

A Destructive Validation of NDE Responses of Service-Induced PWSCC Found in North Anna 2 Control Rod Drive Nozzle 31¹

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Abstract

Studies conducted at the Pacific Northwest National Laboratory (PNNL) in Richland, Washington focused on assessing the effectiveness of nondestructive examination (NDE) techniques for inspecting control rod drive mechanism (CRDM) nozzles and J-groove weldments. The primary objective of this work is to provide information to the United States Nuclear Regulatory Commission (NRC) on the effectiveness of NDE methods as related to the in-service inspection of CRDM nozzles and J-groove weldments, and to enhance the knowledge base of primary water stress corrosion cracking (PWSCC) through destructive characterization of the CRDM assemblies.

The reactor pressure vessel head of North Anna Unit 2 was replaced after evidence of leakage was found during a bare metal visual examination of the head and volumetric examinations found evidence of cracking on some of the J-groove welds. After the head was replaced, suspect nozzles were cut from the pressure vessel head for further testing. The nozzle and J-groove weld metal of North Anna Unit 2 Nozzle 31 was examined at PNNL using a series of nondestructive tests, including ultrasound, eddy current (ET), penetrant testing (PT), visual testing via replicant, visual testing using high-magnification photography, and time of flight diffraction (TOFD). Penetrant testing found three indications at 200, 215, and 225 degrees. High-magnification photography confirmed the indications at 200 and 225 degrees. Eddy current examinations of the J-groove weld metal found sixteen crack-like indications around the wetted surface of the J-groove weld, including those found using penetrant testing. Additionally, the eddy current pattern found by PNNL closely resembled the in-service eddy current inspection results.

Destructive evaluation (DE) of the nozzle found six cracks that had penetrated deeper than 6-8 mm into the weld. A stress corrosion crack had propagated through the weld and penetrated to the annulus located at 155 degrees. A second very deep crack that had propagated through the weld metal but had not yet penetrated to the annulus was found at 255 degrees. Four other cracks greater than 6-8 mm deep were also discovered during destructive evaluation. Eddy current testing was the only nondestructive testing technique used on the J-groove weld that provided any indications of the two deep cracks. The through-weld crack at 155 degrees was then sectioned and reconstructed to provide a detailed understanding of the crack morphology.

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Introduction

Significant degradation has been found in welded assemblies that contain nickel-based alloys [1-5]. Inspections of the CRDM nozzles at Oconee Nuclear Stations 2 and 3 in early 2001 identified circumferential cracking of the nozzles above the J-groove weld. Circumferential cracking above the J-groove weld is considered a safety concern because of the possibility of nozzle ejection, should the circumferential cracking not be detected and corrected.

Inspections at other pressurized water reactors (PWRs) continued to find leakage and cracks in CRDM nozzles or J-groove welds that required repairs or prompted the replacement of the reactor pressure vessel (RPV) head. In response to the increasing number of reported occurrences, the NRC issued Order EA-03-009 on February 20, 2004, to require additional periodic inspections of RPV heads and associated penetration nozzles at PWRs as a function of the unit's susceptibility to pressurized water stress corrosion cracking (PWSCC) and, as appropriate, to address the discovery of boron deposits to provide reasonable assurance that plant operations do not pose an undue risk to the public health and safety.

To provide the data needed to address issues related to cracking of nickel-base alloys and degradation of reactor pressure vessel heads, the NRC and the Electric Power Research Institute (EPRI) initiated a collaborative research effort. CRDM nozzles and J-groove weldments were removed from the decommissioned North Anna Unit 2 RPV head and shipped to PNNL, and Westinghouse Electric Company LLC in Pittsburgh, Pennsylvania, for study.

Six CRDM penetrations were removed from the RPV head and transferred to PNNL. Four of the CRDM penetrations were decontaminated to reduce individual radiation dose and contamination levels in preparation for NDE studies. Round-robin inspections were conducted by four NDE vendor companies. The vendors involved in the round-robin testing performed examinations on only the penetration tube. The vendors used eddy current and ultrasonic testing of the penetration tube and ultrasonic and eddy current testing of the annulus to detect signs of leakage. The purpose of the round robin inspections was to evaluate the CRDM assemblies in a laboratory environment and to perform some of the inspections with advanced technologies and methods.

The results of the round robin inspections were then analyzed. It was decided that PNNL would focus its laboratory studies on CRDM Nozzle 31 (which had cracks, as evidenced by through-wall leakage and the in-service inspection data) and Nozzle 59 (where an outer-diameter circumferential crack but no discernable leakage had been identified). Subsequent NDE found that Nozzle 31 was the most likely to contain a crack resulting in leakage, and all efforts were focused on Nozzle 31.

There were two primary efforts: NDE and DE. Regarding NDE, the surfaces and volumes for the various product forms in the CRDM nozzle assemblies were evaluated. Several nondestructive testing modalities including ultrasound, eddy current (ET), penetrant testing (PT), visual testing via replicant, visual testing using high-magnification photography, and time of flight diffraction (TOFD) The NDE inspections were conducted in a laboratory environment using very high sensitivity to optimize flaw detection but were not performed to meet existing codes and standards.

The NDE data from all of the inspections were combined or fused into an assessment of degradation. This assessment was used to guide the development of a DE plan with subsequent sectioning and metallurgical study of the two CRDM nozzle assemblies.

Figure 1 shows a diagram of a CRDM penetration-nozzle assembly showing the pressure vessel head, the penetration tube, and the J-groove weld. A description of these product forms can be found in [6]. Most of the interface between the penetration tube and the vessel head is a simple interference fit, and is not watertight. When a PWR is at operating pressures and temperatures, the pressure vessel head is slightly deformed, further opening the interference fit in some regions. The only barriers between the primary coolant and the outside are the J-groove weld and the penetration tube above the weld. Any cracks that propagate through either of these two sections can lead to leakage.

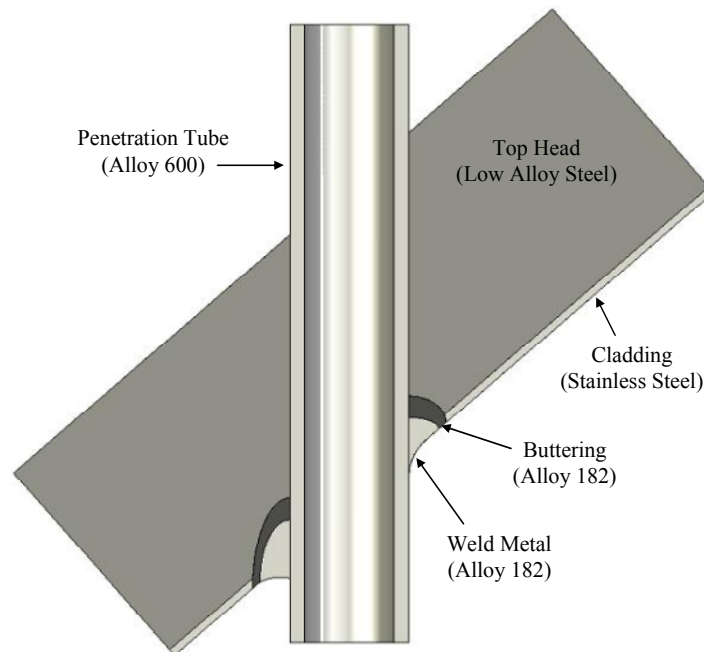


Figure 1: Control rod drive mechanism penetration-nozzle assembly

One objective of this work is to provide information to the NRC on the effectiveness of NDE methods as related to the in-service inspection of CRDM nozzles and J-groove welds. The selected NDE measurements follow standard industry techniques for conducting in-service inspections of CRDM nozzles and the crown of the J-groove welds and buttering. In addition, laboratory based NDE methods were employed to conduct inspections of the CRDM assemblies, with particular emphasis on inspecting the J-groove weld and buttering. This paper focuses on a CRDM removed from the retired North Anna Unit 2 reactor pressure vessel head that contained suspected PWSCC, based on in-service inspection data and through-wall leakage.

A secondary objective is to enhance the knowledge base for PWSCC through destructive characterization of the CRDM assemblies. Project efforts used the results from the NDE studies to guide the DE of the CRDMs. The purpose of the destructive analysis was to reveal the crack morphology compared with NDE responses, to determine what each NDE method detected or missed and how accurately each NDE technique characterized the detected flaws.

While many NDE techniques were applied to Nozzle 31, this paper focuses on the results of the ET examinations and the DE of the flaws, and the ultrasonic examination of the interference fit to determine if one can ultrasonically determine if a nozzle is leaking.

Eddy Current Examination of J-Groove Weld

The J-groove weld area of Nozzle #31 was examined using a plus-point differential eddy current probe. The scan was conducted by performing a series of rectangular scans using the X-Y scanner. The rectangular scans were made every 30° to cover the weld surface with a large degree of overlap in the scans. The scans were taken as close to the penetration tube as possible, and in general covered the buttering and 12-15 mm of the weld taper. The scans were made with the probe in the normal position and with the probe rotated to 45 degrees to assure good coverage of the weld with high sensitivity. The rectangular scans were assembled into the ellipse to show the locations of areas of interest. The assembled ellipses, for the zero degree and 45 degree probe rotations, are given in Figure 2.

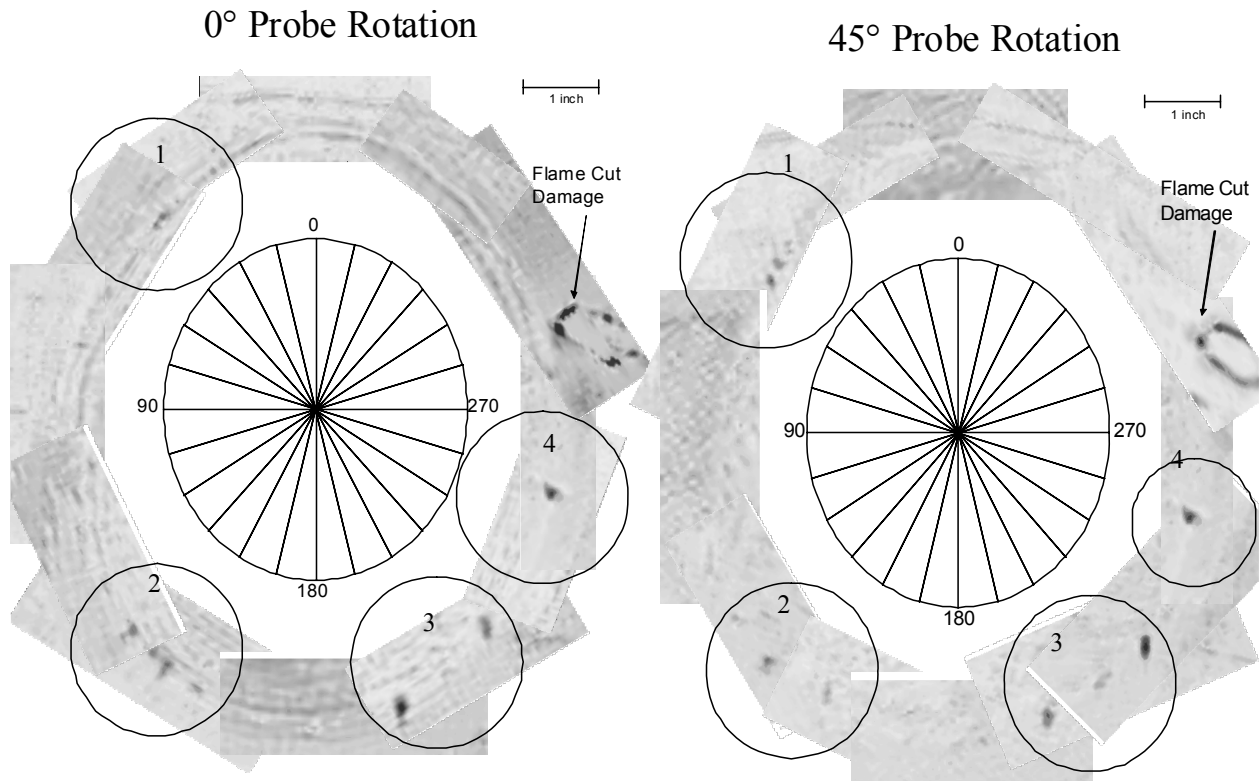


Figure 2: Eddy Current results for zero degree scan of the J-groove weld of Nozzle 31. Four areas of interest were found at close to 60 degrees, 150 degrees, 215 degrees, and 270 degrees.

Four areas of interest were found in the ET data. The areas of interest are centered around 60 degrees, 150 degrees, 215 degrees, and 255 degrees. These areas were examined again in more detail to quantify the indications. The scans were made using 0.5 mm steps and were repeated

until no signs of lift-of or other possible scanning errors were present in the scan. This scanning regime yielded a total of 16 indications with a strong enough ET response to be considered crack-like.

Destructive Evaluation Results

The four regions of interest were then examined via cutting below the weld surface at two depths, 6-8 mm and 25 mm. It should be noted that the 25mm-deep cut is beyond the weld-buttering-annulus triple point, and any cracks beyond this point could result in leakage if the crack intersects with the annulus. These cuts below the weld surface were made to determine which ET indications were associated with deep flaws. On examination of the cut surfaces it was determined that only six of the sixteen indications were associated with cracks that penetrated deeper than 6 mm into the material. Two of the cracked regions contained cracks that penetrated into the buttered region below the triple point.

The wetted surface exposed to PWR primary water was rough and relatively thick oxide corrosion products remained in many locations. SEM revealed an obvious crack in the alloy 182 weld metal perhaps widest in the region near the transition from the butter passes to the J-groove weld metal. SEM of the wetted surface shows that the crack has a bent and discontinuous profile. Many separate and very tight cracks were found on the weld surface. A 4-mm long (1.6-in.), 20–30 μm (0.0008–0.0012 in.) COD discontinuous crack segment begins at the weld/butter boundary and extends at an angle into the buttering. A tail 2 mm (0.08 in.) long and very tight (too tight for the SEM to measure in many places) extends further into the buttering toward the stainless steel cladding. A full crack montage is shown in Figure 3. The widest crack openings at the surface locations were on the order of 30 μm . An important feature of the crack at the surface is its discontinuous nature. Even along the 4-mm-long main segment, there are several ligaments of metal crossing the crack. A section of the crack with several connecting ligaments is shown in Figure 4.

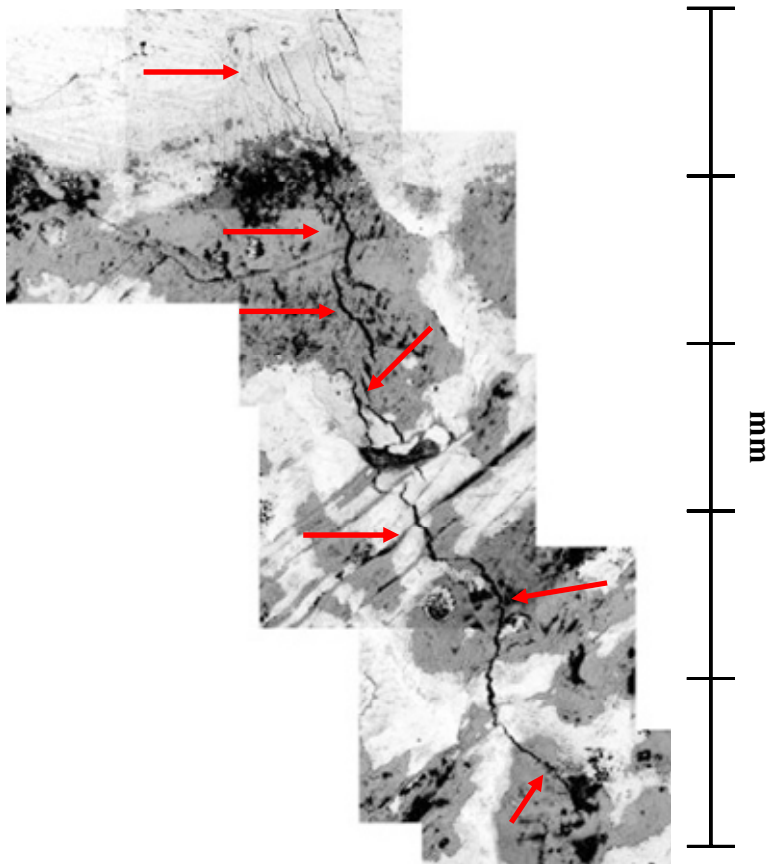


Figure 3: SEM micrographs showing the observed crack on the PWR water surface. The rough as-welded surface and relatively thick corrosion-product oxide is places (white contrast) made imaging of fine secondary cracks difficult. However, the main crack is seen to extend ~6 mm on this surface.

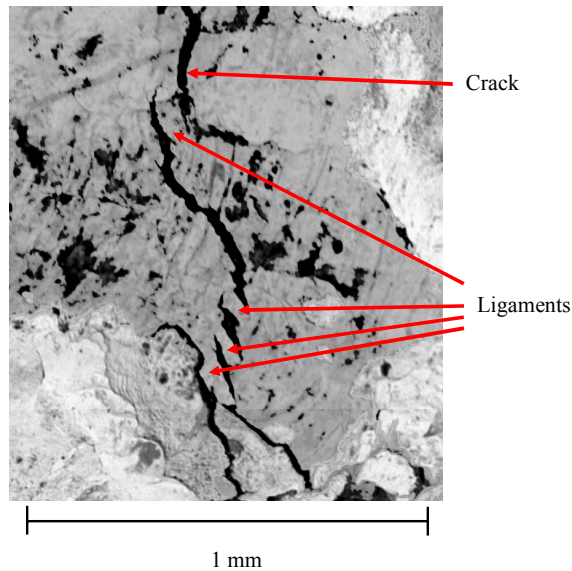


Figure 4: Expanded section of the crack showing ligaments bridging the two sides of the crack.

The Alloy 182 machined surface that made up the interference-fit gap with the Alloy 600 tube was found to have two relatively long cracks, as presented in Figure 5. Combining the two cracks, a total crack length approaching ~7 mm was found on this exit surface, with crack opening reaching ~10 μm in places. The cracks were filled with an unknown material, probably boric acid powder and corrosion-product oxide.

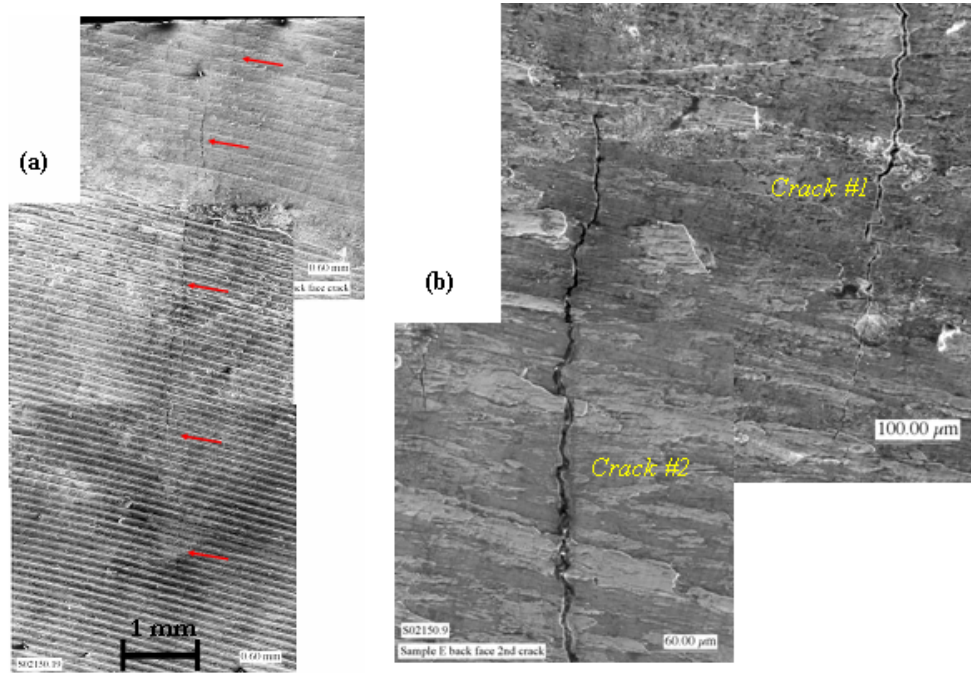


Figure 5: Machined surface and exit location for through-wall cracks from 182 weld metal into interference-fit gap between alloy 182 butter and alloy 600 tube.

The cracked section was sectioned sequentially. Great care was used during low-speed cutting with a diamond saw to maintain cut locations and orientations so that metallographic cross-sections lined up with each other. The crack has a branching and discontinuous morphology in the through-weld orientation. The first three millimeters show nine separate segments with ligaments between them. The segments are all part of the same crack, but they connect with each other outside of the plane shown in the slice.

Also of interest is a detailed look at the crack opening displacement (COD) at various points along the crack. Figure 6 shows the first 1.5 mm (0.06 in.) of the through-wall crack. Looking close to the surface, one finds several closed points very close to the surface of the crack. While the COD is 20-30 μm (0.0008-0.0012 in.), the crack is much tighter less than a tenth of a millimeter into the weld.

Location	COD (μm)
1	10
2	29
3	6
4	2
5	6
6	6
7	2
8	Closed
9	Closed
10	4
11	2
12	9
13	7
14	3
15	2

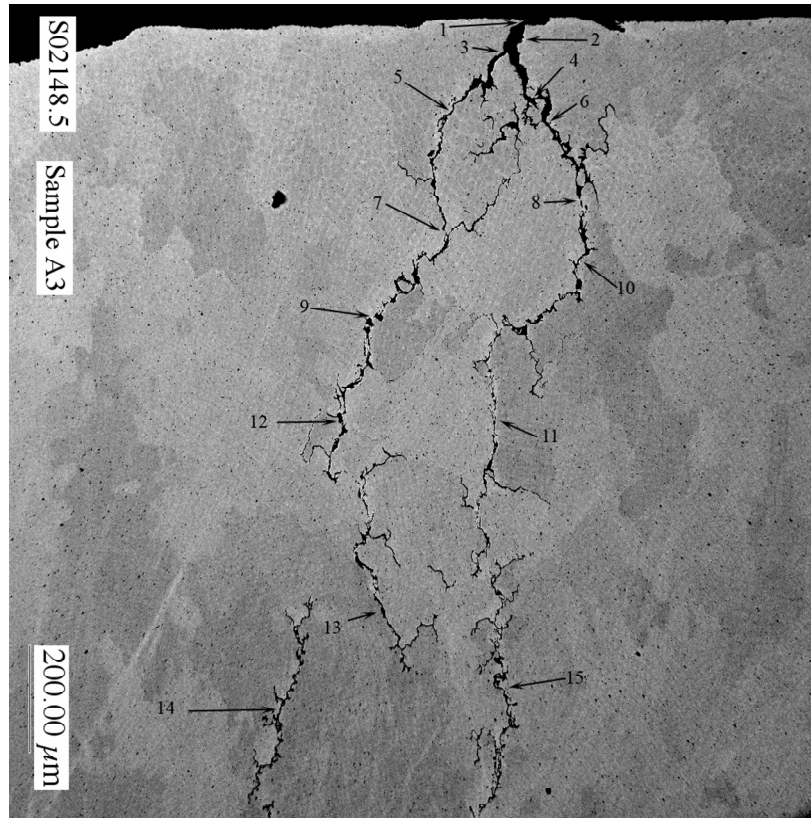


Figure 6: CODs at several points close to the surface.

Comparison of ET and DE results

Comparing the NDE and DE data allows one to determine the effectiveness of the NDE techniques and to help in future interpretation of NDE information. These ET responses, their locations, lengths, ET response strengths, and verified depths are given in Table 1. A minimum ET response was chosen to be 1.8 V, or 18% of the electrical discharge machined (EDM) notch response. This threshold ET response strength was determined by using the ET response strength of indication #14, which was confirmed as a likely crack via previous PT.

The indications associated with cracks deeper than 6 mm have some characteristics in common. The verified flaws deeper than 6 mm are all at least 7 mm in length and all have an ET voltage response greater than 30% of an EDM notch. All cracks confirmed to be greater than 6-8 mm deep into the weld were located at the weld-buttering interface.

Table 1: Comprehensive ET Responses on the J-groove Weld of Nozzle 31

Indication	Angle	Length	Max Voltage	% EDM Notch	Verified Depth
1	45°	2 mm	2.1	20%	Less than 6 mm
2	50°	5 mm	1.9	18%	Less than 6 mm
3	55°	4 mm	3.3	32%	Less than 6 mm
4	65°	2 mm	1.8	18%	Less than 6 mm
5	70°	4 mm	2.2	21%	Less than 6 mm
6	75°	3 mm	2.5	24%	Less than 6 mm
7	80°	3 mm	2.3	22%	Less than 6 mm
8	130°	4 mm	2.3	22%	Less than 8 mm
9	145°	10 mm	3.2	31%	Between 8 mm and 25 mm
10	155°	8 mm	3.3	32%	Through-Weld Leaking
11	160°	14 mm	4.1	40%	Between 8 mm and 25 mm
12	170°	5 mm	2.6	25%	Less than 8 mm
13	200°	8 mm	4.6	45%	Between 6 mm and 25 mm
14	215°	10 mm	1.8	18%	Less than 6 mm
15	225°	9 mm	4.6	45%	Between 6 mm and 25 mm
16	255°	7 mm	4.2	41%	Through-Weld Not Leaking

Leak Path Characterization

Of interest to some in the inspection industry is the possibility of using an ultrasonic examination of the interference fit region to determine if the nozzle is leaking. The analysis would be performed by ultrasonically inspecting the interference fit and measuring the amount of ultrasonic energy being reflected at the interference fit. The original thought was that tight ultrasonic coupling between the penetration tube and steel would transmit ultrasound and that corrosion (sometimes called wastage) caused by leakage would result in poorly-coupled regions that would reflect ultrasound in the interference fit.

While the original scope of work performed at PNNL did not include investigation of ultrasonic leak path measurements, enough data were inadvertently taken during the nondestructive examinations and the process of cutting the CRDM down to allow for destructive evaluation of the cracks to allow for the destructive validation of the use of ultrasound to characterize the annulus for a leakage path.

During a previous volumetric ultrasonic characterization of the J-groove weld metal, a scan of the interference fit was also performed. The ultrasonic data for the interference fit shows a complex pattern of regions that reflect and transmit the ultrasonic energy. The J-groove weld and regions of the interference fit were examined using frequencies ranging from 500 kHz to 5 MHz. The clearest image of the interference fit region was obtained using a 2.25 MHz transducer. The 2.25 MHz ultrasonic data acquired by PNNL showing the penetration tube below the J-groove weld, the J-groove weld, and the interference fit region above the J-groove weld is shown in Figure 7.

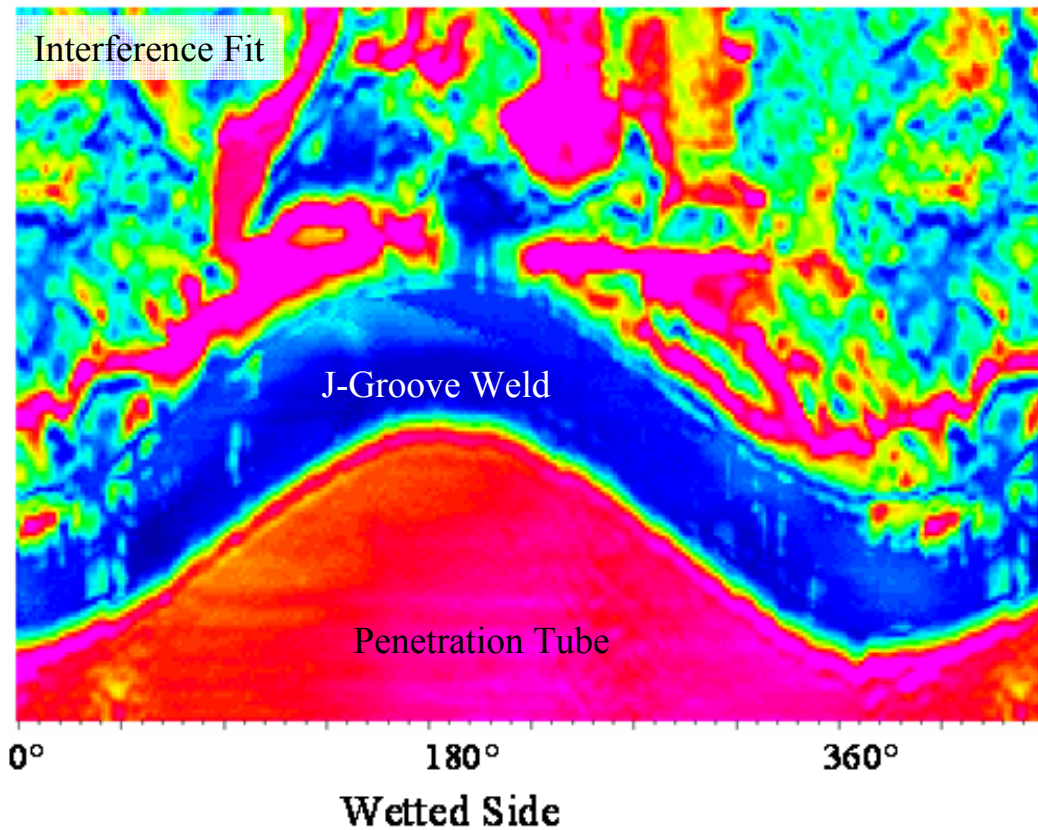


Figure 7 PNNL-Acquired 2.25 MHz Ultrasonic Data on the J-Groove Weld and Part of the Interference Fit of Nozzle 31 After the Nozzle Had Been Removed from the Head

During the destructive examination of Nozzle 31, the penetration tube was removed from the annulus. It was noted that the annulus contained white deposits that were consistent with boric acid deposits, and the ID of the annulus was photographed. Two areas appeared to be possible leakage paths. At 45 degrees, one finds a channel worn into the steel of the annulus. This water path also shows on the penetration tube. A section of the penetration tube was recovered and photographed and is shown in Figure 8.

A large and complex boric acid deposit was found ranging from 90 to 270 degrees. This boric acid deposit is shown in Figure 9 and Figure 10. Again the wetted side is at the top. The entire length of the annulus is present from approximately 100–180 degrees, with the small section containing the leak removed for destructive evaluation. Coolant had clearly leaked through this region, leaving the boric acid deposits. A “clean” channel with no boric acid starts at 90 degrees and bends around to 135 degrees at the “exit” point out of the annulus. It is not known if this “clean” band is a region where extra water flowed through the interference fit or a region where no water flowed.

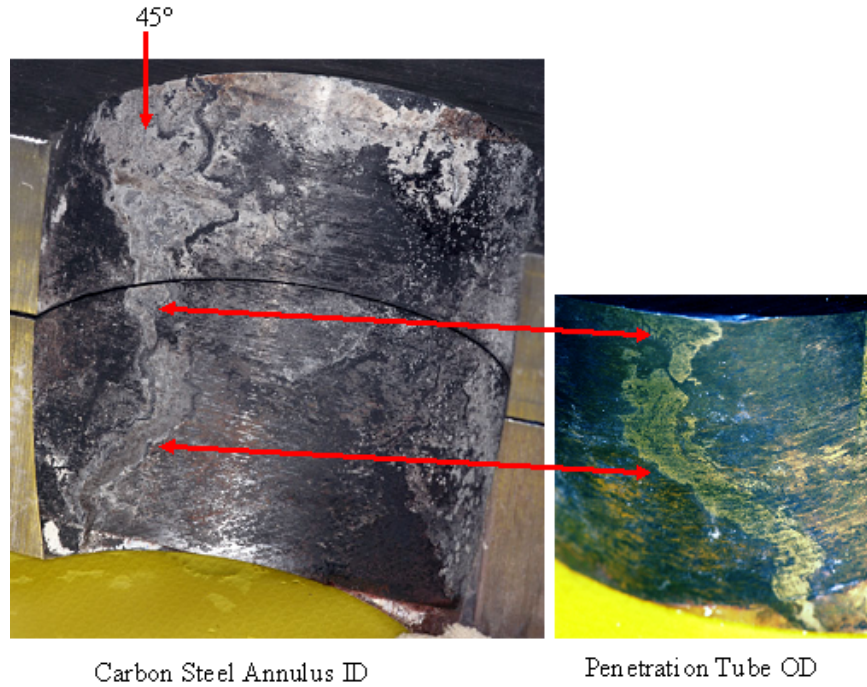


Figure 8 Mirror-Image Damage to the Carbon Steel Annulus and a Section of the Alloy 600 Penetration Tube. The wetted surface is toward the top of the samples.

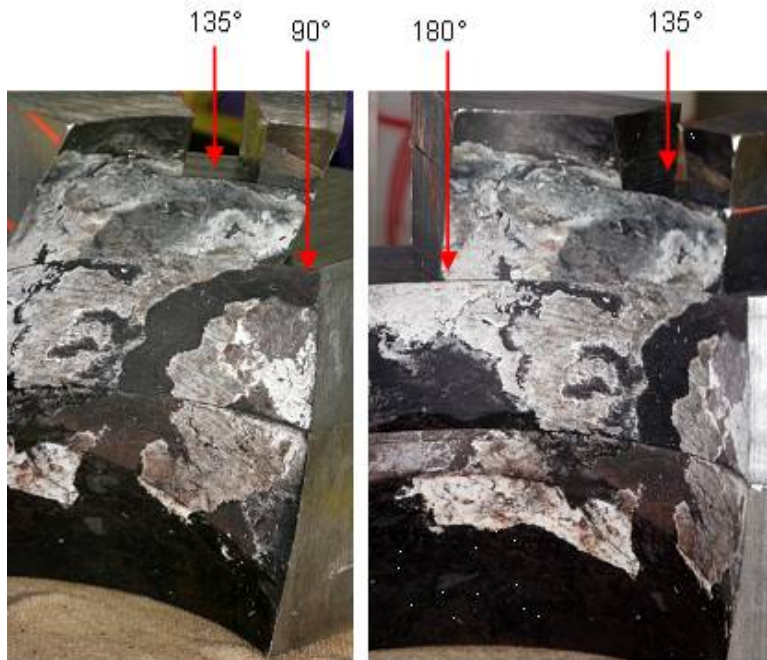


Figure 9 Boric Acid Deposits on the Carbon Steel from 90–180 Degrees. The wetted surface is toward the top of the samples.



Figure 10 Boric Acid Deposits on the Carbon Steel from 180–270 Degrees. The wetted surface is toward the top of the samples.

When the ultrasonic data and the photographs of the annulus are compared, it is clear that the pattern of the boric acid deposits matches the ultrasonic data patterns. Some correlations between the UT data and the boric acid pattern are shown in Figure 11. A “T” shaped region (region 1 in Figure 11) in the boric acid deposit patterns is replicated in the UT data as well. A reflective section (2 in Figure 11) corresponds directly with the clean band in the annulus that starts near 90 degrees.

Although the boric acid patterns show up very well in the UT data, the leakage path at 45 degrees is not visible. The UT data and the carbon steel annulus near 45 degrees are shown in Figure 12. The results for the region near 45 degrees show that leakage can occur without creating an ultrasonic signature.

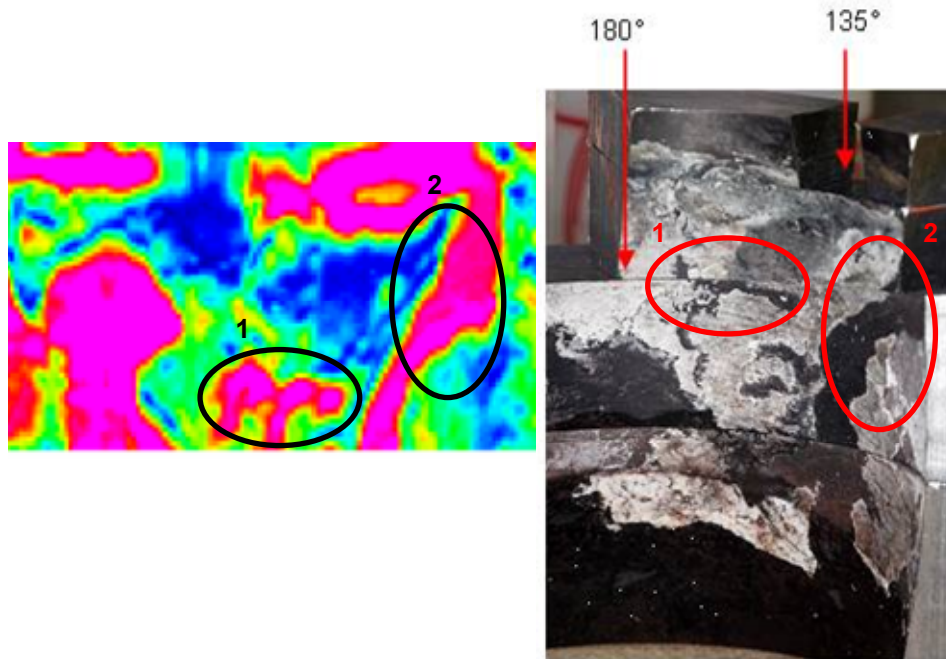


Figure 11 Comparison of Boric Acid Patterns on the Carbon Steel Annulus and UT Patterns on the Left

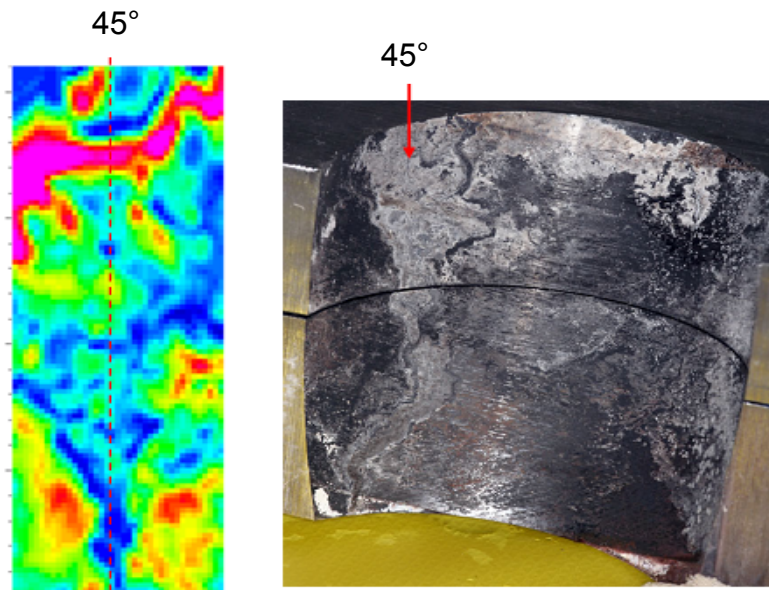


Figure 12 Comparison of the UT Data and the Apparent Corrosion of the Carbon Steel Near 45 Degrees

Discussion

The PWSCC in Nozzle 31 presents interesting challenges to NDE techniques. The destructive characterization of the through-weld leaking flaw showed an interesting and important aspect of PWSCC; that the flaws can be very short on the surface and span the width of the weld within a

few millimeters. A through-weld crack can appear as a very small indication to surface techniques such as visual testing or penetrant and near surface techniques such as ET. Penetrant indications that may otherwise be ignored as weld porosity and short, low voltage ET indications need to be considered important.

One interesting result is that the ET response to the through-weld crack (3.3 V) was lower than the responses for some of the shallower cracks (4.1-4.6 V). The discontinuous, segmented nature of the through-weld crack, both on the surface and along the crack's depth, allows for electrical contact between the two crack faces.

The only drawback of the ET scans was that differential ET used to examine the weld is not able to measure the depth of an indication to detect much of the subsurface extent of the flaw. The differential probes are only sensitive to the first 3 mm and missed the much longer parts of the cracks that were below the surface. The ET scans using the differential probe provided the locations of the crack, but they were not able to identify which of the flaws was the leakage path. The determination of which flaw was the through weld flaw relied on cutting above the triple point with the saw, which is not a feasible ISI technique.

The leakage path measurements showed that the ultrasonic reflections in the interference fit in Nozzle 31 appear to be a function of boric acid deposits. The region near 45 degrees contains corrosion but does not provide a strong ultrasonic response. This lack of response for a clear leak path shows that the ultrasonic leak path measurement technique is not sensitive to all leaks. The pattern of the ultrasonic responses from the region around 180 degrees is very similar to that of the complex boric acid deposits.

It is worth noting that none of the corrosion in this nozzle is deep, and the pattern for a nozzle with severe corrosion may be very different than what was observed in this paper. Further destructive validation of the leakage path measurement technique is required to explain the complex relationship between corrosion and boric acid deposition. The results for Nozzle 31 show that the ultrasonic leak path measurements have some physical basis, but more destructive validation and/or controlled experiments may be required to determine the strengths, weaknesses, and essential variables for the technique.

Conclusions

- PNNL found, removed, and destructively characterized a through-weld PWSCC crack in the J-groove weld of North Anna 2 CRDM Nozzle 31.
- ET testing was able to detect sixteen indications in the J-groove weld of CRDM#31, six of which were verified as being greater than 6 mm in depth. The six verified cracks all had ET indications with voltages higher than 30% of the calibration notch and a length of 7 mm or greater.
- The ultrasonic leakage path investigation showed the pattern of boric acid deposits in the interference fit but missed a leakage path that did not have significant boric acid deposits.

- It would be very useful for a volumetric technique, such as TOFD, to be developed and deployed on the J-groove weld to verify ET results, as currently only ET provides good sensitivity for inspecting the J-groove weld metal and ET is incapable of depth-sizing flaws.

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