**Proposed Alternative**

**In accordance with 10 CFR 50.55a(z)(1)**

**Alternative Provides Acceptable Level of Quality and Safety**

**1. <u>ASME Code Component Affected</u>:**

| | |
|---|---|
| Component: | Reactor Vessel (RV) Bottom Mounted Instrumentation (BMI) Nozzle #48 |
| Code Class: | 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 RV BMI nozzles welded to the inside surface of the RV with partial penetration J-groove welds.

**2. <u>Applicable Code Edition and Addenda</u>:**

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 #48 repair modification installation is ASME Code, Section III, 2015 Edition.

**3. <u>Applicable Code Requirement</u>:**

**Flaw Removal**

- IWA-4412, *Defect Removal*, states " Defect removal shall be accomplished in accordance with the requirements of IWA-4420.”

- IWA-4420, *Defect Removal Requirements*

- IWA-4421, *General Requirements*, states, in part, "Defects shall be removed in accordance with the following requirements:"

**Flaw Characterization and Evaluation**

- IWA-3300, *Flaw Characterization*, states, in part, "*(b)* Flaws shall be characterized in accordance with IWA-3310 through IWA-3390, as applicable."

- IWB-3142.4, *Acceptance by Evaluation*, states, in part, "*(b)* A component containing relevant conditions is acceptable for continued service if an evaluation demonstrates the component's acceptability."

- IWB-3420, *Characterization*, states, "Each detected flaw or group of flaws shall be characterized by the rules of IWA-3300 to establish the dimensions of the flaws. These dimensions shall be used in conjunction with the acceptance standards of IWB-3500."

- IWB-3660, *Evaluation Procedure and Acceptance Criteria for PWR Reactor Vessel Head Penetration Nozzles*, states, in part, "PWR reactor vessel upper and lower head penetration nozzles containing flaws may be evaluated to determine acceptability for continued service in accordance with the evaluation procedure and acceptance criteria of this paragraph."

**Successive Examinations**

- IWB-2420, *Successive Inspections*, states, in part, "*(a)* The sequence of component examinations which was established during the first inspection interval shall be repeated …" and "*(b)* If a component is accepted for continued service in accordance with IWB-3132.3, the areas containing flaws shall be reexamined …"

<u>ASME Code Case N-722-1, *Additional Examinations for PWR Pressure Retaining Welds in Class 1 Components Fabricated With Alloy 600/82/182 Materials*</u>

Item No. B15.80, RPV bottom-mounted instrument penetrations, requires visual examination every other refueling outage with IWB-3522 acceptance standards.

**Welding**

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

- 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. <u>Reason for Request</u>:**

On May 6, 2025, while performing boric acid walkdowns during Callaway's refueling outage (RFO), a dry white residue resembling boric acid was identified at the interface between the Reactor Vessel Bottom Head (RVBH) and Bottom-Mounted Instrument (BMI) Nozzle No. 48. The BMI nozzle is Item No. B15.10 in Table IWB-2500-1, ASME Section XI, and Item No. B15.80 in Table 1, Case N-722-1. The condition is considered to be an active boric acid leak and constitutes a defect in the primary coolant system that is unacceptable under ASME Section XI.

Figure 4-1 depicts the existing configuration of BMI Nozzle No. 48. The leakage discovered on May 6, 2025, is in the annulus between the BMI nozzle and the penetration through the RVBH.

As a result of the leakage, Ameren will perform a modification of BMI Nozzle No. 48 using ASME Section XI, Code Case N-638-11, and ASME Section III. The modification will consist of removing the lower portion of the existing Alloy 600 nozzle and 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 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 Alloy 690 nozzle will be attached to the weld pad with a partial penetration weld using a manual GTAW welding technique. As a result, the modification will move the BMI nozzle penetration pressure boundary from the original construction partial penetration J-groove attachment weld that is inside the RVBH to the new partial penetration J-groove weld outside the RVBH.

The modification of BMI Nozzle No. 48 will also leave the original partial penetration J-groove attachment weld in place. There is not a Performance Demonstration Initiative (PDI) qualified technique that can accurately perform NDE to fully characterize the location, orientation, or size of the potential flaw in the original partial penetration J-groove attachment weld. Therefore, since IWB-3420 and IWB-3610(b) require flaw characterization and IWA-4412 require flaw removal of an identified flaw, an alternative is proposed for leaving the original J-groove weld, with a postulated flaw, in place. A flaw evaluation, using a maximum postulated flaw, will demonstrate the acceptability of leaving in place the original partial penetration J-groove attachment weld for one cycle (see “Basis for Flaw Analytical Evaluation” below).

Ameren is installing a welded pad using ATTB welding 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 NDE. For the modification of BMI Nozzle No. 48, 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 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**

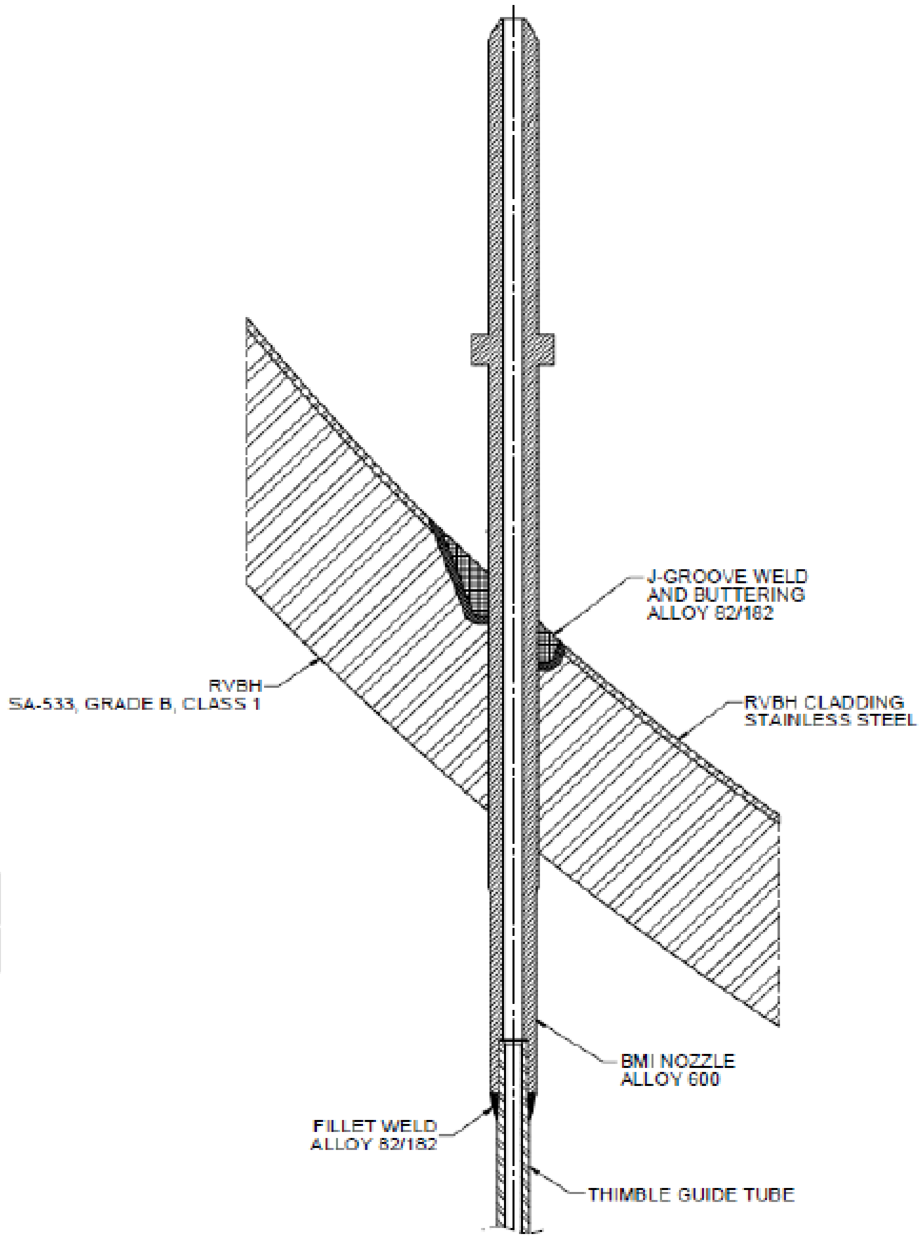
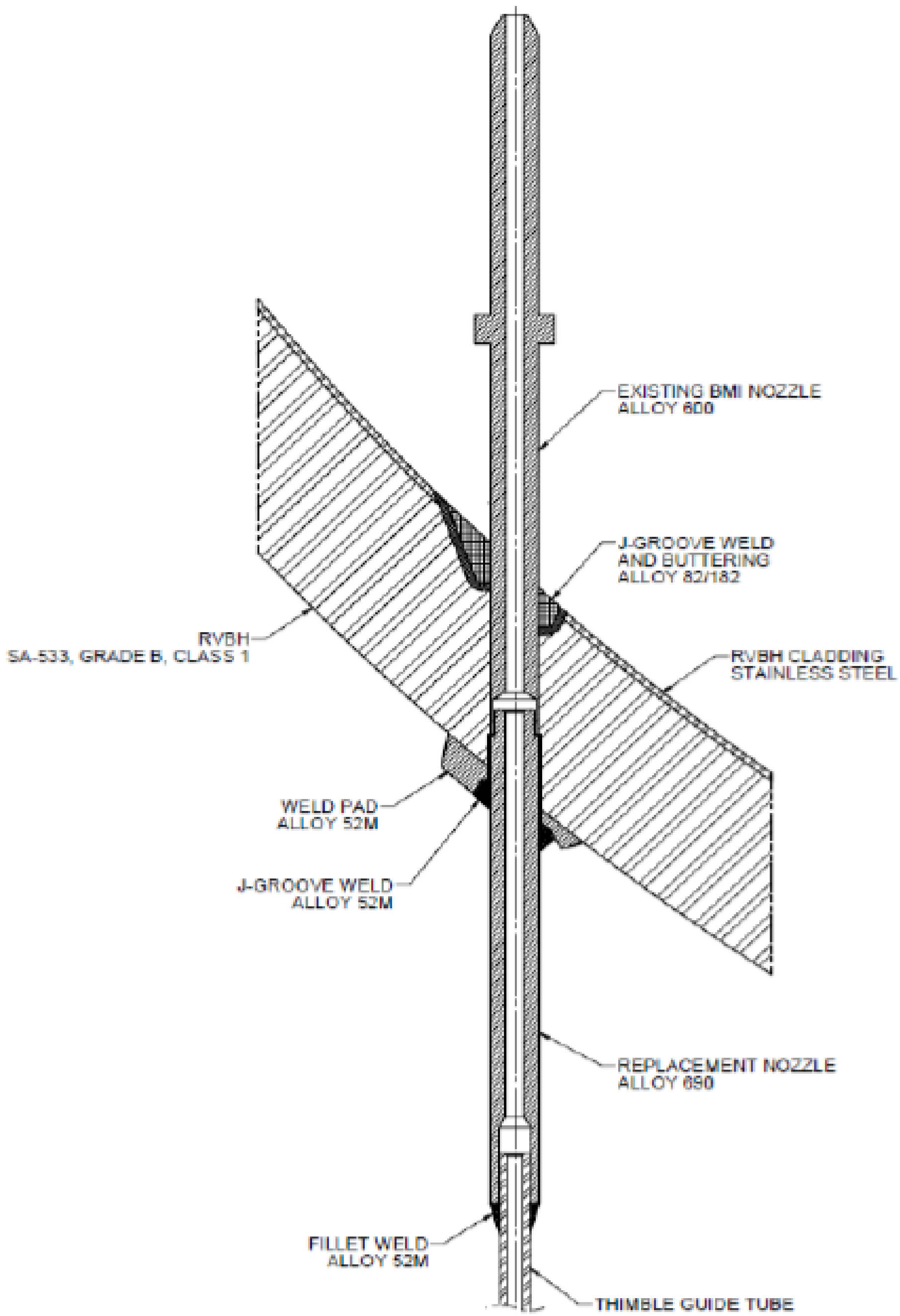


**Figure 4-2**
**Bottom Mounted Nozzle No. 48 – Modified Configuration**



## 5. Propose Alternative and Basis for Use:

A. Propose Alternatives

In accordance with 10 CFR 50.55a, "Codes and Standards," paragraph (z)(1), Ameren proposes alternatives to the requirements specified in Section 4 above on the basis that performing the alternatives stated below provide an acceptable level of quality and safety.

In accordance with the design requirements of ASME Code Section III, Subsection NB, 2015 Edition, a design analysis is being performed for the modification of the BMI Nozzle No. 48. The analysis will demonstrate that all primary stresses, primary plus secondary stresses, fatigue criteria and sizing requirements are satisfied per NB-3200, NB-3300, and NB-3600 for at least one cycle of operation. The analysis will confirm that the new nozzle will not eject from the reactor vessel under design conditions and all service level conditions. A conservative, sustained, corrosion rate will be applied and the resultant increase in bore diameter will be considered in the reinforcement calculation (per NB-3330) as part of the ASME Section III analysis. A one-cycle evaluation of the modification will be submitted to the NRC. Refer to the Summary of Commitments in Table 8-1 for timing of the submittal of the evaluation of the modification.

**Flaw Removal and Flaw Evaluation**

As an alternative to flaw removal, or reduction in size, of the original J-groove weld on the inner surface of the RVBH to meet the applicable acceptance standards per IWA-4412, and as an alternative to performing the NDE required to characterize a flaw under IWB-3420 and IWB-3610(b) in the BMI Nozzle No. 48 penetration, Ameren proposes analyzing a maximum postulated flaw that bounds the range of flaw sizes that could exist in the original J-groove weld. See "Basis for Flaw Analytical Evaluation" below.

**Welding**

In lieu of the preheat and postweld heat treatment requirements of IWA-4411, Ameren is proposing to install 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. Examination (liquid penetrant surface and UT volumetric) 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.

Pursuant to 10 CFR 50.55a(z)(1), Ameren proposes an alternative to Case N-638-11, Paragraph 4(a)(2), that requires a 48-hour hold time prior to performing NDE. 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.

B. Basis for Flaw Analytical Evaluation

The assumptions of IWB-3600 of ASME Section XI for analytical flaw evaluation are that cracks are fully characterized in accordance with IWB-3420 in order to compare the calculated parameters to the acceptable parameters addressed in IWB-3500. There are no qualified UT examination techniques for examining the original nozzle-to-shell RVBH J-groove weld. Therefore, since it is impractical to characterize the flaw geometry that may exist therein, it is conservatively assumed that the “as-left” condition of the remaining J-groove weld includes flaws extending through the entire Alloy 82 J-groove weld and buttering.

Since uphill and downhill hoop stresses in the J-groove weld at the spherical shell are the higher stressed location at the nozzle penetration, the preferential direction for cracking is radial relative to the RVBH shell. Therefore, a radial-axial flaw (radial with respect to the nozzle axis) in the Alloy 82 J-groove weld and buttering is postulated and would propagate by Primary Water Stress Corrosion Cracking (PWSCC) through the weld and buttering to the interface with the low alloy steel RVBH material. Any growth of the postulated “as-left” flaw into the PWSCC resistant low alloy steel would be by fatigue crack growth under cyclic loading conditions.

"Life of Repair" analyses performed for similar repairs have resulted in a fatigue crack growth life for the "as-left" J-groove flaw of 50 years (linear elastic fracture mechanics (LEFM)). The typical process for these types of “Life of Repair” analyses is as follows:

1. The outermost penetration was modeled due to the applied loading conditions being the same or worse than all other locations in the RVBH. The initial flaw size for the J-groove weld is conservatively assumed to include all of the weld and buttering. This is highly conservative since the buttering has been subjected to PWHT, which would tend to reduce welding residual stresses, making it less susceptible to PWSCC. While the analysis considers crack growth on both uphill and downhill sides, the weld on the downhill side of the outermost nozzle has been determined as the bounding one. Therefore, the largest possible initial flaw size on the downhill side is considered.

2. The transients applicable for the “as-left” J-groove weld crack growth are those due to normal and upset conditions only. The controlling loading condition was identified to be during normal cooldown and leak test, for which it was shown, using LEFM criteria of $\sqrt{10} = 3.16$, that the applied stress intensity factor (SIF) was less than the allowable value. The original life of repair analysis is using a more severe KIa curve (fracture toughness curve within ASME Section XI) for crack arrest.

3. The J-groove flaws were evaluated using worst-case BMI nozzle outermost penetration configuration with postulated flaw sizes on uphill and downhill sides of the J-groove weld. Fatigue crack growth for cyclic loading conditions using operational stresses from pressure and thermal loads and crack growth rates from ASME Section XI, Non-mandatory Appendix A, Sub-article A-4300 for ferritic material in a primary water environment was calculated. Based on the results of LEFM analysis only, a postulated flaw remaining in the original Alloy 82/Alloy 182 J-groove weld and buttering for the modified RVBH nozzle was shown to be acceptable.

4. Prior analyses of similar repair configurations have demonstrated that fatigue crack growth is acceptable, and the crack-like indications remain stable, satisfying the ASME Section XI criteria.

Given the emergent nature of the Callaway BMI Nozzle No. 48 modification, there is not sufficient time to perform the detailed “Life of Repair” finite element analysis for the "as-left" J-Groove weld during the outage. Instead, a one cycle justification will be developed based on a comparative analysis between a similar previously performed BMI Nozzle modification and the Callaway BMI Nozzle No. 48 modification. This comparative analysis will be performed against a prior BMI Nozzle analysis performed for the "Life of Repair" that is most representative and bounding relative to the Callaway BMI Nozzle No. 48 modification considering: geometry, materials and transient loading conditions as well as a conservative crack growth prediction for one fuel cycle of operations. This qualitative justification will show that the "as-left" J-groove weld postulated flaw in the Callaway Unit 1 modification will meet the acceptance criteria of IWB-3612 for normal/upset and emergency/faulted operating conditions during one fuel cycle of operation. This one cycle justification will be submitted to the NRC.

Ameren requests relief from the acceptance criteria specified in NB-5330(b) of ASME Section III to permit anomalies, as described herein, at the "as-left" J-groove weld location to remain in service for a single nominal 18-month fuel cycle of operation.

C. Basis for Elimination of the Ambient 48-Hour Hold Time

Elimination of the 48-hour hold is based on Attachment 1, which is a white paper based on PVP 2023-107489, "Elimination of the 48-hour Hold for Ambient Temperature Temper Bead Welding with Austenitic Weld Metal." Removal of the 48-hour hold is supported by the white paper that was developed for the proposed change to ASME Code Case N-888-1. Although this ASME Case is not approved in Reg. Guide 1.147, Revision 21, it has been approved by the ASME Section XI Standards Committee. Since Code 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., the justification is also applicable to the planned use of Code Case N-638-11 at Callaway Plant Unit 1.

D. Corrosion Evaluation

A corrosion evaluation will be performed to address potential corrosion mechanisms due to the modification of the reactor vessel BMI nozzle. The modification will result in the RVBH low alloy steel being exposed to the reactor coolant. These mechanisms include general corrosion, crevice corrosion, galvanic corrosion, stress corrosion cracking, and hydrogen embrittlement of the exposed RVBH. The corrosion evaluation will also evaluate potential corrosion mechanisms for the Alloy 690 and Alloy 52M used in the modification.

The corrosion evaluation will be submitted to the NRC. Refer to Summary of Commitments in Table 8-1 for timing of submittal of the corrosion evaluation.

E. Conclusion

The "as-left" J-groove weld flaw evaluation will demonstrate that the postulated flaw is acceptable through one operating cycle following the modification being performed during the current Callaway refueling outage (i.e., R27). The one-cycle justification of the flaw evaluation will be submitted to the NRC within 14 days of the end of the current refueling outage, see Table 8-1 for Summary of Commitments.

The temper bead technique is an effective tool for performing repairs on carbon and low alloy steel (P-No. 1 and P-No. 3) materials. Case N-638-11 provisions allow for ambient temperature temper bead welding with no post weld heat treatment. 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.

The timing for submittal of analyses and evaluations that support the alternatives is provided in Table 8-1.

## 6. Duration of Proposed Alternative

Authorization is requested for the duration of the Callaway Plant Unit 1 Cycle 28, which is currently scheduled to conclude in the Fall of 2026. A separate relief request will be submitted to justify continued use of the nozzle modification for the life of the plant. This permanent relief request, which will contain the appropriate analyses and justification for the remainder of the plant operating life, will be submitted prior to the end of the upcoming operating cycle.

## 1. Precedents

The following relief requests were previously approved to eliminate the 48-hour hold time specified in Case N-638-10:

- NRC approval via verbal authorization on April 25, 2025 (ADAMS Accession No. ML25118A063) for Palo Verde Nuclear Generating Station, Unit 1.
- NRC approval via verbal authorization on October 27, 2023 (ADAMS Accession No. ML23303A011) for Palo Verde Nuclear Generating Station, Unit 1. The NRC Safety Evaluation was subsequently issued on September 9, 2024 (ADAMS Accession No. ML24197A199).
- NRC verbal authorization on May 9, 2023 [Agencywide Documents Access and Management System (ADAMS) Accession No. ML23129A312] for Beaver Valley, Unit 2 relief request 2_TYP-4-RV-06 (ADAMS Accession No. ML23118A381).
- Letter from David Gudger (Constellation Energy Generation, LLC) to U.S. NRC, "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).

The following relief requests were previously approved for the flaw analytical evaluation:

- NRC approval via verbal authorization on April 25, 2025 (ADAMS Accession No. ML25118A063) for Palo Verde Nuclear Generating Station, Unit 1.
- NRC approval via verbal authorization on October 27, 2023 (ADAMS Accession No. ML23303A011) for Palo Verde Nuclear Generating Station, Unit 1. The NRC Safety Evaluation was subsequently issued on September 9, 2024 (ADAMS Accession No. ML24197A199).
- NRC approval via verbal authorization on November 6, 2020 (ADAMS Accession No. ML20314A028) for Peach Bottom Atomic Power Station, Unit 2. The NRC Safety Evaluation was subsequently issued on April 23, 2021 (ADAMS Accession No. ML21110A680).
- NRC verbal authorization on April 15, 2012, for Quad Cities, Unit 2 (ADAMS Accession No. ML12107A472). The NRC Safety Evaluation was subsequently issued on January 30, 2013 (ADAMS Accession No. ML13016A454).

- NRC approval via a verbal authorization on May 17, 2017, for Limerick, Unit 2 (ADAMS Accession No. ML17137A307). The NRC Safety Evaluation was subsequently issued on August 14, 2017 (ADAMS Accession No. ML17208A090).

## 2. 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.

ASME Code, Section III, Nuclear Power Plant Components, 1971 Edition including Addenda through Winter 1972.

ASME Code, Section III, Rules for Construction of Nuclear Facility Components, Division 1, 2015 Edition.

**Table 8-1 Summary of Commitments**

| Commitment | Committed Date of "Outage" | Commitment Type | |
|---|---|---|---|
| | | One-Time Action (Yes / No) | Programmatic (Yes / No) |
| The final one-cycle flaw analytical evaluation, evaluation of modified configuration, and corrosion evaluation will be submitted within 14 days following the end of the current Callaway Plant Unit 1 refueling outage. | Within 14 days following the end of the current Callaway Unit 1 refueling outage. | | |

**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

<u>Microstructure:</u>

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 390ºF (200ºC) 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 assure 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.

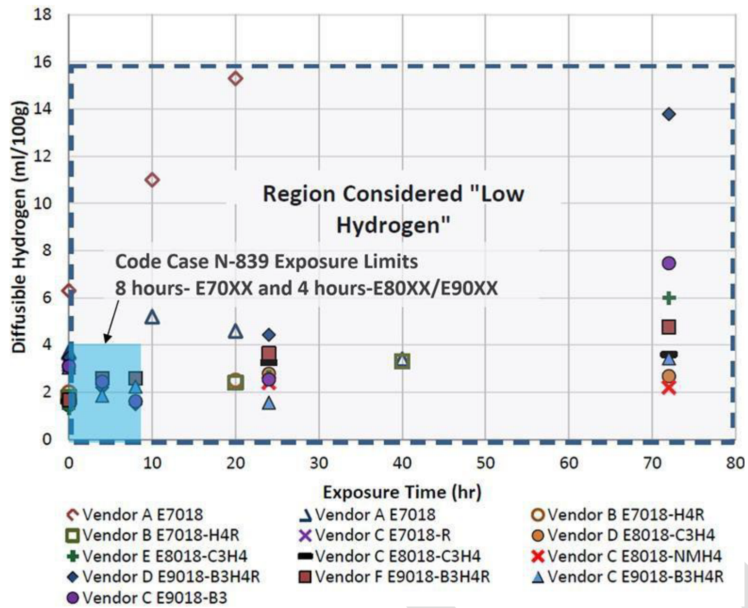



Figure 1. Results of EPRI diffusible hydrogen testing at 27°C 80% Relative Humidity (HR) for zero to 72 hours of exposure [6]

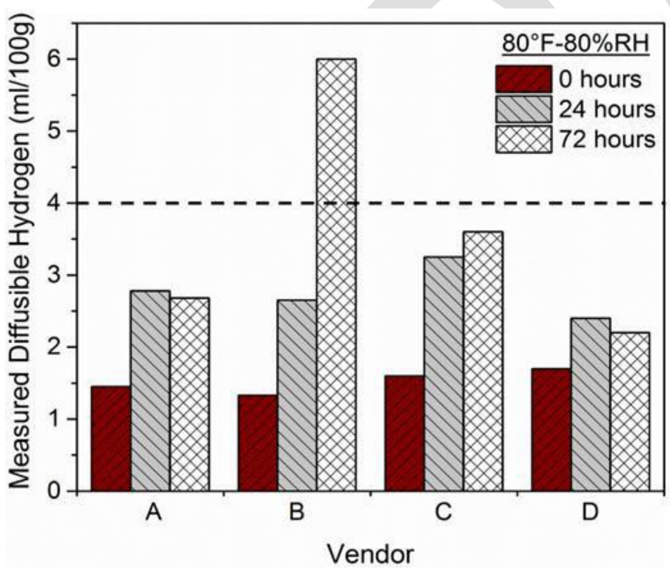



Figure 2. Graph showing slight increase of diffusible hydrogen after exposure of 24 and 72 hours [6]

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 $\alpha$-Fe and $\gamma$-Fe. Note that $\alpha$-Fe is at the saturation limit at ~4ml/100g of hydrogen. At temperatures above ~1700° C the solubility of hydrogen in austenite ($\gamma$-Fe) is nearly five times that of ferrite ($\alpha$-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].

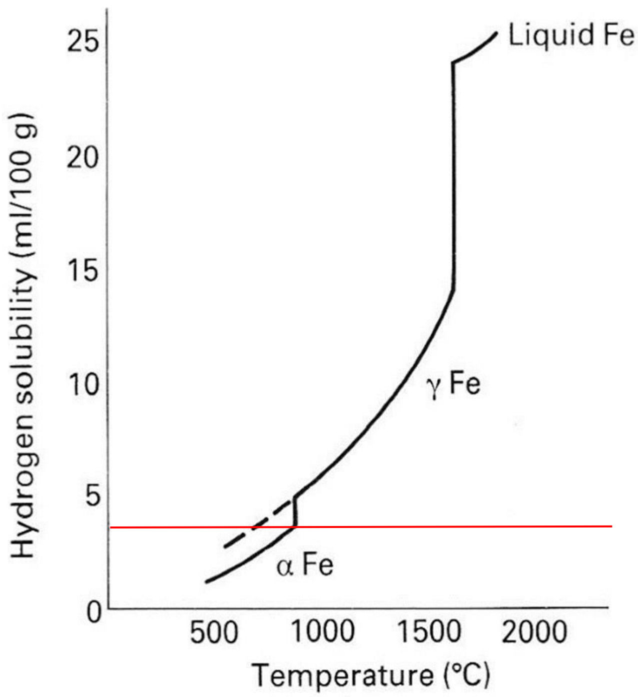



Figure 3 - Hydrogen solubility in ferritic and austenitic materials as a function of temperature

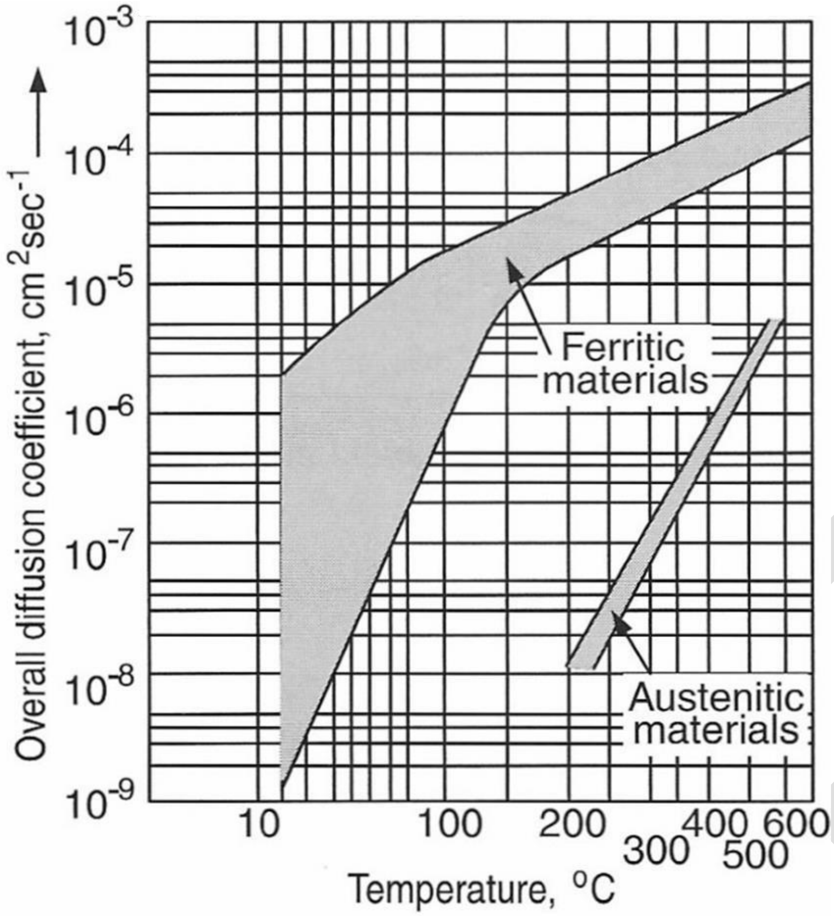



Figure 4 - Diffusion Coefficient of hydrogen in ferritic and austenitic materials as a function of temperature

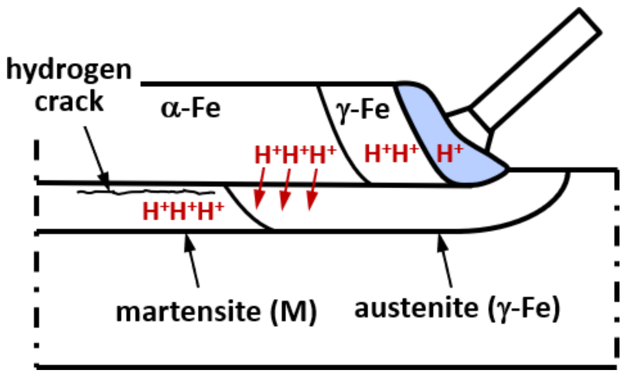



Figure 5 - Hydrogen movement with ferritic electrodes [8]

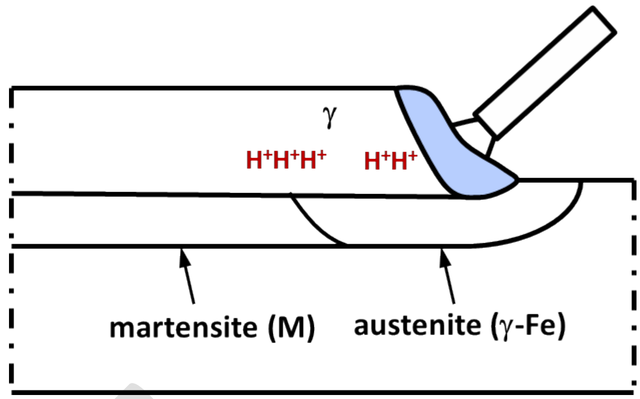



Figure 6 - Hydrogen movement with austenitic electrodes [8]

## 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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