is a smooth radius without sharp corners;

e) on completion of welding the weld fills the groove smoothly to the full thickness of the plate edges being joined;

f) the junction of the longitudinal and circumferential seams are examined radiographically and found to be free from significant imperfections.

D.2.2 Intermediate ends

See Figure D.2.
D.2.3 Backing strip

See Figure D.3.

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

D.2.4 End plate closure

See Figure D.4 for two examples of the many ways of welding flat plates. See also Figure 12.

D.2.5 Non full penetration nozzle weld

See Figure D.5.

Can be used to attach set in nozzles to ends and cylinders provided that the strength of the attachment welds can be demonstrated to be sufficient to contain the design nozzle loadings.

D.2.6 Non continuous fillet weld on attachments

Can be used for all attachments to main pressure components provided that the following criteria are met:

- strength is adequate for design loadings;
- crevices between attached component and main pressure envelope can be demonstrated not to conflict with D.3.

D.3 Oxygen service requirements

The need for cleanliness of equipment in liquid oxygen and other oxidising liquid service is described in EN 1797 and EN 12300.

The internal weld details should be such that debris, contaminants, hydrocarbons or degreasants cannot accumulate so as to cause a fire risk in future operation.
Key
1. Bevel optional
2. As desired
3. Depth of offset = \( e_1 \)
4. Avoid sharp break

Figure D.1 — Joggle joint

Key
1. Tangent point
2. Continuous fillet weld
3. Butt weld
4. Cylinder thickness
5. Cylinder thickness
6. End thickness
7. Need not exceed 25 mm

* NOTE Cylinder thickness \( s_1 \) and \( s_2 \) can vary

Figure D.2 — Intermediate end
Key
1 Intermittent or continuous fillet weld

Figure D.3 — Backing strip

Figure D.4 — End plate closure (examples)

Figure D.5 — Non full penetration nozzle welds
Annex E
(normative)

Increased material property for austenitic stainless steel

The PED stipulates three methods for ensuring that a material is suitable for pressure equipment. However within ADR, for austenitic steels, the specified minimum values according to the material standard can be exceeded by up to 15 % if these higher values are attested in the inspection certificate. This method has been used successful for a number of years. However, for the calculation of the minimum wall thickness according to the formula in Table 1 of 4.3.2.1, the minimum values specified in the material standards shall be used.

\( K \) is the minimum value at 20 °C taken from the material standard.

Higher values of \( K \) can be used provided that the following conditions are met:

- the material manufacturer should guarantee compliance with this higher value, in writing, when accepting the order;
- the increased properties are verified by testing each rolled plate or coil of the material to be delivered;
- the increased properties are attested in the inspection certificate.

In the case of austenitic stainless steels the specified minimum value can be exceeded by up to 15 % provided this higher value is attested in the inspection certificate.

In addition, for austenitic stainless steel a strength value obtained in work hardened material can be used in the design provided this value and the requirement of 5.3.1 are maintained in the finished component. Requirements for welding of work hardened austenitic stainless steels are given in 5.6.4.3.

The value of \( E \) (Young’s modulus) at 20 °C should be used in calculation.
Bibliography


EN 970, Non-destructive examination of fusion welds – Visual examination.


EN 12300, Cryogenic vessels – Cleanliness for cryogenic service.

EN 13133, Brazing – Brazer approval.

EN 13134, Brazing – Procedure approval.

EN 13445-4, Unfired pressure vessels – Part 4 : Fabrication.

EN 13458-3, Cryogenic vessels – Static vacuum-insulated vessels – Part 3: Operational requirements.