Proposed Alternative
In accordance with 10 CFR 50.55a(z)(1)
Alternative Provides Acceptable Level of Quality and Safety

1. **ASME Code Component Affected:**

Components:	Reactor Vessel Bottom Head (RVBH) Bottom Mounted Instrumentation (BMI) Nozzles #48, #35, and #30
Code Class:	ASME Section III Class 1
Examination Category:	B-P, American Society of Mechanical Engineers (ASME) Code Section XI
Code Item Number:	B15.10, Table IWB-2500-1 (B-P) B15.80, Code Case N-722-1, Table 1

There are 58 RVBH BMI nozzles welded to the inside surface of the RV with partial penetration J-groove welds.

2. **Applicable Code Edition and Addenda:**

Callaway's Inservice Inspection (ISI) Program complies with the 2019 Edition of the ASME Boiler and Pressure Vessel Code (BPVC), Section XI.

Callaway's fifth ISI interval began December 19, 2024, and ends on December 18, 2036. Callaway moved from the ten- to the twelve-year ISI interval as allowed by ASME Code Case N-921.

The Code of Construction for the reactor vessel is ASME Code Section III, 1971 Edition with Addenda through Winter 1972.

The Code of Construction for the reactor vessel BMI nozzle repair modification installation is ASME Code, Section III, 2015 Edition.

3. **Applicable Code Requirement:**

IWA-4411, *Welding, Brazing, Fabrication, and Installation*, states, in part, "*(e)* The requirements of IWA-4600(b) may be used when welding is to be performed without the post-weld heat treatment required by the Construction Code."

IWA-4600, *Alternative Welding Methods*, states, in part, "*(b)* When post-weld heat treatment is not to be performed, the following provisions may be used."

Section XI Code Case N-638-11, *Similar and Dissimilar Metal Welding Using Ambient Temperature Machine GTAW Temper Bead Technique Section XI, Division I*

Paragraph 4(a)(2) states, in part, "When austenitic materials are used, the completed weld shall be nondestructively examined after the three tempering layers (i.e., layers 1, 2, and 3) have been in place for at least 48 hr."

4. **Reason for Request:**

On May 6, 2025, during Callaway's refueling outage (RFO), Quality Control inspectors were performing a visual (VT-2) exam of the reactor vessel bottom head (RVBH) bottom mounted instrument (BMI) nozzles. During this exam, the inspectors identified dry white residue, resembling boric acid, coming from the annulus between BMI Nozzle #48 and the penetration through the RVBH. (See Figure 4-1.) The area was cleaned, with no active boric acid leak observed, and the condition was entered into Callaway's Corrective Action Program. Additionally, operators transitioned the plant back down to cold shutdown to satisfy reactor coolant system (RCS) operational leakage Technical Specification requirements.

As part of the extent-of-condition investigation, ultrasonic testing (UT) and visual (VT-1) exams are being performed on all 58 BMI nozzles. It has been determined, from the analysis of the UT and VT-1 data to date that three RVBH BMI nozzles require repair. It is noted that the flaw mechanism(s), as described within this relief request, are preliminary and not conclusive. Further, Ameren will be proposing an alternative (i.e., one-cycle justification), in a separate relief request, related to ASME Section XI Code requirements on flaw indications identified in the BMI nozzles, which is not within the scope of this relief request.

- BMI Nozzle #48: UT data shows weld fabrication flaws in the partial penetration J-groove weld, which have not propagated into the nozzle tube material. Therefore, the most likely leak path is through the annulus between the outer diameter of the BMI nozzle tube and inside surface of the RVBH bore hole.

- BMI Nozzle #35: UT data shows an indication in the partial penetration J-groove weld, which has propagated into the nozzle tube material. The indications are consistent with stress corrosion cracking (SCC).

- BMI Nozzle #30: UT data shows an indication in the partial penetration J-groove weld, which has slightly propagated into the nozzle tube material. The indications are consistent with SCC. UT data shows that the SSC indication is also located within a grouping of J-groove weld fabrication flaws.

Figure 4-3 depicts the locations of the BMI nozzles.

As a result of the RCS leakage and UT data, Ameren will be performing a half-nozzle repair modification of BMI Nozzles #48, #35, and #30 using ASME Section XI, Code Case N-638-11, and ASME Section III. Figure 4-1 depicts the existing configuration of the BMI Nozzles. The modification will consist of removing the lower portion of the existing Alloy 600 nozzle, applying an Alloy 52M weld pad on the outer surface of the RVBH, and installing a replacement Alloy 690 nozzle with an Alloy 52M partial penetration J-groove weld. Figure 4-2 depicts the planned BMI nozzle modification. The new weld pad will be welded to the outer surface of the RVBH using machine Gas Tungsten Arc Welding (GTAW) Ambient Temperature Temper Bead (ATTB) welding with inert shielding gas. The new Alloy 690 half nozzle will be inserted into the bore and welded to the Alloy 52M weld pad with an Alloy 52M partial penetration J-groove weld using a manual GTAW welding technique. As a result of this modification, the BMI nozzle penetration pressure boundary will move from the original construction partial penetration J-groove weld that is inside the RVBH to the new partial penetration J-groove weld outside the RVBH.

As stated above, installation of the new weld pad using ATTB welding will be in accordance with ASME Code Case N-638-11. The NRC approved Code Case N-638-11 in Reg. Guide 1.147, Revision 21, to allow ATTB welding with austenitic filler materials within 1/8-inch of or on ferritic materials without the requirement for preheat or post-weld heat treatment (PWHT). Code Case N-638-11 requires that the three tempering weld layers be in place for at least 48 hours prior to performance of surface and volumetric non-destructive examination (NDE). However, for the modification of BMI nozzles #48, #35, and #30, liquid penetrant and ultrasonic acceptance examinations will be performed before the 48-hour period ends. Technical justification for austenitic filler materials has been developed to allow the NDE methods to be performed after completion of the weld modification, without waiting for the 48-hour hold time.

Figure 4-1
Bottom Mounted Nozzle No. 48 – Existing Configuration

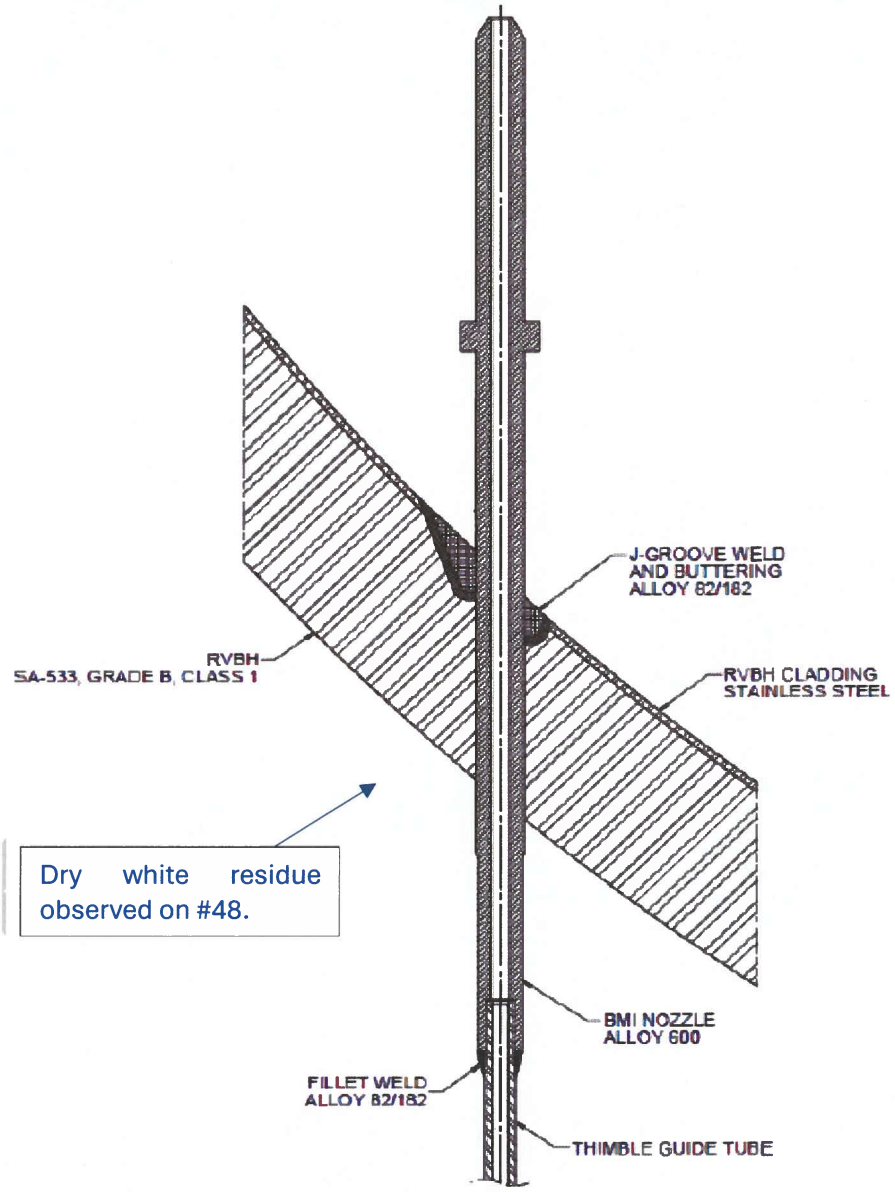


Figure 4-2
Bottom Mounted Nozzle No. 48 – Modified Configuration

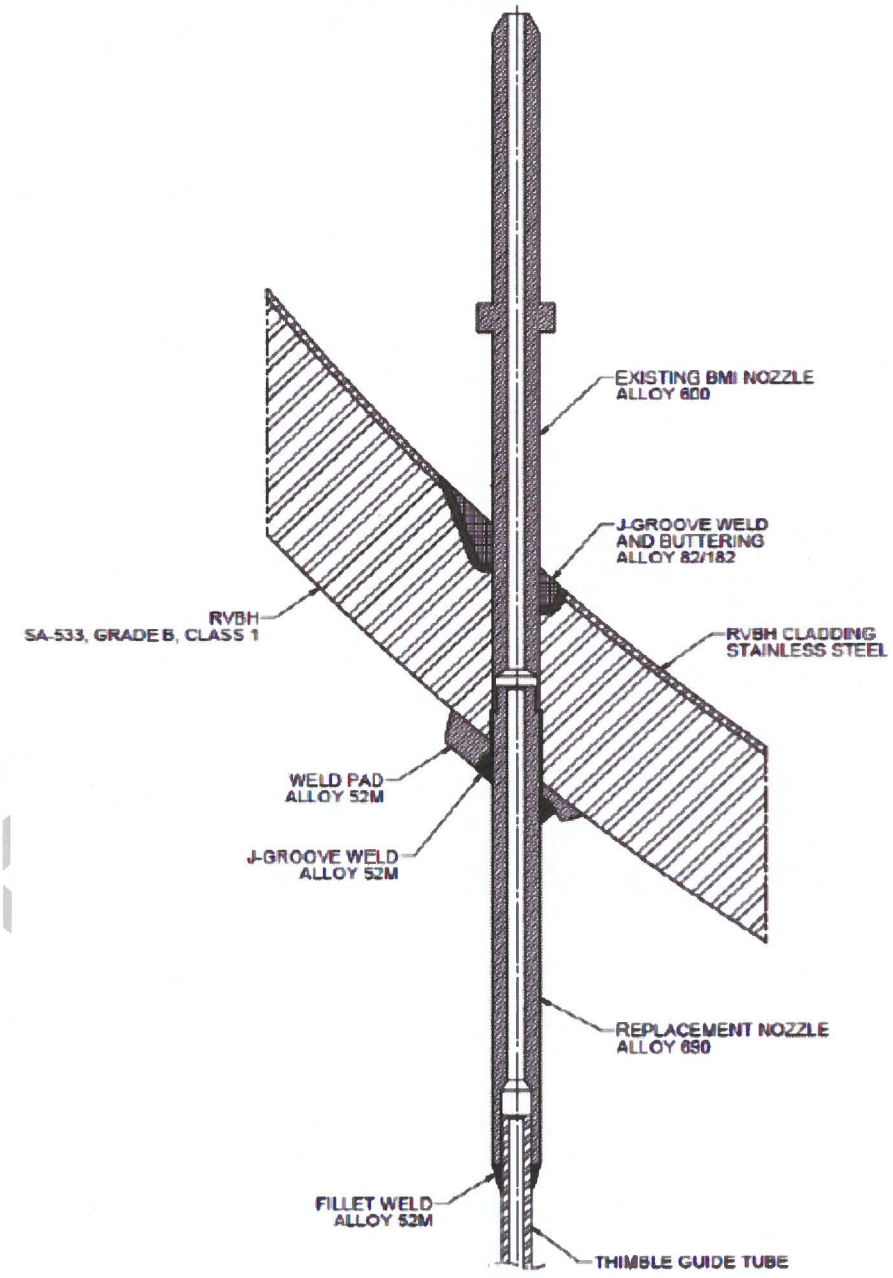
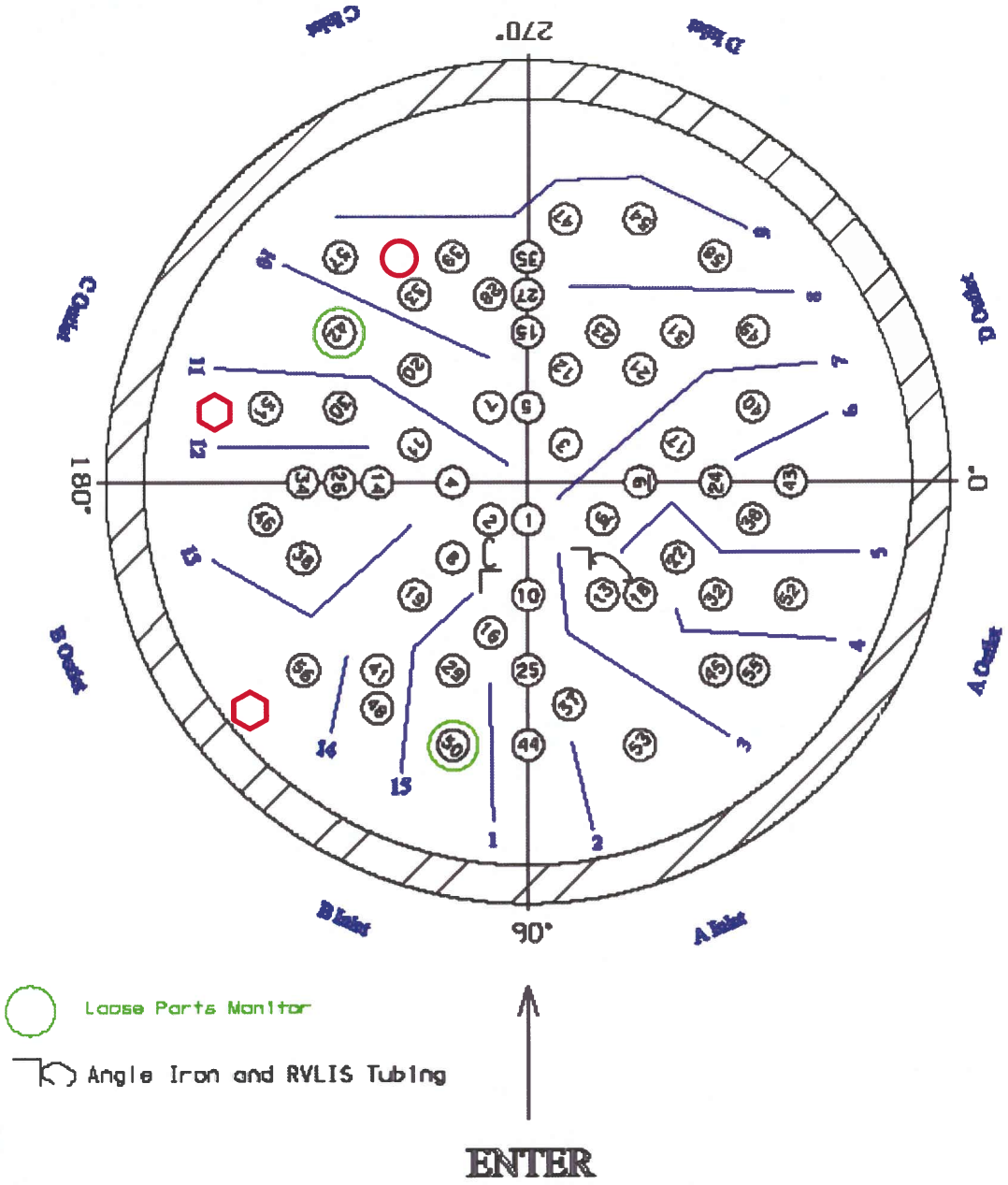


Figure 4-3
Bottom Mounted Nozzle Locations



5. Proposed Alternative and Basis for Use:

Proposed Alternative

In accordance with 10 CFR 50.55a, "Codes and Standards," paragraph (z)(1), Ameren proposes an alternative to the Section XI Code Case N-638-11 requirement on the basis that the alternative provides an acceptable level of quality and safety. Specifically, Ameren proposes an alternative to Case N-638-11, Paragraph 4(a)(2), that requires a 48-hour hold time prior to performing NDE as described below.

Ameren is installing a weld pad using ATTB welding in accordance with ASME Case N-638-11. The NRC has approved ASME Case N-638-11 in Reg. Guide 1.147, Revision 21, to allow ATTB welding of dissimilar materials. The weld pad will consist of a minimum of three (3) layers of Austenitic Nickel-Alloy 52M (SFA-5.14, ERNiCrFe-7A) filler material in accordance with the temper bead requirements in Case N-638-11. Liquid penetrant surface and UT volumetric examination of the completed weld pad will be performed in accordance with ASME Section III acceptance criteria after the weld pad has been prepared for NDE and dimensionally inspected. In lieu of performing the required NDE at least 48 hours after the three tempering layers have been installed, Ameren proposes to perform the NDE methods after completion of the weld pad. See "Basis for Elimination of the Ambient 48-Hour Hold Time" below.

Planned Repair Steps

The planned steps of the proposed repairs of BMI Nozzles #48, #35, and #30 are described below. This plan may change due to varying conditions present during the work. Changes to the plan detailed below will remain in compliance with applicable Code requirements.

1. Sever nozzle and thimble guide tube.
2. Clean and perform surface and volumetric exams of weld pad region.
3. Machine to thin existing Alloy 600 nozzle, as specified in final implementing drawings.
4. Roll expand the existing Alloy 600 nozzle (optional).
5. Machine original RVBH bore to remove the lower portion of the existing Alloy 600 nozzle.
6. Clean RVBH bore.
7. Clean weld dam and install in RVBH bore.
8. Deposit new Alloy 52M weld pad, as specified in final implementing drawings.
9. Perform surface and volumetric exams on new Alloy 52M weld pad.
10. Install wedge dam.
11. Machine and clean final RVBH bore.
12. Form J-groove weld prep on new Alloy 52M weld pad.
13. Perform surface exam on J-groove weld prep and machined RVBH bore.
14. Clean J-groove weld prep and RVBH bore, and insert Alloy 690 nozzle in RVBH bore.
15. Weld the replacement Alloy 690 nozzle to new Alloy 52M weld pad.

16. Perform progressive surface exams as the J-groove weld is deposited, to include a final surface exam.
17. Prep end of thimble guide tube.
18. Weld replacement Alloy 690 nozzle to thimble guide tube and thimble guide tube to coupling.

Basis for Elimination of the Ambient 48-Hour Hold Time

Elimination of the 48-hour hold is based on Attachment 1, and is from a white paper presented at a 2023 ASME Pressure and Vessels & Piping Conference, titled, "PVP 2023-107489: Elimination of the 48-hour Hold for Ambient Temperature Temper Bead Welding with Austenitic Weld Metal," which was developed for the proposed change to ASME Code Case N-888-1. Although Code Case N-888-1 is not approved in Reg. Guide 1.147, Revision 21, it has been approved by the ASME Section XI Standards Committee. Code Case N-888 is the culmination of temper bead Code Cases that have been produced thus far, combining requirements from N-638, N-839, and Appendix I in Code Cases such as N-740 and N-754, etc. Therefore, justification is also applicable to the planned use of Code Case N-638-11 at Callaway Plant Unit 1 (with this exception).

Conclusion

The ATTB technique is an effective tool for performing repairs on carbon and low alloy steel (P-No. 1 and P-No. 3) materials. Code Case N-638-11 provisions allow for ambient temperature temper bead welding with no PWHT. However, the 48-hour hold prior to performing the final weld acceptance NDE has remained a Case requirement. Attachment 1 summarizes the technical basis to eliminate the 48-hour delay for examining temper bead welding when using austenitic filler materials. The data and testing performed shows that when austenitic weld metal is used, the level of diffusible hydrogen content in the ferritic base metal heat affected area (HAZ) is too low to promote hydrogen-induced cracking (HIC). Therefore, the 48-hour hold requirement in Code Case N-638-11 is not necessary prior to examination of the weld as HIC is not considered credible for the described application.

6. Duration of Proposed Alternative

The relief request will remain in effect until Callaway's end of plant life.

7. Precedents

- Arizona Public Service Company (APS) letter, "Palo Verde Nuclear Generating Station, Unit 1 – Relief Request 76 – Proposed Alterative for Pressurizer Lower Shell Nozzle," dated April 23, 2025 (ADAMS Accession No. ML25113A296)

- Arizona Public Service Company (APS) letter, "Palo Verde Nuclear Generating Station, Unit 1 – Relief Request 70 – Proposed Alternative for Pressurizer Lower Shell Temperature Nozzle," dated October 23, 2023 (ADAMS Accession No. ML23296A254)

  - NRR E-mail Capture, "Subject: Palo Verde Unit 1 – Verbal Authorization of Relief Request 70, Proposed Alternatives for Pressurizer Lower Shell Temperature Nozzle (EPID L-2023-LLR-0057)," dated October 27, 2023 (ADAMS Accession No. ML23303A011)
  - NRC Safety Evaluation letter, "Palo Verde Nuclear Generating Station, Unit 1 Re: Relief Request 70 – Proposed Alternatives for Pressurizer Lower Shell Temperature Nozzle (EPID L-2023-LLR-0057)," dated September 9, 2024 (ADAMS Accession No. ML24197A199).

- Energy Harbor Nuclear Corporation letter, "Beaver Valley Power Station, Unit No. 2 – 10 CFR 50.55a Request 2-TYP-4-RV-06 for Alternative Repair Methods for Reactor Pressure Vessel Head Penetrations," dated April 28, 2023 (ADAMS Accession No. ML23118A381)
  - NRR E-mail Capture, "Subject: Beaver Valley Unit 2 – Verbal Authorization of Alternative Request, 2-TYP-4-RV-06 (EPID: L-2023-LLR-0021)," dated May 9, 2023 (ADAMS Accession No. ML23129A312)

- Constellation Energy Generation, LLC letter, "Submittal of Emergency Relief Request I5R-11 Concerning the Installation of a Weld Overlay on Reactor Pressure Vessel Recirculation Inlet Nozzle N2E Safe End-to-Nozzle Dissimilar Metal Weld (32-WD-208)," dated March 24, 2023 (ADAMS Accession No. ML23083B991)
  - NRR E-mail Capture, "Subject: Verbal Approval for NMP1 Proposed Alternative Weld Overlay N2E Safe-end to nozzle DM weld (EPID L-2023-LLR-0011)," dated March 31, 2023 (ADAMS Accession No. ML23090A130)

8. References

ASME Code, Section XI, "Rules for Inspection and Testing of Components of Light-Water-Cooled Plants, Division 1, 2019 Edition."

ASME Code, Case N-638-11, "Similar and Dissimilar Metal Welding Using Ambient Temperature Machine GTAW Temper Bead Technique, Section XI, Division 1," dated August 2, 2019.

Attachment 1
Ambient Temperature Temper Bead- Elimination of 48-Hour Hold Time from N-888 When using Austenitic Filler Material

White Paper

Introduction and Background

In welding, the presence of hydrogen in the weld metal or heat affected zone (HAZ) can cause hydrogen-induced cracking (HIC) occurring phenomena that occurs after the weldment has cooled to at or near room temperature. HIC is largely dependent upon three main factors: diffusible hydrogen, residual stress and susceptible microstructure. There are many theories on the mechanism for HIC, however, it is well understood that HIC requires simultaneous presence of a threshold level of hydrogen, a susceptible brittle microstructure and tensile stress. Additionally, the temperature must be in the range of 32 to 212°F (0 to 100°C). Elimination of just one of these four contributing factors will prevent HIC. [1]

Two early overlay (WOL) repairs involving temper bead welding were applied to two core spray nozzle-to-safe end joints at the Vermont Yankee boiling water reactor (BWR) in 1986 to mitigate intergranular stress corrosion cracking [2]. To avoid post weld heat treatment, temper bead was deployed when installing the repair overlay on the low alloy steel SA-508 Class 2 (P- No. 3 Group 3) reactor pressure vessel nozzle. This early application of temper bead welding required elevated preheat and a post weld hydrogen bake.

As the industry experienced an increased need for temper bead welding the requirement for preheating and post weld bake made temper bead welding complicated. EPRI responded to the industry concern and conducted studies that demonstrated that repair to low alloy steel pressure vessel components could be made without the need for preheat or post weld bake [3,4]. As a result of these studies the preheat and post weld bake requirements were not included in Case N-638 for ambient temperature temper bead welding with machine GTAW.

Deployment of the ambient temperature temper bead technique has been highly successful for many years with no evidence of HIC detected by nondestructive examination (NDE). During the past twenty years, many temper bead weld overlay repairs were successfully performed on BWRs and PWRs using ambient temperature temper bead technique, as illustrated in Table 1. The operating experience shows that with hundreds of ambient temperature temper bead applications, there has not been a single reported occurrence of hydrogen induced cracking.

Case N-888 is the culmination of temper bead code cases that have been produced over the years, combining requirements from N-638, N-839, and Appendix I in cases such as N-740 and N-754, etc. Case N-888 applies to temper bead of P-No. 1 or P-No. 3 materials and their associated welds or welds joining P-No. 8 or P-No. 43 materials to P- No. 1 or P-No 3 materials. Additionally, Case N-888 provides provisions to allow for ambient temperature preheat with no post weld bake. However, the post weld 48-hour hold at ambient temperature has remained as a requirement in N-888. This 48-hour delay between welding completion and cooling to ambient temperature and the final nondestructive examination (NDE) of the fully welded component is intended to assure detection of delayed hydrogen cracking that is known to occur up to 48-hours after the weldment is at ambient temperature.

The post weld 48-hour delay following cooling to ambient temperature has resulted in a considerable cost burden to utilities. As there are significant economic advantages associated with eliminating the 48-hour hold time and immediately performing NDE following the completed weld, it is important to determine the technical advantages and disadvantages of making such a change.

Table 1: Successfully Implemented Repairs Completed Using Temper Bead Technique from 2002-2021

Date	Plant	Component (Qty.)
2002	Oconee[1]	Mid-Wall RVH Repair (15)
2002	ANO[1]	Mid-Wall RVH Repair (6)
2002	Oyster Creek[2]	Recirculation outlet nozzle (1)
2002	Peach Bottom Units 2 & 3[2]	Core spray, recirculation outlet, and CRD return nozzles
2002	Calvert Cliff[2]	Heater Sleeve Repairs (Pads) (~50)
2002	Oconee[1]	Mid-Wall RVH Repair (2)
2002	Davis-Besse[1]	Mid-Wall RVH Repair (5)
2002	Millstone[1]	Mid-Wall RVH Repair (3)
2003	Palo Verde 1[2]	Heater Sleeve Repairs -Pads (36)
2003	Pilgrim[2]	Core spray nozzle and CRD return nozzle
2003	TMI Unit 1[2]	Hot leg and Surge line nozzle
2003	Ringhals[1]	1/2 Nozzle with Structural Pad (2)
2003	Crystal River[1]	1/2 Nozzle with Structural Pad (3)
2003	South Texas[1]	1/2 Nozzle with Structural Pad (2)
2003	Millstone[1]	Mid-Wall RVH Repair (8)
2003	St. Lucie[1]	Mid-Wall RVH Repair (2)
2004	Palo Verde 2[2]	Heater Sleeve Repairs -Pads (34)
2004	Susquehanna Unit 1[2]	Recirculation inlet and outlet nozzles
2004	Hope Creek[1]	SWOL (1)
2004	Palisades[1]	Mid-Wall RVH Repair (2)
2004	Point Beach[1]	Mid-Wall RVH Repair (1)
2004	ANO[1]	Mid-Wall RVH Repair (1)
2005	Palo Verde 3[2]	36 Heater Sleeve Repairs – Pads (36)
2005	ANO[2]	Mid Wall heater sleeve repair
2005	Waterford[2]	Mid Wall heater sleeve repair
2005	Calvert Cliffs Unit 2[2]	Hot Leg Drain and Cold Leg Letdown Nozzles
2005	DC Cook Unit 1[2]	Pressurizer Safety Nozzle
2005	TPC Kuosheng[2]	N1 Nozzle
2005	SONGS 3[2]	Heater Sleeve Repairs -Pads (~29)
2005	Three Mile Island[1]	SWOL (1)
2005	St. Lucie[1]	Mid-Wall RVH Repair (3)
2006	SONGS 2[2]	Heater Sleeve Repairs -Pads (~30)
2006	Davis Besse[2]	Hot and Cold Leg
2006	SONGS 2[2]	Pressurizer Nozzles (6)
2006	Millstone 3[2]	Pressurizer Nozzles (6)
2006	SONGS 3[2]	Pressurizer Nozzles (6)
2006	Oconee 1[2]	Pressurizer Nozzles (6)
2006	Beaver Valley 2[2]	Pressurizer Nozzles (6)
2006	Byron 2[3]	Pressurizer Nozzles (6)
2006	Wolf Creek[3]	Pressurizer Nozzles (6)
2006	McGuire[2]	Pressurizer Nozzles (6)
2006	DC Cook[1]	SWOL (4)
2007	Callaway[3]	Pressurizer Nozzles (6)
2007	St. Lucie[1]	SWOL (4)
2007	Crystal River[1]	SWOL (4)
2007	Three Mile Island[1]	SWOL (4)
2007	North Anna[1]	SWOL (4)
2008	Prairie Island[1]	SWOL (1)
2008	Diablo Canyon[1]	SWOL (6)
2008	Diablo Canyon[1]	SWOL (4)
2008	Seabrook[1]	SWOL (4)
2009	Three Mile Island[1]	SWOL (1)
2009	Three Mile Island[1]	Full Nozzle with Structural Pad (1)

Date	Plant	Component (Qty.)
2009	Crystal River[1]	SWOL (1)
2009	Palisades[1]	Mid-Wall RVH Repair (2)
2010	Oconee[4]	U3 Letdown WOL (1)
2010	Krsko[1]	SWOL (5)
2010	Tihange[1]	SWOL (1)
2010	Davis-Besse[1]	Mid-Wall RVH Repair (24)
2011	Hatch[4]	Nozzle WOL (1)
2011	Talen Energy Corporation[4]	N5 core spray nozzles
2011	Monticello[4]	Emergent WOL (1)
2011	Three Mile Island[4]	TMI PZR Spray Nozzle (1)
2011	Doel[1]	SWOL (1)
2011	Tihange[1]	SWOL (1)
2011	St. Lucie[1]	1/2 Nozzle with Structural Pad (30)
2012	North Anna[4]	SG Nozzle WOLS (3)
2012	Palo Verde[4]	Small Bore CL Nozzles WOL
2012	Grand Gulf[4]	Reactor Vessel Nozzle Contouring and N6 Weld Overlay
2012	Doel[1]	SWOL (1)
2012	Calvert Cliffs[1]	Mid-Wall Przr Heater Repair (119)
2012	Quad Cities[1]	1/2 Nozzle with Structural Pad (1)
2012	Harris Nuclear Plant[1]	Mid-Wall RVH Repair (4)
2013	Farley[4]	Unit 2 FAC Pipe Replacement and WOL
2013	Oconee[4]	Hot/Cold Leg Small Bore Alloy 600
2013	Hope Creek[4]	Emergent N5A WOL
2013	Three Mile Island[1]	SWOL (1)
2013	Palo Verde[1]	1/2 Nozzle with Structural Pad (1)
2013	Harris Nuclear Plant[1]	Mid-Wall RVH Repair (2)
2015	Harris Nuclear Plant[1]	Mid-Wall RVH Repair (3)
2015	Hatch[4]	N4A WOL
2015	Millstone[4]	2" Drain WOL
2015	Hatch[4]	Recirc (N2) WOL
2016	Harris Nuclear Plant[1]	Mid-Wall RVH Repair (4)
2017	Fitzpatrick[4]	RHR WOL
2017	Limerick[1]	1/2 Nozzle with Structural Pad (1)
2018	Waterford[4]	Emergent Drain Nozzle WOLs (2)
2018	Palisades[1]	Mid-Wall RVH Repair (3)
2018	Doel[1]	Mid-Wall RVH Repair (16)
2018	Harris Nuclear Plant[1]	Mid-Wall RVH Repair (1)
2018	Brunswick[1]	SWOL (2)
2020	Peach Bottom[1]	1/2 Nozzle with Structural Pad (1)
2020	Palisades[1]	Mid-Wall RVH Repair (2)
2021	Oconee[4]	Complex nozzle pads on RCS piping
2021	ANO-2[1]	Mid-Wall RVH Repair (1)

Notes: Operating experience provided by Steve McCracken (EPRI), Darren Barborak (EPRI, formerly with AZZ), and Travis Olson (Framatome)

(1) Framatome
(2) Unknown
(3) PCI
(4) AZZ Specialty Welding

Objective

The objective of this white paper is to provide technical justification to eliminate the 48- hour delay when using austenitic filler materials in the temper bead welding process for P-No. 1 and P-No. 3 ferritic materials. The industry and regulatory technical concerns related to this change are examined and the technical bases for changing the requirements for the 48-hour delay are presented. Discussion from white paper for *Ambient Temperature Temper Bead Weld Overlay Gas Tungsten Arc Welding* by Hermann and Associates [9] are included in this white paper.

If adopted, it is expected that the change in the 48-hour delay requirement will become part of a revision to the current ASME Section XI Case N-888 that currently allows for ambient temperature temper bead repairs but requires 48-hour delay after the initial three temper bead layers prior to final NDE.

Technical Issues Related to the 48-Hour Delay

The reason for performing the final NDE after the 48-hour delay is the recognition that alloy steels can become susceptible to HIC. There are two primary weld cracking mechanisms of concern for low alloy steels during cooling or after reaching ambient temperature. These are cold cracking of high restraint geometries (weld shrinkage- induced) and hydrogen induced cracking (HIC), often referred to as hydrogen delayed cracking. Cold cracking occurs immediately as the weldment cools to ambient temperature. In contrast, HIC can occur immediately during cooling to ambient temperature or up to 48-hours after reaching ambient temperature. Cold cracking that occurs with high restraint weldments would therefore be detected by NDE performed immediately after the weldment is complete.

EPRI studies [4] have indicated that cold cracking occurs under conditions of high geometrical restraint especially where low toughness HAZs are potentially present.

Restraint mechanisms can occur either hot (resulting in intergranular or interdendritic cracking), or cold (resulting in transgranular cracking of material having marginal toughness). Cold cracking occurs immediately as the weld deposit cools to ambient temperature. Proper joint design, appropriate welding procedures and bead sequences, are practical solutions that avoid critical cold cracking conditions. This form of cracking is addressed effectively by the ASME code guidance including welding procedure qualification testing and by in-process and / or post-weld inspections.

The other form of cracking at ambient temperature, which is the focus of this white paper, is HIC. This cracking mechanism manifests itself as intergranular cracking of prior austenite grain boundaries and in contrast to cold cracking generally occurs during welding, but also up to 48-hours after cooling to ambient temperature. It is produced by the action of internal tensile stresses acting on low toughness HAZs (generally characterized by inadequate tempering of weld related transformation products). The most widely accepted theory suggests that the internal stresses will be produced from localized buildup of monatomic hydrogen. Monatomic hydrogen can be entrapped during weld solidification, and will tend to migrate, over time, to prior austenite grain boundaries or other microstructure defect locations. As concentrations build, the monatomic hydrogen will recombine to form molecular hydrogen, thus generating highly localized internal stresses at these internal defect locations. Monatomic hydrogen is produced when moisture or hydrocarbons interact with the welding arc and molten weld pool.

The concerns with, and driving factors that cause hydrogen induced cracking, have been identified. These issues are fundamental welding and heat treatment issues related to temper bead welding, requiring a technical resolution prior to modification of the current ASME Code Cases N-888 by the ASME Code and the technical community. Specific concerns relate to the following issues:

-Microstructure

-Sources for Hydrogen Introduction

-Diffusivity and Solubility of Hydrogen

In the following discussion of this white paper each of these factors is briefly described to provide insight into the impact and proper management of these factors that cause HIC.

Discussion of Technical Issues Related to the 48-Hour Delay

Microstructure:

C-Mn and low alloy steels can have a range of weld microstructures which is dependent upon both specific composition of the steel and the welding process/parameters used. Generally, untempered martensitic and untempered bainitic microstructures are the most susceptible to hydrogen cracking. These microstructures are produced when rapid cooling occurs from the dynamic upper critical (Ac3) transformation temperature [1]. Generally, a critical hardness level necessary to promote hydrogen cracking is on the order of Rc 35 for materials with high hydrogen and Rc 45 for low level of hydrogen. Maintaining hardness levels below these thresholds generally avoids hydrogen cracking [1].

EPRI has examined in detail the effects of welding on the hardening of low alloy steels. The microstructure evaluations and hardness measurements discussed in EPRI reports [4, 5, 6] have described the effects of temper bead welding on the toughness and hardness of P-No. 3 materials. The research results have illustrated that the microstructure in the low alloy steel (P-No. 3) beneath the temper bead WOL in the weld HAZ consists of a structure that is tempered martensite or tempered bainite and has maximum hardness at a distance of 2 to 3 mm (80 to 120 mils) beneath the surface of the order of 280 to 300 KHN (28 to 30Rc) or lower. The research outlines that the microstructure resulting from temper bead welding is highly resistant to HIC. Additionally, hardness would not be a concern provided there are adequate hydrogen controls in place.

Furthermore, materials having face-centered-cubic (FCC) crystal structures such as austenitic stainless steels (300 series) and nickel base alloys such as Inconel are not susceptible to hydrogen induced cracking. The reason is that FCC atomic structures have ample unit cell volume space to accommodate atomic (diffusible) hydrogen. It is noted that the diffusion of hydrogen at a given temperature is slightly higher in body-centered- cubic (BCC) materials, ferritic steels, than it is in FCC austenitic materials. The FCC crystal structure has increased capacity to strain significantly without cracking (ductility) providing acceptable levels of toughness capable of resisting HIC. The inherent ability to deform and accommodate diffusible hydrogen are the reasons austenitic stainless steel and nickel base coated electrodes do not have low hydrogen designators that are found for ferritic weld materials [6]. Since the ferritic HAZ is in a tempered condition and an FCC filler material is used, a susceptible microstructure susceptible to HIC is highly unlikely.

Presence/sources of Hydrogen:

Hydrogen can be introduced into the weld from several sources. These include 1) hydrogen in the original base material, 2) moisture in electrode coatings and fluxes,
3) organic contaminants (grease or oils), 4) hydrogen in the shielding gas and 5) humidity in the atmosphere.

The reduction of diffusible hydrogen in temper bead and non-temper bead weldments begins with implementing low hydrogen weld practices. These practices originate with Federal requirements that nuclear utilities control special processes such as welding and design and fabricate components to various codes and standards. These requirements, when followed, will effectively eliminate the contamination, and minimize the environment pathways.

Cleanliness of surfaces to be welded are mandated by Code and subsequently implemented via adherence to sound welding programs. The controls and requirements for cleanliness of the welded surface at nuclear utilities significantly reduce the likelihood of hydrogen entering the weld from surface contamination. Furthermore, repair and replacement applications typically deal with components that have been at operating temperatures above 390°F (200°C) for many years and any hydrogen present in the base material would have diffused from the steel and escaped to the atmosphere. Thus, surface contaminants and the base materials are not expected to be a significant source of diffusible hydrogen.

For SMAW, main pathway for diffusible hydrogen to enter the weldment will be the electrode coating. Welding programs primarily maintain low moisture in electrode coatings through procurement via an approved supplier, controlled storage conditions, and conservative exposure durations. The conservative exposure duration and coatings that resist moisture uptake minimize the amount of additional moisture in the coated electrode taking into consideration that moisture uptake is a function

of time, temperature, and relative humidity. Extensive testing by the EPRI Welding and Repair Technology Center shows there is an extremely low probability of HIC with H4 and H4R electrodes. EPRI performed diffusible hydrogen analysis per AWS A4.3 via gas chromatography on thirteen commercially available electrodes. Electrodes with AWS E7018, E8018, and E9018 from multiple vendors exposed at 27°C at 80% relative humidity (HR) for exposure times from 0 to 72 hours. Many of the electrodes did not have "R" moisture resistant coating.

Figure 1 shows EPRI diffusible hydrogen test results for the thirteen lots of low hydrogen electrodes. All H4R electrodes exhibited < 16ml/100g of diffusible hydrogen at 72 hours of exposure. Figure 3 shows that new electrodes without exposure have < 2ml/100g diffusible hydrogen. Only one of the electrodes tested at the extremely aggressive 27°C and 80% Relative Humidity (HR) 72-hour exposure had diffusible hydrogen > 4 ml/100g. This demonstrates that exposure limits in the field of 24 hours or less is adequate to ensure electrodes maintain the H4R limit. Ferritic electrodes were verified to have less than 4ml/100g diffusible hydrogen [6]. Testing verifies that ambient temperature is acceptable, post weld hydrogen bakeout is not needed, and a 48 hour hold at ambient temperature prior to performing final NDE is unnecessary and diffusible hydrogen levels will be below any susceptibility threshold that supports HIC.

For GTAW, EPRI performed studies investigating the diffusion of hydrogen into low alloy pressure vessel steels [4]. Due to the little information published at the time, EPRI decided to generate experimental data that would provide information on the levels of diffusible hydrogen associated with GTAW welding. The experimentation included individual sets of diffusible hydrogen tests as follows:

1. determination of diffusible hydrogen levels for the GTAW process under severe welding and environmental conditions simulating (or exceeding) repair welding conditions which may be expected in a nuclear plant.
2. measurement of diffusible hydrogen levels for various shieling gas dew point temperatures
3. examination of diffusible hydrogen levels for modern off-the-shelf filler wires

Discussion of these items can be found in the EPRI documents and will not be reiterated in this report. The results demonstrate that introducing hydrogen is unlikely with the GTAW process. The typical hydrogen content for the GTAW process is less than 1.0mL/100g. Therefore, hydrogen cracking is extremely unlikely.

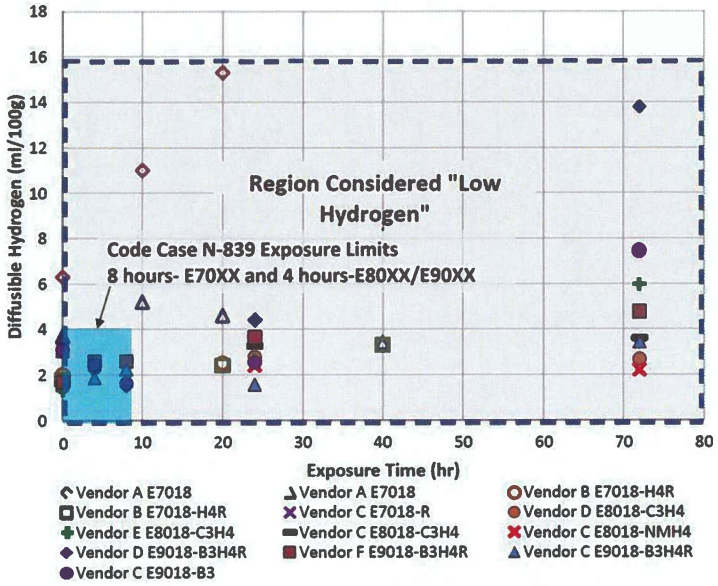


Figure 1. Results of EPRI diffusible hydrogen testing at 27°C 80% Relative Humidity (HR) for zero to 72 hours of exposure [6]

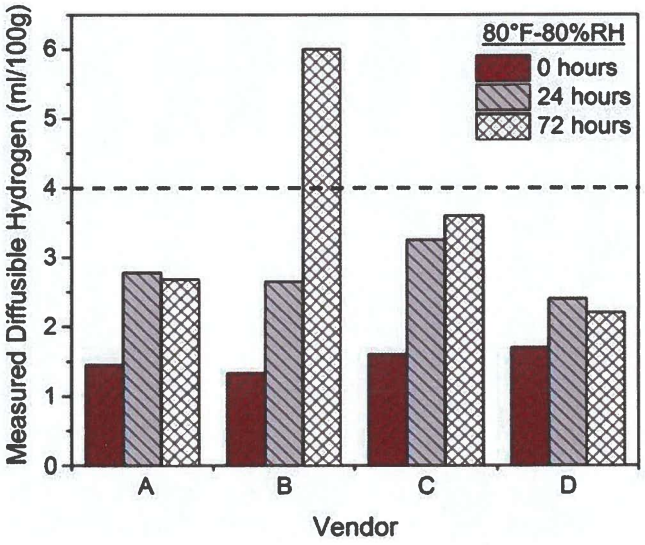


Figure 2. Graph showing slight increase of diffusible hydrogen after exposure of 24 and 72 hours [6]

Diffusivity and Solubility of Hydrogen

Diffusivity and solubility of hydrogen in ferritic, martensitic, and austenitic steels is an important factor to consider. Materials having face-centered-cubic (FCC) crystal structures such as austenitic stainless steels (300 series) and nickel base Inconels generally are not considered to be susceptible to hydrogen delayed cracking as discussed in the microstructure section, above. Additionally, due to the temperatures expected during the welding of the temper bead layers, and during the welding of any non-temper bead layers, the temperature should be sufficient for the hydrogen to diffuse out of the HAZ, either escaping the structure or diffusing into the austenite, where it can be held in much greater quantities. The diffusion rate is clearly from the ferrite to the austenite and whatever hydrogen remains will reside in the austenite, which has little to no propensity to hydrogen related cracking.

Use of fully austenitic weld metal on ferritic base material is a technique that has been used for decades to install welds on ferritic base materials with high potential of HIC. Austenitic filler materials are used in applications where preheat or post weld bake out is not possible because hydrogen (H^+) has high solubility, Figure 3, and low diffusivity, Figure 4, in austenite relative to other phases and acts as a trap for hydrogen to prevent HIC. Figure 3 shows the solubility of hydrogen in α-Fe and γ-Fe. Note that α-Fe is at the saturation limit at ~4ml/100g of hydrogen. At temperatures above ~1700° C the solubility of hydrogen in austenite (γ-Fe) is nearly five times that of ferrite (α-Fe). The benefit regarding HIC is the hydrogen stays in the austenite and is not available to promote HIC. Figure 4 shows the overall difference in hydrogen diffusion between ferritic and austenitic materials. The diffusion of hydrogen in ferritic material is orders of magnitude greater compared to austenite. Again, the obvious advantage regarding HIC prevention is the hydrogen is slow to diffuse out of the austenitic material. When comparing how hydrogen behaves in ferritic versus austenitic weldments the hydrogen stays within the austenitic material whereas in ferritic welds, it tends to diffuse into the base material. For a weld made with ferritic electrodes, the H^+ is absorbed in the molten weld puddle and as the weld solidifies, it transforms from austenite to ferrite and the H^+ is rejected and diffuses into the HAZ of the base material. When the HAZ transforms from austenite to martensite, the H^+ becomes trapped in the brittle microstructure and causes cracking, Figure 5. However, with an austenitic electrode, H^+ is absorbed in the molten weld puddle and there is no solid-state transformation in the solidified weld metal so the H^+ stays in the austenitic weld material. No diffusion of the H^+ into the brittle martensite, thus avoiding the possibility of HIC, Figure 6. Schematics in Figure 5 and Figure 6 are adapted from Lippold and Granjon as shown in draft chapters 2 & 4 for Temper Bead Welding Process in Operating NPP's, International Atomic Energy Agency, [1, 8].

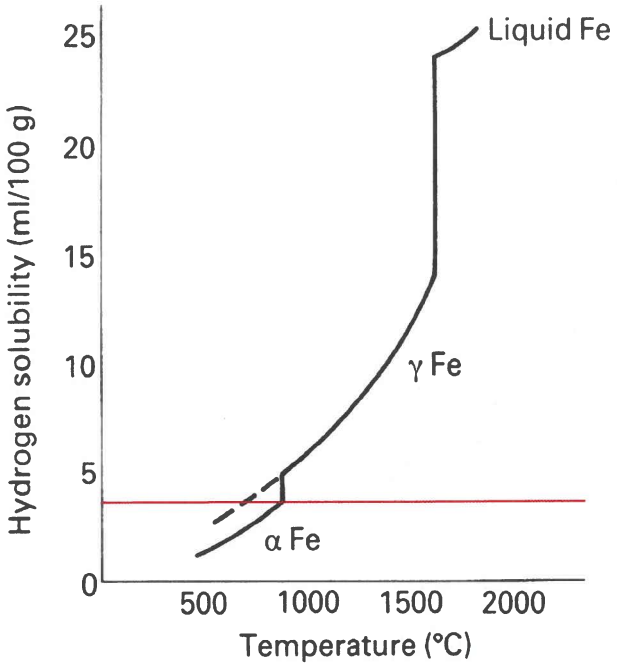


Figure 3 - Hydrogen solubility in ferritic and austenitic materials as a function of temperature

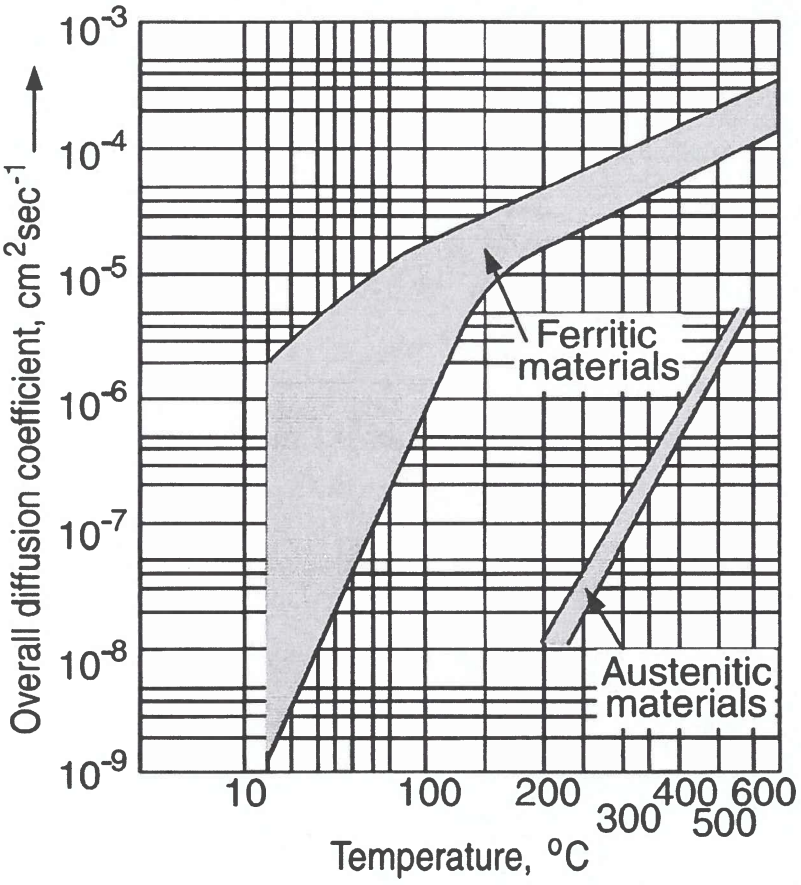


Figure 4 - Diffusion Coefficient of hydrogen in ferritic and austenitic materials as a function of temperature

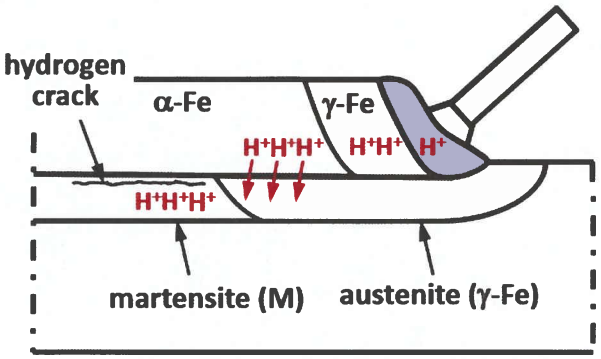


Figure 5 - Hydrogen movement with ferritic electrodes [8]

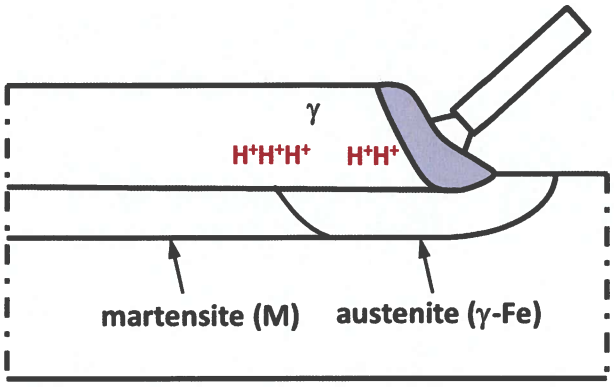


Figure 6 - Hydrogen movement with austenitic electrodes [8]

Conclusion

The temper bead technique has become an increasingly effective tool for performing repairs on carbon and low alloy steel (P-No. 1 and P-No. 3) materials. Case N-888 provisions allow for ambient temperature temper bead welding with no post weld bake. However, the 48-hour hold at ambient temperature prior to performing the final weld acceptance NDE has remained a requirement. This white paper summarizes the technical basis to eliminate the 48-hour delay for temper bead welding when using austenitic filler materials. The data and testing by EPRI and other researchers show that when austenitic weld metal is used the level of diffusible hydrogen content in the ferritic base metal HAZ is too low to promote HIC. The 48-hour hold requirement in Case N-888 can therefore be removed.

Lastly, field experience applying austenitic filler materials to hundreds of dissimilar metal weld overlays using the ambient temperature temper bead procedures has never experienced hydrogen delayed cracking nor would it be expected. The reason is simply that the final diffusible hydrogen content is low – well below any threshold level that would be required for hydrogen induced cracking. Table 1 outlines the last 20 years of temper bead weld repairs in the nuclear industry with no reported occurrence of HIC when using austenitic weld metal.

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