VIRGINIA ELECTRIC AND POWER COMPANY
RICHMOND, VIRGINIA 23261

September 6, 2001

United States Nuclear Regulatory Commission
Attention: Document Control Desk
Washington, D.C. 20555

Serial No.	01-450A
NL&OS/ETS	R0
Docket Nos.	50-280
	50-338
License Nos.	DPR-32
	NPF-4

Gentlemen:

VIRGINIA ELECTRIC AND POWER COMPANY
SURRY AND NORTH ANNA POWER STATION UNITS 1
ASME SECTION XI INSERVICE INSPECTION PROGRAM
REVISED RELIEF REQUESTS - ALTERNATIVE REPAIR TECHNIQUES

In a letter dated August 15, 2001 (Serial No. 01-450), Virginia Electric and Power Company (Dominion) requested relief to use alternative repair techniques in the event that any instances of cracking in reactor vessel head penetrations were discovered during inspections planned for the upcoming Fall 2001 refueling outages for North Anna Unit 1 and Surry Unit 1.

During the NRC's review of the relief requests, the staff identified a need for additional information to facilitate their review. The staff's questions were identified in telephone calls with Mr. Stephen Monarque, the North Anna Project Manager, on August 20, 24, and 28, 2001. Based on the NRC's questions, we are superceding the August 15, 2001 relief requests with the attached relief requests NDE-018 and 019 for North Anna Unit 1 and relief requests SR-25 and 26 for Surry Unit 1. These superceding relief requests include the information requested by the staff.

These relief requests have been reviewed by the Station Nuclear Safety and Operating Committees. If you have any questions or require additional information, please contact us.

Very truly yours,

Leslie N. Hartz
Vice President - Nuclear Engineering

Attachments

A047

Commitments made in this letter: None

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ATTACHMENT 1

REQUEST TO USE AN ALTERNATIVE TO ASME CODE AMBIENT TEMPERATURE TEMPER BEAD WELD REPAIR NORTH ANNA POWER STATION UNIT 1 RELIEF REQUEST NDE-018 SURRY POWER STATION UNIT 1 RELIEF REQUEST SR-25

I. Identification of Components

Drawings:

11715-WMKS-RC-R-1.2 (North Anna Unit 1)	Class 1
11448-WMKS-RC-R-1.2 (Surry Unit 1)	Class 1

Control rod drive mechanism (CRDM) penetrations (65) and the reactor head vent (1) on the upper reactor vessel head, which are ASME Class 1 components.

II. Current Code Requirements

The Construction Code of record for the North Anna and Surry reactor vessels and heads is the 1968 Edition of ASME Section III with Addenda through the Winter of 1968. North Anna Unit 1 and Surry Unit 1 are currently in their third inspection intervals using the 1989 Edition of ASME Section XI. ASME Section XI, paragraph IWA-4120, stipulates the following:

> "Repairs shall be performed in accordance with the Owner's Design Specification and the original Construction Code of the component or system. Later Editions and Addenda of the Construction Code or of Section III, either in their entirety or portions thereof, and Code Cases may be used."

Consequently, the proposed repairs will be conducted in accordance with the 1989 Edition of ASME III and alternative requirements discussed below.

III. Code Requirements for Which Alternatives Are Requested

Both North Anna Unit 1 and Surry Unit 1 will perform VT-2 inspections under the insulation of the reactor vessel heads during their respective refueling outages in the Fall of 2001. If the VT-2 inspections identify any penetration nozzle leakage, additional under the head inspections will be performed. In the event that any subsequent under the head inspections of the reactor vessel head penetrations reveal flaws in those penetrations, it will be necessary to repair the flaws that exceed Section XI acceptance criteria. Specifically, paragraph IWA-4310 requires the repair of any flaw associated with the J-groove weld attaching the penetration to the head which cannot be accepted by the rules of the original Code of Construction. Per paragraph IWA-4120, repair welding must be done in accordance with the original Construction Code. Therefore, for any J-groove weld excavation that resulted in a repair within 1/8-inch of the ferritic material of the vessel head, paragraph NB-4622 of Section III would require a postweld stress relief heat treatment (PWHT) for the repair weld or the use of a temper bead weld technique. The PWHT parameters required by NB-4622 would be difficult to achieve on a reactor vessel head in containment and pose some risk of distortion to the geometry of the head and vessel head penetrations. The temper bead procedure requirements, including preheat and postweld heat soaks contained in NB-4622, likewise would be difficult to achieve in containment and are not warranted by the need to produce a sound repair weld given the capabilities of the proposed alternative temper bead procedure proposed below.

Subparagraph NB-4453.4 of Section III requires examination of the repair weld in accordance with the requirements for the original weld. For vessel head penetration partial penetration welds, paragraph NB-5245 requires a progressive surface exam (PT or MT) at the lesser of 1/2 the maximum weld thickness or 1/2-inch as well as on the finished weld.

IV. Basis for Relief

The alternative to NB-4622 requirements being proposed involves the use of an ambient temperature temper bead welding technique that avoids the necessity of traditional PWHT preheat and postweld heat soaks. The features of the alternative that make it applicable and acceptable for the contemplated repairs are enumerated below:

1) The proposed alternative will require the use of an automatic or machine gas tungsten arc welding (GTAW) temper bead technique without the specified preheat or postweld heat treatment of the Construction Code. The proposed alternative will include the requirements of paragraphs 1.0 through 5.0 of Enclosure 1, "Similar and Dissimilar Metal Welding Using Ambient Temperature Machine GTAW Temper Bead Technique" and specifies that all other requirements of IWA-4000 be met. The alternative may be used to make repairs to P-Nos. 1, 3, 12A, 12B, and 12C (except SA-302 Grade B) material and their associated welds, and P-No. 8 and P-No. 43 material to P-Nos. 1, 3, 12A, 12B, and 12C (except SA-302 Grade B) material. In this case, the reactor vessel head is a P-No. 3 material and the affected welds are those J-groove welds attaching the P-No. 43 vessel head penetrations to the vessel head. The J-groove welds were made with F-No. 43 filler metal.

2) The use of a GTAW temper bead welding technique to avoid the need for postweld heat treatment is based on research that has been performed by EPRI and other organizations. (Reference Enclosure 2, EPRI Report GC-111050, "Ambient Temperature Preheat for Machine GTAW Temperbead Applications," dated November 1998.) The research demonstrates that carefully controlled heat input and bead placement allow subsequent welding passes to relieve stress and temper the heat affected zones (HAZ) of the base material and preceding weld passes. Data presented in Tables 4-1 and 4-2 of the report show

the results of procedure qualifications performed with 300°F preheats and 500°F postheats, as well as with no preheat and postheat. From that data, it is clear that equivalent toughness is achieved in base metal and heat affected zones in both cases. The temper bead process has been shown effective by research, successful procedure qualifications, and many successful repairs performed since the technique was developed. Many acceptable Procedure Qualifications (PQRs) and Welding Procedure Specifications (WPSs) presently exist and have been utilized to perform numerous successful repairs. These repairs have included all of the Construction Book Sections of the ASME Code, as well as the National Board Inspection Code (NBIC). The use of the automatic or machine GTAW process utilized for temper bead welding allows more precise control of heat input, bead placement, and bead size and contour than the manual Shielded Metal Arc Welding (SMAW) process required by NB-4622. The very precise control over these factors afforded by the alternative provides more effective tempering and eliminates the need to grind or machine the first layer of the repair.

3) The NB-4622 temper bead procedures require a 350°F preheat and a postweld soak at 450°-550°F for 4 hours for P-No. 3 materials. Typically, these kinds of restrictions are used to mitigate the effects of the solution of atomic hydrogen in ferritic materials prone to hydrogen embrittlement cracking. The susceptibility of ferritic steels is directly related to their ability to transform to martensite with appropriate heat treatment. The P-No. 3 material of the reactor vessel head is able to produce martensite from the heating and cooling cycles associated with welding. However, the proposed alternative mitigates this propensity without the use of elevated preheat and postweld hydrogen bake out.

The NB-4622 temper bead procedure requires the use of the SMAW welding process with covered electrodes. Even the low hydrogen electrodes, which are required by NB-4622, may be a source of hydrogen unless very stringent electrode baking and storage procedures are followed. The only shielding of the molten weld puddle and surrounding metal from moisture in the atmosphere (a source of hydrogen) is the evolution of gases from the flux and the slag that forms from the flux and covers the molten weld metal. As a consequence of the possibility for contamination of the weld with hydrogen, NB-4622 temper bead procedures require preheat and postweld hydrogen bake-out. However, the proposed alternative temper bead procedure utilizes a welding process that is inherently free of hydrogen. The GTAW process relies on bare welding electrodes with no flux to trap moisture. An inert gas blanket positively shields the weld and surrounding material from the atmosphere and moisture it may contain. To further reduce the likelihood of any hydrogen evolution or absorption, the alternative procedure requires particular care to ensure the weld region is free of all sources of hydrogen. The GTAW process will be shielded with welding grade argon (99.9996% pure) which typically produces porosity free welds. The gas would have no more than 1 PPM of hydrogen (H_2) and no more than 0.5 PPM of water vapor (H_2O). A typical argon flow rate would be about 55 CFH and would be adjusted to assure adequate shielding of the weld without creating a venturi affect that might draw oxygen or water vapor from the ambient atmosphere into the weld.

After the electrical discharge machining (EDM) process used to prepare the excavation for welding, the repair excavation and surrounding area would be cleaned by wire brushing to assure it is free of dust, sediments, oxides, boric acid residue, etc. Quartz halogen heat lamps would then be used to heat the area and ensure it is moisture free.

4) The F-No. 43 (ERNiCrFe-7) filler metal that would be used for the repairs is not subject to hydrogen embrittlement cracking.

5) Final examination of the repair welds would be a combination of surface examination and ultrasonic inspection and would not be conducted until at least 48 hours after the weld had returned to ambient temperature following the completion of welding. Given the 3/8-inch limit on repair depth in the ferritic material, the delay before final examination would provide ample time for any hydrogen that did inadvertently dissolve in the ferritic material to diffuse into the atmosphere or into the nonferritic weld material which has a higher solubility for hydrogen and is much less prone to hydrogen embrittlement cracking. Thus, in the unlikely event that hydrogen induced cracking did occur, it would be detected by the 48-hour delay in examination.

6) Results of procedure qualification work undertaken to date indicate that the proposed alternative produces sound and tough welds. For instance, typical tensile test results have been ductile breaks in the weld metal. A typical set of Charpy test values showed average absorbed energies and lateral expansions of 76 ft.-lbs. and 45 mils for the base metal (a P-No. 3 Gr. 3 material), 114 ft.-lbs. and 57 mils for the heat affected zone, and 254 ft.-lbs. and 84 mils for the weld metal (a F-No. 43 filler metal). It is clear from these results that the ambient temperature GTAW temper bead process has the capability of producing acceptable repair welds.

7) Procedure qualification, performance qualification, welding procedure specifications, examination, and documentation requirements would be as stipulated in the proposed alternative procedure.

Based on the above information it may be concluded that the proposed alternative ambient temperature temper bead weld technique (Enclosure 1) provides a technique for repairing flaws in the CRDM and reactor head vent penetration to vessel head J-groove welds within 1/8-inch of the ferritic base metal that will produce sound and permanent repairs and that the procedure is an alternative to Code requirements that will provide an acceptable level of quality and safety.

IV. Alternate Requirements

Repairs to reactor vessel head penetration J-groove attachment welds which are required when 1/8-inch or less of nonferritic weld deposit exists above the original fusion line, will be made in accordance with the requirements of paragraphs IWA- 4110, 4120, 4130, 4140, 4210, 4330, 4340, 4400, 4600, 4700, and 4800 of the 1989 Edition of ASME Section XI.

The requirements of paragraphs NB-4451, 4452, 4453, and 4622 of the 1989 Edition of ASME Section III are also applicable to the contemplated repairs. As an alternative to the PWHT time and temperature requirements of NB-4622, the requirements of, "Similar and Dissimilar Metal Welding Using Ambient Temperature Machine GTAW Temper Bead Technique," (Enclosure 1) will be used.

In addition, in lieu of the progressive surface examination of the repair weld required by subparagraph NB-4453.4 and paragraph NB-5245, the examination of the repair weld will include liquid penetrant and ultrasonic examinations supplemented by an eddy current surface inspection.

Per the 1989 Edition of ASME Section XI, paragraph IWB-2200(a), no preservice examination is required for repairs to the partial penetration J-grove welds between the vessel head and its penetrations (Examination Category B-E). However, the NDE performed after welding will serve as a preservice examination record if needed in the future. Furthermore, the inservice inspection requirement from Table IWB-2500-01, "Examination Category B-E...," is a VT-2 visual inspection of the external surfaces of 25% of the nozzles each interval with IWB-3522 as the acceptance standard. Currently, we perform visual examination, VT-2, of 100% of the nozzles each refueling outage. Ongoing vessel head penetration inspection activities undertaken as a result of NRC Bulletin 2001-01 and ongoing deliberations in Code committees will be monitored to determine the necessity of performing any additional or augmented inspections.

Using the provisions of this relief request as an alternative to Code requirements will produce sound, permanent repair welds and an acceptable level of quality and safety, as required by 10 CFR 50.55a(a)(3)(i).

Enclosure 1

Similar and Dissimilar Metal Welding Using Ambient Temperature Machine GTAW Temper Bead Technique

The following proposed alternative to Code requirements contained in paragraph NB-4622 of the 1989 Edition of Section III applies to repairs to P-Nos. 1, 3, 12A, 12B, and 12C (P-Nos. 12A, 12B, and 12C designations refer to specific material classifications originally identified in Section III and subsequently reclassified as P-No. 3 material in a later Edition of Section IX) except SA-302 Grade B, material and their associated welds and P-No. 8 or P-No. 43 material to P-Nos. 1, 3, 12A, 12B, and 12C, except SA-302 Grade B, material and may be made by the automatic or machine GTAW temper bead technique without the specified preheat or postweld heat treatment of the Construction Code, provided the requirements of paragraphs 1.0 through 5.0, below and all other requirements of IWA-4000 (IWA-4000 or IWA-7000, as applicable, in the 1989 Edition, with the 1990 Addenda, and earlier Editions and Addenda), are met.

1.0 GENERAL REQUIREMENTS

(a) The maximum area of an individual weld based on the finished surface shall be 100 square inches and the depth of the weld shall not be greater than one-half of the ferritic base metal thickness.

(b) Repair/replacement activities on a dissimilar metal weld in accordance with this procedure are limited to those along the fusion line of a nonferritic weld to ferritic base material on which 1/8 inch, or less of nonferritic weld deposit exists above the original fusion line.

(c) If a defect penetrates into the ferritic base material, repair of the base material, using a nonferritic weld filler material, may be performed in accordance with these requirements, provided the depth of repair in the base material does not exceed 1/8 in.

(d) Prior to welding, the area to be welded and a band around the area of at least 1 and 1/2 times the component thickness or 5-inch, whichever is less shall be at least 50°F.

(e) Welding materials shall meet the Owner's Requirements and the Construction Code and Cases specified in the Repair/Replacement Plan. Welding materials shall be controlled so that they are identified as acceptable until consumed.

(f) Peening may be used, except on the initial and final layers.

2.0 WELDING QUALIFICATIONS

The welding procedures and the welding operators shall be qualified in accordance with Section IX and the requirements of paragraphs 2.1 and 2.2.

2.1 Procedure Qualification

(a) The base materials for the welding procedure qualification shall be of the same P-Number and Group Number, as the materials to be welded. The materials shall be postweld heat treated for at least the time and temperature that was applied to the materials being welded.

(b) Consideration shall be given to the effects of welding in a pressurized environment. If they exist, they shall be duplicated in the test assembly.

(c) Consideration shall be given to the effects of irradiation on the properties of material, including weld material for applications in the core belt line region of the reactor vessel. Special material requirements in the Design Specification shall also apply to the test assembly materials for these applications.

(d) The root width and included angle of the cavity in the test assembly shall be no greater than the minimum specified for the repair.

(e) The maximum interpass temperature for the first three layers of the test assembly shall be 150°F.

(f) The test assembly cavity depth shall be at least one-half the depth of the weld to be installed during the repair/replacement activity and at least 1-inch. The test assembly thickness shall be at least twice the test assembly cavity depth. The test assembly shall be large enough to permit removal of the required test specimens. The test assembly dimensions surrounding the cavity shall be at least the test assembly thickness and at least 6-inch. The qualification test plate shall be prepared in accordance with Figure 1.

g) Ferritic base material for the procedure qualification test shall meet the impact test requirements of the Construction Code and Owner's Requirements. If such requirements are not in the Construction Code and Owner's Requirements, the impact properties shall be determined by Charpy V-notch impact tests of the procedure qualification base material at or below the lowest service temperature of the item to be repaired. The location and orientation of the test specimens shall be similar to those required in (i) below, but shall be in the base metal.

(h) Charpy V-notch tests of the ferritic weld metal of the procedure qualification shall meet the requirements as determined in (g) above.

(i) Charpy V-notch tests of the ferritic heat-affected zone (HAZ) shall be performed at the same temperature as the base metal test of (g) above. Number, location, and orientation of test specimens shall be as follows:

(1) The specimens shall be removed from a location as near as practical to a depth of one-half the thickness of the deposited weld metal. The coupons for HAZ impact specimens shall be taken transverse to the axis of the weld and etched to define the HAZ. The notch of the Charpy V-notch specimen shall be cut approximately normal to the material surface in such a manner as to include as much HAZ as possible in the resulting fracture. When the material thickness permits, the axis of a specimen shall be inclined to allow the root of the notch to be aligned parallel to the fusion line.

(2) If the test material is in the form of a plate or a forging, the axis of the weld shall be oriented parallel to the principal direction of rolling or forging.

(3) The Charpy V-notch test shall be performed in accordance with SA-370. Specimens shall be in accordance with SA-370, Figure. 11, Type A. The test shall consist of a set of three full-size 10 mm x 10 mm specimens. The lateral expansion, percent shear, absorbed energy, test temperature, orientation and location of all test specimens shall be reported in the Procedure Qualification Record.

(j) The average values of the three HAZ impact tests shall be equal to or greater than the average of the three unaffected base metal tests.

2.2 Performance Qualification

Welding operators shall be qualified in accordance with Section IX.

3.0 WELDING PROCEDURE REQUIREMENTS

The welding procedure shall include the following requirements:

(a) The automatic or machine GTAW process shall deposit the weld metal.

(b) Dissimilar metal welds shall be made using A-No. 8 weld metal (QW-442) for P-No. 8 to P-No. 1, 3, or 12 (A, B, or C) weld joints or F-No. 43 weld metal (QW-432) for P-No. 8 or 43 to P-No. 1, 3, or 12 (A, B, or C) weld joints.

(c) The area to be welded shall be buttered with a deposit of at least three layers to achieve at least 1/8-inch overlay thickness, as shown in Figure 2, Steps 1 through 3, with the heat input for each layer controlled to within ± 10% of that used in the procedure qualification test. Particular care shall be taken in placement of the weld layers at the weld toe area of the ferritic material to ensure that the HAZ and ferritic weld metal are tempered. Subsequent layers shall be deposited with a heat input not exceeding that used for layers beyond the third layer in the procedure qualification. For similar metal welding, the completed weld shall have at least one layer of weld reinforcement deposited. This reinforcement shall be removed by mechanical means, so that the finished surface is essentially flush with the surface surrounding the weld as depicted in Figure 3.

(d) The maximum interpass temperature for field applications shall be 350°F regardless of the interpass temperature during qualification.

(e) Particular care shall be given to ensure that the weld region is free of all potential sources of hydrogen. The surfaces to be welded, filler metal, and shielding gas shall be suitably controlled.

4.0 EXAMINATION

(a) Prior to welding, a surface examination shall be performed on the area to be welded.

(b) The final weld surface and the band around the area defined in paragraph 1.0(d) shall be examined using a surface and ultrasonic methods when the completed weld has been at ambient temperature for at least 48 hours. The ultrasonic examination shall be in accordance with Appendix I. (Refer to the 1989 Edition with the 1989 Addenda and later Editions and Addenda.)

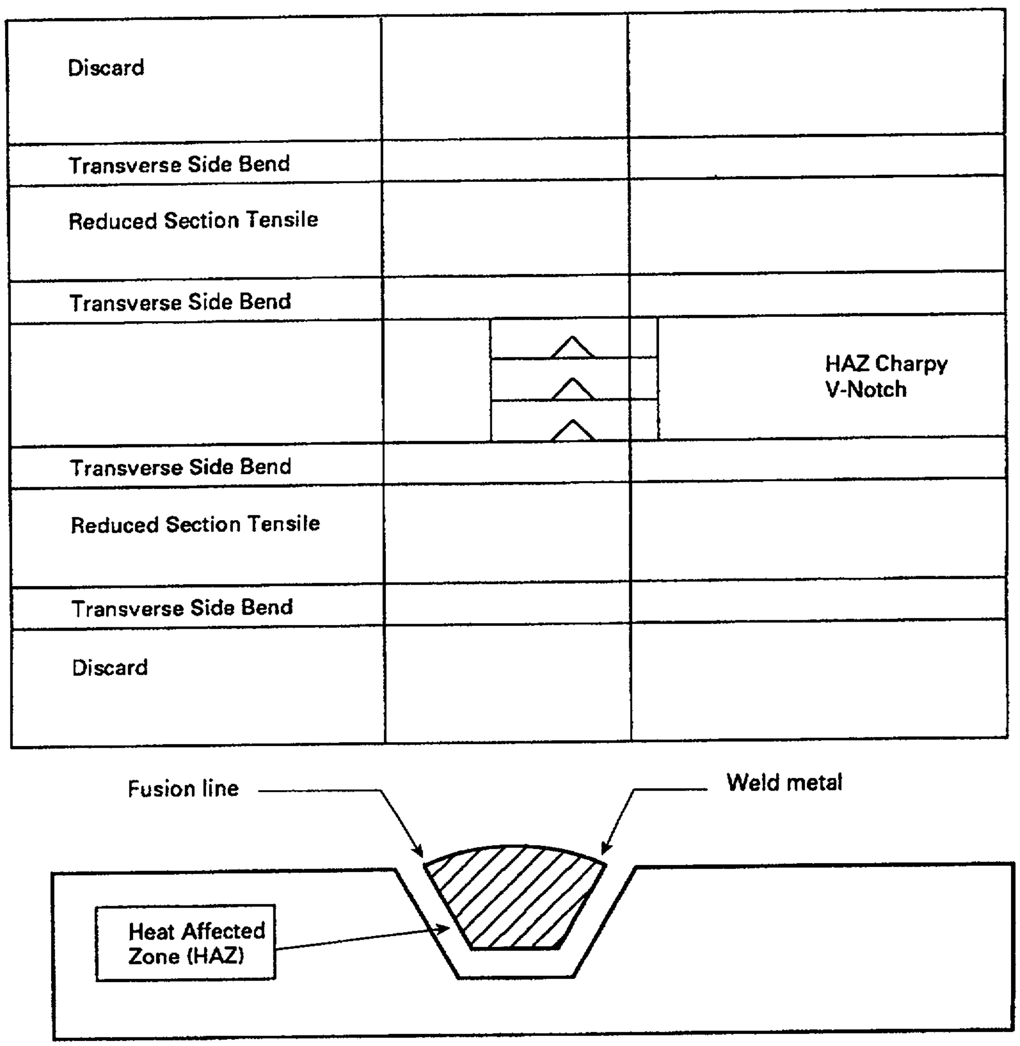
(c) Areas from which weld-attached thermocouples have been removed shall be ground and examined using a surface examination method.

(d) NDE personnel shall be qualified in accordance with IWA-2300.

(e) Surface examination acceptance criteria shall be in accordance with NB-5340 or NB-5350, as applicable. Ultrasonic examination acceptance criteria shall be in accordance with Table IWB-3514-2 of ASME Section XI.

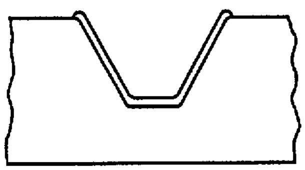
5.0 DOCUMENTATION

The use of this procedure to conduct repairs shall be documented on Form NIS-2.

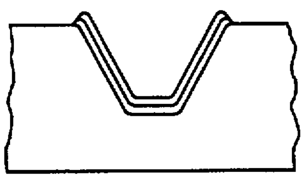


GENERAL NOTE: Base metal Charpy impact specimens are not shown. This figure illustrates a similar-metal weld.

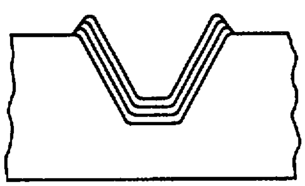
FIG. 1 QUALIFICATION TEST PLATE



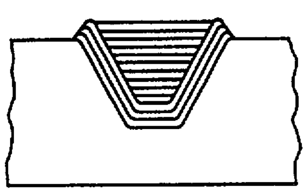
Step 1: Deposit layer one with first layer weld parameters used in qualification.



Step 2: Deposit layer two with second layer weld parameters used in qualification. NOTE: Particular care shall be taken in application of the second layer at the weld toe to ensure that the weld metal and HAZ of the base metal are tempered.



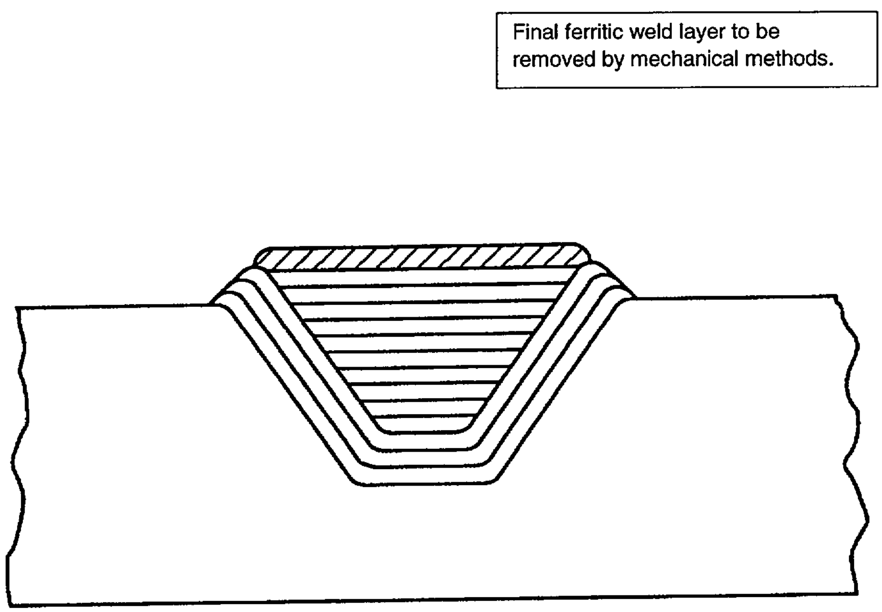
Step 3: Deposit layer three with third layer weld parameters used in qualification. NOTE: Particular care shall be taken in application of the third layer at the weld toe to ensure that the weld metal and HAZ of the base metal are tempered.



Step 4: Subsequent layers to be deposited as qualified, with heat input less than or equal to that qualified in the test assembly. NOTE: Particular care shall be taken in application of the fill layers to preserve the temper of the weld metal and HAZ.

GENERAL NOTE: The illustration above is for similar-metal welding using a ferritic filler material. For dissimilar-metal welding, only the ferritic base metal is required to be welded using steps 1 through 3 of the temperbead welding technique.

FIG. 2 AUTOMATIC OR MACHINE (GTAW) TEMPERBEAD WELDING



GENERAL NOTE: For ferritic filler metals the completed weld shall have at least one layer of weld reinforcement deposited. This reinforcement shall be removed by mechanical means, so that the finished surface of the weld is essentially flush with the surface of the component surrounding the repair.

FIG. 3 FINAL FERRITIC WELD LAYER

Enclosure 2

EPRI Report GC-111050, "Ambient Temperature Preheat for Machine GTAW Temperbead Applications"

Ambient Temperature Preheat for Machine GTAW Temperbead Applications

GC-111050
November 1998

LICENSED MATERIAL

Ambient Temperature Preheat for Machine GTAW Temperbead Applications

GC-111050

November 1998

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

Ambient Temperature Preheat for Machine GTAW Temperbead Applications

The potential for in-situ weld repair of reactor pressure vessel (RPV) components is greatly enhanced with temperbead welding techniques. These techniques eliminate the need for high temperature post-weld heat treatment (PWHT) in low alloy steels. This feature is particularly important for nuclear applications where it is impractical to achieve and maintain high temperature heat treatments especially with water backed components. *ASME Boiler and Pressure Vessel Section XI, Subsection IWA-4600* identifies requirements for temperbead applications on RPV and related components. Requirements include minimum 300^{0}F preheat and a post weld hydrogen bake. Physical property measurements on mock-up demonstrations of GTAW temperbead repairs indicate that these requirements are unnecessary. This report has been assembled to present direct evidence that ambient temperature temperbead repairs on water-backed components are capable of producing acceptable repairs where it is impractical to drain the component for operational or radiological reasons.

BACKGROUND *ASME Boiler and Pressure Vessel Code Section XI, Subsection IWA-4600* provides rules for applying temperbead weld repairs to low alloy steel pressure vessel components (P-Nos. 1, 3, 12A, 12B, and 12C materials). The 300^{0}F preheat temperature and post weld hydrogen bake is required by Code; however, recent data suggest that these steps are unnecessary to develop satisfactory material properties. Further, preheat and postheat requirements for in-situ water-backed applications can be impossible or impractical to achieve. The historical basis for welding preheat temperatures in low alloy steels (LAS) is based upon a desire to minimize any potential for hydrogen induced cracking, cold cracking or restraint cracking. This is especially true for materials having high carbon equivalent chemistries. Recent EPRI evaluations of gas-tungsten arc welds have demonstrated that the machine GTA welding produces welds having very low hydrogen levels even when performed under high moisture conditions (extreme humidity). This report is compiled to assemble a basis document that supports using ambient machine GTAW temperbead repairs. The report also presents information and data supplied by utilities and vendors who have successfully developed and qualified GTAW repair procedures at ambient temperature preheat conditions.

OBJECTIVES

- Support utility members in addressing an ASME Code Case for ambient temperature machine GTA temperbead repair welding.
- Evaluate the technical bases for requiring preheat and postheat treatments.
- Document available industry weld qualifications of temperbead repair without preheat requirements.
- Compare HAZ toughness for weld repair qualifications performed with and without 300^{0}F preheat.
- Produce state-of-the-art guidelines for GTA temperbead weld repairs of RPV and related components at ambient temperatures.

APPROACH This project compiles and evaluates available information from welding qualifications performed by utilities, OEMs, vendors, and EPRI RRAC programs with machine GTA temperbead welding. Results from these studies were used to compare material toughness and ductility for welds prepared using 300^{0}F preheat to those welded at ambient temperatures. Charpy Vee-notch impact test results were emphasized to measure weldment properties. Test results also were used to evaluate welds for minimum ASME toughness and ductility requirements (50 ft-lbs impact energy and 35 mils lateral expansion) at the lowest service temperature. The impact of preheat temperature and post weld hydrogen bake were considered individually for hydrogen delayed cracking, cold cracking, and restraint cracking mechanisms. Residual welding stresses resulting from temperbead applications also were considered.

RESULTS The application of machine GTA temperbead welding techniques to repair LAS RPV and related components, without preheat, can be successfully accomplished without cracking and will provide acceptable toughness and ductility properties. It is also shown that the potential for hydrogen delayed cracking is below a level for concern even with procedures having no postweld hydrogen bake.

It was clearly demonstrated that temperbead repair welds using the machine GTAW process at ambient temperature (no preheat) will produce toughness properties in LAS substrates that are equivalent to those produced using 300°F or greater preheats. Faster quenching rates of a smaller HAZ, related to GTAW parameters and no preheat, improve hardenability. Subsequent tempering of this improved HAZ microstructure by subsequent temperbead layers produces toughness properties that are improved over the original base material. Qualification testing (performed by NUTECH, CBIN, and GE/GPU Oyster Creek) clearly showed that toughness and ductility properties were well above the minimum Code requirements at test temperatures equal to or less than the lowest service temperature (50 ft-lbs absorbed energy and 35 mils lateral expansion).

An EPRI RRAC research program investigating temperbead welding techniques has demonstrated that the risk of inducing hydrogen delayed cracking in LAS is extremely small when using this process. Results of tests on materials having carbon equivalents representing specification limits for P-3 Group 3 showed no susceptibility for the machine GTAW process even when using the severe helical groove implant tests which actively load to stress levels just below yield strength and in extreme humidity environments. Thus neither cold cracking nor restraint cracking have been identified as problems. Postweld inspections required by Code are in-place and provide the means with which to identify potential cracking conditions.

EPRI PERSPECTIVE Over the past several years, a great deal of industry interest has been focused on relieving unnecessary requirements for high temperature preheat and post-weld heat treatments to repair low alloy pressure vessel steels. EPRI has devoted considerable effort to the study of temperbead and related welding techniques since the introduction of qualified temperbead and half-bead procedures more than 15 years ago. The studies have concentrated on the resultant material properties induced in the weld heat-affected zones (with and without heat treatments) and on the life assessment of components repaired using these techniques. This research has shown that the temperbead weld repair of pressure vessel steels consistently provides excellent material toughness without any need for subsequent exposure to elevated temperatures. It has been further shown that component life is extended and component integrity is maintained. Similar results have been produced by EPRI, and others, to support code changes that reduced the required high temperature post-weld heat treatment for temperbead repair of low alloy pressure vessel steels (*ASME Boiler and Pressure Vessel Section XI, Subsection IWA-4600*). In a similar spirit, this report has compiled and evaluated test results from multiple studies and qualifications that demonstrate a large body of evidence supporting ambient temperature preheat for machine GTAW temperbead applications with no postweld bake.

ABSTRACT

Effective repair scenarios can be developed by utilizing alternate temperbead weld repair technologies applied to reactor pressure vessel (RPV) components such as CRD housing, BWR feedwater and recirculation nozzles. Optimizing these procedures is important for large heavy walled components that are difficult to access, exhibit high radiation levels, and may be filled with water. Currently, regulations governing temperbead welding methods permit utilities to perform repairs without the need for high temperature post-weld heat treatments. *ASME Boiler and Pressure Vessel Code Section XI, Subsection IWA-4600* requires that GTAW temperbead welds applied to RPV materials use a 300 ^{0}F preheat followed by a 300 ^{0}F minimum post-weld bake for 2 to 4 hours for both P-No.1 and P-No.3 materials. EPRI has compiled a comprehensive collection of industry qualifications and reviews on gas-tungsten arc (GTA) temperbead weld repairs without preheating and no post weld bake to develop and assemble information justifying ambient preheat temperatures.

EPRI, Georgia Power Company, Chicago Bridge & Iron (CBIN), NUTECH, New York Power Authority (NYPA), General Electric/Oyster Creek, Vermont Yankee Power Station, and Indian Point Nuclear Station performed the industry qualifications discussed in this report. The qualifications covered temperbead weld repairs of nozzle to safe-end joints. In general, one portion of the component was repaired following Code preheat/postheat requirements (300 ^{0}F preheat/500 ^{0}F postheat), while a second portion of the component was repaired using lower preheat temperatures including ambient temperature with similar welding parameters and no postheat bake. Charpy Vee notch impact toughness properties were measured for each portion. Comparisons were made between each portion and with the ASME minimum RPV toughness requirement of 50 ft-lbs impact energy and 35 mils lateral expansion. Results indicated that the temperbead repairs using the lower temperature preheats significantly surpassed minimum ASME Code requirements, and were comparable and often superior to results obtained with 300 ^{0}F preheats and 500^{0}F postweld bakes.

Two primary degradation mechanisms are of concern for low alloy steel welding at ambient temperatures. These are cold cracking of high restraint geometries (weld shrinkage-induced) and hydrogen assisted cracking (hydrogen delayed cracking). Restraint 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). This mechanism is principally a function of high restraint weldment and component geometries coupled with welding approaches that do not provide sufficient tempering of the weld HAZ and result in zones having marginal fracture toughness. As the weldment cools shrinkage stresses build in tension. When these stresses exceed the fracture toughness in local volumes such as the weld HAZ, cracking occurs. Proper joint design, appropriate welding procedures and bead sequences, and effective tempering are practical concerns that avoid critical restraint cracking conditions. This form of cracking is addressed effectively by ASME code guidance including

welding procedure qualification testing, and by in-process and/or post-weld inspection. Therefore, the main concern in this study was to evaluate the more subtle hydrogen assisted or hydrogen delayed cracking.

Welding preheats traditionally are applied to reduce the risk of cracking due to either of these two phenomena. Preheating is not designed to produce significant changes to the weldment microstructures, although the HAZs will be influenced. Preheating does slow the cooling rate of a material during welding because the ΔT is smaller (difference between the temperature of the base material and the temperature of the weld is the driving force for cooling). In general, slower cooling rates should result in less shrinkage distortion (lower residual welding stresses) and a slight reduction in the hardness of the weld heat-affected-zone (HAZ). The current Code requirement to limit repair areas to 100 square inches bounds the effects of weld shrinkage and residual stress. It is recognized that the application of a low temperature preheat can often provide in practical welding benefits under specific circumstances. However, the principal reason for mandated preheat requirements with general temperbead weld repairs was to reduce the risk of hydrogen assisted (delayed) cracking.

The application of GTAW for alternate temperbead welds has a significant influence on the potential cracking mechanisms. Sources for hydrogen are minimized in this process and the control afforded by machine welding permits precise application of highly controlled weld beads. By applying proper weld repair designs, the risk of restraint cracking can also be avoided.

This report discusses these issues in detail. EPRI RRAC research has documented that the use of the GTA welding process significantly minimizes risk for hydrogen induced cracking for temperbead welds. EPRI sponsored programs also have shown that a reduction in HAZ hardness will result when applying proper temperbead welding techniques. In addition, stress mitigation techniques often can be performed in conjunction with temperbead welding to mitigate residual stress effects.

Current code regulations for temperbead weld repair of RPV components are described, several temperbead approaches are identified, and resultant HAZ impact toughness properties are compared for several industry procedure qualifications using temperbead welding with and without 300^0F preheating. The report also discusses the reasons for a very low risk of hydrogen induced cracking with machine GTAW temperbead weld procedure even under extreme humidity conditions.

CONTENTS

1.0
SUMMARY

Temperbead weld repair techniques are designed to enable repairs to low alloy steel (LAS) RPV components without need for high-temperature post-weld heat treatment (PWHT). The machine GTAW temperbead repair process produces sound weldments in these materials that exhibit excellent toughness and ductility. Unique characteristics of the GTAW process minimize the introduction of hydrogen into the welding arc. This factor alone effectively eliminates the potential for hydrogen delayed cracking. An increased control of electrical and mechanical parameters coupled with the capability to precisely place each weld bead assures that effective tempering will be achieved consistently.

The machine GTAW process is, by nature, a low heat input process that produces smaller volume heat affected zones. These zones will cool faster than flux shielded or GMAW welding processes. Eliminating substrate preheat will enhance the cooling rates of the weld HAZ. The rapid cooling is a desired effect because the heat affected zone (HAZ) microstructure that results will be populated with increased percentages of martensite and upper bainite. Since tempering is assured with machine control, the HAZ toughness produced will be equal or superior to the substrate material. Process qualification, demonstration and inspections required by the ASME Code provide added assurance of tough crack-free welds.

Current Code rules found in *ASME Boiler and Pressure Vessel Code, Section XI, Division 1- Subsection IWA-4600* require a 300^{0}F temperature preheat for temperbead welding applications. A 300^{0}F temperature preheat on large pressure vessel components is both difficult to achieve and to maintain, because the component is massive and often needs to remain full of water to facilitate radiation shielding of workers. Large components become huge heat sinks during welding, and when the component is water backed, preheating is impractical and often impossible. Therefore, it is important to carefully evaluate the technical bases requiring elevated temperature preheat and post-weld-bake for machine GTAW temperbead repair welds.

A welding preheat temperature traditionally is prescribed to mitigate one or more of the following concerns:

- solidification entrapped hydrogen
- high HAZ hardness and low toughness (untempered microstructure)
- weld distortion, residual stress, and high restraint loads

The principal reason to preheat a component prior to repair welding is to minimize potential for cold cracking. The two cold cracking mechanisms to avoid are hydrogen delayed cracking and low toughness stress cracking. Hydrogen delayed cracking is manifest as intergranular cracking of prior austenite grain boundaries and generally occurs within a period of 48 hours after completing the weld. 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 internal stresses will be produced from localized buildups 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.

Preheating accomplishes two significant purposes. First it reduces the cooling rate, and second, it increases the diffusion rate of monatomic hydrogen that may be entrapped. These combined actions facilitate diffusion of trapped hydrogen to the atmosphere. The welding method used and consumables applied are key considerations for preheat, because they will determine, in large measure, the degree to which hydrogen will be present in the weld.

Monatomic hydrogen is produced when the welding arc interacts with moisture adsorbed in a shielding flux, moisture contained in filler materials, moisture in the atmosphere, and potentially moisture or hydrocarbons on the surface of the base material being welded. The monatomic hydrogen created will become mixed with the molten weld metal, and potentially become entrapped upon solidification. Trapped hydrogen will attempt to diffuse away from the solidifying weld material and the adjacent base metal HAZ. Since diffusion is time dependent, hydrogen will be trapped if the molten puddle freezes faster than the hydrogen can escape. Entrapped hydrogen will tend to diffuse to locations having void space such as defects. The hydrogen will accumulate, and as the hydrogen concentration increases, recombination to molecular hydrogen will be favored. Internal stresses will build, and delayed cracking is possible if these stresses increase to levels exceeding the fracture toughness of the material.

The potential for cold cracking will be reduced significantly with the machine GTAW process for two important reasons. The most important reason is because most potential hydrogen sources either are not present or are present at minimal levels. GTAW makes use of a dry inert shielding gas that covers the molten weld pool. The process does not rely on a molten flux to shield the weld pool from oxidizing atmospheres. Any moisture on the surface of the component being welded will be vaporized ahead of the welding torch, and the inert shielding gas will prevent the vapor from being mixed with the molten weld pool by blowing the vapor away before it can be mixed. This action is in contrast to SMAW or SAW processes that rely on a flux to shield the molten puddle and adjacent substrate from the atmosphere. Moisture can be adsorbed in the flux coating when exposed to the atmosphere and that moisture would be available to react with the welding arc. In addition, any moisture that may reside on the surface of the metal being welded can be trapped by the molten flux and also would be available to react with the welding arc. Therefore monatomic hydrogen is more likely to be produced with flux welding processes.

Modern filler wire manufacturing practice produces wires having very low residual hydrogen compositions. This consideration is important because filler materials and base material substrates are the most realistic sources of hydrogen for machine GTAW temperbead welding. The monatomic hydrogen levels produced by the GTAW process will be extremely low, and therefore, no benefit will be derived from actions taken to facilitate diffusion of monatomic hydrogen away from the molten weld metal - preheat or post-weld bake. There is very little monatomic hydrogen present to diffuse away, and the levels that might be present will be below that which is necessary to support hydrogen delayed cracking in either P1 or P3 materials.

The second important reason that preheat is unnecessary for machine GTAW temperbead repair is that the microstructure produced in the weld HAZ is desirable. It will be characterized by high toughness and ductility upon being tempered by proper placement of subsequent weld beads. The rapid heat sink quench of the reaustenitized HAZ will result in a more hardened microstructure. Subsequent weld beads will effectively temper this microstructure. Quenched and tempered low alloy steels, such as P3 Group3 materials (SA508 Class 2) develop improved properties by increasing the rates of quenching followed by an appropriate degree of tempering. It is instructive to note that when heavy section product forms of this class of materials are tested and properties (especially Charpy Vee notch impact properties) are lower than desired, the material will be reheat treated and tempered to improve the properties. Every effort will be made to increase the quenching rate in order to produce a microstructure having a greater population of martensite and upper bainite. Upon tempering a tough and ductile material will result. The concern is not that a material is hardenable, but that it will be tempered properly. If the material has a higher carbon equivalent composition, the quenching rate need not be as rapid to produce a similar microstructure.

Tempering quenched low alloy steels normally is accomplished by heating the plate, forging or component to a temperature between 1250 and 1325^{0}F. This is done for the specific purpose of precipitating carbides to reduce internal stresses within the microstructure that developed during the formation of martensite and upper bainite. The precipitation process develops ductility and generates toughness by relieving the peak internal stresses developed during retransformation. It should be noted that elevated temperature stress relief heat treatment is performed at lower temperatures, by design, so that over-tempering will not occur and no grain refinement will occur. This also means that a stress relief heat treatment will contribute very little to the tempering process, because the temperatures are too low to facilitate the carbide precipitation necessary for tempering to take placed within a reasonable time period. Stress relief heat treatment is performed for the purpose of reducing residual welding stresses that result from solidification shrinkage.

The machine GTAW temperbead process is designed to temper the weld HAZ by supplying heat from subsequent adjacent weld beads. Machine GTAW readily controls heat-input parameters. and weld beads can be placed with relative precision in a reproducible manner. A procedure qualification is required by Code and will define bead placement that assures a correct degree of tempering. Mechanical testing documents the properties achieved.

EPRI conducted an experimental testing program in 1989 to address temperbead welding. Significant results were produced concerning the effects of low preheat temperatures during

GTAW temperbead repair. The program entitled *Temperbead Welding Repair of Low Alloy Pressure Vessel Steels*, focused on the following aspects:

- improved temperbead welding controls
- elimination of welding preheat requirements and
- elimination of welding postheat bake

The program concluded that a 300^0F preheat temperature was overly conservative for P3 materials and was unnecessary. Cold cracking was not observed under adverse moisture welding conditions even in the severe implant test at applied loads approaching yield strength of P-3 Group 3 materials (SA508 Class 2). It is noteworthy that the experimenters observed the improved HAZ impact toughness attendant to the slightly faster cooling rates afforded by reduced preheat and interbead tempering.

A number of industry temperbead weld qualifications using reduced preheat have been performed for BWR nozzle to safe-end weld joint repairs. Organizations including New York Power Authority (NYPA), CBIN, NUTECH, GE/Oyster Creek, and EPRI have successfully qualified temperbead welding procedures using reduced (or water backed) welding preheat conditions. Acceptable HAZ toughness, hardness, tensile, and bend properties were obtained in all cases. Charpy impact testing on these qualifications revealed HAZ toughness values exceeding the minimum Code required 50 ft-lbs and 35 mils lateral expansion. In all cases, HAZ toughness properties for the reduced preheat qualifications exceeded or produced comparable values to those measured for 300^0F preheat qualifications. Impact properties exceeded those obtained for the base metals regardless of preheat conditions.

Finally, it is noted that three important requirements *of ASME Section XI, Subsection IWA-4600* help to provide more confidence that satisfactory temperbead repair will be made. These include a procedure qualification that defines details of the procedure and tests for resulting properties, a repair demonstration that mocks-up the repair geometry, implements the procedure and tests the repair result, and nondestructive evaluation. The nondestructive evaluation requires one of two inspection approaches. The first inspects the weld surfaces by magnetic particle inspection as the weld is being made. The weld cavity and each weld layer after it is deposited (including a surface examination 48 hours after completing the weld) are examined. The second requires a magnetic particle examination of the weld cavity prior to welding followed by a full volumetric examination 48 hours after completing the weld. Either of these inspection approaches provides confidence that the repair weld will be free of cracking. The repair procedure qualification and successful demonstration document the capability to produce quality welds, and provide measured evidence that the toughness and ductility will meet requirements.

In summary, no preheat temperature or postweld bake above ambient is required to achieve sound and tough machine GTA temperbead repairs. This conclusion is based on strong evidence that hydrogen assisted (delayed) cracking will not occur with the GTA welding process. In addition machine temperbead welding procedures without preheat will produce satisfactory toughness and ductility properties both in the weld and in the weld HAZ. The results of numerous industry qualifications provide additional documentation to support the conclusions. The elimination of preheat and postheat bake will improve the feasibility of accomplishing localized weld repairs to carbon and low alloy steels that are otherwise impractical or impossible to accomplish without compromising weld quality – even for large water-backed components.

2.0 INTRODUCTION

2.1 Background

The ultimate goal of welded fabrication and repair activities is to produce homogeneous weldments free of defects which provide satisfactory tensile, yield, ductility, toughness and/or corrosion properties for a given service or design. Satisfactory properties typically are generated using traditional welding practices, such as consumable filler control, preheat, grinding, PWHT, etc.; however, novel approaches should not be excluded. In either case, satisfactory results from actual demonstration are documented in accordance with the appropriate code requirements for a welding procedure qualification record (PQR) and implemented via a welding procedure specification (WPS).

In some cases, traditional welding approaches and code criteria have been based upon corporate experience and best judgement, as opposed to experimentation, analysis, and technical demonstration. In the past, overly conservative practices have been required to ensure success because the proper alternative(s) were unknown or sufficient data were unavailable to evaluate alternatives. This is not the case for temperbead techniques. Extensive experimentation and analyses have been developed to document evidence supporting and validating temperbead repair techniques. It is useful to understand the details of the process to fully comprehend the technical rigor of the procedures.

Temperbead welding refers to a specific welding approach in which the heat of deposited weld layers is precisely controlled to provide sufficient heat to temper each previously deposited weld layer. This tempering will produce requisite material strength and toughness properties without a need for any post-weld heat treatment. The approach employs two or more weld layers applied consecutively to generate both weld and HAZ properties that are equal or superior to the base metal. The technique is applicable to a variety of carbon and low alloy steel materials.

The primary objective of temperbead repair welding is to produce a sound weld having HAZ toughness properties equal to or greater than the original base material. The alternate temperbead repair technique when applied to low alloy steel materials (P1 and P3) achieves tempering by introducing heat in subsequent weld beads (layers) sufficient to consistently temper the weld HAZ produced by the initial weld bead. The heat penetration of each layer is carefully applied (overlapping bead placement) to produce overlapping thermal profiles that develop a correct degree of tempering in the underlying weld supporting high toughness and ductility. The technique is designed to assure that tempering is accomplished.

A narrow zone of material adjacent to the molten weld bead will be heated above the critical transformation temperature (A_{C1}). This action produces a degree of grain refinement and creates a zone of untempered transformation products (mixture of martensite, upper bainite, lower bainite, pearlite, ferrite, and potentially retained austenite). The percentage of each transformation product is dependent upon the hardenability of the material and how fast the material is quenched. The welding process, especially the GTAW process, produces a very rapid quench of the HAZ that is faster that the cooling rate of the original base material. The HAZ microstructure will contain greater volumes of martensite and upper bainite, and when tempered properly, the toughness will be superior to the original base material. The temperbead process is carefully designed and controlled such that successive weld beads supply the appropriate quantity of heat to the untempered HAZ such that the desired degree of carbide precipitation (tempering) is achieved. The resulting microstructure is very tough and ductile.

In contrast, traditional PWHT provides no significant tempering (in a reasonable period of time) nor does it produce grain refinement. The PWHT is designed to relieve peak weld residual stresses produced by the shrinkage of solidifying weld metal and subsequent cooling below the transformation temperature.

Current code requirements in *ASME Section XI, Subsection IWA–4600* for temperbead weld repairs do not require high temperature PWHT for P-Nos. 1, 3, 12A, 12B, and 12C materials. This recognition is based on measured data and individual studies that demonstrate satisfactory tempering of the newly formed HAZ transformation products. Specific requirements have evolved over recent years beginning with approval of Code Case N-432 in February 1986 and subsequently adopted into Section XI of the ASME B&PV Code. Details of the procedures have become better defined as pertinent information has been developed. The code bodies have long recognized that heating in-situ is impractical for large pressure vessel components that have seen service. Also, localized heat treatments are extremely difficult to facilitate and often can produce undesirable side effects in terms of component distortion, thermal stresses and material degradation attendant to such procedures. The intrinsic difficulty for obtaining elevated temperatures in large (often water-backed) components for pre-heating or for post-heating makes the process undesirable and in many cases impossible. Therefore, repairs to water-backed RPV components such as nozzles, vessels, and nozzle-to-safe end welds that could not be accomplished without draining the component could be facilitated by eliminating the preheat and postheat requirements for P - 3 Group 3 materials, in particular.

An ambient temperature preheat applied to GTAW temperbead weld repairs will produce excellent weldment properties (weld deposit and HAZ) that are equal to or better than base material properties. In addition recent EPRI evaluations of GTA welds have clearly demonstrated that very low hydrogen levels are to be expected even when performed under severe humidity conditions [1]. GTA welding eliminates the need for elevated preheat temperatures, because the process, by nature, is highly resistant to hydrogen induced cracking (cold cracking). This guideline discusses the details of the process and seeks to summarize and highlight past GTA temperbead welding repair research and development, utility and vendor procedure qualifications, and EPRI developments.

2.2 Current Regulations and Repair Information

Prior to early 1986 the only means of localized weld repair without postweld heat treatment (PWHT) was the *half-bead repair technique* that employed the manual Shielded Metal Arc Welding (SMAW) process. The method provided HAZ and bead-to-bead tempering by removing half of each deposited bead prior to applying the next bead or layer – thus the name "half-bead". The process was demonstrated successfully for large heavy-walled pressure vessels in a cooperative effort between the government supported Heavy Section Steel Technology (HSST) program and EPRI [4]. In this cooperative effort the HSST intermediate test vessel (ITV-7) that had been preflawed and pressure tested to failure, was repaired using a half-bead procedure without PWHT. The SA 508 class 2 vessel was subsequently preflawed at the repair location and retested to failure. The resulting failure pressure was greater than the original test vessel failure. The fracture toughness properties of the half-bead vessel repair were superior to the original forging properties.

The half-bead welding approach is not suited to repair applications having limited access or high radiation exposures because of the need for workers to remove half of each weld layer deposited. During the early 1980s, EPRI initiated a program at Babcock and Wilcox to develop alternative welding parameters that could be used to repair nuclear reactor pressure vessel (RPV) components without the need for PWHT [1]. The repair technique (now referred to as the *"alternate temperbead repair technique"*) provided an alternative to the conventional half-bead approach and was recognized in February 1986 as an acceptable repair alternative by *the ASME Boiler and Pressure Vessel Code under Section XI Code Case N-432*. This alternative recognized the use of either the GTAW or the SMAW processes. A minimum preheat temperature, a maximum interpass temperature, and a postweld bake were required. The essential provisions in this code case were subsequently (1992) incorporated into Section XI Subsection IWA-4600 Alternate Welding Methods. Minor changes and improvements have been adopted into IWA-4600 in the recent past. The *"alternate temperbead technique"* has been qualified for many specific applications related to nuclear pressure vessel applications, and has been implemented in a number of documented repairs.

2.3 GTAW Temperbead Repair Techniques

The *"alternate temperbead repair technique"* applies the machine gas-tungsten arc welding (GTAW) process and provides users with an option for remote repair. An approach similar to that used for the earlier half-bead repair technique was utilized for this alternate temperbead repair making use of the advantages of machine welding. The requirements included:

1. Perform an initial procedure qualification verifying with mechanical testing.
2. Preheat and maintain the repair area at a minimum temperature of 300^0F throughout the repair process.
3. Butter a total of six layers as shown in Figure IWA-4623-1 of Appendix A.
4. Control welding heat input within ten percent (plus or minus) of that used in the procedure qualification for each of the initial six layers.
5. Complete the weld deposit with a heat input equal to or less than that used for the layers beyond the sixth in the procedure qualification.

6. Perform a post-weld bake in the temperature range (450^0F to 550^0F) for a minimum of 2 hours.

The alternate temperbead repair technique has been a valuable tool for the power industry resulting in substantial savings for several users. A number of organizations (utility and vendor) have developed, and/or qualified and applied temperbead welding procedures. Additional refinements to temperbead repair technology have been achieved under several EPRI projects [1, 2, 3, 6 & 7]. These refinements, supported by independent data generated by utilities/vendors, prompted the ASME code bodies to incorporate the alternate temperbead repair technique into the main body of the *1992 ASME Boiler & Pressure Vessel Code Section XI IWA-4600.*

ASME Section XI currently permits temperbead repair on base materials (P-Nos. 1, 3, 12A, 12B, and 12C) without application of post-weld heat treatment requirements of the original Construction Code or Section III provided that the application is qualified and implemented according to Section XI Subsection IWA-4600. It is beneficial to note that as of May 1998 (ASME B31.1), additional piping base material grades (P-Nos. 4 and 5) may be repaired without PWHT when the following conditions are met:

- wall thickness is 1/2 inch or less, and
- carbon content is 0.15 wt. % or less.

Several welding techniques have been developed and utilized over the past 25 years to successfully repair heavy section components such as pressure vessels, nozzles, turbine casings, piping, and headers. These techniques have included the conventional half-bead technique, the alternate temperbead technique, and more recently the controlled deposition and the consistent layer technique [6]. These techniques are valuable because they provide alternatives with which to repair heavy section components without the need or requirement for high temperature (1050 to 1125 ^{0}F) stress relief.

The "*Controlled Deposition Technique*" is a special application of the alternate temperbead technique using SMAW. This approach was developed through a cooperative effort between Ontario Hydro of Canada and the University of Tennessee. The technique initially was conceived to repair fossil power piping that had been degraded by creep embrittlement and/or weld reheat cracking mechanisms. The approach strictly controls the ratio of heat inputs between adjacent SMAW layers so that suitable grain refinement and tempering are produced.

The "*Consistent Layer Temperbead Technique*" (CLTT), is another temperbead approach that is designed to produce tempered microstructures similar to those created by the alternate temperbead technique [6]. The details and controls of the CLTT approach are slightly different. The CLTT approach limits the temperatures applied to previously deposited layers to temperatures below the A_{C1}. Heat input controls for the CLTT are designed to avoid the creation of new transformation products as well as the grain refinement attendant to such transformation products. Instead, CLTT seeks only to temper the HAZ produced by the previous weld layer. This goal is similar to objectives sought in an elevated temperature PWHT. The desired tempering of the weld HAZ is uniquely produced through proper bead placement, by developing a consistent bead shape, and by maintaining a single set of welding parameters. The primary advantages of CLTT are that unnecessary weld layers are eliminated, a single set of welding parameters is employed throughout the welding process, and excessive weld dilution is minimized.

A preheat temperature of at least 300^0F is required by the ASME Code for all three techniques - alternate temperbead technique, CLTT, and the controlled deposition technique currently. The following sections will discuss principles underlying traditional preheats, and how preheats can be avoided when utilizing the GTAW process with the Alternate or Consistent Layer temperbead techniques. The discussion will cover specific developments associated with machine GTAW temperbead repairs and, in particular, will focus on information developed to support reduced preheat welding applications.

3.0 WELDING PREHEAT/POST-WELD BAKE

3.1 Purposes of Welding Preheat

Preheat is the application of heat to a weld or weldment substrate immediately before a welding operation (*ASME Section IX and AWS A3.0-89A*). Traditionally preheat is applied to minimize the potential for cold cracking. Although preheat can influence some of the details of welding, it normally is not intended to alter microstructures. Increasing preheat temperatures will increase the total heat inventory for a given weld and will cause the cooling rate to be lowered. The following benefits have been attributed to preheating: 1) lower heat-affected zone hardness, 2) a reduction in residual stresses, and 3) decreased component distortion. Studies have shown that as preheat and maximum interpass temperature increase, the size of the HAZ increases, tensile strength decreases, and notch toughness properties of both the deposited weld metal and the HAZ decrease [11].

Two principal cold cracking concerns are associated with the need to preheat. These forms of cold cracking are *hydrogen delayed cracking and stress related low toughness fracture*. The mechanisms for each of these types of degradation are very different and must be considered individually.

The application of preheat will reduce the temperature differential ΔT between the weld bead and the base material. A lower ΔT reduces the driving force to produce the austenite-to-martensite transformation in hardenable steel. The microstructure produced with slower cooling in any heat treatable material (untempered or inadequately tempered) will be more tolerant to stresses created during welding, because the microstructure of the HAZ will be less brittle. In addition, the slow cooling rate will increase the capacity of the structure to accommodate thermal distortion, and the stresses will be lower. Thus the tendency for stress related fracture of low toughness volumes (HAZ) would be reduced. Increased preheat temperatures are known to be especially beneficial for welding high restraint geometries.

Equally important, the application of preheat will increase the solubility and diffusion rate of hydrogen in steels. This allows the escape of hydrogen trapped during the solidification process, and will minimize potential for hydrogen delayed cracking. Preheat and post-weld hydrogen bakes traditionally have been performed to facilitate the relief of internal pressure and stresses attendant to trapped hydrogen. P3 Group 3 steels are known to be susceptible to hydrogen delayed cracking if hydrogen is trapped in the structure. Machine GTAW temperbead repair techniques are tolerant to both of these mechanisms and are discussed individually.

3.2 Cold Restraint Cracking

Cold cracking occurs in a transgranular fashion. Cracks travel across the grains and have little tendency to follow grain boundaries. Cold cracking generally occurs during cooling at temperatures approaching room temperature. As stresses build under a high degree of restraint, cracking may occur at defect locations according to fracture mechanics principals. High hardenability without tempering will promote cold restraint cracking.

There are two aspects to cold restraint cracking that should be considered. These are 1) the source of stress applied to a structure and 2) the toughness of the material upon which the stress is applied. Each of these factors is considered.

Two regions may become hardened as a result of 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, and the microstructure within this zone transforms to austenite. Upon cooling the material retransforms into martensite, upper bainite, lower bainite, pearlite, ferrite, and in some cases retained austenite. The transformation products depend upon the hardenability of the material (specific composition) 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 will be more tolerant to stress and weld distortion. When tempered the microstructure of the higher hardenability material is superior. 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 when untempered, but will be a less desirable in the tempered condition. The application of preheat is such an action because the rate of cooling is slowed over the no preheat condition. It is interesting to note that this is one reason that interpass temperature is strictly controlled in low alloy steels.

Untempered martensite and upper bainite microstructures are very hard and brittle structures. Carbon and other interstitial atoms are locked within the microstructure causing a tremendous degree of internal stress. This produces strength, but unfortunately, also produces low ductility and thus low toughness. When heat is applied to the structure in the range of 1250 to 1325 ^{0}F the carbon will begin to precipitate as carbides and the microstructure will toughen very rapidly. Tempering is both time and temperature dependent. 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 1150 ^{0}F.

The temperbead process is designed to provide a sufficient heat inventory so as to produce the desired tempering for high toughness. For this reason, the high martensite microstructure is desired because of the improved toughness that will be developed. The toughness and ductility of the HAZ typically will be superior to the base material substrate, because the quenching rate will be faster than the original product form. The machine GTAW temperbead process provides precision bead placement and control of heat. Therefore the resulting structure will be tempered and preheat is not desired.

The hardenability of the material (ability to form martensite) is strongly dependent upon composition and especially upon the carbon content. The welding community has developed several carbon equivalent (CE) formulas with which to estimate the hardenability based upon the composition. All of these formulas are empirically based. The International Institute of Welding (IIW) formula is generally accepted by the welding industry as a useful tool with which to describe CE [2]. The formula is as follows:

$$CE_{IIW} = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15$$

This formula considers carbon, manganese, chromium, molybdenum, vanadium, nickel, and copper contents. Cooling rates generally determine the microstructure of a given material or CE.

These formulas are especially important considerations for welding, because both the welding filler materials and the base materials will be influenced by variability in restraint, in compositions, in heat inputs during welding, in section sizes and thicknesses. Preheat and interpass temperatures (cooling rates and temperatures) are less of a factor when processes such as machine GTAW is used because of the electrical and mechanical controls afforded by the process. Table 3-1 provides calculated average CE values for selected ASME Code materials.

Table 3-1
Computed CE_{IIW} for Selected ASME Code Materials

P-No.	Material Classification	CE_{IIW} (avg.)
P-1 Gr.1	SA-36	0.44
	SA-106 Grade B	0.57
P-1 Gr.2	SA-516 Grade 70	0.48
P-3 Gr.1	SA-387 Grade 2	0.56
P-3 Gr.3	SA-302 Grade B	0.55
	SA-533 Grade B Class 1	0.61
	SA-508 Class 2	0.65

Based upon the CE_{IIW} the SA508 class 2 materials have the highest hardenability of the P3 materials and typically used in the extra heavy section thicknesses such as tubesheets and large nozzles. SA533 Grade B class 1 is next at $CE_{avg} = 0.61$, and is used in heavy walled pressure vessels. SA302 Grade B was the predecessor to the SA533 Grade B class 1 material and has a $CE_{avg} = 0.55$.

The second region of the weldment that may become hardened is the HAZ of the weld deposit itself. The ability of the weld deposit to form martensite is evaluated in a manner similar to the base material above. If the cooling rate is sufficiently rapid, and if the carbon equivalent is sufficiently high, then the HAZ will become hardened. Without tempering, cracking will be possible; however, the machine GTAW temperbead repair process assures tempering and the same toughness considerations apply. Welding consumables are very carefully selected and formulated to provide properties superior to the base material, and generally will not be a problem.

Residual welding stresses are generated in a structure during cooling. As the weld deposit solidifies, the weldment shrinks. Upon cooling an approximately 7% volume expansion occurs at the critical temperature. Further cooling to room temperature shrinks the heated area according to the coefficients of thermal expansion. This typically will result in distortion and the attendant buildup of stress. If the stress intensities developed exceed the fracture toughness of the HAZ volumes, the structure will crack. High restraint geometries will accentuate the effects of the shrinkage and distortion stresses by focusing the resulting strains at specific locations. When these strains coincide with low toughness material, cracking may result. The application of preheat tends to minimize the strain, while the application of the temperbead process maximizes the toughness.

There is a 100 square inch limitation on the area to be repaired in the ASME Code, and this factor tends to minimize the volumes that can be affected by strain, and thus minimizes the potential for cracking. This control also bounds the volume affected by residual welding stresses, and minimizes the influence of any other potential degradation mechanisms related to residual stress. The size limitation for temperbead repairs also tends to limit the restraint associated with the weld, and will help to minimize the potential for cold cracking. It is essential to remember that repairs are inspected either by magnetic particle inspection methods volumetrically between layers or by volumetric ultrasonic inspection after welding or both. These factors in concert provide defense against any potential for cold stress cracking.

3.3 Hydrogen Delayed Cracking

Hydrogen delayed cracking is the second form of cold cracking. It is manifest by intergranular cracking of prior austenite grain boundaries, and normally, occurs within a period of 48 hours after welding. This form of cracking requires the presence of hydrogen in the weldment and low toughness material. If the volume of hydrogen is limited, this form of cracking will not be operative. Similarly, if the material is characterized by high fracture toughness, the process will not be operative. These factors will be considered in light of a need for preheating the structures.

Fracture toughness has been considered in detail in Subsection 3.2 and it was concluded that the machine GTAW temperbead process would consistently produce high toughness in the weld HAZs because of the control of process variables. Improved hardenability yields better toughness and thereby resistance to cracking. This holds true for hydrogen delayed cracking as well. The principal difference rests with inspection requirements. Therefore the main point to consider is the presence and effects of entrapped hydrogen. It will be shown that the possible levels of entrapped hydrogen that can be developed with the machine GTAW temperbead process are below the levels needed to support hydrogen delayed cracking. Measurements clearly demonstrate that the process can only develop hydrogen contents described as very low to low hydrogen processes and are not susceptible to hydrogen delayed cracking because there is insufficient hydrogen present to support delayed cracking mechanisms regardless of hardenability.

The sequences of events that might lead to hydrogen-induced cracking begin with the conversion of molecular hydrogen and hydrogen containing compounds into monatomic hydrogen in an ionized state in the molten weld pool. The solubility of hydrogen in solid metals is very low, especially with modern manufacturing practices. The International Institute for Welding provides definitions for hydrogen content. In general,"extra-low" hydrogen content is considered to be less than 5ml/100g H_2 of deposited weld metal and a "low" hydrogen content is less than 10 ml/100g H_2. Hydrogen contents between 10 and 15 ml/100g H_2 are considered "medium" hydrogen contents. Hydrogen contents greater than 15ml/100g H_2 are not considered as "hydrogen controlled".

A recent EPRI program, *Temperbead Welding of Low Alloy Pressure Vessel Steel*, Gandy, et al, conducted extensive research examining the levels of hydrogen associated with the GTAW process [(2)]. Their research included several key aspects:

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 power plant,
2. measurement of diffusible hydrogen levels for various shielding gas dew point temperatures,
3. examination of the diffusible hydrogen levels for modern off-the-shelf filler wires, and
4. conservative hydrogen diffusion rate calculations based on diffusion rate data developed over the past 30 years.

Severe welding environment conditions were examined (95 percent humidity and 120 ^{0}F atmosphere) that were similar to or exceeding those expected for reactor dry well conditions. Results indicated that extremely low diffusible hydrogen levels (on the order of 1.0 ml/100g H_2) should be expected when welding at a preheat temperatures between 150 ^{0}F or 300 ^{0}F. The hydrogen levels were judged to be dependent primarily upon the moisture content of the shielding gas, and possibly the filler wire employed or the surface cleanliness of the component surface being welded. The heat from the GTAW welding arc is very hot and will quickly vaporize surface moisture ahead of the welding arc. The shielding gas covers the arc and effectively dissipates the vaporized moisture away from the arc before it can react and from monatomic hydrogen to mix with the molten weld pool. Therefore, any effect of surface moisture on the substrate being welded is minimized with the GTAW process - an inherent characteristic.

Diffusible hydrogen tests were conducted by Gandy, et al for conditions between –60 ^{0}F (extremely dry) and 55 ^{0}F (wet or moist). The results are shown in Figure 4-1. The results indicate that the GTAW process produces extremely low diffusible hydrogen levels (less than 2.0 ml/100g H_2 were measured when the dew point of the shielding gas was below a –10 ^{0}F). Typical welding conditions stipulate "welding grade" cover gases (dew point temperatures are –65 °F or less) shielding cover gases, and should produce even lower resulting hydrogen levels in the deposited materials.

The significance of these studies is that *extremely low volumes of diffusible hydrogen should be expected for modern GTAW filler wires.* Modern techniques for producing quality GTAW filler wires have resulted in improved alloy compositional consistency and in lowering of diffusible hydrogen levels. The typical hydrogen content for the GTAW process is less than 1.0 ml/100g H_2. Table 3-2 provides measured hydrogen contents for several 80 series filler wires. Therefore the volumes of hydrogen available in the base material or the consumables are so low, they do not represent credible sources of hydrogen in sufficient quantities to support hydrogen delayed cracking. The source of hydrogen cannot be base metal nor is it the metallic consumable.

Table 3-2
Measured Diffusible Hydrogen Contents for GTAW Filler Wires using a 150°F Preheat

Filler Wire	Heat Number	Avg. Diffusible Hydrogen Content (ml/100 g H_2)
ER80S-B2	2301309	0.32
ER80S-B2	F5409	1.86
ER80S-G	9331612	0.73
ER80S-G	349866	0.45
ER80S-G	485936	0.52

The principal sources of hydrogen in welding are found with flux shielding processes such as SMAW, SAW, and FCAW. The hydrogen source comes from high temperature reactions among hydrogen bearing compounds and from moisture adsorbed in the fluxes. Environmental moisture (humidity) is a secondary source of hydrogen. As the weld pool cools, most of the monatomic hydrogen in the melt combines to form molecular hydrogen gas or react with other elements or compounds to form other low solubility gases then vent to the atmosphere.

The second step is for the monatomic hydrogen to become entrapped in the solidified weld metal or adjacent base material lattice during cooling. The material rapidly becomes supersaturated with hydrogen and a state of equilibrium is sought between the material and the hydrogen. Equilibrium is achieved by the diffusion of monatomic hydrogen to internal cavities within the microstructure. These internal cavities include void space surrounding nonmetallic inclusions, or gas pockets, but the principal discontinuities of interest are the prior austenite grain boundaries of the substrate microstructure. Equilibrium diffusion will tend towards discontinuities in the atomic lattice such as are created by the formation of martensite. As monatomic hydrogen concentrates at these cavity and/or discontinuity locations, it will combine to form the more stable hydrogen molecule (H_2). Considerable pressure stresses build as the molecular hydrogen is generated.

Steel has a very low solid solubility for molecular hydrogen, and the molecule is incapable of diffusing through the metal lattice. Therefore, the molecule becomes trapped in the weld metal or HAZ. High pressure-stresses develop, and when the stress intensity exceeds the fracture toughness of the material, a crack will initiate and begin to grow. The hydrogen concentration is time dependent and thus time is required for hydrogen-induced cracking to take place. (See References 12, 13, 14, & 15)

The best control for limiting the potential for hydrogen delayed cracking is to effectively limit the sources of hydrogen. This control is inherent with the machine GTAW temperbead process because the hydrogen content developed is very low (typically less than 1.0 ml / 100 g H_2 – too low to support hydrogen delayed cracking.

Preheating can effectively minimize sources of hydrogen for flux shielded welding processes such as SMAW and SAW. However GTAW processes do not use fluxes and the need to control that source of hydrogen is unnecessary. Therefore, the need to preheat for the purpose of eliminating hydrogen concentration does not exist.

3.4 Heat-Affected Zone Hardness

Preheating lowers or slows the cooling rate following welding, regardless of all other welding conditions and effects. Cooling rates will be faster for a weld performed without preheat than with a preheat, for any given set of welding conditions. Higher preheating temperatures result in slower cooling rates after the weld is completed. This is because the ΔT (difference in temperature between the material immediately following welding and the base temperature) provides the driving force to cool the component. The cooling rates, in-turn, determine the final microstructures of the steel. The typical microstructure of low alloy steel formed upon welding is a mixture of martensite and both upper and lower bainite. Faster cooling rates will change the proportions of these phases (the proportion of martensite will tend to increase for a given alloy composition). In addition, preheating lowers the thermal conductivity of iron and steel. This factor also slows the withdrawal of heat from the weld zone (i.e. slower cooling rates). An increase in base metal temperature also tends to promote superheat of the weld puddle in arc welding.

Reduced preheat temperatures, below 300 ^{0}F, for 1/2Cr-1/2Mo RPV steels have been shown to be technically beneficial when proper welding techniques are employed. Welding techniques such as the consistent layer temperbead technique, which promote the formation of martensite during the initial weld layer and subsequently temper the martensite during application of additional layers, have been shown to develop mechanical properties exceeding those of the original base metal. These properties often exceed those produced by welding methods aimed at retransformation and grain refinement of the heat-affected zone generated from the first layer during application of a subsequent layer.

The formation of martensite within the heat-affected zone results in increased hardness and tensile strength within this region. In the absence of tempering processes (i.e. subsequent weld deposited layers) an extremely hard and potentially brittle volume is formed. Hardness values exceeding Rc

48 have been observed. Tempering provided by subsequent layers marginally softens the peak hardness of the HAZ. Testing shows that hardness values around Rc 36 are typical for temperbead applications. It is noted that the fracture toughness of this region is often superior to the toughness of the original base material. A tempered martensite microstructure is an excellent fracture toughness microstructure.

Heat affected zone hardness is not a concern in nuclear environments. It is recognized that in other environments, such as petrochemical, the materials and degradation mechanisms can be different and hardness needs to be controlled. Different requirements are appropriate for such cases.

3.5 Residual Stresses and Component Distortion

Residual stresses can be developed through a variety of fabrication processes. Welding is a means common to most fabrication processes. Experiments conducted in EPRI sponsored programs have measured residual welding stresses near the weld fusion line that exceed yield strength of the base material. Elevating the preheating temperatures can provide a beneficial result in that the lower thermal gradient in the weld region produces slightly lower peak residual stresses.

Additional residual stresses are developed from volumetric changes associated with microstructural changes within the weld and the HAZ. The microstructure transforms from the high temperature face-center cubic (austenitic) microstructure to a body-center cubic (banite) or hexagonally-close packed (martensitic) structure. These atomic reordering processes produce significant volume increase which tends to offset shrinkage stress throughout the weld region. Further cooling to room temperature will produce additional shrinkage and develop residual stresses and distortion. Residual stress in some cases can increase the susceptibility of a material to stress corrosion cracking. This is generally not a problem for low alloy steel nuclear components.

The EPRI program *Temperbead Welding Repair of Low Alloy Pressure Vessel Steels* investigated residual stresses and shrinkage associated with temperbead repair of low alloy steel materials. In particular the program evaluated the stresses and shrinkage for overlay and vee-groove weld repair geometries using a 1-1/4Cr, 1/2 Mo (P-No. 4) pipe. A P-No. 4 material has increased hardenability over P-No.3 material. These repairs were made utilizing the Consistent Layer Temperbead Technique. The study evaluated several techniques to improve as-welded residual stresses. It was determined that bead placement along the toe area of the 2nd layer pass provided for some degree of reduction in residual stress. Residual stress at the weld fusion line was measured at approximately 65ksi – a reasonable value for the weld fusion line. Residual stress values drop rapidly to a value approximately zero at a position 0.35-inch (9mm) from the fusion line.

Residual stresses on the order of the yield strength of the substrate are to be expected with the temperbead process using conventional filler materials. Experimental welding studies using high nickel content fillers has produced encouraging results for low residual stresses. These initial experimental results are based upon lowering the transformation temperatures such that the austenitic to body-centered cubic transformation occurs just above service temperature. This approach takes advantage of the volume expansion that occurs upon reordering and tends to offset shrinkage-developed stresses. Although early test results are encouraging, filler materials of this type are not available commercially, and have insufficient test data to justify current usage.

4.0 WELD REPAIR EVALUATIONS AND PREVIOUS QUALIFICATIONS

4.1 Industry Qualifications with Preheat Below 300^{0}F

Chicago Bridge & Iron Nuclear

CBIN addressed the need for water-backed nozzle to safe-end weld repairs in 1989. They embarked on a program to:

1. develop baseline materials properties employing a Code Case N-432 type qualification and
2. qualify and provide supporting technical data for an Inconel 82 overlay repair method which could be utilized with or without water backing in the affected nozzle to safe-end.

A mock-up nozzle was configured with a partial thermal sleeve to accomplish this task. This configuration allowed water to be confined to one-half of the nozzle (0 to 180 degrees), while using air backing on the opposite half (180^0 to 360^0). No preheat or PWHT was employed during the repair activity.

CBIN also performed a Code Case N-432 groove weld on another section of the nozzle forging without water backing to provide a baseline with which to compare overlay weld properties. The results of the CBIN qualification suggested HAZ toughness properties for the water backed and the non-water backed repairs were comparable to those that employed a 300 ^{0}F preheat temperature. HAZ and plate toughness data for each qualification is shown in Tables 4-1 and 4-2. As shown, the majority of the HAZ toughness values are on the order of 90-100 ft-lbs with lateral expansion values in the 50 to 65 mils range.

NUTECH

NUTECH developed procedures and qualified two weld overlay approaches as part of contingency plans for Oyster Creek Nuclear Plant during the period 1988-1989. The first overlay qualification was performed dry (non-water backed condition), and followed the approach described in Code Case N-432. A five layer, 300^{0}F preheat, 500^{0}F post heat, temperbead overlay repair was applied to one-half of the nozzle to safe-end. Following completion of the initial weld, a second overlay qualification was performed with 80^{0}F water backing for the remaining half of the nozzle to safe-end overlay. This weld was performed without preheat or PWHT. The second portion of the NUTECH program evaluated groove weld repairs from the outer surface that were performed to different depths within the nozzle section of the nozzle to safe-end mock-up. The first groove temperbead repair qualification was performed at a depth of 1/2-inch, while the second was performed at 1-1/4-inch depth.

Groove repairs were conducted in a manner similar to the overlay repairs described above. For example the first one-half diameter of each groove weld was performed following Code Case N-432 requirements, and the second half diameter of each groove repair applied water backing - welded at an average temperature of 70-75^{0}F with no PWHT. Five temperbead weld layers were applied in each case. The balances of the grooves were completed using normal welding parameters. Each of the four welds (overlays with and without water backing/preheat and grooves with and without water backing/preheat) were subsequently sectioned and the mechanical properties were evaluated including Charpy Vee-notch impact tests. Satisfactory results were observed for bend, hardness, and tensile tests with each condition. Toughness impact test results were satisfactory with each condition and are detailed in Tables 4-1 and 4-2.

New York Power Authority

New York Power Authority (NYPA) also recognized a potential future need for reduced preheat temperatures to address repairs to water backed components. In conjunction with General Electric, NYPA developed two welding procedures using temperbead groove welds similar to those called for in *ASME Boiler and Pressure Vessel Section XI, Subsection IWA-4600.* Both procedures utilized a SA508 Class 2 ring forging (to which the groove weld repairs were applied). The first of the two procedures applied the Code required welding preheat of 300^{0}F and a 500^{0}F PWHT. The second procedure utilized a 200^{0}F preheat and no PWHT. Identical welding parameters were used for both welding procedures, and Inconel 82 was utilized as the filler metal in each case. The ring forging was sectioned after welding and both mechanical and metallurgical evaluations were performed. Mechanical tests included bends, tensiles, HAZ microhardnesses, and Charpy Vee-notch impact tests. Results for each procedure were excellent. Acceptable bends, tensile and hardness values were recorded for every coupon. HAZ impact energy absorbed ranged from 103 to 129 ft-lbs and lateral expansion values ranged from 51 to 75 mils for the groove weld employing the 300^{0}F preheat. The second groove weld (200^{0}F preheat) produced similar results (adsorbed impact energies ranging from 98 to 112 ft-lbs and lateral expansion ranging from 58 to 66 mils (Table 4-1). Subsequently, NYPA also demonstrated the 300 ^{0}F preheat weld overlay procedure on a full-scale ring forging to Type 304 stainless steel (simulated) safe-end.

General Electric/Oyster Creek

The General Electric Company (GE) also addressed the need for a water-backed temperbead weld overlay repair technique. A temperbead welding procedure was successfully qualified with neither welding preheat nor PWHT. Initially a welding overlay procedure was qualified closely following the requirements of *ASME Boiler and Pressure Vessel Section XI, Subsection IWA-4600.* This procedure served to act as a control weldment as a comparison with other weld overlay test procedures. The qualification was performed on a SA508 Class 2 nozzle forging into which a groove had been machined. HAZ Charpy Vee-notch impact tests were performed on the completed weld repair. The room temperature adsorbed impact energy ranged from 95 to 116 ft-lbs, and the lateral expansion ranged from 46 to 71 mils (Table 4-1). Both measures of toughness are excellent.

Next GE performed two overlays on a thinner region of the SA508 Class 2 nozzle forging. The first overlay was applied without preheat or PWHT around one-half of the nozzle. The second half of the overlay was also deposited without preheat or PWHT, but included water backing to produce a rapid cooling rate during welding. The nozzle to safe-end was partitioned utilizing a vertical divider plate to separate the wet and dry locations in a manner similar to that used for the CBI qualification described above. Following welding, the qualification weldment was sectioned and mechanical testing was performed. Acceptable properties were recorded for bend, tensile, and hardness testing of each condition (with and without water backing). Charpy Vee-notch impact tests removed from the HAZ of the first weld (without water-backing) produced adsorbed energy values that ranged from 105 to 122 ft-lbs and lateral expansion that ranged from 56 to 68 mils (Table 4-1). The companion water-backed weld produced adsorbed impact energy values that ranged from 116 to 130 ft-lbs and lateral expansion that ranged from 90 to 95 mils (Table 4-2). As can be seen from these results, little difference in toughness was observed between the two different welding conditions. The impact toughness actually appears to have improved over the original groove weld qualification results.

4.2 EPRI Research on GTAW Temperbead Welding and Weld Qualifications

EPRI initiated a program at the EPRI RRAC in late 1989 to address concerns expressed by utilities related to temperbead welding and to petition ASME for changes to the existing N-432 Code Case. The program *Temperbead Welding Repair of Low Alloy Pressure Vessel Steels* was completed in December 1993 [1]. The EPRI program significantly increased the level of understanding of the temperbead welding process and the variables surrounding temperbead applications. It incorporated information from earlier EPRI programs/reports [1,3] and industry applications [4-12] and coupled those results with detailed investigations of factors affecting temperbead welding. Several important conclusions/products were realized during the program (EPRI Report TR-103354):

- GTA welding controls were developed to assist in producing consistent HAZ toughness properties and microstructures.
- Diffusible hydrogen effects were characterized and found to be negligible for GTAW.
- Weld preheat effects were determined.
- Alternate filler metals were recommended.
- Residual stresses associated with repairs were identified.
- Properties resulting from specific applications of temperbead technology were documented.

Specific data, from EPRI Report TR-103354, pertaining to reduced welding preheat temperature generated under the program has been included in Tables 4-1 and 4-2. A total of five weld pad evaluations were performed utilizing the consistent layer technique described in Section 3.1. Four of the five weld property evaluations, WPEs, were performed utilizing different preheat temperatures and a single set of parameters. In comparing the first four weldments, identical welding parameters were employed, thereby allowing a direct comparison of the effects of preheat temperatures. Two weld overlay pads, WPE1 and WPE5, were performed at 300^{0}F, while weld overlay pads WPE2, WPE3, and WPE4 were performed at 200^{0}F, 150^{0}F, and 75^{0}F respectively. The power ratio was held at a constant 85.5 for all WPEs. In normal practice an increase in power ratio would be employed to compensate for decreased preheat temperatures. The appropriate power ratio increase ensures saturation of heat and slower cooling rates.

The results of the study showed the 300^{0}F preheat welds produced a range of room temperature adsorbed impact energies between 96 and 108 ft-lbs (65 to 67 mils lateral expansion). The reduced preheat welds generated average room temperature adsorbed impact energies of 90, 85, and 82 ft-lbs (57, 57, and 58 mils lateral expansion) respectively.

The results in this study indicated that welding preheat has a small, but measurable influence on the HAZ toughness. A decrease in the average toughness of 13.7 ft-lbs was observed between samples WPE1 (300^{0}F preheat) and WPE4 (75^{0}F). However, it is important to note that even the reduced preheat welds substantially exceeded the ASME toughness requirements of 50 ft-lbs adsorbed impact energy and 35 mils lateral expansion at lowest service temperature, RTNDT + 60^{0}F (20^{0}F in these cases). These properties are significant in that they demonstrates the capability to obtain high toughness welds using the temperbead techniques at low preheat temperatures.

The observed HAZ microstructures for these welds and related information extracted from open technical literature, provided convincing evidence to conclude that a lower preheat temperature can be beneficial in that martensite is formed more readily near the weld fusion line. Subsequent weld layers result in a tempered martensite structure within this zone that possesses excellent toughness.

High Dew Point Conditions

Extreme moisture environmental conditions during welding were also studied. Results indicted that, even with high dew point conditions, reduced preheat temperatures did not cause adverse effects on machine GTAW temperbead repairs. Therefore preheating was unnecessary. The following specific conclusions were drawn from both the 1989 program and a later EPRI program dealing with repairs to control rod drive (CRD) penetrations, entitled *Internal- Access Weld Repair for Leakage in BWR CRD Penetrations* (1995).[3]

- preheat levels between 150^{0}F and 300^{0}F produced no measurable difference in hydrogen content for GTAW process welds performed under severe environmental conditions (95^{0}F or greater humidity).

- high moisture content (high dewpoint) of the shielding gas is insufficient to cause hydrogen related damage with GTA welding of low alloy RPV steels.

- hydrogen content of modern GTAW filler wires is insufficient to produce welds having hydrogen levels that will cause hydrogen related damage.

- the GTAW process produces extremely low as-welded diffusible hydrogen contents provided that:

  a. moisture is removed from the component being welded,
  b. welding grade gas shielding is used,
  c. the filler metal is clean and free of residual drawing compounds,
  d. base metals do not contain appreciable contents of residual hydrogen,
  e. all lubricants, coatings, and paints are removed (2).

GTAW welds performed at preheat levels between ambient temperature and 300 ^{0}F produced no measurable differences in hydrogen contents even under severely humid environmental conditions (95 ^{0}F or greater humidity). Figure 4-1 is taken from Reference 3 and shows the limited hydrogen pickup in GTAW welds with 150^{0}F temperature preheat conditions.

4.3 Industry Qualifications with Preheat Temperatures of 300^{0}F

NYPA, EPRI RRAC, NUTECH, CBIN, GE/Oyster Creek, Georgia Power, and Vermont Yankee all performed nozzle to safe-end welding qualifications using a 300 ^{0}F preheat temperature. These specific temperbead repair qualifications were performed in conjunction with the low preheat procedure qualifications discussed previously (Section 4.2). All of these qualifications followed the *ASME Boiler and Pressure Vessel Section XI, Subsection IWA-4600* requirements for a non water-backed repair utilizing a 300 ^{0}F temperature preheat and a 500 ^{0}F temperature postweld bake. Most of the repairs were either groove or weld overlay repairs performed on nozzle to safe-end joints. Temperbead welding processes were used and Inconel 82 was the common filler metal. Charpy Vee-notch impact test results for these qualifications are shown in Table 4-1. The 300 ^{0}F preheat may be compared to the ambient temperature test results shown in Table 4-2.

NYPA performed two temperbead groove weld qualifications, one with a 300^{0}F preheat/500^{0}F PWHT and the other with a 200^{0}F preheat/no postheat. The same welding parameters were used in each case, and both welds produced comparable HAZ Charpy impact test results. The 300^{0}F preheat qualification produced an average HAZ impact energy of 108 ft-lbs (744 and 746 ID groove welds), and the 200^{0}F preheat qualification produced an HAZ impact energy of 104 ft-lbs (745 ID groove weld). These small differences may be explained by either material or testing variability, and should be considered equivalent.

EPRI RRAC performed a nozzle weld overlay repair utilizing multiple preheat conditions. These included preheating temperatures of 300^{0}F, 200^{0}F, 150^{0}F, and 75 ^{0}F. All welds were performed using a single set of welding parameters, and utilized the Consistent Layer Temperbead Technique. The 300^{0}F temperature preheat qualification produced an average HAZ Charpy Vee-notch adsorbed impact energy of 102 ft-lbs. The 200^{0}F, 150^{0}F, and 75^{0}F preheat produced average impact energies of 90, 85, and 82 ft-lbs respectively. It was noted that all of these test results far exceeded ASME code requirements of 50 ft-lbs adsorbed impact energy and 35 mils lateral expansion at the lowest service temperature, RTNDT + 60^{0}F (20^{0}F).

NUTECH performed groove weld repairs utilizing both water backing (no preheat) and a 300^{0}F preheat following Code requirements (300^{0}F preheat/500^{0}F PWHT). CBIN and GE/Oyster Creek also performed groove weld repair following Code requirements and compared toughness results to weld overlays performed on a water-backed nozzle (no preheat). A detailed examination of test results actually indicated higher HAZ toughness for the water-backed test conditions than for the 300^{0}F preheat in half the qualifications, and the other half showed a reduction of less than 10%. For example, the GE/Oyster Creek qualification showed a Charpy impact value of 106 ft-lbs for the repair performed with a 300^{0}F preheat, while the water-backed repair (no preheat) recorded an average toughness value of 122 ft-lbs. These differences indicate a 7% improvement in adsorbed impact energy for the water backed repair. It is important to note that all of the impact test results for the NUTECH, GE/Oyster Creek, and CBIN qualifications without preheat greatly exceeded the ASME code minimum of 50 ft-lbs adsorbed energy/35 mils lateral expansion at the lowest service temperature, RTNDT + 60^{0}F.

All of the welding preheat experiments and test results for the industry qualifications discussed in this report are shown in Figure 4-2 taken from Reference 3. Although Georgia Power, Vermont Yankee, and Indian Point did not perform temperbead qualifications at ambient temperature preheat, their results for impact energy at the 300^{0}F preheat repairs have been included for comparison. Note that Indian Point was granted relief from Case N-432 by USNRC to meet a minimum 30 ft-lbs absorbed energy. It is clear that the impact energy toughnesses obtained for temperbead weld repairs without preheat are acceptable and comparable to those obtained using a 300 ^{0}F temperature preheat. All ambient temperature preheat qualifications surveyed recorded HAZ toughness greater than minimum requirements.

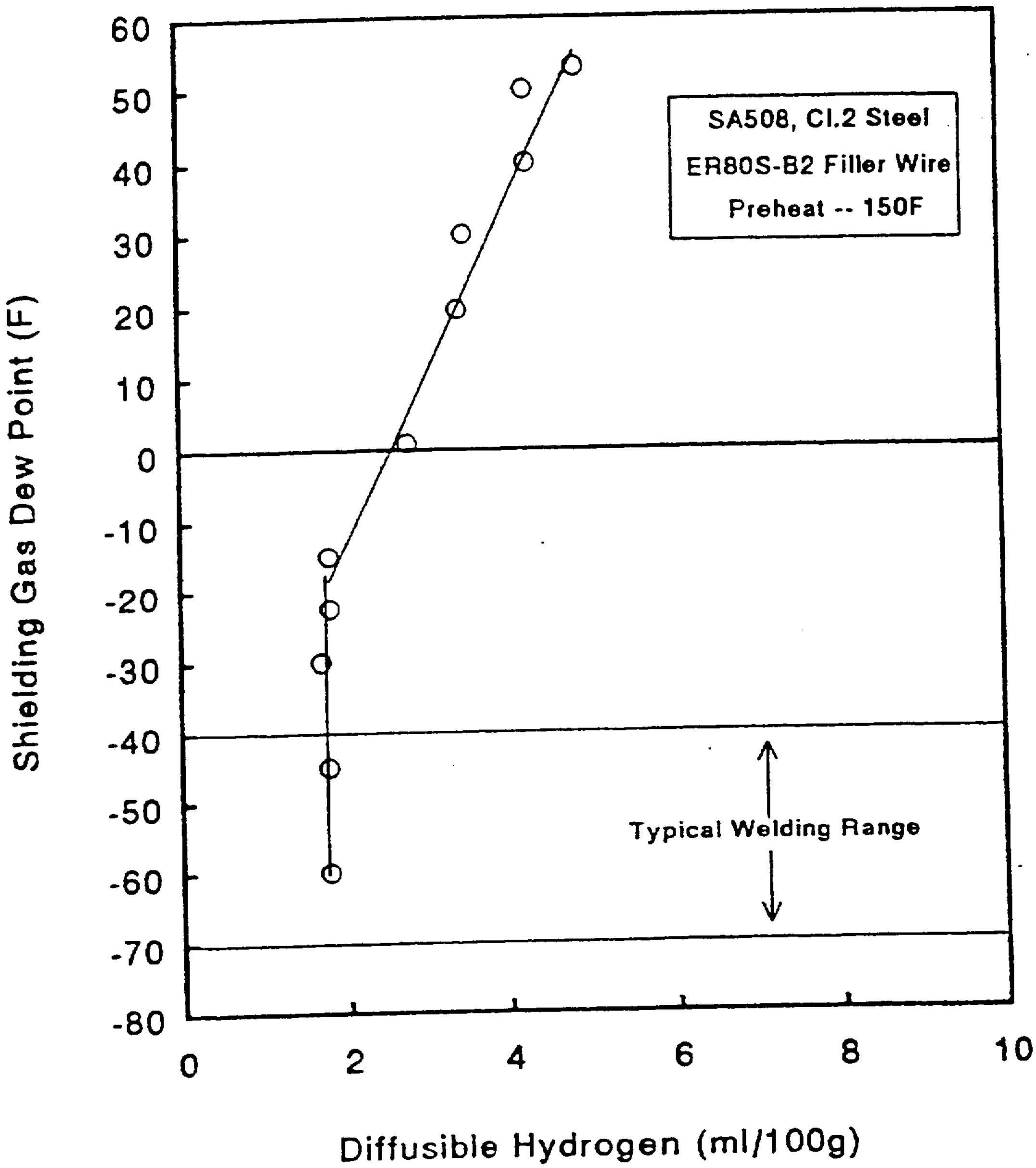

Figure 4-1
Diffusible Hydrogen Levels at Various Shielding Gas Dewpoint Temperatures

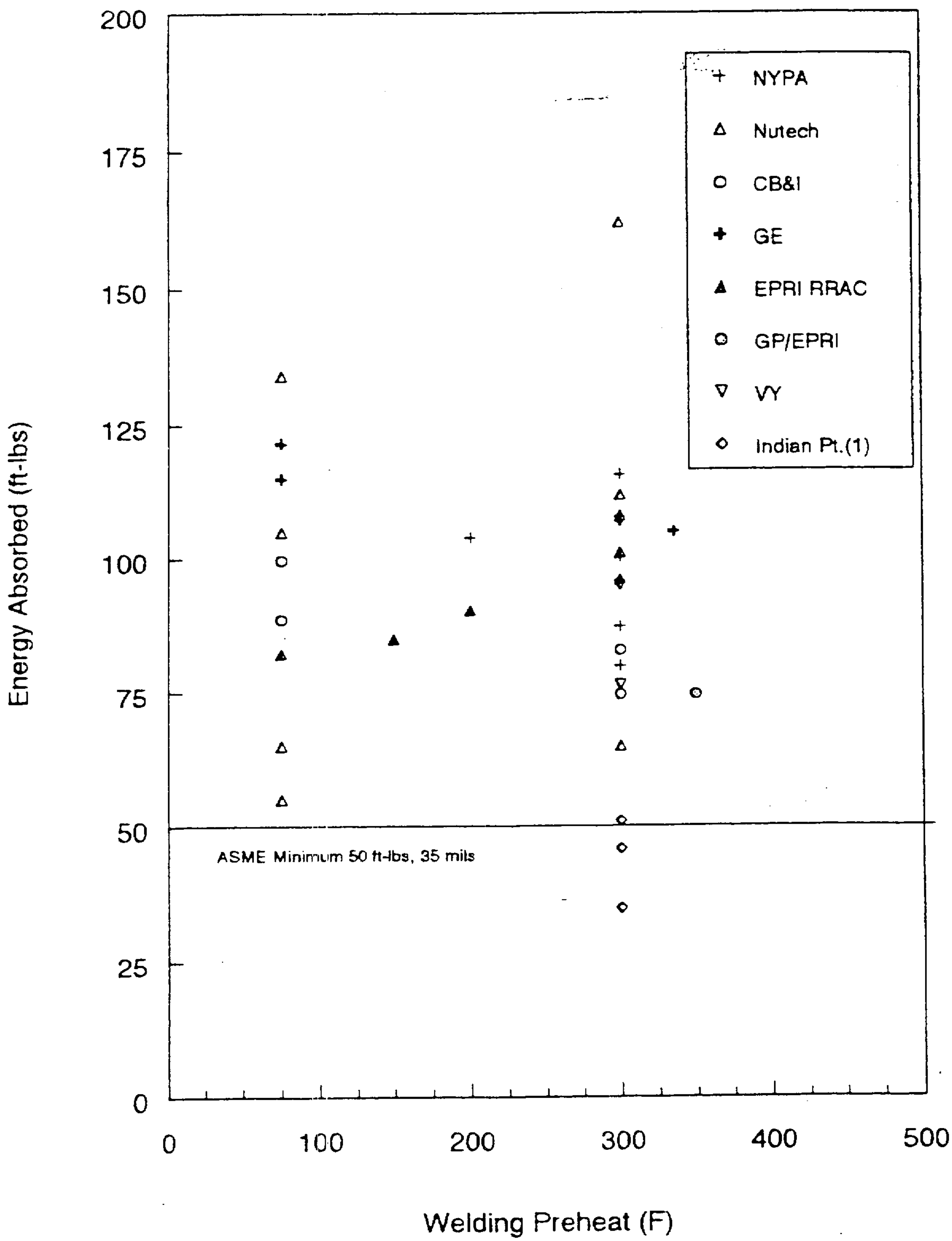

Figure 4-2
HAZ Toughness Data from Various Industry Qualifications on RPV Steels. (Note 1—Under an USNRC Relief Request, Indian Point was qualified to 30 ft-lbs minimum.)

Table 4-1
Industry Welding Qualifications Performed at 300F

Type of Repair	ID No.	Preheat/ Postheat	Location/Other	Test Temperature	Base Metal			Heat-Affected Zone		
					Charpy Impact ft-lbs (avg)	Lateral Expansion inch (avg)	Percent Shear % (avg)	Charpy Impact ft-lbs (avg)	Lateral Expansion inch (avg)	Percent Shear % (avg)
NYPA										
Groove	744	300F/500F	Nozzle/Safe-End	40F	59.3	0.046	30	100.3	0.060	86.7
Groove	746	300F/500F	Nozzle/Safe-End	40F	110	0.064	92	115.7	0.066	88.3
Groove	395	300F/500F	Nozzle/Safe-End	40F	114.3	0.074	88.3	87.3	0.057	88.3
Overlay	395	300F/500F	Nozzle/Safe-End	40F				80	0.053	80
EPRI RRAC										
Weld Pad	WPE1	300F	Nozzle	20F				96	0.065	47
Weld Pad	WPE5	300	Nozzle	20F				108	0.067	66
NUTECH										
Groove	1/2"	300F/500F	Nozzle/Side	40F	165	0.084	89.5	112	0.064	100
Groove	1/2"	300F/500F	Nozzle/Bottom	40F	165	0.084	89.5	162	0.083	100
Groove	1-1/4"	300F/500F	Nozzle/Side	40F	121	0.074	88	101	0.063	86
Groove	1-1/4"	300F/500F	Nozzle/Bottom	40F	121	0.074	88	65	0.053	52
CBIN										
Groove	7673	300F/500F	Nozzle/Safe-End	20F	50.3	0.043	46.7	83	0.052	56.7
Groove	7673	300F/500F	Nozzle/Safe-End	20F	46.3	0.037	36.7	74.7	51.7	60.0
GE/Oyster Creek										
Groove	1WA-4500-1	336/500F	Nozzle/Safe-End	40F	78	0.051	31.7	105.8	0.057	61.7
GEORGIA POWER/EPRI										
Groove		350F		40F	74.7	0.054	56.7	74.7	0.058	60
VERMONT YANKEE										
Groove	A1	300F/500F	HAZ-Hoop	40F	89	0.064		107	0.072	
Groove	B1	300F/500F	HAZ-Radial	40F	93.3	0.064		76.5	0.061	
Overlay	--	300F/500F	HAZ-Radial	40F	89	0.064		95	0.075	

Table 4-2

Industry Welding Qualifications Performed at a Reduced Preheat or With Water Backing

Type of Repair	ID No.	Preheat/ Postheat	Location/Other	Test Temperature	Base Metal: Charpy Impact ft-lbs (avg)	Base Metal: Lateral Expansion inch (avg)	Base Metal: Percent Shear % (avg)	Heat-Affected Zone: Charpy Impact ft-lbs (avg)	Heat-Affected Zone: Lateral Expansion inch (avg)	Heat-Affected Zone: Percent Shear % (avg)
NYPA										
Groove	745	200F/None	Nozzle/Safe-End	40F	110	0.066	90	104	0.063	91.7
NUTECH										
Groove	1/2"	75F/None	1/2" Deep/Side	40F	163	0.083	90	134	0.066	98
Groove	1/2"	75F/None	1/2" Deep/Bottom	40F	163	0.083	90	65	0.045	62
Groove	1-1/4"	75F/None	1-1/4" Deep/Side	40F	101	0.063	76	105	0.060	91
Groove	1-1/4"	75F/None	1-1/4" Deep/Bottom	40F	101	0.063	76	55	0.042	55
CBIN										
Overlay	7717	None	Wet	20F	50.3	0.04	46.7	88.7	0.061	48.3
Overlay	7718	None	Dry	20F	46.3	0.037	36.7	99.7	0.070	53.3
GE/Oyster Creek										
Overlay	MTB 43.3.6-W	None	Wet	40F	93	0.064	33.3	121.6	0.065	93.3
Overlay	MTB 43.3.6-D	None	Dry	40F	93	0.064	33.3	115	0.065	83.3
EPRI RRAC										
Weld Pad	WPE2	200F	Nozzle/Dry	20F				90.3	57.3	66.0
Weld Pad	WPE3	150F	Nozzle/Dry	20F				85.0	57.0	44.7
Weld Pad	WPE4	75F	Nozzle/Dry	20F				82.3	58.0	44.7

5.0
INDUSTRY APPLICATIONS

Many successful temperbead weld repairs have been applied to nuclear power plant components. The RPV nozzle to safe-end weldment is a typical example where these technologies have been applied. Reference 3 cites three boiling water reactor plants that successfully applied temperbead technology to repair multiple RPV nozzle to safe-end locations. In all cases the repair procedures followed *ASME Boiler and Pressure Vessel Section XI, Subsection IWA-4600* Code requirements. Weld overlays were applied at both plants to temporarily repair ultrasonic indications that had propagated into low alloy steel nozzle material, or that had grown into the Alloy 182 cladding to the extent that the minimum requirement for weld butter buffering had been encroached. The weld overlay repairs were performed as temporary measures so that the plant could be operated while the utility prepared to replace nozzle safe-ends and attached recirculation and core spray piping. Weld overlay repairs have been implemented in other plants as permanent repairs.

5.1 Chinshan Units 1 and 2

Inspections performed at the Chinshan Nuclear Station (Taiwan Power Company) during the summers of 1986 (Unit 1) and 1987 (Unit 2) identified extensive IGSCC in many weldments between the recirculation inlet nozzles and the ringheaders. Nozzle N2E of Unit 2 indicated crack propagation into the LAS nozzle material. A repair strategy was adopted to design and install weld overlay repairs on all affected locations including the N2E nozzle. Special temperbead repair procedures were required for the N2E nozzle because the defect had propagated into the LAS nozzle material and the minimum 3/16-inch LAS butter material boundary had been encroached. In this case the defect was confined to a small volume. Therefore, the defect was removed by local grinding and the nozzle material restored using a manual GTA temperbead technique with Alloy 82 filler. The nozzle butter restoration was accomplished using a technique known as the sacrificial spool butter replacement. This procedure provides for removal of the old Alloy 182 butter and replacement with Alloy 82 material using machine GTAW methods. The resulting deposit/nozzle interface is given a localized PWHT via heating the sacrificial spool directly then allowing the heat to conduct into the nozzle material. The spool is then removed leaving only the new butter interface on which to weld the new safe-end.

All other Chinshan nozzles safe-ends (Type 304 stainless steel) were replaced during the 1988 fall/winter refueling outage for Unit 2, and the 1998 winter refueling outage for Unit 1. All repair cases (except the Unit 2 N2E nozzle) applied a corrosion resistant cladding to cover and seal all Alloy 182 butter and all cladding exposed to the reactor coolant. The weld overlay was removed and the safe-ends replaced with new Type 316 NG stainless steel safe-ends. This was accomplished by preserving at least 3/16 inch of the original nozzle butter while cutting and machining the weld preparation to receive the new safe-ends. After the safe-ends were fitted, standard GTAW safe-end replacement techniques were used to install the new safe-ends and riser piping.

5.2 Brunswick Unit 1

Inspections performed during November and December 1988 revealed extensive indications of axial cracking associated with the LAS nozzles. The cracks appeared to have initiated in the Alloy 182 cladding transition between the nozzle butter and the stainless steel cladding in the nozzle bore. Once initiated the cracks appeared to have propagated toward the LAS. Both axial and circumferential indications were in the Inconel 600 safe-end to piping welds. Note: the original Brunswick safe-ends had been replaced prior to placing the two Brunswick units into service and were Inconel instead of stainless steel. The piping was Type 304 stainless steel. A temporary repair approach was selected to apply weld overlay repairs to mitigate the effects of the crack indications. Because the cracking was positioned slightly within the LAS nozzle bore, a temperbead technique was adopted with which to apply the overlay following the Code requirements. Water in the vessel annulus was lowered to a level below the nozzles prior to welding and three to six layers of weld deposit were applied to the LAS nozzle using the temperbead procedure covering the outer surface of the nozzle immediately over the potential cracking paths of the defects. A total of 12 nozzles were repaired including the 10 inlet riser nozzles and 2 core spray nozzles. As mentioned earlier, the overlay repairs were considered temporary prior to replacement of inlet risers and safe-ends with Type 316 NG material. All defects in the LAS were removed by grinding and cavities restored using GTA temperbead welding. The overlays were removed at the next refueling outage, and all nozzle safe-end butters were restored with Type 309L stainless filler material using a sacrificial spool piece technology similar to that described for Chinshan replacements. Finally, the new Type 316 NG safe-ends and replacement piping were installed.

5.3 Hope Creek

Inservice inspections performed in 1997 at the Hope Creek Nuclear Station during Refueling Outage 7 revealed a through-wall leak in the vicinity of the N5B core spray nozzle [8]. Upon further investigation, it was determined that the leak was the result of three pin holes in the nickel base alloy 600 safe end to the low alloy steel (LAS) nozzle weld. The root cause investigation of these defects determined that the defects were due to intergranular stress corrosion cracking in the nickel base alloy 182 weld metal. Since the locations of the flaws were adjacent to the LAS nozzle, it was determined that a full structural "standard" weld overlay repair would be applied. The repair was to meet the design stress requirements of USNRC Generic Letter 88-01 and NUREG-0313, Revision 2. The overlay was qualified and performed using a temperbead process on the LAS part of the overlay. Guidance was taken from *ASME Code Case N-432* for the temperbead repair. The repair weld metal used for the overlay was nickel base alloy 52, a material determined to be highly resistant to IGSCC in BWR environments. Based upon the design, fabrication, materials and code considerations the overlay repair is considered to be a long term fix subject to the inspection requirements for IGSCC Category E weldments in USNRC Generic Letter 88-01 and NUREG-0313, Revision 2.

5.4 Vermont Yankee

Inspections performed during the 1986 refueling outage revealed indications in the LAS nozzle to nickel base alloy 600 safe end in two welds of the core spray system at Vermont Yankee [9]. The indications were located in the nickel base alloy 182 weld metal used to join the nozzle to safe end. Analysis revealed that repair or replacement were the only suitable options with which to disposition the indications. A temperbead weld overlay repair was developed taking guidance from *ASME Code Case N-432*. A full structural overlay was designed and fabricated using nickel base alloy 82 weld metal, a material identified in *NUREG-0313*, as resistant to IGSCC in the BWR environment. This repair has performed satisfactorily in-service to the present time for both welds, and continues to be inspected periodically, in accordance with the requirements of *Generic Letter 88-01, and NUREG-0313, Revision 2.*

5.5 Calvert Cliffs Unit 2

Primary water stress corrosion cracks were discovered in the pressurizer heater sleeves during the spring 1989 in-service inspection at Baltimore Gas & Electric Calvert Cliffs Unit 2 facility. Evidence of leaking was identified for twenty three of the 120 heater penetrations (alloy 600). The utility decided to replace all of the heater sleeves with the more resistant alloy 690 material. The repair approach was to deposit an Inconel weld pad on the outside surface of the lower head around each penetration to accommodate the structural weld between the lower head and the outer heater sleeve. The alternate temperbead process detailed in *ASME Code Case N-432* was selected for pad welding to avoid potentially harmful side effects related to implementing PWHT to the complex geometry of the lower head. The repair was qualified and demonstrated, and welding was performed using preprogrammed computer-controlled equipment that was monitored outside containment in a non-radiation area. All 120 penetration welds were successfully completed [10].

5.6 Pilgrim

Boston Edison's Pilgrim Station used a temperbead approach on a LAS 28-inch discharge nozzle to fill a repair cavity. The repair cavity had been created during the removal of indications in the LAS nozzle that originated as IGSCC in the safe-end in the weld HAZ (Alloy 182) away from the nozzle. The defect appeared to have propagated around the Alloy 82 root and into the end of the LAS nozzle. The defect(s) were removed by grinding and repaired using a temperbead approach. The cavity was filled and the nozzle butter restored locally. A corrosion resistant cladding (CRC) procedure was used to isolate all Alloy 182 materials from the coolant flowing through the piping.

5.7 General

The *1998 Edition of the ASME Section XI Boiler and Pressure Vessel Code* incorporates temperbead technology that had been addressed previously in earlier codes based upon the original Code Case N-432. These rules are issued as *Alternate Welding Methods under Section XI Subsection IWA-4600*. These rules describe acceptable temperbead processes and requisite qualifications. One noteworthy requirement is that repair areas are limited to 100 square inches. This was incorporated as a measure to minimize the effects of residual stresses. Both SMAW and

GTAW processes are identified as being acceptable for use in the alternate welding rules. Procedure qualification, demonstration, testing and inspection requirements are detailed. Specific requirements for dissimilar materials and cladding applications are also described.

6.0 CONCLUSIONS

The elimination of preheat and postheat bake will improve the feasibility of accomplishing localized weld repairs to carbon and low alloy steels that are otherwise impractical or impossible to accomplish without compromising weld quality – even for large water-backed components. Acceptable weld quality and HAZ impact toughness properties have been developed using machine GTAW temperbead repairs without a need to preheat (i.e. ambient temperature) or post weld bake, and without risking hydrogen assisted (delayed) cracking.

No preheat temperature or post-weld bake above ambient is required to achieve sound machine GTAW temperbead repairs that have high toughness and ductility. This conclusion is based on the fact that the GTAW process is an inherently low hydrogen process regardless of the welding environment. Insufficient hydrogen is available to be entrapped in solidifying weld material to support hydrogen delayed cracking. Therefore no preheat nor post-weld bake steps are necessary to remove hydrogen because the hydrogen is not present with the machine GTAW process.

In addition machine temperbead welding procedures without preheat will produce excellent toughness and ductility properties both in the weld and in the weld HAZ. The results of numerous industry qualifications provide extensive documentation supporting high toughness welds. The machine GTAW process is, by nature, a low heat input process that produces small volume heat affected zones. These zones will cool faster than flux shielded or GMAW welding processes. Eliminating substrate preheat will enhance the cooling rates of the weld HAZ. The rapid cooling is a desired effect because the heat affected zone (HAZ) microstructure that results will be populated with increased percentages of martensite and upper bainite. Tempering is assured with machine control of electrical and mechanical parameters, and the HAZ toughness produced with the machine GTAW temperbead process will be equal or superior to the substrate material. Therefore component toughness requirements are readily achievable.

The available information regarding the application of machine GTAW temperbead repairs have been evaluated in detail and the following conclusions reached:

- Repair of RPV components utilizing machine GTA temperbead welding at ambient temperature produces mechanical properties that are commonly superior to those of the service-exposed substrate. The risk for hydrogen delayed cracking is minimal using the GTAW process. Cold stress cracking is resisted by the excellent toughness and ductility developed in the weld HAZ. Process design and geometry largely control restraint considerations, and these factors are demonstrated during weld procedure qualification.

- Inspection requirements of the current Section XI Subsection IWA 4624 provide additional confidence for weld soundness.

- Several successful industry welding qualifications have been performed using reduced preheats (75°F-300°F) on BWR nozzle to safe-end joint repairs. These qualifications include those performed by: CBIN, New York Power Authority (NYPA), NUTECH, GE/Oyster Creek, and EPRI. In every instance, sound welds, excellent HAZ toughness, hardness, tensile and bend properties were obtained.

7.0
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APPENDIX A

AMBIENT TEMPERATURE TEMPERBEAD WELDING PROCEDURE QUALIFICATION GUIDELINES FOR P-NO.1, P-NO.3 AND P-NOS.12A, 12B, & 12C MATERIALS[1] USING A MACHINE GTAW PROCESS.

The following guidelines should be employed for the qualification of ambient temperbead repair procedures on ASME Code materials P-No.1, P-No.3, and P-Nos.12A, 12B, & 12C:

Material Identification—The component material that is to be repaired shall be identified based upon available information including Quality Assurance records, fabrication records, and material testing if required. If the repairs are to be applied to locations having dissimilar metal interfaces, then all materials shall be identified from records and delineated on the component to be repaired by testing. Testing may include component surface etching procedures, in-place metallography, or plastic replication techniques. Where metallographic or replication techniques are to be used, identifiable marks shall be made on the component suitable to relate the technique results to specific component locations.

Test Coupon Selection and Size Requirements--The test coupon material employed for the Welding Procedure Qualification should be of the same material specification, type, grade, class and condition of heat treatment as the material used to fabricate the component. A weld test mock-up shall be prepared that accurately represents the repair to be performed particularly with respect to environment (temperature, humidity, water backing, etc.), geometry [material thickness, stiffness and similar restraint factors], and welder accessibility.

Weld Preheat – Welding preheat is not required for the process and is unnecessary.

Welding Filler Wire—The recommended wire consumable depends upon the application and should be selected based upon the requirements. Table 1.1 describes some of the potential choices.

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[1] P-Nos. 12A, 12B, and 12C designations refer to specific material classifications originally identified in Section III and subsequently reclassified as P-No.3 material in a later Edition of Section IX.

P-Number Combinations	Filler Materials
P-No.1 to P-No.1	ER70S-3
P-No.3 to P-No.3	ER70S-6 or ER80S-6
P-No.1 to P-No.3	ER70S-6 or ER80S-6

Table A-1 **Recommended Filler Metal Selections for Different P-Number Combinations using GTAW**

Excavation — Machining, grinding or air-arc gouging followed by grinding are the preferred methods of excavation. The repair cavity geometry should be designed to facilitate machine welding, and the cavity volume should be minimized.

Layer Sequence and Bead Overlap - A 50 percent bead overlap should be used for each weld pass. Each layer should apply the same input energy from the GTAW parameters. Interlayer grinding should be avoided.

Welding Heat Input—Specific parameters for the GTAW process are to be selected such that consistent control is provided to assure interbead tempering. The "consistent layer" approach is particularly well suited to deliver uniform GTAW temperbead layers. The "Power Ratio" technique, described in Reference 7 of this report, provides a methodology to precisely control the desired heat introduced with each weld bead. It provides a useful mechanism with which to adjust welding parameters to accommodate specific groove geometries and still produce consistent heat penetration and filler metal deposition for each layer. This means that welding parameters may be adjusted for individual weld beads to accommodate a changing geometry and still deliver the same thermal penetration and deposit thickness. This degree of control with machine GTAW to make every layer the same avoids the generating retransformation products yet maximizes heat useful for tempering. Temperbead welding is optimized in this way.

Post bake—Hydrogen delayed cracking is not a concern for the GTAW process; therefore, postweld baking is unnecessary and is not required.

Mechanical Testing—The testing requirements for welding qualifications are defined in ASME Section XI Subsection IWA-4622. Charpy Vee notch impact test temperatures are defined for the test assembly base material, the weld metal, and the HAZ. All impact testing is keyed to temperatures at or below the lowest service temperature of the component being repaired. This process effectively assures that the weldment toughness will as good as or better than the toughness of the repaired component. Charpy Vee notch impact test values of 50 ft-lbs adsorbed energy and 35 mils lateral expansion are the minimum criteria for acceptance at the prescribed test temperature. Side bend tests and reduced section tensile specimens are prescribed in Figure IWA-4622-1 Qualification Test Plate.

Implementation of Ambient Temperbead Welding Repair(s) Sequence

Identification and Layout of Repair(s). Most defects are identified via one or more of the various nondestructive examinations (NDE) methods, and are characterized as satisfactory or unsatisfactory. Once the location and extent of repairs is known, maps can be developed and the scope of work for the repair can be defined. The location and extent of repair required affects the qualification(s) and welders required, as well as, practical factors including scaffolding, weld metal consumables, welding machines and other equipment that may be required.

Excavation of Defect(s). Unacceptable indications and defects must be removed. Removal may be achieved by mechanical means such as grinding or machining, or by thermal methods including flame and air arc gouging. Usually no preheat is required when using mechanical methods, but at least some (warm to the touch) is advisable when air arc gouging is used.

Where multiple repair cavities are encountered, it can be advantageous to connect them to gain better access for welding and bead placement. It should be kept in mind that the area of a repair is controlled to a maximum of 100 square inches.

Preparation and Geometry of Repair Cavity. The geometry of the repair cavity must complement the repair operation. A temperbead repair cavity must have enough width and overall volume to permit deposition of the proper number of weld layers. In particular, the root or bottom of the repair cavity must be able to accept multiple beads to ensure that tempering of the base metal HAZ and subsequent weld beads can be accomplished.

Inspection of Repair Cavity. Unacceptable indications and defects must be removed prior to repair. ASME Code requires that the excavated area to be repair welded be examined by either magnetic particle testing (MT) or liquid penetrant testing (PT) to establish a substrate having no defect(s).

Depositing the First, Second, and Third Layer. Deposition of the first and second layer of repair weld metal is the most important portion of a temperbead repair operation because of their effect on the base metal HAZ. Weld beads must be placed and deposited such that approximately 50 percent overlap is achieved. The use of the Power Ratio develops and controls the heat input effects for GTAW. Repairs having acceptable and reproducible results should be obtained, provided the prescribed overlap, preheat, interpass temperature, other Welding Procedure Specification parameters and average workmanship standards are observed

Depositing Remaining Fill Layers. Technique for depositing the remaining layer is rather easily completed because all beads are deposited identically to produce optimum properties. This technique does not require preheat and interpass maximum temperature is easily monitored and controlled.

Deposition of Final Layer/Weld Reinforcement. Even though the final weld reinforcement is required to be removed substantially flush with the surface of the component, care must be observed to avoid creating an additional HAZ in the base material that will not be tempered.

Post Bake. No post-weld bake is required for the GTAW process.

Interim and Final NDE

Rules for examining the temperbead weld repair are given in ASME Section XI Subsection IWA-4624. These rules require an examination of the initial repair layer by magnetic particle method. In addition, each subsequent layer must be examined by magnetic particle testing unless a final volumetric examination will be performed. If the final volumetric examination is to be performed, then the interim examination is optional. Note: Individual layer examinations may be considered of practical value even if a final volumetric examination is optioned so that any small problems can be determined during welding so that they can be corrected immediately before they become a problem.

A final nondestructive examination is required after the weld has been completed for 48 hours. The final examination will be a full volumetric evaluation plus a surface examination. Even though the machine GTAW temperbead process is highly resistant to delayed cracking, this examination will provide confirmation of weld soundness. The option for individual layer examinations permits eliminating the volumetric examination.

Documentation

Documentation will vary depending upon the extent of repair and local jurisdictional requirements but the following would typically be required:

- Welding Procedure and Welder Performance Qualification Records
- Weld Filler Metal Information
- Repair Location Information/maps
- Weld History Record (data sheet, form to record information, etc.)
- NDE Results
- Certificate of Authorization, NR-Stamp
- Code Data Reports

ATTACHMENT 2

REQUEST TO USE ALTERNATIVE TO ASME CODE
REQUEST TO USE EMBEDDED FLAW REPAIR TECHNIQUE
NORTH ANNA POWER STATION UNIT 1 RELIEF REQUEST NDE-019
SURRY POWER STATION UNIT 1 RELIEF REQUEST SR-26

I. Identification of Components

Drawings:

11715-WMKS-RC-R-1.2 (North Anna 1)	Class 1
11448-WMKS-RC-R-1.2 (Surry 1)	Class 1

Control rod drive mechanism (CRDM) penetrations (65) and a head vent penetration (1) on the upper reactor vessel head, which are ASME Class 1 components.

II. Current Code Requirements

The Construction Code of record for the North Anna and Surry Reactor vessels and heads is the 1968 Edition of ASME Section III with Addenda through the Winter of 1968. North Anna Unit 1 and Surry Unit 1 are currently in their third inspection intervals using the 1989 Edition of ASME Section XI. ASME Section XI, paragraph IWA-4120 specifies the following:

> "Repairs shall be performed in accordance with the Owner's Design Specification and the original Construction Code of the component or system. Later Editions and Addenda of the Construction Code or of Section III, either in their entirety or portions thereof, and Code Cases may be used."

Consequently, the proposed repairs will be conducted in accordance with the 1989 Edition of ASME III and the alternative requirements proposed below.

III. Code Requirements for Which Alternatives Are Requested

Paragraph IWA-4310 of the 1989 Edition of Section XI mandates flaw acceptability be assessed according to original Construction Code requirements, in this case ASME Section III, paragraphs NB-5351 and NB-5352. Per paragraph IWA-4120, repairs, if required, would be performed in accordance with Section III. Prior to welding, the repair excavation would require examination per paragraph NB-4453 with the acceptance criteria of NB-5351 and NB-5352. In neither case would it be permissible to weld over, or embed, an existing flaw.

IV. Basis for Relief

A request to use the embedded flaw technique to repair cracks on the inside diameter (ID) of control rod drive mechanism (CRDM) penetration tubes was previously submitted and approved by the NRC (see references 6.1 - 6.4). This current request expands the scope of the previous submittal to include repair of cracks on the outside diameter (OD) of reactor vessel head penetrations plus repair of cracks on the J-groove attachment welds of these penetrations.

The 1995 Edition of Section XI with 1996 Addendum, subparagraph IWA-46.11, permits the use of Section XI flaw evaluation criteria which would not require the complete removal of a flaw unless repairs were being undertaken per the temper bead welding procedures of paragraph IWA-4620, or paragraphs IWA-4630 and IWA-4640 with the flaw penetrating the base metal. The flaw evaluation criteria of Section XI (refer to Table IWB-3514-2) establishes acceptance criteria for surface connected and embedded flaws.

Both North Anna Unit 1 and Surry Unit 1 will perform VT-2 inspections under the insulation of the reactor vessel head during the Fall of 2001 refueling outages. If the VT-2 inspections identify any penetration nozzle leakage, additional under the head inspections will be performed. In the event that any subsequent under the head inspections of the reactor vessel head penetrations reveal flaws in those penetrations, it will be necessary to repair the flaws that exceed Section XI acceptance criteria. This relief request will permit any flaws identified on reactor vessel head penetrations and on J-groove attachment welds to be evaluated utilizing criteria documented in WCAP-13998, Revision 1, "RV Closure Head Penetration Tube ID Weld Overlay Repair," (Reference 6.1) and repaired using an embedded flaw repair technique. The embedded flaw repair technique is considered a permanent repair lasting through plant life extension for the following reasons: first, as long as a Primary Water Stress Corrosion Cracking (PWSCC) flaw remains isolated from the primary water (PW) environment, it cannot propagate. Since Alloy 52 weldment is considered highly resistant to PWSCC, a new PWSCC crack cannot initiate and grow through the Alloy 52 overlay to reconnect the PW environment with the embedded flaw. Second, the residual stresses produced by the embedded flaw technique have been measured and found to be relatively low (Reference 6.1). This implies that no new cracks will initiate and grow in the area adjacent to the repair weld. Third, there are no other known mechanisms for significant crack propagation in this region because the cyclic fatigue loading is considered negligible. Cumulative Usage Factor (CUF) in the upper head region was calculated in aging management review reports (WCAP 15268, Rev. 1 for Surry and WCAP 15269, Rev.1 for North Anna, dated September 2001) as 0.0.

Therefore, the embedded flaw repair technique is considered to be an alternative to Code requirements that provides an acceptable level of quality and safety, as required by 10 CFR 50.55a(a)(3)(i).

V. Alternate Requirements

The embedded flaw repair method will be used as an alternative to 1989 ASME Section XI and Section III Code requirements.

For a postulated ID repair, as described in the aforementioned submittals (ibid.), an unacceptable axial flaw will be first excavated (or partially excavated) to a specified depth no greater than 0.125-inches. An electric discharge machining (EDM) process will be utilized to minimize tube distortion. After the EDM is complete, either an ultrasonic test (UT) or eddy current test (ECT) will be performed to ensure the entire flaw length is captured. Then an Alloy 52 weldment will be applied to fill the excavation. Finally, the finished weld will be examined by dye penetrant (PT), UT or ECT to ensure acceptability. In the event that an unacceptable ID circumferential flaw is detected, the NRC shall be contacted before an embedded flaw repair is attempted.

For a postulated OD repair, there are a number of hypothetical CRDM tube repairs covered by this relief request. First, an unacceptable OD axial or circumferential flaw in a tube below a J-groove attachment weld will be sealed off with Alloy 52 weldment. Excavation or partial excavation of such flaws is not necessary, since CRDM clearance is not an issue on the outside of a tube. Second, unacceptable radial OD flaws on the J-groove attachment weld will be sealed off with a 360-degree overlay of Alloy 52 covering the entire weld. Again, no excavation is necessary. Third, unacceptable axial tube cracks extending into the J-groove weld will be sealed with Alloy 52 as described before. In addition, the entire J-groove weld will be overlaid with Alloy 52 tied to the embedded axial crack seal weld on the CRDM penetration. In each of the above scenarios, the finished weld will be examined by PT, UT, or ECT to ensure acceptability. Finally, the NRC will be contacted prior to utilizing the embedded flaw technique to isolate OD circumferential cracks at or above the attachment weld.

For a postulated circumferential OD flaw in the J-groove weld, the embedded flaw technique will not be employed. Instead, the flaw will be completely removed and the resultant cavity in the J-groove weld will be repaired with Alloy 52.

Per the 1989 Edition of ASME Section XI, paragraph IWB-2200(a), no preservice examination is required for repairs to the partial penetration J-grove welds between the vessel head and its penetrations (Examination Category B-E) or for the penetrations themselves. However, the NDE performed after welding will serve as a preservice examination record if needed in the future. Furthermore, the inservice inspection requirements from Table IWB-2500-01, "Examination

Category B-E...," is a VT-2 visual inspection of the external surfaces of 25% of the nozzles each interval with IWB-3522 as the acceptance standard. There are no ISI requirements for the penetration tubes or repairs to the tube. Currently, we perform visual examination, VT-2, of 100% of the nozzles each refueling outage. Ongoing vessel head penetration inspection activities undertaken as a result of NRC Bulletin 2001-01 and ongoing deliberations in Code committees will be monitored to determine the necessity to perform any additional or augmented inspections.

Using the provisions of this requested relief as an alternative to Code requirements will produce sound, permanent repairs and an acceptable level of quality and safety, as required by 10 CFR 50.55a(a)(3)(i).

References

1. WCAP-13998, "RV Closure Head Penetration Tube ID Weld Overlay Repair," March 1994

2. VEPCO Letter to NRC from James P. O'Hanlon, "Virginia Electric and Power Company, North Anna Power Station Unit 1, Reactor Vessel Head Penetrations Use of an Alternative Repair Technique," Serial Number 95-605, November 22, 1995

3. VEPCO Letter to NRC from James P. O'Hanlon, "Virginia Electric and Power Company, North Anna Power Station Unit 1, Reactor Vessel Head Penetrations Supplemental Information For Use of an Alternative Repair Technique," Serial Number 95-605A, January 26, 1996

4. NRC SER to J. P. O'Hanlon from David B. Matthews, "North Anna Unit 1- Use of an Alternate Repair Technique for Reactor Vessel Head Penetrations," Serial Number 96-079, February 5, 1996

5. VEPCO Letter to the NRC from Leslie N. Hartz , "Virginia Electric and Power Company, North Anna Power and Surry Power Stations - Response to NRC Bulletin 2001-01, Circumferential Cracking Of Reactor Vessel Head Penetration Nozzles," Serial Number 01-490, August 31, 2001

6. WCAP-15268, Rev.1, "Aging Management Review and Time Limited Aging Analysis for the Surry Units 1 and 2 Reactor Pressure Vessels," September 2001

7. WCAP-15269, Rev.1, "Aging Management Review and Time Limited Aging Analysis for the North Anna Units 1 and 2 Reactor Pressure Vessels," September 2001