Foreword

This document (EN 13445-6:2002, EN 13445-6:2002/A1:2004, EN 13445-6:2002/A2:2006 and EN 13445-6:2002/A3:2008) has been prepared by Technical Committee CEN/TC 54 "Unfired pressure vessels", the secretariat of which is held by BSI.

EN 13445-6:2002 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of an identical text or by endorsement, at the latest by November 2002, and conflicting national standards shall be withdrawn at the latest by November 2002. EN 13445-6:2002/A1:2004 shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by October 2004, and conflicting national standards shall be withdrawn at the latest by October 2004. EN 13445-6:2002/A2:2006 shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by June 2007, and conflicting national standards shall be withdrawn at the latest by June 2007. EN 13445-6:2002/A3:2008 shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by April 2009, and conflicting national standards shall be withdrawn at the latest by April 2009.

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

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(s).

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

In this standard the Annexes A D, E, G and H are normative and the Annexes B, C and F are informative.

This European Standard consists of the following Parts:

Part 1: General

Part 2: Materials

Part 3: Design

Part 4: Fabrication

Part 5: Testing and Inspection

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, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and the United Kingdom.

1 Scope

This European Standard specifies requirements for the design, materials, manufacturing and testing of pressure vessels and pressure vessel parts intended for use with a maximum allowable pressure, PS, equal or less than 100 bar and shell wall thicknesses not exceeding 60 mm, which are constructed of ferritic or austenitic spheroidal graphite cast iron. The thickness limitation of the shell does not apply to thickness of flanges, reinforcements, bosses etc.

The allowable grades do not include lamellar graphite cast iron grades for ferritic and austenitic grades, which are explicitly excluded from this European Standard because of low elongation and brittle material behaviour, which requires the use of different safety factors and a different approach.

NOTE 1 Austenitic spheroidal graphite cast iron grades are principally used for high and low temperature applications and for their corrosion resistance properties.

NOTE 2 The allowable grades of spheroidal graphite cast iron are listed in Tables 3 and 4. Service conditions are given in Clause 4.

2 Normative references

The following referenced documents are indispensable for the application 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 764-2:2002*, Pressure equipment — Part 2: Quantities, symbols and units*

EN 764-5:2002, *Pressure equipment — Part 5: Compliance and inspection documentation of materials*

EN 764-7:2002 *, Pressure Equipment — Part 7: Safety systems for unfired pressure equipment*

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 1369:1996*, Founding — Magnetic particle inspection*

EN 1370:1996*, Founding — Surface roughness inspection by visual tactile comparators*

EN 1371-1:1997, *Founding — Liquid penetrant inspection — Part 1: Sand, gravity die and low pressure die castings*

EN 1559-1:1997, *Founding — Technical conditions of delivery — Part 1: General*

EN 1559-3:1997, *Founding —Technical conditions of delivery — Part 3: Additional requirements for iron castings*

EN 1563:1997, EN 1563:1997/A1:2002, EN 1563:1997/A2:2005, *Founding — Spheroidal graphite cast irons*

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

EN 12680-3:2003, *Founding — Ultrasonic examination — Part 3: Spheroidal graphite cast iron castings*

EN 12681:2003, *Founding — Radiographic examination*

EN 13445-1:2002*, Unfired pressure vessels — Part 1 : General*

EN 13445-2:2002*, Unfired pressure vessels — Part 2 : Materials*

EN 13445-3:2002*, Unfired pressure vessels — Part 3 : Design*

EN 13445-5:2002*, Unfired pressure vessels — Part 5 : Inspection and testing*

EN 13835:2002, EN 13835/A1:2006, *Founding - Austenitic cast irons*

EN ISO 945 :1994*, Cast iron — Designation of microstructure of graphite (ISO 945:1975)*

EN ISO 8062-1:2007, *Geometrical product specifications (GPS) - Dimensional and geometrical tolerances for moulded parts - Part 1: Vocabulary (ISO 8062-1:2007)*

EN ISO 8062-3:2007, *Geometrical product specifications (GPS) - Dimensional and geometrical tolerances for moulded parts - Part 3: General dimensional and geometrical tolerances and machining allowances for castings (ISO 8062-3:2007)*

3 Terms, definitions, units and symbols

3.1 Terms and definitions

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

3.1.1
critical zone
highly stressed area where a fracture is expected to occur in a burst test or where surface fatigue cracks are expected to be initiated due to fluctuating pressure loads

NOTE 1 Critical zones may occur, for example, by any of the following:

— sudden change in cross section;

— sharp edges;

— sharp radii;

— peak stresses;

— bending stresses;

— stresses due to other than membrane stress;

— changes in curvature.

NOTE 2 A critical zone is analysed by any appropriate method, e.g. holographic, interferometric, strain gauge methods, burst test, fatigue testing, FEM analysis etc.

NOTE 3 Additionally, thermal gradients and thermal stresses due to different operating wall temperatures need to be considered in defining critical zones.

3.1.2
purchaser
individual or organisation that buys pressure equipment, including assemblies or parts, for its own use or on behalf of the user and/or operator

3.1.3
manufacturer
individual or organisation responsible for the design, fabrication, testing, inspection, installation of pressure equipment and assemblies where relevant

NOTE 1 The manufacturer may subcontract one or more of the above mentioned tasks under its responsibility.

NOTE 2 In EU member states the manufacturer is responsible for compliance with the Pressure Equipment Directive 97/23/EC. For those manufacturers outside of the EU their authorized representative inside the EU assumes this responsibility.

3.1.4
casting manufacturer
subcontractor that produces the castings used in the manufacture of pressure equipment.

3.1.5
testing factor
A reduction factor applied to the nominal design stress to take account of possible manufacturing deficiencies.

3.1.6
temperature factor
A reduction factor applied to the 0,2 % proof strength to take account of temperature influence.

3.1.7
wall thickness factor
a reduction factor applied to the nominal design stress to take account of reduced mechanical properties

3.1.8
ferritic spheroidal graphite cast iron
cast material, iron and carbon based (carbon being present mainly in the form of spheroidal graphite particles) with a predominantly ferritic matrix

3.1.9
austenitic spheroidal graphite cast iron
cast material, iron and carbon based (carbon being present mainly in the form of spheroidal graphite particles) with an austenitic matrix and alloyed with nickel and where appropriate, manganese, copper and/or chromium

3.2 Units

For the purposes of this European Standard, the units given in EN 764-2:2002 apply.

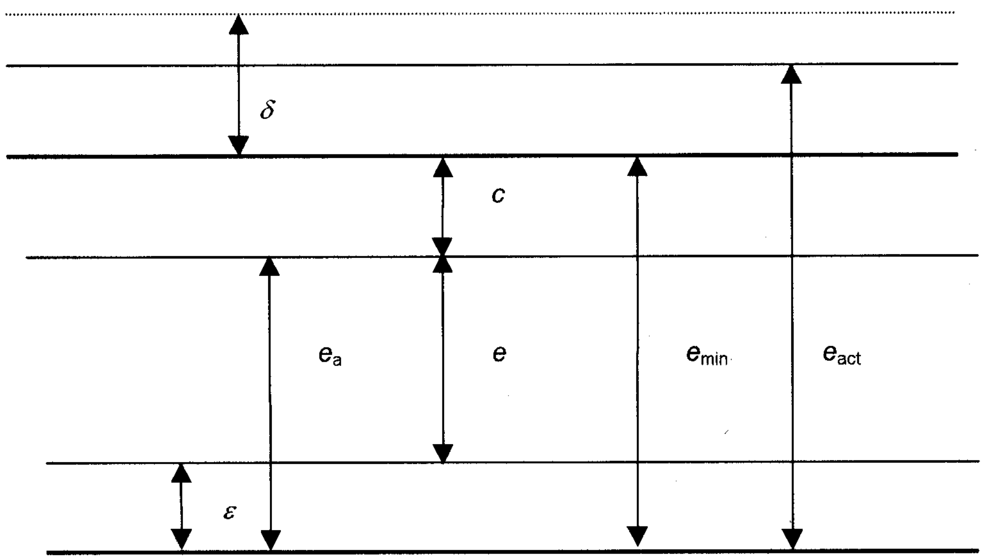
3.3 Symbols

Symbols used in this European Standard are listed in Table 3.3-1.

Table 3.3-1 — Symbols

Symbol	Quantity	Unit
c	Corrosion allowance	mm
e	Required thickness	mm
e_a	Analysis thickness (without corrosion allowance)	mm
e_{act}	Actual thickness	mm
e_{min}	Minimum thickness including corrosion allowance as specified on drawing	mm
E	Modulus of elasticity	N/mm² or MPa
f	Nominal design stress	N/mm²
F	Fatigue factor related to 99,8 % survival	dimensionless
$P_{\mathrm{b,act}}$	Actual burst test pressure	N/mm² or MPa
P_{b}	Minimum required bursting pressure	N/mm² or MPa
P_{d}	Design pressure	MPa, N/mm^2
PS, P_{S}	Maximum allowable pressure	bar, MPa, N/mm^2
RM	Material strength parameter	N/mm² or MPa
$R_{\mathrm{p0,2}}$	Minimum 0,2 %-proof strength at room temperature	N/mm² or MPa
$R_{\mathrm{m(3)}}$	Average tensile strength of 3 test bars taken from the same lot or heat	N/mm² or MPa
TS_{min} , TS_{max}	Minimum / maximum allowable temperature	°C
T	Calculation temperature	°C
V	Internal volume of the vessel	L
C_{e}	Wall thickness factor	dimensionless
C_{T}	Temperature factor	dimensionless
C_{Q}	Testing factor	dimensionless
n	Factor depending on shape of shell	dimensionless
f_{e}	Thickness correction factor	dimensionless
f_{m}	Mean stress correction factor	dimensionless
f_{s}	Surface finish correction factor	dimensionless
S	Safety factor	dimensionless
γ_{R}	Partial safety factor	dimensionless
δ	Casting tolerance	mm
ε	Extra thickness due to casting process	mm
ν	Poisson's ratio	dimensionless

3.4 Inter-relation of thicknesses definitions



Key

e is the required thickness

e_a is the analysis thickness

e_{min} is the minimum thickness including corrosion allowance as indicated on drawings

e_{act} is the actual thickness

c is the corrosion allowance

ε is the extra thickness due to casting process

δ is the casting tolerance

Figure 3.4-1 - Inter-relation of thicknesses definitions

4 Service conditions

4.1 Cyclic loading

Spheroidal graphite cast iron pressure vessels and vessel parts can be used for cyclic operation if the stress factor is limited to 3. If the calculated number of cycles is close to a limit number of cycles mentioned in Table 4.1-1 below to determine the need for fatigue analysis, a worst-case model shall be implemented for this determination.

If it is expected that under service conditions the maximum number of full pressure cycles will exceed the limit number according to Table 4.1-1, or exceeds more than the equivalent number of cycles with smaller amplitude, then a fatigue analysis shall be performed according to Annex D.

Table 4.1-1 — Number of full pressure cycles for cyclic loading consideration

Testing factor	Maximum number of full pressure cycles without mandatory fatigue analysis according to Annex D	
$C_Q = 0,9$	1 000	
$C_Q = 0,8$	40 000	if stress factor ≤ 3
	200 000	If stress factor ≤ 2,5

NOTE 1 A testing factor of 0,9 implies the application of higher nominal design stresses and consequently results in a lower maximum number of full pressure cycles without mandatory fatigue analysis.

NOTE 2 A stress factor (ratio of peak stress to fatigue stress) of more than 3, determined by any of the design methods given in 5.2 can be the result of inappropriate design. By enlarging radii or other small changes, an acceptable design may be generated.

For pressure cycles at a pressure difference ΔP_i less than the full pressure, the number of equivalent full cycles is given by Equation (4.1-1):

$$n_{eq} = \sum_{i=1}^{i=N} n_i \cdot \left(\frac{\Delta P_i}{P_{max}} \right)^{8,6} \tag{4.1-1}$$

where

N is the total number of envisaged types of pressure cycles with different amplitude;

n_i is the number of cycles of amplitude ΔP;

ΔP_i is the pressure cycle amplitude;

P_{max} is the maximum permissible pressure, as defined in 3.15 of EN 13445-3:2002.

4.2 Limitations on temperature and energy content

The minimum and maximum allowable temperatures TS_{min} and TS_{max} shall be in accordance with the limits given in Tables 5.1-1 and 5.1-2.

The product $PS \cdot V$ for a single casting shall not exceed 10 000 MPa·l (100 000 bar·l).

5 Requirements

5.1 Materials

All cast iron grades subject to internal or external pressure shall comply with EN 1563 for ferritic spheroidal graphite cast iron and EN 13835 for austenitic spheroidal graphite cast iron.

The ferritic material grades given in Table 5.1-1 shall be used for applications where the minimum allowable temperature is higher or equal to – 10 °C.

The material grades listed in Table 5.1-2 are intended for low temperature or high temperature design conditions.

Table 5.1-1 — Allowable material grades for usual design temperatures (-10 °C up to 300 °C)

Material standard	Material designation [b]		Design temperature limits °C
	Symbol	Number	
EN 1563	EN-GJS-350-22	EN-JS1010	$-10 \le TS \le 300$
	EN-GJS-350-22-RT	EN-JS1014	$-10 \le TS \le 300$
	EN-GJS-350-22 U [a]	EN-JS1032	$-10 \le TS \le 300$
	EN-GJS-350-22U-RT [a]	EN-JS1029	$-10 \le TS \le 300$
	EN-GJS-400-18	EN-JS1020	$-10 \le TS \le 300$
	EN-GJS-400-18-RT	EN-JS1024	$-10 \le TS \le 300$
	EN-GJS-400-18U [a]	EN-JS1062	$-10 \le TS \le 300$
	EN-GJS-400-18U-RT [a]	EN-JS1059	$-10 \le TS \le 300$

[a] Mechanical properties verified on test pieces from cast-on samples. These grades should be chosen in preference to the material grades with the separately cast samples when the unit mass of the casting is equal to or greater than 2 000 kg or when the relevant wall thickness varies between 30 mm and 200 mm.

The material grades listed in Table 5.1-1 and Table 5.1-2 may be produced in the as-cast or heat treated condition (see EN 1563:1997, Clause 6).

[b] When materials specified in these tables are not available, other suitable materials may be used when the technical documentation defining the characteristics of the materials has been accepted in accordance with the requirements for European approval for materials (EAM) or particular material appraisal (PMA).

Table 5.1-2 — Allowable material grades for low or high temperature design conditions

Material standard	Material designation [b]		Design temperature limits °C
	Symbol	Number	
EN 1563	EN-GJS-350-22-LT	EN-JS1015	-40 ≤ *TS* ≤ 300
	EN-GJS-350-22U-LT [a]	EN-JS1019	-40 ≤ *TS* ≤ 300
	EN-GJS-400-18-LT	EN-JS1025	-20 ≤ *TS* ≤ 300
	EN-GJS-400-18U-LT [a]	EN-JS1049	-20 ≤ *TS* ≤ 300
EN 13835	EN-GJSA-XNiMn23-4	EN-JS3021	-196 ≤ *TS* ≤ 300
	EN-GJSA-XNi22	EN-JS3041	-40 ≤ *TS* ≤ 540
	EN-GJSA-XNiMn13-7	EN-JS3071	-40 ≤ *TS* ≤ 300

[a] Mechanical properties verified on test pieces from cast-on samples. These grades should be chosen in preference to the material grades with the separately cast samples when the unit mass of the casting is equal to or greater than 2 000 kg or when the relevant wall thickness varies between 30 mm and 200 mm.

The material grades listed in Table 5.1-1 and Table 5.1-2 may be produced in the as-cast or heat treated condition (see EN 1563:1997, Clause 6 and EN 13835:2002, Clause 6).

[b] When materials specified in these tables are not available, other suitable materials may be used when the technical documentation defining the characteristics of the materials has been accepted in accordance with the requirements for European approval for materials (EAM) or particular material appraisal (PMA).

Material grades EN-GJS-350-22-LT or EN-GJS-350-22U-LT can be used at design temperatures down to – 60 °C. When used between (-40 ± 2) °C and (-60 ± 2) °C, impact testing at the minimum design temperature shall be:

- mean value from 3 tests 12 J for e_{act} ≤ 60 mm;
- 10 J for 60 mm ≤ e_{act} ≤ 200 mm;
- individual value 9 J for e_{act} ≤ 60 mm and 7 J for 60 mm ≤ e_{act} ≤ 200 mm.

The applicable requirements for the delivery conditions given in EN 1559-1 and EN 1559-3 shall also apply.

NOTE The use of materials working in the creep domain is not applicable to this standard since stress ranges are limited to elastic behaviour.

5.2 Design

5.2.1 Technical documentation

The manufacturer shall document those items listed in Clause 5 of EN 13445-5:2002 prior to fabrication.

5.2.2 Design methods

5.2.2.1.1 Principle

The loadings to be accounted for shall be in accordance with EN 13445-3:2002, Clause 5.

The service conditions of Clause 4 shall be accounted for.

Design methods shall be in accordance with this European Standard and, when applicable, with the relevant clauses of EN 13445-3.

If the geometry of the component or the loading case do not allow calculation by the formulas given in EN 13445-3 and Annex G, design by analysis (DBA) (see Annex E) or design by experiment (DBE) shall be applied.

Depending on the complexity of the component, the loading conditions and the level of NDT testing, the designer may choose one of the following available design methods mentioned below. Guidance is given on the correlation between safety factor, testing factor and the method to assess dynamic loading (see Table 5.2-1).

5.2.2.1.2 Static loading

In order to design the part for static loading, the following options can be considered by the designer.

5.2.2.1.3 Design by formula (DBF)

Equations for the calculation of the various components of the pressure part are given in EN 13445-3 and Annex G. Annex G gives additional equations for non-standard shaped parts often used in casting design.

5.2.2.1.4 Design by analysis (DBA)

The following applies:

1) decide whether the direct route (limit load – EN 13445-3:2002, Annex B) or the stress categorisation method (EN 13445-3:2002, Annex C) will be followed. Decide whether linear or non-linear approach will be used;

2) base modelling and interpretation of calculation results shall be based on analysis thicknesses (e_a) and material characteristics at operation temperature;

3) for interpretation of calculation results, follow the evaluation procedures and assessment criteria in order to evaluate the fitness for purpose of the real structure. These design checks and related procedures are typical for the failure mode to be dealt with. For the different failure modes see EN 13445-3.

5.2.2.1.5 Design by experiment (DBE)

Where design by equations according to EN 13445-3 is not considered appropriate due to complex shape of the component, then a hydraulic burst test to determine the analysis thickness e_a and the minimum thickness e_{min} shall be performed according to the procedure in 5.2.2.1.6. This test is also a part of the technical documentation.

This design method may be used without additional calculations if $P_d \cdot V < 600$ MPa·l (6 000 bar·l).

If $P_d \cdot V > 600$ MPa·l (6 000 bar·l) for the complete vessel, this method can be used in addition to DBA or DBF.

The minimum required thickness at a specific location is given by:

$$e_a = e_{act} \cdot \left(\frac{S \cdot PS \cdot R_{m(3)}}{P_{b,act} \cdot R_{p0,2} \cdot C_Q \cdot C_T \cdot C_e} \right)^{1/n} \tag{5-1}$$

$$e_{min} \geq e_a + c \tag{5-2}$$

where

$e_{act.}$ is the minimum measured wall thickness at the specific location;

$R_{p0,2}$ is in accordance with Annex A;

$P_{b,act}$ is the actual obtained value of burst pressure or the highest pressure during the test;

n = 1 for curved surfaces (cylinders, spheres) or cones with angles $\alpha \leq 60°$, stayed surfaces and stressed parts if bending stress is less than 2/3 of the total stress;

n = 2 for all other surfaces.

5.2.2.1.6 Determination of the hydraulic burst pressure and maximum allowable pressure for static loading

A random sample from the production of the vessel or vessel part shall be taken for the burst test or to determine the maximum allowable working conditions. The procedure shall be as follows:

1) verify that the part or vessel to be tested is cast according to the specified drawing and any revision thereof. The material used shall be the same type and grade as for the production part;

2) verify that the part or vessel is machined to the same dimensions as the production part;

3) verify that the material properties meet the requirements of 5.1. For each casting used for the burst test, 3 test pieces for tensile testing, and, if applicable, for impact testing, shall be separately cast and tested. The results and the calculated average tensile strength shall be certified in accordance with 6.5;

4) the wall thicknesses of the entire casting shall be measured (at least one measurement per 100 mm x 100 mm). The results shall be marked on the casting at the location of the measurement or on the drawing;

5) verify that a calibrated pressure gauge is used; maximum tolerance shall conform to at least class 1 or better according to EN 837-1 and EN 837-3. The scale of the pressure gauge shall be approximately 4/3 of the anticipated burst pressure;

6) the pressure shall be increased in a controlled manner until the minimum required burst pressure is obtained:

$$P_{\mathrm{b}} \geq PS \cdot \frac{R_{\mathrm{m(3)}}}{f} \left(\frac{e_{\mathrm{act}}}{e_{\mathrm{min}} - c} \right)^{n} \qquad (5\text{-}3)$$

The pressure shall be increased further in a controlled manner until rupture occurs. Record burst pressure $P_{\mathrm{b,act}}$, test date, material specification, details of material, part number, and wall thickness e_{act} measured at burst location. A relation with the actual burst pressure $P_{\mathrm{b,act}}$, which can be higher than P_{b} on account of a better stress distribution, and the maximum allowable pressure *PS*, can be deducted according the converted Equation 5-3, replacing P_{b} by $P_{\mathrm{b,act}}$

$$PS \leq P_{\mathrm{b,act}} \cdot \frac{f}{R_{\mathrm{m(3)}}} \left(\frac{e_{\mathrm{min}} - c}{e_{\mathrm{act}}} \right)^{n} \qquad (5\text{-}4)$$

7) if a part fails to meet any of those requirements, a second identical production part may undergo the same test procedure. If this second part meets the test requirements, this part may be accepted after investigation of the cause of failure of the first part. If the second part does not meet the test requirements, the design of the part shall be deemed not to conform to the specification;

8) during the burst test, it is acceptable for leaks and lack of pressure tightness to occur between flanged, gasketted or bolted parts as long as the pressure P_b can be reached during the test. It is acceptable for gasket(s) to break during the burst test; their characteristics may be modified without unduly changing flange load properties as long as their design meets the design rules of EN 13445-3 for the anticipated maximum allowable pressure P_s;

9) only for the test, bolts of higher mechanical strength than required by the design specification may be accepted;

10) when flanged connections are designed according to the requirements of EN 13445-3 with respect to minimum required thickness, minimum required bolt area and shape, it is acceptable, in order to reach burst test pressure, to install extra bolts in addition to the number specified for production;

11) the rupture under test pressure or any hydraulic test shall not be performed by means of a construction on a hydraulic press that can counteract the free shell bending under pressure.

5.2.2.1.7 Dynamic loading

If the number of full pressure cycles or equivalent full pressure cycles according to Equation (4.1-1) exceeds the number of full pressure cycles for static loading considered in Table 4.1-1, a fatigue assessment of the complete design is required. In order to design the part for dynamic loading, the following options can be considered by the designer.

5.2.2.1.8 Simplified fatigue assessment (SFA)

A simplified fatigue assessment will return a value of maximum allowable number of equivalent pressure fluctuations under service conditions. The assessment shall be performed according to Annex D. A maximum stress factor of 3 is pre-supposed, unless for construction details as limited in Table D.1A where equal or lower values than 3 may be used.

NOTE This Table D.1A may also be used for other metallic castings than spheroidal graphite cast iron (e.g. cast steel, cast aluminium and so on).

5.2.2.1.9 Detailed fatigue assessment (DFA)

A detailed fatigue assessment returns a value of maximum allowable number of equivalent pressure fluctuations using detailed stress analysis in service conditions. The assessment shall be performed according to Annex D.

5.2.2.1.10 Experimental fatigue assessment (EFA)

This method, as described in Annex H, shall be used if a theoretical stress analysis is inadequate or for which the design analysis shows abnormal low fatigue life values indicating a too conservative approach by theory.

An evaluation of a part by experimental fatigue design is not required when a similar part underwent already such a fatigue assessment and the data are available and transposable into the new design.

Cyclic loading shall be in accordance with EN 13445-3:2002, subclause 5.3.

This method does not take into account excessive wall thickness of the material, linings and all material, which does not contribute to strength.

NOTE For vessels for which $P_d \cdot V \geq 600$ MPa·l this experimental method may be used in addition to detailed fatigue design.

Table 5.2-1 — Determination of safety factor, testing factor and design method

Non destructive testing	Safety factor S	Testing factor C_Q	Design method Static loading	Design assessment dynamic loading
Not required	3,0	0,8	DBF DBA DBE	SFA
				DFA
				EFA
Required	2,0	0,9		(SFA) [a]
				DFA
				EFA

NOTE: DBF = design by formula
DBA = design by analysis
DBE = design by experiment
SFA = simplified fatigue analysis
DFA = detailed fatigue analysis
EFA = experimental fatigue analysis

[a] not recommended

5.2.2.2 Design conditions

The design stress for ferritic and for austenitic grades shall be calculated as follows:

$$f = \frac{R_{p\,0,2} \cdot C_T \cdot C_Q \cdot C_e}{SF} \qquad (5.2\text{-}1)$$

where

0,2 % proof strength at calculation temperature:

$$R_{p0,2/T} = C_T \cdot R_{p0,2} \qquad (5.2\text{-}2)$$

The temperature reduction factor C_T is:

for ferritic grades

$C_T = 1$ for $T \leq 20$ °C (5.2-3)

$C_T = 1 - 0{,}001\,(T - 20)$ for 20 °C < $T \leq$ 200 °C (5.2-4)

$C_T = 0{,}82$ for 200 °C < $T \leq$ 300 °C (5.2-5)

and for austenitic grades

$C_T = 1$ for $T \leq 20$ °C (5.2-6)

$C_T = 1 - 0{,}000\,5\,(T - 20)$ for 20 °C < $T \leq$ 540 °C (5.2-7)

Wall thickness reduction factor:

$C_e = 1$ for $e_{min} \leq 60$ mm (5.2-8)

$C_e = 0{,}8$ for $60 < e_{min} \leq 200$ mm (5.2-9)

5.2.2.3 Testing conditions

The test pressure may exceed the value given in equation 7.2-1 either intentionally or occasionally. However, the nominal design stress for testing conditions, f_{test} shall not exceed the 0,2 % proof strength $R_{p0,2/T_{test}}$ corrected with the factor C_e at test temperature divided by the safety factor 1,33.

$$f_{test} = \frac{R_{p0,2/T_{test}} \cdot C_e}{1,33} \tag{5.2-10}$$

5.2.2.4 Reinforcement of openings in cylinders, flat ends, dished ends, cones, etc.

Reinforcement of openings in cylinders, flat ends, dished ends, cones, etc. shall be determined in accordance with EN 13445-3:2002. When reinforcement is calculated with the area replacing method, the reinforcing length along the vessel wall considered shall be $\leq 2e_{min}$ to calculate the additional reinforcing area.

5.2.2.5 Design for external pressure

Design for external pressure shall be carried out according to EN 13445-3:2002, clause 8, where :

$$f = R_{p0,2/T} \cdot C_Q \cdot C_e \tag{5.2-11}$$

The minimum safety factor, which applies throughout this clause, is given by

$$S = 3,5 \tag{5.2-12}$$

5.2.2.6 Fillet radius

The largest possible fillet radius shall be used for walls under internal or external pressure in accordance with good foundry practice (fabrication tolerances are to be taken into account). Good foundry practice makes it sometimes necessary to increase wall thickness and to choose a corresponding fillet radius. Parts cast according to this European Standard therefore exhibit enhanced fatigue properties. It is important to verify that local stresses never exceed the maximum permissible values, especially at changes in section thickness or at change in radii.

If it is not possible, for any reason, to avoid sudden changes in cross-section area, and the pressure bearing wall is subject to cyclic loading, a taper of maximum ratio 1:3 from the thin wall to the thick wall shall be included.

All radii applied to a vessel part, including external cast lugs, support feet, etc. shall be greater than or equal to 1,5 times the thickness of the thinnest adjacent wall.

If, for any reason, a smaller radius is applied (as cast or after machining), the design verification shall be made by DBA.

6 Material testing

6.1 General

All material tests as required by EN 1563 or EN 13835 shall be performed.

6.2 Frequency and number of tests

For each batch the amount of testing shall be, on each ladle treated for spheroidization or each heat treatment batch:

— chemical analysis;

— one tensile test;

— one hardness test;

— impact testing, when required by material specification (consisting of 3 test pieces).

If the spheroidizing treatment is carried out in the mould, the same amount of testing for each 2 500 kg cast weight of identical parts produced during the same day shall be carried out.

For series production of RT grades according to Table 5.1-1, the amount of impact testing can be reduced to one test per day on the ladle with the highest silicon content.

The separately cast or cast–on test pieces shall be chosen according to EN 1563 or EN 13835. The test sample size shall represent the wall thickness of the part (see EN 1563 or EN 13835 for size determination).

NOTE Cast-on test pieces are representative of the castings to which they are attached and their size depends on the relevant wall thickness of the casting.

6.3 Chemical analysis

The methods used to determine the chemical composition of the material shall be in accordance with recognised standards.

For ferritic spheroidal graphite cast iron the following elements shall be analysed: C, Si, Mn, P, S and Mg.

For austenitic spheroidal graphite cast iron the following elements shall be analysed: C, Si, Mn, P, S, Mg, Cu and Ni.

6.4 Graphite structure

Graphite morphology of the material shall comply with form VI and V in accordance with EN ISO 945. The verification of nodularity shall preferably be carried out either by microscopic examination or by an ultrasonic method. Visual or computerised and/or automated methods are allowed.

When the ultrasonic method is used, the ultrasonic velocity shall be a minimum of 5 460 m/s using a calibrated measuring device. If the velocity is less than 5 460 m/s, the nodularity may still be verified and approved using the microscopic method on the worst test specimen. If the spheroidization is found acceptable, the material is approved. When ultrasonic examination is used, the verification shall be carried out on the last cast metal of each ladle.

6.5 Inspection documents

Inspection documents shall be in accordance with EN 764-5:2002, 4.3.3.

7 Testing and final assessment

7.1 Testing

7.1.1 General

All material tests of cast vessels and vessel parts, manufactured according to this part, shall be in accordance with Table 7.1-1 and Table 7.1-2.

Table 7.1-1 — Summary of testing requirements

	Testing factor C_Q	Magnetic particle inspection	Ultra sonic testing/ radiographic testing	Sectioning	Visual inspection	Wall thickness measure-ment
Initial sample	0,8	-	+	+	+	+
	0,9	+	+	+	+	+
0-serie: pre-production	0,8	-	+ (10 %)	-	+	+
	0,9	+	+	+ (1 part)	+	+
Serial production	0,8	-	-	-	+	+
	0,9	+	-	-	+	+
NOTE + = required, - = not required						

7.1.2 Testing requirements for C_Q = 0,8

Testing shall be carried out in accordance with the requirements and adopting the acceptance criteria given in Table 7.1-2 for surface imperfections only.

7.1.3 Testing requirements for C_Q = 0,9

— At non critical zones: testing same as for C_Q = 0,8 as given in 7.1.2;

— at critical zones: all castings shall be subjected to a magnetic particle inspection of all critical zones as indicated on the drawing, without revealing any unacceptable imperfection.

The last casting representing a batch of castings made from the same ladle or during the same day shall be subjected to a radiographic examination or equivalent (see footnote [b] in Table 7.1-2) of a zone indicated on the drawing, without revealing any unacceptable imperfections.

Table 7.1-2 — Testing according testing factor

	Testing factor		
	C_Q = 0,8	C_Q = 0,9	
Location	Complete part	Non critical zone	Critical zone
Surface imperfections			
Requirement	See 7.1.4 Cracks, laps, cold shot and non-fused chaplets are not permitted. See 7.1.5		
Testing method	Visual (both for C_Q = 0,8 and C_Q = 0,9)		
Testing frequency	100%		
Imperfections close to the surface			
Requirement	No requirement	No requirement	See 7.1.7
Testing method	Not applicable.	Not applicable.	Magnetic particle testing for ferritic grades. Dye penetrant testing for austenitic grades.
Testing frequency	Not applicable.	Not applicable.	100 %
Internal imperfections (micro and macro porosity)			
Requirement	See 7.1.6 (EN 12680-3, severity level 3)	See 7.1.6 (EN 12680-3, severity level 3)	See 7.1.9
Testing method	Ultrasonic testing/ sectioning	Ultrasonic testing/ sectioning	Radiographic testing [b]
Testing frequency	Initial samples Random sampling production series [a]	Initial samples Random sampling production series [a]	Initial samples Last casting of each batch

[a] According to agreement between the parties concerned.

[b] Ultrasonic testing of castings may substitute radiographic testing following an agreement between the parties concerned.

7.1.4 Surface imperfections

Sand inclusions, slag inclusions and blowholes shall be limited as follows.

For C_Q = 0,8 and C_Q =0,9 - non critical zone:

A maximum of five imperfections in a square 100 mm x 100 mm facing inwards or outwards shall be accepted. None of these shall cover an area larger than 100 mm² and the total area of the imperfections shall not exceed 200 mm².

The maximum permissible depth of an imperfection is such that the minimum wall thickness is maintained. Grinding of such surface imperfections is permitted down to the minimum wall thickness indicated on the drawing.

C_Q = 0,9 - critical zone:

No imperfections are permitted within the critical zone. Grinding of surface imperfections is permitted down to the minimum dimensions as indicated on the drawing, provided no stress concentration occurs.

7.1.5 Cracks, laps, cold shut and non-fused chaplets

No visible cracks, laps, cold shuts or non-fused chaplets are permitted.

In case of doubt about the severity of the imperfection, liquid penetrant inspection according to EN 1371-1 can be necessary.

7.1.6 Ultrasonic testing and/or sectioning

The ultrasonic testing shall be carried out in accordance with EN 12680-3.

If ultrasonic testing is not feasible, sectioning shall be carried out to visually detect internal imperfections.

Imperfections shall not be permitted on the main pressure bearing part (casting section with minimum required wall thickness specified on the drawing). However, micro shrinkage (centreline porosity) is permitted provided that all mechanical properties in the material standard are fulfilled.

NOTE Micro shrinkage is defined as a cavity smaller than 0,5 mm.

On other parts of the casting imperfections which are centrally located and not covering an area of 300 mm² shall be permitted, provided the minimum distance of the imperfection from the surface is a minimum of 1/3 of the wall thickness or at least 3 mm. Imperfections are not permitted around drilled holes, or where holes are to be drilled, within an area with a diameter of two times the diameter of the hole and concentric with the hole. Only micro shrinkage on the centreline is accepted provided that the required mechanical characteristics of the material standard are fulfilled.

7.1.7 Magnetic particle testing (only for ferritic grades)

The testing shall be carried out in accordance with EN 1369. The maximum severity level shall be equal to or better than SM 3 in Table 2 of EN 1369:1996 and LM4/AM4 in Table 3 of EN 1369:1996.

7.1.8 Penetrant testing

The testing shall be carried out in accordance with EN 1371-1. The maximum severity level shall be equal to or better than SP 02/CP 02 in Table 2 of EN 1371-1:1997 and LP 2/AP 2 in Table 3 of EN 1371-1:1997.

7.1.9 Radiographic testing

The testing shall be carried out in accordance with EN 12681 on a film size at least 100 mm x 240 mm.

The following is not permitted at any size:

- mottling, inserts, cracks, hot tears;
- porosity > Type A Grade 5;
- sand inclusions > Type B Grade 5;
- shrinkage > Type C Grade 5.

7.1.10 Surface roughness

Casting roughness or surface finish shall be approved by the purchaser on a sample casting. Production castings shall have a surface roughness comparable to the approved sample.

The casting surface roughness shall, when required, be tested and specified according to EN 1370 using visual tactile comparators, or as specified by the manufacturer.

7.1.11 Minimum wall thickness

Castings shall be measured on specified locations in order to verify that the required minimum wall thickness has been reached.

Results shall be recorded in an appendix to the material certificate.

The measurement shall be made by ultrasonic or any mechanical measuring devices with an accuracy in accordance with indicated design tolerances.

7.1.12 Wall thickness tolerances

The casting manufacturer shall determine on a regular basis the wall thickness tolerance.

The wall thickness tolerance shall be given in accordance with EN ISO 8062-3.

The casting tolerance grade to be applied depends on the casting process. The casting manufacturer shall prove its capability to meet the agreed tolerances.

7.1.13 Other dimensions

A full dimensional examination shall be made on the initial samples.

During series production, relevant dimensions shall be inspected on a regular basis to guarantee conformity to the drawing.

7.1.14 Qualification of testing personnel

The personnel carrying out testing shall be qualified as indicated in EN 13445-5.

7.2 Final assessment

7.2.1 General

Final assessment shall be carried out according to EN 13445-5:2002, Clause 10, except for the standard hydraulic test pressure.

7.2.2 Hydraulic test pressure

All pressure bearing spheroidal graphite cast iron parts shall be hydraulically tested with a test pressure, greater or equal to:

$$P_t = \frac{1{,}43 \cdot P_d}{C_t \cdot C_Q} \qquad (7.2\text{-}1)$$

When the assembly consists of spheroidal graphite cast iron parts designed with different testing factors, the highest test pressure shall be applied. It shall be checked that at the hydraulic test pressure no part exceeds the allowable stress specified for that part, as defined in 5.2.2.3.

8 Pressure vessels constructed of a combination of parts in different materials

When spheroidal graphite cast iron parts are linked by non-permanent joining with other metallic parts fabricated by welding, forging etc. to form a pressure vessel, the components made according to different fabrication techniques shall satisfy design, inspection and test requirements of the relevant clauses of EN 13445-5.

The assembled vessel shall satisfy the requirements for hydraulic testing at the pressure which is the highest test pressure of the individual components of the assembly. It shall be checked that at the hydraulic test pressure no component exceeds the allowable stress specified for that component.

9 Marking and documentation

9.1 Marking of castings

Pressure vessel castings and cast vessel parts, irrespective of the testing factor, shall be marked at least with the following information, preferably in cast characters with a minimum height of 6 mm:

— casting manufacturer logo or identification;

— type or designation;

— material grade according to EN 1563 or EN 13835.

— cast date, mould or batch number;

— testing factor if $C_Q = 0{,}9$;

Cast characters, either standing proud, raised or embedded shall not cause any adverse effect on the strength, static and dynamic stability or local stress concentration of the pressure vessel or vessel parts. The cast marking described above may be replaced by a coded system agreed between the parties concerned, and may also be hard stamped. Full traceability of the part to material and test certificates shall be guaranteed.

9.2 Name plate for the complete pressure vessel

The marking of the vessel shall be made according to EN 13445-5:2002, clause 11.

9.3 Documentation

The written declaration of compliance with the standard, records and other relevant documents shall be in accordance with EN 13445-5:2002.

D.4 Limitations

D.4.1 These rules apply to components designed by:

a) Formulae;

b) Finite Element Analysis

D.4.2 These rules apply only to components operating outside the creep range (i.e. when the nominal design stress is time-independent).

D.4.3 The data on which these rules are based are valid for fatigue in non corrosive environment. It is assumed that in the case of corrosive conditions precautions are taken i.e. corrosion allowance and / or surface protection.

D.5 General

D.5.1 ΔP shall be obtained by applying either the simplified cycle counting method described in EN 13445-3:2002, 18.9.2 or the reservoir cycle counting method in EN 13445-3:2002, 18.9.3.

D.5.2 The calculations according to D.6 or D.7 shall be performed for the various components of the vessel. The stress determination in castings is based on a stress analysis of notched parts. The lowest life obtained from each component is the fatigue life of the vessel.

D.5.3 Any notch radius should be at least 1,5 times the adjacent minimum wall thickness in order to reduce the local stress factor. To avoid abrupt section thickness transitions a taper ratio of 1:3 should be introduced as pointed out in 5.2.2.6.

D.6 Simplified fatigue assessment

D.6.1 Pseudo-elastic stress range

The simplified assessment is based on the determination of a corrected pseudo-elastic stress range $\Delta\sigma^{*}$ in conjunction with fatigue design curves as defined in D.6.3.

$$\Delta\sigma^{\bullet} = \frac{\Delta P \cdot \eta \cdot f}{P_{\max} \cdot f_{\mathrm{e}} \cdot f_{\mathrm{t}}^{\bullet}} \qquad \text{(D.6.1)}$$

For simplification the maximum allowable pressure of the component (P_{max}) may be set equal, either to the maximum allowable pressure *PS* of the whole vessel, or to the calculation pressure *P*.

NOTE 1 These simplifications lead to more conservative results.

NOTE 2 Since f and P_{max} in Equation (D.6.1) are taken at the calculation temperature, no consideration need to be given to at which temperatures cycles occur.

NOTE 3 P_{max} can be calculated in accordance with EN 13445-3. When a calculation is not possible with a design by formulae for the main pressure bearing parts, an experimental value according to this European Standard can be taken.

For each component the value of the stress factor η is obtained from Table D.1A of this Part.

For details which are not described in Table D.1A, a value for η of 3 shall be used, except if a lower value can be justified by e.g. 3-D finite element stress analysis, experimental analysis, etc.

NOTE 4 It is no longer required to use Table 17-1 from EN 13445-3 substituting the weld joint factor z=1.

The correction factors f_e and f_{t*} shall be determined as indicated in D.6.2.

A correction factor for surface finish and mean stress level is not required since this factor is already taken into account in the fatigue design curves of D.6.3. The actual surface conditions should meet the requirements of 7.1.

D.6.2 Correction factors

D.6.2.1 Correction for wall thickness

$$f_e = \left(\frac{25}{e_{max}}\right)^{0,182} \quad \text{(D.6.2)}$$

$$f_e = 1 \text{ for } e_{max} \leq 25 \text{ mm} \quad \text{(D.6.3)}$$

For $e_{max} > 150$ mm, the value of f_e for $e_{max} = 150$ mm applies.

D.6.2.2 Correction for temperature

The temperature correction factor f_{t*} is given by:

— for ferritic materials:

$$f_t = 1{,}03 - 1{,}5 \cdot 10^{-4} \cdot t^{\bullet} - 1{,}5 \cdot 10^{-6} \cdot t^{\bullet 2} \quad \text{(D.6.4)}$$

— for austenitic materials:

$$f_t = 1{,}043 - 4{,}3 \cdot 10^{-4} \cdot t^{\bullet} \quad \text{(D.6.5)}$$

where the mean cycle temperature is:

$$t^{\bullet} = 0{,}75 \cdot t_{max} + 0{,}25 \cdot t_{min} \quad \text{(D.6.6)}$$

$f_{t*} = 1$ for temperatures $t* < 100$ °C,. (D.6.7)

D.6.3 Fatigue design curves

The fatigue design curves given in Figure D.1 are described by the following equation:

$$\Delta\sigma_R = \frac{C_Q}{0{,}9} \cdot \frac{C_C}{N^{1/m_c}} \quad \text{(D.6.8)}$$

where

C_C and m_C are constants whose values are given in Table D.1.

For constant amplitude loading, the endurance limit $\Delta\sigma_D$ (i.e. stress range below which the fatigue life can be assumed to be infinite) corresponds to the stress range $\Delta\sigma_R$ at 2×10^6 cycles.

The dotted lines in Figure D.1 apply only to cumulative damage calculations (Equation D.8.1) under variable amplitude loading which includes stress ranges larger than $\Delta\sigma_D$. The curves end at $N = 10^8$ cycles. The corresponding stress range is the cut-off limit $\Delta\sigma_{Cut}$. For appropriate values of $\Delta\sigma_{Cut}$ see Table D.1. The fictitious stress ranges below this limit $\Delta\sigma_{Cut}$ are assumed to be non-damaging in fatigue for the pressure equipment.

Table D.1 — Coefficients of the fatigue design curves for spheroidal graphite cast iron grades- simplified assessment

Material	Constants of curve $\Delta\sigma_R - N$ ([a])				Allowable stress range at *N* cycles MPa			
	$10^3 < N < 2 \times 10^6$		$2 \times 10^6 < N < 10^8$		$C_Q = 0,9$		$C_Q = 0,8$	
	$1/m_C$	C_C	$1/m_C$	C_C	$\Delta\sigma_D$ at 2×10^6	$\Delta\sigma_{cut}$ at 10^8	$\Delta\sigma_D$ at 2×10^6	$\Delta\sigma_{cut}$ at 10^8
EN-GJS-400-18	0,116	786	0,1	623	146	99	130	88
EN-GJS-350-22	0,116	731	0,1	579	136	92	121	81
EN-GJSA-XNiMn23-4	0,116	714	0,1	566	133	89	118	79
EN-GJSA-XNi22	0,116	642	0,1	507	119	80	106	71
EN-GJSA-XNiMn13-7	0,116	714	0,1	566	133	89	118	79
([a]) For *E* according to Table A.2.1-1 and Table A.2.2-1.								

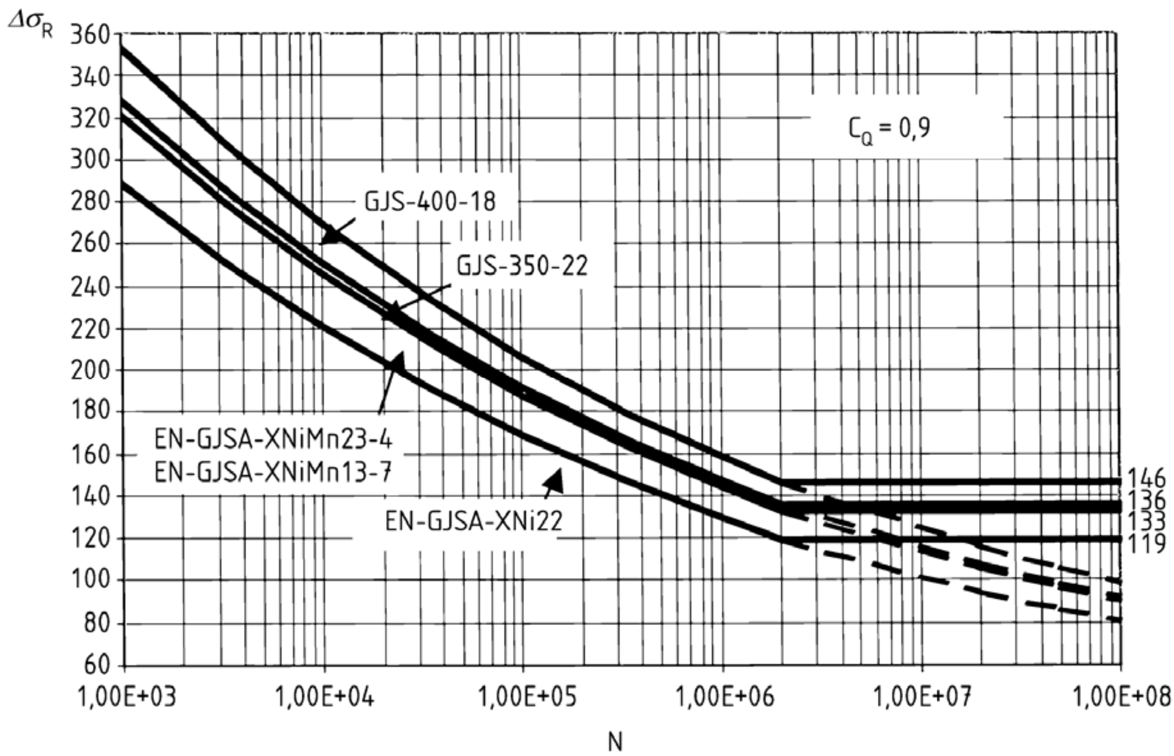


Figure D.1 — Fatigue design curves for ferritic and austenitic spheroidal graphite cast iron grades at ambient temperature - Simplified assessment

NOTE 1 These fatigue design curves have been derived from those given in D.7 for detailed assessment (Figure D.2). They incorporate the notch effect of all local stress concentrations whose K_t Kt factor does not exceed approximately 2 Instead of 2, also the more accurate value of 1, 88 may be used This value is the ratio of the endurance limit of the design curves in figure D.2 over that in figure D.1.For the definition of the theoretical stress factor K_t, see D.7.1, equation D.7.3). They are valid for the same probability of survival, i.e. Ps > 97, 7%.

The value of η is obtained from Table D.1A for each vessel detail. It is an upper bound of the following ratio:

$$\eta = \frac{\text{maximum structural stress in the detail at } P_{\text{max}}}{\text{nominal design stress at calculating temperature}}$$

To assess the fatigue life of a detail not covered by Table D.1A, the η value shall be obtained through an estimate of the maximum structural stress in the detail under pressure P_{max}.

For simplification, the maximum value η for the whole vessel can be assumed to apply for any detail.

NOTE 2 These values apply equally for any cast part made from metallic material (cast steel, cast aluminium, etc..) since it is independent from the material.

Table D.1A — Stress factor η and associated maximum pressure for typical cast constructions

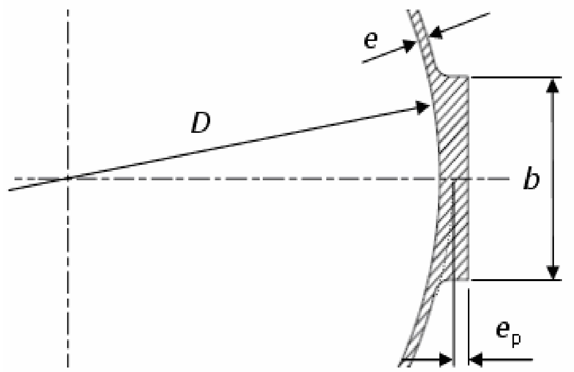
Detail description	Detail	Maximum permissible pressure P_{max}	Conditions	Stress factor η
Cylindrical or conical shells	Left intentionally blank	Cylindrical shell: EN 13445-3, equation (7.4.3) Conical Shell: EN 13445-3, equation (7.6.4)		1,0
Pad for data plate on cylindrical or conical shell		As for shell details	$b \leq 0{,}4 \cdot D$ $e_{\text{p}} \leq 2 \cdot e$	1,1

Table D.1A *(continued)*

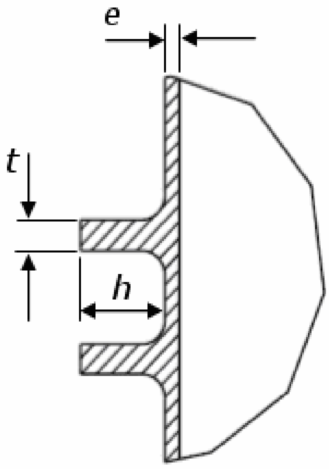
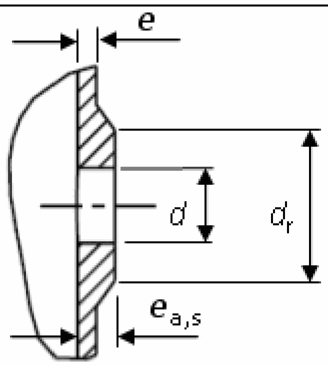
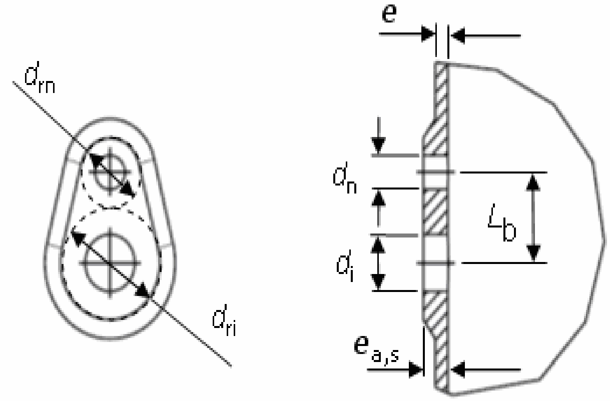
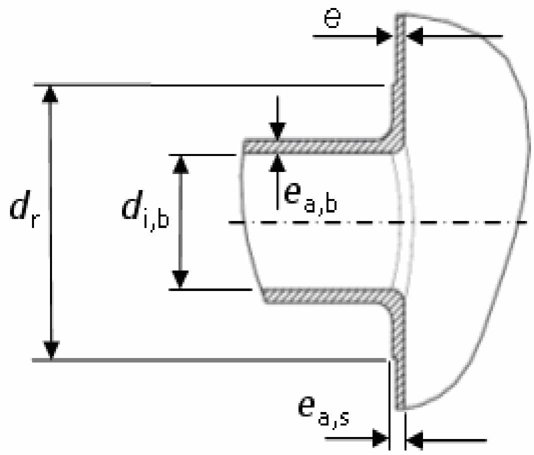
Detail description	Detail	Maximum permissible pressure P_{max}	Conditions	Stress factor η
Stiffening ring (single or multiple) on cylindrical or conical shell		As for shell details	$2 \cdot e \leq t \leq 4 \cdot e$ $2 \cdot e \leq h \leq 6 \cdot e$	1,0
Single opening with reinforcement in shell or spherical end		As for shell details	$e_{a,s} \geq 2 \cdot e$ $d_r \geq 2 \cdot d$	3,0
Multiple openings with reinforcement in shell or spherical end		As for shell details	$e_{a,s} \geq 2 \cdot e$ $d_{r,i} \geq 2 \cdot d_r$ $d_{r,n} \geq 2 \cdot d_r$ $L_b \geq d_i + d_n$	3,0
Nozzle with reinforcement in shell or spherical end		As for shell details	$e_{a,s} \geq 1{,}5 \cdot e$ $e_{a,b} \geq 1{,}5 \cdot e$ $d_r \geq 2 \cdot d_{i,b}$ $d_{i,b} / D_i^e < 0{,}6$	2,0
Nozzle without reinforcement in shell or spherical end			$e_{a,s} = e$ $e_{a,b} = e$ $d_{i,b} / D_i^e < 0{,}6$	3,0

Table D.1A *(continued)*

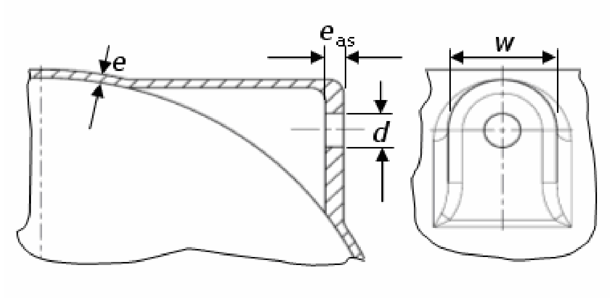
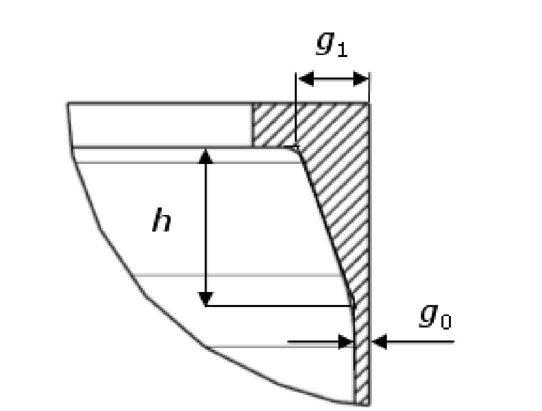
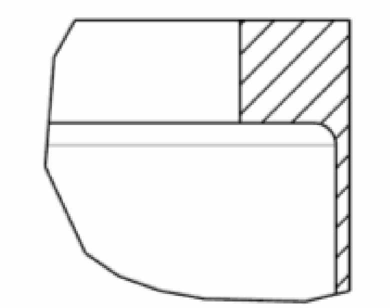
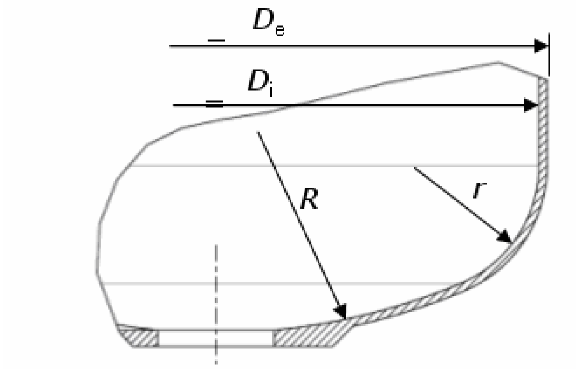
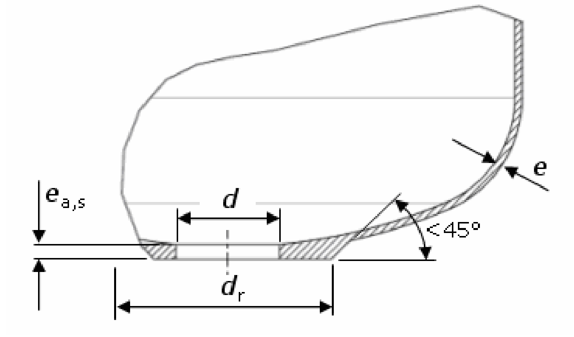
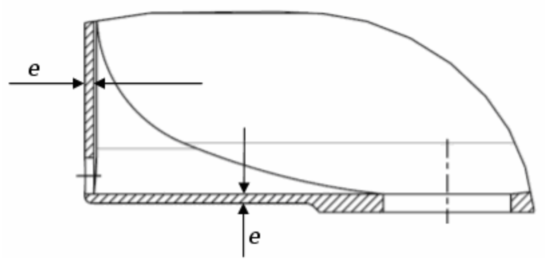
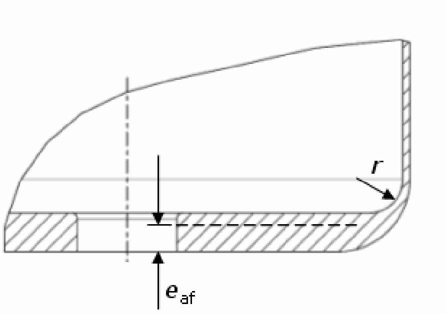
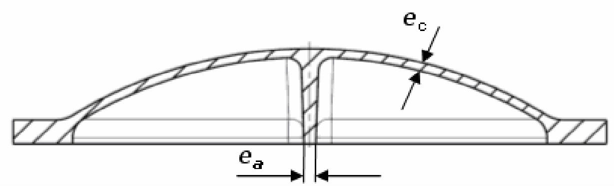
Detail description	Detail	Maximum permissible pressure P_{max}	Conditions	Stress factor η
Tangential inlet/outlet in cylindrical or conical shell		As for shell details	$e_{a,s} \geq 2 \cdot e$ $3 \cdot d \leq w \leq 5 \cdot d$	2,5
Flange with hub		See EN 13445-3, Clause 11 or EN 13445-3, Annex G[a]	$g_1 \geq 4 \cdot g_0$ $h \geq 3 \cdot (g_1 - g_0)$	1,5
			$4 \cdot g_0 \geq g_1 \geq 2 \cdot g_0$ $h \geq (g_1 - g_0)$	2,0
Flange without hub		See EN 13445-3, Clause 11 or EN 13445-3, Annex G[a]	$g_1 = g_0$ $h = 0$	2,0
Torispherical end knuckle region		See EN 13445-3, equation (7.5-7) [b]	$R / D_e \leq 0{,}8$ $r / D_i \geq 0{,}15$	2,0
			Other parameters according EN 13445-3 Clause 7.5.3.1	2,50

Table D.1A *(continued)*

Detail description	Detail	Maximum permissible pressure P_{max}	Conditions	Stress factor η
Reinforced opening in torispherical end		As for torispherical end detail	$e_{a,s} \geq 2 \cdot e$ $d_r \geq 2 \cdot d$	2,0
Opening for drain in torispherical end		As for torispherical end detail		3,0
Flat end knuckle region		See EN 13445-3 Clause 10 [c]	$r \geq 1{,}3 \cdot e_{af}$ [d]	1,5
			$1{,}3 \cdot e_{af} > r \geq e_{af}$	3,0
Opening in flat end			See EN 13445-3, Clause 10.6.1	2,0
Separation rib in dished cover		As for cover detail, see Annex G	$e_a \geq e_c$	1,1

NOTE e_{af} is the analysis thickness of flat end calculated without opening (see EN 13445 -3 Clause 10.4.3)

[a] The maximum calculation pressure is not given explicitly in EN 13445-3 Clause 11. It shall be calculated as the pressure which gives stresses to their allowable limits, or in EN 13445-3 Annex G a load ratio equal to 1,0. As a conservative simplification P_{max} may be taken as P_{design}.

[b] For use within the present clause P_{max} is taken as equal to P_y given by equation 7.5-7 in EN 13445-3. The other possible determinations P_s and P_b (given by equations 7.5-6 and 7.5-8 respectively) are not relevant here.

[c] The maximum calculation pressure is that of the flat end (not that of the adjacent cylindrical shell). In formula D.6-1, the value f to be introduced is the lowest of that for the end and that for the shell.

[d] Since no explicit formula is given for P_{max} in EN 13445-3 Clause 10 P_{max} shall be calculated as the pressure which gives the required end thickness equal to the analysis thickness. As a conservative simplification P_{max} may be taken as P_{design}.

[e] D_i is the vessel internal diameter

D.6.4 Allowable number of cycles

In order to obtain the allowable number of load cycles *N*, at a specified stress range $\Delta\sigma^*$, the following shall be calculated:

$$N = \left(\frac{C_Q}{0{,}9} \cdot \frac{C_C}{\Delta\sigma^{\bullet}} \right)^{m} \quad \text{(D.6.9)}$$

The value for $\Delta\sigma^*$ shall be calculated using Equation (D.6.1)

D.6.5 Allowable stress range $\Delta\sigma$

Alternatively, to obtain the allowable stress range $\Delta\sigma$ for a specified number of applied load cycles *N* :

$$\Delta\sigma \le \Delta\sigma_R \cdot f_e \cdot f_{t^{\bullet}} \quad \text{(D.6.10)}$$

where

$$\Delta\sigma_R = \frac{C_Q}{0{,}9} \cdot \frac{C_C}{N^{1/m_c}} \quad \text{(D.6.11)}$$

f_e and f_{t*} shall be calculated according to D.6.2.

D.7 Detailed fatigue assessment

D.7.1 Pseudo-elastic stress ranges

According to the method described in EN 13445-3:2002, Clause 18 for un-welded components the values of the maximum equivalent stress range $\Delta\sigma_{eq}$ and the structural stress range $\Delta\sigma_{eq,struc}$ are determined using a detailed numerical calculation method. From these values the corrected equivalent effective notch stress range $\Delta\sigma^*$ can be obtained by use of K_{eff} :

$$\Delta\sigma^{\bullet} = K_{eff} \cdot \frac{\Delta\sigma_{eq,struc}}{f_s \cdot f_e \cdot f_t \cdot f_m} \quad \text{(D.7.1)}$$

where

$$K_{eff} = 1 + \frac{1{,}5 \cdot (K_t - 1)}{1 + 0{,}5 \cdot MAX\left\{1; K_t \cdot \frac{\Delta\sigma_{eq,struc}}{\Delta\sigma_D}\right\}} \le K_t \quad \text{(D.7.2)}$$

$$K_t = \frac{\Delta\sigma_{eq}}{\Delta\sigma_{eq,struc}} \quad (D.7.3)$$

where

$\Delta\sigma_D$ is the endurance limit for $N \geq 2 \times 10^6$ cycles from Table D.2.

It is conservative to assume $K_{eff} = K_t$. The correction factors f_s, f_e, f_{t*} and f_m shall be determined as indicated in D.7.2.

D.7.2 Corrections to stress range

D.7.2.1 Correction for wall thickness

$$f_e = F_e^{(0,1\ln N - 0,465)} \quad (D.7.4)$$

where

$$F_e = \left(\frac{25}{e_{max}}\right)^{0,182} \quad (D.7.5)$$

where

$f_e = 1$ for $e_{max} \leq 25$ mm.

For $e_{max} > 150$ mm, the value of f_e for $e_{max} = 150$ mm applies

D.7.2.2 Correction for temperature

The temperature correction factor f_{t*} is given in D.6.2.2.

D.7.2.3 Surface finish correction factor

In order to keep local stresses low, a finer surface finish due to appropriate moulding techniques is advantageous on the side opposite to the fluctuating pressure.

$$f_s = F_s^{(0,1\ln N - 0,465)} \quad (D.7.6)$$

where

$$F_s = 1 - 0,03 \cdot \ln(R_z) \cdot \ln\left(\frac{R_m}{200}\right) \quad (D.7.7)$$

$f_s = F_s$ if $N > 2 \cdot 10^6$

where

R_Z is the peak-to-valley height in µm. (Set R_Z = 200 if not specified.)

D.7.2.4 Correction for mean stress

The mean stress correction factor f_m is to be determined from EN 13445-3:2002, 18.11.1.3. However the mean stress sensitivity factor *M f*or spheroidal graphite cast iron grades according this European Standard is:

$$M = 0{,}00035 \cdot R_m + 0{,}08 \quad \text{(D.7.8)}$$

D.7.2.5 Plasticity correction factors

Correction factors for mechanical k_e and thermal k_υ loadings in the hyper plastic range can be ignored, as a result of the high safety factors on 0,2 % proof strength used for the calculation of the nominal design stress in EN 13445-6 together with structural stresses never exceeding 3*f.*

D.7.3 Fatigue design curves

The fatigue design curves given in Figure D.2 are described by the following equation:

$$\Delta\sigma_R = \frac{C_Q}{0{,}9} \cdot \frac{C_C}{N^{1/m}} \quad \text{(D.7.9)}$$

where

C_C and m_C are constants whose values are given in Table D.2.

Table D.2 — Coefficients of the fatigue design curves for spheroidal graphite cast iron grades - detailed assessment

Material	**Constants of curve $\Delta\sigma_R$ – N ([a])**				**Allowable stress range at N cycles Mpa**			
	$10^3 < N < 2 \times 10^6$		$2 \times 10^6 < N < 10^8$		C_Q = 0,9		C_Q = 0,8	
	$1/m_C$	C_C	$1/m_C$	C_C	$\Delta\sigma_D$ at 2×10^6	$\Delta\sigma_{cut}$ at 10^8	$\Delta\sigma_D$ at 2×10^6	$\Delta\sigma_{cut}$ at 10^8
EN-GJS-400-18	0,10	1 173	0,10	1 173	275	186	244	165
EN-GJS-350-22	0,10	1 091	0,10	1 091	256	173	227	154
EN-GJSA-XNiMn23-4	0,10	1 065	0,10	1 065	249	168	222	150
EN-GJSA-XNi22	0,10	957	0,10	957	224	151	199	135
EN_GJSA-XNiMn13-7	0,10	1 065	0,10	1 065	249	168	222	150
([a]) For *E* according Table A.1 and Table A.3.								

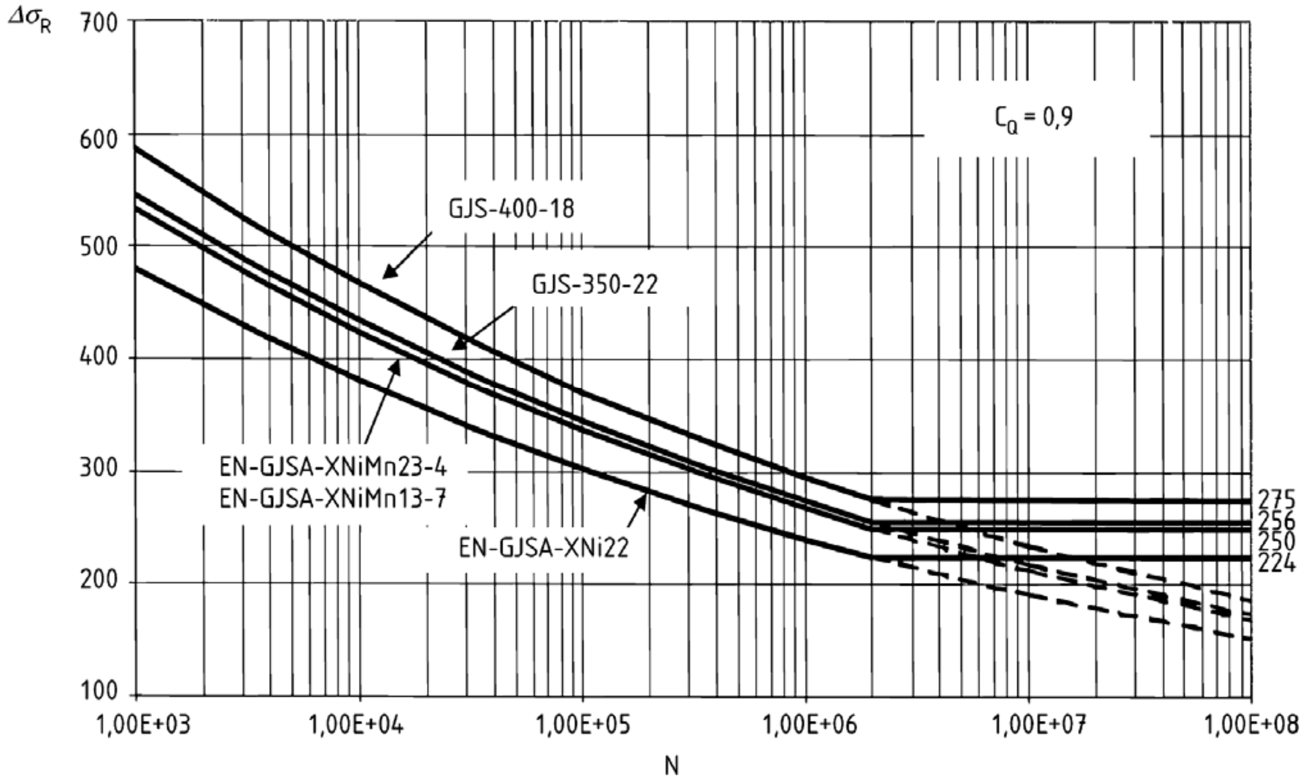


Figure D.2 — Fatigue design curves for ferritic and austenitic spheroidal graphite cast iron grades at ambient temperature - Detailed assessment

NOTE The fatigue design curves in Figure D.2 have been derived from data (See ref [1]) obtained from un-notched test pieces of spheroidal graphite cast iron grade EN-GJS-400-18 from axial and bending fatigue tests performed under load control or, for applied strains exceeding yield (low cycle fatigue), under strain control. The allowable stresses have been derived from the mean results by applying safety factors of 5 on fatigue life and 1,3 on stress range. The resulting design curves embody a probability of survival P_s of at least 97, 7%.

The dotted lines in Figure D.2 apply only to cumulative damage calculations (Equation D.8.1) under variable amplitude loading which includes stress ranges larger than $\Delta\sigma_D$. The curves end at $N = 10^8$ cycles. The corresponding stress range is the cut-off limit $\Delta\sigma_{Cut}$. For appropriate values of $\Delta\sigma_{Cut}$ see Table D.2. The stress ranges below this limit $\Delta\sigma_{Cut}$ are assumed to be non-damaging in fatigue for the pressure equipment.

D.7.4 Allowable number of cycles

In order to obtain the allowable number of load cycles *N*, at a specified stress range $\Delta\sigma^*$, the following shall be calculated:

$$N = \left(\frac{C_Q}{0,9} \cdot \frac{C_C}{\Delta\sigma^\bullet} \right)^m \qquad \text{(D.7.10)}$$

The value for $\Delta\sigma^*$ shall be calculated using Equation (D.7.1).

D.7.5 Allowable stress range

Alternatively, in order to obtain the allowable structural stress range $\Delta\sigma_{eq,struc}$ for a specified number of applied load cycles *N*:

$$\Delta\sigma_{eq,struc} \leq \Delta\sigma_R \cdot f_e \cdot f_s \cdot f_m \cdot f_{t^*} / K_{eff} \qquad \text{(D.7.11)}$$

where

f_e , f_s , f_m and f_{t*} shall be calculated according to D.7.2. K_{eff} is calculated from Equation (D.7.2) or conservatively set equal to K_t .

D.8 Assessment rule for total fatigue damage

The total fatigue damage index due to the cumulative effect of cycles of variable amplitude loading, forming a specified design stress range spectrum, is calculated as follows:

$$D = \sum_i^k \frac{n_i}{N_i} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + ... \quad \text{(D.8.1)}$$

Where n_i are the numbers of cycles of each stress range $(\Delta\sigma^*)_i$ applied during the design life of the vessel, and N_i are the allowable number of cycles corresponding to that stress range, obtained in accordance with D.6.4 or D.7.4 from the appropriate fatigue design curve.

The design is acceptable if the following condition is met:

$$D \leq 1 \quad \text{(D.8.2)}$$

If $D > 1$, the condition is not met and the design shall be modified.

D.9 Repairs of surface imperfections

If an unacceptable surface imperfection occurs which does not meet the requirements of 7.1, an improvement can only be made by grinding. The minimum actual required thickness shall be calculated according to this annex, taken into account all clauses of this European Standard about the design requirements. Welding is not allowed, as has been stated in 5.3-2.

Annex E
(normative)

Design by analysis for castings

E.1 Introduction

For cast iron pressure vessels the general procedures and corresponding rules as covered by:

— Annex B "Design by Analysis – Direct Route" and

— Annex C "Design by Analysis – Method based on stress categories"

of EN 13445-3 shall be modified as follows.

E.2 Special requirements to EN 13445-3:2002, Annex B

E.2.1 Addition to B.8.2.3: Design checks for normal operating load cases

Material strength parameters (*RM*) and partial safety factors (γ_R) shall be as given in following table:

Table E.1 — *RM* and γ_R for normal operating load cases

Material	*RM*	γ_R
Spheroidal graphite cast iron [a]	$R_{p0,2/t}$	$1.67/(C_Q.C_e)$
[a] For allowable material grades see Table 5.1-1 and Table 5.1-2.		

E.2.2 Addition to B.8.2.4: Design checks for testing load cases

RM and γ_R shall be as given in following table:

Table E.2 — *RM* and γ_R for testing load cases

Material	*RM*	γ_R
Spheroidal graphite cast iron [a]	$R_{p0,2/Ttest}$	$1,33/C_e$
[a] For allowable material grades see Table 5.1-1 and Table 5.1-2.		

E.3 Additions to EN13445-3:2002, Annex C

The symbol "*f* " used in C.7. "Assessment criteria" is defined in 5.2.2.2.

E.4 Requirements

Design by analysis calculations shall include the following:

- a detailed description of the numerical method used, including the name and version of computer software, if applicable;
- description of model geometry (including element type for finite element analysis);
- loading conditions and boundary conditions used to address the load cases in the User's Design Specification;
- material characteristics used for all required physical properties (i.e. modulus of elasticity, Poisson's ratio, thermal expansion coefficient, thermal conductivity, thermal diffusivity), strength parameters (i.e. yield and tensile strength), and the design membrane stress intensity;
- description of whether material nonlinearity is utilized in the analysis including a description of the material model (i.e. stress-strain curve and cyclic stress-strain curve);
- description of the numerical analysis procedure (i.e. static analysis, buckling analysis, natural frequency analysis, dynamic analysis) and whether geometrically linear or non-linear option is invoked;
- Graphical display of relevant results (i.e. numerical model, deformed plots, and contour plots of thermal and stress results);
- method used to validate the numerical model (i.e. mesh sensitivity review and equilibrium check for finite element analysis, e.g. check of hoop stress in a component away from structural discontinuity and a check to ensure that global equilibrium is achieved between applied loads and reactions at specified boundary conditions);
- description of processing the numerical analysis results in order to obtain final results (i.e. stress linearization method, use of centroidal or nodal values for stress, strain, and temperature results);
- a summary of the numerical analysis results showing the acceptance criteria utilized to meet the requirements of this European Standard;
- electronic storage of analysis results including input files and output files that contain numerical analysis results utilized to demonstrate code compliance.

Annex F
(informative)

Recommendations for in-service validation and inspection

F.1 Purpose

This annex gives recommendations for the continued acceptance of cast equipment made according to this European Standard.

The instructions for use issued by the manufacturer may contain requirements for in-service inspections and may contain recommendations for re-inspections depending on the design, service and required service life.

F.2 Tests during operation

Every pressure vessel or pressure vessel part should be externally and, if necessary, internally inspected (by non-destructive methods) at a period not later than the calculated allowable fatigue lifetime according to Annex D. If the lifetime due to normal service conditions is considered to be infinite by the manufacturer an inspection shall be made after 10 years of service when no adverse situation has been signalled from the operator or the inspector to the manufacturer.

NOTE 1 This time corresponds to the allowable number of cycles when the design stress range spectrum includes only one type of cycle. For more complex loading spectra, it corresponds to the time when a total fatigue damage index of 0,5 (see definition in Annex D) has been reached.

The operator should record the number of load cycles in use in a suitable way and, if necessary, arrange for internal or external inspections.

NOTE 2 The records can indicate a need for a sooner inspection interval than originally laid down. If no records exist, the inspector may choose the least favourable occurring condition during operation of the vessel or vessel part.

NOTE 3 Longer inspection intervals may possibly result from calculations according to Annex D with a detailed assessment of fatigue life than from the simplified fatigue assessment method.

NOTE 4 A damage to be expected can also be found in non-pressure bearing parts such as intersections between supporting lugs and vessel wall which might induce fatigue crack initiation and consequently reduce the life of the pressure part.

If no record exists the number of load cycles may be estimated in normal operating conditions and agreed upon between the user and the inspector.

For pressure vessels subject to cyclic loading, in-service inspections are of particular importance to detect incipient damage in good time. Therefore, the internal inspections should be supplemented by non-destructive tests on highly stressed locations, especially by test methods suitable to detect surface cracks.

For monitoring inaccessible areas, ultrasonic testing from the outside surface of the vessel is recommended.

If the operating conditions deviate greatly from those assumed in the calculation according to Annex D in terms of a greater cyclic loading, or if damage of the vessel wall is to be expected before the end of the inspection intervals owing to other operating influences, the inspection intervals should be shortened.

Conversely, if no incipient cracks are detected during the regular inspections, the vessel can be operated further up to the next inspection in the interval laid down or agreed, even if the allowable lifetime as calculated according to Annex D has already been reached or has been exceeded.

F.3 Measures to be taken when the calculated allowable fatigue lifetime has been reached

F.3.1 General

If the allowable fatigue lifetime for a vessel or component, determined by calculation according to Annex D or by experiment according to Annex H, shows an infinite lifetime by calculation or experimentation, no non-destructive tests have to be carried out when the vessel or vessel part has been working at no higher than the design conditions where it was intended for.

If the allowable fatigue lifetime of the component given in the operating instructions has been reached (i.e. if the allowable number of cycles has been reached different from an infinite number of cycles or if the total fatigue damage index according to Annex D has reached the value 1, non-destructive tests should be performed as completely as possible concentrating on highly stressed locations and critical zones.

If no cracks are detected by the non-destructive tests conducted in the inspection intervals and in the test above, continued operation may be allowed.

If cracks or crack-like defects or other more extensive damage are found, the component or the structural element concerned should be replaced, unless continued operation appears admissible after verification by appropriate measures.

F.3.2 Testing of vessels and pressure parts at end of life without indicated damages

When the number of equivalent full pressure cycles has reached the end of life, a pressure test should be performed when deemed necessary for certain service parameters. For the method of testing see next paragraph.

F.3.3 Hydraulic testing of vessels and vessel parts with indicated damages

When the number of equivalent full pressure cycles has reached the end of life, a hydraulic pressure test should be performed. The time held shall be at least sufficient to perform a complete inspection with a minimum time of 10 min irrespective of part size.

If the test is successfully passed, then the operation can be continued.

When indicated damages are visible before the number of equivalent full pressure cycles has been reached, a reconsidering of the design may be necessary, either to choose another material grade, to lower design parameters or to verify if all possible load cases have been considered.

Annex G
(normative)

Specific design requirements

G.1 Scope

This annex will give requirements to the designers in detail designs of cast nodular parts to determine the required thickness by formulae of uncommon shapes, not included in EN 13445-3 but frequently used in cast design.

NOTE This Annex G contains only one example of flange design, but may be extended with other construction details when such is indicated by the manufacturers and no specific DBF rules are given in EN 13445-3. Odd shapes can always be verified by DBA design methods, but are often more expensive.

This design rule is applied to cast dished covers without the knuckle radius, subject to pressure, for which the following conditions are satisfied.

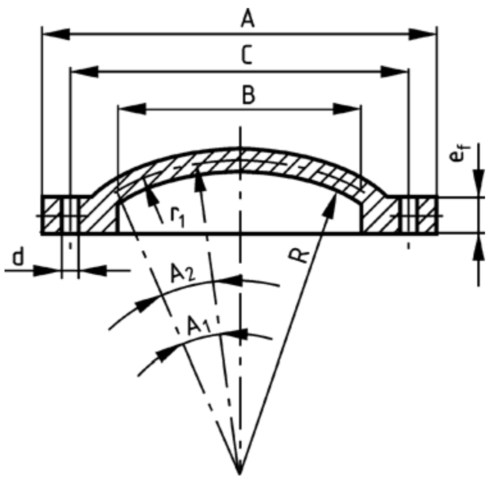


Figure G.1 — Cast dished cover

$A_1 \geq 20°$ and

$A_1 \geq 115 \cdot \sqrt{\frac{e_a}{R}}$ where

$R \leq 1000$ mm.

The spherical part needs to be above the flange horizontal half centreline.

G.2 Design

G.2.1 General

Calculation of nominal design stress according 5.2.

Bolt loads and areas, calculation according 11.4.3 and 11.5.2 of EN 13445-3:2002.

G.2.2 Cover thickness, pressure to convex side

$$e_{\mathrm{c}} = 0{,}85 \cdot \frac{PS \cdot R}{f} \qquad \text{(G.2-1)}$$

G.2.3 Pressure to concave side

If the pressure on the convex side is larger than on the concave side the thickness of the crown shall not be less than

$$e_{\mathrm{c}} = 1{,}65 \cdot R \cdot \sqrt{\frac{PS \cdot n}{E}} \qquad \text{(G.2-2)}$$

where

n is determined according to the table below. Intermediate values are obtained by linear interpolation.

Table G.1 — Form factor

e_C/R	n
0,001	5,5
0,003	4,0
0,005	3,7
0,01	3,5
0,1	3,0

G.2.4 Flange thickness

For metal to metal contact and O-ring gaskets:

$$e_{\mathrm{f}} = 2{,}3 \cdot \sqrt{\frac{W_{\mathrm{op}}}{f} \cdot \frac{C - B}{2\pi \cdot C - \frac{n \cdot d}{2}}} \qquad \text{(G.2-3)}$$

For gaskets inside the bolt circle diameter

$$e_{\mathrm{f}} = 1{,}1 \cdot \sqrt{\frac{W_{\mathrm{op}}}{f} \cdot \frac{C - B}{A - B - d}} \qquad \text{(G.2-4)}$$

where

n is the number of bolts;

W_{op} is the operating force determined by EN 13445-3:2002, Clause 11.

Annex H
(normative)

Experimental cyclic pressure testing procedure

H.1 Purpose

This annex gives requirements for the fatigue testing of pressure vessels or pressure vessel parts in cases where a fatigue assessment cannot be adequately performed due to special shape or lack of experience.

All the requirements given form a consistent set which should be applied as a whole. This test is also a part of the technical documentation.

H.2 Validity

The fabrication of pressure vessels or vessel parts presumes that the manufacturer intending the production has acquired the necessary competence and sufficient experience to manufacture according to the specified standard. This means that tests, performed by the manufacturer or a recognised laboratory are only valid for the same manufacturer producing the production parts with the same casting process.

H.3 Tests requirements

H.3.1 General

Test conditions shall be deduced from the maximum operating conditions. When a pressure part is subject to cyclic pressure testing at ambient temperature, and when TS_{max} and TS_{min} differs from the test temperature, test pressure shall be increased by $1/f_{t^*}$ according eq. D.6-3 for ferritic grades and D.6.4 for austenitic grades.

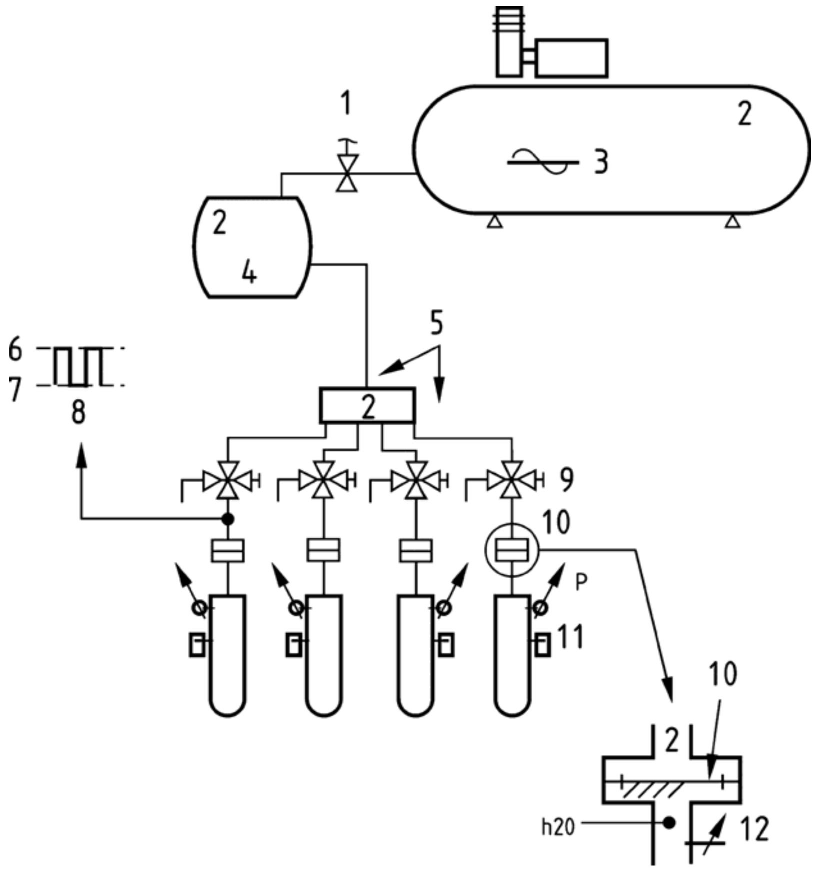
H.3.2 Number of parts

Random samples taken from production of the vessel or vessel part shall be used for fatigue test to determine the allowable number of load cycles. This is called the fatigue batch.

H.3.3 Procedure

- Verify that the vessels or vessel parts to be tested are in accordance with the appropriate drawing and specification.
- Verify that the vessel or vessel part is machined to the same dimensions and tolerance specifications as the production part.
- Verify that a calibrated pressure gauge is used; maximum tolerance shall conform to at least class 1 or better according to EN 837-1 and EN 837-3.
- The scale of the pressure gauge shall be approximately 4/3 of the anticipated maximum cyclic test pressure.

The following test set–up may be used for a layout.



Key

1	pressure regulation	7	P_{min}
2	air tank,	8	pressure pulse frequency
3	variable pressure	9	three way valve
4	constant pressure	10	membrane
5	air circuit as short as possible	11	cycle counter
6	P_{max}	12	water level detector

Figure H.1 — Test set-up

Pressure cycling shall be performed in accordance with the following procedure:

- fill the pressure part to be tested with a non-corrosive fluid such as oil, inhibited water or glycol;
- vent all air pockets.
- The rate of pressurization shall not exceed 14 bar/s. If, for pressure in excess of 80 % of the design burst pressure, the rate of pressurization exceeds 3,5 bar/s, then either the temperature shall be recorded to show no abnormal or excessive heating of the vessel, or there shall be a 5 s hold at the next pressure pulse.
- Ensure that the number of pressure cycles shall not exceed 10 cycles/min.

It is not acceptable that, during the test, leaks and lack of tightness occur between flanged, gasketed or bolted parts.

The test shall not be performed by means of a clamped construction on a hydraulic press which can counteract the shell bending stress resulting in no free movement of the wall under pressure.

The number of cycles to failure shall be reported, along with the location and description of the failure initiation.

H.3.4 Material tests

The following tests and examinations shall be carried out on each vessel submitted for approval tests:

- a hydraulic pressure test according to 7.2.1 shall be carried out prior to the cyclic pressure testing;
- visual examination in the final condition according to 7.1.1;
- magnetic particle inspection (only for ferritic grades). The inspection shall be carried out in accordance with EN 1369;
- after the test a material sample shall be taken from the location where the fatigue crack occurred. The following tests shall be carried out:

  a) thickness measurement;

  b) microstructure investigation;

  c) analysis of the type of fracture.

H.4 Allowable number of cycles

To decrease the test time a higher cyclic pressure than the maximum allowable pressure can be applied. Three or more tests are required. In each test the pressure shall be cycled between the minimum value given by the installation P_{min} and P_{maxexp} where the elasticity limit is expected to be reached for the most stressed vessel component. In most designs, $2 \cdot PS \leq P_{max\,exp} \leq \min(P_{max}, 3 \cdot PS)$.

If the required fatigue life exceeds 10000 cycles, it is permissible to accelerate the test by applying a higher cyclic pressure range ΔP where $\Delta P = P_{max\,exp} - P_{min}$.

The geometric mean fatigue life (in cycles) obtained shall not be less than

$$N_{c.gm} = \left(\frac{PS}{\Delta P}\right)^{m_c} \cdot N_{req} \cdot F \qquad \text{(H.4-1)}$$

where

$N_{c.gm}$ is the geometric mean fatigue life obtained from the tests;

N_{req} is the required number of full pressure cycles;

PS is the maximum allowable pressure (MPa)

ΔP is the pressure range in fatigue test

m_c is the exponent in the equations describing the fatigue design curves

F is a test factor

NOTE $N_{c.gm}$ should be a lower value compared with N_{req}. If the value is still too high one could used a higher ΔP or a larger amount of samples.

The test factor *F* depends on the required probability of survival, the number of test results and the standard deviation of *log N* , σ . For consistency with the design $\Delta\sigma_R - N$ curves for spheroidal graphite cast iron Annex D of this standard, the required probability of survival is 97, 7 %.A selection of values of *k* , which correspond to 95 % confidence in 97,7 % survivability are given in Table H.1. Values for other numbers of tests may be obtained from ISO 12107.

Table H.1 — Values of *k* with number of test specimen

Number of tests	*k*
3	9,1
4	6,1
5	5,0
6	4,4
7	4,0
8	3,8
9	3,6
10	3,5

F is derived using the one-sided tolerance limit factor, k, such that:

$$F = 10^{k\sigma}$$

The standard deviation of $\log N$ may be obtained from these tests or other representative tests.

NOTE The standard deviation of log N is a measure of the scatter in fatigue lives obtained from a number of fatigue tests.

Values of F for a standard deviation of 0,222, which is the largest value found from fatigue tests of spheroidal graphite cast iron pressure vessels, are given in Table H2.

Table H.2 — Values of *F*

Number of tests	*F*
3	105,3
4	22,6
5	12,6
6	9,4
7	7,8
8	6,9
9	6,3
10	5,8

If a lower value for the standard deviation of $\log N$ =0,222 is obtained in the test, it may be applied.

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