BRITISH STANDARD

BS EN 13445-3:2002
Incorporating Corrigendum No. 1

Unfired pressure vessels —

Part 3: Design

The European Standard EN 13445-3:2002 has the status of a British Standard

ICS 23.020.30

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Full document details: BS EN 13445-3:2002 Unfired pressure vessels — Part 3: Design, Incorporating Corrigendum No. 1

National foreword

This British Standard is the official English language version of EN 13445-3:2002.

CEN letter of correction June 2002 reissued pp97, 468, 653, 665 and 666 of EN 13445-3:2002. These changes to the original EN were incorporated on publication of the BS EN and are indicated in the text by a sideline.

CEN letter of correction November 2002 reissued pp4, 5, 197, 244 and 692 and CEN letter of correction February 2003 reissued pp86, 100, 137, 140 and 353 of EN 13445-3:2002. Changes to the original EN are indicated by a sideline.

CEN operate a system in which corrigenda are issued and numbered biannually. Therefore if there is no corrigendum issued for the English version of a standard, an issue number may still be used for the French or German language versions. To determine whether you have the latest edition of a page, please consult the index at http://www.unm.asso.fr/EN13445EN/.

When the reference to this European Standard has been published in the Official Journal of the European Communities (OJ), compliance with it will confer a presumption of conformity with the essential requirements covered by the standard in respect of the Pressure Equipment Directive (97/23/EC).

The UK participation in its preparation was entrusted by Technical Committee PVE/1, Pressure vessels, to Subcommittee PVE/1/15, Design methods, which has the responsibility to:

— aid enquirers to understand the text;

— present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep the UK interests informed;

— monitor related international and European developments and promulgate them in the UK.

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

Cross-references

The British Standards which implement international or European publications referred to in this document may be found in the *BSI Catalogue* under the section entitled "International Standards Correspondence Index", or by using the "Search" facility of the *BSI Electronic Catalogue* or of British Standards Online.

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This British Standard, having been prepared under the direction of the Engineering Sector Policy and Strategy Committee, was published under the authority of the Standards Policy and Strategy Committee on 12 July 2002

Summary of pages

This document comprises a front cover, an inside front cover, the EN title page, pages 2 to 707 and a back cover.

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EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN 13445-3

May 2002

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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 23 May 2002.

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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.

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Foreword

This document (EN 13445-3:2002) 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 November 2002, and conflicting national standards shall be withdrawn at the latest by November 2002.

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association, and supports essential requirements of EU Directive 97/23/EC.

For relationship with EU Directive(s), see informative Annex ZA, which is an integral part of this document.

In this standard the Annexes A, B, C, E, F, G, J, P and Q are normative and the Annexes D, H, I, K, L, M, N and O are informative.

This European Standard consists of the following Parts:

— *Part 1: General.*

— *Part 2: Materials.*

— *Part 3: Design.*

— *Part 4: Fabrication.*

— *Part 5: Inspection and Testing.*

— *Part 6: Requirements for the design and fabrication of pressure vessels and pressure parts constructed from spheroidal graphite cast iron.*

CR 13445-7, *Unfired pressure vessels - Part 7: Guidance on the use of conformity assessment procedures.*

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

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1 Scope

This Part of this European Standard specifies requirements for the design of unfired pressure vessels covered by EN 13445-1:2002 and constructed of steels in accordance with EN 13445-2:2002.

EN 13445-5:2002, Annex C specifies requirements for the design of access and inspection openings, closing mechanisms and special locking elements.

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 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 288-8:1995, *Specification and approval of welding procedures for metallic materials — Part 8: Approval by a pre-production welding test.*

prEN 764-1:2001, *Pressure equipment — Terminology — Part 1: Pressure, temperature, volume, nominal size*

EN 764-2:2002, *Pressure equipment — Part 2: Quantities, symbols and units*

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

EN 1092, *Flanges and their joints. Circular flanges for pipes, valves, fittings and accessories, PN-designated.*

EN 1591-1:2001, *Flanges and their joints - Design rules for gasketed circular flange connections – Calculation method.*

EN 1708-1:1999, *Welding - Basic weld joint details in steel – Part 1: Pressurized components*

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

EN ISO 4014, *Hexagon head bolts — Product grades A and B (ISO 4014:1999).*

EN ISO 4016, *Hexagon head bolts — Product grade C (ISO 4016:1999).*

3 Terms and definitions

For the purposes of this Part of this European Standard, the terms and definitions given in EN 13445-1:2002, EN 13445-2:2002 and the following apply:

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 loadings in corroded condition

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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 calculations of a component

[prEN 764-1:2001]

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

[prEN 764-1:2001]

3.6
chamber
single fluid space within a unit of pressure equipment

[prEN 764-1:2001]

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

[prEN 764-1:2001]

3.8
cryogenic applications
applications involving liquefied gases at low temperature

3.9
design pressure
pressure at the top of each chamber of the pressure equipment chosen for the derivation of the calculation pressure of each component

[prEN 764-1:2001]NOTE Any other location may be specified.

3.10
design temperature
temperature chosen for the derivation of the calculation temperature of each component

[prEN 764-1:2001]

3.11
differential pressure
pressure for which the algebraic value is equal to the difference of pressure on both sides of a component

[prEN 764-1:2001]

3.12
governing weld joint
main full penetration butt joint the design of which, as a result of membrane stresses, governs the thickness of the component

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3.13
load case
combination of coincident actions

3.14
main joint
weld joint assembling main pressure bearing parts

3.15
maximum permissible pressure
pressure obtained with the analysis thickness at the calculation temperature for a given component from the design by formulae

3.16
minimum possible fabrication thickness
minimum possible thickness after fabrication

3.17
nominal design stress
stress value to be used in the formulae for the calculation of pressure components

3.18
nominal thickness
thickness as specified on the drawings

3.19
test pressure
pressure at which the equipment is subjected for test purposes

[prEN 764-1:2001]

3.20
test temperature
temperature at which the pressure test of the pressure equipment is carried out

[prEN 764-1:2001]

3.21
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)

NOTE EN 13445-1:2002 and EN 13445-2:2002 have adopted terminology, symbols and definitions of prEN 764-1:2001, EN 764-2:2002:2002 and EN 764-3:2002:2002.

4 Symbols and abbreviations

For the purposes of this Part of this European Standard, the general symbols and abbreviations shall be in accordance with EN 13445-1:2002, EN 13445-2:2002 and Table 4-1:

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

Symbol	Quantity	Unit
e	required thickness	mm
e_n	nominal thickness	mm
e_{min}	minimum possible fabrication thickness	mm
e_a	analysis thickness	mm
c	corrosion or erosion allowance	mm
f	nominal design stress	MPa or N/mm²
f_d	maximum value of the nominal design stress for normal operating load cases	MPa or N/mm²
f_{exp}	maximum value of the nominal design stress for exceptional load cases	MPa or N/mm²
f_{test}	maximum value of the nominal design stress for testing load cases	MPa or N/mm²
n_{eq}	number of equivalent full pressure cycles (see 5.4.2)	-
P	calculation pressure	MPa or N/mm² [a]
P_d	design pressure	MPa or N/mm² [a]
P_{max}	maximum permissible pressure	MPa or N/mm² [a]
PS ; P_s	maximum allowable pressure	MPa or N/mm² [a]
P_{test}	test pressure	MPa or N/mm² [a]
R_{eH}	minimum upper yield strength	MPa or N/mm²
R_m	minimum tensile strength	MPa or N/mm²
$R_{m/t}$	minimum tensile strength at temperature t in °C	MPa or N/mm²
$R_{p0,2}$	minimum 0,2 % proof strength	MPa or N/mm²
$R_{p0,2/t}$	minimum 0,2 % proof strength at temperature t in °C	MPa or N/mm²
$R_{p1,0}$	minimum 1,0 % proof strength	MPa or N/mm²
$R_{p1,0/t}$	minimum 1,0 % proof strength at temperature t in °C	MPa or N/mm²
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 of a vessel (or a chamber)	mm³ [b]
z	weld joint coefficient	—
ν	Poisson's ratio	—

[a] MPa or N/mm² for calculation purpose only, otherwise the unit may be bar (1 MPa = 1 N/mm²).

[b] mm³ 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

The requirements in clause 5 shall apply when:

a) the materials and welds are not subject to localized corrosion in the presence of products which the vessel is to contain; and

b) the design is outside the creep range. Unless otherwise specified in the relevant clauses, design requirements are applicable up to 370 °C for ferritic steels and 425 °C for austenitic steels.

NOTE This will be changed when the section on creep design is prepared.

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.

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.

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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).

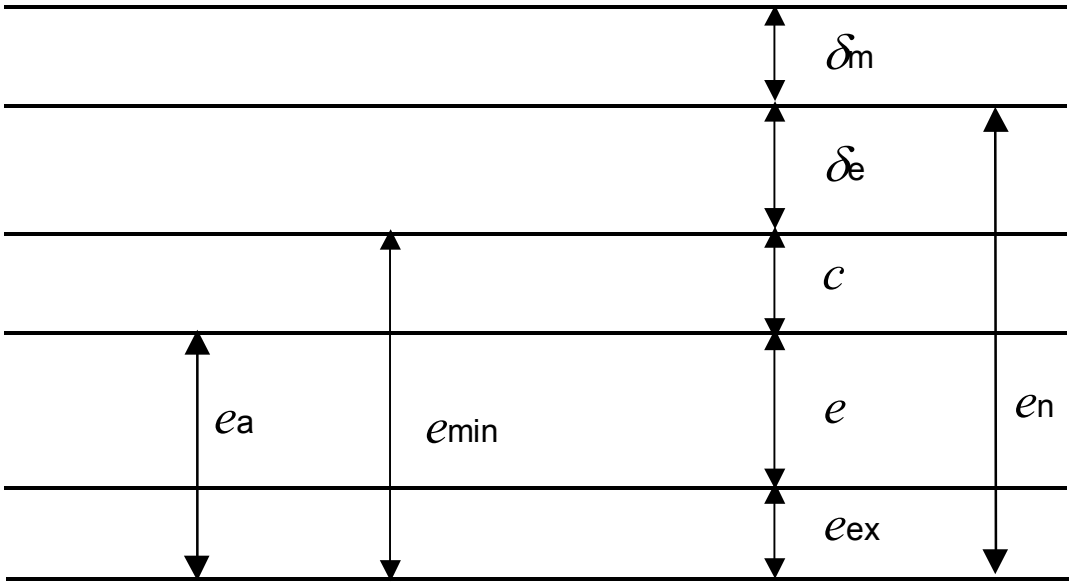
No corrosion allowance is required for heat exchanger tubes and other parts in similar heat exchanger duty, unless a specific corrosive environment requires one.

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 3-1.



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 or erosion 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 3-1 — 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.

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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;

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.

5.3.2 Classification of load cases

a) Normal operating load cases

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

b) 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;

c) Testing load cases

Testing load cases are those related to tests after manufacture;

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.

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

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

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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.

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.

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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 components using design by formulae (DBF).

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

a) design by analysis (DBA), which is covered in Annexes B and C;

b) experimental techniques.

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

The requirements specified in clauses 7 to 16 (DBF) 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.

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

Then no fatigue analysis is necessary and the standard requirements of non-destructive testing given in EN 13445-5 shall be applied.

For n_i pressure cycles at pressure ΔP_i less than the full pressure P, the number of equivalent full pressure cycles is given by:

$$n_{eq} = \Sigma\, n_i \cdot \left(\frac{\Delta P_i}{P_{max}} \right)^3 \qquad (5.4\text{-}2)$$

In the above formula, P_{max} is the maximum permissible pressure based on the analysis thickness.

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P_{max} is generally given in the different clauses of this Part for usual components. If necessary, 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 may occur before 500 cycles.

5.4.2 Vessels of testing group 4

Pressure vessels to testing group 4, as defined in EN 13445-5, are intended for non-cyclic operation and are limited to 500 full pressure cycles or equivalent full pressure cycles.

5.4.3 Vessels of testing group 1, 2 and 3, 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 13445-5:2002, Annex G.

5.4.4 Fatigue analysis of bellows

Specific fatigue curves are given in clause 14 for bellows.

5.4.5 Design by analysis

If for a component no requirements are supplied in clauses 7 to 16, the rules given in Annexes B and C shall be applied.

The rules of Annex B are not applicable to testing group 4 vessels.

5.4.6 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.

NOTE Experimental techniques will be covered in detail in a next edition.

5.4.7 Pevention of brittle fracture

Detailed recommendations to safeguard against brittle fracture of vessels in carbon, carbon manganese, low alloy and fine grain steels are given in EN 13445-2:2002, Annex B.

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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 3-1.

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: $f_{\text{base material}}$.

If the nominal design stress of the cladding f_{cladding} 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.

$$e_{\text{eq}} = e_{\text{a, base material}} + e_{\text{a, cladding}} \tag{5.5-1}$$

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

$$e_{\text{eq}} = e_{\text{a, base material}} + e_{\text{a, cladding}} \cdot \frac{f_{\text{cladding}}}{f_{\text{base material}}} \tag{5.5-2}$$

In the fatigue analysis checks of clause 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.

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5.6 Weld 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 weld 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;

— 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 13445-5:2002, Clause 6.

Table 5.6-1 — Weld 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;

— manufacturing means.

Annex A gives requirements and recommendations for pressure bearing welds.

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 13445-4:2002. 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 13445-4:2002.

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 13445-4:2002.

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;

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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 288-8:1995. For cryogenic applications the diameter is not limited.

f) calculation temperature

— -10 °C $\leq t \leq$ 120 °C for materials 1.1 and 1.2;

— -196 °C $\leq t \leq$ 120 °C for materials 8.1;

— -40 °C $\leq t \leq$ 120 °C for materials 1.1 and 1.2, for cryogenic applications.

g) non-corrosive conditions;

h) manufacturing tolerances of EN 13445-4:2002.

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 288-8:1995. For cryogenic applications the diameter is not limited.

f) calculation temperature

— -10 °C $\leq t \leq$ 120 °C for materials 1.1 and 1.2;

— -196 °C $\leq t \leq$ 120 °C for materials 8.1;

— -40 °C $\leq t \leq$ 120 °C for materials 1.1 and 1.2, for cryogenic applications.

g) non-corrosive conditions;

h) manufacturing tolerances of EN 13445-4:2002 for thicknesses not exceeding 8 mm; half of these tolerances for thicknesses exceeding 8 mm in cryogenic applications.

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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

$-10\ °C \leq t \leq 120\ °C$;

g) non-corrosive conditions;

h) both sides of the lap shall be welded (see Figures C 31 and C 34) except for the cases C 32, C 33 and C 35 in Table A-2;

i) manufacturing tolerances of EN 13445-4:2002.

5.7.4.3.2 Connection of bellows

Cases B 2, B 3 and B 5 of Table A-9 shall be used only under non-corrosive conditions.

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.

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.

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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.

For testing group 4 vessels, the maximum value of the nominal design stress for the normal operating load cases shall be multiplied by 0,9.

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 13445-5:2002, clause 5.

NOTE These values will generally be achieved when the heat treatment procedures conform to EN 13445-4:2002.

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 13445-2:2002, 4.2 shall be used.

6.1.7 For the definition of rupture elongation see EN 13445-2:2002, Clause 4.

6.2 Forged steels, other than austenitic, 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.

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6.3 Forged austenitic steels with a minimum elongation after rupture, as given in the relevant technical specification for the material, greater than 30 % up to 35 %.

6.3.1 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.

6.3.2 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.

6.4 Forged austenitic steels with a minimum rupture elongation, as given in the relevant technical specification for the material, greater than 35 %.

6.4.1 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 6.3.1; 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.

6.4.2 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 6.3.2; and

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

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6.5 Cast steels

6.5.1 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.

6.5.2 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.

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

	Normal operating load cases [a] [b]	Testing and exceptional load cases [2)]
Steels other than austenitic as per 6.2 $A < 30\ \%$ [c]	$f_d = \min\left(\frac{R_{p0,2/t}}{1,5}; \frac{R_{m/20}}{2,4}\right)$	$f_{test} = \left(\frac{R_{p0,2/t_{test}}}{1,05}\right)$
Austenitic steels as per 6.3 $30\ \% < A \leq 35\ \%$ [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 6.4 $A > 35\ \%$ [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	$f_d = \min\left(\frac{R_{p0,2/t}}{1,9}; \frac{R_{m/20}}{3}\right)$	$f_{test} = \min\left(\frac{R_{p0,2/t_{test}}}{1,33}\right)$

[a] For testing category 4 the nominal stress shall be multiplied by 0,9.

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

[c] For definition of rupture elongation see EN 13445-2:2002, Clause 4.

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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

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.

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7.4 Cylindrical and spherical shells

7.4.1 Conditions of applicability

The requirements in 7.4.2 and 7.4.3 are valid for e/D_e not greater than 0,16. The requirements 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 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 equations:

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

or

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

For a given geometry:

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

7.4.3 Spherical shells

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

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

or

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

For a given geometry:

$$P_{max} = \frac{4f \cdot z \cdot e_a}{D_m} \tag{7.4-6}$$

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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 equation;

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

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

N is a parameter defined by equation (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 equation (7.5-9);

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

ß 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 equations 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.

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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:

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

$r \geq 0{,}06 D_i$

$r \geq 2e$

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

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

$R \leq D_e$

7.5.3.2 Design

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

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

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

where

ß is found from Figure 7.5-1 or the procedure in 7.5.3.5.

and

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

where

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

except for cold spun seamless austenitic stainless steel, where:

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

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At test conditions the value 1,5 in the equations 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 $e_y > 0{,}005D_i$.

NOTE 4 The inside height of a torispherical end is given by

$$h_i = R - \sqrt{(R - D_i/2)\cdot(R + D_i/2 - 2r)}$$

7.5.3.3 Rating

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

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

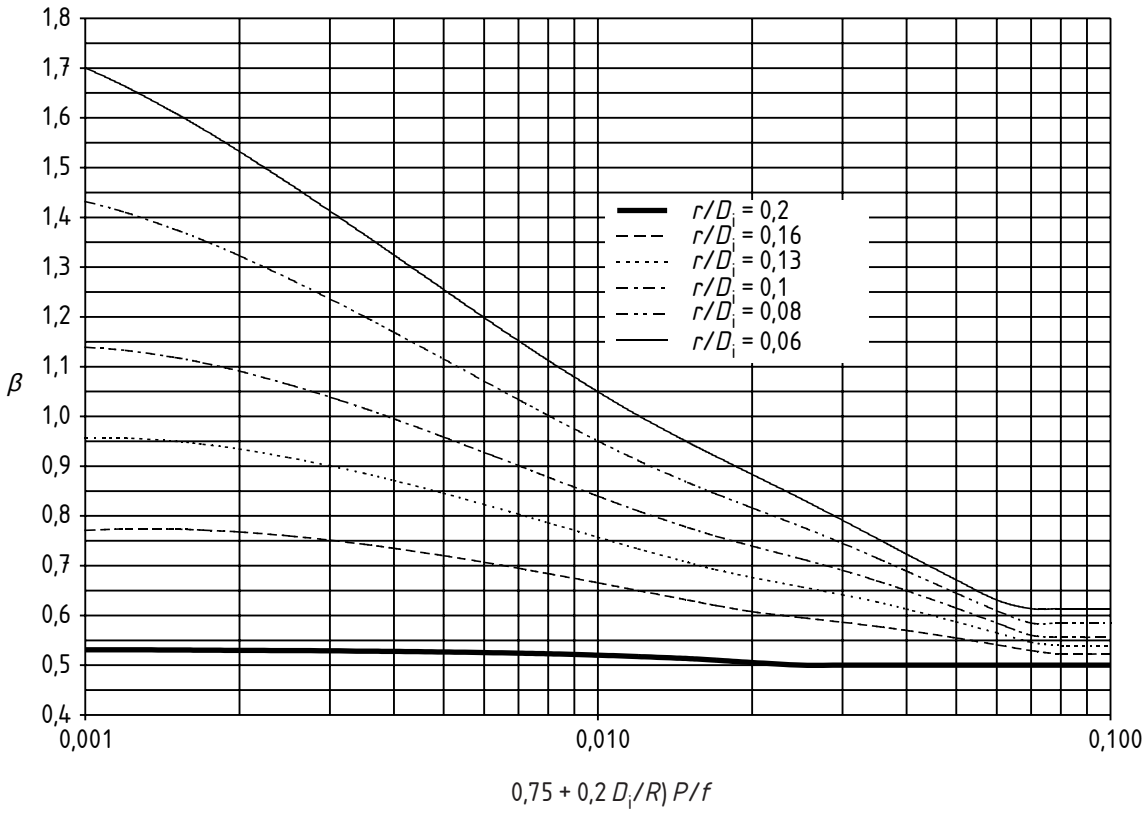


Figure 7.5-1 — Parameter β for torispherical end – Design

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

where

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

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

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

7.5.3.4 Exceptions

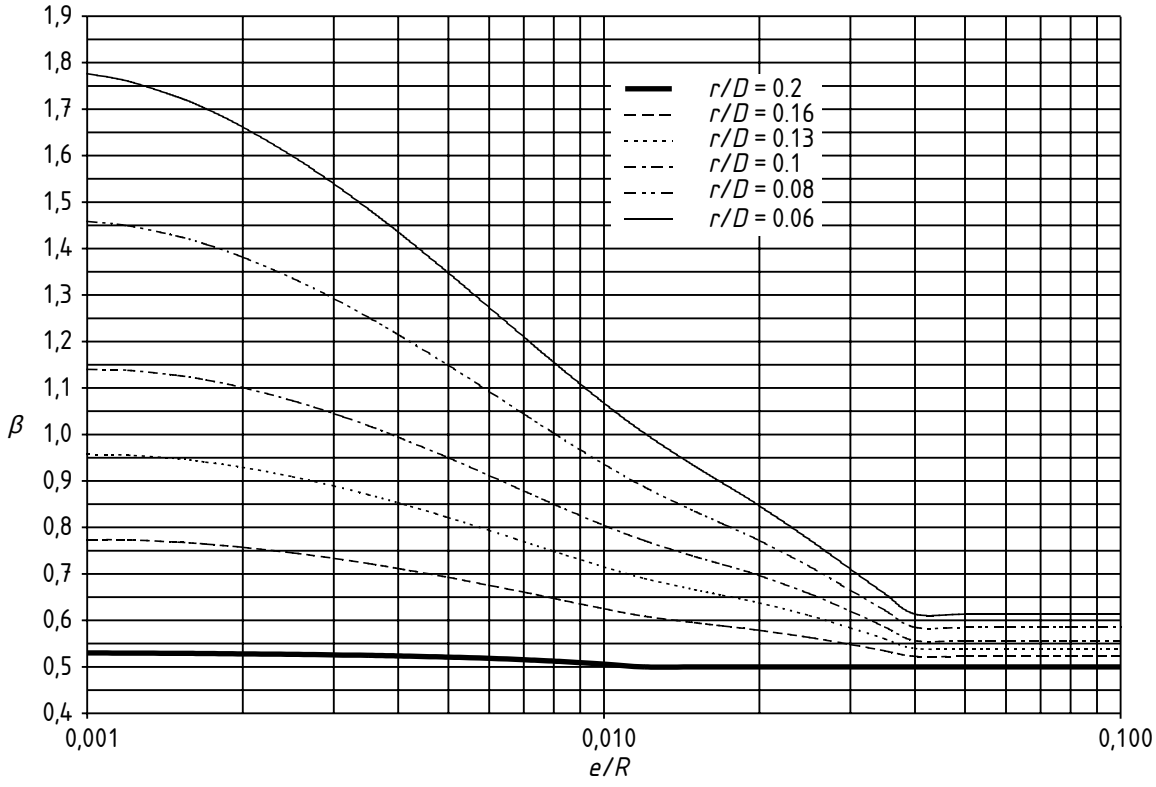


Figure 7.5-2 — Parameter ß for torispherical end - rating

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, unless its length is not greater than $0{,}2\sqrt{D_i \cdot e}$, in which case it may be the same thickness as required for the knuckle.

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7.5.3.5 Formulae for calculation of factor β

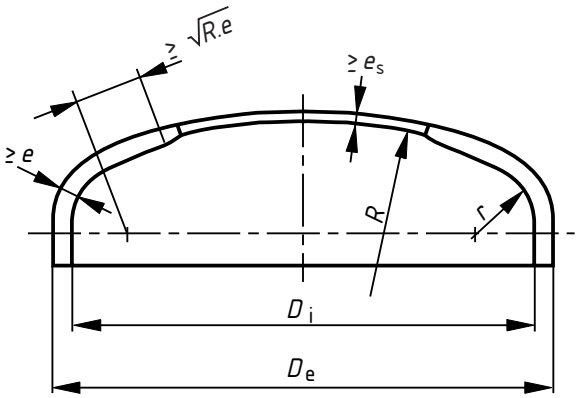


Figure 7.5-3 — Geometry of torispherical end

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

$$Z = \log 10(1/Y) \tag{7.5-10}$$

$$X = r/D_i \tag{7.5-11}$$

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

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 $0{,}06 < X < 0{,}1$

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

For $X = 0{,}1$

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

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For 0,1 < X < 0,2

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

For X = 0,2

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

NOTE When used in 7.5.3.2 the above equations for ß 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.

$$K = D_i/(2h_i) \quad (7.5\text{-}18)$$

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

$$r = D_i\left(\left(0{,}5/K\right) - 0{,}08\right) \quad (7.5\text{-}19)$$

and

$$R = D_i(0{,}44K + 0{,}02) \quad (7.5\text{-}20)$$

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;

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

c) short cones joining a jacket to a shell.

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

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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)

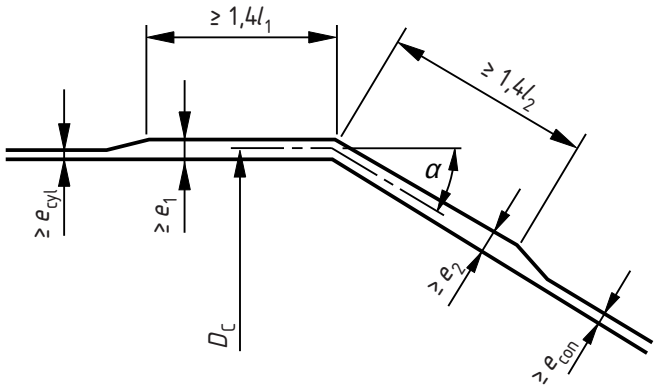


Figure 7.6-1 — Geometry of cone/cylinder intersection without knuckle — Large end

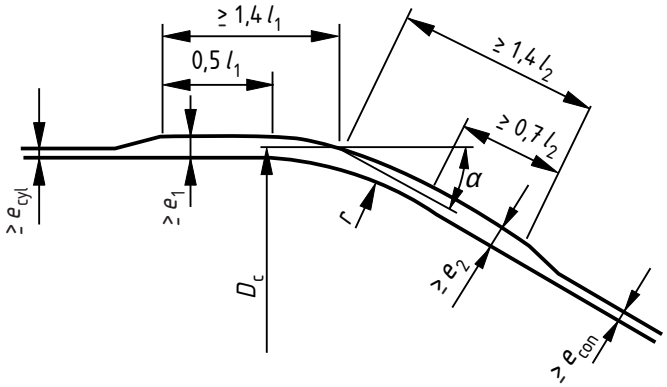


Figure 7.6-2 — Geometry of cone/cylinder intersection with knuckle — Large end

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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 equation (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_{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;
α is the semi angle of cone at apex (degrees);
β is a factor defined in 7.6.6;
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 equations:

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

or

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

where

D_i and D_e are at the point under consideration.

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For a given geometry:

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

where

D_m is at the point under consideration.

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

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

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

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

where

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

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.

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:

$$l_1 = \sqrt{D_c \cdot e_1} \quad (7.6\text{-}9)$$

$$l_2 = \sqrt{\frac{D_c \cdot e_2}{\cos(\alpha)}} \quad (7.6\text{-}10)$$

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 all the following conditions are satisfied:

a) 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; and

b) the weld at the junction shall be subject to 100 % non-destructive examination, either by radiography or ultrasonic techniques, unless the design is such that the thickness at the weld exceeds $1{,}4e_j$, in which case the normal rules for the relevant construction category shall be applied.

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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:

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

$$e_j = \frac{P \cdot D_c \cdot \beta}{2f} \qquad (7.6\text{-}12)$$

The result is acceptable if the value given by equation (7.6-12) is not less than assumed in equation (7.6-11). 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.

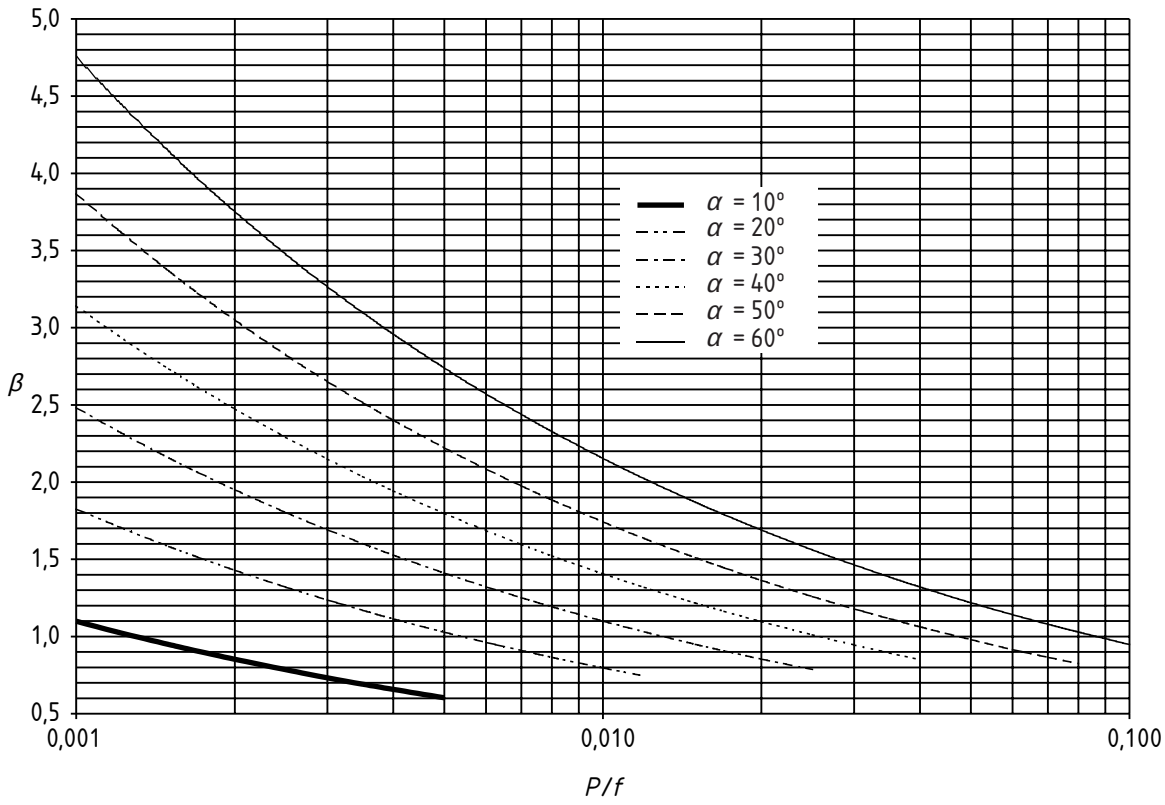


Figure 7.6-3 — Values of coefficient β for cone/cylinder intersection without knuckle

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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 $1{,}4e_1l_1$. 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 $1{,}4e_2l_2$.

7.6.6.3 Rating

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

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

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

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

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

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

h) 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

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

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.

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

The answer is acceptable if it is not greater than assumed in 1).

6) If the answer is unacceptable, return to 1).

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7) Use a similar procedure to find e_{2a} making.

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

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 sub-clause 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 clause 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:

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

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

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

$$e_j = \frac{P \cdot D_c \cdot \beta}{2f\gamma} \qquad (7.6\text{-}20)$$

The answer is acceptable if the value given by equation (7.6-20) is not less than 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.

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

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

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

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

$$P_{max} = \frac{2f \cdot \gamma \cdot e_j}{\beta \cdot D_c} \qquad (7.6\text{-}21)$$

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;

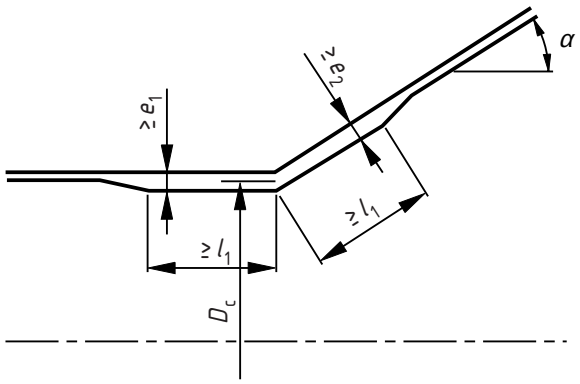


Figure 7.6-4 — Geometry of cone/cylinder intersection: small end

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7.6.8.2 Design

Required thicknesses e_1 and e_2 shall be determined by the following procedure:

Assume values of e_1 and e_2:

$$s = \frac{e_2}{e_1} \tag{7.6-22}$$

when $s < 1$

$$\tau = s\sqrt{\frac{s}{\cos(\alpha)}} + \sqrt{\frac{1+s^2}{2}} \tag{7.6-23}$$

when $s \geq 1$

$$\tau = 1 + \sqrt{s\left\{\frac{1+s^2}{2\cos(\alpha)}\right\}} \tag{7.6-24}$$

$$\beta_H = 0{,}4\sqrt{\frac{D_c}{e_1}} \cdot \frac{\tan(\alpha)}{\tau} + 0{,}5 \tag{7.6-25}$$

If

$$P \leq \frac{2f \cdot z \cdot e_1}{D_c \cdot \beta_H} \tag{7.6-26}$$

then e_1 and e_2 are acceptable. If not, repeat with increased values of e_1 and/or e_2.

NOTE The above procedure does not provide values for e_1 and e_2 independently. Any values may be selected to suit the needs of the design, for example to obtain a favourable value of l_1 or l_2.

Provided that the requirements of 7.4.2 and 7.6.4 continue to be met, it is permissible to modify a design according to the above rule in one of the following ways:

a) Where $e_1 = e_2$ a knuckle of the same thickness may be included. l_1 and l_2 continue to be measured from the junction (i.e. the point where the centre lines of cone and cylinder meet).

b) The thickness of 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 l_1 from the junction is not less than $l_1 e_1$. 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 l_2 from the junction is not less than $l_2 \cdot e_2$.

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7.6.8.3 Rating

The maximum permissible pressure for a given geometry shall be:

$$P_{max} = \frac{2f \cdot z \cdot e_1}{D_c \cdot \beta_H} \qquad (7.6\text{-}27)$$

β_H is found from equations (7.6-22) to (7.6-25) using e_{1a} and e_{2a} in place of e_1 and e_2 .

NOTE 1 The procedure for finding e_{1a} and e_{2a} is as provided in the note to 7.6.6.3.

NOTE 2 Analysis thicknesses may exceed the required thickness without leading to any increase in l_1 or l_2.

7.6.9 Offset cones

This requirement applies to offset cones between two cylinders (see Figure 7.6-5). The cylinders shall have parallel centre lines offset from each other by a distance no greater than the difference of their radii. A required thickness shall be calculated in accordance with 7.6.6 for the junction at the large end. A required thickness shall be calculated in accordance with 7.6.8 for the junction at the small end. The greater of these shall apply to the whole cone. The angle (α) shall be taken as the greatest angle between cone and cylinder.

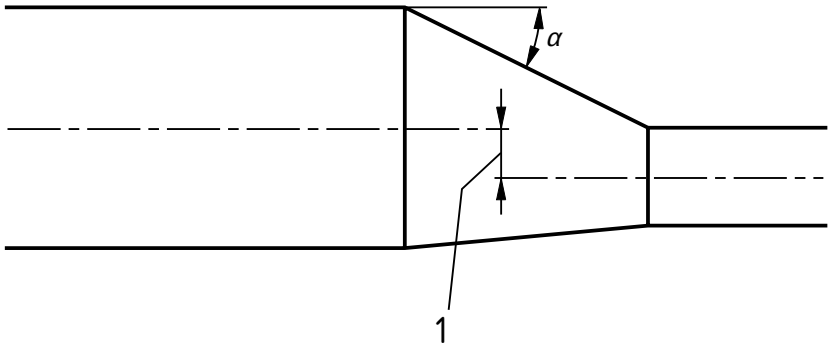


Figure 7.6-5 — Offset cone

7.7 Nozzles which encroach into the knuckle region

7.7.1 Specific symbols and abbreviations

The following symbols and abbreviations apply in addition to those in 7.5.1:

A is a parameter defined by equation (7.7-4) or (7.7-8);

A_1 is a parameter defined by equation (7.7-12) or (7.7-16);

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B is a parameter defined by equation (7.7-5) or (7.7-9);

B_1 is a parameter defined by equation (7.7-13) or (7.7-17);

β_K is the weakening factor due to presence of nozzle given by (7.7-10);

d_i is the inside diameter of the nozzle;

X is a parameter defined by equation (7.7-11) or (7.7-15);

V is a parameter defined by equation (7.7-3) or (7.7-7).

7.7.2 Conditions of applicability

In this sub-clause requirements are given for increasing the thickness of a dished end to compensate for nozzles which are not entirely within the central area of the head as defined in 9.7.2.4 and are therefore not covered by clause 9.

The requirements are limited in application to Kloepper and Korbbogen ends for which:

$$d_i / D_e \leq 0{,}6 \tag{7.7-1}$$

and

$$\frac{d_i}{\sqrt{e \cdot D_e}} \leq 6{,}7 \tag{7.7-2}$$

The nozzle centre line shall lie in the same plane as the centre line of the vessel. The nozzle centre line shall lie between normal to the wall of the end and parallel to the vessel centre line. The location of the nozzle shall be such that it does not cross the tangent line between knuckle and cylinder. Nozzles parallel to the vessel centre line and with outside diameter in line with the outside diameter of the vessel are included in these requirements.

The requirements of 7.7 may also be applied to ellipsoidal ends for which the aspect ratio $K \leq 2$. The thickness of such an ellipsoidal end with a nozzle intruding into the knuckle region shall be as for a Korbbogen end of the same diameter.

The increased thickness required by this clause applies to the whole knuckle region. Welded-on compensation is not permitted. The thickness of the crown may be reduced provided that the requirements of 7.5.3.4 are met and reinforcement for nozzles in the crown region meets the requirements of clause 9.

When the distance between the edge of the nozzle where it meets the knuckle and the knuckle/cylinder tan, line is less than $2{,}5\sqrt{e \cdot r}$ (measured along the surface) the validity of the method is in doubt. Unless the design is supported by special analysis or extensive experience, the design pressure shall be multiplied by two in such cases, or in a rating the allowable pressure shall be halved.

7.7.3 Design

For Kloepper type end:

$$V = \log 10\left(1000\frac{P}{f}\right) \tag{7.7-3}$$

$$A = \max\left(0{,}5;\ 0{,}264 + 0{,}938V - 0{,}592V^2 + 0{,}14V^3\right) \tag{7.7-4}$$

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$$B = \min (4{,}2;\ 4{,}9 - 2{,}165V + 0{,}151V^2) \tag{7.7-5}$$

$$\beta_k = \max\left(A + B\frac{d_i}{D_e};\ 1 + 0{,}3B\frac{d_i}{D_e} \right) \tag{7.7-6}$$

For Korbbogen type end:

$$V = \log 10\left(1000\frac{P}{f} \right) \tag{7.7-7}$$

$$A = 0{,}54 + 0{,}41V - 0{,}044V^3 \tag{7.7-8}$$

$$B = 7{,}77 - 4{,}53V + 0{,}744V^2 \tag{7.7-9}$$

$$\beta_k = \max\left(A + B\frac{d_i}{D_e};\ 1 + 0{,}5B\frac{d_i}{D_e} \right) \tag{7.7-10}$$

Replace P by $P\beta_k$ in equation (7.5-2) and in Figure 7.5-1 to arrive at the required thickness. The substitution shall be made before the calculation of β *in 7.5.3.5.* Equations (7.5-1) and (7.5-3) continue to apply without modification.

NOTE The graphs of Figure 7.7-1 and Figure 7.7-2 are based on the above procedure and give $\frac{e\,f}{P\,R}$ as a function of P/f and d_i/D_e.

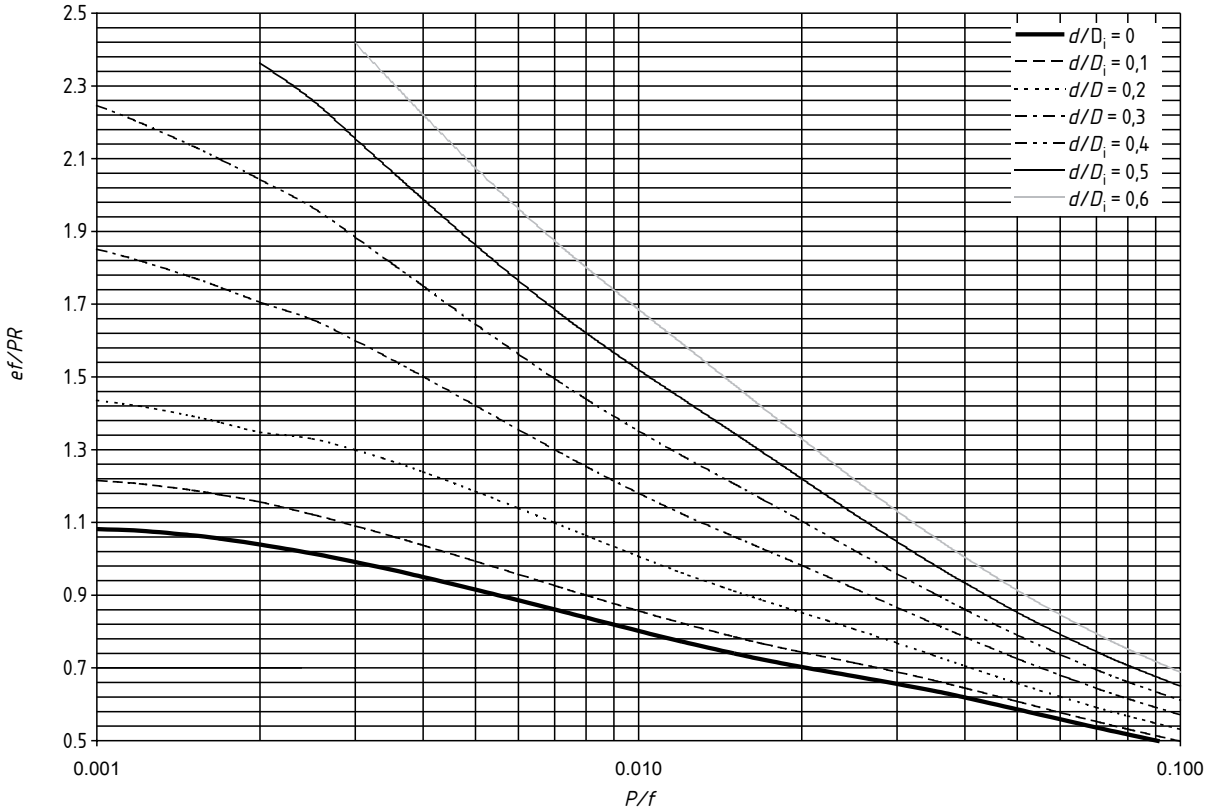


Figure 7.7-1 — Design ratio for Kloepper ends

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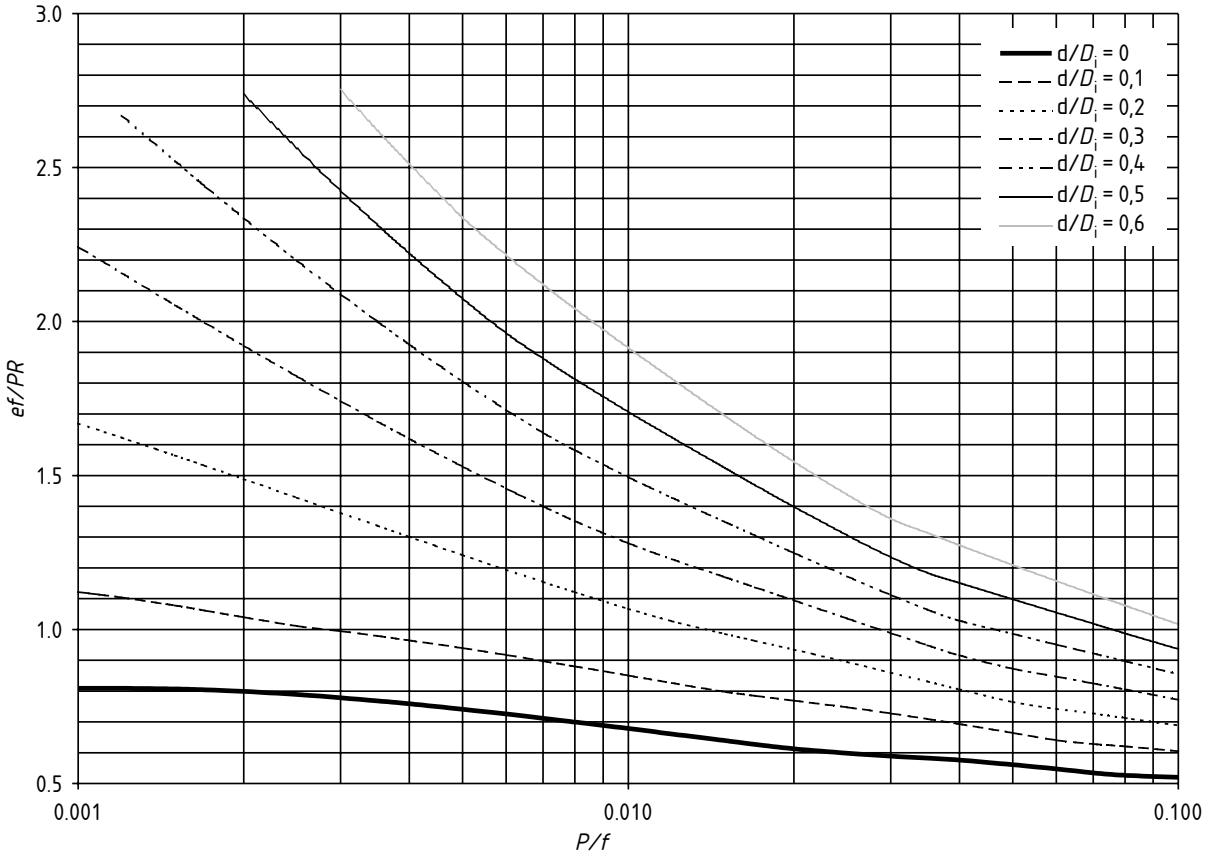


Figure 7.7-2 — Design ratio for Korbbogen end

7.7.4 Rating

To determine the maximum permissible pressure corresponding to a given geometry (rating) a trial and error procedure may be adopted. Alternatively the following procedure provides an approximate and always conservative estimate of β_k.

For Kloepper type end:

$$X = \log 10\left(1000\frac{e_a}{D_e}\right) \qquad (7.7\text{-}11)$$

$$A_1 = 1{,}07 \max(0{,}71 - X;\ 0{,}19X + 0{,}45) \qquad (7.7\text{-}12)$$

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$$B_1 = 1{,}02\left\{\min\left((3+5X);\frac{1}{0{,}241+0{,}116\left(X-0{,}26\right)^3}\right)\right\} \quad (7.7\text{-}13)$$

$$\beta_k = \max\left(A_1 + B_1\frac{d_i}{D_e};\ 1+0{,}3B_1\frac{d_i}{D_e}\right) \quad (7.7\text{-}14)$$

For Korbbogen type end:

$$X = \log 10\left(1000\frac{e_a}{D_e}\right) \quad (7.7\text{-}15)$$

$$A_1 = \frac{1}{1{,}136+0{,}0053\left(\frac{D_e}{d_i}\right)^{0{,}8}} \quad (7.7\text{-}16)$$

$$B_1 = (8{,}87 - 4{,}35X + 0{,}19X^3) \quad (7.7\text{-}17)$$

$$\beta_k = \max\left\{(1+0{,}1\frac{d_i}{D_e})\left(A_1 + B_1\frac{d_i}{D_e}\right);\ (1+1{,}1\frac{d_i}{D_e})\left(1+0{,}5B_1\frac{d_i}{D_e}\right)\right\} \quad (7.7\text{-}18)$$

Replace β by $\beta \cdot \beta_k$ in equation (7.5-7). Equations (7.5-6) and (7.5-8) continue to apply without modification.

7.7.5 Multiple nozzles which encroach into the knuckle region

The requirements for multiple nozzles in clause 9 apply also to nozzles designed to these requirements if the ligament between adjacent nozzles is entirely within the central area defined in 9.7.4. If the connecting line between adjacent nozzles is not entirely within the central area, the ligament shall not be less than half the sum of the nozzle bores.

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8 Shells under external pressure

8.1 Purpose

This clause provides requirements for the design of shells under external pressure loading. They apply to stiffened and unstiffened cylinders and cones, spheres and dished ends.

Where other significant loadings are present, additional strengthening shall be provided by increasing either the shell thickness or the stiffening. The rules do not apply in the creep range.

8.2 Specific definitions

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

8.2.1
nominal elastic limit
elastic limit applied in this clause for design under external pressure

8.2.2
heavy stiffener
circumferential stiffener, designated as heavy by the designer, to which particular requirements in this clause apply

8.2.3
light stiffener
circumferential stiffener, designated as 'light' by the designer, to which particular requirements in this clause apply.

8.2.4
interstiffener collapse
collapse of a section of cylinder between two stiffening rings, or between a stiffening ring and a vessel end

8.2.5
overall collapse
collapse of a section of cylinder which includes a light or heavy stiffener

8.2.6
plane of substantial support
vessel end or a plane dividing a vessel into two parts, each of which is treated separately for external pressure design purposes

8.2.7
safety factor
ratio of the lower bound expected collapse pressure to the calculation pressure

8.2.8
stiffener tripping
sideways twisting of a stiffener about its point of connection to the shell

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8.3 Specific symbols and definitions

The following specific symbols and abbreviations apply in addition to those in clause 4.

a length of shell covered by heating/cooling coil, see figures 8.5-11 and 8.5-12

A_e is cross-sectional area of stiffener and effective length of shell, see equation (8.5.3-30);

A_f is the cross-sectional area of the flange of a stiffener;

A_m is the modified area of a stiffener, see equation (8.5.3-17);

A_s is the cross-sectional area of stiffener;

A_w is the cross-sectional area of web;

B is a parameter in the interstiffener collapse calculation, see equation (8.5.3-18);

C is a coefficient in the stiffener tripping calculation, see equations (8.5.3-61) and (8.5.3-62);

CGs indicates the position of the centroid of a stiffener;

CGc indicates the centroid of the stiffener plus the effective length of shell;

$\overline{d}$ is the distance to the extremity of a stiffener, see equation (8.5.3-49);

d is radial height of stiffener between flanges, see Figures 8.5-14, 8.5-15, 8.5-16 and 8.5-17;

e_f is the thickness of the flange of a stiffener;

e_w is the thickness of the web of a stiffener;

G is a parameter in the interstiffener collapse calculation, see equation (8.5.3-22);

h, h', h'' are external heights of dished ends, see Figures 8.5.1 and 8.5.2;

I_e is the second moment of area of the composite cross-section of the stiffener and effective length of shell acting with it (Le) about an axis parallel to the axis of the cylinder passing through the centroid of the combined section, see equation (8.5.3-26);

I_{est} is the estimated second moment of area of a stiffener;

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