EPRI

BWR Vessel and Internals Project CRD Internal Access Weld Repair (BWRVIP-58NP)

BWR Vessel and Internals Project

CRD Internal Access Weld Repair (BWRVIP-58NP)

The Boiling Water Reactor Vessel and Internals Project (BWRVIP), formed in June, 1994, is an association of utilities focused exclusively on BWR vessel and internals issues. This BWRVIP report documents the development and qualification of an internal access welded repair for leaking BWR Control Rod Drive (CRD) housings. "Internal access" refers to the fact that the repair is conducted from beneath the vessel and tooling access to the repair location is from the inside of the CRD housing.

BACKGROUND In some domestic and non-domestic BWRs, CRD penetrations have leaked due to cracking in the region of the J-groove weld joining the CRD housing to the stub tube. A variety of repair techniques have been proposed and some have been used to reduce or eliminate leakage from the penetration. Each of the previously proposed or utilized techniques, other than the internal access welded repair, had at least one significant disadvantage. They either required defueling and vessel draindown, or they did not provide a welded seal between the CRD housing and the stub tube and/or the reactor pressure vessel.

OBJECTIVE To develop and qualify a welded repair for CRD housings that overcomes the disadvantages of other techniques.

APPROACH The contractors designed a repair based on work previously performed by EPRI. The repair uses a temperbead welding process to attach the CRD housing directly to the vessel bottom head. The design of the repair was analyzed and found to meet structural requirements. Next, tooling was designed and fabricated to perform the repair. Welding Procedure Qualification tests and a number of full-scale demonstrations which utilized the tooling were performed.

RESULTS Metallurgical examinations of test samples indicate that the temperbead process results in a satisfactory repair. In addition, the full-scale tests have demonstrated that the tooling is suitable for performing the repair under in-plant conditions.

EPRI PERSPECTIVE The CRD internal access weld repair has been evaluated and found to be a satisfactory method of repairing leaking CRD housings. It provides utilities with an additional option in the event that leaks are found.

PROJECT
WOB501
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TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

Tables

Figures

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EXECUTIVE SUMMARY

In some domestic and non-domestic BWRs, control rod drive (CRD) penetrations have leaked due to cracking in the region of the J-groove weld joining the CRD housing to the stub tube. A variety of CRD penetration repair techniques have been proposed and some have been used to reduce or eliminate leakage from the penetration.

Each of the previously proposed or utilized techniques had at least one significant disadvantage. They either required defueling and vessel draindown, or they did not provide a welded seal between the CRD housing and the stub tube and/or the reactor pressure vessel. The internal access welded repair described in this report overcomes these disadvantages.

This report provides the results of a demonstration project that applied the internal access weld repair process for a leaking CRD housing in BWR/2 through BWR/5 reactors. It includes:

- A description of the internal access weld repair process
- A description of the demonstration of the internal access weld repair for leaking CRD housing penetrations
- A discussion of the technical basis for the repair
- The metallurgical evaluation of the repair
- The analytical evaluation of the stresses produced by welding and design loading conditions on the CRD housing/stub tube repair design.

The report provides confirmation that the internal access weld repair is technically adequate, suitable for field implementation, and compatible with nuclear plant schedule and economic constraints.

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1.0 BACKGROUND

1.1 PURPOSE

The purpose of the project was to develop the technical basis and demonstrate the application of an internal access weld repair for leaking CRD housing penetrations in BWR/2 through BWR/5 reactors. The repair weld was designed to replace the load carrying capability of the CRD housing to stub tube J-weld in addition to providing a seal to prevent leakage from the RPV. A supporting analytical evaluation of the stresses produced by welding and design loading conditions on the CRD housing/stub tube repair design was performed.

The project included the development and qualification of the "Ambient Temperature" Temperbead welding technique on P-No. 3, Group 3 materials using the Machine Gas Tungsten Arc Welding (GTAW) process with ER-NiCrFe-7 filler metal. The work provided the technical basis for Code Case N-606 "Similar and Dissimilar Material Welding Using The Ambient Temperature Machine GTAW Temperbead Technique". The term "ambient temperature" which is mentioned throughout this report refers to ambient base material temperature and has been defined in the Code Case as 50° F minimum. The term also implies that no preheat or post weld heat treatments are applied.

This project demonstrated that the internal access weld repair is a technically adequate and economically viable repair option.

The issuance and regulatory approval of this document is not intended to imply that the internal access weld repair is the only, or preferred, repair method. The specific repair option to be utilized by an individual plant will be determined by the plant licensee.

1.2 BACKGROUND

1.2.1 CRD Housing Physical Description

Penetrations for CRDs are located in the reactor vessel lower head of boiling water reactors (BWRs). The CRD penetrations were fabricated by welding a stainless steel housing to a stainless steel or Inconel stub tube in the field. For the reference design, Nine Mile Point Unit 1, the stub tube was welded to the vessel head during the vessel fabrication process and post weld heat treated with the vessel bottom head. In some later BWR plants, an Inconel 600 CRD housing was welded directly to the reactor vessel bottom head, i.e., no stub tube was used. A typical CRD housing is shown in **Figure 1.1**.

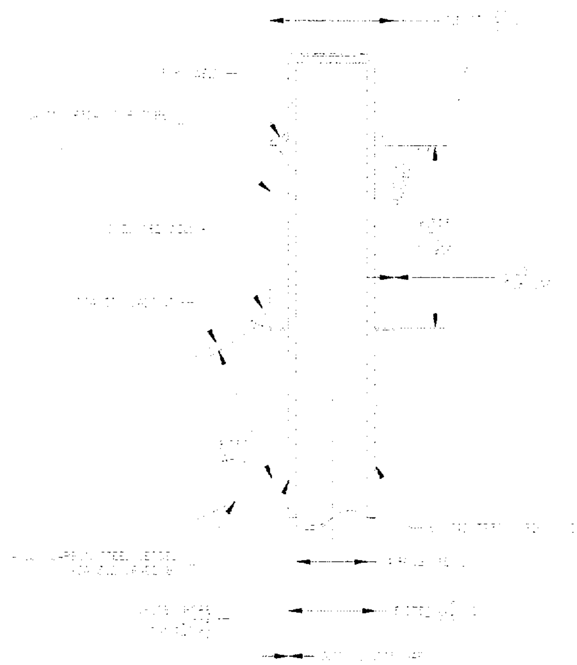

Figure 1.1 CRD Housing and Stub Tube Geometry

1.2.2 Operational and Safety Functions

The operational and safety functions of the CRD penetration are:

Provides a portion of the reactor coolant pressure boundary.

Provides location and support for the bottom end of the CRD guide tube (the guide tube supports the weight of the fuel assemblies and fuel support castings).

Provides housing and support for the CRD mechanisms and reacts design mechanical loads including those from CRD insertion and scram events.

Provides a thermal barrier to limit heat flow from the reactor vessel lower head to the interior of the CRD housing.

1.2.3 Need for Repair

Some CRD penetrations have leaked in service due to cracking. To date, the cracking has been limited to furnace-sensitized stainless steel. However, for BWRs there is a potential for cracking of CRD penetrations at various locations:

For the two plants with furnace-sensitized stainless steel stub tubes, the carbon content of the stub tubes is typically in the range where significant furnace-sensitization would be expected. The locations for cracks have been in the areas which had the highest residual tensile stresses as a result of the fabrication history of the CRD penetration.

- For all other plants with Inconel or non furnace-sensitized stainless steel stub tubes, cracking in the stub tubes is possible in weld-sensitized material in tensile residual stress areas (toe of welds to vessel and housing) and Inconel 182 welds.

- Cracking is possible, but not as likely in the weld-sensitized CRD housing adjacent to the CRD housing to stub tube field weld. Because this weld is not a full penetration weld, sensitization of the housing in the heat affected base metal next to the weld does not extend through the housing thickness. Therefore, it is unlikely that any intergranular stress corrosion cracking (IGSCC) would penetrate the housing wall, although it cannot be ruled out. Any cracks, which follow the heat affected zone on the housing OD, would have the same effect as a stub tube leak.

The cracking is not a significant safety issue since the leakage would be detected and the plant could be safely shutdown. The leakage is an operational issue that could cause or extend an outage. Since leakage could be identified at any time, a repair that does not require defueling and vessel draindown, and that can be quickly mobilized, is very desirable. The internal access weld repair has these attributes.

1.2.4 Repair Process Overview

The CRD Internal Access Weld repair is designed to seal a leaking CRD penetration and to structurally replace the J-weld between the CRD housing and the stub tube. The approach is based on earlier work performed by EPRI (Ref. 1) and includes the following major steps:

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Section 2 of this report presents the analysis that was performed to demonstrate the adequacy of the repair; tooling developed to perform the repair is described in Section 3; and welding qualifications and results are discussed in Section 4.

Portions of this work related to qualification of the welding and inspection processes were conducted according to the applicable provisions of 10 CFR 50, Appendix B.

2.0 REPAIR DESIGN

The repair is a welded design which establishes a new pressure boundary outside of the flawed area.

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Figure 2.1 BWR CRD Housing Repair

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2.1 STRUCTURAL DESIGN ANALYSIS

A structural evaluation (Reference 4) was performed to determine the acceptability of the below listed components that are affected by the repair method.

a. CRD Housing
b. Stub Tube
c. Stub Tube-to-Vessel Weld
d. CRD Housing-to-Stub Tube Weld
e. CRD Housing Repair Weld
f. Vessel Wall

The loadings considered were the dead weight, seismic, scram loading on the housing (stuck rod scram and scram end of stroke, no buffer), internal pressure and the steady state temperature distribution.

2.1.1 Code Design Compliance

The repair weld geometry is not explicitly recognized in the ASME Section III NB-3300 weld categories but is similar to a partial penetration weld Category D. The penetration continues to meet the Code reinforcement requirements with no credit from the housing.

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2.1.2 Analysis of Weld Repair Stresses

Two finite element models were developed to bound existing CRD penetration configurations; a three dimensional model for analysis of "uphill" CRD penetrations located far from the vessel centerline (Penetration U) and a two dimensional, axisymmetric model for analysis of a CRD penetration located at the vessel centerline

(Penetration X). Each model includes the stub tube, the CRD housing, and a portion of the reactor vessel. The weld repair with a ¼ inch wide root is included in both models.

2.1.3 Loading Conditions

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2.1.4 Stress Analysis Results.

Stress results for the finite element evaluations were determined for the mechanical and thermal loading cases for the three-dimensional (Penetration U) and two-dimensional (Penetration X) models.

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2.2 WELD ANOMALY ANALYSIS

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The assumed deviated geometry was evaluated for net section ASME code requirements, potential for crack growth and potential for non-ductile failure in the low alloy steel head.

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2.3 SUSCEPTIBILITY OF CRD REPAIR TO IGSCC

The CRD internal weld repair is potentially susceptible to stress corrosion cracking because of the inherent susceptibility of the materials, residual and thermally induced tensile stresses, and the crevice geometry at the housing OD above the repair weld. However the probability of safety significant cracking is considered to be acceptably low for the reasons discussed below.

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Table 2-1

Summary of Results for CRD Penetrations

Far From Reactor Vessel Centerline - Intact CRD Housing

(Stainless Steel Stub Tube)

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Table 2-2

Summary of Results for CRD Penetrations

Near Reactor Vessel Centerline - Intact CRD Housing

(Stainless Steel Stub Tube)

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Table 2-3

Summary of Results for CRD Penetrations

Near Reactor Vessel Centerline - Failed CRD Housing

(Stainless Steel Stub Tube)

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Table 2-4

Summary of Results for CRD Penetrations

Near Reactor Vessel Centerline - Intact CRD Housing

(Alloy 600 Stub Tube)

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3.0 REPAIR EQUIPMENT DESIGN

Implementation of the weld repair involves the following activities.

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The following equipment was designed and fabricated to implement the internal access weld repair:

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3.1 CRD NOZZLE BORE PLUG

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3.2 WELD PREP MACHINING TOOL

The weld prep machining tool was designed to cut the weld prep configuration shown in **Figure 3.1.**

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Figure 3.1 BWR CRD Repair
Weld Prep Geometry

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3.3 *REMOTE MACHINE WELDING SYSTEM*

The machine welding system was designed to perform all welding with fully remote equipment.

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Figure 3.2 FFID Weld Head

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3.4 DISTORTION MONITORING SYSTEM

A distortion monitoring system was designed to measure the displacement of the lower end of the CRD housing.

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3.5 CRD HOUSING NDE TOOLING

The CRD housing NDE tooling consists of three independent devices.

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Figure 3.3 Manipulator Base

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3.5.1 *CRD Nozzle Weld Repair Dye Penetrant (PT) Tool*

After all machining and welding is complete the PT tool (**Figure 3.4**) applies solvent as required to clean the area of interest for penetrant application. The tooling is designed to deliver approved solvent removable penetrant and approved solvent suspended developer with minimum mess and waste associated with the application of PT materials. The tooling is designed to deliver PT materials to meet the time limitations established for dwell times and maximum times between developer drying and indication visual examination for sizing.

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Figure 3.4 Remote Dye Penetrant Tool

3.5.2 *CRD Housing Weld Repair Ultrasonic Testing (UT) Tool*

The UT tool (**Figure 3.5**) is designed to inspect the entire inspection volume. Both axial and circumferential motions are automated with the ability to scan and index with either motion.

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Figure 3.5 Remote Ultrasonic Tool

4.0 *REPAIR PROCESS QUALIFICATIONS*

The BWRVIP CRD Repair Project included development, qualification and mock-up demonstrations including Water Jet Machining, Machine Gas Tungsten Arc Welding, and the NDE methods VT, PT, and UT.

4.1 *WATER JET MACHINING QUALIFICATIONS*

Extensive testing was performed with the waterjet cutting equipment to establish the weld prep geometry and the CNC parameters that control the geometry. This testing was performed on short mock-up specimens made of carbon steel with an outer stainless steel ring.

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4.2 *WELD QUALIFICATION*

4.2.1 *ASME Code Case*

A Code Case, entitled Similar and Dissimilar Material Welding Using Ambient Temperature Machine GTAW Temper Bead Technique Section XI, Division I, was prepared for the use of automatic or machine GTAW temper bead technique without the use of preheat or post-weld heat treatment on BWR control rod housings and stub tubes. The Position Paper, Reference 3, that provides the technical data to justify the Code Case was presented to the American Society of Mechanical Engineers (ASME) in December 1997 at the Reno meeting. The Code Case, designated N-606, was approved on March 2, 1998 and has since been published.

The Code Case, N-606, provides the requirements for performing a dissimilar metal weld repair without preheat and post soak heat treatments on the reactor vessel CRD housing interface. The Code Case also contains other minor modifications to current temperbead rules published in Sections III and XI. These modifications are the result of the work performed in the Section XI Task Group for Temperbead Welding.

The standard temperbead requirements for preheat and post-weld soak heat treatment (PSHT) have been specified primarily to preclude the presence of hydrogen in the final weld. Hydrogen, the source of delayed cracking in the base material HAZ, is of primary concern when welding ferritic materials. Elevated preheat is intended to eliminate moisture and contaminants (hydrocarbons) that could be introduced into the molten metal during welding. The PSHT, initiated immediately after welding is completed, allows the hydrogen potentially trapped in the HAZ and weld metal an extended time period to diffuse out of the HAZ and weld metal. However, these requirements were initially imposed for Shielded Metal Arc Welding (SMAW) temperbead welding where coated electrodes, susceptible to hydrogen pick-up, were used. Extensive EPRI studies have shown that the effects of humidity, shielding gas dew point, and modern solid wire weld filler materials are negligible sources of dissolvable hydrogen during GTAW welding. Therefore, if the weld joint receives proper cleaning and drying, the primary sources of dissolvable hydrogen will not be present during GTAW welding. Cleaning of the joint area prior to welding is a part of the process.

The current machine GTAW Temperbead process requires the application of six layers with controlled temperbead welding techniques. The Section XI Task Group found this requirement to be very conservative and inconsistent with other existing Code repair requirements. Several of the dissimilar material temperbead repair methods presented in Section XI invoke a temperbead repair if the existing thickness of the cladding or austenitic material in a repair area is less than 0.125 inch. The 0.125 inch austenitic material thickness is regarded by the Code as a sufficient buffer between the HAZ produced from standard welding practices and the ferritic substrate to insure that the substrate will not develop untempered martensite. With an approximately 50% overlap, the typical thickness of a single machine GTAW layer is approximately 0.060 inch. Three layers of the Machine GTAW process with a 50% over lap will typically approach 0.180 inch which is well above the 0.125 inch minimum ligament thickness. In addition, the heat input for the balance of welding (after the 3 temperbead layers) is restricted to the maximum used during the qualification. Considering the deposit thickness and the heat input controls imposed on the subsequent welding, the low alloy steel substrate is adequately protected.

Section 2.0 of Code Case N-606 imposes a 150°F maximum interpass temperature during the welding of the procedure qualification. This requirement has been proposed to restrict base metal heating during the qualification that could produce slower cooling rates that are not achievable during field applications. However, this requirement does not apply to field applications as they are permitted a 350°F maximum interpass temperature in Section 3.0 of the Code Case. Although it is unlikely that a water backed thick section weld repair will exceed the 350°F maximum interpass temperature, the higher interpass temperature is permitted because it would only result in slower cooling rates which could be helpful in producing more ductile transformation products in the HAZ. A complete description of the materials, test assemblies, and the mechanical and metallographic testing which support the code case are presented in Reference 3.

4.2.2 *Welding Procedure Qualifications*

Following an extensive development process using numerous weld coupons and the trial and error method based on parameters from previous experience, a welding procedure was established suitable for qualification. Two (2) Welding Procedure Qualifications were performed in accordance with the rules of Code Case N-606.

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Figure 4.1 PQ Assembly

4.2.3 *Repair Procedure Demonstrations*

A full-size mock-up facility was designed and fabricated to support developing and demonstrating the CRD-weld repair. The mock-up facility accurately represented the access limitations under a BWR vessel, as shown in Figure 4.2, and the physical constraints expected in the field were simulated to provide a realistic work environment. The mock-up was representative of the housing length, RPV head location and thickness.

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Figure 4.2 CRD Mock-up Facility

A total of four CRD Penetration Mock-ups were fabricated. All of the mock-ups were representative of a peripheral CRD location, thus providing the maximum angle between the lower head and penetration, equivalent to Penetration "U". The gap between the CRD housing and RPV head was also representative of actual conditions.

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Figure 4.3 Pressurized Mock-up

The demonstration mock-up welded assemblies were required by the BWRVIP development project to demonstrate the process and tooling on the actual repair configuration under field conditions. All demonstration mock-ups were welded in accordance with the rules of Code Case N-606. The full scale mock-ups were constructed from a SA-508, Grade 3, Class 2 forging material. The SA-508 portion of the mock-up was forged as a bar and then machined to the final configuration.

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Figure 4.4 Non-Pressurized Mock-up

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Figure 4.5 Mock-up Details

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Table 4.2.1

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4.2.3.1 Mock-up NDE Results

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4.2.3.2 Metallurgical Analysis of Repair Weldments

Metallographic examination was performed on the same specimen cross sections that were subjected to microhardness evaluation to determine if any untempered martensitic structure or cracking existed. Metallographic examinations were conducted throughout the entire cross section, but primarily at the HAZs, with emphasis on the locations where microhardness testing was performed. For this class of steels, the microhardness of a bainitic structure is expected to be approximately the same as tempered martensite. Therefore, microhardness alone cannot be used to judge the existence of tempered martensite.

The microstructure of tempered martensite is expected to generally consist of carbide precipitation and (in some cases) ferrite formation in the matrix martensite. In general, the degree of carbide and ferrite formation is time and temperature dependent. The criterion to consider a martensitic microstructure to be "tempered" was any evidence of carbide precipitation or ferrite formation. For comparison, an untempered martensitic base metal specimen was also prepared from each weld assembly base material by heat treatment.

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4.2.3.3 Distortion Measurements

As discussed previously the demonstration mock-ups were instrumented for distortion monitoring.

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4.2.4 *Non-Destructive Examinations (NDE)*

4.2.4.1 Examination Requirements

The CRD housing internal access weld repair is subject to ASME Inspection and Repair/Replacement Plan criteria. The inspection requirements of ASME Section XI, 1995 Edition, 1995 Addenda, Subsection IWA-4000 "Repair/Replacement Activities" were applied to this program. IWA-4520 states that the weld shall be examined in accordance with the Construction Code identified in the Repair/Replacement Plan. This is defined as ASME Section III, 1995 Edition, 1995 Addenda. ASME Section III, NB-5000 contains these examination requirements. Figure 4.6 identifies the required examination zones and Table 4.4 summarizes the examination requirements for each of the zones. Note: Section III, NB-5279 states that if the radiographic examination (required) can not be performed due to inaccessible OD surface, ultrasonic examination plus liquid penetrant can be substituted.

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Figure 4.6 Examination Zones

Table 4.4 – ASME Examination Requirements

Examination Area	NDE Method	NDE Requirements	Acceptance Standard	Reject Criteria
Weld Volume b-c-e-f-b	Ultrasonic Examination	Section V, Article 5 1995 Edition/ Addenda	Section III, NB-5330 1995Edition/ Addenda	1) Indications >100% DAC and > 1/4" long 2) All cracks, lack of fusion, and incomplete penetration >20% DAC
Weld Surface b-c	Penetrant Examination	Section V, Article 6 1995 Edition/ Addenda	Section III, NB-5350 1995Edition/ Addenda	1) All cracks or linear indications >1/16" long 2) Rounded Indications >3/16" 3) Four of more rounded indications >1/16" in line separated by 1/16" or less 4) Ten or more rounded indications in any 6 sq. inch area
Adjacent Base Metal a-b and c-d	Penetrant Examination	Section V, Article 6 1995 Edition/ Addenda	Section III, NB-2546 1995Edition/ Addenda	1) All cracks or linear indications >1/16" long 2) Rounded Indications >1/8" 3) Four of more rounded indications >1/16" in line separated by 1/16" or less 4) Ten or more rounded indications in any 6 sq. inch area

4.2.4.2 Dye Penetrant (PT) Examination Qualification

The procedure used for dye penetrant examination was developed and qualified for examination of the CRD nozzle weld repair from the ID Surface.

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4.2.4.3 Ultrasonic (UT) Examination Qualification

Ultrasonic techniques were applied to examine the deposited weld for unacceptable flaws in accordance with the requirements of the ASME Code identified in Table 4.4. An array of UT transducers is positioned at the repaired region by a remotely operated manipulator to perform the examination.

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4.2.4.4 NDE Demonstration Results

The EPRI NDE Center supplied two (2) stub tube mock-ups for demonstration of the effectiveness of the Code prescribed ultrasonic examination technique. The blocks contain implanted flaws with various through-wall depths and orientations and include fatigue cracks, lack of fusion and flat-bottomed holes. The ASME Code prescribed ultrasonic procedure was demonstrated on the BWRVIP mock-ups. These mock-ups, having known flaws of various size and orientation, are used as a gauge for detectability using the ASME, Section III acceptance criteria. The data is compared (actual flaw vs. recorded flaw values) and documented for the remote ultrasonic procedure qualification. The results are presented in Table 4.5. Satisfactory performance for detection of the flaws was accomplished.

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Table 4.5 Mock-up Detection Results

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The detailed results of the NDE qualifications are presented in Reference 6.

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5.0 SUMMARY

The activities of this project have demonstrated that internal access weld repair is a qualified process for repair of leaking CRD housing penetrations in BWRs. The activities that have been successfully completed are as follows:

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Successful completion of these activities has demonstrated that the internal access weld repair of CRD housings is a qualified procedure that meets all ASME Code and NUREG requirements and can be accomplished under field conditions.

6.0 REFERENCES

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5. Niagara Mohawk Power Corporation letter to US Nuclear Regulatory Commission, "Visual Examinations of Stub Tubes and Safety Assessment", May 11, 1984.

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Targets:
Nuclear Power

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