Review of Postweld Heat Treatment Requirements for P-4 and P-5A Cr-Mo Materials

Technical Report

EPRI Powering Progress

R E P O R T S U M M A R Y

Review of Postweld Heat Treatment Requirements for P-4 and P-5A Cr-Mo Materials

INTEREST CATEGORIES

Component reliability
Operations and maintenance

KEYWORDS

Postweld heat treatment
Cr-Mo materials
Piping

BACKGROUND Exemptions from mandatory postweld heat treatment (PWHT) are currently provided in the ASME Boiler and Pressure Vessel Codes (B&PV) for welding P-4 and P-5A materials for 4 inch or less NPS pipe diameter where nominal wall thickness is less than 0.50 inch and the carbon content is below 0.15 percent. However, among various sections of the ASME Code (ANSI B31.1, Section I, III, and VIII) there are some differences in the actual minimal thickness required. In certain cases, ASME recommends 0.500 inch and in others it recommends 0.625 inch. Subscribers of the EPRI Repair and Replacement Applications Program have asked EPRI to review these Codes and their histories, and to assemble information aimed at expansion beyond the present exemption requirements. Expansion of the exemption requirements to 0.625 inch will result in huge savings in terms of dollars and significantly reduce the number of PWHTs conducted.

OBJECTIVES

- Review and evaluate requirements and exemptions for postweld heat treatment in P-4 and P-5A materials.
- Develop data and provide background information to support utilities in an ASME Code modification associated with PWHT exemptions.
- Prepare a report which can be employed in support of PWHT exemptions associated with Class 2 and 3 nuclear service piping system applications.

APPROACH The approach employed to examine current ASME B&PV Code rules for PWHT included:

- An extensive review with many fabricators and experienced ASME members to determine the origin and basis of the ASME B&PV Code requirements.
- Identification of current exemptions for PWHT of these materials in the Code rules.
- Evaluation of the appropriateness of current exemption rules for nuclear service applications.
- Recommend the appropriate modifications/changes to ASME Code rules.

RESULTS P-4 and P-5A materials employed in nuclear service applications operate well below the creep regime and are generally limited to temperatures below 600°F. At these temperatures, high temperature phenomena (such as embrittlement, stress relief cracking, or creep degradation), which could be influenced by PWHT, are not a concern. Large diameter, thin walled pipe employed in these applications should also aid in weldability, reducing the need for PWHT. Based upon these facts, pipe diameter should not be considered as a limiting factor for exemption from PWHT requirements. The recommended criteria for exemptions for P-4 and P-5A pipe materials in nuclear service applications should be limited solely to those applications having a wall thickness of 0.625 inch or less regardless of pipe diameter.

EPRI PERSPECTIVE Relaxation of the current ASME requirements for P-4 and P-5A pipe materials employed in nuclear applications can provide a significant savings to utilities in terms of dollars and outage time. Consistent treatment of these materials in terms of thickness among various Code sections should substantially reduce the number of PWHTs required during any given outage. As a result, this effort was initiated to examine current ASME requirements and to see if relaxation of these requirements could indeed be achieved. As of June 1997, the review document has been completed and discussions are underway with ASME to seek relief for these materials.

PROJECT

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ABSTRACT

Postweld heat treatment of piping and piping components can be an extremely costly part of any outage for a nuclear utility. Any reduction in the number of piping weldments which have to undergo high temperature heat treatment can significantly reduce both expenditures and the length of an outage. As a result, subscribers of the EPRI Repair and Replacement Applications Program asked EPRI to examine current ASME requirements to determine if relaxation of existing requirements was technically feasible. Specifically, the subscribers asked that a review of existing discrepancies in terms of thickness and diameter observed among various sections of the ASME Boiler and Pressure Vessel Code be examined. This report was assembled to document this review.

In nuclear applications P-4 and P-5A piping materials are employed specifically for improved corrosion resistance performance, unlike fossil applications where high temperature mechanical property performance is a top priority. Concerns with high temperature phenomena such as embrittlement, stress relief cracking, or creep degradation are of little concern, and, as a result, the influence of postweld heat treatment is of less importance for these materials when utilized in nuclear environments. This review and evaluation have shown that the weldability of thin walled P-4 and P-5A pipe actually improves with diameter increases. The likelihood for cracking in these materials is diminished for a given thickness as the diameter increases due to the flexibility at the weldment region. Based upon this fact, pipe diameter should not be considered as a limiting factor for exemption of PWHT in nuclear service applications. The recommended exemptions for these materials in nuclear service applications should be limited solely to those applications having a wall thickness of 0.625 inch or less without regard to pipe diameter.

SUMMARY

This report evaluates current requirements, their origin, and the basis for exemptions from mandatory postweld heat treatment (PWHT) of P-4 and P-5A chromium-molybdenum materials as they pertain to nuclear service. Of particular interest were exemptions based on diameter and wall thickness. No specific documentation was available for determination of original or current criteria that exempts weldments with less than 0.015 weight percent carbon, less than 4 inches in diameter, and less than or equal to one-half inch thickness for ASME III piping. Industry experts were canvassed to ascertain the origin of current requirements, and it was found that criteria for exemption from PWHT were based on successful practices and experience dating from the 1920s to 1930s in the petrochemical and power industries rather than technical data, design calculations, or experimentation.

Factors including stress, creep and stress rupture, fracture toughness, fatigue, erosion/corrosion, stress corrosion cracking, tempering, hardenability, and welding were considered and evaluated with respect to whether or not the application or absence of PWHT was of technical significance. Consistency and variations in PWHT criteria and exemptions among selected ASME Codes (B31.1, B31.3, Section I, Section III and Section VIII) were also compared. Based on the current code requirements and research performed for this project, it is observed that the requirements for PWHT are based more on traditional practices and experiences within given industries rather than upon specific metallurgical, structural, or experimental considerations. Analysis performed in this study revealed that as pipe diameter increased, the area affected by welding or welding residual stresses actually reduces and becomes more favorable—contrary to what current code rules infer. The origin of current thickness limitations listed in the codes was also indeterminate with values varying between 1/2 and 5/8 inch, depending on the individual code.

This evaluation concluded that criteria for exempting PWHT for P-4 and P-5A chromium-molybdenum pipe materials and weldments for nuclear service applications should be solely limited to those applications having wall thicknesses of 0.625 inch or less without regard to pipe diameter. Revision of existing requirements or exemptions to coincide with known technical data and sound engineering principles should therefore be possible, especially for nuclear piping service applications.

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CONTENTS

FIGURES

TABLES

1

PROJECT PURPOSE AND APPROACH

The purpose of this review is to evaluate the requirements and exemptions for postweld heat treatment (PWHT) in P-4 and P-5A materials and to determine if the current ASME Boiler and Pressure Vessel Code rules regarding PWHT of these materials are appropriate for application to Classes 2 and 3 nuclear service piping systems. The approach is to: 1) determine the origin and basis for the requirements, 2) identify current exemptions for PWHT of these materials in the Code rules, and 3) evaluate the appropriateness of current exemption rules for nuclear service applications. The effects of PWHT on weldability and on service performance are examined.

2

ORIGIN AND BASIS OF REQUIREMENTS

The ASME Boiler and Pressure Vessel Code, Section IX (QW-420), assigns P numbers and Group numbers to identify classes of materials for welding requirements. The same numbering system is used in other codes, such as ASME B31.1 Power Piping Code, the National Board Inspection Code (NB-23), and other sections of the ASME Boiler and Pressure Vessel Code. P-4 and P-5A designations refer to Cr-Mo steels having chromium contents nominally 1 1/4 to 2 1/4 wt.% and molybdenum contents nominally 1/2 to 1 wt.%, respectively. Welding these materials requires special consideration because the reaustenitized portion of the weld heat affected zones (HAZ) (attendant to each weld bead) will form martensite and/or banitic decomposition products depending upon the rates of cooling. This means that portions of base material in the HAZ adjacent to the weld fusion line and portions of the weld deposit itself (HAZs of adjacent weld beads) can have properties significantly different from the rest of the material. Hardness is increased. If these localized HAZ properties are incompatible with the specific piping application, then steps must be taken to control the properties and thus the mechanical and/or corrosion behavior of the HAZ. Normally, the metallurgical issues created during welding are managed by one or more of the following factors:

- Selection of base material and weld filler material chemistry.
- Application of minimum welding preheats of 250°F (P-4 materials) and 300°F (P-5A materials).
- Application of a postweld heat treatment to relieve residual stresses created during welding (typical PWHT temperatures are 1100°F minimum for P-4 materials and 1250°F minimum for P-5A materials) and to temper the weldment microstructure.
- Application of temperbead techniques to improve and control the toughness and ductility of HAZ properties (Temperbead techniques produce changes in the microstructure of the weld HAZ. Normally a postweld bake of over 400°F is included after welding to eliminate any hydrogen that may be trapped in the material during welding, since traditional PWHT is not used. This extra step eliminates the potential for delayed hydrogen cracking.). Where low hydrogen processes or consumables are used, this operation becomes less important.

3

CURRENT EXEMPTIONS FOR PWHT

Exemptions from mandatory PWHT are provided in the Codes for welding P-4 and P-5A materials. The exemptions state that mandatory postweld heat treatment is not required for piping 4 inch NPS or less which has a nominal wall thicknesses of 0.625 inch or less (per ASME Sections I and VIII). The origin and technical basis for these exemptions have been reviewed in detail through interviews with leaders of various Code bodies (Appendix A) and by review of available documentation including the discussion provided by Spaeder and Doty (1). Based upon these reviews, it is believed that the criteria for exemptions to PWHT were established on the basis of successful practices in the petrochemical and power industries rather than technical data, design calculations, or experimentation. These practices, dating from the initial implementation of electric arc welding (mid to late 1920s), apparently have been passed along with minimal changes through the years.

4

EXAMINATION OF CURRENT EXEMPTION RULES FOR NUCLEAR SERVICE

4.1 Stress Considerations

The stresses developed from butt welding two pipe sections together are the result of shrinkage from the cooling weld metal. Once the root and hot pass are deposited, shrinkage across subsequent weld beads will create tensile stresses perpendicular to the welding direction (along the axial direction of the pipe). This effect is most pronounced for the outer weld passes as the weld cavity fills. The stress distribution through the thickness of the pipe wall will vary from tensile stress near the outer surface to compressive stress through the interior (initial weld passes are compressed by shrinkage deformation of the later weld beads). The shrinkage along the length of the weld bead will create compressive forces in the hoop direction at the weld root location. As additional layers are deposited, the tangential stresses change from compressive to tensile at this location. The weld bead will tend to constrict the pipe diameter as the circumference is shortened in a manner analogous to tightening a rope or cable wrapped around the pipe circumference.

The magnitude of weld shrinkage stresses can be large and must be accommodated either by: 1) deformation of the pipe and weld metal (elastic and plastic), or 2) localized cracking. If cracking occurs, it will be manifest as solidification cracking of the weld deposit or cracking in the weakest locations of the adjacent weld heat affected zone (HAZ). Reheat cracking during PWHT is one example of HAZ cracking.

In a thin walled pipe (standard wall, schedule 40 or less), the loads generated by weld shrinkage may cause the pipe to warp or yield, usually evidenced by constriction (necking) of the pipe at the weld. Improper weld bead sequencing or multiple weld repairs in the same area exacerbate this condition. Conversely, the greater stiffness associated with thicker walled sections provides resistance to both bending and axial yielding. If the material is unable to accommodate these loads by elastic and plastic deformation mechanisms, cracking may occur to accommodate the loads. Localized resistance to this deformation is described in fracture mechanics as “constraint.”

The key determinants for bending or deformation versus cracking behavior of the pipe lie in the strength of the section and the volume of material influenced by localized welding stresses. The strength or stiffness is proportional to the moment of inertia and the shape and extent (size) of the area under stress. The first factor, the moment of inertia, is proportional to the cube of the pipe thickness. This third order relationship will create very large increases in pipe stiffness as thickness increases. This term is the most significant factor in the stiffness of the pipe section local to the weld, and it should be noted that this term is independent of pipe diameter.

The remaining two factors, the size and shape of the area under stress, are more complicated and are related to pipe diameter. The affected area will consist of the pipe wall material within some distance from the weld. This area will possess some degree of curvature depending on the size of the area relative to the pipe diameter. A “rule of thumb” for defining the radius of an area under stress as a result of a piping load is $\sqrt{Rt}$. This is based loosely on the area of reinforcement requirements from Section III NB-3600. Applying this rule to the weldment suggests that all material within a distance of approximately $\sqrt{Rt}$ from the weld will be influenced by the weld metal shrinkage, where R is the pipe outside radius and t is the pipe wall thickness. An angle θ can be defined by the arc swept by the distance $2\sqrt{Rt}$ of the pipe circumference (Figure 4-1) as follows:

$$\theta = \frac{2\sqrt{Rt}}{R} = \frac{2\sqrt{t}}{\sqrt{R}}$$

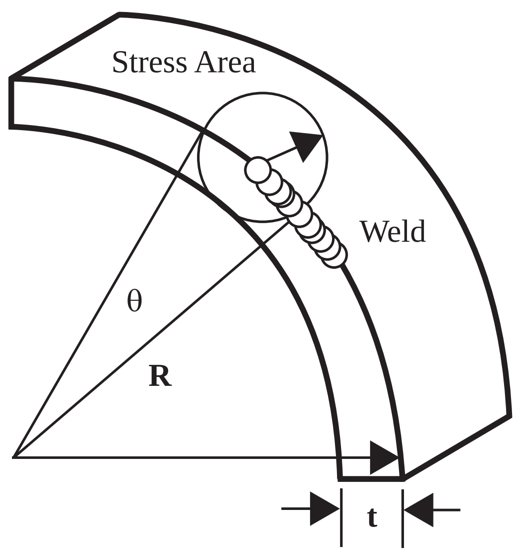

Figure 4-1
Schematic of Analytical Model Describing the Area Influenced by Localized Welding Stresses.

From this equation, it can be seen that for large radii and small thickness (large diameter, thin walled pipe) the angle of the area under stress “θ“ will become small, and the stressed pipe section will approach flat plate behavior (see Table 4-1). The actual stiffness as a function of R, t, and θ is a complicated three-dimensional problem, and its calculation is beyond the scope of this effort. It also can be seen that for large thicknesses and small radii, the angle “θ“ becomes large, and the curvature of the section becomes more important because it will produce additional bending stiffness. In the limiting case, where t = R, the stressed pipe section will approach a solid wedge where θ = 2 radians. The solid wedge resists bending and produces a maximum constraint.

The qualitative relationship of the thickness and radius to the section stiffness is therefore as follows. If the thickness of the pipe is held constant and the radius (and diameter) is increased, a smaller portion of the pipe cross-section is influenced (θ decreases), and the local mechanical behavior of the pipe section more closely approximates that of a flat plate. The section is less stiff and more likely to deform or to absorb the stresses. If the radius is held constant and the thickness is increased, the influenced section is characterized by a larger arc (θ increases), and the section stiffness increases due both to the greater thickness of material and to the extended curvature of the section geometry. This produces a section less likely to deform.

Table 4-1
Values of “θ“ (radians) as a Function of Pipe Wall Thickness and Diameter

	2	4	6	8	10	12	14	16	18	20	22	24
“t”												
0.375	1.124	0.816	0.673	0.590	0.528	0.485	0.463	0.433	0.408	0.387	0.369	0.354
0.500	1.298	0.943	0.777	0.681	0.610	0.560	0.534	0.500	0.471	0.447	0.426	0.408
0.625	1.451	1.054	0.869	0.761	0.682	0.626	0.598	0.559	0.527	0.500	0.477	0.456

The value of “θ“ is plotted in Figure 4-2 for a variety of pipe sizes typically used in a nuclear power plant. It can be seen that “θ“ decreases or becomes assumtotic to the x-axis for increasing pipe sizes. This means that as the pipe diameter gets larger, the proportionate arc of the pipe circumference (region influenced by the stresses of welding) remains essentially unchanged or decreases slightly. Therefore, PWHT or the need to reduce residual stresses becomes less important as the pipe diameter increases for given wall thickness. Also, the geometrical factors influencing weldability should improve as the pipe diameter increases and the wall thickness is held constant.

Figure 4-3 displays the pipe diameters and wall thicknesses for typical pipe schedules that might be used for low to moderate pressure Class 2 and 3 piping systems. It should be noted that the “standard” pipe wall thickness, usually acceptable for these applications, remains constant at 0.375 inches for pipe sizes exceeding 12 inches in diameter.

Also, Figure 4-3 shows that the area of the stressed region drops and then remains nearly constant for pipe diameters larger than 5 inches. Table 4-2 shows the required wall thickness for a variety of pressures and pipe diameters based on B31.1 hoop stress pipe thickness sizing criteria and assuming a 15,000 psi allowable stress material. From this table it can be seen that the 0.375-inch wall thickness is acceptable for 500 psig design pressures for all sizes up to 20 inches in diameter.

Industry experience in welding P-4 and P-5 pipe materials has been quite good over the past several decades. This satisfactory experience appears to be based almost entirely on factors related to the pipe wall thickness as opposed to pipe diameter and can be explained as follows. Thick walled piping tends to offer a greater resistance to bending and will be more likely to be damaged by weld shrinkage and stresses. Conversely, an increase in diameter for a restricted range of thicknesses will reduce stiffness and facilitate bending to accommodate weld shrinkage. Hence, as the diameter is increased for a given wall thickness, a pipe can more easily accommodate weld shrinkage.

Based on this analysis, PWHT to relax residual stresses created during welding is of greater importance for thick walled components and of much lesser importance for thin walled components. Additionally, examination of the current Code limitations suggest the 4-inch limit on diameter could be removed without detriment for standard piping schedules, since the piping material should be capable of more easily accommodating welding stresses as the diameter increases.

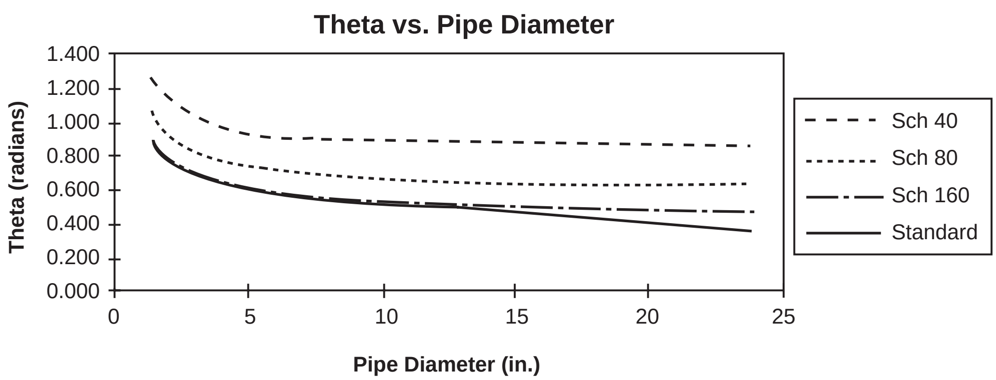

Figure 4-2
Relationship between Theta "θ" and Pipe Diameter (Showing the reduction in the angle of stressed material for piping. Flat plate criteria is approached for pipe diameters larger than 5 inches).

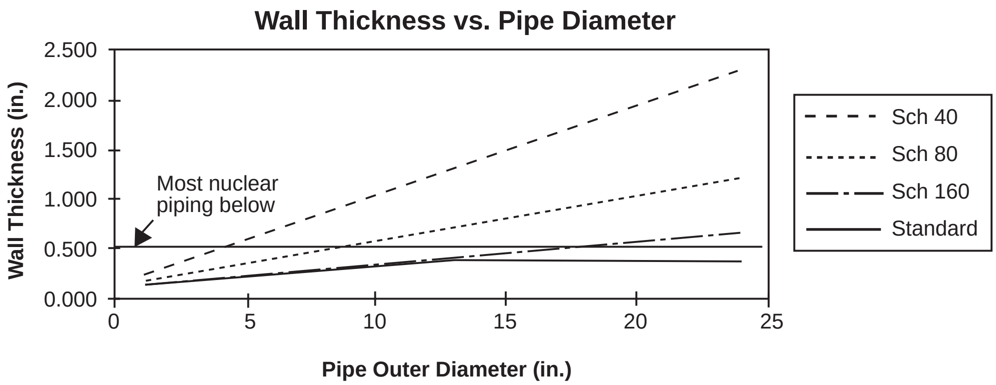

Figure 4-3
Pipe Diameter and Wall Thickness for Typical P-4 and P-5A Pipe Schedules.

Table 4-2
Required Pipe Wall Thickness for 15 ksi Materials Based on B31.1 Sizing Equations

Pipe Size (in)	Pipe Diameter (in)	Design Pressure (psig)				
		100	200	300	400	500
1.000	1.315	0.004	0.009	0.013	0.017	0.022
2.000	2.375	0.008	0.016	0.024	0.031	0.039
4.000	4.500	0.015	0.030	0.045	0.059	0.074
6.000	6.625	0.022	0.044	0.066	0.087	0.109
8.000	8.625	0.029	0.057	0.086	0.114	0.142
10.000	10.750	0.036	0.071	0.107	0.142	0.177
12.000	12.750	0.042	0.085	0.126	0.168	0.210
14.000	14.000	0.047	0.093	0.139	0.185	0.230
16.000	16.000	0.053	0.106	0.159	0.211	0.263
18.000	18.000	0.060	0.119	0.179	0.237	0.296
20.000	20.000	0.066	0.133	0.198	0.264	0.329
22.000	22.000	0.073	0.146	0.218	0.290	0.362
24.000	24.000	0.080	0.159	0.238	0.317	0.395
26.000	26.000	0.086	0.172	0.258	0.343	0.428
28.000	28.000	0.093	0.186	0.278	0.369	0.461
30.000	30.000	0.100	0.199	0.298	0.396	0.493
32.000	32.000	0.106	0.212	0.317	0.422	0.526
34.000	34.000	0.113	0.225	0.337	0.449	0.559
36.000	36.000	0.120	0.239	0.357	0.475	0.592

4.2 Material and Service Considerations

The intent of this section is to address all materials and service considerations germane to P-4 and P-5A materials irrespective of specific code rules for which they are applied.

4.2.1 Creep and Stress Rupture

The material requirements for each specific application will determine the material properties which must be assured. For example, the design temperatures for fossil plant components govern the material selection because resistance to creep degradation must be assured. Typically, Cr-Mo materials are considered when design temperatures exceed 800°F, because these materials possess better elevated temperature mechanical properties over low carbon steel and because they exhibit improved performance with time-dependent creep degradation.

In the nuclear industry, P-4 and P-5A materials are applied to piping which is susceptible to erosion and corrosion degradation mechanisms. The temperature of these applications is typically less than 600°F, and high temperature localized degradation mechanisms such as creep and stress rupture are not operative at these temperatures. Consequently, precautions to assure properties that avoid high temperature degradation mechanisms are unnecessary.

4.2.2 Fracture Toughness Considerations

High tensile stresses are characteristic of localized residual stress fields in as-welded structures. Since tensile stress fields provide the driving force for fracture, it follows that residual stresses should be linked in some way to the fracture process. Residual stresses are short range elastic stresses localized to the weld. They may or may not contribute directly to the fracture stress depending upon the degree of plasticity exhibited by the material. In materials that behave elastically (or are fully constrained by material behaving elastically), the magnitudes of the residual welding stresses will contribute directly to the fracture loads. However, for materials that exhibit some degree of plasticity, the influence of the residual stresses on the fracture process will be limited to a secondary role. This behavior is recognized in ASME Section III where fracture toughness is not required for thin sections. The P-4 and P-5 materials discussed in this review exhibit a high degree of ductility even in untempered weld heat affected zones that show high hardness (4). The characteristic fracture toughnesses of these materials, welds, and heat affected zones are too high for piping materials less than one-half inch in thickness to create the required elastic constraint conditions that support any form of low energy fracture. Thus, weld residual stress and HAZ fracture toughness issues do not provide a technical basis to justify a PWHT requirement for piping wall thicknesses less than 5/8 inch.

Piping codes are inconsistent in their treatment of fracture toughness and residual stress considerations. For example, fracture toughness is considered for piping applications governed by the rules of ASME B&PV Code Sections III and XI and for certain petrochemical applications. Current ASME Code rules do not require toughness testing at or below 5/8-inch thickness regardless of product form (plate, pipe, tubing, etc.) for low alloy steel materials or weldments. Further, no PWHT is required for welds of P-1 materials regardless of wall thickness up to 1.5 inches. No similar exemptions exist in B31.1 or in B31.3 piping codes; however, B31.1 piping code does require mandatory PWHT for these same materials or weldments in thicknesses over 3/4 inch regardless of diameter (12). Inconsistencies among the codes for requirements, exemptions, or simply ignoring certain cases are believed to be related to typical practices that have evolved over the years based upon application experience as opposed to different interpretations of technical data bases.

4.2.3 Fatigue Considerations

Fatigue is a material degradation mechanism caused by alternating applied loads. The rate of fatigue crack growth is directly proportional to the magnitude of the range of alternating loads. Because of design controls, fatigue loading will normally be elastic in nature and alternating loads that result in plasticity are not a reasonable design consideration. Elastic loads will be influenced by residual stress fields. In effect the residual stress becomes the mean stress about which the applied loads will alternate. The mean stress is known to influence fatigue behavior. Stress ratio (known as the R ratio in fatigue) is defined as the ratio of maximum stress to minimum stress, and therefore, is a parameter that can be used to used to evaluate fatigue behavior. Fatigue crack growth rates are known to change with different R ratios. Since PWHT will lower the peak residual stresses, it will influence the stress ratio and thus fatigue behavior. PWHT does not determine if fatigue will actually occur, but can influence on the rate of cracking. Because the magnitude of residual stresses vary widely near welds, the cracking path and the shape of the crack front will be influenced. PWHT will only be of consequence if alternating applied loads are of sufficient magnitude to result in fatigue degradation of the component irrespective of whether the weldment receives a PWHT or not. In that case only the paths and rates of cracking will be influenced. Therefore, a proper design will see no influence of PWHT. Fatigue should not be a determining factor for establishing exemptions for PWHT in weldments of P-4 and P-5A materials.

4.2.4 Erosion/Corrosion Considerations

As stated previously, the principal reason chromium-molybdenum materials are considered for use in the nuclear industry is to mitigate pipe degradation due to erosion/corrosion mechanisms. These phenomena are controlled by the flow characteristics of fluid in the pipe, by the fluid environmental conditions such as temperature and water chemistry, and by chemistry of the material (primarily chromium content). Since PWHT has no influence on any of these factors, the erosion/corrosion considerations are not a consideration for exemptions to PWHT.

4.2.5 Stress Corrosion Cracking Considerations

Tensile residual stresses are well known to contribute to stress corrosion cracking (SCC) of susceptible materials in certain aqueous environments. Typically, austenitic stainless steels and nickel-based materials are candidates, especially where aggressive specific anions are present such as chlorides and sulfates. In special cases, carbon and low alloy steels experience a form of SCC when nitrates are present in sufficient concentrations. In dry steam environments, none of these materials is susceptible. Furthermore, the environment is not conducive to promote SCC.

4.2.6 Tempering Considerations

Conventional PWHT is designed primarily to temper the weldment microstructure and to provide a level of stress relief. When high creep and rupture strength are the primary concerns (as in the fossil power industry), it is important to avoid undesirable changes by over tempering the material. Consequently, PWHT temperatures often are selected in the lower end of the ranges given in Table 4-3. However, when resistance to corrosion and hydrogen damage are the primary concerns (as in the petroleum and chemical industries), the higher end of the temperature range is used to minimize residual stresses and to provide softening via tempering (10).

Table 4-3
Comparison of ASME Code PWHT Requirements for P-4 and P-5A Materials

Requirements for Exemptions to PWHT				
P-Number	**ANSI B31.1**	**ASME Section I**	**ASME Section III**	**ASME Section VIII**
P-4	$t_m \leq 1/2"$ Pipe Dia $\leq$ 4" NPS Carbon $\leq$0.15%	$t_n \leq 5/8"$ Pipe Dia $\leq$ 4" NPS Carbon $\leq$0.15%	$t_n \leq 1/2"$ Pipe Dia $\leq$ 4" NPS Carbon $\leq$0.15%	$t_n \leq 5/8"$ Pipe Dia $\leq$ 4" NPS Carbon $\leq$0.15%
P-5A	$t_m \leq 1/2"$ Pipe Dia $\leq$ 4" NPS Carbon $\leq$0.15%	$t_n \leq 5/8"$ Pipe Dia $\leq$ 4" NPS Carbon $\leq$0.15%	$t_n \leq 1/2"$ Pipe Dia $\leq$ 4" NPS Carbon $\leq$0.15%	$t_n \leq 5/8"$ Pipe Dia $\leq$ 4" NPS Carbon $\leq$0.15%

Minimum Preheat Temperatures				
P-Number	**ANSI B31.1/1992**	**AWS D10.8**	**ASME Section III**	**ASME Section VIII**
P-4	250°F	250°F	250°F	250°F
P-5A	300°F	300°F	300°F	300°F

PWHT Temperatures				
P-Number	**ANSI B31.1**	**ASME Section I**	**ASME Section III**	**ASME Section VIII**
P-4	1300 -1375°F	1100°F (Min)	1100 -1250°F	1100°F (Min)
P-5A	1300 -1400°F	1250°F (Min)	1250 -1400°F	1250°F (Min)

Material Thickness Definitions				
Description	**ANSI B31.1**	**ASME Section I**	**ASME Section III**	**ASME Section VIII**
Thickness	Thickness of the weld or material, whichever is less	Thickness of the weld or base metal, whichever is less	Thickness of the weld or base metal, whichever is less	Thickness of the weld or base metal, whichever is less

t_n = nominal thickness
t_m = material thickness

Postweld tempering is not a specific requirement identified or required in the aforementioned Codes. However, special welding techniques have been used in some cases in lieu of PWHT.

4.2.7 Hardenability Considerations

A number of material and welding consumable variables influence as-deposited weldment characteristics. Carbon content strongly influences material behavior. Strength is increased as the carbon level increases. In addition, the metallurgical microstructure can also be changed by changing the carbon content. For example, hardenability (ability to form martensite) will increase as the carbon level increases. Of course, other elements also influence hardenability, and normally a carbon equivalent (CE) value is used to describe the hardenability characteristics of the material. CE formulas have recently been reviewed and used as guides for preheat requirements (2). The International Institute of Welding (IIW) formula is recommended as being generally applicable. This formula considers carbon, manganese, chromium, molybdenum, vanadium, nickel, and copper contents. Cooling rates generally determine the microstructure for a given material or CE.

These formulas are especially important considerations for welding, because both the welding filler materials and the base materials will be influenced by variability in restraint, in compositions, in heat inputs during welding, in section sizes and thicknesses, and in the welding preheat and interpass temperatures achieved (cooling rates and temperatures). Table 4-4 provides calculated maximum CE values for selected Code materials. It should be noted that there is a substantial difference between the hardenability of P-4 and P-5A materials as measured by their carbon equivalence. The hardenability of the weldment HAZ should be thoroughly evaluated for each material application. In some cases of high hardenability, heat treatment may be useful. Normally, the preheating parameters are selected to provide appropriate weldability.

Table 4-4
Carbon Equivalents (CE) for ASME Code Materials

P-Number	Material Classification	CE_{IIW}
P-1 Gr. 1	SA106 B	0.44
P-1 Gr. 2	SA210 Gr. C	0.48
P-3 Gr. 1	SA672 L65	0.44
P-3 Gr. 2	SA672 L75	0.49
P-3 Gr. 3	SA672 J80	0.58
P-4 Gr. 1	SA335 P11	0.58
P-5A	SA335 P22	0.94

4.3 Welding Considerations

The ease of welding structures or components without introducing injurious defects during welding or immediately after welding (weldability) is an essential consideration when determining appropriate criteria for exempting PWHT. Four factors are key to successfully completing a quality weld. First, the material itself must be capable of being welded. Weldability is not a PWHT concern for the P-4 and P-5A materials since each is a readily weldable material. Second, the environment for welding must be suitable. This means that hydrogen uptake is minimized and the presence of contaminants is avoided. These factors are not affected by a high temperature PWHT. In some cases a 400°F minimum postweld bake is prescribed to drive off any trapped hydrogen and reduce the risk of hydrogen delayed cracking (where PWHT is not required). Third, the carbon contents of the P-4 and P-5A materials are limited to 0.15 wt.% maximum, and since modern welding practices use (dry) low hydrogen electrodes or a bare wire process, the likelihood for hydrogen delayed cracking is minimal. Fourth, geometry also should be considered in terms of weldability because the stresses and strains created during welding of highly constrained cross-sections, can lead to weld metal cracking and HAZ cracking in some cases. ASME Section IX effectively screens these concerns through the use of bend tests.

Welding considerations also can be very important relative to time-dependent metallurgical processes. The metallurgical structure of the weld HAZ is the principal factor governing localized time-dependent behavior. This structure is influenced by the heat input from welding, the rate of cooling, and by the degree of tempering which occurs after a weld bead is deposited. Tempering can be accomplished by the heat input of subsequent weld beads (temperbead techniques) or by postweld heat treatment procedures specifically designed for tempering the affected microstructure.

Weldability considers those factors that contribute to producing an acceptable weld. Materials effects, weld solidification shrinkage, and the potential for welding-related defects are addressed. Service performance considers the effects of welding on possible degradation mechanisms that might occur in service. Fracture toughness, corrosion susceptibility, and heat affected zone (HAZ) microstructural weaknesses have been addressed in terms of potential impact on service performance.

5

DISCUSSION

A comparison of the various requirements for PWHT of P-4 and P-5A piping weldments in the various Codes is given in Table 4-3. It is apparent that PWHT is not required for weldments of thin sections (less than 1/2 inch in thickness) in these materials. In fact, ASME Sections I and VIII exempt PWHT for weldments up to 5/8 inch in thickness. In general, the piping diameter limit for exemption to PWHT is limited to 4 inches.

There is less agreement in other piping codes. For example, pipe diameter is not a limiting factor for exemption from PWHT requirements for P-4 and P-5A materials in ANSI B31.3 for Chemical Plant and Petroleum Refinery Piping.

The different codes are not in agreement on the diameters or thicknesses exempted from PWHT. It is believed that the reason for these differences lies with the application requirements for different industries. ANSI B31.1 piping code applies to all power plant piping service and tends to be more conservative because it is based on the assumption that piping systems could be operating in or near the creep range and at high pressure. This code also specifically acknowledges conservative design rules and permits the designer to use a less conservative design, with justification, and still remain within the intent of the code.

Normally, a PWHT is prescribed in order to effect stress relief, to temper the weldment microstructure, or to diffuse hydrogen (10). A combination of these can reduce the risk of cracking, improve mechanical properties, and provide improved corrosion resistance (11). Based on the current code requirements and research performed for this project, it is concluded that the requirements for PWHT are based more on traditional practices for given industries rather than upon specific metallurgical or structural considerations. Relief from the existing requirements is therefore possible with consideration of the requirements for the application.

Current geometrical limits for exempting the requirements for PWHT based both upon pipe diameter and wall thickness are overly restrictive and costly. Exemptions based on pipe wall thickness address the primary factor, weldability (the ability to weld the section without producing cracks). For a given thickness, larger diameter thin wall pipe will be more flexible local to the weld, and weldability will be increased. The likelihood for producing cracking during welding will diminish for a fixed wall thickness as pipe diameter increases, and postweld heat treatment will not reduce the chance for cracking. Cracking mechanisms, such as hydrogen delayed cracking, are less of a concern with current code limits on material carbon content (less than 0.15 wt. %) and the use of low hydrogen processes and electrodes (typical for modern welding processes and consumables).

6

CONCLUSIONS AND RECOMMENDATIONS

Nuclear service applications employing P-4 or P-5A materials generally are limited to temperatures less than 600°F, well below the range of creep or other high temperature phenomenon which might require PWHT. In addition, it has been shown that large diameter, thin walled pipe should aid weldability and that the pipe diameter should not be a limiting factor for exemption from PWHT requirements. ASME BP&V Sections I and VIII specifically exempt materials of 5/8 inch or less from PWHT. A review of other piping codes has shown that the variation in requirements is inconsistent and/or application dependent. *Therefore, it is recommended that the criterion for requiring exemptions to PWHT for P-4 and P-5A pipe materials in nuclear service applications be limited solely to those applications having wall thicknesses of 0.625 inches or less without regard to pipe diameter.* This recommendation is consistent with Code toughness criteria and the results of this investigation.

7

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Appendix A

INDUSTRY EXPERIENCE

The following individuals were contacted while attempting to determine the origin of existing code requirements for post weld heat treatment. Individuals were chosen for familiarity with early and current codes or extended experience in industry.

Doer Doty (Consultant)

Harry Ebert (Exxon Research)

Joel Feldstein (Foster-Wheeler)

Tony Giannuzzi (SIA)

Roy Lorentz (ABB-CE, Retired)

Martin Prager (MPC / WRC)

Don Randolf (ABB-CE)

Blaine Roberts (TVA)

Dave Thomas (Consultant; Arcos, Retired)

Chris Sanno (ASME Staff)

Ted Ward (ABB-CE, Retired)

The consensus offered was that current requirements were based on experience and good practice rather than specific technical experimentation or analysis. Mr. Ward provided the following summary from a historical perspective that was substantiated in whole or part by those contacted:

> ... *Mr. Roy Emerson, while at Pittsburgh Piping, spearheaded the use of postweld heat treatment on P4 and P5 type materials during the 1920s and 1930s based on extensive practical petrochemical experience. This experience was subsequently incorporated into various Codes during the 1950s and 1960s...*

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