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PWHT Exemptions for Low Hardenability Materials

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EPRI Project Manager

Andrew McGehee

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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This document was prepared by

EPRIr
1300 W.T. Harris Blvd.
Charlotte, NC 28262

Principal Investigator
A. McGehee

Flenner Engineering Services, LLC
6537 Wyndham Dr.
Kalamazoo, MI 49009

Principal Investigator
P. D. Flenner

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ABSTRACT

Significant differences in the Postweld Heat Treatment (PWHT) requirements exist between several Codes that are commonly used in Fossil and Nuclear Power Plants. One difference is the stated thicknesses for PWHT exemptions for P No. 1 carbon steel materials. In ASME B31.1 and B31.3, these materials require the greater material thickness to be less than or equal to ¾ inches (for butt welds). In ASME Section I, the thickness exemption is based on the thinner material but the same ¾ inch limitation exists. However, ASME Section III and Section VIII Codes allow a PWHT exemption for thicknesses up to 1½ inches. Code Case 174 for B31.1 also allows an increased exemption up to 1½ inches but with significant additional requirements. This investigation reviewed the requirements of the different codes and provides a justification for proposals within B31.1, B31.3, and Section I to allow further PWHT exemptions for P No. 1 welds. The justification is based on several papers and technical data that have studied the effects of PWHT on materials based on thickness and hardenability. These proposed changes have not yet been made in the affected documents since the justification is in current review by the ASME Code Committees.

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INTRODUCTION

The requirements for postweld heat treatment (PWHT) for P No. 1 carbon steels are different in nearly every ASME Code. The Codes normally thought of as dealing with vessels (ASME Section III and ASME Section VIII) allow the exemption of PWHT for P No. 1 steels up to a thickness of 1½ in., while those that deal with piping or tubing (B31.1, B31.3, and Section I) limit this exemption to ¾ in. There are several technical approaches that may be used to provide additional exemptions for PWHT in low-hardenability steels. Based on the current requirements in the related B&PV and B31 Codes, the application of low-hardenability exemptions from PWHT for materials other than P No. 1 would require additional justification. Work is ongoing in a separate EPRI RRAC project to provide technical data which addresses the appropriate exemption thickness limits for P1,3,4 and 5A materials. This report is therefore aimed at exemption limits for P No. 1 carbon steels up to 1½ in. thickness where sufficient data exists to justify additional PWHT exemptions for the Codes that have a lesser exemption thickness limit. The Codes that are specifically targeted are:

B31.1 Power Piping

B31.3 Process Piping

ASME B&PV Section I Power Boilers

Performing PWHT results in a substantial cost to the owner utility, both from the direct costs of the process but also from indirect costs associated with outage lengths and plant system availability. The Repair and Replacement Applications Center (RRAC) of the Electric Power Research Institute (EPRI) therefore recommended that a project be initiated to justify and process code changes in B31.1 to increase the exemption limits for PWHT of low-hardenability materials where PWHT is unnecessary. This document is intended to support that change within the B31.1 Code but it may also be used to support changes in other Code Sections. This information will be presented to the other targeted Codes (B31.3 and Section I) through the Section II/Section IX Strength of Weldments Sub Group.

2
CODE REQUIREMENTS

General

The different codes used in power plants have a significant variation in the rules for PWHT. In some cases, these variations may be justified based on service conditions addressed by the applicable code. Minor variations are not generally a safety concern. Requiring a PWHT where it is unnecessary imposes a significant cost on the user, both from the direct costs of the process and also from indirect costs associated with outage length and plant system availability. Understanding the technical implications associated with this issue is key in setting code rules because exempting a needed PWHT can be a safety concern and conversely, performing PWHT on some materials may reduce strength properties and impact properties below expected levels.

The following discussions relate to Code requirements only and do not include any requirements of the welding procedure specification or of contract specifications.

B31.1- Power Piping Code – 2001 Edition

The B31.1 Code for Power Piping Table 132 requires PWHT of P No. 1 and P No. 3 materials when the thickness > ¾ in. or > ⅝ in., respectively. There are criteria for low-hardenability PWHT exemptions in B31.1. These are embedded in the criteria for thickness exemption for P Nos.1 and 3 materials. B31.1 allows the lesser of the weld thickness or the greater of the material thicknesses at the joint to be the controlling thickness for the PWHT exemption for P Nos. 1 and 3 materials due to their lower hardenability.

The B31 Committee recently passed a Code Case [1] that would allow additional exemptions of PWHT for P No. 1 welds up to 1½ in. with significant restrictions on the materials and processes.

B31.3 Process Piping Code – 2002 Edition

The B31.3 Code for Process Piping, Table 331.1.1 requires postweld heat treatment of welds in P Nos. 1 and 3 where the thickness of the thicker base material is > ¾ in. In addition, welds in P No. 3 base materials where the specified minimum tensile strength is > 71 ksi, also require PWHT. However, in those cases where this criterion is met but where branch connections or fillet welds are being made, the thickness criteria of Para. 331.1.3, Governing Thickness, may apply. This effectively eliminates PWHT for branch connections and fillet welds where the thickness of the weld in any plane is ≤ 1½ in. for P Nos. 1 and 3 materials. An additional criteria is imposed on P No. 3 materials; PWHT is required if the hardness of the weld or heat affected zone > 225 bhn.

Section I – Power Boilers – 2001 Edition with 2003 Addenda

ASME Section I, Power Boilers, Table PW-39, requires PWHT for welds on P No. 1 materials > ¾ in. and P No. 3 materials > ⅝ in. The thickness considered for all materials is the "thickness of the weld, pressure retaining material, or the thinner of the sections being joined, whichever is least" (PW-39.3).

3
TECHNICAL REVIEW

Requirements for PWHT

The primary reasons that components are required to be subjected to PWHT within the ASME Code rules are: (1) to reduce residual stresses and (2) to provide some tempering of hardened microstructures [2]. Smaller welds are typically expected to develop lower residual stresses so many of the Codes described above have reduced PWHT requirements when the weld size is less than the thickness requiring PWHT. Opposing this concept is the need to consider PWHT for thicker materials where the greater heat sink may result in faster cooling and therefore higher hardness in the weld. While this is considered in varying ways in the Codes, only B31.1 applies the concern for hardenability differently with regard to the thickness used for exemption from PWHT. This difference is implemented in B31.1 by allowing the weld thickness to be a consideration for the thickness exemption in P Nos. 1 and 3 materials but not for higher hardenability materials such as P Nos. 4 and 5A.

Both B31.1 and B31.3 define the thickness of the material as the greater thickness being joined. Section I defines the thickness of the material as the thinner of the sections being joined.

Thicker materials act as a greater heat sink, resulting in faster cooling of the weld area by conduction. The faster cooling results in potentially greater hardness in the weld and adjacent heat affected zone (similar to quenching). The concern for the greater hardness is that the weldment may be more susceptible to fatigue failure and may have low impact toughness or ductility.

There is a precedent for allowing greater thicknesses than ¾ in. to be exempted from PWHT in the ASME Codes. This occurs in ASME Boiler and Pressure Vessel Code Sections III and VIII, both which allow thickness exemptions for P No. 1 material up to 1½ in. In addition, the B31.1 Code Case 174 [1] also allows similar thickness exemption (with material requirements that are similar to Section VIII applications). With the exception of B31.3 (where the exemption thickness for P No. 3 materials is ¾ in. with a limit on the hardness) the only Code precedent permitting PWHT exemptions for P No. 3 materials greater than ⅝ in. are the allowances resulting from the definitions of the thickness to be used.

Code exemptions from PWHT are also based (in part) on the hardenability of the materials. P Nos. (established by ASME Section IX for the general purpose of weldability) are used, although in this case they are not necessarily good criteria. A review of the strengths of the materials in Section IX reveals that P No. 1 materials may have minimum specification tensile strengths within the range of 45 to 95 ksi. Carbon equivalence is a better and more reliable measure of the hardenability of materials than the P Nos.

Preheat is also a consideration when determining the resultant hardness of weldments. As the temperature of the material prior to welding increases, the cooling rate (and therefore the hardness) will decrease. The Code exemptions for thicker materials usually require a minimum preheat.

The welding techniques are not directly considered by the Codes for PWHT exemption rules. The welding techniques are in part controlled by successful qualification of welding procedures per ASME Section IX. The variables for Section IX qualified procedures are not particularly restrictive for these issues, so the control is not very effective. Additional controls on welding techniques may be used to justify increased exemptions from PWHT. This has been used in limited repair applications by the use of temper bead techniques to eliminate the need for PWHT. The use of multiple pass welds will allow some beneficial microstructural changes to occur, even though not conducted in a strictly controlled temper bead type welding procedure.

Justification of Additional Exemptions from PWHT for Low Hardenability Materials

Carbon Equivalence

Determining what materials should be considered "low-hardenability materials" is necessary in order to define any exemption for them. As stated previously, the use of carbon equivalence is better than P Nos. as a measure of hardenability. Carbon equivalence (CE) is defined by several formulas; the formula used in most ASME applications is:

CE = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15

However, if the analysis of all of the elements is not available, the CE may be determined by using 0.1 for the last two terms of the equation, resulting in the CE equation:

CE = C + (Mn + Si)/6 + 0.1

The use of this formula can be very restrictive if actual composition information is not available. McGehee and Sims found in EPRI Report 1006799, *Realistic Carbon Equivalent for Underwater Welding* [3] that there are quite significant differences in the CE when actual composition values are used vs. specification maximum values. The use of carbon equivalence as a criterion for the exemption of PWHT is therefore most effective if the actual composition is known or can be obtained. Nevertheless, determining the CE is a relatively easy calculation and can provide a partial basis for the exemption of PWHT in carbon steels.

The American Welding Society Structural Welding Code – Steel, D1.1, establishes hardness control approaches to determine the need for preheat in structural applications (Appendix XI). The D1.1 approach considers single pass fillet welds without preheat in order to determine the need for preheat. This is significantly different than the multiple pass groove and fillet welds that are typical for heavier thickness boiler and piping applications.

The D1.1 approach may be modified to apply to the need for PWHT. In Figure 3-1 [4], it is seen that for a CE of 0.50 and a cooling rate of 20ºC/sec (at 540ºC), a hardness of 350 VH may be expected in the HAZ. A hardness of 350 VH is used as the limit where no cold cracking will occur. However, since the goal here is to determine if PWHT (which would have the effect of HAZ tempering) can be avoided, additional steps are needed to justify the use of a CE of 0.50 as the limit for exemption. The use of a CE limit alone will not determine the resultant hardness. It would also be necessary to address the factors which affect the cooling rate of the weld and the welding process techniques which would affect the hardness of the weldment. These issues are discussed later.

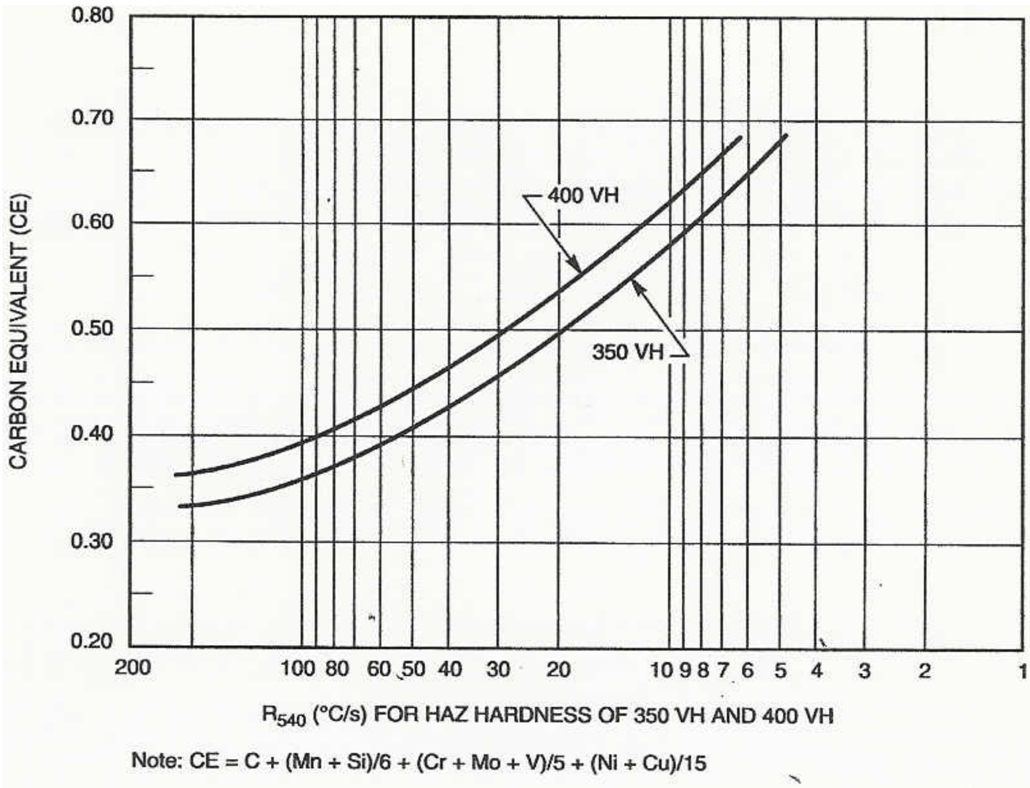

Figure 3-1: Critical Cooling Rate for 350 VH and 400 VH

Preheat

Preheat is a very significant variable that affects the cooling rate of the weldment and therefore the resulting hardness. Linnert [5] showed the significance of this effect in Figure 3-2. The use of preheat has the effect of reducing the driving force of temperature difference between the weld area and the base metal. This becomes more significant to the welding process as the material thicknesses increase since greater thicknesses create a greater heat sink effect for cooling by conduction. The greater heat sink results in faster cooling and therefore greater hardness.

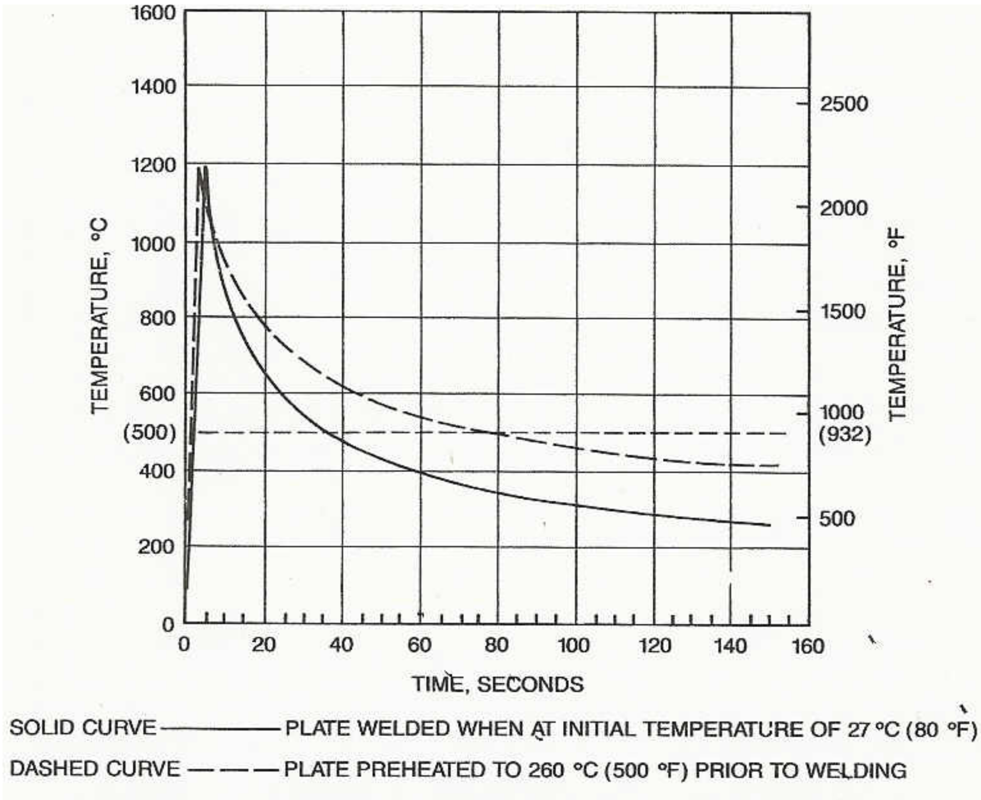

Figure 3-2: Influence of preheating as found in cooling curves for SMAW process on 13 mm (1/2 in.) thick steel plate using arc energy of 1970 J/mm (50kJ/in.)

Dorschu [6] stated that the weld metal cooling rate, *d*T/*d*t, would be equal to the square of the temperature minus the initial plate temperature $(T - T_0)^2$, times a constant for any specific set of welding variables. The cooling rate at any specific temperature is therefore decreased exponentially with the increase in the preheat temperature. This is a very significant effect that could contribute to reducing the need for PWHT when the goal is the reduction of hardness.

In order to maintain some equivalency with the current PWHT rules in the piping and boiler codes, a higher preheat than is currently required for PWHT exemption is recommended (200ºF is currently required for thicknesses > 1 inch). This higher preheat will have the effect of reducing the cooling rate during phase transformation which will provide some additional compensation for the thicker sections being exempted. This ultimately reduce the final hardness of the weld deposit and base metal heat affected zone resultant from quenching during the welding process.

Welding Technique

Adjustments to the welding techniques and parameters can have the effect of reducing the cooling rate and therefore the hardness resulting from welding on steels. Included among these is the use of higher heat input welds and multiple pass welds. Using higher heat input welds would be a difficult approach to control in most of the ASME Codes, since this would require controlling a variable that is more often controlled in the opposite direction (i.e., some welding procedures addressing impact properties allow lower heat inputs but not higher heat inputs). Therefore this may not be a good approach for lowering the need for PWHT.

However, the use of multiple passes is a very common and often unavoidable technique used during welding within ASME Code applications. The weld metal, heat affected zone hardness and residual stresses can be reduced as a result of tempering from subsequent passes of multipass welds when the heat flux between passes is sufficient. This is the principle behind temper bead welding techniques for eliminating the need for PWHT. Temper bead techniques are currently used in several ASME Codes to eliminate PWHT. There are actions in progress within ASME (i.e. new Section IX qualification rules for temper bead welding) to increase the use of this technique. Significant effort is required to qualify this technique. The same types of benefits can be achieved, albeit with less accuracy, just by using multiple passes with some consistency in heat input.

Conclusions

The requirements for the PWHT of P No. 1 steels are different in nearly every ASME Code. While there are also differences in the PWHT requirements for P No. 3 materials, the thickness limit for exemption is fairly consistent at about ⅝ in. As a result, applying new thickness exemption limits for P No. 3 materials require additional research. The Codes which are normally thought of as dealing with vessels (ASME Section III and ASME Section VIII), allow the exemption of PWHT for P No. 1 steels up to a thickness of 1½ in. while those that deal with piping or tubing (B31.1, B31.3, and Section I) limit this exemption to ¾ in. There are several technical approaches that may be used to provide additional exemptions for PWHT in these low-hardenability steels.

Information provided in this report is intended to support PWHT exemptions of P No. 1 carbon steels up to 1½ in. thickness when certain criteria is met. This thickness was chosen since the vessel Codes currently address that limit. The criteria requires a base metal carbon equivalent ≤ 0.50, an elevated preheat of 250ºF, and use of multiple pass welds to fill the joint.

The selection of 0.50 as the limiting CE is based on the evidence that cold cracking is not likely if reasonable hydrogen control processes are used. The selection of 250ºF as the minimum preheat is based on the need to identify some elevated preheat to provide some compensation for the increased thickness proposed for exemption from PWHT for thicknesses over ¾ inch. The elevated preheat required by the vessel code is only 200ºF and is only required above 1¼ inch. The intent is to significantly slow the cooling rate down to reduce hardening of the weld and HAZ.

The choice to require multiple passes versus a single pass is to gain the beneficial effect of multiple passes to provide some degree of tempering of the HAZ and the weld metal. It is realized that larger welds may not gain much in beneficial effects but those larger welds also have a higher heat input that would slow the cooling rate. The use of multiple passes is a normal approach to welding within the ASME Codes and does not present an undue burden. A limit of ¼ inch weld deposit thickness is proposed to ensure that effective multiple pass welds are used. It is anticipated that future code changes may broaden the use of the temper bead techniques in the piping codes to address tempering of the base metal HAZ.

Recommendations

For the B31.1, B31.3, and Section I Codes, concerning additional exemptions to PWHT low hardenability materials, the following changes are recommended:

1. Apply an additional exemption only to materials which are shown to have a carbon equivalent ≤ 0.50.
2. Apply an additional exemption only to materials which have an elevated preheat of at least 250ºF.
3. Apply an additional exemption only to welds that have a maximum weld deposit thickness for each weld pass of ¼ inch (6 mm).

Due to reasons of consistency, this exemption is also recommended to apply only to a thickness limit of 1½ in. in P No. 1 materials. No changes are recommended in this analysis for P No. 3 materials and higher. Future work is currently underway that may allow additional exemptions on thicker materials of higher P No. groups. Discoveries made during the current work may allow a more simplified approach to determining the materials which the exemption may apply (e.g. the use of P No. Group Nos. may be adequate to justify low hardenability versus the CE).

Status

As of the writing of this report the proposed change to the B31.1 Code is in discussion. The justification for the changes to B31.1, B31.3, and Section I is being reviewed by the Section II/Section IX Strength of Weldments Subgroup.

4 REFERENCES

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