BS EN 13445-3:2021+A1:2026

BSI Standards Publication

Unfired pressure vessels

Part 3: Design



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National foreword

This British Standard is the UK implementation of EN 13445-3:2021+A1:2026. It supersedes BS EN 13445-3:2021+A1:2025, which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee PVE/1/15, Pressure Vessels - Design methods.

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

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Published by BSI Standards Limited 2026

ISBN 978 0 539 41962 7

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ICS 23.020; 23.020.30

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This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 May 2021.

Amendments/corrigenda issued since publication

Date	Text affected
31 October 2023	Implementation of CEN correction notice 8 March 2023: corrections to numerous formatting and lay-out errors and inconsistencies, particularly related to formulae and tables
30 November 2025	Implementation of CEN amendment A1:2025 (collated by BSI)
30 April 2026	Implementation of CEN amendment A1:2026 (consolidated version)

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EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN 13445-3:2021+A1

April 2026

ICS 23.020.30

Supersedes EN 13445-3:2021

English Version

Unfired pressure vessels - Part 3: Design

Récipients sous pression non soumis à la flamme - Partie 3: Conception

Unbefeuerte Druckbehälter - Teil 3: Konstruktion

This European Standard was approved by CEN on 24 February 2021 and includes Amendment 1 approved by CEN on 18 August 2025 and Amendment 1 approved by CEN on 4 February 2026.

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European foreword

This document (EN 13445-3:2021+A1:2026) has been prepared by Technical Committee CEN/TC 54 “Unfired pressure vessels”, the secretariat of which is held by BSI.

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of an identical text or by endorsement, at the latest by October 2026, and conflicting national standards shall be withdrawn at the latest by October 2026.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN shall not be held responsible for identifying any or all such patent rights.

This document includes Amendment 1, approved by CEN on 18 August 2025.

This document supersedes EN 13445-3:2021.

This document has been prepared under a standardization request addressed to CEN by the European Commission. The Standing Committee of the EFTA States subsequently approves these requests for its Member States.

For relationship with EU Legislation, see informative Annex ZA, which is an integral part of this document.

This new edition incorporates the Amendments which have been approved previously by CEN members, and the corrected pages up to Issue 5 without any further technical change. Annex Y provides details of significant technical changes between this European Standard and the previous edition.

Corrections to the standard interpretations where several options seem possible are conducted through the Migration Help Desk (MHD). Information related to the Help Desk can be found at https://unm.fr/en/maintenance-agencies/maintenance-agency-en-13445/. A form for submitting questions can be downloaded from the link to the MHD website. After subject experts have agreed an answer, the answer will be communicated to the questioner. Corrected pages will be given specific issue number and issued by CEN according to CEN Rules. Interpretation sheets will be posted on the website of the MHD.

A list of all parts in the EN 13445 series can be found on the CEN website.

Although these Parts may be obtained separately, it should be recognised that the Parts are inter-dependant. As such the manufacture of unfired pressure vessels requires the application of all the relevant Parts in order for the requirements of the Standard to be satisfactorily fulfilled.

According to the CEN-CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Türkiye and the United Kingdom.

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1 Scope

This Part of this document specifies requirements for the design of unfired pressure vessels covered by EN 13445-1:2021 and constructed of steels in accordance with EN 13445-2:2021+A1:2023.

EN 13445-5:2021, Annex C specifies requirements for the design of access and inspection openings, closing mechanisms and special locking elements.

NOTE This Part applies to design of vessels before putting into service. It may be used for in service calculation or analysis subject to appropriate adjustment.

2 Normative references

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

EN 286-2:1992, *Simple unfired pressure vessels designed to contain air or nitrogen — Part 2: Pressure vessels for air braking and auxiliary systems for motor vehicles and their trailers*

EN 764-1:2015+A1:2016, *Pressure equipment — Terminology — Part 1: Pressure, temperature, volume, nominal size*

EN 764-2:2012, *Pressure equipment — Part 2: Quantities, symbols and units*

EN 764-3:2002, *Pressure equipment — Part 3: Definition of parties involved*

EN 837-1:1996, *Pressure gauges — Part 1: Bourdon tube pressure gauges — Dimensions, metrology, requirements and testing*

EN 837-3:1996, *Pressure gauges — Part 3: Diaphragm and capsule pressure gauges — Dimensions, metrology, requirements and testing*

EN 1092-1:2018, *Flanges and their joints — Circular flanges for pipes, valves, fittings and accessories, PN-designated — Part 1: Steel flanges*

EN 1591-1:2013, *Flanges and their joints — Design rules for gasketed circular flange connections — Calculation method*

EN 1708-1:2010, *Welding — Basic weld joint details in steel — Part 1: Pressurized components*

EN 1990:2023, *Eurocode — Basis of structural and geotechnical design*

EN 1991-1-4:2005[1)], *Eurocode 1: Actions on structures — Part 1-4: General actions — Wind actions*

EN 1991-1-6:2005[2)], *Eurocode 1 — Actions on structures — Part 1-6: General actions — Actions during execution*

EN 1992-1-1:2023, *Eurocode 2 — Design of concrete structures — Part 1-1: General rules and rules for buildings, bridges and civil engineering structures*

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1) EN 1991-1-4:2005 is impacted by the stand-alone amendment EN 1991-1-4:2005/A1:2010 and the corrigendum EN 1991-1-4:2005/AC:2010.

2) EN 1991-1-6:2005 is impacted by the corrigendum EN 1991-1-6:2005/AC:2013.

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EN 1998-1:2004[3)], *Design of structures for earthquake resistance — Part 1: General rules, seismic actions and rules for buildings*

EN 10204:2004, *Metallic products — Type of inspection documents*

EN 10222-1:2017, *Steel forgings for pressure purposes — Part 1: General requirements for open die forgings*

EN 12195-1:2010[4)], *Load restraining on road vehicles — Safety — Part 1: Calculation of securing forces*

EN 12952-3:2022, *Water-tube boilers and auxiliary installations — Part 3: Design and calculation for pressure parts of the boiler*

EN 13445-1:2021, *Unfired pressure vessels — Part 1: General*

EN 13445-2:2021+A1:2023, *Unfired pressure vessels — Part 2: Materials*

EN 13445-4:2021+A1:2023, *Unfired pressure vessels — Part 4: Fabrication*

EN 13445-5:2021, *Unfired pressure vessels — Part 5: Inspection and testing*

EN 13445-8:2021, *Unfired pressure vessels — Part 8: Additional requirements for pressure vessels of aluminium and aluminium alloys*

EN 13555:2021, *Flanges and their joints — Gasket parameters and test procedures relevant to the design rules for gasketed circular flange connections*

EN ISO 4014:2022, *Fasteners — Hexagon head bolts — Product grades A and B (ISO 4014:2022)*

EN ISO 4016:2022, *Fasteners — Hexagon head bolts — Product grade C (ISO 4016:2022)*

EN ISO 15613:2004, *Specification and qualification of welding procedures for metallic materials — Qualification based on pre-production welding test (ISO 15613:2004)*

ISO 261:1998, *ISO general purpose metric threads — General plan*

3 Terms and definitions

For the purposes of this Part of this document, the terms and definitions given in EN 13445-1:2021, EN 13445-2:2021+A1:2023 and the following apply:

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

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

NOTE EN 13445-1:2021 and EN 13445-2:2021+A1:2023 have adopted terminology, symbols and definitions of EN 764-1:2015+A1:2016, EN 764-2:2012 and EN 764-3:2002.

3) EN 1998-1:2004 is impacted by the stand-alone amendment EN 1998-1:2004/A1:2013

4) EN 12195-1:2010 is impacted by the corrigendum EN 12195-1:2010/AC:2014

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3.1
action
imposed thermo-mechanical influence which causes stress and/or strain in a structure, e.g. an imposed pressure, force, temperature

3.2
analysis thickness
effective thickness available to resist the loading depending on the load case, see 5.3.2

3.3
assumed thickness
thickness assumed by the designer between the minimum required shell thickness e and the shell analysis thickness e_a

3.4
calculation pressure
differential pressure used for the purpose of the design calculations for a component

[SOURCE: EN 764-1:2015+A1:2016]

3.5
calculation temperature
temperature used for the purpose of the design calculations for a component

[SOURCE: EN 764-1:2015+A1:2016]

3.6
chamber
fluid space within a unit of pressure equipment

[SOURCE: EN 764-1:2015+A1:2016]

3.7
component
part of pressure equipment which can be considered as an individual item for the calculation

[SOURCE: EN 764-1:2015+A1:2016]

3.8
creep range
temperature range in which material characteristics used in design are time dependent

Note 1 to entry: See also 5.1.

3.9
cryogenic applications
applications involving liquefied gases at low temperature

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3.10

design pressure

pressure at the top of each chamber of the pressure equipment chosen for the derivation of the calculation pressure of each component

[SOURCE: EN 764-1:2015+A1:2016]

Note 1 to entry: Any other location may be specified.

3.11

design temperature

temperature chosen for the derivation of the calculation temperature of each component

[SOURCE: EN 764-1:2015+A1:2016]

3.12

differential pressure

pressure which algebraic value is equal to the pressure difference on either side of a separation wall

[SOURCE: EN 764-1:2015+A1:2016]

3.13

governing weld joint

main full penetration butt joint the design of which, as a result of membrane stresses, governs the thickness of the component

3.14

load case

combination of coincident actions

3.15

main joint

weld joint assembling main pressure bearing parts

3.16

maximum permissible pressure

maximum pressure obtained from the design by formulae or relevant procedures of EN 13445-3:2021 for a given component in a given load case, or for the whole pressure vessel the minimum of these maximum permissible pressures of all components

Note 1 to entry: The differences of the nominal design stress f, the analysis thickness e_a and the joint coefficient z for the calculation of the maximum permissible pressure in different load cases are specified in 5.3.2.

Note 2 to entry: If no explicit formula is given for the maximum permissible pressure P_{max} then P_{max} may be calculated as pressure which gives the required thickness equal to the analysis thickness.

Note 3 to entry: The maximum permissible pressure P_{max} used for the simplified assessment of fatigue life in Clause 17 and for the calculation of the equivalent full pressure in 5.4.2 is calculated for normal operating load cases.

3.17

minimum possible fabrication thickness

minimum possible thickness after fabrication

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3.18
nominal design stress
stress value to be used in the formulae for the calculation of pressure components

3.19
nominal thickness
thickness as specified on the drawings

3.20
test pressure
pressure to which the equipment is subjected for test purposes

[SOURCE: EN 764-1:2015+A1:2016]

3.21
test temperature
temperature at which the pressure test of the pressure equipment is carried out

[SOURCE: EN 764-1:2015+A1:2016]

3.22
volume
internal volume of a chamber, including the volume of nozzles to the first connection (flange, coupling, weld) and excluding the volume of internal permanent parts (e.g. baffles, agitators)

[SOURCE: EN 764-1:2015+A1:2016]

3.23
weld throat thickness of a fillet weld
height of the inscribed isosceles triangle measured from the theoretical root point

4 Symbols and abbreviations

For the purposes of this Part of this document, the general symbols and abbreviations shall be in accordance with EN 13445-1:2021, EN 13445-2:2021+A1:2023 and Table 4-1:

Table 4-1 — Symbols, quantities and units [c]

Symbol	Quantity	Unit
a	weld throat thickness	mm
e	required thickness	mm
e_n	nominal thickness	mm
e_{min}	minimum possible fabrication thickness	mm
e_a	analysis thickness	mm
c	corrosion allowance	mm

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Table 4-1 — Symbols, quantities and units [c] *(continued)*

Symbol	Quantity	Unit
f	nominal design stress	MPa
f_d	maximum value of the nominal design stress for normal operating load cases	MPa
f_{exp}	maximum value of the nominal design stress for exceptional load cases	MPa
f_{test}	maximum value of the nominal design stress for testing load cases	MPa
n_{eq}	number of equivalent full pressure cycles (see 5.4.2)	—
P	calculation pressure	MPa [a]
P_d	design pressure	MPa [a]
P_{max}	maximum permissible pressure	MPa [a]
PS, P_s	maximum allowable pressure	MPa [a]
P_{test}	test pressure	MPa [a]
R_{eH}	upper yield strength	MPa
R_m	tensile strength	MPa
$R_{m/T}$	tensile strength at temperature T	MPa
$R_{p0,2}$	0,2 % proof strength	MPa
$R_{p0,2/T}$	0,2 % proof strength at temperature T	MPa
$R_{p1,0}$	1,0 % proof strength	MPa
$R_{p1,0/T}$	1,0 % proof strength at temperature T	MPa
T	calculation temperature	°C
T_d	design temperature	°C
T_{test}	test temperature	°C
TS_{max}, TS_{min}	maximum/minimum allowable temperatures	°C
V	volume	mm^3 [b]
z	joint coefficient	—
ν	Poisson's ratio	—

[a] MPa for calculation purpose only, otherwise the unit may be bar (1 MPa = 10 bar).
[b] mm^3 for calculation purpose only, otherwise the unit should be litre.
[c] Formulae used in this standard are dimensional.

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5 Basic design criteria

5.1 General

EN 13445-3:2021 is applicable only when:

a) materials and welds are not subject to localized corrosion in the presence of products which the vessel is to contain or which can be present in the vessel under reasonably foreseeable conditions.

b) either all calculation temperatures are below the creep range or a calculation temperature is in the creep range and time dependent material characteristics are available in the materials standard.

NOTE See definition 3.8 of creep range.

For the purpose of design, the creep range is the temperature range in which time independent material characteristics are no more governing in the determination of the nominal design stress.

The material strength characteristics used shall be related to the specified lifetimes in the various creep load cases.

5.2 Corrosion, erosion and protection

5.2.1 General

Whenever the word "corrosion" is used in this standard it shall be taken to mean corrosion, oxidation, scaling, abrasion, erosion and all other forms of wastage.

NOTE 1 Stress corrosion cracking may occur under certain conditions of temperature and environment. A corrosion allowance is not an appropriate way of dealing with stress corrosion. Under such conditions, consideration shall be given to the materials used and the residual stresses in the fabricated vessel.

NOTE 2 It is impossible to lay down definite precautionary guidelines to safeguard against the effects of corrosion owing to the complex nature of corrosion itself, which may occur in many forms, including but not limited to the following:

— chemical attack where the metal is dissolved by the reagents. It may be general over the whole surface or localized (causing pitting) or a combination of the two;

— rusting caused by the combined action of moisture and air;

— erosion corrosion where a reagent otherwise innocuous flows over the surface at velocity greater than some critical value;

— high temperature oxidation (scaling).

Consideration should be given to the effect which corrosion (both internal and external) may have upon the useful life of the vessel. When in doubt, corrosion tests should be undertaken. These should be carried out on the actual metal (including welds or combination of metals) under exposure to the actual chemicals used in service. Corrosion tests should be continued for a sufficiently long period to determine the trend of any change in the rate of corrosion with respect to time.

NOTE 3 It is very dangerous to assume that the major constituent of a mixture of chemicals is the active agent, as in many cases small traces of a substance can exert an accelerating or inhibiting effect out of all proportion to the amount present. Fluid temperatures and velocities from corrosion test data should be equivalent to those met in operation.

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5.2.2 Additional thickness to allow for corrosion

In all cases where reduction of the wall thickness is possible as a result of surface corrosion or erosion, of one or other of the surfaces, caused by the products contained in the vessel or by the atmosphere, a corresponding additional thickness sufficient for the design life of the vessel components shall be provided. The value shall be stated on the design drawing of the vessel. The amounts adopted shall be adequate to cover the total amount of corrosion expected on either or both surfaces of the vessel.

A corrosion allowance is not required when corrosion can be excluded, either because the materials, including the welds, used for the pressure vessel walls are corrosion resistant relative to the contents and the loading or are reliably protected (see 5.2.4).

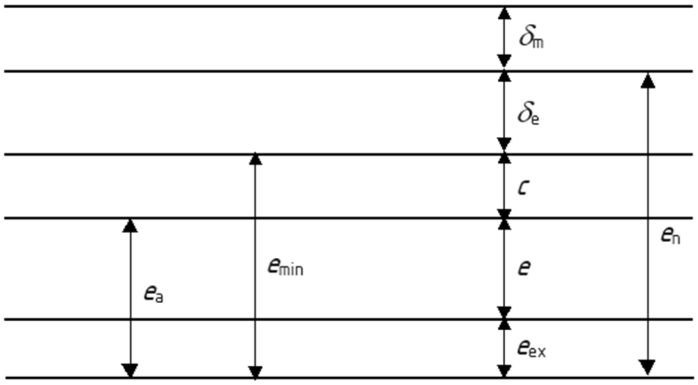
No corrosion allowance is required for heat exchanger tubes and other parts in similar heat exchanger duty, unless a specific corrosive environment requires one.

This corrosion allowance does not ensure safety against the risk of deep corrosion or stress corrosion cracking, in these cases a change of material, cladding, etc. is the appropriate means.

Where deep pitting may occur, suitably resistant materials shall be selected, or protection applied to the surfaces.

5.2.3 Inter-relation of thickness definitions

The inter-relation of the various definitions of thickness is shown in Figure 5-1.



Key

e is the required thickness;

e_n is the nominal thickness;

e_{min} is the minimum possible fabrication thickness ($e_{min} = e_n - \delta_e$);

e_a is the analysis thickness ($e_a = e_{min} - c$);

c is the corrosion allowance;

δ_e is the absolute value of the possible negative tolerance on the nominal thickness (e.g. taken from the material standards);

δ_m is the allowance for possible thinning during manufacturing process;

e_{ex} is the extra thickness to make up to the nominal thickness.

Figure 5-1 — Relationship of thickness definitions

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5.2.4 Linings and coatings

Only completely impervious, sufficiently thick and chemically stable layers with an average life not less than that of the pressure vessel shall be considered to be reliable protection against corrosion, but thin layers (like painting, electroplating, tinning, etc.) and coatings which are known to have to be renewed during the lifetime of the pressure vessel components shall not be used. For plastic coatings the suitability shall be justified, taking into account, among other factors, the risk of diffusion. The test of corrosion protection outlined in EN 286-2:1992 is not considered to be adequate for the pressure vessels covered by this standard.

Vessels may be fully or partially lined (or coated) with corrosion-resistant material. Linings should be integrally bonded to the vessel base metal. Loose or intermittently attached linings may be used taking the following into consideration:

— sufficient ductility of the lining to accommodate any strain likely to be imposed on it during service and testing conditions, differential thermal expansion being taken into consideration;

— for non-metallic coatings, the surface finish of the base material.

Provided contact between the corrosive agent and the vessel base material is excluded, no corrosion allowance needs be provided against internal wastage of the base material.

5.2.5 Wear plates

Where severe conditions of erosion and abrasion arise, local protective or wear plates shall be fitted directly in the path of the impinging material.

5.3 Load cases

5.3.1 Actions

In the design of a vessel the following actions shall be taken into account, where relevant:

a) internal and/or external pressure;

b) maximum static head of contained fluid under operating conditions;

c) weight of the vessel;

d) maximum weight of contents under operating conditions;

e) weight of water under hydraulic pressure test conditions;

f) wind, snow and ice loading;

g) earthquake loading;

h) other loads supported by or reacting on the vessel, including loads during transport and installation.

When necessary, consideration shall be given to the effect of the following loads in cases where it is not possible to demonstrate the adequacy of the proposed design e.g. by comparison with the behaviour of other vessels:

i) stresses caused by supporting lugs, ring, girders, saddles, internal structures or connecting piping or intentional offsets of median lines on adjacent components;

j) shock loads caused by water hammer or surging of the vessel contents;

k) bending moments caused by eccentricity of the centre of the working pressure relative to the neutral axis of the vessel;

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l) stresses caused by temperature differences including transient conditions and by differences in coefficients of thermal expansion;

m) stresses caused by fluctuations of pressure, temperature, and external loads applied to the vessel;

n) stresses caused by the decomposition of unstable fluids.

NOTE The combination of actions is given in 5.3.2.4.

5.3.2 Classification of load cases

5.3.2.1 Normal operating load cases

Normal operating load cases are those acting on the pressure vessel during normal operation, including start-up and shutdown.

For normal operating load cases the following calculation parameters shall be used:

— the calculation pressure P as defined in 5.3.10;

— the nominal design stresses $f = f_d$ as defined in 6.1.3 at calculation temperature;

— the analysis thickness is $e_a = e_{min} - c$ as defined in 5.2.3;

— the joint coefficient z as specified in Table 5.6-1.

5.3.2.2 Exceptional load cases

Exceptional load cases are those corresponding to events of very low occurrence probability requiring the safe shutdown and inspection of the vessel or plant. Examples are pressure loading of secondary containment or internal explosion.

For exceptional load cases the following calculation parameters shall be used:

— the calculation pressure P as defined in 5.3.10;

— the nominal design stresses $f = f_{exp}$ as defined in 6.1.2 and 6.1.3 at calculation temperature;

— the analysis thickness is is $e_a = e_{min} - c$ as defined in 5.2.3;

— the joint coefficient $z = 1{,}0$ as specified in 5.6.

5.3.2.3 Testing load cases

Testing load cases are:

— Testing load cases for final assessment related to tests after manufacture defined by EN 13445-5:2021;

or

— Testing load cases in service related to repeated tests during the lifetime defined by the user.

For testing load cases for final assessment the following calculation parameters shall be used:

— the test pressure $P_{test} = P_t$ as defined in EN 13445-5:2021;

— the nominal design stresses $f = f_{test}$ as defined in 6.1.2 and 6.1.3 at test temperature;

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— the analysis thickness is $e_a = e_{min}$ with e_{min} as defined in 5.2.3 (no corrosion allowance);

— the joint coefficient z = 1,0 as specified in 5.6.

For testing load cases in service the following calculation parameters shall be used:

— the test pressure P_{test} = test pressure in service as defined by the user taking into account possible national regulation. The modification of the test pressure for vessels with hydrostatic pressure according to EN 13445-5:2021, 10.2.3.3.1 b) shall be applied using the user specified test pressure in service instead of P_t;

— the nominal design stresses $f = f_{test}$ as defined in 6.1.2 and 6.1.3 at test temperature;

— the analysis thickness is $e_a = e_{min} - c$ as defined in 5.2.3;

— the joint coefficient z = 1,0 as specified in 5.6.

5.3.2.4 Load combinations

5.3.2.4.1 General

Load combinations of non-pressure loads in Table 5.3.2.4-1 are used in connection with calculations according to Clause 16 and Annex C (linear elastic behaviour). The basic calculation of pressure envelope by design pressures and temperatures shall be made before Clause 16 (or Annex C) calculations. The load combinations in Table 5.3.2.4-1 are minimum to be taken into account, if they are relevant. There may also be other loads.

5.3.2.4.2 Specific definitions

5.3.2.4.2.1 Dead loads

Maximum dead load (G_{max}) is the weight of the whole un-corroded vessel with all internals (trays, packing, etc.), attachments, insulation, fire protection, piping, platforms and ladders.

Corroded dead load (G_{corr}) is defined as G_{max} but with the weight of the corroded vessel.

Minimum dead load (G_{min}) is the weight of the un-corroded vessel during the installation phase, excluding the weight of items not already mounted on the vessel before erection (e.g. removable internals, platforms, ladders, attached piping, insulation and fire protection).

NOTE A scaffold is normally self-supported. In this case, the weight of the scaffold is not included in the vessel weight.

Transport dead load (G_{trans}) is the case, when vessel has the removable internals and insulation already mounted on the vessel in the workshop.

5.3.2.4.2.2 Live loads

Live loads (L) used in this subclause are weight loads of the contents (fluids or solids in the bottom of the vessel, on trays and in packing) and traffic loads on platforms and ladders by personnel and machinery.

5.3.2.4.2.3 Wind loads

Wind loads (W) are horizontal global pressure loads caused by wind and acting on the projected area of the vessel and its attachments, as influenced by the force coefficients (see EN 1991-1-4:2005).

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5.3.2.4.2.4 Earthquake loads

Earthquake loads (E) are quasi-static horizontal forces on the vessel sections caused by seismic accelerations at the base of vessel calculated by the "lateral force method of analysis" (see EN 1998-1:2004).

5.3.2.4.2.5 Forces from attached external piping

Reaction forces from attached external piping are forces resulting from weight (G), wind (W), earthquake (E) and other additional forces (F) as far as they influence the global equilibrium of the vessel (see 22.4.6 for columns).

NOTE Forces and moments on nozzles and supports on the vessel caused by attached external piping can act as internal and/or external loads. Internal loads are those that cause local loads only and have no influence on the global equilibrium because they are self-compensating. Furthermore, attached pipes can either load the vessel or restrain it depending on their layout. Consideration of these aspects is given in the recommendations in 22.4.6.

5.3.2.4.3 Specific symbols and abbreviations

The following specific symbols and abbreviations are used in Table 5.3.2.4-1 in addition to those in Clause 4:

E earthquake load (see 5.3.2.4.2.4);

F additional loads from piping (thermal expansion loads) (see 5.3.2.4.2.5);

$f_{B,op}$ nominal design stress for operation conditions for anchor bolts, see Formula (6.7–1);

G_{min} minimum dead loads (see 5.3.2.4.2.1);

G_{max} maximum dead loads (see 5.3.2.4.2.1);

G_{corr} corroded dead loads (see 5.3.2.4.2.1);

G_{trans} transport dead loads (see 5.3.2.4.2.1);

L live loads of each loading case (contents, etc.) (see 5.3.2.4.2.2);

P_i internal calculation pressure as defined in 5.3.10 for $P > 0$ (including hydrostatic pressure);

P_e external calculation pressure as defined in 5.3.10 for $P < 0$ (e.g. vacuum);

W wind load (see5.3.2.4.2.4);

$\sigma_{c,all}$ maximum allowable compressive stress for operation conditions in accordance with 16.14.8, with σ_e as defined in 8.4 and with a safety factor of 1,5 in Formula (16.14–29);

$\sigma_{c,all,test}$ maximum allowable compressive stress for test conditions in accordance with 16.14.8, with σ_e as defined in 8.4 and with safety factor 1,05 in Formula (16.14–29);

& operator which means: superposition of the different load types for the axial and lateral forces, the bending moments and the resulting shear and longitudinal stresses using the beam theory for non-pressure loads and the membrane theory for pressure loads.

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Table 5.3.2.4–1 — Load combinations [d]

Load Case	Types of load included	Load combination including weighting factors	Allowable tensile stress for shells	Allowable compressive stress for shells	Allowable tensile stress for anchor bolts	Explanations
LC0	P_i, G_{max}	P_i & G_{max}	f_d	$\sigma_{c,all}$	$f_{B,op}$	Operation with internal pressure
LC1	P_i, G_{max}, L, F, W	$0,9 \cdot P_i$ & G_{max} & L & F & $1,1 \cdot W$ [b]	f_d	$\sigma_{c,all}$	$f_{B,op}$	Operation with internal pressure and wind
LC2	P_e, G_{max}, L, F, W	P_e & G_{max} & L & F & $1,1 \cdot W$	f_d	$\sigma_{c,all}$	$f_{B,op}$	Operation with external pressure and wind
LC3	G_{max}, L, F, W	G_{max} & L & F & $1,1 \cdot W$	f_d	$\sigma_{c,all}$	$f_{B,op}$	Operation without pressure but with wind
LC4	G_{corr}, W	G_{corr} & $1,1 \cdot W$	f_d	$\sigma_{c,all}$	$f_{B,op}$	Shut down (no pressure, contents and thermal reactions)
LC5	G_{min}, W	G_{min} & $0,7 \cdot W$	f_d	$\sigma_{c,all}$	$f_{B,op}$	Installation
LC6	P_i, G_{max}, L, E	$0,9 \cdot P_i$ & G_{max} & L & E	f_{exp} [c]	$\sigma_{c,all,test}$	$1,2 \cdot f_{B,op}$	Operation with internal pressure and earthquake
LC7	P_e, G_{max}, L, E	P_e & G_{max} & L & E	f_{exp} [c]	$\sigma_{c,all,test}$	$1,2 \cdot f_{B,op}$	Operation with external pressure and earthquake
LC8	G_{max}, L, E	G_{max} & L & E	f_{exp} [c]	$\sigma_{c,all,test}$	$1,2 \cdot f_{B,op}$	Operation without pressure but with earthquake
LC9	P_{test}, G_{max}, L_{test}, W	P_{test} & G_{max} & L_{test} & $0,6 \cdot W$	f_{test}	$\sigma_{c,all,test}$	$f_{B,op}$	Test with test pressure, test filling and wind
LC10	G_{max}	$\geq 1,5 \cdot G_{max}$	f_{test}	$\sigma_{c,all,test}$	N/A	Lifting (Crane)
LC11	G_{trans}	[a]	f_{test}	$\sigma_{c,all,test}$	N/A	Transport

[a] Transport load case shall be taken into account on basis of manufacturer's risk analysis for the vessel, if it proves to be critical for the vessel depending on the transport way (road, ship or train). If no special regulations are specified the following transport loads shall be considered: downwards: $1,4 \cdot G_{trans}$, sidewards and upwards: $0,5 \cdot G_{trans}$ driving direction: $0,8 \cdot G_{trans}$. The transport loads shall be agreed with transport company so that the transport will not damage the vessel (see EN 12195-1).

[b] Real operating pressure may be used instead of $0,9 \cdot P_i$, if it is limited either naturally (e.g. steam temperature) or by safety related control and instrumentation system.

[c] After exceptional load case the vessel shall have re-inspection.

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Remarks

For LC1 and LC2: If more than one combination of coincident design pressure and design temperature exists then all combinations shall be investigated.

Alternatively a single combination of the maximum pressure and maximum temperature of all the cases may be used. It is not certain that the governing condition of coincident pressure and temperature is also governing for the load combinations.

For LC1 and LC6: The factor 0,9 is applied to the internal calculation pressure P_i because the internal operating pressure is normally 10 % below *PS* due to the pressure limiting device.

For LC3 and LC8: These load cases are not required when both loading cases LC1 and LC2, or LC6 and LC7 are applicable, i.e. internal and external pressure are applied.

For LC5: The wind load in this case depends on configuration at this time (with or without scaffold, platforms, insulation). The reduced factor for the wind load is in accordance with EN 1991-1-6:2005 for duration times < 12 months.

For LC9: The reduced factor for the wind load is in accordance with EN 1991-1-6:2005 for duration times < 3 d.

For LC6, LC7 and LC8: For Earthquake Loading conditions the simultaneous presence of wind loading need not be considered (see EN 1990:2023, Annex A)

For LC10 and LC11: In calculation of allowable bending stress $\sigma_{b,all}$ for transport and lifting cases according to 16.6.6, the nominal design stress f_{test} can be used instead of f and K_2 shall be set equal 1,05.

The global effect of additional piping loads on shell stresses or anchoring shall be taken into account by designer, if considered relevant.

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5.3.3 Failure modes considered in this Part

a) gross plastic deformation (GPD);

b) plastic instability (burst);

c) elastic or plastic instability (buckling);

d) progressive deformation (PD);

e) fatigue;

f) creep rupture;

g) creep deformation;

h) creep fatigue.

NOTE 1 For more detailed information on failure modes see Annex B.

NOTE 2 Plastic instability is covered by the limits on GPD.

5.3.4 Maximum allowable pressure *PS* of a vessel (or a chamber)

The maximum allowable pressure *PS* of a vessel (or a chamber), for normal operating load cases, shall be defined at a specified location. This shall be the location of connection of protective and/or limiting devices or the top of the vessel (or chamber) or, if not appropriate, any point specified.

1) For internal pressure, the maximum allowable pressure shall not be less than:
   a) the differential pressure which will exist at the same specified location in the vessel (or chamber) when the pressure relieving device starts to relieve;
   b) the maximum differential pressure which can be attained in service at the same specified location where this pressure is not limited by a relieving device;
2) For external pressure, the absolute value of the maximum allowable pressure shall not be less than:
   a) the absolute value of the differential pressure which will exist at the same specified location in the vessel (or chamber) when the pressure relieving device starts to relieve;
   b) the largest absolute value of the differential pressure which can be attained in service at the same specified location where this pressure is not limited by a relieving device.

5.3.5 Design pressure of a vessel (or a chamber)

The absolute value of the design pressure P_d for normal operating load cases shall not be smaller than the absolute value of *PS*.

5.3.6 Maximum/minimum allowable temperatures TS_{max} and TS_{min} of a vessel (or a chamber)

TS_{max} and TS_{min} shall be specified for normal operating load cases.

5.3.7 Design temperature of a vessel (or a chamber)

The design temperature T_d shall be not less than the maximum fluid temperature corresponding to the coincident design pressure.

If the maximum allowable temperature TS_{max} is below 20 °C, the design temperature shall be 20 °C.

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5.3.8 Design pressure - temperature combinations for normal operating load cases

More than one set of coincident design pressures and temperatures are permissible.

5.3.9 Design pressure-temperature combinations for testing or exceptional load cases

Design pressure-temperature combinations corresponding to testing or exceptional load cases (see 5.3.2) are also permissible.

5.3.10 Calculation pressure of a component

The calculation pressure *P* shall be based on the most severe condition of coincident differential pressure and temperature. It shall include the static and dynamic head where applicable, and shall be based on the maximum possible differential pressure in absolute value between the inside and outside of the vessel (or between the two adjacent chambers).

Vessels subject to external pressure shall be designed for the maximum differential pressure in absolute value to which the vessel may be subjected in service. Vessels subject to vacuum shall be designed for a full pressure of 0,1 MPa unless it can be shown that the amount of partial vacuum is limited, e.g. by a vacuum break valve or similar device, in which case a lower design pressure between 0,1 MPa and the set pressure of this safety device may be agreed.

5.3.11 Calculation temperature of a component

The calculation temperature *T* shall not be less than the actual metal temperature expected in service or, where the through thickness temperature variation is known, the mean wall temperature. The calculation temperature shall include an adequate margin to cover uncertainties in temperature prediction. Where different metal temperatures can confidently be predicted for different parts of the vessel, the calculation temperature for any point in the vessel may be based on the predicted metal temperature.

5.4 Design methods

5.4.1 General

This Part provides requirements for the design of pressure vessels or pressure vessel parts using design by formulae (DBF):

In addition, two series of methods may be used to supplement or replace DBF:

a) methods based on design by analysis (DBA), namely Design by Analysis – Direct Route covered by Annex B and Design by Analysis – Method based on Stress Categories, covered by Annex C;

b) methods based on experimental techniques, covered by Annex T.

5.4.2 Vessels of all testing groups, pressure loading predominantly of non-cyclic nature

The DBF requirements specified in Clauses 7 to 16, Annexes G and J, and in Clause 19 (for testing sub-groups 1c and 3c only) and the DBA requirements of Annex B and Annex C provide satisfactory designs for pressure loading of non-cyclic nature, i.e. when the number of full pressure cycles or equivalent full pressure cycles is less than or equal to 500.

$$n_{eq} \leq 500 \qquad (5.4\text{-}1)$$

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The equivalent number of full pressure cycles n_{eq} is given by:

$$n_{eq} = \sum n_i \left(\frac{\Delta P_i}{P_{max}} \right)^3 \quad (5.4\text{-}2)$$

In the above formula, P_{max} is the maximum permissible pressure P_{max} calculated for the whole vessel (see 3.16) in the normal operating load case (see 5.3.2.1).

For simplification, P_{max} may be replaced by the calculation pressure P.

NOTE The value of 500 equivalent full pressure cycles is only a rough indication. It can be assumed that for components with irregularities of profile, strongly varying local stress distributions, subjected to additional non-pressure loads, fatigue damage can occur before 500 cycles.

Cyclic thermal loads can be neglected if:

— for start-up and shutdown cycles, the number shall not exceed 2 000 and the rate of temperature change at the surface shall be less than 60 °C per hour for ferritic steel sections. The designer can specify a higher rate of surface temperature change based on favourable/good industry experience and practice;

— if the requirements of Annex U are satisfied for operating conditions.

If these conditions on pressure and thermal loads are met, then no fatigue analysis is necessary and the standard requirements of non-destructive testing given in EN 13445-5 shall be applied.

If these conditions cannot be met, then a fatigue assessment is necessary according to either Clause 17 or Clause 18

5.4.3 Vessels of testing group 4

Pressure vessels to testing group 4, as defined in EN 13445-5:2021, are intended for predominantly non-cyclic operation and calculation temperatures below the creep range. They are limited for operation up to 500 full pressure cycles or equivalent full pressure cycles.

NOTE When the number of equivalent full pressure cycles has reached 500, a hydraulic test should be performed and followed by a complete visual examination. If the test is successfully passed, then the operation can be continued for a new 500 cycles period.

5.4.4 Vessels of testing group 1, 2, and 3, working below the creep range, pressure loading of predominantly cyclic nature

If the number of full pressure cycles or equivalent full pressure cycles is likely to exceed 500, the calculations of vessels of testing group 1, 2 and 3 shall be completed by a simplified fatigue analysis, as given in Clause 17 or, if necessary, by a detailed fatigue analysis, as given in Clause 18.

In addition Clauses 17 and 18 specify conditions for the determination of critical zones where additional requirements on weld imperfections and NDT shall be applied, as defined in EN 13445-5:2021, Annex G.

5.4.5 Fatigue analysis of bellows

Specific fatigue curves are given in Clause 14 for bellows.

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5.4.6 Design by analysis

If for a part no requirement is supplied in Clauses 7 to 16, Annexes G and J, the rules given in Annexes B and C shall be applied.

The rules of Annex B, Design by Analysis – Direct Route, are applicable to vessels or vessel parts designed to testing group 1 only.

5.4.7 Experimental techniques

Experimental techniques may be used to verify the adequacy of the design. These methods may be applied without calculation when the product of the maximum allowable pressure *PS* and the volume *V* is less than 6 000 bar·L otherwise they supplement a design by formulae or a design by analysis. The rules of Annex T shall be applied.

5.4.8 Prevention of brittle fracture

Detailed recommendations to safeguard against brittle fracture of steel vessels are given in EN 13445-2:2021+A1:2023, Annex B.

5.5 Thickness calculations (DBF)

5.5.1 Determination of the required thickness

Unless otherwise stated, all design calculations shall be made in the corroded condition with a consistent set of dimensions (thickness, diameter, etc.).

The formulae in this Part comprise either:

— a direct method to give the required thickness; or

— an iterative check that the analysis thickness is adequate.

Tolerances and fabrication allowances shall be additional, as shown in Figure 5-1.

NOTE Possible limitations of the thickness may exist in requirements dealing with details.

5.5.2 Clad components

Corrosion-resistant claddings may be included in the calculation of the required wall-thickness against design pressure only in the case of cladding of integrally-bonded type (i.e. explosion cladding, weld cladding, or such other methods).

In the case of design against instability, the strength of the cladding shall not be taken into account.

DBF rules of Clauses 7 to 16 can be applied with an equivalent thickness which takes into account the presence of the cladding. The nominal design stress to use is that for the base material: f_{m1}.

If the nominal design stress of the cladding f_{m2} is greater or equal to that of the base material, the equivalent thickness e_{eq} is equal to the sum of the analysis thickness for the cladding and the base material.

$$e_{\mathrm{eq}} = e_{\mathrm{a,m1}} + e_{\mathrm{a,m2}} \tag{5.5-1}$$

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If the nominal design stress of the cladding is less than that of the base material, the equivalent thickness is:

$$e_{eq} = e_{a,m1} + e_{a,m2} \cdot \frac{f_{m2}}{f_{m1}} \quad (5.5\text{-}2)$$

where

subscript m1 is used for base material; and

subscript m2 is used for cladding.

In the fatigue analysis checks of Clauses 17 and 18, the presence of the cladding shall be considered with respect to both the thermal analysis and the stress analysis. However when the cladding is of the integrally-bonded type and the nominal thickness of the cladding is not more than 10 % of the total nominal thickness of the component, the presence of the cladding may be neglected, i.e. the model is based on the base material geometry.

5.6 Joint coefficient

For the calculation of the required thickness of certain welded components (e.g. cylinders, cones and spheres), the design formulae contain *z*, which is the joint coefficient of the governing welded joint(s) of the component.

Examples of governing welded joints are:

— longitudinal or helical welds in a cylindrical shell;

— longitudinal welds in a conical shell;

— any main weld in a spherical shell/head; and

— main welds in a dished head fabricated from two or more plates.

The following welded joints are not governing welded joints:

— circumferential weld between a cylindrical or conical shell and a cylinder, cone, flange or end other than hemispherical;

— welds attaching nozzles to shells;

— welds subjected exclusively to compressive stress.

NOTE Circumferential joints may become governing joints due to external loads.

For the normal operating load cases, the value of *z* is given in Table 5.6-1. It is related to the testing group of the governing welded joints. Testing groups are specified in EN 13445-5:2021, Clause 6.

Table 5.6-1 — Joint coefficient and corresponding testing group

z	1	0,85	0,7
Testing Group	1, 2	3	4

In parent material, away from governing joints, $z = 1$.

For exceptional and testing conditions, a value of 1 shall be used, irrespective of the testing group.

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5.7 Design requirements of welded joints

5.7.1 General requirements

The manufacturer shall choose the most suitable joints to meet the standard requirements. In particular, he shall take account of the following parameters:

— grade and properties of the metals used;

— operating conditions: e.g. loading of predominantly non-cyclic nature or cyclic nature; dangerous or corrosive fluid;

— applicable testing groups, see EN 13445-5:2021, 6.6.1.1;

— manufacturing means.

Annex A gives requirements and recommendations for pressure bearing welds. Specific requirements are included when Design by Analysis – Direct Route of Annex B is used for vessels or vessel parts working in the creep range.

5.7.2 Longitudinal joints

The components of cylindrical or conical shells, spherical components, and domed or flat ends shall be assembled by butt welding, using a welding procedure that ensures full penetration.

The mean lines of the components that form longitudinal joints of cylindrical or conical shells as well as joints on spherical shells shall be aligned in the vicinity of the welded joint within the manufacturing tolerance limits given in EN 13445-4:2021+A1:2023. Bending effects shall be taken into account in the design.

5.7.3 Circumferential joints

The mean lines of components of same thickness shall be aligned within the tolerance limits of EN 13445-4:2021+A1:2023.

The mean lines of components of different thicknesses may be non-aligned, but the offset shall not exceed the alignment of inner or outer surfaces within the tolerances limits given in EN 13445-4:2021+A1:2023.

5.7.4 Special requirements for certain types of joints

5.7.4.1 Joggle joints

Joggle joints, where used, shall satisfy the following conditions:

a) testing groups 3 or 4 for non-cyclic operation, or, in addition, testing groups 1 or 2 for cryogenic applications;

b) circumferential seams attaching head to shell; all circumferential seams for cryogenic applications;

c) materials 1.1, 1.2 or 8.1;

d) material thickness not exceeding 8 mm; 12 mm for cryogenic applications;

e) diameter not exceeding 1 600 mm, otherwise a full size weld procedure test is required for diameters exceeding 1 600 mm. The diameter of the test piece shall not be less than the nominal diameter and not be larger than twice the nominal diameter. The test shall be performed and recorded in accordance with EN ISO 15613:2004. For cryogenic applications the diameter is not limited.

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f) calculation temperature

–10 °C ≤ T ≤ 120 °C for materials 1.1 and 1.2;

–196 °C ≤ T ≤ 120 °C for materials 8.1;

–40 °C ≤ T ≤ 120 °C for materials 1.1 and 1.2, for cryogenic applications.

g) non-corrosive conditions;

h) manufacturing tolerances of EN 13445-4:2021+A1:2023.

5.7.4.2 Joints with permanent backing strips

Joints with permanent backing strips shall be allowed if the following conditions are all satisfied:

a) testing groups 3 or 4 for non-cyclic operation, or, in addition, testing groups 1 or 2 for cryogenic applications;

b) circumferential seams attaching head to shell; all circumferential seams for cryogenic applications;

c) materials 1.1, 1.2 or 8.1;

d) material thickness not exceeding 8 mm; 30 mm for cryogenic applications;

e) diameter not exceeding 1 600 mm, otherwise a full size weld procedure test is required for diameters exceeding 1 600 mm. The diameter of the test piece shall not be less than the nominal diameter and not be larger than twice the nominal diameter. The test shall be performed and recorded in accordance with EN ISO 15613:2004. For cryogenic applications the diameter is not limited.

f) calculation temperature

–10 °C ≤ T ≤ 120 °C for materials 1.1 and 1.2;

–196 °C ≤ T ≤ 120 °C for materials 8.1;

–40 °C ≤ T ≤ 120 °C for materials 1.1 and 1.2, for cryogenic applications.

g) non-corrosive conditions;

h) manufacturing tolerances of EN 13445-4:2021+A1:2023 for thicknesses not exceeding 8 mm; half of these tolerances for thicknesses exceeding 8 mm in cryogenic applications.

5.7.4.3 Lap joints

5.7.4.3.1 General case

Lap joints with fillet welds shall be used only when all the following conditions are fulfilled:

a) testing group 4;

b) circumferential joints attaching head to shell;

c) material thickness not exceeding 8 mm;

d) maximum diameter 1 600 mm;

e) materials 1.1;

f) calculation temperature:

–10 °C ≤ T ≤ 120 °C;

g) non-corrosive conditions;

h) both sides of the lap shall be welded except where indicated in Table A-2;

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i) manufacturing tolerances of EN 13445-4:2021+A1:2023.

5.7.4.3.2 Connection of bellows

Outside lap joints (weld types 1.1 and 2.1 in Table 14.4.5-1) shall be used only under non-corrosive conditions (see also Table A-9).

6 Maximum allowed values of the nominal design stress for pressure parts

6.1 General

6.1.1 This clause specifies maximum allowed values of the nominal design stress for pressure parts other than bolts and physical properties of steels.

The values to be used within the creep range are given in Clause 19.

NOTE Nominal design stresses for bolting materials are given in Clauses 11 and 12.

6.1.2 For a specific component of a vessel, i.e. specific material, specific thickness, there are different values of the nominal design stress for the normal operating, testing, and exceptional load cases.

For exceptional load cases, a higher nominal design stress may be used (see 6.1.3). The manufacturer shall prescribe, in the instructions for use, an inspection of the vessel before returning it to service after occurrence of such an exceptional case.

In assessing testing or exceptional load cases, progressive deformation and fatigue requirements need not be taken into consideration.

6.1.3 The maximum values of the nominal design stress for normal operating and testing load cases shall be determined from the material properties as specified in 6.1.5 and the safety factors given in 6.2 to 6.5. The formulae for deriving the maximum values of nominal design stresses are given in Table 6-1.

The nominal safety factor for exceptional load cases shall not be less than that for the testing load cases.

6.1.4 Special considerations may require lower values of the nominal design stress, e.g. risk of stress corrosion cracking, special hazard situations, etc.

6.1.5 For the tensile strength and the yield strength the values shall be those which apply to the materials in the final fabricated condition and shall conform to the minimum values of the technical documentation prepared in accordance with EN 13445-5:2021, Clause 5.

NOTE These values will generally be achieved when the heat treatment procedures conform to EN 13445-4:2021+A1:2023.

The minimum values, specified for the delivery condition, can be used for design purposes unless the heat treatment is known to lead to lower values, in which case these lower values shall be used. If the weld metal gives lower strength values after fabrication, these shall be used.

6.1.6 For the determination of the tensile strength and the yield strength above 20 °C procedure of EN 13445-2:2021+A1:2023, 4.2 shall be used.

6.1.7 For the definition of rupture elongation see EN 13445-2:2021+A1:2023, Clause 4.

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6.2 Steels (except castings), other than austenitic steels covered by 6.4 and 6.5, with a minimum rupture elongation, as given in the relevant technical specification for the material, below 30 %

6.2.1 Normal operating load cases

The nominal design stress for normal operating load cases f shall not exceed f_d, the smaller of the two following values:

— the minimum yield strength or 0,2 % proof strength at calculation temperature, as given in the technical specification for the material, divided by the safety factor 1,5; and

— the minimum tensile strength at 20 °C, as given in the technical specification for the material, divided by the safety factor 2,4.

6.2.2 Testing load cases

The nominal design stress for testing conditions f shall not exceed f_{test}, the minimum yield strength or 0,2 % proof strength at test temperature, as given in the technical specification for the material, divided by the safety factor 1,05.

6.3 Alternative route for steels (except castings), other than austenitic steels covered by 6.4 and 6.5, with a minimum rupture elongation, as given in the relevant technical specification for the material, below 30 %

6.3.1 General

Alternative route allows the use of higher nominal design stress with an equivalent overall level of safety if all of the following conditions are met:

a) Material requirements as specified in EN 13445-2:2021+A1:2023 for Design by Analysis – Direct Route.

b) Restriction in construction and welded joints as specified in Clause 5 and in Annex A for Design by Analysis – Direct Route.

c) All welds which must be tested by non-destructive testing (NDT) according to the requirements of EN 13445-5:2021 shall be accessible to NDT during manufacture and also for in-service inspection.

d) Fatigue analysis according to Clause 17 or 18 in all cases.

e) Fabrication requirements as specified in EN 13445-4:2021+A1:2023 for Design by Analysis – Direct Route.

f) NDT as specified in EN 13445-5:2021 for Design by Analysis – Direct Route.

g) Appropriate detailed instructions for in-service inspections are provided in the operating instructions of the manufacturer.

NOTE Until sufficient in-house experience can be demonstrated, the involvement of an independent body, appropriately qualified, is recommended for the assessment of the design (calculations) and for assurance that all requirements are met in materials, fabrication and NDT.

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6.3.2 Normal operating load cases

The nominal design stress for normal operating load cases f shall not exceed f_d, the smaller of the two following values:

— the minimum yield strength or 0,2 % proof strength at calculation temperature, as given in the technical specification for the material, divided by the safety factor 1,5; and

— the minimum tensile strength at 20 °C, as given in the technical specification for the material, divided by the safety factor 1,875.

6.3.3 Testing load cases

The nominal design stress for testing conditions f shall not exceed f_{test}, the minimum yield strength or 0,2 % proof strength at test temperature, as given in the technical specification for the material, divided by the safety factor 1,05.

6.4 Austenitic steels (except castings) with a minimum rupture elongation, A %, as given in the relevant technical specification for the material, such as $30\ \% \leq A\ \% < 35\ \%$

6.4.1 Normal operating load cases

The nominal design stress for normal operating load cases f shall not exceed f_d, the minimum 1 % proof strength at calculation temperature, as given in the technical specification for the material, divided by the safety factor 1,5.

6.4.2 Testing load cases

The nominal design stress for testing load cases f shall not exceed f_{test}, the minimum 1 % proof strength at test temperature, as given in the technical specification for the material, divided by the safety factor 1,05.

6.5 Austenitic steels (except castings) with a minimum rupture elongation, A %, as given in the relevant technical specification for the material, such as $A\ \% \geq 35\ \%$

6.5.1 Normal operating load cases

The nominal design stress for normal operating load cases f shall not exceed f_d the greater of the two values:

a) that derived from 6.4.1; or

b) if a value of $R_{m/T}$ is available, the smaller of two values:

— the minimum tensile strength at calculation temperature, as given in the technical specification for the material, divided by the safety factor 3,0; and

— the minimum 1 % proof strength at calculation temperature, as given in the technical specification for the material divided by the safety factor 1,2.

6.5.2 Testing load cases

The nominal design stress for testing load cases f shall not exceed f_{test}, the greater of the two values:

a) the value derived from 6.4.2; and

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b) the minimum tensile strength at test temperature, as given in the technical specification for the material, divided by the safety factor 2.

6.6 Cast steels

6.6.1 Normal operating load cases

The nominal design stress for normal operating load cases f shall not exceed f_d, the smaller of the following two values:

— the minimum yield strength or 0,2 % proof strength at calculation temperature, as given in the technical specification for the material divided by the safety factor 1,9;

— the minimum tensile strength at 20 °C, as given in the technical specification for the material, divided by the safety factor 3,0.

6.6.2 Testing load cases

The nominal design stress for testing load cases f shall not exceed f_{test}, the minimum yield strength or 0,2 % proof strength at test temperature, as given in the technical specification for the material, divided by the safety factor 1,33.

NOTE Physical properties of steels are given in Annex O.

Table 6-1 — Maximum allowed values of the nominal design stress for pressure parts other than bolts

Steel designation	Normal operating load cases [a]	Testing and exceptional load cases [a] [b]
Steels other than austenitic, as per 6.2 $A \leq 30$ %[c]	$f_d = \min\left(\frac{R_{p0,2/T}}{1,5}; \frac{R_{m/20}}{2,4}\right)$	$f_{test} = \left(\frac{R_{p0,2/T_{test}}}{1,05}\right)$
Steels other than austenitic, as per 6.3: Alternative route $A < 30$ % [c]	$f_d = \min\left(\frac{R_{p0,2/T}}{1,5}; \frac{R_{m/20}}{1,875}\right)$	$f_{test} = \left(\frac{R_{p0,2/T_{test}}}{1,05}\right)$
Austenitic steels as per 6.4 30 % ≤ A < 35 % [c]	$f_d = \left(\frac{R_{p1,0/T}}{1,5}\right)$	$f_{test} = \left(\frac{R_{p1,0/T_{test}}}{1,05}\right)$
Austenitic steels as per 6.5 $A \geq 35$ %[c]	$f_d = \max\left[\left(\frac{R_{p1,0/T}}{1,5}\right); \min\left(\frac{R_{p1,0/T}}{1,2}; \frac{R_{m/T}}{3}\right)\right]$	$f_{test} = \max\left[\frac{R_{p1,0/T_{test}}}{1,05}; \frac{R_{m/T_{test}}}{2}\right]$
Cast steels as per 6.6	$f_d = \min\left(\frac{R_{p0,2/T}}{1,9}; \frac{R_{m/20}}{3}\right)$	$f_{test} = \left(\frac{R_{p0,2/T_{test}}}{1,33}\right)$

[a] Yield strength R_{eH} may be used instead of $R_{p0,2}$ if the latter is not available from the material standard.

[b] See 5.3.2 and 6.1.2.

[c] For definition of rupture elongation, see EN 13445-2:2021+A1:2023, Clause 4.

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6.7 Nominal design stress of anchor bolting

The nominal design stress for the anchor bolts for the operation condition shall be calculated as follows:

$$f_{B,op} = \min\left(\frac{R_{p0,2/TB}}{1,65}; \frac{R_{m/20}}{2,0625}\right) \quad (6.7\text{-}1)$$

where

TB is design temperature for anchor bolts.

NOTE In most cases the design temperature *TB* of the anchor bolts will be 20 °C and will generally be much lower than the design temperature of the vessel.

7 Shells under internal pressure

7.1 Purpose

This clause provides requirements for design against internal pressure of axisymmetric shells - cylinders, spheres, parts of spheres, dished ends, cones and cone to cylinder intersections. Methods are also provided for the design of offset cones connecting two cylinders and for nozzles encroaching into the knuckle region of dished ends.

7.2 Specific definitions

The following definitions apply in addition to those in Clause 3.

7.2.1
cylinder
right circular cylinder

7.2.2
torispherical end
dished end, made up of a spherical cap, a toroidal knuckle and a cylindrical shell, the three components having common tangents where they meet

7.2.3
Kloepper type
torispherical end for which R/D_e = 1,0 and r/D_e = 0,1

7.2.4
Korbbogen type
torispherical end for which R/D_e = 0,8 and r/D_e = 0,154

7.2.5
ellipsoidal end
dished end made on a truly ellipsoidal former

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7.3 Specific symbols and abbreviations

The following symbols and abbreviations apply in addition to those in Clause 4:

D_e is the outside diameter of shell;

D_i is the inside diameter of shell;

D_m is the mean diameter of shell;

r is the inside radius of curvature of a knuckle.

7.4 Cylindrical and spherical shells

7.4.1 Conditions of applicability

The rules in 7.4.2 and 7.4.3 are valid for e/D_e not greater than 0,16. The rules for spheres apply also to spherical parts of shells, hemispherical ends, the central zones of torispherical ends, and that part of a sphere used to join a cone and a cylinder (a knuckle of r/D_i = 0,5).

NOTE 1 The rules in 7.4.2 and 7.4.3 may be used for larger ratios if accompanied by a detailed fatigue analysis.

NOTE 2 The thickness given by this section is a minimum. Thickness may have to be increased at junctions with other components, or to provide additional reinforcement at nozzles or openings, or to carry non-pressure loads.

7.4.2 Cylindrical shells

The required thickness shall be calculated from one of the following two formulae:

$$e = \frac{P \cdot D_i}{2f \cdot z - P} \tag{7.4-1}$$

or

$$e = \frac{P \cdot D_e}{2f \cdot z + P} \tag{7.4-2}$$

For a given geometry:

$$P_{max} = \frac{2f \cdot z \cdot e_a}{D_m} \tag{7.4-3}$$

NOTE For application of this formula to different load cases, see 3.16, Note 1.

7.4.3 Spherical shells

The required thickness shall be calculated from one of the following two formulae.

$$e = \frac{P \cdot D_i}{4f \cdot z - P} \tag{7.4-4}$$

or

$$e = \frac{P \cdot D_e}{4f \cdot z + P} \tag{7.4-5}$$

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For a given geometry:

$$P_{max} = \frac{4 f \cdot z \cdot e_a}{D_m} \quad (7.4\text{-}6)$$

NOTE For application of this formula to different load cases, see 3.16, Note 1.

7.5 Dished ends

7.5.1 Specific symbols and abbreviations

The following symbols and abbreviations apply in addition to or modify those in 7.3:

D_e is the outside diameter of the cylindrical flange;

D_i is the inside diameter of the cylindrical flange;

e_b is required thickness of knuckle to avoid plastic buckling;

e_s is required thickness of end to limit membrane stress in central part;

e_y is required thickness of knuckle to avoid axisymmetric yielding;

f_b is design stress for buckling formula;

h_i is inside height of end measured from the tangent line;

K is shape factor for an ellipsoidal end as defined in Formula (7.5-18);

N is a parameter defined by Formula (7.5-12);

R is inside spherical radius of central part of torispherical end;

X is ratio of knuckle inside radius to shell inside diameter;

Y is a parameter defined by Formula (7.5-9);

Z is a parameter defined by Formula (7.5-10);

β is a factor given by Figures 7.5-1 and 7.5-2 or by the procedure in 7.5.3.5.

7.5.2 Hemispherical ends

The required thickness of a hemispherical end is given by the formulae in 7.4.3. The mean radius of the end shall be nominally the same as that of the cylinder to which it is welded. The thickness of the cylinder up to the tangent line shall be kept at or above the minimum for the cylinder in accordance with to 7.4.2.

7.5.3 Torispherical ends

7.5.3.1 Conditions of applicability

The following requirements are limited in application to ends for which all the following conditions are met:

$r \leq 0{,}2\ D_i$

$r \geq 0{,}06\ D_i$

$r \geq 2e$

$e \leq 0{,}08\ D_e$

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$e_a \geq 0{,}001\ D_e$

$R \leq D_e$

7.5.3.2 Design

The required thickness e shall be the greatest of e_s, e_y and e_b, where:

$$e_s = \frac{P \cdot R}{2f \cdot z - 0{,}5P} \tag{7.5-1}$$

$$e_y = \frac{\beta \cdot P \cdot (0{,}75R + 0{,}2D_i)}{f} \tag{7.5-2}$$

where

β is found from Figure 7.5-1 or the procedure in 7.5.3.5, replacing e by e_y.

and

$$e_b = (0{,}75R + 0{,}2D_i) \cdot \left[\frac{P}{111 f_b} \cdot \left(\frac{D_i}{r} \right)^{0{,}825} \right]^{\left(\frac{1}{1{,}5}\right)} \tag{7.5-3}$$

where

$$f_b = \frac{R_{p0,2/T}}{1{,}5} \tag{7.5-4}$$

except for cold spun seamless austenitic stainless steel, where:

$$f_b = \frac{1{,}6 R_{p0,2/T}}{1{,}5} \tag{7.5-5}$$

At test conditions the value 1,5 in the formulae for f_b shall be replaced by 1,05.

NOTE 1 For stainless steel ends that are not cold spun, f_b will be less than f.

NOTE 2 The 1,6 factor for cold spun ends takes account of strain hardening.

NOTE 3 It is not necessary to calculate e_b if $e_y > 0{,}005 D_i$.

NOTE 4 The inside height of a torispherical end is given by $h_i = R - \sqrt{(R - D_i/2) \cdot (R + D_i/2 - 2r)}$

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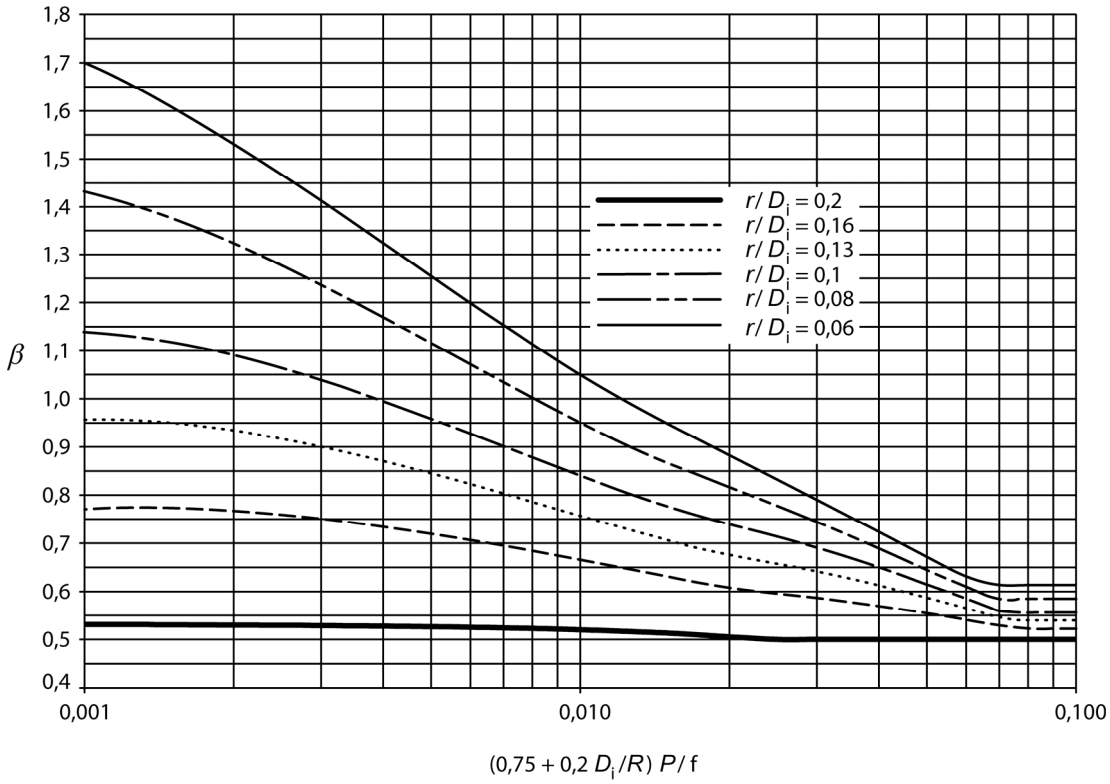


Figure 7.5-1 — Parameter β for torispherical end – design

7.5.3.3 Rating

For a given geometry P_{max} shall be the least of P_s, P_y and P_b, where:

$$P_s = \frac{2f \cdot z \cdot e_a}{R + 0{,}5e_a} \tag{7.5-6}$$

$$P_y = \frac{f \cdot e_a}{\beta \cdot \left(0{,}75R + 0{,}2D_i\right)} \tag{7.5-7}$$

where

β is found from Figure 7.5-2 or the procedure in 7.5.3.5, replacing e by e_a.

$$P_b = 111 f_b \cdot \left(\frac{e_a}{0{,}75R + 0{,}2D_i}\right)^{1{,}5} \cdot \left(\frac{r}{D_i}\right)^{0{,}825} \tag{7.5-8}$$

NOTE 1 For application of the above Formulae to different load cases, see 3.16, Note 1.

NOTE 2 It is not necessary to calculate P_b if $e_a > 0{,}005D_i$.

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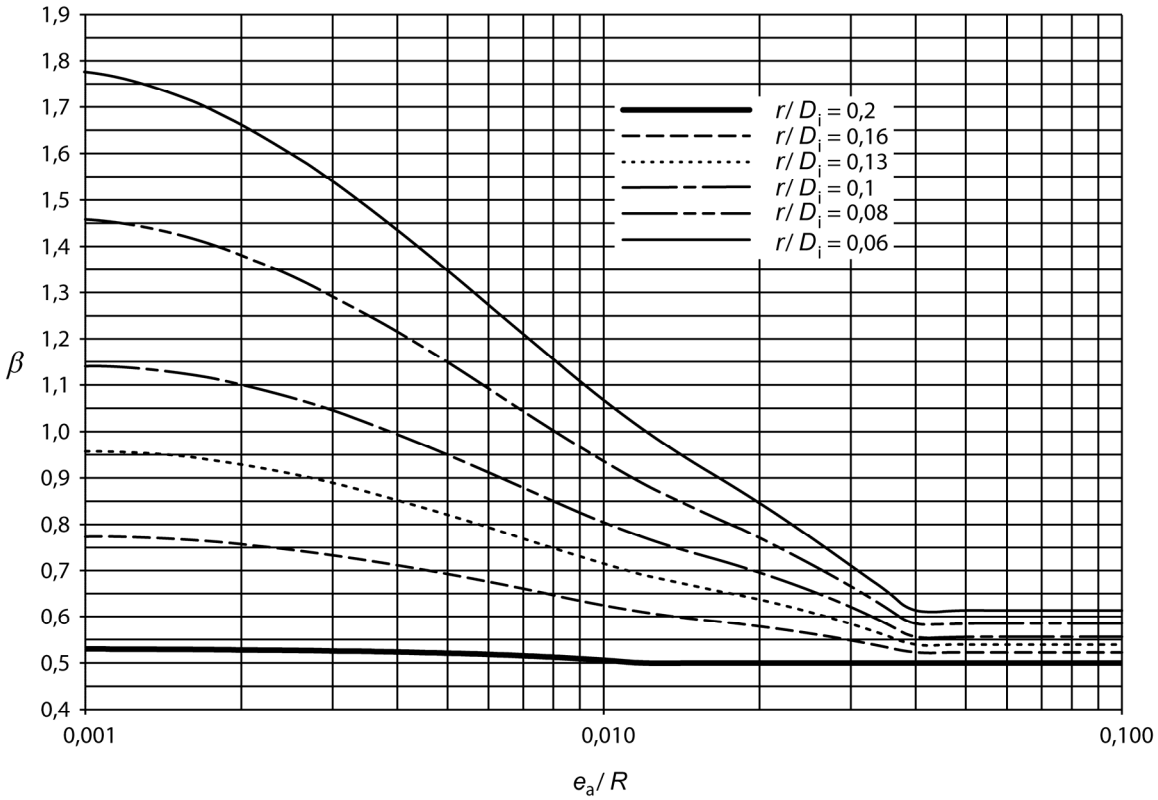


Figure 7.5-2 — Parameter β for torispherical end – rating

7.5.3.4 Exceptions

It is permissible to reduce the thickness of the spherical part of the end to the value e_s over a circular area that shall not come closer to the knuckle than the distance $\sqrt{R \cdot e}$, as shown in Figure 7.5-3.

Any straight cylindrical flange shall meet the requirements of 7.4.2 for a cylinder, if its length is greater than $0,2\sqrt{D_i \cdot e}$. When the length is equal to or smaller than $0,2\sqrt{D_i \cdot e}$, it may be the same thickness as required for the knuckle.

7.5.3.5 Formulae for calculation of factor β

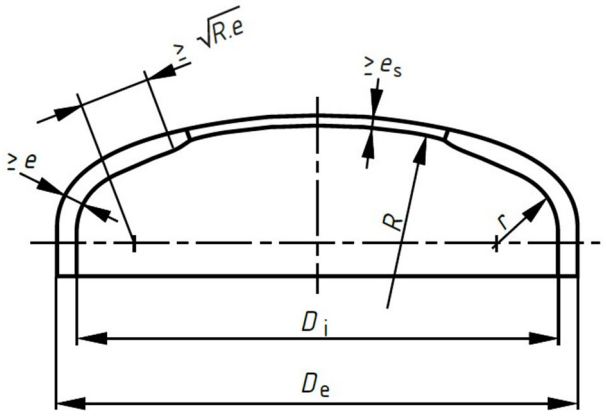


Figure 7.5-3 — Geometry of torispherical end

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$$Y = \min\left(e/R\,;0{,}04\right) \tag{7.5-9}$$

$$Z = \log_{10}\left(1/Y\right) \tag{7.5-10}$$

$$X = r/D_{\mathrm{i}} \tag{7.5-11}$$

$$N = 1{,}006 - \frac{1}{\left\{6{,}2 + \left(90Y\right)^4\right\}} \tag{7.5-12}$$

For X = 0,06

$$\beta_{0{,}06} = N\left(-0{,}3635Z^3 + 2{,}2124Z^2 - 3{,}2937Z + 1{,}8873\right) \tag{7.5-13}$$

For 0,06 < X < 0,1

$$\beta = 25\left\{\left(0{,}1 - X\right)\cdot\beta_{0{,}06} + \left(X - 0{,}06\right)\cdot\beta_{0{,}1}\right\} \tag{7.5-14}$$

For X = 0,1

$$\beta_{0{,}1} = N\left(-0{,}1833Z^3 + 1{,}0383Z^2 - 1{,}2943Z + 0{,}837\right) \tag{7.5-15}$$

For 0,1 < X < 0,2

$$\beta = 10\left\{\left(0{,}2 - X\right)\cdot\beta_{0{,}1} + \left(X - 0{,}1\right)\cdot\beta_{0{,}2}\right\} \tag{7.5-16}$$

For X = 0,2

$$\beta_{0{,}2} = \max\left\{0{,}95\left(0{,}56 - 1{,}94Y - 82{,}5Y^2\right);0{,}5\right\} \tag{7.5-17}$$

NOTE When used in 7.5.3.2 the above formulae for β lead to an iterative calculation. A computer procedure is recommended.

7.5.4 Ellipsoidal ends

These requirements apply only to ends for which 1,7 < K < 2,2.

$$K = D_{\mathrm{i}}/\left(2h_{\mathrm{i}}\right) \tag{7.5-18}$$

Ellipsoidal ends shall be designed as nominally equivalent torispherical ends with:

$$r = D_{\mathrm{i}}\cdot\left\{\left(0{,}5/K\right) - 0.08\right\} \tag{7.5-19}$$

and

$$R = D_{\mathrm{i}}\cdot\left(0{,}44K + 0{,}02\right) \tag{7.5-20}$$

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7.6 Cones and conical ends

7.6.1 Conditions of applicability

Requirements are given in 7.6.4 to 7.6.8 for right circular cones and cone/cylinder intersections where the cone and the cylinder are on the same axis of rotation. Requirements for offset cones are given in 7.6.9.

The requirements do not apply to:

a) cones for which the half angle at the apex of the cone is greater that 75°;

b) cones for which;

$$\frac{e_a \cdot \cos\alpha}{D_c} \leq 0{,}001 \qquad (7.6\text{-}1);$$

c) short cones joining a jacket to a shell.

Limits on the minimum distance from other major discontinuities are given in individual subclauses.

7.6.2 Specific definitions

The following definition applies in addition to those in 7.2.

7.6.2.1

junction between the cylinder and the cone

intersection of the mid-thickness lines of cylinder and cone, extended if necessary where there is a knuckle (see Figure 7.6-1 and Figure 7.6-2 for examples at the large end)

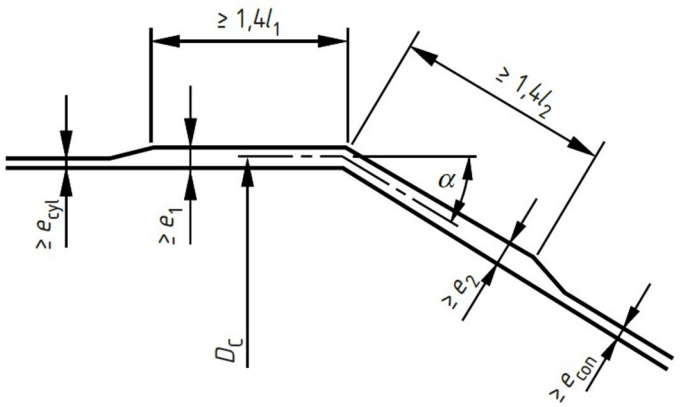


Figure 7.6-1 — Geometry of cone/cylinder intersection without knuckle – Large end

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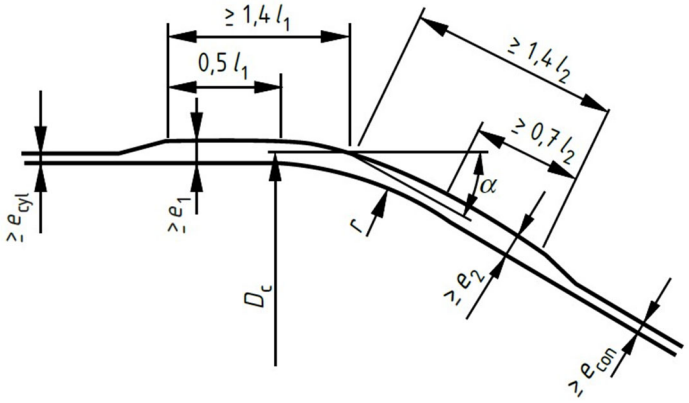


Figure 7.6-2 — Geometry of cone/cylinder intersection with knuckle – Large end

7.6.3 Specific symbols and abbreviations

The following symbols and abbreviations are in addition to or modify those in 7.3:

D_c is the mean diameter of the cylinder at the junction with the cone;

D_e is the outside diameter of the cone;

D_i is the inside diameter of the cone;

D_K is a diameter given by Formula (7.6-8);

D_m is the mean diameter of the cone;

e_{con} is required thickness of cone as determined in 7.6.4;

$e_{con,a}$ the analysis thickness of the conical shell;

e_{cyl} is required thickness of cylinder as determined in 7.4.2;

e_j is a required or analysis thickness at a junction at the large end of a cone;

e_1 is required thickness of cylinder at junction;

e_{1a} is analysis reinforcing thickness in cylinder;

e_2 is required thickness of cone and knuckle at junction;

e_{2a} is analysis reinforcing thickness in cone;

f is the nominal design stress. In the design of junctions to 7.6.6 to 7.6.9 it is the lowest of the values for the individual component parts;

l_1 is length along cylinder;

l_2 length along cone at large or small end;

r is the knuckle radius;

α is the semi angle of cone at apex (degrees);

β is a factor defined in 7.6.6;

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β_H is a factor defined in 7.6.8;

γ is a factor defined in 7.6.7;

ρ is a factor defined in 7.6.7;

τ is a factor defined in 7.6.8.

7.6.4 Conical shells

The required thickness at any point along the length of a cone shall be calculated from one of the following two formulae:

$$e_{con} = \frac{P \cdot D_i}{2f \cdot z - P} \cdot \frac{1}{\cos\alpha} \quad (7.6\text{-}2)$$

or

$$e_{con} = \frac{P \cdot D_e}{2f \cdot z + P} \cdot \frac{1}{\cos\alpha} \quad (7.6\text{-}3)$$

where

D_i and D_e are at the point under consideration.

For a given geometry:

$$P_{max} = \frac{2f \cdot z \cdot e_{con,a} \cdot \cos\alpha}{D_m} \quad (7.6\text{-}4)$$

where

D_m is at the point under consideration.

NOTE For application of the above Formulae to different load cases, see 3.16, Note 1.

At the large end of a cone attached to a cylinder it is permissible to make the following substitutions:

$$D_i = D_K \quad (7.6\text{-}5)$$

$$D_e = D_K + 2e_2 \cdot \cos\alpha \quad (7.6\text{-}6)$$

$$D_m = \left(D_i + D_e\right)/2 \quad (7.6\text{-}7)$$

where

$$D_K = D_c - e_1 - 2r \cdot \left(1 - \cos\alpha\right) - l_2 \cdot \sin\alpha \quad (7.6\text{-}8)$$

NOTE 1 The thickness given by this section is a minimum. Thickness may have to be increased at junctions with other components, or to provide reinforcement at nozzles or openings, or to carry non-pressure loads.

NOTE 2 Since the thickness calculated above is the minimum allowable at that point along the cone, it is permissible to build a cone from plates of different thickness provided that at every point the minimum is achieved.

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7.6.5 Junctions - general

The requirements of 7.6.6, 7.6.7 and 7.6.8 apply when the junction is more than $2l_1$ along the cylinder and $2l_2$ along the cone from any other junction or major discontinuity, such as another cone/cylinder junction or a flange, where:

$$l_1 = \sqrt{D_c \cdot e_1} \tag{7.6-9}$$

$$l_2 = \sqrt{\frac{D_c \cdot e_2}{\cos\alpha}} \tag{7.6-10}$$

If this requirement for the distance to another cone/cylinder junction is not fulfilled a conical shell and conical transition without knuckles may be designed according to 16.15.

7.6.6 Junction between the large end of a cone and a cylinder without a knuckle

7.6.6.1 Conditions of applicability

The requirements of 7.6.6.2 and 7.6.6.3 apply provided that the following condition is satisfied: the joint is a butt weld where the inside and outside surfaces merge smoothly with the adjacent cone and cylinder without local reduction in thickness.

NOTE Specific NDT rules apply in EN 13445-5:2021 when the design is such that the thickness at the weld does not exceed $1{,}4e_j$.

7.6.6.2 Design

The required thickness e_1 of the cylinder adjacent to the junction is the greater of e_{cyl} and e_j,where e_j shall be determined by the following procedure:

Assume a value of e_j and calculate:

$$\beta = \frac{1}{3}\sqrt{\frac{D_c}{e_j}} \cdot \frac{\tan\alpha}{1+1/\sqrt{\cos\alpha}} - 0{,}15 \tag{7.6-11}$$

$$e_j = \frac{P \cdot D_c \cdot \beta}{2f} \tag{7.6-12}$$

The thickness given by Formula (7.6-12) is an acceptable thickness if not less than the value assumed.

NOTE The minimum required value for e_j can be obtained by iterative application of this procedure, until Formula (7.6-12) gives the same value as that assumed.

β can also be read from the graph in Figure 7.6-3.

This thickness shall be maintained for a distance of at least $1{,}4l_1$ from the junction along the cylinder.

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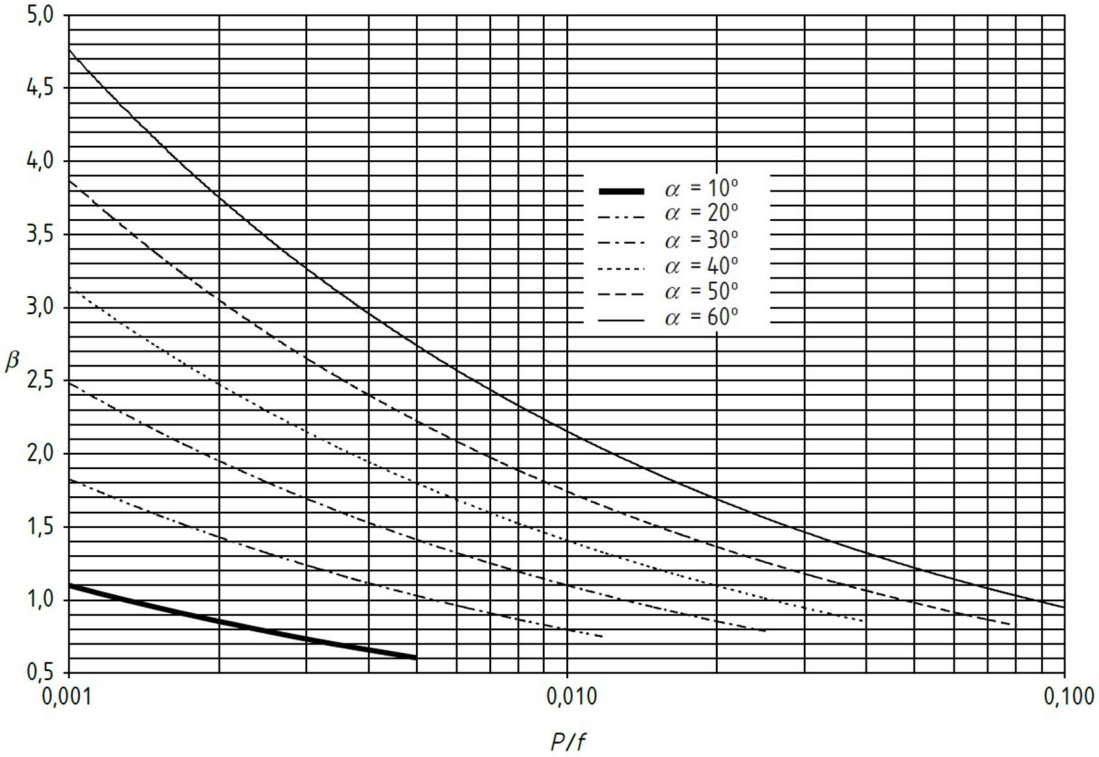


Figure 7.6-3 — Values of coefficient β for cone/cylinder intersection without knuckle

The required thickness e_2 of the cone adjacent to the junction is the greater of e_{con} and e_j. This thickness shall be maintained for a distance of at least $1{,}4l_2$ from the junction along the cone, see Figure 7.6-1.

It is permissible to redistribute the reinforcement in the following way, provided that the minimum thicknesses given by 7.4.2 and 7.6.4 continue to be met.

The thickness for the cylinder may be increased near the junction and reduced further away provided that the cross-sectional area of metal provided by the cylinder within a distance $1{,}4l_1$ from the junction is not less than $1{,}4e_1 \cdot l_1$. In addition, the thickness of the cone may be increased near the junction and reduced further away provided that the cross-sectional area of metal provided by the cone within a distance $1{,}4l_2$ from the junction is not less than $1{,}4e_2 \cdot l_2$.

7.6.6.3 Rating

The maximum permissible pressure for a given geometry shall be determined as follows:

a) apply Formula (7.4-3) to cylinder;

b) apply Formula (7.6-4) to the cone;

c) determine the analysis reinforcing thickness e_{1a} of the cylinder at the junction;

d) determine the analysis reinforcing thickness e_{2a} of the cone at the junction;

e) apply Formula (7.6-4) with thickness e_{2a} and diameter D_m;

f) find e_j, the lesser of e_{1a} and e_{2a};

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g) calculate β from Formula (7.6-11), then,

$$P_{max} = \frac{2f \cdot e_j}{\beta \cdot D_c} \cdot \quad (7.6\text{-}13)$$

a) the maximum permissible pressure is the lowest of the pressures determined in a), b), e) and g).

NOTE The following procedure may be used to find the analysis reinforcing thickness at c) or d) above:

1) Assume e_{1a} (the initial choice should be the thickness at the junction).
2) Calculate

$$l_1 = 1,4\sqrt{D_c \cdot e_{1a}} \quad (7.6\text{-}14)$$

3) If the thickness is constant within the distance l_1 then e_{1a} is confirmed.
4) If not, calculate the metal area A_1 within the distance l_1 from the junction.
5) Obtain a better estimate by:

$$e_{1a} = A_1 / l_1 \quad (7.6\text{-}15)$$

6) The answer is acceptable if it is not greater than assumed in 1).
7) If the answer is unacceptable, return to 1).
8) Use a similar procedure to find e_{2a} making.

$$l_2 = 1,4\sqrt{\frac{D_c \cdot e_{2a}}{\cos\alpha}} \quad (7.6\text{-}16)$$

7.6.7 Junction between the large end of a cone and a cylinder with a knuckle

7.6.7.1 Conditions of applicability

This subclause applies provided that all the following conditions are satisfied:

a) the knuckle is of toroidal form and merges smoothly with the adjacent cone and cylinder, and;

b) the inside radius of curvature of the knuckle, $r < 0,3\ D_c$.

NOTE This subclause does not prescribe a lower limit to the radius of curvature of the knuckle.

7.6.7.2 Design

The value of e_j shall be determined by the following procedure:

Assume a value of e_j and calculate:

$$\beta = \frac{1}{3}\sqrt{\frac{D_c}{e_j}} \cdot \frac{\tan\alpha}{1 + 1/\sqrt{\cos\alpha}} - 0,15 \quad (7.6\text{-}17)$$

$$\rho = \frac{0,028r}{\sqrt{D_c \cdot e_j}} \times \frac{\alpha}{1 + 1/\sqrt{\cos\alpha}} \quad (7.6\text{-}18)$$

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$$\gamma = 1 + \frac{\rho}{1{,}2\left(1 + \frac{0{,}2}{\rho}\right)} \tag{7.6-19}$$

$$e_j = \frac{P \cdot D_c \cdot \beta}{2f \cdot \gamma} \tag{7.6-20}$$

The thickness given by Formula (7.6-20) is an acceptable thickness for the knuckle if not less than the value assumed.

NOTE The minimum required value for e_j can be obtained by iterative application of this procedure, until Formula (7.6-20) gives the same value as that assumed.

The required thickness e_1 of the cylinder adjacent to the junction is the greater of e_{cyl} and e_j.

This thickness shall be maintained for a distance of at least $1{,}4l_1$ from the junction and $0{,}5l_1$ from the knuckle/cylinder tangent line along the cylinder.

The required thickness e_2 of the knuckle and the cone adjacent to the junction is the greater of e_{con} and e_j. This thickness shall be maintained for a distance of at least $1{,}4l_2$ from the junction and $0{,}7l_2$ from the cone/knuckle tangent line along the cone.

7.6.7.3 Rating

The maximum permissible pressure for a given geometry shall be determined as follows:

a) Determine e_{1a}, the analysis thicknesses for the cylinder next to the knuckle, and e_{2a}, the analysis thickness for the knuckle and the adjacent part of the cone;

b) Check that the limitations of 7.6.7.1 are met;

c) Apply Formula (7.4-3) to the cylinder with $e_a = e_{1a}$;

d) Apply Formula (7.6-4) to the cone with $e_{con,a} = e_{2a}$;

e) Find e_j, the lesser of e_{1a} and e_{2a};

f) Find β and γ from Formulae (7.6-17) and (7.6-19), then

$$P_{max} = \frac{2f \cdot \gamma \cdot e_j}{\beta \cdot D_c} \tag{7.6-21}$$

g) The maximum permissible pressure is the lowest of the pressures determined in c), d) and f).

7.6.8 Junction between the small end of a cone and a cylinder

7.6.8.1 Conditions of applicability

The requirements of 7.6.8.2 and 7.6.8.3 apply provided that all the following conditions are satisfied:

a) the required thickness of the cylinder e_1 is maintained for a distance l_1 and that of the cone e_2 is maintained for a distance l_2 from the junction (see Figure 7.6-4); and

b) the thicknesses meet the requirements of 7.4.2 and 7.6.4.

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