Technical Justification

for

Applying the PWHT Exemptions of NB-4620

to

Weld Overlays on P-No. 1 Materials

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1.0 INTRODUCTION

Design, fabrication and inspection activities associated with the construction and operation of nuclear power reactors are performed using the rules of the ASME Boiler and Pressure Vessel Code (ASME Code). These rules specify minimum requirements associated with the fabrication of pressure boundary components and other components important to the safe operation of the nuclear power plant. The original fabrication of piping for these nuclear plants has been generally performed in accordance with the ASME Nuclear Construction Code, Section III [1-1] or the B31.1 Power Piping Section of the American National Standards Institute (ANSI) [1-2]. The rules of ASME Section III and the rules of ANSI B31.1 specify postweld heat treatment (PWHT) requirements for both carbon and low alloy ferritic steels.

Historically, carbon steel piping components used in the nuclear industry have been exempted from many of the requirements involving preheat and post weld heat treatment as associated with welding processes. The reason is that carbon steels simply do not possess the characteristic hardenability necessary to result in brittle weld heat affected zones (HAZs). (A discussion of hardenability will follow in the section of this report dealing with the metallurgy of carbon steels). As a consequence, carbon steels, including the weld HAZs, maintain sufficient ductility even when quenched or air cooled from molten temperatures such that susceptibility to hydrogen embrittlement is virtually nonexistent. In addition, the microstructures developed during the rapid cooling experienced with weld HAZs are associated with mechanical properties that meet or exceed the requisite properties for carbon steels.

On the other hand, low alloy steels of the P-3, Group 3 type used in reactor pressure vessel and nozzle application, are reasonably hardenable, and develop improved strength and fracture toughness from quench and temper heat treatments. The microstructure that forms from rapid cooling is extremely strong but less ductile. The associated material hardness developed, as-quenched or as-welded, can be sufficient to produce a structure supportive of hydrogen embrittlement. Consequently, P-3, Group 3 type low alloy steels typically receive a post-quench heat treatment that tempers the microstructure (precipitates carbides) and develops improved ductility such that a tougher microstructure is produced with enhanced strength. The result is improved fracture toughness.

As a result of the differences in metallurgical properties between carbon and low alloy steels, the ASME Code and other power piping codes have established different preheat and postweld heat treatment (PWHT) protocols for these ferritic materials. The distinctions will be discussed within the body of this report and the results will be used to demonstrate differences in performance between these classes of materials. Although this report is based on the 1989 Editions of ASME Section III, Subsection NB and B31.1, the information in this report could be applied to any edition/addenda of these codes.

1.1 References

1-1. ASME Section III, Subsection NB, 1989 Edition.

1-2. ASME B31.1-1989 Edition, Paragraph 132.

2.0 BACKGROUND

Dissimilar metal weld (DMW) overlays have been applied as a repair measure to light water reactor pressure boundary piping for more than 25 years and have proven to be an extremely effective tool for mitigating weld cracking issues. Weld overlay (WOL) repairs have been applied to austenitic materials, including stainless steels and nickel alloys, and to ferritic materials, such as carbon steels (P-1) and low alloy steels (P-3). When overlays are applied to low alloy steels such as P-3, Group 3 steels, they are normally applied using temperbead welding techniques provided in the ASME Code to avoid the need for PWHT. PWHT of localized repairs can result in undesirable thermal distortion of major plant components and is often associated with increased worker exposures to radiation. When WOL repairs have been applied to low carbon steels, the rules of ASME Section III, paragraph NB-4620, have been used to determine the PWHT requirements for these welds. These rules take into consideration both the carbon content and the thicknesses of the components being welded and in some cases require a minimum preheat temperature. It should be noted that NB-4620 does not include any PWHT exemptions for P-3, Group 3 low alloy steels.

The ASME Code has recently prepared and approved additional provisions for dissimilar metal WOL repairs to materials involving both austenitic and ferritic materials. Revision 1 of ASME Code Case N-740 [2-1] (N-740-1 [2-2]) has added a provision to clarify that the Construction Code (e.g., ASME Section III, NB-4620) PWHT exemptions for butt welds in P-1 materials may be applied to exempt austenitic weld overlays involving P-1 base material. In providing these exemptions, the following clarifications have been made to Code Case N-740-1. These are: (a) the nominal weld thickness is defined as the maximum weld overlay thickness applied over the ferritic base material, and (b) the base material thickness is defined as the maximum thickness of the ferritic material to which the weld overlay is applied. These provisions are the commonly accepted provisions that have been used in the past for weld overlay repairs to ferritic components, and are conservative as will be illustrated in this report.

Code Case N-740-1 failed at the BPV Standards Committee as the result of single negative from the NRC. The negative was based in part on the inclusion of the provision which allows the application of Construction Code PWHT exemptions to weld overlays on P-1 materials.

The industry would like to apply the ASME Section III, NB-4620 PWHT exemptions to various P-1 weld overlay applications, and, thereby, eliminate the need to perform ambient temperature temper bead welding on several DMWs. The proposed use of these exemptions is technically acceptable and consistent with many years of successful industry experience using the PWHT exemptions for carbon steel provided in Section III, NB-4620.

2.1 References

2-1. ASME Section XI Code Case N-740, Dissimilar Metal Weld Overlay For Repair of Class 1, 2 and 3 Items, October 12, 2006.

2-2. ASME Section XI Code Case N-740-1, Dissimilar Metal Weld Overlay For Repair of Class 1, 2 and 3 Items, DRAFT.

3.0 OBJECTIVE

The objective of this activity is to prepare a technical report justifying the use of the provisions of the ASME Code Section III, Paragraph NB-4620 for application of a weld overlay repair to P-1 carbon steel piping, and to DMWs involving austenitic materials joined to P-1 carbon steel piping components.

4.0 PLAIN CARBON STEEL AND LOW ALLOY STEEL

4.1 Metallurgy of Plain Carbon Steel

Steels are iron alloys combined with other elements, of which the most important is carbon. In fact, steels can be defined generally as iron-carbon alloys containing less than 2.0 wt % carbon. Carbon exists as an interstitial element within an iron matrix in steel alloys. A binary equilibrium phase diagram graphically illustrates the thermodynamically stable solubility limits established by alloying one element with another. Figure 4.1 is the iron-carbon equilibrium phase diagram, which shows the solubility limits/ phase stability of carbon additions up to 6.67 wt % carbon; 6.67% wt % carbon is the carbon/iron ratio that results in the formation of an intermetallic phase called cementite which has the chemical composition Fe_3C. For example, the iron-carbon equilibrium phase diagram explains the 2 wt % carbon limit used to define steels – the limit of carbon solubility in austenite is 2.06 %; therefore, steels are defined as ferrous (iron based) alloys having a fully austenitic phase that is stable at some temperature that depends upon the carbon content. Alloys beyond 2.06%C are considered cast irons. Low carbon steels generally have maximum carbon limits equal to or less than 0.30 %C.

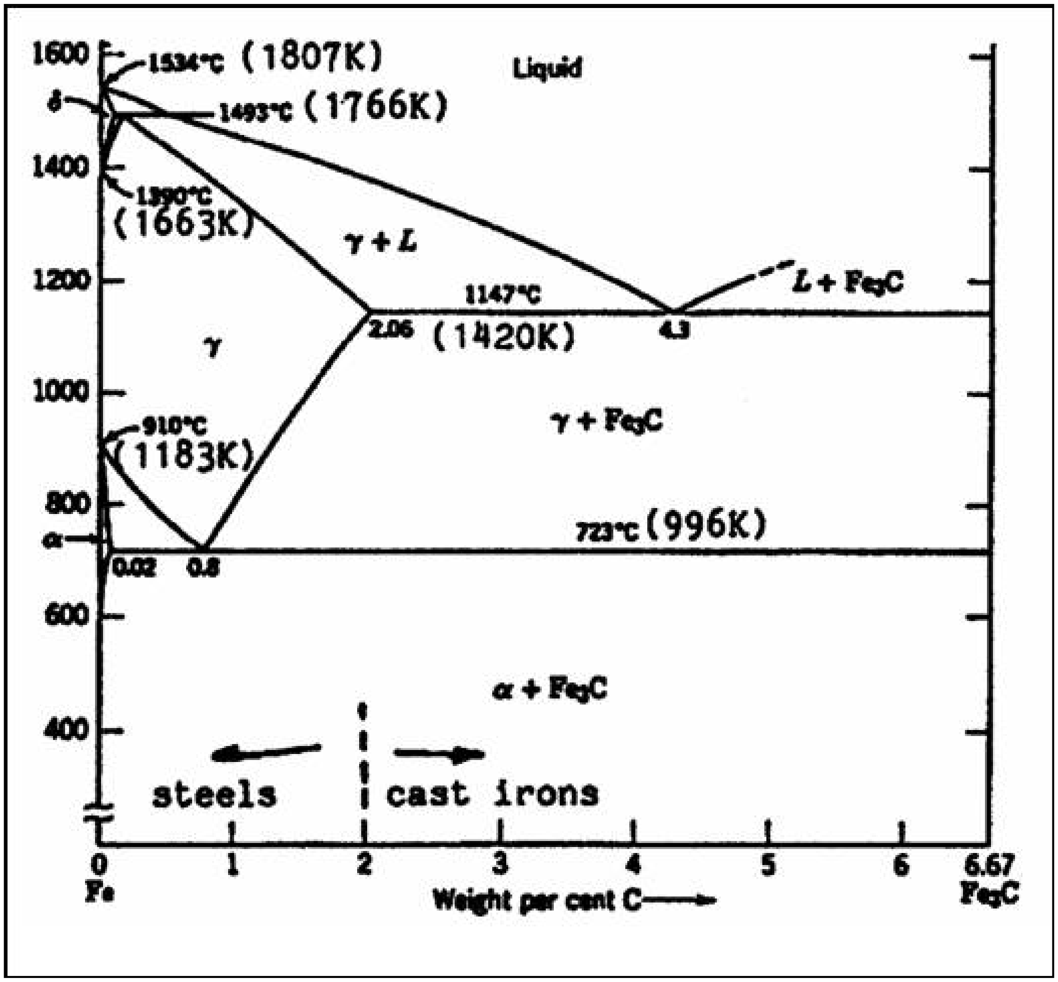

Figure 4-1. The Iron-Carbon Binary Equilibrium Phase Diagram, which shows how the allotropic iron phases change with temperature and carbon composition

Table 4-1: Typical Carbon Steel Specifications used in Nuclear Components

Specification (ASME Section II Part A or B31.1)	Carbon Content max.
SA-36 structural steel	0.25 to 0.29 depending on thickness
SA-515 plate (Grades 60, 65, & 70)	0.24-0.31, 0.28-0.33, & 0.31-0.35 respectively, and depending on thickness
SA-516 plate (Grades 55, 60, 65, & 70)	0.18-0.26, 0.21-0.27, 0.24-0.29, & 0.27-0.31 respectively, and depending on thickness
SA-105 forgings	0.035
SA-106 seamless pipe (Grades A, B & C)	0.25, 0.30 and 0.35 respectively
SA-335 seamless pipe (K11522)	0.10 - 0.20
SA-508 Grade 1 & 1A (formerly Class 1 and 1A)	0.35 & 0.30 respectively

In addition to carbon and iron, all commercial steels contain varying amounts of Mn, Si, S, P, gases and other trace impurities that are present from the raw materials and methods used for steel production. Consequently, steels are defined as plain carbon even when they contain one or more percent manganese, up to 0.3% Si, 0.06%P plus S, etc. The structure and properties of plain carbon steels depend not only on composition, but also on the heat-treatment and on the hot and cold working operations prior to or after heat-treatment. Consequently, specifying only the composition is insufficient to provide an adequate description of properties. Each of the specifications identified above prescribe melting practice, composition and heat treatment to generate the properties required.

Finally, plain carbon steels are generally grouped as P-1 either Group 1 or Group 2 for the purposes of classifying groups of materials that respond similarly to welding. Such groupings are identified for each material in ASME Section II Part D and in B31.1 piping code.

Microstructural Constituents

Carbon is an interstitial alloying addition that changes the phase stabilities of the fundamental iron alloy phases. The iron carbon equilibrium phase diagram illustrates how additions of carbon increase the stability of the austenite phase; note in Figure 4.1 that as the carbon content increases (moving right on the diagram), that the austenite (γ-iron) phase is stable at lower temperatures (up to 0.8% carbon addition). The iron-carbon equilibrium phase diagram also shows that γ-iron has more solubility for carbon than does the body centered cubic α-iron phase. Therefore, upon cooling γ-iron into the α-iron stability region (where γ-iron is no longer thermodynamically stable), α-iron crystals are nucleated on the edges of, and grow into, the γ-iron crystals while rejecting carbon into the remaining γ-iron matrix. Through this rejection process, eventually enough carbon is built up locally in the remaining γ-iron crystal, that regions of cementite, Fe_3C, (the next stable low temperature iron-carbon phase) are formed. See Figure 4.2 for a description of the equilibrium phase transformation sequence for a typical low carbon steel.

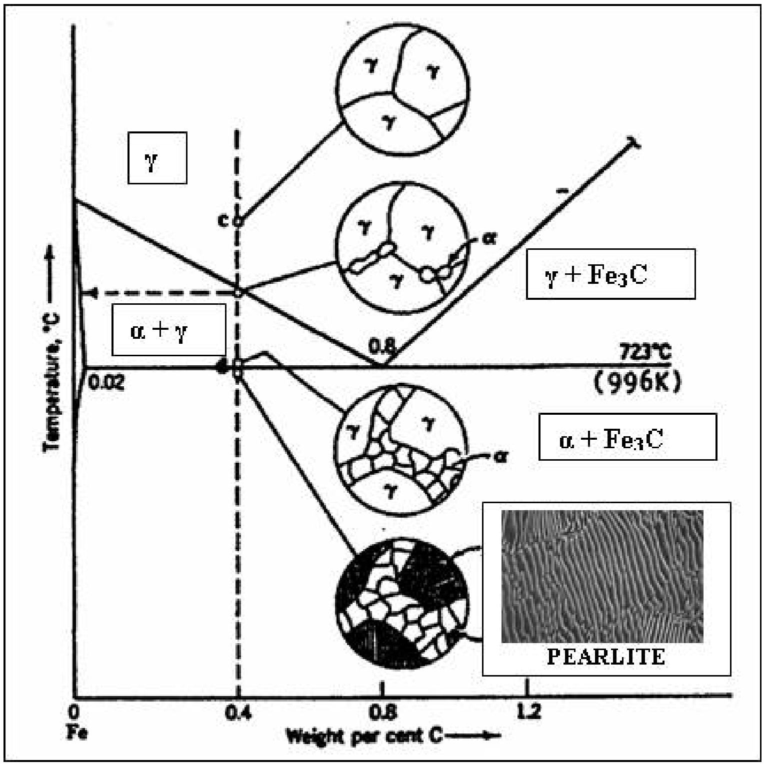

Figure 4-2. Detail of the iron carbon diagram illustrating microstructures formed during equilibrium cooling

The iron carbon equilibrium phase diagram includes a solid state transformation called the eutectoid reaction. In an eutectoid reaction, two distinct solid phases form from the decomposition of one. In the case of P-1 carbon steels, at 1333ºF and 0.8 wt % carbon, γ-iron decomposes into a mixture of α-ferrite and Fe_3C at the lower critical or eutectoid temperature. Since this decomposition into the two product phases happens simultaneously, the structure formed is lamellar. A lamellar structure is a stacked sandwich-like structure, with thinner sheets of cementite sandwiched between thicker sheets of α-iron. An example of the lamellar microstructure is shown at the bottom of Figure 4.2 and in Figure 4.3b.

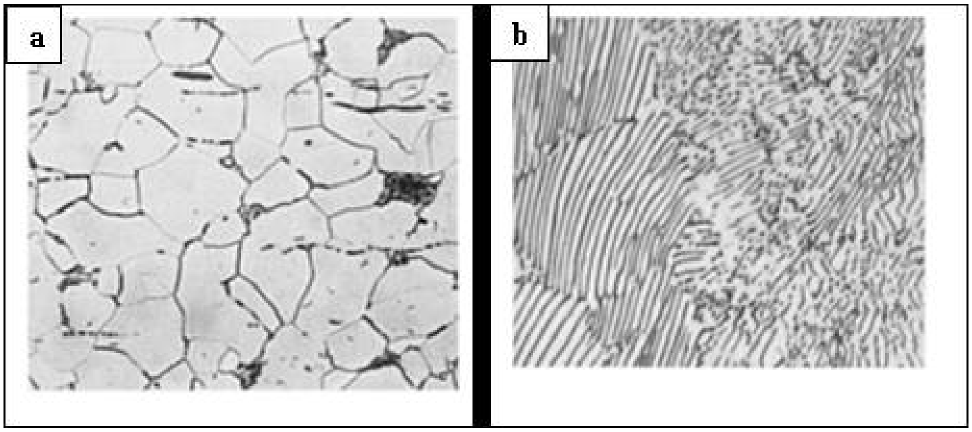

Figure 4-3. Typical micrographs of carbon steel, showing predominantly ferrite with about 10% pearlite (a), and showing detail of the pearlitic microstructure (b)

The iron-carbon equilibrium phase diagram only describes phase stability and solubility limits under equilibrium cooling conditions; that is, when an alloy is cooled slowly enough to allow atomic diffusion and reorganization during phase transformations. Diffusion is temperature sensitive and requires a certain amount of energy to occur. There is another important class of transformation products that are metastable phases. These phases are formed under rapid cooling conditions when diffusion is not sufficiently fast to facilitate atomic reorganization into the stable equilibrium phases. The phases that are formed under fast cooling conditions are not thermodynamically stable and would reorganize themselves into the stable phases shown on the iron-carbon equilibrium phase diagram when given sufficient time for the required diffusion to occur. Atomic diffusion is both temperature and time dependent.

The phase transformation from γ-iron to α-iron and cementite requires time for the carbon to diffuse out of the α-iron and into the γ-iron. If the cooling rate is too great to allow carbon rejection/diffusion, then a new series of metastable phases, bainite and martensite, can be formed. The formation of these phases is dependent on the cooling rate, and normally a mixture of phases will be produced.

Bainite is a phase formed in carbon steels when the high temperature austenite phase is rapidly quenched to temperatures around 350-800^{0}F. Bainite consist of a fine submicroscopic dispersion of cementite particles in a highly strained alpha iron matrix. Some diffusion is present but to a lesser degree than is required for equilibrium transformation. Because the crystal structure of bainite is strained during its transformation process, bainite is stronger (more able to resist deformation) and consequently harder than the equilibrium phases.

Martensite phase is formed when the quench rate is so fast that the carbon atoms do not have sufficient time to diffuse out of the face centered gamma iron. The carbon gets trapped and distorts the crystal from a face centered cubic structure into an elongated body centered tetragonal structure. Martensite is a strong, hard, and brittle phase. Typically, “hardening” steels involves heat treating them to force as much martensite in the microstructure as possible. Therefore, the term “hardenability” is defined as the ability to form martensite. With plain carbon steels, the critical cooling rate needed to form bainite and martensite depends on the carbon content. From a practical standpoint a carbon content exceeding 0.35 % C is required to trigger the martensitic reaction. This is why low carbon steels have very little hardenability, because the carbon content is less than 0.30 %C. When the material is held at temperatures slightly below the transformation temperature for some time, the carbon will diffuse from the hardened phases to precipitate as carbides. This action tempers the martensite and makes it softer and much tougher.

The martensitic phase is characterized by a very hard structure but hardenability should not to be confused with the term “hardness”. Hardness is the resistance to penetration by an indenter, and is measured by several test methods that have been standardized. The Rockwell Hardness Test is one such indentation test, and several scales (A, B and C) are used to characterize materials that range from soft to very hard. Hardness is influenced by the carbon content and the presence of some significant percentage of bainite and martensite. Hardness is also identified with thresholds for cracking susceptibility such as might be present for susceptibility to hydrogen delayed cracking. The generally accepted threshold for hydrogen delayed cracking is R_C 35 as noted on page 4-1 of EPRI Report 1013558. It is practically impossible to achieve a hardness of R_c 35 with low carbon steels.

The measured Rockwell B scale hardness for low carbon steels will vary with specific carbon level but typically will be measured between 75 R_B and 90 R_B. In many cases, the material specifications will limit the total residual content at around 1.0%. Such residual elements include Cu, Ni, Mo and V. Each of these elements will typically impart some modest degree of strengthening in addition to the carbon. However, because the total content of these residual elements is very low, their impact on the strength and hardness is also low.

4.2 Low Alloy Steel Metallurgy

Low alloy steels (typically P- 3, Group No.3) respond differently to heating and cooling than do low carbon steels (P- 1, Group Nos. 1 and 2). The P-3 materials have a significant degree of hardenability, due to their increased alloy content. An EPRI study [Reference 4-1] identified two major regions that may become hardened as a result of arc welding. The first region is the high temperature region adjacent to the weld fusion line. The welding heat raises the temperature of a small zone of adjacent base material (or weld substrate) above a critical transformation temperature range (A_{C1}) unique to the material composition. Austenite is reformed and upon cooling that material retransforms into a mixture of martensite, upper bainite, lower bainite, pearlite, cementite, and ferrite. Figure 4.4 presents a Continuous Cooling Transformation Diagram for SA-508 Class 2 (renamed SA-508, Grade 2 Class 1) low alloy steel – a material typical of nozzle designs used in reactor pressure vessels. The martensitic transformation is a homogeneous shear of the face centered cubic crystal structure to the body centered tetragonal crystal structure. This process as noted earlier is not dependent upon diffusion, but the degree of completion is temperature dependent. Thus, martensite start and martensite finish temperatures characterize the range over which the reaction occurs. One notes from the curve that any heat treatment below 550ºF will be below the martensite finish temperature. Thus, weld preheating and post weld bakes below 550ºF will have no effect on the microstructure [Reference 4-1].

Transformation products depend upon the hardenability of the material (specific composition dependent) and the rate of cooling through the transformation temperature range. A high hardenability composition will favor martensite and upper bainite, and a low hardenability composition will favor bainite and pearlite microstructures. In the untempered state, the bainite and pearlite mixtures are more tolerant to stress and weld distortion. When tempered, the microstructure of the higher hardenability material produces outstanding fracture toughness, because the material is strong but also possesses significant ductility. The more rapid the cooling rate through the critical transformation temperature range, the transformation from austenite to martensite will be favored for any given composition. Therefore, any action that slows the cooling rate will tend to favor bainite and pearlite in the microstructure. This microstructure mixture will have increased tolerance to stress cracking in the untempered condition. However, when tempered the predominantly martensite phase will develop superior properties.

The application of preheat is one way to slow the rate of cooling, because the difference in temperature driving the cooling rate is reduced. It is interesting to note that this is one reason that interpass temperature is strictly controlled in low alloy steels so that a hardened microstructure will develop more fully.

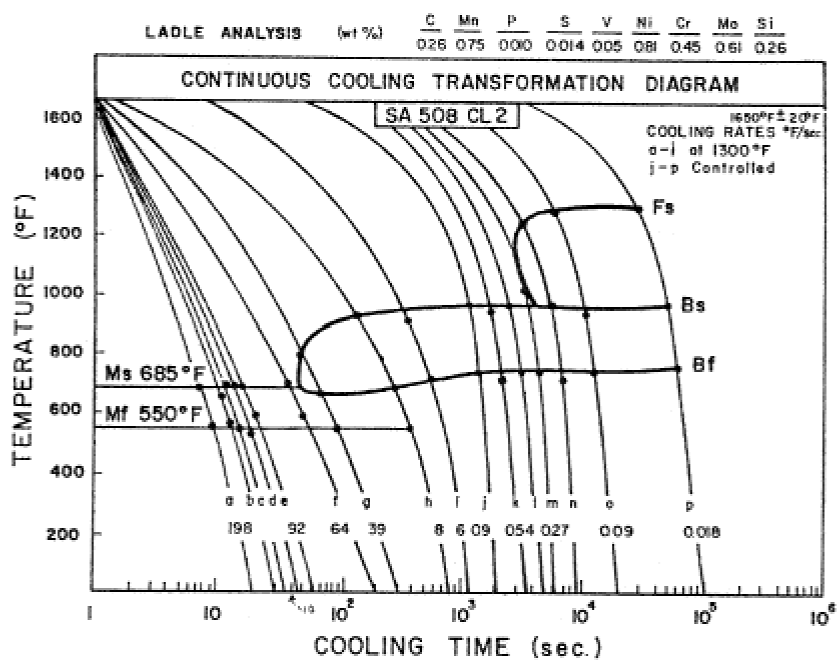

Figure 4-4. Continuous Cooling Transformation Diagram of SA-508, Class 2 Steel (4-1)

Untempered martensite and upper bainite microstructures are very hard and brittle structures. Carbon and other interstitial atoms are locked within the microstructure preventing deformation mechanisms to take place and resulting in increasing internal stress. This produces strength, but unfortunately, also results in low ductility and thus low fracture toughness. When heat is applied to the structure in the range of 1250 to 1325ºF, the carbon will precipitate as carbides and diffuse from the hardened microstructures. This action reduces the locked in strain and rapidly increases ductility and toughness. Tempering is both time and temperature dependent because the movement of carbon atoms to precipitate carbides is diffusion controlled. Tempering is rapid at the upper temperatures, but drops off very rapidly as temperature decreases. Very little tempering occurs at traditional stress relief temperatures between 1050 and 1150ºF, because carbon is less mobile.

Therefore, it can be readily seen that P-3, Group 3, low alloy steels generally used in vessel construction have higher hardenability than P-1 steels due to their alloy content. This is the reason that there are no PWHT exemptions in NB-4620 for P-3, Group 3 materials. Conversely, P-1 Groups 1 and 2 are characterized by low hardenability meaning it is practically impossible to form martensite with any reasonable fabrication process including welding. This it the reason that PWHT exemptions are provided in NB-4620 for low carbon steels. Since they are not hardenable there is no value in applying a PWHT.

4.3 References

4-1 Temperbead Welding Applications, 48-Hour Hold Requirements for Ambient Temperature Temperbead Welding, EPRI Report 1013558, Technical Update December 2006.

5.0 WELD OVERLAYS

The weld overlay (WOL) is a repair technique designed to restore full structural integrity to components degraded by weldment cracking assuming complete through wall cracking 360^0 around the component (worst case scenario). The method is applicable to weldments of piping, safe-ends, and nozzle geometries. A weld deposit is placed around the outer circumference of the component in layers using a machine welding process. Concentric layers are applied until the designed overlay thickness is achieved.

The WOL deposit material is selected to be highly resistant to the crack degradation mechanism so that cracking will not propagate through the overlay. In addition to providing a cracking barrier, the overlays provide other valuable features.

- Weld solidification shrinkage constricts the component under the overlay causing the inner portion of the component to be in a compressive residual stress state. Since most degradation mechanisms require a tensile stress, the method mitigates the mechanism.
- Many pipe-safe-end-nozzle weld configurations are in close proximity such that ultrasonic testing volumes are partially restricted. In many cases, the overlay can be designed to enhance the coverage of inspection volumes such that inspections are improved by the presence of the WOL.

WOL materials are typically austenitic (either stainless steel or nickel based). WOLs were conceived, developed and first applied in the early 1980s as mitigation for intergranular stress corrosion cracking (IGSCC) of stainless steel piping weldments in boiling water reactors (BWRs). In most cases, stainless steel overlays (having minimum levels of ferrite in the deposit) were placed around the welds joining stainless steel pipes or pipes and safe-ends. The applications were highly successful and many of these overlays are still in service today.

Initially, the WOL service life was considered temporary, but with time it became apparent that the repairs were highly effective as permanent repairs. Later, applications to Alloy 600 safe-ends or Alloy 82/182 weldments utilized Alloy 82 (ERNiCrFe-3) filler material because it was compatible with both nickel based materials and stainless steels and also provided high resistance to IGSCC due to its chromium (Cr) content so it could function as a crack barrier. Eventually, DMWs between low alloy steel nozzle materials and stainless steel pipes or safe-ends required similar mitigation methods and overlays were designed for those applications as well. Later, the reality of primary water stress corrosion cracking (PWSCC) was discovered in Alloy 600 weldments, and overlays have been successfully applied there as well. Due to the nature of PWSCC weldments and the design of the PWR plants, most of these overlays are between dissimilar metals and nickel based filler materials have been used. In general, the Alloy 52 (ERNiCrFe-7) or Alloy 52M (ER NiCrFe7A) filler materials which have 30% Cr content have been used due to their excellent resistance to PWSCC . All of these applications have been applied using the machine Gas Tungsten Arc Welding (GTAW) process.

DMWs present a unique application challenge for WOLs, because non-austenitic materials are involved – namely the P-1 carbon steel and P-3 low alloy steel nozzles. These materials transform as they are heated and cooled whereas austenitic materials are single phase and do not experience phase transformations on heating or cooling. Phase transformations can potentially result in hardening of weld HAZs if the the hardenability is sufficiently high. The ASME Construction Code requires PWHT after welding P-3 materials to temper any hardened transformation products in the weld HAZ and to effect some relief of residual stresses. The ASME Construction Code recognizes the low hardenability developed by P-1 low carbon steels and exempts them from PWHT if certain thickness, carbon level maximum, and preheat criteria are met. These exemptions are discussed fully in "Section 6.0 ASME and Other Piping Code Rules and History". The metallurgy of the pertinent phase transformations are discussed in detail in "Section 4.0 Plain Carbon Steel and Low Alloy Steel" above.

PWHT presents a challenge for WOL repairs at nozzles. Since PWHT of nozzles typically is performed at temperatures exceeding 1100°F, significant thermal strains and distortion can result because of having to heat non-uniform geometries. Second, water is present in many applications and it is virtually impossible to achieve the uniform high temperatures needed for PWHT. Removing it greatly increases radiation exposure to workers. Third, the exposure times required to apply PWHT are significant and can result in significant additional personnel radiation exposure. For these reasons, temperbead welding methods were developed as alternatives to Construction Code PWHT requirements. WOLs applied with temperbead techniques have been used successfully on many WOL applications in both BWR and PWR applications over the past 20 years.

The reasons for PWHT are primarily tied to achieving requisite fracture toughness and minimizing any chance for hydrogen delayed cracking in hardened weld HAZs. Most WOL deposits utilize austenitic materials such as stainless steels or nickel based materials, and so neither of these issues is a concern for the overlay deposit itself. The concern is for the weld HAZ of the ferritic substrate (normally the nozzle) under the overlay deposit. Therefore, the focus is to assure that the ferritic HAZ under the overlay possesses the required properties. It is noted that the HAZ for an overlay is created only on the outer surface of the component. As such it is different from butt welds joining piping and nozzle components in that the HAZ does not extend from the OD to the ID of the component, but rather is manifest only on the outer surface. In essence it is only a surface effect influencing only a small volume of ferritic material completely bound by a thick covering of austenitic material not subject to phase transformations. This fact minimizes any small hardening effects in the HAZ of even P-3 Group 3 materials – much less P-1 Groups 1 and 2.

To better understand the PWHT requirements, it is useful to consider that ASME Section III addresses weld buildups, cladding, fillet welds, socket welds, and base material cavity repairs as well as groove welds. During welding operations, weld beads tend to be restrained by the component parts. This restraint introduces high stress from thermal gradients and from shrinkage as the weld metal cools but is resisted by the structures being welded. The amount of stress varies with the type of weld and component thickness for a given material. The ASME Code developed PWHT rules over the years to accommodate the requirements for these different types of welds, and the rules have remained the same since the early days of nuclear construction. While there are differences, it is interesting to note that similar PWHT rules and exemptions are found in other Construction Codes as well.

As stated above, the welding of WOLs is strictly a surface weld deposit application (similar to cladding except the application is on the OD instead of the ID surface). See Figure 5-1 below.

Geometrical constraints are minimal except for resisting modest axial shrinkage. Therefore, the primary concern is for the behavior of the weld HAZ in the substrate material under the overlay. When the material is austenitic (stainless steel or nickel base materials such as Alloy 600), the HAZ will remain austenitic during welding. As a result, PWHT of austenitic stainless steels and nickel based alloys is not required by Construction Codes such as ASME Section III.

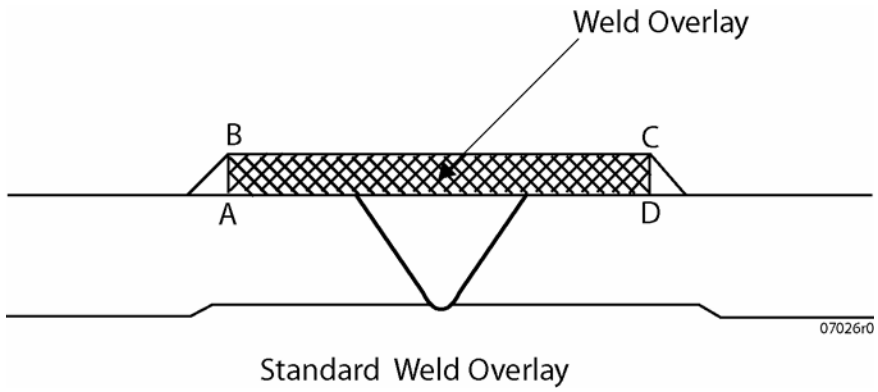

Figure 5-1. Schematic Cross-section of a Standard Weld Overlay

The HAZ of ferritic substrates (discussed previously) involves phase transformations adjacent to the fusion line, and the range of temperatures over which the transformations occur generally limits the depth of the HAZ to about 0.10 to 0.15 inch. The rate of cooling due to the heat sink of the material under the overlay also helps to limit the depth of the zone influenced by weld heat. These HAZs are the only areas of concern for WOLs dealing with toughness and resistance to hydrogen delayed cracking identified above.

The ASME Code treatment of PWHT exemptions applicable to P-1 materials is discussed in detail in Section 6.0 below. The consideration here is that the nominal weld thickness, when applying the PWHT exemptions of the Construction Code, is best characterized as only those WOL layers that could affect the HAZ properties of the ferritic material; but conservatively, it will be considered the WOL thickness itself. This means that WOL application to most P-1 material should be exempted from PWHT and thus requires no temperbead weld procedure. The portion of the WOL applied over austenitic materials is already exempted from PWHT. Since it can be shown by mock-up demonstration that the P-1 HAZ is characterized by hardness at or below R_C 35, neither fracture toughness nor hydrogen delayed cracking are issues. The hardness threshold of R_C 35 has long been recognized by the ASME Code since Code Case 217-1 was introduced in 1982 and included in the ASME Section III Construction Code in the Summer 1985 Addenda.

Austenitic weld overlays applied over P-1, Group 1 or Group 2 materials develop HAZs that are too soft to support hydrogen assisted cracking because the hardenability of P-1 compositions is insufficient to develop a maximum hardness exceeding R_C 35 even for single weld beads. For multiple passes associated with multiple weld layers, the hardness is even lower. It should be noted that the hardenability of even P-3 Group 3 materials (such as SA-508, Grade 2 nozzle materials) is marginal for developing maximum hardnesses greater than R_C 35 – especially with multipass welds such as weld overlays.

6.0 ASME CODE RULES AND HISTORY

6.1 ASME Boiler and Pressure Vessel Code, Section III

6.1.1 PWHT Requirements

NB-4620 of ASME Section III provides PWHT requirements for components fabricated from ferritic materials. The need for and the specific requirements for PWHT are dependent upon several variables, such as material composition and carbon content, restraint, type of weld (e.g. butt weld, fillet weld, cladding, etc), component type and thickness, and preheat temperature as noted in Table NB-4622.7(b)-1 of ASME Section III.. One key feature for ferritic materials relates to the hardenability of the material, as discussed in Section 4 above. The differences in hardenability among the ferritic materials are significant for materials classified from P-1 materials to P-11A materials. These differences in hardenability lead to distinctly different requirements for PWHT time and temperature for the various classes of ferritic materials.

Materials classified as P-1 and P-3 typically are used for pressure vessels. Rules controlling the PWHT requirements for these materials are presented in Table NB-4622.1-1 of ASME Section III and exemptions from PWHT requirements are presented in Table NB-4622.7(b)-1. The rules for these materials are longstanding. Although these rules have been tweaked over time based on industry experience and technological developments, PWHT exemptions have been part of ASME Section III since the 1965 Edition.

The pertinent portion of Table NB-4622.7(b)-1 dealing with P-1 and P-3 materials, excerpted from the 1989 Edition of ASME Section III, is presented below.

TABLE NB-4622.7(b)-1
EXEMPTIONS TO MANDATORY PWHT[1]

P-No. (QW-420, Sect. IX)		Type of Weld [Note (5)]	Nominal Thickness (NB-4622.3)	Max. Reported Carbon, % [Note (6)]	Min. Preheat Req'd, °F
1	Vessels	Circumferential butt and socket welds connecting pipe and tubes to nozzles where the materials being joined are 1½ in. and less	1¼ in. and less	0.30 or less	. . .
			Over 1¼ in. to 1½ in.	0.30 or less	200
			¾ in. or less	Over 0.30	. . .
			Over ¾ in. to 1½ in.	Over 0.30	200
		Fillet welds	¾ in. or less	. . .	200
		All welds, except repair welds and fillet welds, provided welding procedure qualification is made using equal or greater thickness base material than the production weld	⅝ in. or less	0.25 or less	200
	Other components	All welds where the materials being joined are 1½ in. and less	1¼ in. and less	0.30 or less	. . .
			Over 1¼ in. to 1½ in.	0.30 or less	200
			¾ in. or less	Over 0.30	. . .
			Over ¾ in. to 1½ in.	Over 0.30	200
		All welds in material over 1½ in.	¾ in. or less	. . .	200
1, 3		For repair without required PWHT, see NB-4622.9, NB-4622.10, and NB-4622.11	. . .	. . .	350
1 Gr. 1 or Gr. 2		Cladding or repair of cladding [Note (2)] with A-No. 8 or F-No. 43 filler metal on base material of:			
		1½ in. or less	. . .	0.30	100
		over 1½ in. to 3 in.	. . .	0.30	200 [Note (3)]
		over 3 in.	. . .	0.30	250 [Note (4)]
3 except Gr. 3		All welds, except repair welds in vessels, provided welding procedure qualification is made using equal or greater thickness base material than the production weld	⅝ in. or less	0.25 or less	200
		Attachment welds joining nonpressure-retaining material to pressure retaining material	½ in. or less	0.25 or less	200

NOTES:

(1) The exemptions noted in this Table do not apply to the following:

(a) electron beam welds in ferritic materials over ⅛ in. in thickness;

(b) inertia and friction welds in material of any thickness of P-No. 3, P-No. 4, P-No. 5, P-No. 7 (except for Types 405 and 410 S), P-No. 10, and P-No. 11 materials.

(2) Maximum process heat input = 150,000 J/in. The maximum resulting hardness in the procedure qualification test plate shall not exceed 35 Rc.

(3) Intermediate postweld soak at not less than 200°F for 2 hr minimum.

(4) Intermediate postweld soak at not less than 300°F for 2 hr minimum.

(5) Where the thickness of material is identified in the Type of Weld column, it is the thickness of the base material at the welded joint.

(6) Carbon level of the pressure retaining materials being joined.

TABLE NB-4622.7(b)-1 (CONT'D)

GENERAL NOTE:

(a) The exemptions noted in this Table do not apply to the following:

(1) electron beam welds in ferritic materials over 1/8 in. (3 mm) in thickness;

(2) inertia and friction welds in material of any thickness of P-No. 3, P-No. 4, P-No. 5, P-No. 7 (except for Types 405 and 410S), P-No. 10, and P-No. 11 materials.

NOTES:

(1) Where the thickness of material is identified in the Type of Weld column, it is the thickness of the base material at the welded joint.

(2) Carbon level of the pressure-retaining materials being joined.

(3) Maximum process heat input = 150,000 J/in. (5 910 J/mm) The maximum resulting hardness of the heat affected zone in the procedure qualification test plate shall not exceed 35 Rc.

(4) Intermediate postweld soak at not less than 200°F (95°C) for 2 hr minimum.

(5) Intermediate postweld soak at not less than 300°F (150°C) for 2 hr minimum.

(6) Weld Procedure Qualification coupon need not exceed 1.5 in. (38 mm) in thickness.

One can note from the information provided in Table NB-4622.7(b)-1 for butt welds in P-1 non-vessel components, that no PWHT is required for welds in base materials over 1-1/2" with a nominal thickness of ¾" or less provided a 200°F preheat is applied. For welds in non-vessel base materials 1-1/2" or less in thickness, no PWHT is required provided the following conditions are met as applicable:

- Nominal thickness is 1-1/4 or less, and carbon content is 0.30% or less.
- Nominal thickness is over 1-1/4 but equal to or less than 1-1/2", carbon content is 0.30% or less, and a 200° F preheat is applied.
- Nominal thickness is 3/4 or less, and carbon content is over 30%.
- Nominal thickness is over 3/4 but equal to or less than 1-1/2", carbon content is over 0.30%, and a 200° F preheat is applied.

PWHT exemptions for vessels vary with type of weld and other variables. However, as shown in Table NB-4622.7(b)-1, the PWHT exemptions for butt welds in P-1 vessels are identical to those for butt welds in P-1 non-vessels or other components.

ASME Section III Code Case N-217-1 was approved on September 7, 1982 [6-1] to provide rules for applying austenitic stainless steel or nickel alloy cladding on P-1 materials without performing PWHT. This Code Case was incorporated into Section III in the 1983 Edition, Summer 1985 Addenda. A feature of the Code Case and all subsequent editions of Section III, Table NB-4622.7 (b)-1 is that the maximum acceptable hardness of the heat affected zone was to be Rockwell C 35. Provided that these features are met, the weld deposit and underlying P-1 material is acceptable. The justifications for the R_C 35 hardness level and the acceptable thicknesses for P-1 components are related to hydrogen assisted embrittlement (or cracking) and have been discussed in Section 4 of this report.

6.1.2 ANSI B31.1 Standards

The 1989 Edition of the ANSI B31.1 Standards was reviewed as part of this report because the ANSI Standards have been employed in many instances for fabricating power piping for nuclear power plants. A review of the PWHT requirements of Table 132 of the standards reveals exemptions for P-1 materials that are very similar to those for P-1 materials in ASME Section III, Table 4622.7(b)-1. Note 1 for P-1 materials states, "PWHT of P-No. 1 materials is not mandatory, provided that all of the following conditions are met: (A) the nominal thickness, as defined in Paragraph 132.4.1 is ¾-inch or less, (B) a minimum preheat of 200ºF is applied when the thickness of either of the base metals exceed 1-inch".

These reviews illustrate that as long as the nominal thickness is less than ¾ inch, no PWHT is required for P-1 materials provided a 200°F preheat is established when the base material thickness is greater than 1".

6.2 Applicability of Construction Code PWHT Exemptions to Weld Overlays

Construction Codes such as ASME Section III do not specifically address WOLs. During construction, defects in welds are excavated and repair welded. However, repair of defects by excavation and repair welding is often not a viable option in operating nuclear power plants. As an alternative to the repair welding methods of the Construction Code, ASME Code Case N-740 provides rules for the installation of weld overlays on the outside surface of piping, components, and welds as a means of reducing a defect to a flaw of acceptable size. Paragraph 1(b) of Code Case N-740 states the following:

> "Weld overlay filler metal shall be deposited using a Welding Procedure Specification (WPS) for groove welding, qualified in accordance with the Construction Code and Owner's Requirements identified in the Repair/Replacement Plan. As an alternative to the postweld heat treatment requirements of the Construction Code and Owner's

Requirements, the provisions of Appendix 1 may be used for ambient temperature temper bead welding."

The ability to reduce a defect to a flaw of acceptable size by the application of a WOL is an important repair alternative for operating nuclear power plants. However, in providing this alternative, Code Case N-740 does not specify any new PWHT requirements for WOLs. It simply invokes the PWHT requirements of the Construction Code. While this certainly makes sense, it is important to remember that PWHT exemptions for WOLs are not specifically addressed by the Construction Code as noted above. To address this issue, Section 1 of Code Case N-740 was revised (Code Case N-740-1) to provide guidance on using the Construction Code PWHT exemptions as shown below:

> "For P-No. 1 base materials the Construction Code PWHT exemptions permitted for circumferential butt welds may be applied to exempt the weld overlay from PWHT, with the following clarifications.
>
> (a) The nominal weld thickness shall be defined as the maximum overlay thickness applied over the ferritic base material.
>
> (b) The base material thickness shall be as defined as the maximum thickness of the ferritic material where the overlay is applied."

The above guidance provides a consistent and conservative means for applying the PWHT exemptions of the Construction Code to WOLs involving P-No. 1 material. This guidance is consistent with years of WOL and PWHT experience. The clarifications in this new guidance applicable to nominal weld thickness and base material thickness are discussed in Sections 6.2.1 and 6.2.2.

6.2.1 Nominal Weld Thickness Considerations

The ASME Code Section III, paragraph NB-4622.3 [1-1], provides a definition of "Nominal Thickness Governing PWHT" (i.e. nominal weld thickness). This paragraph states the following:

> "Nominal thickness in Table NB-4622.7(b)-1 is the thickness of the weld, the pressure-retaining material for structural attachment welds or the thinner of the pressure-retaining materials being joined, whichever is least. It is not intended that nominal thickness include material provided for forming allowance, thinning, or mill overrun when the excess material does not exceed 1/8-in. (3 mm). For fillet welds, the nominal thickness is the throat thickness, and for partial penetration and material repair welds, the nominal thickness is the depth of the weld groove or preparation."

The 1989 Edition of B31.1 defines "nominal weld thickness" in paragraph 132.4.1 as the lesser of the (a) thickness of the weld or (b) the thicker of the materials being joined at the weld. In Paragraph 132.4.2, B31.1 further defines "thickness of the weld" as follows:

- (A) groove welds (girth and longitudinal) – the thicker of the two abutting ends after weld preparation, including I.D. machining;
- (B) fillet welds – the throat thickness of the weld;
- (C) partial penetration welds – the depth of the weld groove;
- (D) material repair welds – the depth of the cavity to be repaired;
- (E) branch welds – the weld thickness is the dimension existing in the plane intersecting the longitudinal axes and is calculated as indicated for each detail

The definitions of "nominal weld thickness" in Construction Codes such as ASME Section III and B31.1 are specific to butt, branch connection, structural attachment, fillet, partial penetration, and material repair welds. However, Construction Code definitions for nominal weld thickness do not specifically include WOLs. To address this issue, Code Case N-740 was revised to provide guidance on applying the PWHT exemptions of the Construction Code. This guidance included a definition for nominal weld thickness which is provided in Section 6.2 above.

The Code Case N-740-1 definition of nominal weld thickness for WOLs is technically sound - if not conservative. First of all, WOLs are deposited with austenitic weld filler metals which do not require PWHT. Because austenitic base materials beneath the WOL are also exempt from PWHT, the area of concern for a WOL is limited to the weld HAZ in the ferritic base material just below the WOL. Unlike groove welds and cavity repair welds, WOLs are applied by depositing one weld layer on top of another. That said, the only WOL layers that can affect the microstructure and properties of the weld HAZ in the ferritic base material are the first three layers or until an overlay thickness of 1/8" is achieved. Beyond this thickness, welding heat from individual weld passes is insufficient to adversely affect the base material properties in the weld HAZ. While WOL layers beyond this thickness may increase the compressive residual stresses along the inside surface of the original weld, this is a positive result reducing the potential for stress corrosion cracking and is accounted for in the stress analysis supporting the design.

The argument that the base materials properties in the weld HAZ are unaffected by welding once a WOL thickness of 1/8" is well established. This point has been demonstrated many times over in testing programs and procedure qualification performed by EPRI, welding vendors, and owners. Based on this fact, the ASME Code has long maintained that PWHT is not required when performing welding along the fusion line of a non-ferritic weld to ferritic base material where greater than 1/8" of non-ferritic weld metal exists. This position has been incorporated into the temper bead rules of ASME Section III (NB-4600), ASME Section XI (IWA-4000), and ASME Code Cases N-606-1, N-638-1, and N-740. For example, IWA-4631(b) of the 2001 Edition/2003 Addenda of ASME Section XI states the following:

> "Repair/replacement activities in accordance with this paragraph are limited to those along the fusion line of a non-ferritic weld to ferritic base material where 1/8" or less of non-ferritic weld deposit exists above the original fusion line following defect removal."
> In other words, if greater than 1/8" of non-ferritic weld metal exists above a ferritic base material, temper bead welding is not necessary because PWHT would not be required.

One other point should be considered. Although the PWHT exemptions applicable to butt welds are to be used for WOLs, it is interesting to note that nominal weld thickness is not even a consideration for the PWHT exemptions applicable to weld cladding in ASME Section III, Table NB-4622.7(b)-1. Therefore, the Code Case N-740-1 definition of nominal weld thickness for WOLs is clearly conservative when applying the PWHT exemptions of the Construction Code.

6.2.2 Base Material Thickness Considerations

Code Case N-740-1 defines the base material thickness as the maximum thickness of the ferritic material where the WOL is applied. This definition is consistent with ASME Section III, Table NB-4622.7(b)-1 in which base material thickness for a butt weld is considered the thickness of the materials being joined. The Code Case N-740-1 definition is also conservative since it is based upon the maximum base material thickness beneath the WOL.

P-1 carbon steels have little hardenability due to their low carbon content as described in Section 4.0 of this report. Because the weld HAZs of P-1 materials are characterized by hardness levels that are at or below R_C 35, neither fracture toughness nor hydrogen delayed cracking are issues. P-1 steels also exhibit good resistance to cold or restraint cracking.

The tempering benefit of multipass welding on the weld HAZ should also be considered. As explained in Section 6.2.1 above, only the first three layers (or 1/8") of the WOL can affect the properties of the weld HAZ of the underlying ferritic base material. Although not considered in the PWHT exemptions of the Construction Code, the tempering of multipass welding produces a tough, fine grained microstructure in underlying ferritic materials. The American Welding Society's (AWS) technical reference entitled Welding Metallurgy (Volume 1 – Fourth Edition) states the following on pages 887-888:

> "Of equal importance for toughness is the refinement and tempering of subsequent passes on previously-made passes. Of course, this heat effect involves a gradient of temperatures being applied, which does not produce a uniform microstructure overall. Nevertheless, deposition of each subsequent bead causes the immediately adjacent region of metal to be heated above the Ac_3 critical temperature. The next region is heated to within the Ac_3–Ac_1 critical range, and the more remote regions of this new HAZ are subject to sub-critical annealing, or to tempering. Again, a rapid rate of cooling will occur in these reheated regions because of the relatively low heat input, and this will favor the formation of a fine-grained microstructure."

It is also important to note that Construction Codes such as ASME Section III include preheat requirements in the exemptions to PWHT for butt welds. The inclusion of preheat temperature into the PWHT exemptions for P-1 materials is generally based on the base material thickness, nominal weld thickness, and carbon content (above 0.30%). When a minimum preheat temperature is specified in the Construction Code PWHT exemptions, its application is a conservative measure that results in a slower cooling rate. In turn the slower cooling rate results in a slight reduction in hardness, lower residual stresses, and improved resistance to hydrogen and restraint cracking. In some cases, these preheat requirements could apply to WOLs when applying the PWHT exemptions of the Construction Code in accordance with Code Case N-740-1.

The application of designed weld overlay repairs typically does not require any excavation (although that is not precluded if the removed thickness is restored), but rather, the overlay is applied on top of the OD surface. Such a repair is structurally more robust than merely filling a cavity with a weld deposit because the overlay adds SCC resistant material over top of the weldment being repaired. Consequently, the nominal thickness of a weld overlay repair should be at most, the thickness of the overlay itself, not the thickness of the component to which the overlay is applied. In fact, the appropriate nominal material thickness influenced by the weld overlay is only the depth of the weld heat affected zone created at the outer surface of the weldment being repaired (approximately 0.100 inch to 0.150 inch depth). This consideration is really no different than the analogy of the excavation, cavity or preparation that is exempted from post weld heat treatment for P-1 substrate materials. Austenitic substrates are already exempted such that the PWHT requirements for the weldment are governed solely by the ferritic material. Thus PWHT for the entire weldment would be exempted according to the codes.

6.2.3 PWHT Exemptions for Weld Overlays

The industry experience using the ASME and B31.1 Construction Codes has been exemplary. All of the pressure vessels in this country have been constructed to these codes, and all repairs have been made through guidance from these codes without pressure boundary piping failures.

Code Case N-740-1 provides clear guidance for applying the Construction Code PWHT exemptions to WOLs. This guidance is based on years of WOL and PWHT experience and is conservative but technically sound approach. To demonstrate how this guidance would be applied to a WOL of an ASME Class 1 DMW, the ASME Section III PWHT exemptions of Table NB-4622.7(b)-1 have been modified in accordance with Code Case N-740-1. The modified PWHT exemptions for WOLs are shown below.

ASME Section III PWHT Exemptions for Weld Overlays of DMWs Involving P-1 Materials

Component Type	Base Material Thickness	Nominal Weld Thickness	Carbon Content (Max)	Preheat Required (Min.)
Vessels	1-1/2" and less	1-1/4" and less	0.30% or less	None
		Over 1-1/4" to 1-1/2"	0.30% or less	200°F
		3/4" and less	Over 0.30%	None
		Over 3/4" to 1-1/2"	Over 0.30%	200°F
All Components Except Vessels	1-1/2" and less	1-1/4" and less	0.30% or less	None
		Over 1-1/4" to 1-1/2"	0.30% or less	200°F
		3/4" and less	Over 0.30%	None
		Over 3/4" to 1-1/2"	Over 0.30%	200°F
	Over 1-1/2"	3/4" and less	All	200°F

6.3 Welding Procedure Impact Testing Requirements

According to Code Case N-740-1, a weld overlay must be deposited using a groove welding WPS using one of the following PWHT options.

(1) PWHT is performed in accordance with the Construction Code. (This is generally an impractical option.)

(2) PWHT is exempted by the Construction Code based on the guidance in Section 1 of Code Case N-740-1.

(3) As an alternative to the PWHT requirements of the Construction Code, ambient temperature temper bead welding is performed in accordance with Appendix 1 of Code Case N-740-1.

Any of the above PWHT options can be used for depositing WOL onto DMWs involving P-1 materials in accordance with Code Case N-740-1. Since several PWHT options are available under Code Case N-740-1, it is important to understand how these different options affect the impact testing requirements of the welding procedure. While there are differences, the impact testing provisions applicable to each option are acceptable because they ensure that the toughness of the weld HAZ in the ferritic base material meets applicable design requirements.

6.3.1 ASME Section III Impact Testing Requirements

Welding procedure impact testing requirements applicable to Class 1 components are specified in NB-4300 of ASME Section III. Prior to reviewing these impact test requirements, it is important to note that ASME Section III exempts some materials from impact testing. Impact testing exemptions are specified in NB-2310. If component materials are exempt from impact testing, then welding procedures for these items are also exempt from ASME Section III impact testing. Some examples of component materials that are exempt from impact testing by NB-2310 are listed below:

- Austenitic stainless steel and nickel alloy base materials and weld metals.
- Ferritic piping with either a nominal wall thickness of 5/8" or less or a nominal pipe diameter of 6" or less
- Ferritic pumps, valves, and fittings whose connecting pipe has either a nominal wall thickness of 5/8" or less or a nominal pipe diameter of 6" or less

Welding procedure impact testing requirements are specified in NB-4335 and are summarized herein. Impact testing of the weld metal is addressed in NB-4335.1 while HAZ testing is addressed in NB-4335.2. According to NB-4335.1, impact testing of the weld metal is required when joining or repairing materials that require impact testing in accordance with NB-2300 with one exception: austenitic and nonferrous weld metals do not require impact testing because of their inherent toughness. Impact testing of the weld HAZ is also required by NB-4335.2 when the base materials being welded requires impact testing. However, there is an exception to this requirement. According to NB-4335.2, impact testing of the weld HAZ is not required when PWHT of the production weld is performed in accordance with NB-4620 and welding is not performed using the electroslag, electrogas, or thermit welding process. ASME exempts weld

HAZs from impact testing when PWHT is performed because of the beneficial affects of PWHT on HAZ impact properties.

The impact testing requirements and exemptions of NB-2310 and NB-4335 significantly affect the welding procedure qualification requirements for WOLs. First of all, the austenitic nickel alloy weld metal (i.e. ERNiCrFe-7 or ERNiCrFe-7A) is exempt from impact testing. Secondly, austenitic P-8 and P-43 base materials are exempt from impact testing. Finally, impact testing of the weld HAZ is exempt from impact testing if PWHT is performed. Under these conditions, the welding procedure can be qualified without any impact testing. However, PWHT of ferritic base materials beneath a WOL is generally impractical, and this option is rarely utilized. Since PWHT will almost always be avoided when allowed by the Construction Code (e.g. NB-4620), impact testing is the weld HAZ will be required in accordance with NB-4335.2.

The ASME Section III, NB-4335.2 impact testing protocol for welding procedures is very detailed and must be carefully followed. When impact testing of the weld HAZ in accordance with NB-4335.2, the following criteria must be met:

1. Cvn specimens representing the unaffected base material and weld HAZ must be tested at the same test temperature.
2. Cvn specimens representing the unaffected base material must first meet be the code specified acceptance standards.
3. Average lateral expansion values for Cvn test specimens representing the unaffected base material and weld HAZ are to be calculated based on test results or values.
4. The calculated average lateral expansion value of the Cvn specimens representing the weld HAZ must be equal to or greater than the calculated average lateral expansion value of the Cvn specimens representing the unaffected base material.

The basis of the NB-4335.2 acceptance standards is simple. Impact testing of the weld HAZ of the test coupon is performed to demonstrate that the welding variables of the proposed welding procedure do not result in degradation of base material impact properties within the weld HAZ.

If the acceptance standards of NB-4335.2 are met, then the welding procedure is acceptable and can be used.

6.3.2 Impact Testing for Ambient Temperature Temper Bead Welding

Ambient temperature temper bead welding techniques have been used in many weld overlay applications in recent years. The technical basis for ambient temper bead welding has been well documented in EPRI Reports GC-111050 and 1013558. With respect to ASME Section XI Code Case N-740-1, the ambient temperature temper bead techniques of Appendix 1 have been tailored for WOLs. That said, the impact testing protocol of Appendix 1 is very similar to that of ASME Section III, NB-4335 as noted below:

- Both codes use the welding procedure requirements and variables of ASME Section IX as a basis for qualification.
- Both codes require that test coupon materials for the procedure qualification be of the same P-No. and Group No. as that to be welded in production.
- Both codes require that the test coupon base material meet the impact test requirements of the Construction Code (if applicable).
- Both codes exempt austenitic and nonferrous base materials and weld metal from impact testing.
- Both codes require that the test coupon weld be oriented in a direction parallel to the principle direction of rolling or forging when the test material is in the form of a plate or forging.
- Both codes require qualification on a groove weld test coupon.
- Both codes require that Cvn testing be performed in accordance with SA-370 and that each test consist of a set of three 10mm x 10mm specimens that comply with Figure 11, Type A.
- Both codes require that HAZ impact specimens be taken transverse to the axis of the weld and etched to define the HAZ.
- Both codes require that notch of the Cvn specimens be cut approximately normal to the material surface in such a manner as to include as much HAZ as possible in the resulting fracture.

- Both codes require that the Cvn tests of the unaffected base material and weld HAZ be performed at the same temperature.
- The test protocol and acceptance standards described in Section 6.3.1 is used by both codes when testing the weld HAZ.

The impact testing requirements of Code Case N-740-1, Appendix 1 are very similar to those of ASME Section III, NB-4330 while the acceptance standards are identical. In both code applications, welding requirements are specified to ensure that the impact properties of the weld HAZ are equivalent or superior to those of the unaffected base material without the application of PWHT. In other words, the testing protocols of ASME Section III, NB-4330 and Code Case N-740-1 are designed to demonstrate that the welding variables of the proposed welding procedure do not result in degradation of base material impact properties within the within the weld HAZ.

6.4 References

6-1 ASME Section III, Code Case N-217-1, Post Weld Heat Treatment of Weld Deposit Cladding on Classes 1, 2, 3, MC, and CS Items, September 7, 1982.

6-2 ASME Section III, Subsection NB, 1989 Edition6-3 Code Case N-740-1, Dissimilar Metal Weld Overlay for Repair of Class 1, 2, and 3 Items.

7.0 DISCUSSION

This report is evaluating the application of austenitic overlays over P-1 carbon steel materials with respect to the need for PWHT. Three key questions have been examined as follows:

1. Does the HAZ produced in P-1 carbon steel materials by overlay welding have unacceptably low fracture toughness?
2. Is the HAZ produced in P-1 carbon steel materials by overlay welding susceptible to hydrogen delayed cracking?
3. Are the ASME construction code exemptions for P-1 carbon steel materials applicable to weld overlays?

Section 4.1 above thoroughly discusses the metallurgy of plain carbon steels – those unalloyed steels having less than 0.30 wt.% carbon. It was shown that ferritic steels having this composition will begin to reform the austenite phase when heated above the critical transformation temperature (1333ºF on an equilibrium basis and a little higher on dynamic heating). On cooling the transformed portions of the microstructure will retransform to mixtures of phases that depend upon how fast the material is cooled. The weld HAZ will cool faster than the original material since the mass of the material provides a rapid heat sink to dissipate the heat. Plain carbon steels (P-1) are simply too low in carbon and too lean in alloy content to be able to suppress the equilibrium phases sufficiently to harden (i.e., form martensite) for any reasonable quenching rate associated with weld HAZs. As a result, the martensite phase will not be present in sufficient quantities to have any practical consequence to degrade fracture toughness. Therefore, the fracture toughness in the weld HAZ will not be degraded from the substrate material.

The second question regards delayed cracking due to uptake of monotonic hydrogen into the HAZ matrix. Again, the HAZ will have insufficient hardening to produce a microstructure susceptible to hydrogen delayed cracking. The ductility of this material is simply too great to result in fissuring from the recombination of hydrogen within the microstructure. Any strain caused by recombination of atomic hydrogen is readily accommodated by the ductility of the carbon steel matrix even in the weld HAZ. In fact, if the hardness of the material is kept at or below R_C 35 even for materials having higher hardenability such as P-3 low alloy steels (see Section 4.2 and Section 4.4), hydrogen delayed cracking is not an issue. The ASME Code has long recognized this hardness threshold for susceptibility to hydrogen delayed cracking (see Section 6.0). The maximum hardness of weld HAZ in P-1 carbon steels is well below this hardness threshold. Therefore, hydrogen delayed cracking is not an issue for as-welded P-1 materials.

The ASME Construction Code has long recognized the lack of hardenability in P-1 carbon steel materials and provided PWHT exemptions for this material so long as certain requirements are met. These exemptions are conservative. Section 6.0 describes the exemptions in detail based upon base material thickness, nominal weld thickness, carbon content, and the potential application of elevated preheat. Section 6.0 also discusses the guidance provided by Code Case N-740-1 for applying the Construction Code PWHT exemptions to WOLs. The code case guidance is conservative, technically sound, and based on years of WOL and PWHT experience. WOLs do not have excavated depth, and so the only zone of that can be affected during installation is the weld HAZ of the ferritic base material beneath the WOL. Because the weld HAZ depth is on the order of 0.10 to 0.15 inch for overlay welding processes such as GTAW, only the first three layers or 1/8 of WOL thickness can affect the ferritic base material properties and microstructure.

Finally, welding procedure impact testing requirements were reviewed. It was shown that the impact testing requirements of Code Case N-740-1, Appendix 1 applicable to ambient temperature temper bead welding are similar to those of ASME Section III, NB-4330 while the acceptance standards are identical. In both code applications, welding requirements are specified to ensure that the impact properties of the weld HAZ are equivalent or superior to those of the unaffected base material without the application of PWHT. This fact is demonstrated by impact testing associated with the WOL welding procedure qualification.

8.0 SUMMARY AND CONCLUSIONS

This report provides a technical basis for applying the PWHT exemptions of the Construction Code such as ASME Section III to WOLs involving P-1 base materials. These PWHT exemptions have been used historically by the industry when applying WOLs over DMWs involving ferritic materials. In fact, the very reason that WOLs involving P-3, Group 3 vessel nozzles are applied using an ambient temperature temper bead weld process is that there are no PWHT exemptions for welding on P-3, Group 3 materials in ASME Section III. So, these PWHT exemptions are still being used today.

This report has addressed the metallurgical and welding issues associated with exempting P-1 materials from PWHT and including: (1) relevance of the PWHT exemptions to weld overlays over P- 1 materials, (2) hardenability of P-1 materials, differences in restraint and residual stress in a butt weld or butt weld repair and a WOL, (3) differences/similarities in the qualification of an ambient temperature temperbead welding procedure and a standard welding procedure qualified per ASME Sections III and IX (i.e. impact testing requirements, etc.) and the resultant effect on microstructure of weld overlays, (4) hydrogen cracking issues or concerns, (5) industry experience with welding of P-1 materials using the current ASME Sections III and XI rules.

The reviews clearly show that PWHT is not required for P-1 carbon steel substrates. The ASME Code has conservatively limited the base material thicknesses of components and nominal thicknesses of welds as noted in Table NB-4622.7(b)-1 (see Section 6). No further conservatism is believed to be warranted. This conclusion is based upon the following:

- The hardenability of P-1 carbon steel is insufficient to produce an as-welded HAZ having degraded fracture toughness.
- The hardness of the as-welded HAZ in P-1 carbon steel is too low to be susceptible to hydrogen delayed cracking
- The ASME construction code applies to weld overlays and exempts P-1 materials from PWHT.

- The service history of carbon steel components fabricated to the rules of the ASME construction code (including the PWHT exemptions for P-1 materials) have been exceptional and provided safe operation.

This report has demonstrated that a strong technical basis exists and a clear construction code exemption exists to justify the application of the Code Case N-740-1 PWHT exemptions for austenitic WOLs applied to P-1 substrates. Since PWHT is not required, then neither are temperbead welding procedures and rules that govern the application of temperbead.