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Attention: Ms. Meena Khanna

Subject: Project 704 - Non Proprietary Version of "BWRVIP-97: BWR Vessel and Internals Project, Guidelines for Performing Weld Repairs to Irradiated BWR Internals", EPRI Report 1003020NP

Reference: Letter from Carl Terry (BWRVIP Chairman) to C.E. Carpenter (NRC) "Project 704-- BWRVIP-97: BWR Vessel and Internals Project, Guidelines for Performing Weld Repairs to Irradiated BWR Internals", dated November 27, 2001

Enclosed are ten (10) copies of the non proprietary BWRVIP report "BWRVIP-97NP: BWR Vessel and Internals Project, Guidelines for Performing Weld Repairs to Irradiated BWR Internals". The proprietary version of this report was submitted to the NRC by the BWRVIP letter referenced above.

Should you have any questions regarding the subject report, please contact Denver Atwood, BWRVIP Repair Focus Group Chairman, at 205.992.7461.

Sincerely,

Carl Terry
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BWRVIP-97NP: BWR Vessel and Internals Project Guidelines for Performing Weld Repairs to Irradiated BWR Internals

Technical Report

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BWRVIP-97NP: BWR Vessel and Internals Project

Guidelines for Performing Weld Repairs to Irradiated BWR Internals

1003020NP

Final Report, May 2002

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BWRVIP-97NP: BWR Vessel and Internals Project, Guidelines for Performing Weld Repairs to Irradiated BWR Internals, EPRI, Palo Alto, CA: 2001. 1003020NP.

REPORT SUMMARY

The BWR Vessels and Internals Project (BWRVIP), formed in 1994, is an association of utilities focused on boiling water reactor (BWR) vessel and internals issues. Between 1994 and 1998, BWRVIP developed a set of Repair Design Criteria guidelines for BWR internal components. This BWRVIP report supplements those guidelines by providing additional information related to performing welded repairs on irradiated components.

Background

The BWRVIP Repair Design Criteria documents were developed to provide guidance to utilities for designing, fabricating, and installing repairs to BWR internal components. Both mechanical and welded repairs are addressed. However, at the time the reports were developed, information was not available in sufficient detail to appropriately address welded repair of irradiated components. Welding on irradiated material, if not done properly, can result in cracking due to release of helium gas that may be contained in the material.

Objective

To provide guidance to utilities performing welded repairs to irradiated stainless steel components.

Approach

An interim welding guideline was developed in 2000 based on the best information available at that time. The project team began with the interim guideline and supplemented it with recent test results. The most significant new results are based on tests performed on irradiated materials by the Japanese Owners Group. These tests were conducted over several years and were recently made available to BWRVIP. Tests were performed using various welding techniques, a range of welding parameters, and were performed on materials with widely varying irradiation levels. Information from this research significantly enhanced the technical basis for the Guideline.

Results

The Welding Guidelines conclude that, in a typical BWR, there are a number of components that can be repaired by welding with conventional techniques. These locations are not highly irradiated. The number of locations is most numerous during the early years of operation and decreases as the reactor ages and the fluence increases. The report specifies a list of components that can be safely welded even after 40 years of operation. A second category of locations with intermediate fluence levels is defined where welding can be performed if special techniques are used. Methods are presented for determining the helium content of metal at a given location and, based on the helium determination, selecting an appropriate welding technique. Finally, high-fluence regions exist where successful welding has not been demonstrated. However, even in

these regions it is possible that successful welds can be made if appropriate controls are applied. The Guideline includes a method for performing an in-situ welding qualification at the location of interest as a means of demonstrating the acceptability of the technique.

EPRI Perspective

Welding is often the preferred method of repairing degraded reactor internal components. As reactors age and repairs become necessary, it will become more important to consider irradiation effects on the weldability of stainless steel components. These guidelines provide a means for determining the weldability of reactor internal components and, therefore, allow designers to assess whether weld repair is an acceptable option.

Keywords

BWR
Repair specifications
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Stress corrosion cracking
Vessels
BWR internals

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BACKGROUND

1.1 Introduction

BWRs have experienced intergranular stress corrosion cracking (IGSCC) in a number of austenitic stainless steel and nickel alloy reactor pressure vessel (RPV) internal and external (e.g., recirculation piping, etc.) components. Figure 1-1 presents the various components where IGSCC has been identified in the BWR, while Table 1-1 details the history of BWR internals cracking [1-2]. Significant cracking has occurred in jet pump riser pipes and braces, core spray piping and core shrouds.

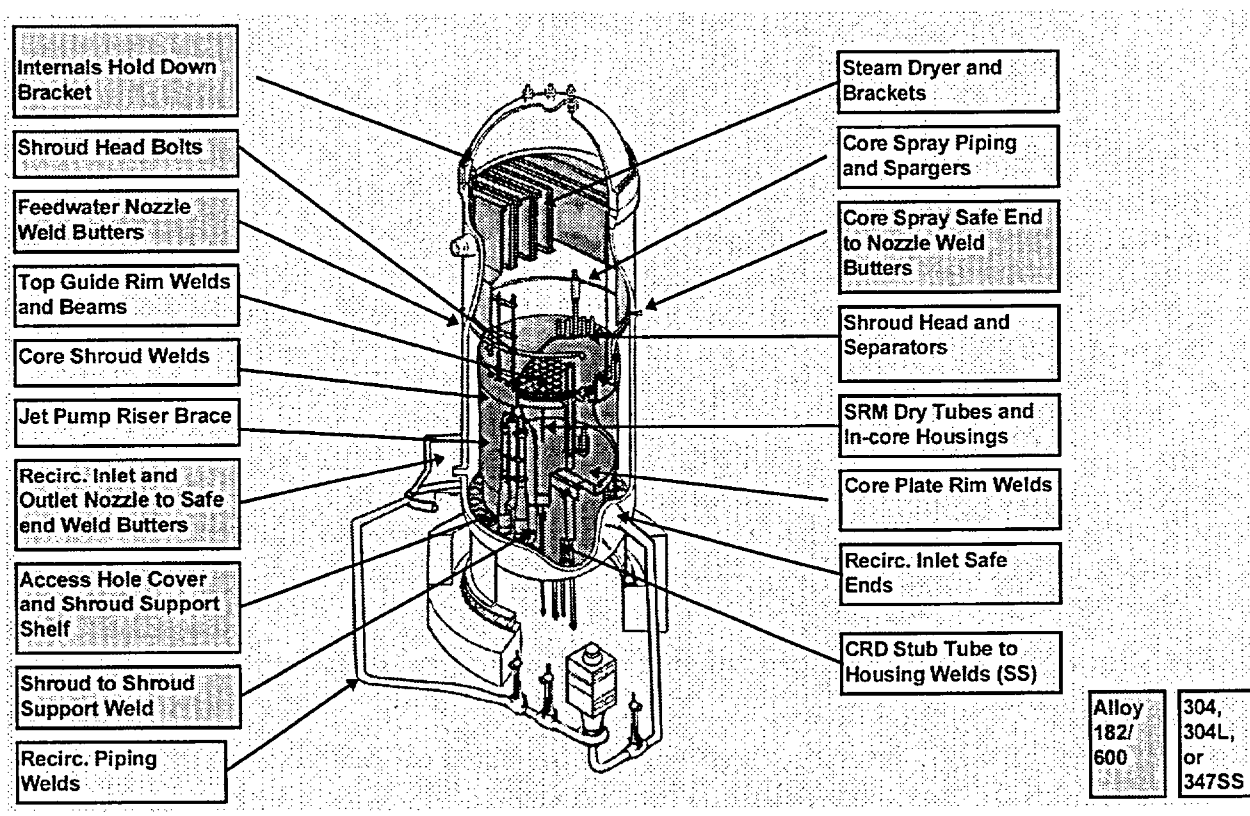

Figure 1-1
Summary Schematic of BWR Components with IGSCC [1]

Table 1-1
History of BWR Internals IGSCC [1-2]

EVENT	*YEAR OF DETECTION*
IGSCC of Alloy X750 Jet Pump Beam	Late 1970s
Accelerating Occurrence of IGSCC of BWR Internals	Late 1970s
Core Spray Spargers	
Shroud Head Bolts (Alloy 600)	
Access Hole Covers (Alloy 182/600)	
Nozzle Butters	
Control Blades	
SRM/IRM Dry Tube Cracking	
Jet Pump Beam Bolts	
Cracking of Low Carbon (304L/316L) and Stabilized Stainless Steels (347/321/348) in Vessel Locations	Late 1980s – present
Core Spray	
Creviced Safe Ends	
Shrouds (304L and 347)	
Top Guide (304, 304L, 347)	
Core Support Plate (347)	
Cracking of Internal Core Spray Piping	1990 - present

In some cases the preferred or only method of repair or replacement for the affected RPV internal component is welding. For components located in regions of low thermal fluence, the welding process is difficult and complicated, but metallurgically straightforward. However, in high thermal fluence regions, weld repair of irradiated BWR internal components is further complicated by the presence of insoluble He in the irradiated base material [3, 4]. Helium is produced by the transmutation of B and Ni. The release of the He when the metal melts during welding produces porosity and cracking. High He concentrations produce porosity along grain boundaries in the fusion zone. Lower concentrations of He can produce cracking in the heat affected zone (HAZ) resulting from bubbles formed by migration of He under the influence of high temperatures and stress. Thus, if a sufficient accumulation of He is present, the gaseous He released when the metal is melted can result in degraded mechanical properties of the welded joint, (e.g., reduced strength, cracking, etc.).

The BWRVIP has undertaken three activities to help improve the understanding of the effects of irradiation on welding:

1. In September 1997, the report "Weldability of Irradiated LWR Structural Components (BWRVIP-45)" was published [3]. This report included:
    a. A literature review to estimate the maximum amount of He for which conventional welding techniques could be used.
    b. Fluence calculations for a typical BWR/4 to predict He concentrations at various locations in the reactor.

c. A "Weldability map" based on the fluence calculations that indicated locations in the typical BWR where conventional welding techniques could (and could not) be used.

2. The BWRVIP has negotiated with the Japanese Owners Group (JOG) for rights to use Japanese data on welding of irradiated materials. This information includes results of experiments conducted to define the maximum He concentration under which conventional welding may be used, as well as results of experiments with welding techniques that allow welding on metal with higher He concentrations, (e.g., low heat input methods).

3. The BWRVIP, in collaboration with the NRC, has conducted a project to obtain samples of irradiated metal from the jet pump riser brace pad location in three operating BWRs. The samples were analyzed to determine the He content, the initial B content, the fluence and other parameters.

The results of these three activities have been key sources of information for this Guideline.

1.2 Welding Guidelines Objective

The objective of this Guideline is to provide utilities with a methodology that can be used to determine if weld repair to an irradiated component can be successfully performed and, if so, by which welding techniques. Note that the Guideline deals only with the aspects of performing a welded repair that are directly affected by the fact that the component has been irradiated. Other guidance for performing welded repairs that may be applicable is found in the BWRVIP Repair Design Criteria [5-13]

This Guideline has the following major elements:

1. Definition of Weldability Boundary - A "weldability boundary" is defined in Section 2. This boundary defines the locations in any BWR where He levels are sufficiently low (with a very high degree of assurance) to allow a repair to be performed using conventional welding techniques. For locations that do not fall within the boundary, additional considerations are required to determine if welding can be successfully performed.

2. Methodology for Helium Determination – For locations outside the weldability boundary, one method for determining weldability requires that the He content of the metal be known. This requires a plant specific evaluation. The methodology for such an evaluation is discussed in Section 3.

3. Survey of Applicable Welding Techniques – While welding on irradiated components may not be successful with conventional welding techniques; it has been successfully performed using low heat input methods. Section 4 presents these welding methods and describes the conditions where each may be used.

4. Welding Guidelines - Based on Items 1, 2 and 3 above, a Guideline for welded repair of irradiated components is presented in Section 5. The Guideline contains the methodology for determining which welding techniques may be used and presents guidance on required qualification tests, inspections, etc.

The flow chart shown in Figure 1-2 presents the overall logic of this Guideline.

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Figure 1-2
Flow Chart for Determining Applicable Welding Techniques

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Figure 1-2
Flow Chart for Determining Applicable Welding Techniques (Continued)

1.3 References

1. R. M. Horn, et al., "*Experience and Assessment of Stress Corrosion Cracking in L-Grade Stainless Steel BWR Internals*," Nuclear Engineering and Design, 174 (1997), p. 313.

2. "*BWR Vessel and Internals Project, BWR Water Chemistry Guideline – 2000 Revision (BWRVIP-79),*" EPRI TR-103515-R2, Palo Alto, CA, March 2000.

3. "*BWR Vessel and Internals Project, Weldability of Irradiated LWR Structural Components (BWRVIP-45),*" EPRI TR-108707, Palo Alto, CA, September 1997.

4. A. L. Lund, "*Underwater Welding of Highly Irradiated In-Vessel Components of Boiling Water Reactors – A Literature Review,*" NUREG-1616, paper presented at the Welding of Irradiated materials Workshop, September 3-4, 1997, Charlotte, NC.

5. "*BWR Vessel and Internals Project, Internal Core Spray Piping and Sparger Replacement Design Criteria (BWRVIP-16),*" EPRI report TR-106708, March 1997.

6. "*BWR Vessel and Internals Project, Internal Core Spray Piping and Sparger Repair Design Criteria (BWRVIP-19),*" EPRI Report TR-106893, September 1996.

7. "*BWR Vessel and Internals Project, Top Guide/Core Plate Repair Design Criteria (BWRVIP-50),*" EPRI Report TR-108722, May 1998.

8. "*BWR Vessel and Internals Project, Jet Pump Repair Design Criteria (BWRVIP-51),*" EPRI Report TR-108718, May 1998.

9. "*BWR Vessel and Internals Project, Shroud Support and Vessel Bracket Repair Design Criteria (BWRVIP-52),*" EPRI Report TR-108720, June 1998.

10. "*BWR Vessel and Internals Project, Standby Liquid Control Line Repair Design Criteria (BWRVIP-53),*" EPRI Report TR-108716, July 1998.

11. "*BWR Vessel and Internals Project, Lower Plenum Repair Design Criteria (BWRVIP-55),*" EPRI Report TR-108719, September 1998.

12. "*BWR Vessel and Internals Project, LPCI Coupling Repair Design Criteria (BWRVIP-56),*" EPRI Report TR-108717, November 1998.

13. "*BWR Vessel and Internals Project, Instrument Penetrations Repair Design Criteria (BWRVIP-57),*" EPRI Report TR-108721, December 1998.

2 DEFINITION OF WELDABILITY BOUNDARY

In this section, a He threshold for weldability is first established. Below the threshold, welding by conventional techniques may be used. Above the threshold, low heat input methods will be required. Using this threshold and the results of a BWR fluence calculation, a generic weldability boundary is defined that is applicable to any BWR. Conventional welding may not be successful on reactor components outside the weldability boundary. Additional evaluations must be performed if a welded repair is to be considered.

2.1 Helium Induced Cracking Background

Helium is produced by irradiation of metals via an (n, α) reaction where the metallic element nucleus absorbs a neutron and emits an alpha particle (α) that is identical to a He nucleus [1]. The He atom thus produced is very stable and remains in the metal indefinitely. In BWRs, the dominant method of production is by (n, α) reactions due to the interaction of thermal neutrons ($E < 0.5$eV) with boron (B) and nickel (Ni).

Boron is typically present as an impurity in stainless steels and Ni base alloys in concentrations from <5 to >30 ppm. However, B is sometimes deliberately added to improve the hot workability of steel. Boron has two naturally occurring isotopes ^{11}B and ^{10}B where ^{10}B is 19.9% of total B. Only ^{10}B atoms undergo the (n,α) reaction with thermal neutrons.

Helium is often quantified in atomic percent rather than weight percent because it is such a light element. One weight percent of B in Fe is equivalent to 5.18 atomic percent. Since ^{10}B is only 19.9% of B, one weight percent B is equivalent to 1.03 atomic percent ^{10}B. Since every atom of ^{10}B will eventually transmute to ^{4}He, one weight percent natural B can produce one atomic percent He.

Depending on the exact alloy, Ni becomes a larger source of He at high thermal fluences $>10^{21}$ to 10^{22} n/cm^2. The behavior of Nickel is more complex than that of B since two transmutation steps are required. Nickel 58 is 68.1% of natural Ni and undergoes the following reactions with thermal neutrons:

$$^{58}Ni + n \rightarrow {}^{59}Ni + \gamma$$

$$^{59}Ni + n \rightarrow {}^{56}Fe + {}^{4}He$$

Since ^{59}Ni is not naturally occurring, the production rate of He is initially zero, but increases as ^{59}Ni accumulates. Unlike B, Ni is a major alloying element of BWR austenitic stainless steels, i.e., 8 to 14%, and, of course, Ni base alloys. Alloy 600 is 76% Ni. Therefore, the concentration of He can increase to many thousands of atomic ppm (appm) provided there is sufficient thermal fluence. The thermal fluence threshold where He from Ni becomes greater than from B is approximately 7 x 10^{21} for Type 304 stainless steel [1].

The preferred nucleation sites for He cracking are lattice inhomogeneities such as radiation-induced defects, precipitate interfaces, dislocations and, most importantly, grain boundaries [2]. Since boron is an insoluble impurity element, it is expected that helium produced from boron will be located preferentially at the grain boundaries, and since nickel is an alloying element and present throughout the matrix, helium produced from nickel will be found spread throughout the matrix.

Once He is produced above threshold levels, it can produce serious materials degradation during a welding process since He is basically insoluble in metals. He diffuses through the matrix and segregates at various defects and grain boundaries. Helium coalesces into bubbles that degrade cohesion at grain boundaries and will eventually cause failure [1]. During welding, He bubbles are typically trapped in the fusion zone. The high temperatures allow rapid diffusion and rapid He accumulation at grain boundaries. Damage occurs at the HAZ at lower He concentrations. The presence of a tensile stress due to volumetric contraction during solidification and subsequent cooling allows the formation of larger He bubbles. Rapid growth of the He bubbles fed by rapidly diffusing He leads to grain boundary cracking in the HAZ.

2.2 Helium Concentration Cracking Threshold

A previous literature review indicated that the threshold for He induced weldability problems is 1 appm [1] when conventional welding techniques are employed. It is the He concentration in the metal, not the thermal (or fast) fluence, per se, that determines whether He induced cracking is possible. Higher He thresholds have been obtained when compressive stress or low heat input weld overlays have been applied. For example, successful welds in irradiated material containing 80 appm He (He from tritium decay) have been produced through the application of a compressive stress during welding. Although low heat input overlays have also been successfully made in materials containing up to 85 appm He, the welds contained small amounts of underbead cracking [1].

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2.3 Calculation of Helium Content in a Typical BWR

Analyses have been performed to calculate He concentrations throughout a typical BWR/4 (Susquehanna) for 1, 15 and 30 full power years [1]. These analytical results can be used to define a generic weldability boundary. Table 2-1 shows the predicted He concentrations for a material containing 1 ppm B at various locations in the typical reactor. For alloys with different B concentrations, the data are simply multiplied by the concentration of B. For example, if the material contained 5 ppm B, the amount of He generated would be increased by a factor of five.

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Table 2-2 summarizes the He data for a material containing 10% Ni. For alloys with different Ni concentrations, the data are simply multiplied by the Ni ratio. For example, if the material contained 12% Ni, the amount of He generated would be increased by a factor of 1.2.

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2.4 Bounding Helium Evaluation

To establish a generic weldability boundary, a worst-case calculation was performed using conservative values of B and Ni concentrations. A "worse-case" Type 316 stainless steel containing a specification maximum allowable Ni content of 14 % plus a high end B concentration of 20 ppm is assumed. The 1999 average B for Type 316 stainless steel was 16 ppm [2]. Although Type 304 stainless steel has been used more commonly for BWR internals, Type 316 stainless steel was used for this example due to its higher Ni content (10–14% versus 8 – 10.5 %) and typically higher average B content (16 ppm versus 12 ppm for 1999) than Type 304 stainless steel.

Table 2-3 presents the Helium concentrations predicted using the Susquehanna calculations with the conservative values of B and Ni.

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2.5 Generic Weldability Boundary

Based on the results of the worst-case evaluation performed above and shown in Table 2-3, a "generic weldability boundary" may be defined.

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Using this criterion, a review of Table 2-3 indicates that the following locations will be weldable in any BWR without consideration of helium content:

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These locations define the generic weldability boundary. Other components not specifically mentioned, but lying in close proximity to those listed, are also considered weldable.

This model is consistent with the actual RPV welding experience since the following internal components have been successfully weld repaired in BWRs:

Core spray line

Feedwater sparger pipe

Jet pump adjusting screw tack welds

Steam dryer

Table 2-1
Atomic ppm He from Only 1 ppm B as a Function of Component and Location Based on Susquehanna

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Table 2-2
Atomic ppm He from Only 10% Ni as a Function of Component and Location Based on Susquehanna

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Table 2-3
Total Atomic ppm He from 20 ppm B and 14% Ni as a Function of Component and Location Based on Susquehanna

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2.6 References

1. "*BWR Vessel and Internals Project, Weldability of Irradiated LWR Structural Components (BWRVIP-45),*" EPRI TR-108707, Palo Alto, CA, September 1997.

2. W. T. Wood e-mail to B. M. Gordon, "*Boron Concentrations of Types 304 and 316 Stainless Steel,*" June 1, 2000.

3 DETERMINATION OF HELIUM CONTENT

For locations in the reactor that do not fall within the generic weldability boundary, it will be necessary to estimate the He content of the subject material to determine if welding can be successfully performed. This may be accomplished by calculations or by measurements as described in the following sections.

3.1 Helium Concentration By Calculation

Calculation of the He concentration at a specific location begins with a calculation of the thermal fluence at the location projected to the time at which the weld repair is anticipated. It is important to use the thermal fluence (as opposed to the *fast* fluence) since it is the thermal neutrons that are responsible for the conversion of B and Ni to He. Details of such a calculation for the Susquehanna BWR 4 are presented in Appendix B of [1] and may be used as an example.

Once the thermal fluence is known, the following equations may be used to estimate the He concentration at the location:

$$He_B = 1 - \exp(-2.38 \times 10^{-21} \phi t)$$

$$\log_{10} He_{Ni} = 2.121 \log_{10} (\phi t) - 44.44$$

where He_B and He_{Ni} are the He concentrations generated from B and Ni, respectively, and t is the thermal fluence at the BWR component of interest. Note that these equations assume that the material contains 1 ppm B and 10% Ni. The calculated concentrations must be adjusted to account for the actual B and Ni composition of the material. The Ni composition can be readily obtained from handbooks. The B concentration may be available from material certifications or from an archive sample. In the event that a B concentration for the material cannot be found, a conservative bounding value of 50 ppm may be used.

For most BWR components, the He produced from B will provide a sufficiently accurate estimate of the He concentrations. However, high thermal fluence regions require consideration of He contributions from the transmutation of Ni.

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3.2 Sample Removal

The most accurate method to obtain He concentration is by performing laboratory measurements on a sample removed from the target component. Helium (as well as thermal fluence, boron content, and other parameters) can be determined from small shavings removed from the component. Acceptable methods for removing and analyzing these samples are described in [2]. The required sample size is approximately 50 milligrams and the accuracy of the He determination is approximately one percent.

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In one sense sample removal is superior to calculation as a method for determining helium content in that it eliminates uncertainties and conservatisms that are inherent in the fluence calculation process.

3.3 References

1. "*BWR Vessel and Internals Project, Weldability of Irradiated LWR Structural Components (BWRVIP-45),*" EPRI TR-108707, Palo Alto, CA, September 1997.

2. "*BWRVIP-96: BWR Vessel and Internals Project, Sampling and Analysis Guideline for Determining Helium Content of Reactor Internals,*" EPRI 1003019, Palo Alto, CA 2001.

4
APPLICABILITY OF WELDING TECHNIQUES

4.1 Introduction

A number of sources were used to establish the weldability of irradiated materials using various welding techniques. These include the BWRVIP literature survey conducted in 1997 [1], the JOG data recently obtained by the BWRVIP [2], as well as over one hundred articles identified from Metal Abstracts (ASM), Energy Science and Technology (DOE), USG/NTIS and Engineering Index and Weldasearch.

Following is a brief summary of the test results that were evaluated. A more complete discussion may be found in [2].

4.2 Applicability Of Welding Techniques

4.2.1 Weldability Boundary

Figure 4-1 summarizes the effect of He concentration on cracking as a function of heat input based on JOG, BWRVIP-45 and other studies for Type 304, 304L, 316 and 316L stainless steel and for Alloy 600. The points are annotated to show which conditions resulted in cracking and which did not. For some tests, results indicate that small He "bubbles" were observed. Due to their spherical shape, small diameter (<100 nm) and spacing (1 μm), He bubbles were not considered an engineering concern and were not treated as cracks.

A weldability border between the cracking and no cracking points was constructed on Figure 4-1 for the stainless steel data. The most conservative values were used to anchor the borders with a minimum of a factor of two additional margins based on He content. For example, if no He cracking was identified at 1 appm He and cracking was identified at 2 appm at the same heat input, the borderline was constructed to be at or below the 0.5 appm point. Figure 4-1 indicates that successful welds can be obtained on irradiated material at relatively high He contents if the appropriate technique is selected.

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It is important to note that, even if the He content of a component is on the "cracking" side of the weldability boundary, it is not necessarily true that welding cannot be performed by a suitable welding technique. This concept is supported by the fact that there were several successful welds performed at higher He concentrations (open points to the right of the line).

Additionally, the majority of the data shown in Figure 4-1 was obtained from specimens that were shield welded inside a habitat. It is expected that water-backed welded (or underwater welded) components would be characterized by superior results than the results obtained inside a habitat, i.e., water-backed welding should allow welding at higher heat inputs and/or higher He contents due to the quenching effects of the adjacent water.

Due to the paucity of data on Alloy 600, no general boundary between cracking and no cracking could be defined. Utilities may, however, find the data useful in making plant specific decisions regarding the weldability of those materials.

4.2.2 Transmutation Helium versus Tritium Decay Data

A technique for producing He in materials that does not require irradiation is often used in laboratory studies. Since the isotope of hydrogen, tritium, decays to ^{3}He, tritium can be utilized to study the effects of He on welding in irradiated material. This technique known as the "tritium trick" method and consists of diffusing tritium into a metal at elevated temperatures and pressures. The metal is then cooled and aged at cryogenic temperatures until the desired concentration of He is formed. It is then heated in a vacuum to permit the tritium to diffuse out leaving the He. Although the 12.3 year tritium half life means a slow He doping process, the use of sufficient amounts of tritium allows significant He generation to be achieved. The greatest advantage of this technique is that the material is not irradiated and thus not activated. This eliminates the need for hot cells in performing tests. This "helium doping" methodology is often used in testing materials simulating He damage due to irradiation.

However, implanting He by irradiation or tritium can result in different levels of cracking in the material after welding [3]. This difference can be explained by the difference in He locations. Irradiation of the material results in transmutation of B at the grain boundaries and transmutation of Ni homogeneously throughout the material. Tritium decay will only result in a homogeneous distribution of He with no concentration of He at the grain boundaries. These differences are critical in interpreting test results.

Irradiated material is also metallurgically damaged, i.e., high dislocation densities, dislocation loops, vacancies, etc. Such damage to the matrix has a role in subsequent material performance. No such irradiation damage exists in tritium decay treated materials.

Due to these differences, data obtained using the tritium trick method that are shown on Figure 4-1 with the notation "TD" (tritium decay) and were not considered in establishing the weldability boundary.

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Figure 4-1
Effect of He and Heat Input on the Weldability of Stainless Steel and Alloy 600 [4]

4.2.3 Successful Industry Experience with Welding of Irradiated Material

Numerous tests have been performed to investigate suitable techniques for successfully welding irradiated stainless steel. Samples of those tests are described in the following paragraphs.

Westinghouse Savannah River has developed a low penetration gas metal arc (GMAW) overlay welding technique that minimized cracking in irradiated Type 304 stainless steel that contained 10 appm He from tritium decay [3-4]. Surface cracking that was present in conventional welds made on the same steel at the same and lower He concentrations was eliminated. Underbead cracking was minimal compared to conventional welding methods. This overlay technique provides a potential method for repair or modification of irradiated materials.

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4.3 Summary of Advanced Welding Techniques

Based on the welding data presented in this guideline, as summarized in Figure 4-1, it is clearly possible to weld repair highly irradiated austenitic materials using a number of techniques. These techniques include:

1. Low heat input GTAW, also referred to as TIG.
2. Low penetration GMAW or (GMAW-S)
3. Laser beam welding (LBW)

In some instances, successful welding may require the use of autogenous techniques.

Although there is no information currently available in the open literature, other welding techniques may also be applicable provided suitable qualifications are performed.

4.4 References

1. "*BWR Vessel and Internals Project, Weldability of Irradiated LWR Structural Components (BWRVIP-45)*," EPRI TR-108707, Palo Alto, CA, September 1997.
2. "*BWR Vessel and Internals Project, BWRVIP-98: Technical Basis for Guidelines for Performing Weld Repairs to Irradiated BWR Internals)*," EPRI TR-1006385, Palo Alto, CA, 2001.
3. W. R. Kanne, et al. "*Welding Irradiated Stainless Steels*," Journal of Nuclear Materials, Vol. 225, August 1995, p. 69.
4. W. R. Kanne, et al. "*Weld Repair of Irradiated Materials*," Materials Characterization, Vol. 43, August – September 1999, p. 203.
5. S. Nishimura, et al., "*YAG Laser Welding of Neutron Irradiated Stainless Steels*," Journal of Nuclear Materials, Vol. 258-263 (Part B), October 1998, p. 2002.
6. C. A. Wang, et al., "*Welding of Irradiated Steels*," Journal of Nuclear Materials, Vol. 233-237, October 1996, p. 213.
7. C. A. Wang, et al., "*The Effect of an Applied Stress on the Welding of Irradiated Steels*," Journal of Nuclear Materials, Vol. 239, November 1996, p. 85.
8. W. R. Kanne, Jr. et al, "*Repair Welding of Irradiated 304 Stainless Steel*," paper presented at Maintenance and Repair Welding In Power Plants V, November 30 – December 2, 1994, Orlando, FL, published in Proceedings, American Welding Society, Miami, FL, 1995, p. 129.
9. E. A. Franco-Ferreira and W. R. Kanne, Jr., "*Remote Reactor Repair: Avoidance of Helium-Induced Cracking Using GMAW*," Welding Journal, Vol. 71, No. 2, February 1992, p. 43.
10. K. Tsuchiya, H. Kawamura and R. Oyamada, "*Joining Technology Development of Advanced Materials/SS304 by Friction Welding*," JAERI Technical Report 95-017.

5 WELDING GUIDELINES SUMMARY

Section 5.1 presents a simple guideline for determining the weldability of a component based on the considerations discussed in previous sections. If the component is determined to be weldable, certain qualifications, analyses and inspections are required. These are presented in Sections 5.2 through 5.4.

5.1 Weldability Determination

The process for determining whether a weld repair can be successfully performed is shown schematically in the flow chart presented in Figure 1-2. It consists of the following steps:

1 Determine if the component lies within the generic weldability boundary as defined in Section 2. If so, welding may be performed by conventional means without regard for effects of irradiation.

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3 If the component is outside the boundary and the thermal fluence exceeds $1x10^{18}$ n/cm^2, then two options are available for determining weldability:

a. Weldability Determination by Estimation of He Concentration

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b. Weldability Determination by Test

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5.2 Additional Considerations

Welding on irradiated austenitic materials in nuclear power plants may involve special issues related to the irradiation-induced degradation of the material. The production of He in the alloy as a result of neutron exposure may affect the weldability of the component depending upon the amount of He that has been produced and the welding heat input employed. This section of this report provides guidance related to additional controls that are required to weld on these highly irradiated components. It is the intention of the BWRVIP for these controls to be implemented for both ASME Code and non-Code vessel internals components in the BWR.

5.2.1 Required Qualification Tests

The ASME Code, Section IX, provides the essential and non-essential variables in its weld procedure specifications (WPS) and procedure qualification records (PQR) that give the criteria for welding on materials in power plant applications. These guidelines do not provide for additional requirements in the event that the material has become susceptible to specific environmental effects that would compromise the weldability of the material. The guidance for providing additional welding requirements when performing specialized welding, such as underwater welding, falls to the individual book Section of the Code for which the construction is performed. In the case of nuclear power plants, Section XI is the responsible book section for in-service repairs or replacements, and therefore, it is Section XI that should provide the specific guidance for such repairs. Section XI does not, however, provide specific guidance with respect to welding on irradiated materials.

This report has described three regimes of varying helium concentration where welding may or may not be possible. A generic weldability boundary has been defined within which the effects of irradiation are benign and conventional welding may be used. A second regime is identified in which welding is possible provided the heat input is controlled. And a third regime exists where welding at these He levels has not been completely demonstrated, and a demonstration will be required to show that successful welding on the specific component can be performed.

The following paragraphs describe the required qualifications for welding in each of these three regimes. In some cases, the requirements are in addition to the requirements of the Code. For ASME Code repairs, it is anticipated that the additional welding requirements identified below can be represented as "supplementary essential variables" and be incorporated into the Plant welding program when appropriate.

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5.2.2 Required Inspections

5.2.2.1 Kinetics of He Cracking

It is believed that the detrimental effects of He would be seen immediately, i.e., it is not a time dependent reaction, and that, if a component was welded without any evidence of cracking, cracking would not appear at a later date.

Underbead cracking is a concern and may be difficult to detect. Welding studies have indicated that while overlay welds eliminated weld toe cracking that had been observed in conventional welds, both conventional and overlay welds can suffer underbead cracking [1]. Underbead cracking is typically confined to within one or two grains of the weld interface.

However, since underbead cracking is embedded in the material, remote from the weld toe and not exposed to the environment, underbead cracking is more of a net section concern and must be analyzed to assure structural integrity. Since the weld repair itself is designed to address any net section or embedded flaw concern, this evaluation should be rather straightforward. Any weld toe cracking should be repaired by grinding and repair.

5.2.2.2 ASME Code Requirements

The ASME Code requires that following the detection and repair of a flaw, the inspection to be performed should be the same as the inspection that identified the flaw. In the case of welding on irradiated materials, i.e., those materials for which the level of He in the alloy produces a risk for HAZ cracking, the Code rules are inadequate. Whereas the weld repair may repair or remove the flaw that necessitated the repair, the actual weld may create new defects in the weld HAZs produced on each toe of the weld. In addition, the repair may also produce imbedded cracking beneath the weld repair in the original base metal. As a result of this additional potential cracking, additional NDE testing is required to demonstrate that no cracking detrimental to the future performance of the component remains.

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5.2.3 Required Analyses

No additional analyses are required by the rules of the ASME Code for these irradiated and welded components. However, an analysis may be used to demonstrate the acceptability of certain observed flaws. Paragraph IWB-3600 of Section XI of the ASME Code provides for the acceptance of flaws in a component if one can justify that the design safety margin has not been compromised for the ensuing operating interval. (Note that paragraph IWB-3600 specifically addresses flaws found during in-service inspections. For the current purpose, flaws that are found during a post-weld inspection will be addressed by the same paragraph.) This Code provision allows the utility Owner to accept a limited distribution of defects that could occur during the weld repair allowing for continued operation of the component. These include embedded defects, where no additional driving mechanism is available, since the environment cannot get to the flaw, and the stress has been reduced to an acceptable level due to the weld repair. For toe cracks associated with high He level HAZ cracking, removal of these surface cracks and analysis of the slight depression may allow for continued successful operation of the component. Additionally, depending upon the location and severity of the He induced HAZ cracking, the defect may be benign and allow for additional operation with the defect in place. Each of these cases would need to be evaluated individually, and a decision made accordingly.

5.3 References

1. "*BWR Vessel and Internals Project, Weldability of Irradiated LWR Structural Components (BWRVIP-45),*" EPRI TR-108707, Palo Alto, CA, September 1997.

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Nuclear Power

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