FIXED EQUIPMENT NEWSLETTER

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- Minimum Thicknesses and Undertolerance for Plates and Pipes
- Pressure Vessel Fabricated by Layered Construction
- Postweld Heat Treatment
- True Stress versus Engineering Stress
- Appendix 46: Rules for Use of Section VIII, Division 2

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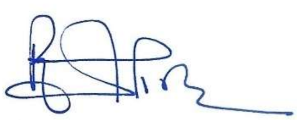
VESSEL THICKNESS – ASME CODE VS REPAIR CODES

As we know, ASME Section VIII, Division 1 is a construction code for new pressure vessels, and its applicability ends after the pressure vessel has been tested, the nameplate has been attached, and the data report has been signed by both the Manufacturer and the Authorized Inspector. The design procedures of the ASME code specify minimum thicknesses for the pressure-retaining components; the nominal thicknesses of all pressure-retaining components exceed the minimum required thicknesses. One exception is Appendix 32 that permits acceptable local thin areas (LTAs) in cylindrical shells or spherical segments of spherical shell, hemispherical heads and the spherical portions of torispherical and ellipsoidal heads under internal pressure to be less than the minimum required thickness.

Once the pressure vessel has been installed and is put into operation, ASME Section VIII, Division 1 in no longer the governing code, but is referred when the vessel undergoes repairs and alterations during operation. One of the major codes that is used for repairs and alterations of pressure vessels in operation is the National Board Inspection Code (NBIC). NBIC is composed of four parts – two parts that are widely used during repairs and alterations are Part 2 (Inspection) and Part 3 (Repairs and Alterations).

One major difference between the ASME Section VIII, Division 1 and the NBIC is with respect to the minimum thickness requirement. While ASME's new construction code emphasizes minimum thicknesses in the design procedures (LTAs permitted by Appendix 32 being the exception), NBIC Part 2 (Inspection) permits averaging of least thicknesses over a representative length. The representative lengths used for averaging least thicknesses are provided in NBIC Part 2, Paragraph 4.4.7.2(h) and (i) for circumferential stress and longitudinal stress respectively. It is possible, therefore, under certain conditions, for a vessel to be repaired with "R" stamp with thicknesses that are less than the minimum required thicknesses (including the exceptions provided by Appendix 32).

API 510, another widely used repair and alteration code in the petrochemical industry, also utilizes the concept of average thicknesses rather than the minimum required thicknesses.



Ramesh K Tiwari
ramesh.tiwari@codesignengg.com

Featured in this issue…

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CoDesign Engineering provides a wide range of engineering services for heat exchangers, pressure vessels, storage tanks and piping design with a mission to achieve engineering excellence, customer satisfaction and innovative solutions. We bring over 50 years of combined experience with technical and commercial requirements of large capital projects and understanding of major design requirements across all engineering disciplines.

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- Design and fabrication services for pressure vessels complying with the requirements of ASME Section VIII, Divisions 1 and 2
- Review and certification of repair plans for pressure vessels
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- Finite element analysis of pressure vessel components
- Registration of pressure vessels and accessories in Canadian provinces
- Design of lifting lugs and tailing lugs for tall columns
- Cyclic service analysis for pressure vessels per ASME Section VIII, Division 2, Part 5

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- Design, analysis and rerating of atmospheric storage tanks and low-pressure storage tanks based on API 650 and API 620 respectively

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13703 Brighton Park Dr, Houston, Texas 77044 (USA)   *Contact: ramesh.tiwari@codesignengg.com*

MINIMUM THICKNESSES AND UNDERTOLERANCE FOR PLATES AND PIPES

The requirements for the minimum thicknesses and undertolerance for plates and pipes is provided in paragraph UG-16 of ASME Section VIII, Division 1.

Question 1:

What is the minimum thickness permitted for shells and heads, after forming and exclusive of any corrosion allowance?

Answer**:**

1/16 in. (1.5 mm)

Question 2:

What are exceptions to the minimum thickness requirement in Question 1 above?

Answer**:**

The minimum thickness requirement in Question 1 above is not applicable to:

a. Heat transfer plates of plate type heat exchangers. Refer to Appendix 45 of ASME Section VIII, Division 1 for the minimum thickness requirements for single wall heat transfer plates or combined thickness of double wall heat transfer plates.
b. Inner pipes of double pipe heat exchangers where such pipes are NPS 6 (DN150) and less.
c. Pipes and tubes that are enclosed in a shell, casing or ducting where such pipes are NPS 6 (DN150) and less.
d. Shells and heads of unfired steam boilers. These shall be a minimum 1/4-inch (6 mm) thickness exclusive of any corrosion allowance.
e. Shells and heads used in compressed air service, steam service and water service made from carbon and low alloy steels. These shall be a minimum 3/32 inch (2.5 mm) thick exclusive of any corrosion allowance.
f. Tubes in air-cooled heat exchangers and cooling towers if certain conditions are met.

Question 3:

Under what conditions are the tubes in air-cooled heat exchangers and cooling towers exempt from the minimum thickness requirement of 1/16 inch (1.5 mm)?

Answer**:**

Following conditions shall be met:

a. Tubes shall not be used for lethal service applications.
b. Tubes shall be protected by fins or other mechanical means.
c. Tube outside diameter shall be a minimum of 3/8 inch (10 mm) and a maximum of 1-1/2 inch (38 mm).

d. Minimum thickness used shall not be less than that calculated by the formulas given in UG-27 or Appendix 1-1, and in no case less than 0.022 inch (0.5 mm).

Question 4:

What is meant by “required thickness”, “design thickness”, and “nominal thickness”?

Answer**:**

Required thickness -	Thickness computed by equations of the code before corrosion allowance is added.
Design thickness -	The sum of required thickness and the corrosion allowance.
Nominal thickness -	Thickness selected as commercially available. For plate material, the nominal thickness is, at manufacturer’s option, either the thickness shown on the “Material Test Report” before forming, or the measured thickness of the plate art the joint or location under consideration.

Question 5:

What is the code requirement for the nominal thickness of a plate material?

Answer**:**

Plate material shall not be ordered with a nominal thickness less than the design thickness.

Question 6:

Is it permitted to use plate material with actual thickness less than the design thickness?

Answer:

Plate material with an actual thickness less than the design thickness shall not be used unless the difference in thicknesses is less than the smaller of 0.01 inch (0.3 mm) or 6% of the design thickness.

Question 7:

What is the code requirement with respect to pipe undertolerance?

Answer:

If the pipe is ordered by its nominal wall thickness, the manufacturing undertolerance on wall thickness shall be taken into account except for nozzle reinforcement area requirements in accordance with UG-37 and UG-40 of the code.

The manufacturing undertolerances are given in several pipe specifications; for SA-106-B, the minimum wall thickness at any point shall not be more than 12.5% under the specified wall thickness.

References:

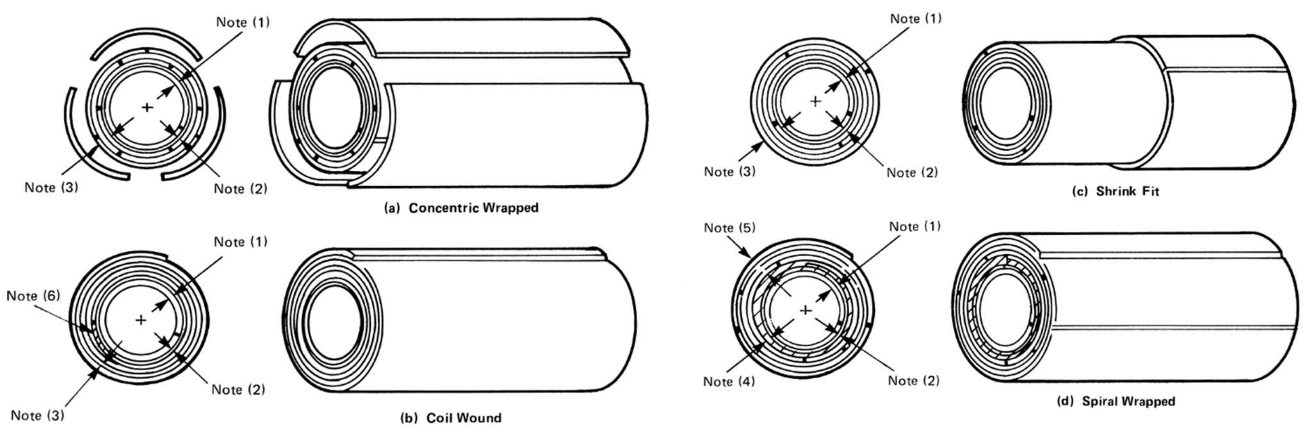
ASME Boiler and Pressure Vessel Code, Section VIII, Division 1: Edition 2021, Paragraph UG-16.

PRESSURE VESSELS FABRICATED BY LAYERED CONSTRUCTION

INTRODUCTION

Layered vessels are used in a wide range of high-pressure applications in the petrochemical industry such as heat exchangers, urea reactors, ammonia converters, autoclaves, and coal gasification reactors. These vessels consist of a multitude of layers wrapped tightly around an inner shell to form a pressure retaining envelope, as shown in Figures 1 and 2.

Layered vessels are constructed by various methods. The difference between these methods is in the thickness of individual layers, wrapping procedure, and welding technique. In general, layered-vessel construction can be divided into three categories. The first is the concentric- or spiral-wrapped method where the layers consist of segments welded together in a spiral or concentric fashion to form the required thickness, as shown in Figure 1(a) and (d). The second is the shrink-fit method whereby layers are individually formed into cylinders and shrunk on each other to form the required total thickness, as shown in Figure 1(c). The third is the coil-wrapped method whereby a continuous sheet or strip is wound in a spiral or helical fashion to form a cylinder as in Figure 1(b).



Notes: (1) Inner shell (2) Dummy layer (if used) (3) Layers (4) Shell layer (tapered) (5) Balance of layers (6) Gap

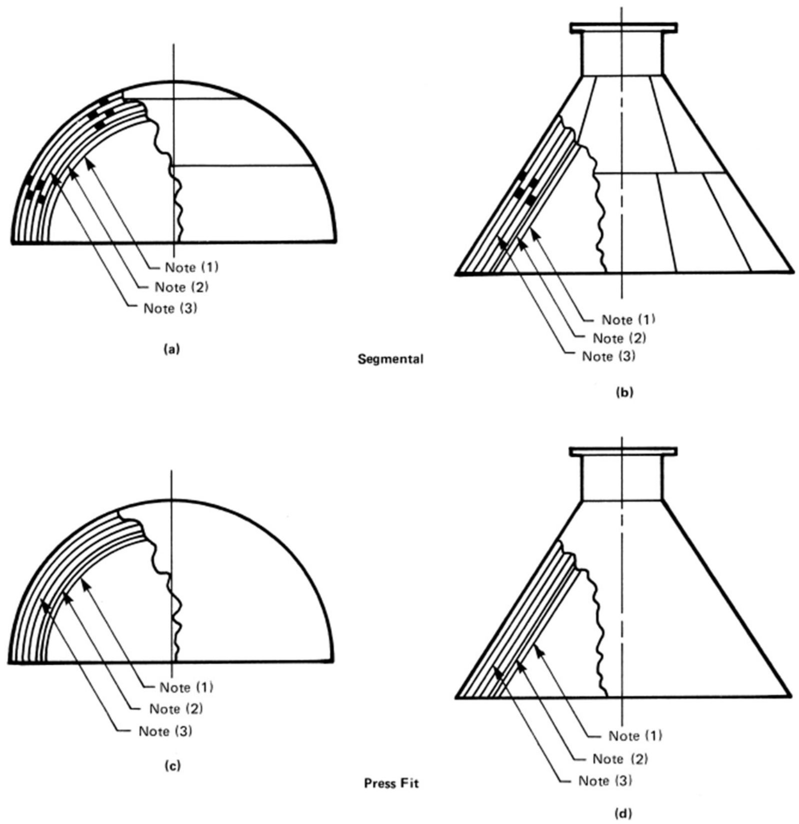
Figure 1: Some Acceptable Layered Shell Types
(*Courtesy of ASME Boiler & Pressure Vessel, Section VIII, Division 1*)

MAIN COMPONENTS

Cylindrical portion of layered vessels consist of an Inner liner made of corrosion resistant material, over which shell layers formed from plates or sheets are added. Dummy layer will be provided between inner shell and Shell layers, to function as secondary containment, to protect the carbon steel shell layers. Leak detection system will help in early detection of any leak. Heads of the vessel will be constructed from single wall forgings with an inner lining, or, as a layered construction which is comparatively difficult to construct and is not warranted. Dummy layer and leak detection system should be provided for the heads also.

ADVANTAGES OF LAYERED CONSTRUCTION

It is possible to achieve uniform shell properties and stress distribution which is difficult to achieve for thick single wall. Thin plates exhibit superior mechanical properties (strength as well as notch toughness) compared to thick plates. When thin plates are wrapped without any gap, the layered section forms a virtually solid wall with uniform properties. In addition, the compression stress induced by the tight wrapping is distributed throughout the inner two-thirds of shell courses. The tensile stress resulting from operating pressure is superimposed over this pre-stress to provide an almost uniform tensile stress over the entire thickness. Materials of different properties can be used for the layers, if required, to enhance the strength characteristics.



Notes: (1) Inner shell (2) Dummy layer (if used) (3) Head Layers

Figure 2: Some Acceptable Layered Head Types
(*Courtesy of ASME Boiler & Pressure Vessel, Section VIII, Division 1*)

Multiwall vessels can be easily fabricated to any desired thickness and diameter, whereas single wall construction is limited by the available plate thickness and fabrication facilities.

By suitably selecting the materials and thickness of layers, PWHT can be avoided. Therefore, the inner liner can be made of Titanium, 25-22-2 or any other similar material, without fear of any degradation due to PWHT. Whereas PWHT is mandatory for thick-walled construction, which can degrade the inner lining.

The rupture mode of layered construction is only by tearing without fragmentation; the propagation of any brittle fracture/crack will stop at layer interface. Single wall construction has the risk of brittle fracture and hence may fragment to small pieces during a rupture which can fly off in all directions.

DEFINITIONS

Layered Vessel: A vessel having a shell and/or heads made up of two or more separate layers.

Inner Shell: The inner cylinder that forms the pressure tight membrane.

Inner Head: The inner head that forms the pressure tight membrane.

Shell Layer: Layers may be cylinders formed from plate, sheet, or forging, or the equivalent formed by coiling, or by helically wound interlocking strips (This does not include wire winding).

Head Layer: Any one of the head layers of a layered vessel except the inner head.

Overwraps: Layers added to the basic shell or head thickness for the purpose of building up the thickness of a layered vessel for reinforcing shell or head openings or making a transition to thicker sections of a layered vessel.

Dummy Layer: A layer used as a filler between the inner shell (or inner head) and other layers, and not considered part of the required total thickness.

SPECIFIC REQUIREMENTS

1. When the vessel contains lethal substance(s), the requirements of UW-2(a) apply only to the inner shell and inner heads.
2. Torispherical layered heads are not permitted.
3. Openings are not permitted in the shell sections of helically wound interlocking strip construction.
4. Category D joints between layered nozzles and shells or heads are not permitted.
5. The Manufacturer's Quality Control System must include the construction procedures that will outline the sequence and methods of application of layers and measurement of layer gaps.
6. Use of 5%, 8% and 9% nickel steel materials are permitted only for the inner shells and heads.
7. A description of the layered shell and/or layered heads must be given on the data report describing the number of layers, their thickness or thicknesses, and type of construction.
8. Letters "WL" must be designated directly under the Certification mark to indicate layered construction.

VENT HOLE SYSTEM

The vent hole system is a safety feature. It consists of a multitude of small holes radially drilled into the layers and extending from the outermost later to and including the layer adjacent to the inner shell. The holes are sized and spaced so that they do not affect the structural integrity of the vessel. The venting system is provided to detect leakage of the inner shell and to prevent buildup of pressures within the layers.

In each shell course or head segment, a layer may be made up of one or more plates. Each layer requires at least two vent holes 1/4" in. minimum diameter. Holes may be drilled radially through the multiple layers or may be staggered in individual layer plates.

For continuously coil wrapped layers, each layered section requires at least four vent holes 1/4" minimum diameter. Two of these vent holes are required to be located near each end of the section and spaced approximately 180° apart.

The minimum requirement for spirally wound strip layered construction is 1/4" minimum diameter vent holes drilled near both edges of the strip. They are spaced for the full length of the strip and are located approximately $\pi R \tan\theta$ from each other where "R" is the mean radius of the shell and "θ" is the acute angle of spiral wrap measured from longitudinal centerline. If a strip weld covers a vent hole, partially or totally, an additional vent hole is drilled on each side of the obstructed hole. In lieu of the above, holes may be drilled radially through multiple layers.

DESIGN

a) The design of layered vessels shall conform to the design requirements given in UG-16 through UG-46 except that:

    1. Reinforcement of openings is required as illustrated in Figure 3.
    2. In calculating the requirements for vacuum per UG-28, only the inner shell or inner head thickness shall be used.

3. Layered shells under axial compression shall be calculated using UG-23 and utilizing the total shell thickness.

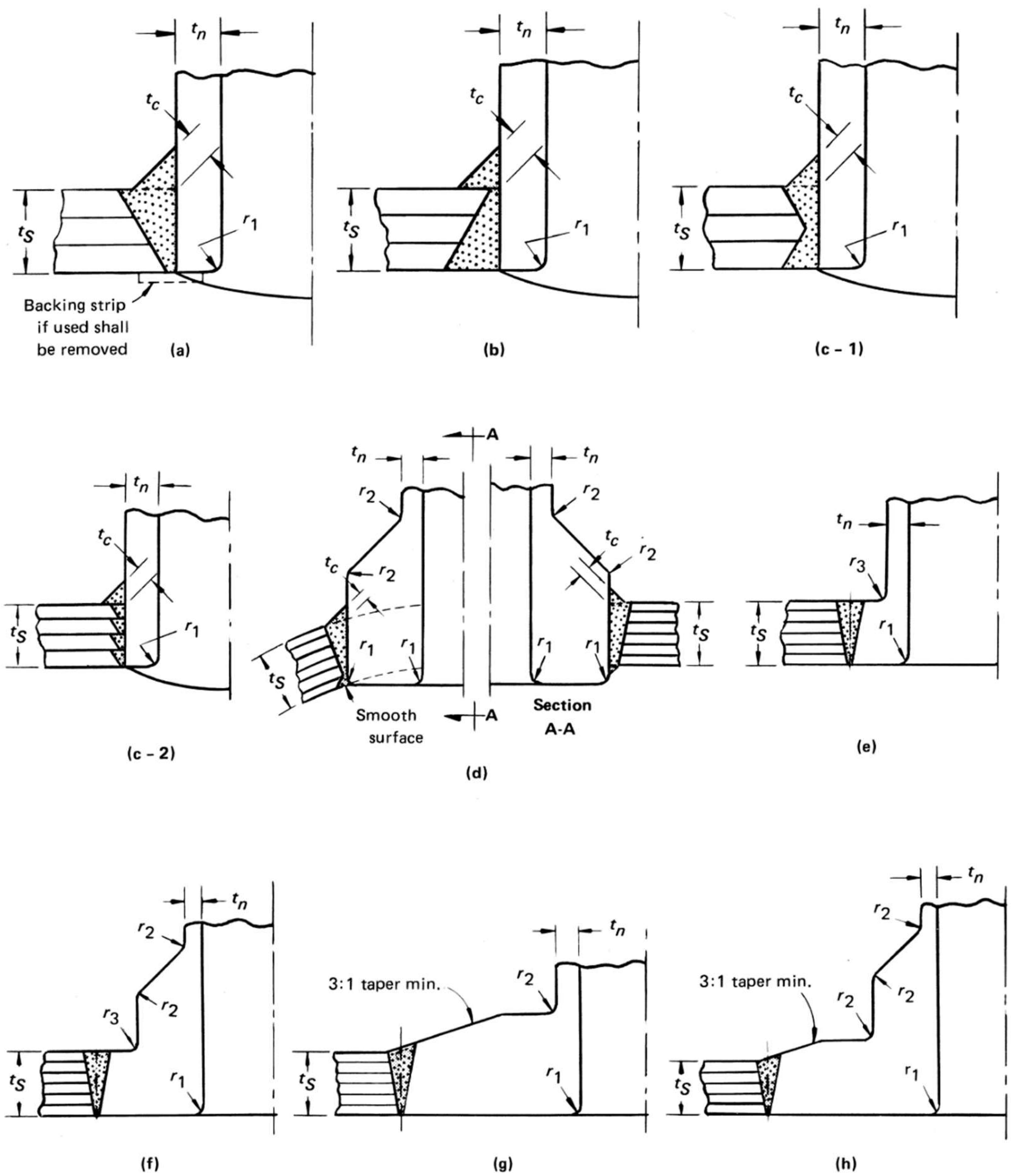


Figure 3: Some Acceptable Nozzle Attachments in Layered Shell Sections (Contd. Next page)

b) The inner shell or inner head material which as a lower allowable design stress than the layer materials may only be included as credit for part of the total wall thickness if S_1 is not less than 0.50 S_L by considering its effective thickness to be:

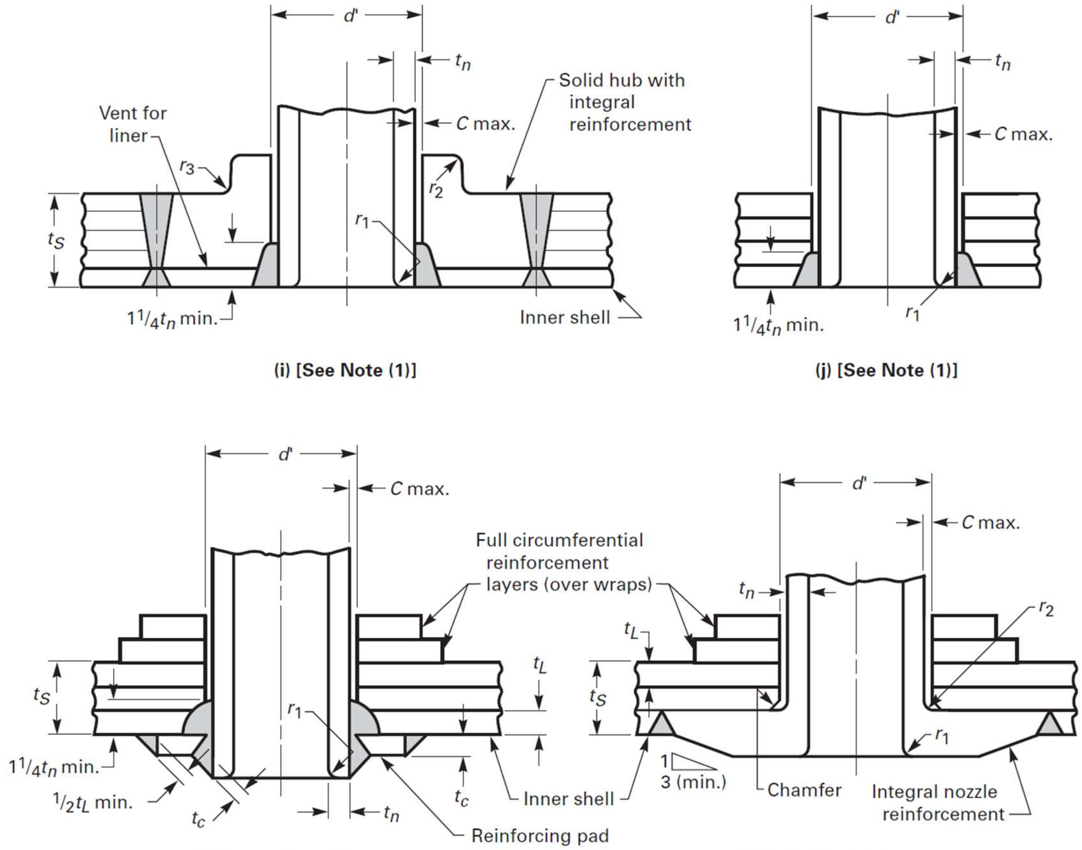
$$t_{eff} = t_{act}\,\frac{S_1}{S_L}$$

where, S_1 = Design stress of inner shell or inner head

S_L = Design stress of layers

t_{act} = Nominal thickness of inner shell or inner head

t_{eff} = Effective thickness of inner shell or inner head



(i) [See Note (1)] (j) [See Note (1)]

(k) [See Note (1)] (l) [See Note (1)]

C max. = $^1/_8$ in. (3 mm) radial clearance between nozzle neck and vessel opening

d' = finished opening in the wall (refer to ULW-18 for maximum permissible diameter)

r_1 min. = $^1/_4 t_n$ or $^1/_8$ in. (3 mm), whichever is less

r_2 = $^1/_4$ in. (6 mm) minimum

r_3 min. = $^1/_4 t_n$ or $^3/_4$ in. (19 mm), whichever is less

t_c = not less than $^1/_4$ in. (6 mm) or 0.7 of the smaller of $^3/_4$ in. (19 mm) or t_n

t_L = thickness of one layer

t min. = the smaller of $^3/_4$ in. (19 mm) or t_n

t_n = nominal thickness of nozzle wall

t_S = thickness of layered shell

NOTE:

(1) Provide means, other than by seal welding, to prevent entry of external foreign matter into the annulus between the layers and the nozzle neck O.D. for sketches (i), (j), (k), and (l).

Figure 3: Some Acceptable Nozzle Attachments in Layered Shell Sections (Contd.)

c) Layers in which the maximum allowable stress value of the materials is within 20% of the other layers may be used by prorating the maximum allowable stress of the layers in the thickness formula, provided the materials are compatible in the modulus of elasticity and coefficient of thermal expansion.

d) The minimum thickness of any layer cannot be less than 1/8 in.

e) When the nondestructive examinations outlined in ULW-50 through ULW-57 have been complied with, the weld joint efficiency for design purposes shall be 100%.

NOZZLE ATTACHMENTS AND OPENING REINFORCEMENT

Openings, NPS 2 and smaller, need not be reinforced when installed in layered construction, but must be welded on the inside as shown in Figure 3, sketch (j). The nozzle nominal wall thickness must not be less than Schedule 80 pipe as fabricated, in addition to meeting the requirements of UG-45.

Openings greater than NPS 2 may be constructed as shown in Figure 3, sketch (i). The diameter of the finished openings in the wall shall be d’ as specified in the sketch; and the thickness t_r is the required thickness of the layered shells.

Openings up to and including 6 in. nominal pipe size may be constructed as shown in Figure 3, sketches (k) and (l). Such partial penetration weld attachments may only be used for instrumentation openings, inspection openings etc., on which there are no external mechanical loadings. The diameter of the finished openings in the wall shall be d’ as specified in the sketch; and the thickness t_r is the required thickness of the layered shells.

DESIGN OF WELDED JOINTS

Only major joints are shown here (not nozzle welds):

Category A and B joints of inner shells and inner heads of layered section	Category A – Type No. (1)
	Category B – Type No. (1) or (2)
Category A joint of layered section	Layers over 7/8” in thickness – Type No. (1)
	Layers 7/8” or less in thickness – Type No. (1) or (2). Final outside weld joint of spiral-wrapped layer may be a single lap weld.
Category B joint of layered shell sections to layered shell sections, or layered shell sections to solid shell sections	Type No. (1) or (2)
Category A joints of solid hemispherical heads to layered shell sections	Type No. (1) or (2)
Category B joints of solid elliptical, torispherical, or conical heads to layered shell section	Type No. (1) or (2)
Category C joints of solid flat heads and tubesheets to layered shell section	Type No. (1) or (2)
Category C joints attaching solid flanges to layered shell sections, and layered flanges to layered shell sections	Type No. (1) or (2)
Category A joints of layered hemispherical heads to layered shell section	Type No. (1) or (2)
Category B joints of layered conical heads to layered shell sections	Type No. (1) or (2)

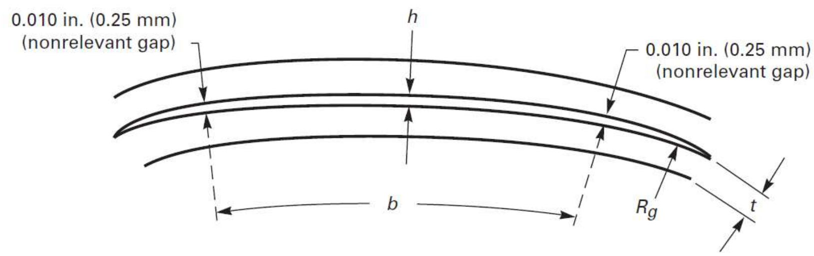
CONTACT BETWEEN LAYERS

Paragraph ULW-77 of Part ULW of ASME Section VIII, Division 1 given additional rules for layered vessel construction.

All Category A weld joints shall be ground to ensure contact between the weld area and the succeeding layer before application of the layer. These weld joints shall be in an offset pattern so that the centers of the welded longitudinal joints of adjacent layers are separated circumferentially by a distance of at least five times the layer thickness.

The Category A weld joints in layered heads may be in an offset pattern; if offset, the joints of adjacent layers shall be separated by a distance of at least five times the layer thickness.

After weld preparation and before welding circumferential seams, the height of the radial gaps between any two adjacent layers shall be measured at the ends of the layered shell section or layered head section at right angles to the vessel axis, and also the length of the relevant radial gap in inches shall be measured [neglecting radial gaps of less than 0.010 in. as nonrelevant]. An approximation of the area of the gap shall be calculated as indicated in Figure 4.



Legend:

A_g = area of gap (approx.)
= $\frac{2}{3}hb$
b = arc length of relevant radial gap
h = radial gap
R_g = radius of vessel at gap
t = layer thickness

Figure 4: Typical Gap Between Two Layers

The gap area A_g shall not exceed the thickness of a layer expressed in square inches. The maximum length of any gap shall not exceed the inside diameter of the vessel. Where more than one gap exists between any two adjacent layers, the sum of the gap lengths shall not exceed the inside diameter of the vessel. The maximum height of any gap shall not exceed 3/16 in.

In the case of layered spheres or layered heads, if the gaps cannot be measured as described above, measurement of gap heights shall be taken through vent holes in each layer course to assure that the height of layer gaps between any two layers does not exceed the gap permitted above. The spacing of the vent holes shall be such that gap lengths can be determined. In the event an excessive gap height is measured through a vent hole, additional vent holes shall be drilled as required to determine the gap length. There shall be at least one vent hole per layer segment.

References:

ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 (2021 Edition)

Structural Analysis and Design of Process Equipment – *Maan H. Jawad and James R. Farr*

What is the definition of "Application Design Calculations" as per ASME Section VIII, Division 1?

The term "applicable design calculations" means that all pressure-retaining components covered by the Certification Mark stamping are supported by calculations and/or proof tests that comply with the requirements of this Division. The method of verifying that applicable design calculations have been made will vary with the individual Inspector and depend largely on the Manufacturer's procedures for producing the design calculations and any subsequent quality checks performed by the Manufacturer.

POSTWELD HEAT TREATMENT

HEAT TREATMENT

Heat treatment is used for stress relieving of weldments to achieve a desirable improvement in the characteristics of the material, or to regain those characteristics which may have been adversely affected by production processes such as welding/ bending/ forming etc. In this article, we will discuss just one heat treatment process, namely, Post Weld Heat Treatment, or PWHT.

UNDERSTANDING THE AREAS OF THE WORK PIECE

When dealing with the work piece, there are some important areas and key terms one needs to be aware of. They are: weld area, heat affected zone (HAZ), and soak band (SB).

WELD AREA AND HEAT AFFECTED ZONE

Weld area is the widest width of butt or attachment weld. HAZ is the area of the base material which has had its microstructure and properties altered by welding, heat intensive cutting, and sometimes bending/ working. In any heat treatment process, the primary objective is to fix this – to restore HAZ to its normal condition.

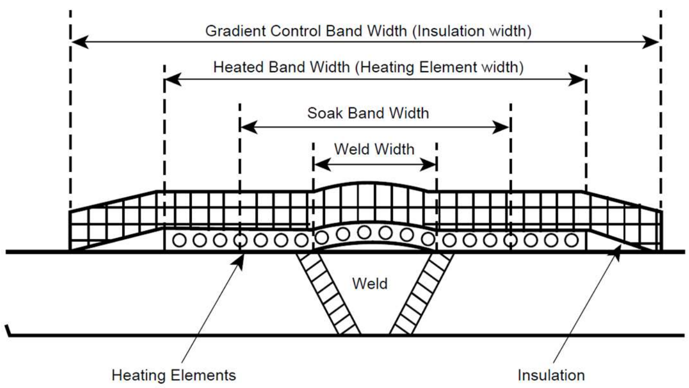


Figure 1: Weld Area and Heat Affected Zones

SOAK BAND

The soak band consists of the through thickness volume of metal, which is heated to the minimum but does not exceed the maximum required temperature. As a minimum, it should consist of the weld metal, HAZ, and any portion of the base metal adjacent to the weld being heated. The soak band width is established to ensure that the required volume of metal achieves the desired effect. The minimum width of this volume is the widest width of the weld PLUS 1t or 2 in, whichever is less, on each side of the weld. Term “t” is the nominal thickness of the metal used in specifying PWHT requirements. For pressure vessels or parts of pressure vessels being postweld heat treated:

1) Welded joints connecting parts of same thickness using a full penetration butt weld, the nominal thickness is the total depth of weld exclusive of any permitted weld reinforcement.
2) For groove welds, the nominal thickness is the depth of groove.
3) For fillet welds, the nominal thickness is the throat dimension. If fillet weld is used in conjunction with groove weld, the nominal thickness is the depth of the groove or the throat dimension, whichever is greater.

4) For stud welds, the nominal thickness is the diameter of the stud.
5) When welded joint connects parts of unequal thickness:
    a. For two adjacent butt-welded parts, including head-to-shell connection, the nominal thickness is the thinner of the two parts.
    b. For connection of intermediate head to shell, the nominal thickness is the thickness of shell or head, whichever is greater.
    c. For connection of tubesheets, flat heads, covers, flanges, or similar construction to the shell, the nominal thickness is the thickness of the shell.
    d. For connection of welded nozzles or small fittings to the shell or head, the nominal thickness is the thickness of the weld across the nozzle neck or shell or head or reinforcing pad or attachment fillet weld, whichever is the greater.
    e. For nozzle neck to flange connections, the nominal thickness is the thickness of nozzle neck at the joint.
    f. For connection of a non-pressure part to a pressure part, the nominal thickness is the thickness of weld at the point of attachment.
    g. For tube-to-tubesheet connection, the nominal thickness is the thickness of the weld.
    h. When weld overlay is the only welding applied, the nominal thickness is the thickness of the weld metal overlay.
6) For repairs, the nominal thickness is the depth of the repair weld.

As a result of welding processes used to join metals together, the base materials near the weldment, the deposited weld metal and, in particular, the heat affected zones (HAZ) transform through various metallurgical phases. Depending on the chemistry of metals in these areas, hardening occurs in various degrees, dependent mainly upon carbon content. Again, this is particularly true in the HAZ adjacent to the weld metal deposit where the highest stresses due to melting and solidification result.

WHAT IS POSTWELD HEAT TREATMENT (PWHT)?

PWHT, defined as any heat treatment after welding, is often used to improve the properties of a weldment. The need for PWHT is driven by code and application requirements, as well as the service environment. In general, when PWHT is required, the objective is to increase the resistance to brittle fracture and relaxing residual stresses.

PWHT is designed to relieve a proportion of the imposed residual stresses by reducing the hardness and increasing ductility, thus reducing danger of cracking in the vessel weldments. It reduces and redistributes the residual stresses in the material that have been introduced by welding. The extent of the relaxation of the residual stresses depends on the material type and composition, the temperature of PWHT, and the soaking time at that temperature. A commonly used guideline for PWHT is that the joint should be soaked at peak temperature for 1 hour for each 1 in. (25mm) of thickness although for certain cases a minimum soak time will be specified.

PWHT is a mandatory requirement in many codes and specifications when certain criteria are met. It reduces the risk of brittle fracture by reducing the residual stress and improving toughness and reduces the risk of stress corrosion cracking. It has, however, little beneficial effect on fatigue performance unless the stresses are mostly compressive.

PWHT temperatures for welds made in accordance with the requirements of EN 13445, ASME VIII and BS PD 5500 are given below in Table 1.

Table 1: PWHT Temperatures from Pressure Vessel Specifications

Steel Grade	BS EN 13445	ASME VIII	BS PD 5500
Carbon Steel	550-600 °C	1100 °F	580-620 °C
1/2 Mo	550-620 °C	1100 °F	630-670 °C
1Cr-1/2 Mo	630-680 °C	1100 °F	630-700 °C
2 1/4 Cr/Mo	670-720 °C	1250 °F	630-750 °C
5CrMo	700-750 °C	1250 °F	710-750 °C
3 1/2 Ni	530-580 °C	1100 °F	580-620 °C

Note from Table 1 that ASME VIII specifies a minimum holding temperature and not a temperature range as in the BS and EN specifications.

As mentioned above, PWHT is a mandatory requirement when certain criteria are met, the main one being the thickness. BS EN 13445 and BSPD 5500 require that joints over 35 mm (1 3/8 inch) thick are PWHT'd, ASME VIII above 3/4 inch (19 mm). If, however, the vessel is to enter service where stress corrosion is a possibility, PWHT is mandatory, irrespective of thickness. The soak time is also dependent on thickness. As a very general rule this is one hour per 1 inch (25 mm) of thickness; for accuracy, reference must be made to the relevant specification.

These different requirements within the specifications mean that great care needs to be taken if a procedure qualification test is to be carried out that is intended to comply with more than one specification. A further important point is that the PWHT temperature should not be above that of the original tempering temperature as there is a risk of reducing the strength below the specified minimum for the steel. It is possible to PWHT above the tempering temperature only if mechanical testing is carried out to show that the steel has adequate mechanical properties. The testing should, obviously, be on the actual material in the new heat treatment condition.

Maximum and minimum heating and cooling rates above 660-750°F are also specified in the application codes. Too fast a heating or cooling rate can result in unacceptable distortion due to unequal heating or cooling and, in very highly restrained components, may cause stress cracks to form during heating.

APPLICATION OF PWHT

The method of PWHT depends on several factors; what equipment is available, what is the size and configuration of the component, what soaking temperature needs to be achieved, can the equipment provide uniform heating at the required heating rate? The best method is by using a furnace. This could be a permanent fixed furnace, or a temporary furnace erected around the component, this latter being particularly useful for large unwieldy structures or to PWHT a large component on site. Permanent furnaces may be bogie loaded with a wheeled furnace bed on to which the component is placed or a top hat furnace that uses a fixed hearth and a removable cover.

Furnaces can be heated using electricity, either resistance or induction heating, natural gas or oil. If using fossil fuels, care should be taken to ensure that the fuel does not contain elements such as sulphur that may cause cracking problems with some alloys, particularly if these are austenitic steels or are nickel based – corrosion resistant cladding for example. Whichever fuel is used, the furnace atmosphere should be closely controlled such that there is not excessive oxidation and scaling or carburisation due to unburnt carbon in the furnace atmosphere. If the furnace is gas or oil fired the flame must not be allowed to touch the component or the temperature monitoring thermocouples; this will result in either local overheating or a failure to reach PWHT temperature.

Monitoring the temperature of the component during PWHT is essential. Most modern furnaces use zone control with thermocouples measuring and controlling the temperature of regions within the furnace, control being exercised automatically via computer software. Zone control is particularly useful to control the heating rates when PWHT'ing a component with different thicknesses of steel. It is not, however, recommended to use monitoring of the furnace temperature as proving the correct temperatures have been achieved in the component. Thermocouples are therefore generally attached to the surface of the component at specified intervals, and it is these that are used to control the heating and cooling rates and the soak temperature automatically so that a uniform temperature is reached. There are no hard and fast rules concerning the number and disposition of thermocouples, each item needs to be separately assessed.

As mentioned earlier, the yield strength reduces as the temperature rises and the component may not be able to support its own weight at the PWHT temperature. Excessive distortion is therefore a real possibility. It is essential that the component is adequately supported during heat treatment and trestles shaped to fit the component should be placed at regular intervals. The spacing of these will depend on the shape, diameter and thickness of the item. Internal supports may be required inside a cylinder such as a pressure vessel; if so, the supports should be of a similar material so that the coefficients of thermal expansion are matched.

While heat treating a pressure vessel in one operation in a furnace large enough to accommodate the entire vessel is the preferred method this is not always possible. In this case, the pressure vessel application codes permit a completed vessel to be heat treated in sections in the furnace. It is necessary to overlap the heated regions – the width of the overlap is generally related to the vessel thickness. ASME VIII specifies an overlap of 5 ft (1.5 meters). It should be remembered that if this is done there will be a region in the vessel (which may contain welds) that will have experienced two cycles of PWHT and this needs to be taken into account in welding procedure qualification testing. There is also an area of concern, this being the region between the heated area within the furnace and the cold section outside the furnace. The temperature gradient must be controlled by adequately lagging the vessel with thermally insulating blankets and the requirements are given in the application codes.

It is, of course, possible to assemble and PWHT a vessel in sections and then to carry out a local PWHT on the final closure seam.

BENEFITS AND DETRIMENTAL EFFECTS

Three primary benefits of PWHT are tempering, relaxation of residual stresses, and hydrogen removal. Consequential benefits such as avoidance of hydrogen induced cracking, dimensional stability, and improved ductile toughness and corrosion resistance result from the primary benefits. It is important that PWHT conditions be determined based on the desired objectives.

Sometimes ageing/ precipitation processes can cause deterioration in the mechanical properties of steel, in which case, specialist advice should be taken on the appropriate times and temperatures to use. Excessive or inappropriate PWHT temperatures and/ or long holding times can adversely affect properties. The adverse effects can include distortion, over-softening, decreased tensile strength, and reduced creep strength and notch toughness (generally caused by embrittlement due to precipitate formation).

The influence of PWHT on properties primarily depends upon the composition of weld metal and base metal, and prior thermal and mechanical processing of the base metal. If PWHT is run at higher than specified temperatures and/ or longer specified soak times, the work piece can become more brittle than desired. Control of heating and cooling rates, holding temperature tolerances, and the times at temperature are extremely important, and must be carefully controlled in order to realize the full benefit of PWHT process.

WHAT CAUSES HIGH RESIDUAL STRESSES?

Welding involves the deposition of molten metal between two essentially cold parent metal faces. As the joint cools, the weld metal contracts but is restrained by the cold metal on either side; the residual stress in the joint therefore increases as the temperature falls. When the stress has reached a sufficiently high value (the yield point at that temperature), the metal plastically deforms by means of a creep mechanism so that the stress in the joint matches the yield strength. As the temperature continues to fall, the yield strength increases, impeding deformation, so that at ambient temperature the residual stress is often equal to the yield strength.

To reduce this high level of residual stress, the component is reheated to a sufficiently high temperature. As the temperature is increased, the yield strength falls, allowing deformation to occur and residual stress to decrease until an acceptable level is reached. The component would be held at this temperature (soaked) for a period of time until a stable condition is reached and then cooled back to room temperature. The residual stress remaining in the joint is equal to the yield strength at the soak temperature.

WHAT ARE THE DRIVERS FOR PWHT?

The need for PWHT depends on several factors: material, service requirements, welding parameters, and the likely mechanism of failure. In some codes, PWHT is mandatory for certain material types or thicknesses. These fabrication code requirements are aimed at reducing susceptibility to brittle fracture, and as such is targeted to improve notch toughness and relax residual stresses. But where there is an option, cost and potential adverse effects need to be balanced against possible benefits. The energy costs are generally significant due to the high temperatures and long times involved, but costs associated with time delays may be more important.

The need for PWHT based upon service environment is not treated by fabrication codes. Instead, guidance may be found in recommended practices regarding service environment. Applying PWHT for “service” can have a variety of objectives. Reduction of hardness and stress relaxation are two of the more common objectives related to service environments. It is important to note that the threshold stress levels in such cases are often less than those required for brittle fracture related concerns, and more detailed requirements may therefore apply.

Some points to remember:

- PWHT is designed to return a metal as near as possible to its prefabrication state of yield, ultimate tensile and ductility.
- The rate of temperature rise, holding time at temperature and rate of cooling are vitally important. For this reason, the furnace thermocouples must measure metal temperature, not furnace atmospheric temperature.

ASME CODE PROCEDURES FOR PWHT

The ASME Code procedures for post weld heat treatment (PWHT) are provided in paragraph UW-40 of Section VIII, Division 1. Eight procedures are listed in the paragraph that can be broadly grouped under one of the three types given below:

Depending on the size of the vessel and capacity of the furnace (size and maximum temperature), a full or partial PWHT is performed. In full PWHT, there are two types of firing methods. The most common one is the furnace PWHT wherein the vessel is loaded inside the furnace and heated to the required level in a single firing. This is the most desirable type of PWHT because all parameters in the heating, soaking and cooling cycle can be controlled well. However, the availability of such furnaces are the only constraint. If PWHT in one go is not possible due to the size of the vessel, paragraph UW-40 of the ASME VIII-1 code permits the use of part-by-part PWHT with sufficient overlap of the heated zones.

In the second method, the vessel itself is made the furnace by providing burners at appropriate points and by giving insulation all around the pressure vessel. This method is called internal firing and is very much dependent on the skill of those that perform this feat.

The third method is to do the PWHT of welds alone when the design permits, using electrical resistance heating. Here again, proper overlap between two PWHT zones shall be given.

The eight procedures listed in paragraph UW-40 are as follows:

1) Heating of pressure vessel as a whole in an enclosed furnace. This is the preferred method and is recommended to be used wherever practical.
2) Heating the pressure vessel in more than one heat in a furnace, provided the overlap of the heated sections of the pressure vessel is at least 5 ft (1.5 m). When this procedure is used, the portion outside of the furnace shall be shielded so that the temperature gradient is not harmful. The cross section where the vessel projects from the furnace shall not intersect a nozzle or other structural discontinuity.

3) Heating of shell sections and/ or portions of pressure vessel to post weld heat treat longitudinal joints or complicated welded details before joining to make the completed pressure vessel. When the vessel is required to be postweld heat treated. and it is not practical to postweld heat treat the completed vessel as a whole or in two or more heats, as provided in 2) above, any circumferential joint not previously postweld heat treated may be thereafter locally postweld heat treated by heating such joints by any appropriate means that will assure the required uniformity. For such local heating, the soak band shall extend around the full circumference. The portion outside the soak band shall be protected so that the temperature gradient is not harmful. This procedure may also be used to postweld heat treat portions of new vessels after repairs.

4) Heating the vessel internally by any appropriate means and with adequate indicating and recording temperature devices to aid in control and maintenance of a uniform distribution of temperature in the pressure vessel wall. Previous to this operation, the pressure vessel should be fully enclosed with insulating material, or the permanent insulation may be installed provided it is suitable for the required temperature. In this procedure, the internal pressure should be kept as low as practicable but shall not exceed 50% of MAWP at the highest metal temperature expected during the postweld heat treatment period.

5) Heating a circumferential band containing nozzles or other welded attachments that require PWHT in such a manner that the entire band be brought up uniformly to the required temperature and held for a specified time.

   The soak band should extend around the entire pressure vessel and shall include nozzle or welded attachment. The circumferential soak band width may be varied away from the nozzle or attachment weld requiring PWHT, provided the required soak band around the nozzle or attachment weld is heated to the required temperature and held for the required time.

   As an alternative to varying the soak band width, the temperature within the circumferential band away from the nozzle or attachment may be varied and need not reach the required temperature, provided the required soak band around the nozzle or attachment weld is heated to the required temperature, held for the required time, and the temperature gradient is not harmful throughout the heating and cooling cycle.

   The portion of the vessel outside of the circumferential soak band shall be protected so that the temperature gradient is not harmful. This procedure may also be used to postweld heat treat portions of pressure vessels after repairs.

6) Heating the circumferential joint of a pipe or tubing by any appropriate means using a soak band that extends around the entire circumference. The portion outside the soak band shall be protected so that the temperature gradient is not harmful.

7) Heating a local area around nozzles or welded attachment in the larger radius section of a double curvature head or a spherical shell or head in such a manner that the area is brought up uniformly to the required temperature and held for a specified time. The soak band shall include the nozzle or welded attachment. The soak band shall include a circle that extends beyond the edges of the attachment weld in all directions by a minimum of t or 2 in (50mm), whichever is less. The portion of the pressure vessel outside of the soak band shall be protected so that the temperature gradient is not harmful.

8) Heating of other configurations. Local area heating of other configurations such as “spots” or “bulls eye” local heating not addressed in 1) through 7) above is permitted provided that other measures are taken that consider the effect of thermal gradients, all significant structural discontinuities and any mechanical loads which may be present during PWHT. The portion of the pressure vessel or component outside the soak band shall be protected so that the temperature gradient is not harmful.

Tables for various materials in Subsection C, when provided for the PWHT temperatures and the holding times, list requirements that include minimum holding temperatures, the maximum holding temperatures, and minimum holding time at nominal temperature for weld thicknesses.

PWHT requirements for UCS materials are listed in Tables UCS-56-1 through UCS-56-11 as follows:

Table UCS-56-1	P. No. 1
Table UCS-56-2	P. No. 3
Table UCS-56-3	P. No. 4
Table UCS-56-4	P. No. 5A, 5B and 5C
Table UCS-56-5	P. No. 9A
Table UCS-56-6	P. No. 9B
Table UCS-56-7	P. No. 10A
Table UCS-56-8	P. No. 10B
Table UCS-56-9	P. No. 10C
Table UCS-56-10	P. No. 10F
Table UCS-56-11	P. No. 15E

PWHT of UNF materials is not normally desired. PWHT requirements are provided for welded castings of SB-148 Alloy CDA954, all products of zirconium grade R600705, and nickel alloys UNS Nos. N08800, N08810 and N08811.

PWHT requirements for high alloy steels are provided in Tables UHA-32-1 through UHA-32-6 as follows:

Table UHA-32-1	P. No. 6
Table UHA-32-2	P. No. 7
Table UHA-32-3	P. No. 8
Table UHA-32-4	P. No. 10H
Table UHA-32-5	P. No. 10I
Table UHA-32-6	P. No. 10K
Table UHA-32-7	P. No. 45

PWHT requirements for UHT materials are provided in Table UCS-56.

The minimum temperatures referred to above shall be the minimum temperature of the plate material of the shell or head of any pressure vessel. Where more than one pressure vessel or pressure vessel parts are post weld heat treated in one furnace charge, thermocouples shall be placed on the vessels at the bottom, center and top of the charge, or in other zones of possible temperature variations so that the temperature indicated shall be true temperatures for all pressure vessels or pressure vessel parts in these zones.

When pressure parts of two different P-number groups are joined by welding, the PWHT shall be that specified according to either UCS-56 or UHA-32, for the material requiring higher PWHT temperature.

PWHT, when required, shall be done before the hydrostatic test and after any welded repairs. Exceptions are provided for weld repairs to P. No. 1 Group No. 1, 2 and 3 materials, P. No. 3, Group No. 1, 2 and 3 materials, and to weld metals used to join these materials in paragraph UCS-56(f). A preliminary hydrostatic test to reveal leaks prior to PWHT is permitted.

References:

ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 (2021 Edition)

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TRUE STRESS VERSUS ENGINEERING STRESS

This article is brought to you courtesy of Ray Delaforce. Ray is an engineer at Hexagon/ Intergraph and lives in Houston, Texas.

When the engineer thinks of stress, he thinks of ultimate tensile stress, yield stress the elastic modulus. Often, little thought goes beyond that. He is familiar with the Stress-Strain diagram as shown here:

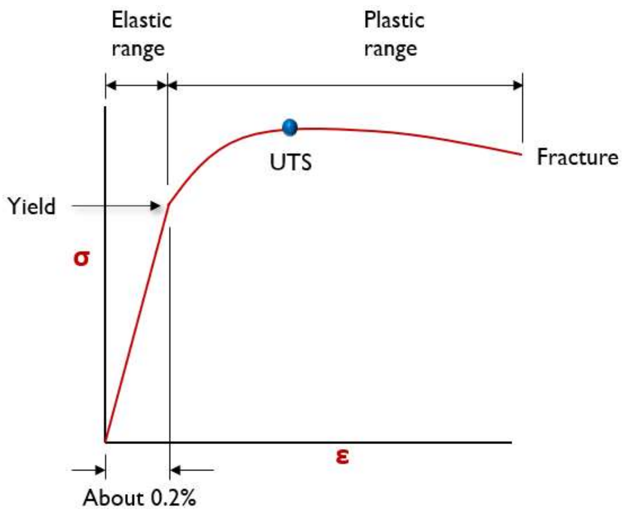

Figure 1

This is the 'standard' diagram[1] used by engineers. Question: Does that diagram tell us the whole story about the true state of affairs for a metal? That diagram is based on what is called Engineering Stress. Is there any other stress that can be considered? Stay with me; I shall develop stress from a different point of view. We start of by considering the concept of strain as normally defined in textbooks. Figure 2 sets the scene:

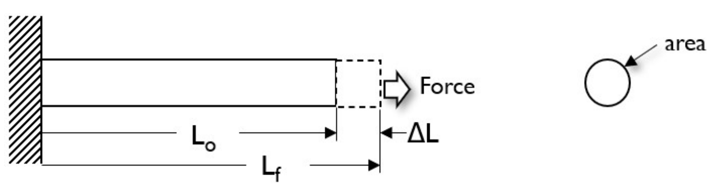

Figure 2

The definition of strain is usually given as:

$$\varepsilon = \frac{L_f - L_o}{L_o} \text{ or } \frac{\Delta L}{L_o}$$

[1] The diagram refers to carbon steel as diagram for stainless steel would look a little different

And the stress is usually defined as:

$$\sigma = \frac{\text{Force}}{\text{Area}}$$

In the case of the stress, it assumes the cross-sectional area remains the same once the metal has been stretched by the distance ΔL. It is well known that the area is reduced in the process. Knowing that let us re-draw the diagram to look at a small incremental extension as shown in Figure 3:

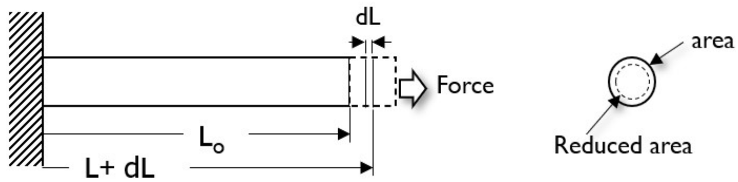

Figure 3

The incremental strain is now:

$$d\varepsilon_T = \frac{dL}{L}$$

It is a simple matter to obtain the total true strain:

$$\varepsilon_T = \int_{L_o}^{L_f} \frac{dL}{L} = \ln\left(\frac{L_f}{L_o}\right) \quad \text{but } \varepsilon = \frac{L_f}{L_o} - 1 \text{ therfore } \frac{L_f}{L_o} = \varepsilon + 1$$

Finally, we have true strain in terms of engineering strain:

$$\varepsilon_T = \ln(1 + \varepsilon)$$

What about true stress now that we know the area is reduced. Based upon the assumption that in the plastic region the volume of the metal remains the same, we can state this:

$$A_o \cdot L_o = A_f \cdot L_f \quad \text{so} \quad A_f = A_o \cdot \frac{L_o}{L_f}$$

Thus: $A_f = \dfrac{A_0}{1 + \varepsilon}$

Now we can look at the true stress:

$$\sigma_T = \frac{F}{A_f} = \frac{F \cdot (1 + \varepsilon)}{A_o} \quad \text{but} \quad \frac{F}{A_o} = \sigma$$

Finally:

$$\sigma_T = \sigma(1 + \varepsilon)$$

We now have both the true strain and true stress in terms of the engineering strain and engineering stress.

Let us revisit the stress-strain diagram in figure 1 and see how the true strain compares with engineering strain. Let the engineering strain be 0.2% or 0.002, which is within the elastic range:

$$e_T = \ln(1 + e) = \ln(1 + 0.002) = 0.001\,998$$

There is hardly any difference between true strain and engineering strain. The same is true for true stress. Therefore, our concern is not what happens in the elastic region. Our concern in the plastic region where the difference is significant.

Experimentally, if we by using the correct instrumentation using a test specimen in a tensile testing machine we get a result like this if plotted on log-log paper:

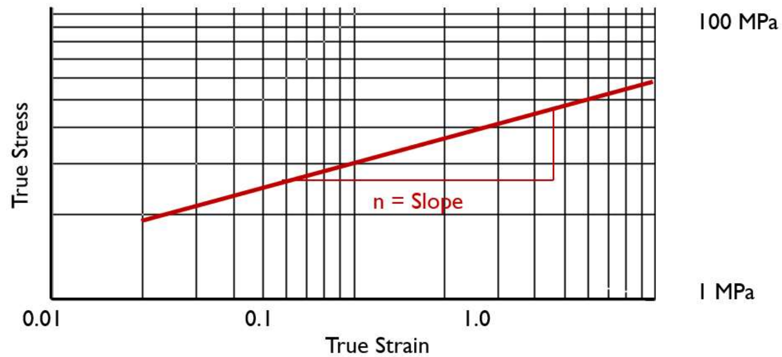

Figure 4

That is a remarkable result – we get a straight line! That is a linear relationship, but in logarithmic terms. So, using an adjusted normal straight-line equation we have this expression:

$$\ln(\sigma_T) = \ln(c) + n \cdot \ln(\varepsilon_T) \text{ where c is a constant}$$

$$\sigma_T = c(\varepsilon_T)^n$$

The constant 'n' is called the Strain Hardening exponent, and 'c' is called the Strength Coefficient. What is strain hardening? We again refer to the stress-strain diagram. Suppose we stress a specimen such that the stress goes into the plastic region like this:

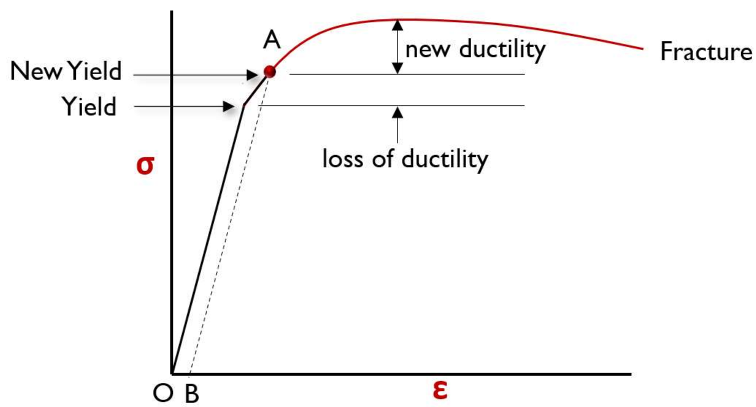

Figure 5

As the stress travels up the elastic line from O to A the original elastic line is now lost, as the new elastic line becomes the line A to B. The yield point is increased, and there is loss of ductility as a consequence. The phenomenon is known as strain hardening, because the new strain at yield has moved from O to B. This can be a serious problem for formed head makers working in stainless steel. OB is also known as Offset. As the stress is cycled, strain hardening progresses further. The metal can end up being susceptible to brittle fracture with a complete loss of ductility when UTS/Yield becomes 1.

From experimental work, researchers have managed to obtain these figures for the strain hardening exponent and strength coefficient:

Metal	**Condition**	**n**	**c MPa**
0.05%C Steel	Annealed	0.26	530
0.60%C Steel	Quenched	0.15	640
Copper	Annealed	0.54	320

Now we have enough information to construct the true stress-strain diagram:

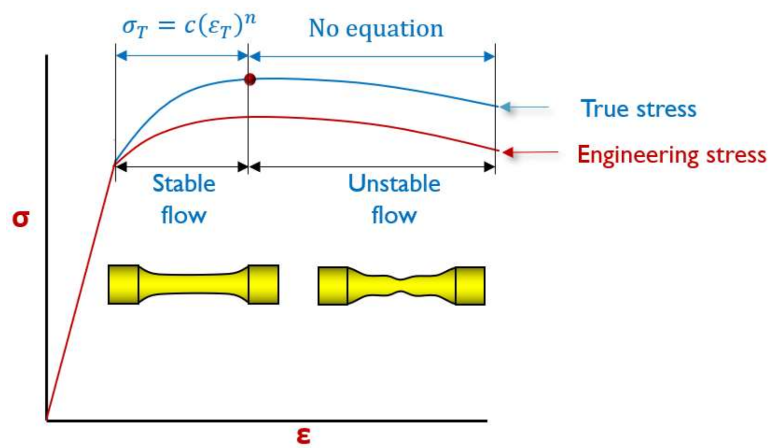

Figure 6

The equation for true stress is only valid up till UTS is reached. Once necking start in the unstable region, the equation is no longer valid. This brings us to the end of this article.

APPENDIX 46: RULES FOR USE OF SECTION VIII, DIVISION 2

1) When design rules do not exist in ASME VIII-1, what methods can be used to design the vessel part?

Paragraph U-2(g) permits the use of one of the following three methods in such cases:

- Mandatory Appendix 46.
- Proof test in accordance with UG-101.
- Other recognized and generally accepted methods, such as those found in other ASME, EN, ISO, national, and other industry standards or codes.

2) When the rules for the design of a vessel part are provided in ASME VIII-1, can the vessel part be alternatively designed using the rules in Part 4 of ASME VIII-2?

Yes. Paragraph UG-16(a) states:

The design of pressure vessels and vessel parts shall conform to the general design requirements in the following paragraphs and in addition to the specific requirements for design given in the applicable Parts of Subsections B and C. As an alternative, the design rules of Mandatory Appendix 46 may be used.

3) What is Appendix 46 of ASME Section VIII, Division 1?

Mandatory Appendix 46 in Section VIII, Division 1 permits the use of Division 2 to determine thickness and other design details of a component for a Section VIII, Division 1 pressure vessel, but with certain restrictions and conditions. This is largely because the Alternate Rules of Section VIII, Division 2 have their own material, design, and fabrication requirements. Since the Division 1 vessel will not meet all these Division 2 requirements, there are restrictions in using Division 2 in the design of Division 1 pressure vessels.

4) What methods are available in ASME Section VIII, Division 2 for the design of vessels and vessel parts?

ASME Section VIII, Division 2 allows "Design by Rule" in accordance with Part 4, and/or "Design by Analysis" in accordance with Part 5.

5) Does Appendix 46 permit use of "Design by Rule" or "Design by Analysis" or both?

Appendix 46 permits the use of rules provided in Part 4 of ASME Section VIII, Division 2 to design vessels and vessel parts with some restrictions and conditions. However, when design rules are not available in part 4, then "Design by Analysis" provisions of part 5 may be used in the design of vessel and vessel parts.

6) What restrictions and conditions apply when using "Design by Rule" provisions of Part 4 of Division 2?

For designs in accordance with "Design by Rules":

- The allowable stress shall be in accordance with UG-23, except that the maximum allowable compressive stress shall be limited as prescribed in Division 2, 4.4.12 in lieu of the rules of UG-23(b).
- The weld joint efficiency shall be established in accordance with UW-11 and UW-12.

7) What restrictions and conditions apply when using "Design by Analysis" provisions of Part 5 of Division 2?

For designs in accordance with "Design by Analysis":

- The allowable tensile stress shall be in accordance with UG-23.
- The weld joint efficiency shall be established in accordance with the full radiography requirements of UW-11 and UW-12.

8) What additional conditions are applicable when determining thickness of a shell section or formed head using the design rules in Division 2, Part 4 (4.3 for shell and 4.4 for formed head)?

Following conditions apply when thickness of a shell section or formed head is determined using the design rules in Division 2, 4.3 or 4.4:

- For design of nozzles, any nozzle and its reinforcement attached to that shell section or formed head shall be designed in accordance with Division 2, 4.5.
- For conical transitions, each component comprising the cylinder-to-cone junction shall be designed in accordance with Division 2, 4.3 or 4.4.
- Material impact test requirements shall be in accordance with the rules of ASME Section VIII, Division 1, except that the required thickness used in calculating the coincident ratio under the rules of UCS-66(b) or UCS-66(i) shall be calculated in accordance with the rules of Division 2.

9) What fabrication tolerances apply when using "Design by Rule" provisions of Part 4 of Division 2?

The fabrication tolerances specified in Division 2, 4.3.2 and 4.4.4 (as applicable) shall be satisfied. The provisions of Division 2, 4.14, Evaluation of Vessels Outside of Tolerance, is not permitted.

10) Are the full set of design loads and load case combinations in Part 4, 4.1.5.3 required when using Appendix 46?

No. The full set of design loads and load combinations in 4.1.5.3 are not required except when necessary to satisfy the requirements of UG-22. When the design load combinations of Division 2, Table 4.1.2 are used, the allowable stress increase of UG-23(d) is not permitted. The factors present in Division 2, Table 4.1.1 for wind loading and earthquake loading are based on ASCE/ SEI 7. If a different recognized standard is used, the User shall inform the Manufacturer of the standard to be applied and provide suitable load factors if different from ASCE/ SEI 7.

11) What other restrictions/ conditions/ exceptions apply when using Appendix 46 to design vessels and vessel parts to Part 4 of ASME Section VIII, Division 1?

Evaluation of the stresses during the test condition of Division 2, 4.1.6.2 is not required. However, such calculations may form the basis of a calculated test pressure as described in UG-99© or UG-100(b).

The fatigue screening criterion of Division 2, 4.1.1.4 is not required. However, it may be used when required by UG-22.

Weld joint details shall be in accordance with Division 2, 4.2, with the exclusion of Category E welds.

12) What restrictions and conditions are applicable when requirements in Division 2, Part 5 are used to design vessel or vessel part?

When the requirements of Part 5 are used, the following restrictions and conditions apply:

- The allowable stress increase of UG-23(d) is not permitted.
- All the failure modes listed in Division 2, Part 5 shall be considered.
  1. When demonstrating protection against plastic collapse, the load case combinations of Division 2 shall be considered in addition to any other combinations defined by the User. In evaluating load cases involving internal and external specified design pressure, P, additional cases with P equal to zero shall be considered.
  2. When demonstrating protection against local failure, the load case combination of Division 2 shall be considered. The exemption provided in Division 2, 5.3.1.1 is applicable to weld details in Division 2, Part 4 only.
  3. When demonstrating protection against collapse from buckling, the design margin of Division 2 assessment procedure shall be used.
  4. When demonstrating protection against failure from cyclic loading:
     - Ratcheting in Division 2, 5.5.6 or 5.5.7, the design margin of Division 2 assessment procedure shall be used, except that where it is used, the allowable stress shall be as per UG-23.
     - Fatigue in Division 2, 5.5.3, 5.5.4 or 5.5.5, the design margin of the Division 2 assessment procedure shall be used, except that where it is used, the allowable stress shall be as per UG-23.

References:

ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 (2021 Edition)

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In the math puzzle below, there is a specific relationship between the numbers in the squares. Can you figure out the pattern and fill in the missing piece?

18	6	2	2
6	3	3	1
16	2	1	3
32	8	2	$\frac{1}{3}$
9	?	4	6

BUILDING A BETTER TOMMORROW

Pressure Vessels ● Heat Exchangers ● Storage Tanks

Oil & Gas ● Petrochemical ● Chemical ● Power ● Fertilizer