

Guidance on the specification of pressure vessels

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Registered and Trading Address:
EEMUA, Second Floor, 16 Black Friars Lane, London EC4V 6EB
Telephone: +44 (0)20 7488 0801
Email: sales@eemua.org
Website: www.eemua.org



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Overview

The purpose of this Publication is to provide guidance on the specification of pressure vessels for circumstances not addressed in design codes. Additionally, this Publication aims to compare international standards, particularly those from the USA, with UK and European equivalents. It has been prepared by the Pressure Vessels Committee (PRV) of EEMUA, the Engineering Equipment and Materials Users' Association. As such, this Publication brings together the practical lessons learnt about design, manufacturing and testing of pressure vessels by users in EEMUA member companies.

Where this text contains a document reference which is unqualified by version, the version to be used is that listed in the references.

EEMUA 211 is composed of five Chapters:

1. Considerations on the avoidance of repeat post-weld heat treatment

Post-weld heat treatment (PWHT) may be of considerable importance to the structural integrity of a pressure vessel. This Chapter examines the circumstances under which repeat PWHT may be waived.

2. Design for exceptional internal pressure

This Chapter describes methods for assessing both existing and new pressure vessels for exceptional internal pressures. Simple and advanced design methods are provided for two levels of service performance.

3. Minimum nozzle loadings and nozzle design

There are three sections to this Chapter which all relate to improvement in the specification and reliability of nozzles. In the first, tables of minimum design loadings are provided to ensure that nozzles, made in steel, nickel alloys or glass reinforced plastics, are suitable for certain minimum loadings. In the second, requirements on standout and minimum pipe schedule are given for nozzles made from pipe. In the third, particular designs of small bore nozzles are specified.

4. Evaluating creep damage to pressure equipment

This Chapter gives a basic appreciation of creep and how to assess situations where creep is suspected. It primarily intended to be used in relation to pressure vessels and similar equipment but does not specifically address piping where additional factors influence its design and assessment.

5. Fatigue assessment

This Chapter provides some background to the issues of fatigue in pressure equipment including basic theory. The different methods of assessing fatigue provided in different standards are outlined too. Finally, the Chapter includes guidance on practical steps to be taken to prevent, how to react when fatigue is detected and forward planning after detection to prevent its recurrence.

1. Considerations on the avoidance of repeat post-weld heat treatment

1.1 Introduction

Post-weld heat treatment (PWHT) relieves the residual stress at welds. It is beneficial in avoiding brittle fracture (for which the design codes give rules) and environmentally assisted cracking (for which purchasers determine requirements). In fabricating new equipment, PWHT may be planned into the manufacturing process and is generally very cost effective.

However, with existing vessels, carrying out repeat PWHT may present many practical difficulties. There may be restrictions at the site on keeping the components hot over the length of time needed. It may be difficult or impossible to provide sufficient heat. Undertaking PWHT in an oven, which is the standard practice for new fabrication, may not be feasible. The disturbance to adjacent equipment caused by carrying out PWHT may also be unacceptable.

Occasionally the need may arise to weld on a vessel after its original fabrication and heat treatment has been completed. Such a welding operation might be necessary almost immediately, before or during commissioning the vessel, due to a design change; however, the need is more likely to occur in-service. New clips or studs may be needed for insulation supports or new anchors for fire-proofing materials. Components such as doubler plates or nozzles may be needed because of corrosion, or due to a process or mechanical design change. Overlay welding may be necessary to build up the thickness of a corroded part. In the extreme, for a major modification, a full circumferential butt-weld may be needed.

This Chapter indicates the thicknesses of components on which the codes currently permit welding without PWHT. It also discusses the welding techniques by which welds on thicker components can be made without repeat PWHT.

It applies predominantly to vessels made in ferritic (i.e. carbon, carbon manganese or low alloy) steels.

1.2 Exemptions from PWHT given in the codes

1.2.1 When PWHT is a code requirement

1.2.1.1 Main pressure parts

For avoidance of brittle fracture, PWHT is usually specified for a given material above a certain thickness in the codes. Table 1 overleaf indicates the maximum thicknesses of components which may be welded without PWHT for vessels in accordance with ASME VIII Div. 1⁽¹⁾ or BSI PD 5500⁽²⁾. The rules apply particularly to new vessels, but are also a major influence when the feasibility of modifying existing vessels is under review.

When heat treating a complete vessel in a furnace for the first time table 1 nominal thickness is the greatest weld thickness on the vessel. For modifications involving local PWHT, ASME and PD5500 generally defines the nominal thickness as the depth of the groove weld or the fillet weld throat thickness, although ASME section UW40(f) provides further clarification.

Table 1 Maximum thickness which may be welded without PWHT

Code	Material			
	ASME P1/ BS EN Gr 1.1, 1.2, 1.3 (C Mn steel)	ASME P3/ BS EN Gr 1.1, 1.2 (C Mo steel)	ASME P4/ BS EN Gr 5.1 (1¼ and 2¼ Cr Mo steels)	ASME P5/ BSI PD BS EN Gr 5.2, 5.3, 5.4 (5 Cr Mo steel)
ASME VIII Div. 1 (Paragraph UCS-56)	32mm (38mm with 95°C preheat) See Note 1	16mm with 95°C preheat and 0.25% C max. See Note 2	16mm with 120°C preheat and 0.15% C max. See Note 3	16mm with 150°C Preheat and 0.15% C max. See Note 3
BSI PD 5500 (Section 4) See Note 5	35mm See Note 4	35mm See Note 4	PWHT required See Note 4	PWHT required See Note 4

Notes

1. Preheat not required for SA841 grades A & B where $C \leq 0.14\%$ and $CE \leq 0.40\%$.
2. P3 Gr 3 materials PWHT required in all thicknesses.
3. Only applicable to pipe butt welds.
4. Greater thicknesses permissible on agreement between purchaser, manufacturer and inspection authority based on fracture mechanics.
5. For vessels operating below 0°C, PD5500 requires more demanding impact testing requirements for vessel without PWHT. In these circumstances impact testing requirements should be considered where a vessel previously with PWHT is repaired without PWHT. ASME VIII Div 1 does not change impact testing requirements based on PWHT.

The codes allow for some difference when welding non-pressure bearing attachments such as internal and external clips onto pressure bearing parts which may have been PWHT during manufacture.

ASME VIII Division 1: generally table 1 requirements apply with exceptions for the following:

Table 2 Requirement for repeat PWHT on clips welded to vessels

Code	Material			
	ASME P1 (C Mn steel)	ASME P3/ (C Mo steel)	ASME P4/ (1¼ and 2¼ Cr Mo steels)	ASME P5/ (5 Cr Mo steel)
ASME VIII Div. 1 (Paragraph UCS-56)	As table 1	Groove weld $\leq$ 13mm Fillet throat thickness $\leq$ 13mm. Studs $\leq$ 16mm dia. welded with 95°C preheat and 0.25% C max. Corrosion resistant weld overlay cladding or attachment weld to corrosion resistant lining with 95°C preheat and 0.25% C max.	Fillet throat thickness $\leq$ 13mm with 120°C preheat. Studs $\leq$ 16mm dia. to pipe welded with 120°C preheat.	For pipe with Cr $\leq$ 3.0%, $\leq$ 16mm thick, C $\leq$ 0.15% the following apply: Fillet throat thickness $\leq$ 13mm with 150°C preheat. Studs $\leq$ 16mm dia. welded with 150°C preheat.

ASME section UW40(f) defines the nominal thickness. For non-pressure parts this is defined as the thickness of the weld at the point of attachment, for studs it is defined as the diameter of the stud, for weld overlay it is the thickness of the overlay.

PD5500: generally Table 1 requirements apply with the thickness defined as the thickness of the weld applied; under special circumstances welding of non-pressure parts is permitted to a vessel previously PWHT by agreement between manufacturer, purchaser and any body which approves modification or repair e.g. in the UK this would likely be a government Pressure System Safety Regulation approved organisation.

1.2.2 When PWHT is a service requirement

PWHT may be specified by the purchaser to avoid environmentally assisted cracking with certain process fluids. In these circumstances, when there is any welding on the surface which is in contact with the process fluid, repeat PWHT is required. The only exception to this is that small clips or rings may be welded without PWHT to an internal corrosion resistant cladding (e.g. in austenitic stainless steel or nickel alloy) if it is fitted. This is subject to appropriate checks being made that the cladding thickness is adequate and the controls applied to the welding are acceptable.

For the surface which is not in contact with the process fluid, normally the outside of the vessel, the welding of small clips without PWHT may be acceptable in some circumstances because of the small heat affected zone associated with such welds. However, if the vessel is thin walled, repeat PWHT may still be needed depending on the type of environmentally assisted cracking which is being avoided.

NACE SP0472⁽⁴²⁾ offers guidance for petroleum refining equipment subject to duties which may cause cracking. Where hydrogen stress cracking or sulphide stress cracking are possible it allows either controlled cooling following welding or temper bead welding as techniques which may be used to avoid PWHT. Where alkaline stress corrosion cracking, amine cracking or carbonate cracking are possible PWHT is required.

1.2.3 Further aspects

1.2.3.1 BSI PD 5500

In BSI PD 5500 Clause 4.4.3.1, welding on lightly loaded and non-pressure parts of previously heat treated vessels is permitted without repeat PWHT, providing it can be demonstrated that the material will not be adversely affected. This permits welding without repeat PWHT under carefully controlled conditions on a limited range of components.

1.2.3.2 ASME VIII Division 1

ASME VIII Div. 1 (Clauses UG-55, UG-4b) contains rules for the attachment of lugs, clips and other non-pressure parts by arc welding (Clause UW-5b). It requires a suitable weld procedure, qualified to ASME IX⁽³⁾, to be used. To assess whether PWHT is required, the nominal thickness, which is the thickness of the weld at the point of attachment of the non-pressure part to the pressure part, (see ASME VIII Div. 1 Clause UW-40f (5f)) is used in conjunction with ASME VIII Div. 1 Tables UCS-56 and UCS-56.1.

1.2.3.3 Temper bead welding

ASME VIII Div.1 and the National Boiler Inspection Code⁽⁴⁾ specify high preheat/temper bead repair options that exempt PWHT for P-1, P-3, P-4 and P-5A materials.

Temper bead welding is an advanced technique, where advice should be sought from welding specialists experienced in this field when the feasibility of the job is first being considered. Several runs of weld are usually needed to obtain the tempering and therefore it is mainly used on repairs. For the attachment of a clip, it may be more practical to weld a thick pad onto the vessel using temper bead welding and weld the clip to the pad by conventional means.

The skill of the welder and the control of the welding technique are likely to be the major factors in the success of temper bead welding. Welding procedure and welder qualification tests would need to be carefully monitored and the test pieces thoroughly evaluated. For more information on the technique, see Welding Research Council Bulletin No. 412⁽⁵⁾ and Brett et al. ⁽⁶⁾

1.2.3.4 Nickel alloy filler

Attachment of small appurtenances to the external surface of vessel components in carbon or carbon manganese steel may be made using suitable non-hardenable nickel alloys. The risk of hydrogen cracking is significantly reduced through the use of an austenitic nickel alloy filler metal, compared to carbon manganese or low alloy steel ferritic filler metals. There are also other potential additional practical advantages, as nickel alloy electrodes generally do not require re-drying prior to use. The potential for galvanic corrosion should be assessed prior to the use of nickel alloy filler metal for welding carbon-manganese or low alloy steel.

However, the risk of cracking in the ferritic base material due to high hardness (as opposed to hydrogen) is not altered by the use of an austenitic filler. Appropriate levels of pre-heat should be applied and maintained during the welding operation. In a procedure test, a thorough check should be made of the hardness of the heat affected zone to ensure that it is within acceptable limits.

1.2.3.5 Stud welding

Studs for attaching insulation or fireproofing may be attached by discharge welding and this is considered to be acceptable in some circumstances. Table 2 gives some guidance on PWHT requirements for attaching studs using various welding methods. Means for checking such welds using non-destructive examination are very limited.

1.2.3.6 Repair welding

Some codes require PWHT to be applied after repair welding with a ferritic filler metal, regardless of whether or not the base material was originally subject to PWHT. However, this requirement is waived if a nickel alloy or stainless steel electrode is used. It may therefore be very advantageous to use the latter.

In any repair welding, a critical review needs to be made of the weld procedure, the state of the material and the information available from NDT. There should also be a trial (preferably on material which may have been in service) to demonstrate that the repair can be satisfactorily carried out. Where creep is a factor, the available operating life with the repair may be limited.

There may be practical issues associated with major repairs, such as the cutting of a hole in the shell for access which then has to be re-welded.

1.2.4 General requirements for welds where PWHT is waived

The following general requirements apply for welds where PWHT is waived:

- An approved Welding Procedure Specification and a Procedure Qualification Record should be available. (As PWHT is an essential variable both need to, of course, apply where there is no PWHT). Where welding is being carried out on material which has been in service, the approval needs to take into account any environmental effects on the parent material.
- All welding should be made with the required pre-heat.
- All welds should be given 100% surface inspection (by magnetic particle or dye penetrant methods). A volumetric inspection (by ultrasonics or X-ray) should also be made. Advanced inspection techniques should be considered to provide a high level of scrutiny.
- Those supervising the work should have a thorough understanding of any potential mechanisms for deterioration or cracking in the weldment, i.e. the weld, heat affected zone and adjacent parent material.
- A materials specialist should always be consulted before attempting any weld.
- A welding and/or materials specialist should be consulted if doubt exists over the correct welding approach to be taken during the repair or modification of the vessel.

1.3 Example from the power industry

Boiler Shell Weld Repair by IMechE, 1999⁽⁷⁾ describes in considerable detail a major repair carried out on three boilers in low alloy steel at Sizewell 'A' Power Station. The welds were 57 mm thick in cylinders of 6.86 m diameter.

The boiler shells had been subject to PWHT originally (in the 1960's) and, after detailed consideration of several other options, PWHT was repeated following repairs at site made in 1996. The issues associated with carrying out PWHT after the repair, or waiving it, are well described.

In order to carry out PWHT, the problems to be solved were:

- the thermal stresses induced in the shell;
- the support of the tube bank during PWHT;
- the ability of the shell material to withstand further heat treatment; and
- the loads transmitted during the PWHT to the reactor nozzles.

According to ASME XI⁽⁸⁾, a repair without PWHT is permissible providing:

- the repaired depth does not exceed 50% of the plate thickness;
- a temper bead repair technique is developed and validated; and
- the repair is reassessed to either the original code of construction or the current equivalent code.

This option of making the repair without PWHT was thoroughly assessed. The residual stresses were modelled using finite element analysis. A very substantial programme of weld procedure development and welder qualification was carried out. However, it was finally decided that a feasible repair with PWHT could be made and the work was satisfactorily completed in this way.

2. Design for exceptional internal pressure

2.1 Introduction

This Chapter describes methods for assessing both existing and new pressure vessels for exceptional internal pressures. An exceptional pressure is one that occurs infrequently and for which application of the safety factors normally used in design would be unduly onerous. Simple and advanced design methods are provided for two levels of service performance. For Level 1, the vessel should withstand the exceptional pressure without any permanent deformation and, after inspection, be suitable for re-use. For Level 2, it should contain the pressure without release of the contents but may not be suitable for re-use. The simple method is generally based on linear-elastic material behaviour and the advanced method assumes non-linear behaviour. In Section 2.4, a brief comparison is made with EN 14460: 2006⁽⁹⁾, which has some similarities with this Chapter but also many differences.

The occurrence of an exceptional pressure inside a pressure vessel may be a credible, though infrequent, event. (Internal explosions are one type of exceptional pressure, but there are many other causes). The vessel has to be designed for the pressure, but the safety factors which are specified in the codes may lead to designs which are not economically viable. In addition, it may be evident when the risk is assessed that the conservatism applied in routine design is unnecessary for allowing for the exceptional pressure.

The size of the exceptional pressure is the major parameter in the design loading. Its duration is of significance largely in the assessment of dynamic effects. The number of occasions on which it occurs is a determinant of the risk associated with the event rather than the design of the vessel, and is not addressed here.

Rules are proposed in this Chapter for design against two levels of service performance, depending on the level of deformation which may be accepted. In all cases, full code compliance is required at normal design conditions.

The following definitions apply in this Chapter.

- **Explosion-pressure-resistant.** The property of vessels and equipment designed to withstand the expected explosion pressure without becoming permanently deformed (EN 14460:2006).
- **Yield strength.** Specification of minimum yield strength (SMYS) of the shell material at the exceptional design temperature.
- **Tensile strength.** Specification of minimum tensile strength (SMTS) of the shell material at the exceptional design temperature.

2.1.1 Assumptions

The following assumptions have been made:

- Dynamic effects with respect to vessel deformation are fully taken into account. Dynamic effects may be expected if the time scale of the pressure increase is smaller than five times the natural period of the shell. At such short loading times, the dynamic loading may be the equivalent to twice the applied static pressure. A basic discussion on dynamic loading of vessels is given by Faupel, et al.⁽¹⁰⁾ and a means for manually estimating the natural period of a cylinder is provided by Calladine⁽¹¹⁾.
- Any impact on attached piping and appurtenances from the exceptional pressure has been taken into consideration.
- The magnitude of the peak pressure has been obtained from a rigorous analysis of the process conditions.

- The required design temperature at the exceptional internal pressure condition is not significantly higher than the design temperature for the vessel.
- Material behaviour is ductile.

Note: There is no specific requirement to use transient dynamic analysis. An elastic-plastic analysis (without transient/dynamic effects) based on the calculated maximum peak pressure (of twice the static pressure) is a valid assessment approach.

2.2 Design methods

2.2.1 Service levels

For Level 1 service, the vessel may deform but, subject to a satisfactory inspection, it may be re-used without repair. The design is therefore explosion/pressure-resistant.

For Level 2, the vessel may be severely damaged and beyond economic repair, but major leakage does not occur.

It is permissible to apply the methods below either for the initial design of new vessels or for changed process conditions on existing vessels.

2.2.2 Simple design method

2.2.2.1 General

Under both Levels 1 and 2, some plasticity is tolerated in the vessel wall. The size of the primary stresses and the size of the average primary stress across the wall are therefore both of particular importance.

Because peak and secondary stresses are smoothed out by the plastic deformation, they are less relevant than the primary stresses.

Assuming that a typical pressure vessel steel is being used (where yield strength of the material is less than 0.7 times tensile strength), bending stresses are more strictly limited in Level 1 than in Level 2. This is to restrict the extent of plastic deformation.

The method is based on the practice given in ASME VIII Div. 1 Appendix H and ASME III⁽¹²⁾. In specifying the stress and strain limits, comparable values in ASME VIII Div. 2 and EN 13445-3⁽¹³⁾ have been taken into account.

2.2.2.2 Level 1

For Level 1, the following limits apply:

- average (membrane) primary stress should be limited to yield strength;
- membrane plus bending stresses should be limited to 1.5 times yield strength;
- shear stress should be limited to 0.6 times yield strength;
- the stress in flange bolting should not exceed 0.8 times bolt yield strength;
- the maximum primary and secondary stress at all nozzle intersections due to the exceptional pressure only should be less than 3 times yield strength.

Note: The prime concerns are the effects of the primary load source - the direct blast pressure. The original design system stresses are likely to be relatively low and self-limiting compared to those in the blast load collapse mechanism. Therefore the additional effects due to attached pipework are ignored. The need to include pipe movement due to pipe shock response would require an additional complicated transient/dynamic analysis of the pipework to predict the effect of the vibrating pipework attached. This would be outside the scope of this Chapter, which is not a complete design code. The stresses should be calculated using linear elastic methods.

The stress concentration factors for nozzles should be taken from the literature but recommended methods are BSI PD 5500 Figure G.2.5-1 to 8 (from Leckie and Penny⁽¹⁴⁾) or Decock⁽¹⁵⁾. Even though the nozzle may be made from a weaker material than the shell, it is considered acceptable to limit the maximum stress in the nozzle to 3 times yield strength of the shell material.

2.2.2.3 Level 2

For Level 2, the limits applied are:

- average membrane stress should be limited to 0.7 times tensile strength;
- membrane plus bending stress should be limited to tensile strength;
- shear stress shall be limited to 0.42 times tensile strength;
- the stress in bolting should be limited to 0.7 times tensile strength of the bolting or yield strength, whichever is less;
- the equivalent plastic strain in any part of the vessel should be limited to 2% and the maximum of the strain components should be limited to 5%;
- plastic deformation in bolts should be limited to an equivalent plastic strain of 1% and/or an axial strain of 2%. (If gasket blowout is feasible then this should also be considered).

Stresses should be calculated by linear elastic methods, but elastic-plastic methods may be used to prove that containment is maintained. For the latter, the assumed material behaviour should preferably be either consistent with that of the actual material at operating temperature or non-work hardening.

2.2.3 Advanced design method

Criteria are also given for an assessment method based on non-linear elastic-plastic behaviour. The method is a limit load approach based on the design check for gross plastic deformation (GPD) in EN 13445-3 Annex B. The criteria are stated in Table 3 overleaf and also compared with those in Annex B. It is a direct method, which provides some insight into the failure mechanism that applies. The limits are solely based on the level of local principal strain (shown in bold lettering in Table 3).

Table 3 Advanced assessment methods for Levels 1 and 2 based on non-linear behaviour (limit load)

	Advanced assessment methods for exceptional pressure		Design check in EN 13445-3 Annex B for GPD
	Level 1	Level 2	
Material behaviour	Elastic-perfectly plastic	Elastic-plastic including strain hardening	Elastic-perfectly plastic
Yield criterion & associated flow rule	Tresca* (or Von Mises** corrected with $\sqrt{3}/2$)	Von Mises**	Tresca* (or Von Mises** corrected with $\sqrt{3}/2$)
Nonlinear geometry behaviour	No (first order theory)	Yes	No (first order theory)
Partial safety factor on pressure γ_p	1.0	1.0	1.2 (pressure load without natural limit, EN 13445 Table B.9-2)
Partial safety factor on material resistance γ_R	1.25	1.25	1.25
Additional criterion: Maximum absolute value of local principal strain	7% peak 2% membrane	5% membrane	5% peak (anywhere)

* Tresca stress is equal to 'stress intensity'. For definition refer to BSI PD 5500: 2009 Section A3.4.1.1, formula 5.1.

** For definition of Von Mises yield criterion refer to ASME VIII Div.2 2015 Section 5.2.2.1, formula 5.1.

To make the method consistent with the simple method, some of the conservatism in EN 13445-3 Annex B has been reduced, for example:

- at both levels the partial safety factor on pressure (γ_p) has been reduced from 1.25 to 1.0;
- at Level 1 the allowable strain is significantly higher than in EN 13445-3 and at Level 2 it is higher still.

2.3 Testing

The vessel should be subjected to a hydrostatic test related to its normal design pressure. This should be adequate proof of the quality of design and fabrication. Application of the design methods given above is considered to be the main justification for the vessel being exposed to the exceptional pressure. It is not considered necessary that it should be subjected to a pressure test based on the exceptional pressure. Pressure testing is discussed in EEMUA Publication 168⁽¹⁶⁾. Pressure test waivers are discussed in EEMUA Publication 223⁽¹⁷⁾.