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An Ultrasonic Leak Path Assessment of a Pressurized Water Reactor Control Rod Drive Mechanism Nozzle

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ABSTRACT

Leakage of reactor coolant at the reactor pressure vessel (RPV) head in pressurized water reactors (PWRs) may occur because of primary water stress corrosion cracking of nickel-based alloy penetrations and welds. U.S. Nuclear Regulatory Commission regulations require surface or volumetric leak path assessments of RPV head penetrations in PWRs. The objective of this investigation was to evaluate the efficacy of ultrasonic testing (UT) for the leak path assessments with a control rod drive mechanism nozzle removed from an operating reactor. Using a phased-array probe, the nozzle was examined and the UT response indicated leakage paths and surface deposits left by reactor coolant between the nozzle penetration and the RPV head. Following acquisition of the UT data, destructive examination visually confirmed the features identified by UT. Measurements were made of the surface deposit thicknesses and they were found to correlate with the amplitude of the UT response. Further, surface replication of the leak path indicated minimal loss of material on the RPV head surface

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* The views expressed in this article are those of the authors and are not necessarily those of the U.S. Nuclear Regulatory Commission.

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1. Introduction

Nickel-based alloys exposed to reactor coolant in pressurized water reactors (PWRs) may experience a form of degradation known as primary water stress corrosion cracking (PWSCC) [1-3]. One component that is susceptible of PWSCC is the control rod drive mechanism (CRDM) nozzle and associated J-groove weld. As shown in Figure 1(a), the CRDM nozzles are cylindrical penetrations through machined bores in the upper reactor pressure vessel (RPV) head that allow for the insertion and removal of control rods. Above the weld there is no mechanical bond between the penetration and the RPV head. At ambient temperature, the penetration diameter is slightly larger than that of the bore. The penetration may be cooled to shrink it, allowing it to be inserted through the bore. Then upon returning to ambient temperature, the penetration and RPV head are in close contact. The part of the annulus where the RPV head surrounds the penetration for the full 360° circumference is referred to as the interference fit.

Most CRDM nozzles originally placed into service in PWRs were fabricated from Alloy 600, using Alloy 82 and 182 weld metals. Cracking in CRDM nozzles and welds may compromise the reactor pressure boundary by allowing primary water leakage through a path in the annulus of the interference fit between the CRDM nozzle and the RPV head. The primary water may eventually reach the top of the RPV head where boric acid may leave visible white deposits, as shown in Figure 1(b). PWSCC of a CRDM nozzle in a PWR was first identified in the Bugey Unit 3 plant in France in 1991 [4], and has since been detected in U.S. plants. At the Davis Besse plant in 2003, significant wastage of a portion of the RPV head occurred in the vicinity of a leaking CRDM nozzle, leaving only stainless steel cladding at the pressure boundary [5].

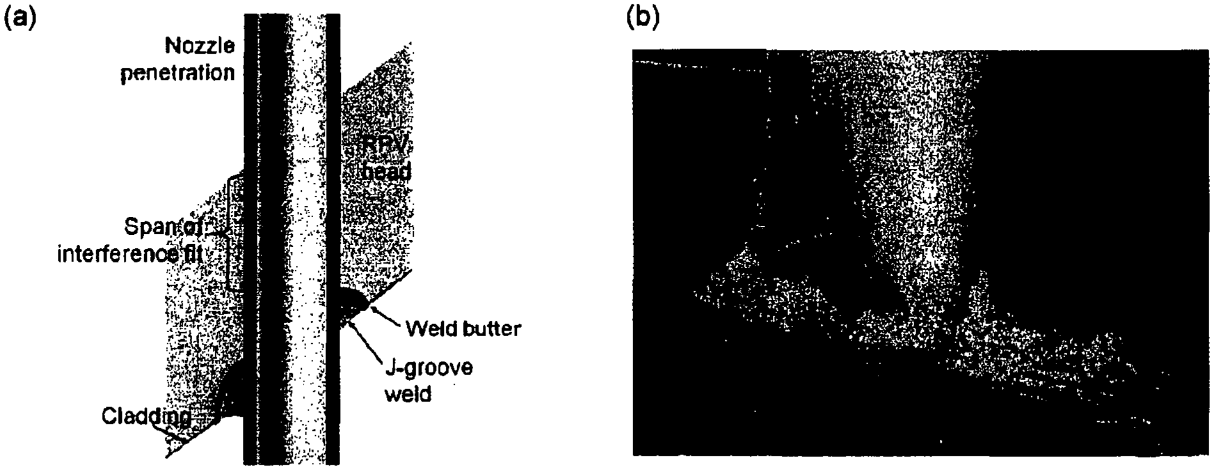

Figure 1. (a) Schematic illustration of CRDM penetration in a PWR, (b) Boric acid deposits on top of a RPV head near a leaking CRDM penetration [6].

After the incident at the Davis Besse plant, U.S. Nuclear Regulatory Commission (NRC) regulations were modified to require a more robust inspection program for PWR upper head penetrations. Title 10 of the Code of Federal Regulations, Part 50.55(a), requires PWR licensees to perform a demonstrated surface or volumetric leak path assessment of all J-groove welds in upper head penetrations. This involves the use of a non-destructive examination technique to determine whether a flow path exists between the nozzle and the RPV that would allow reactor coolant to access the outside of the RPV head. Ultrasonic testing (UT) is one non-destructive technique that may be used for the leak path assessment. The UT methodology relies on the principle that at an interface between two materials with different elastic properties, part of the ultrasonic energy is transmitted through the interface and a part is reflected back. The amount of energy that is transmitted through the interface depends on the relative acoustic impedance of the respective materials. More energy is transmitted when the acoustic impedance of the materials are similar, as would be the case if the nozzle and RPV head were in contact at the interference fit. Less energy is transmitted when the acoustic impedance of the materials is dissimilar, as would be the case if there were an air gap or leakage path between the nozzle and RPV head.

For this investigation, the NRC sponsored an evaluation of the UT leak path assessment methodology at the Pacific Northwest National Laboratory (PNNL). PNNL used a phased array (PA) UT system to acquire leak path data for a CRDM nozzle, referred to as Nozzle 63, removed from the North Anna Unit 2 RPV head that was replaced in 2002. Following acquisition of the UT data, the nozzle was destructively examined to confirm the features identified by UT. This paper will present the findings of this investigation.

2. Experimental Methods

2.1 Testing Setup

Nozzle 63, shown in Figure 2(a), was a peripheral CRDM nozzle in the upper head of North Anna Unit 2, a Westinghouse PWR that entered service in 1980. The materials of construction for Nozzle 63 were Alloy 600 base metal and Alloy 182 J-groove weld metal. Following indications of leakage of reactor coolant onto the upper head during an outage in 2001, the J-groove weld was overlaid with Alloys 52 and 152 in 2001 [7]. Subsequent visual examination during the fall 2002 outage revealed six CRDM nozzles that were suspected of leaking and 21 that were masked to the extent that their status could not be determined, including Nozzle 63. Given the level of degradation of the RPV head, the decision was made to replace the head. The Electric Power Research Institute took possession of a number of the nozzles, including number 63, which were transferred to PNNL and made available for NRC research.

The UT leak path data acquisition for nozzle 63 was performed at PNNL using a ZETEC Tomoscan III system with a pulse-echo longitudinal-wave immersion PA probe. The PA probe was designed in a 1-D annular configuration with 8 elements and a total aperture of 296.81 mm^2. Further details on the UT system are found in Cinson *et al* [8]. The scanning apparatus attached to the nozzle, with the probe face oriented to direct the ultrasonic beam radially towards the interface between the nozzle and RPV head, as illustrated in Figure 2(b). The

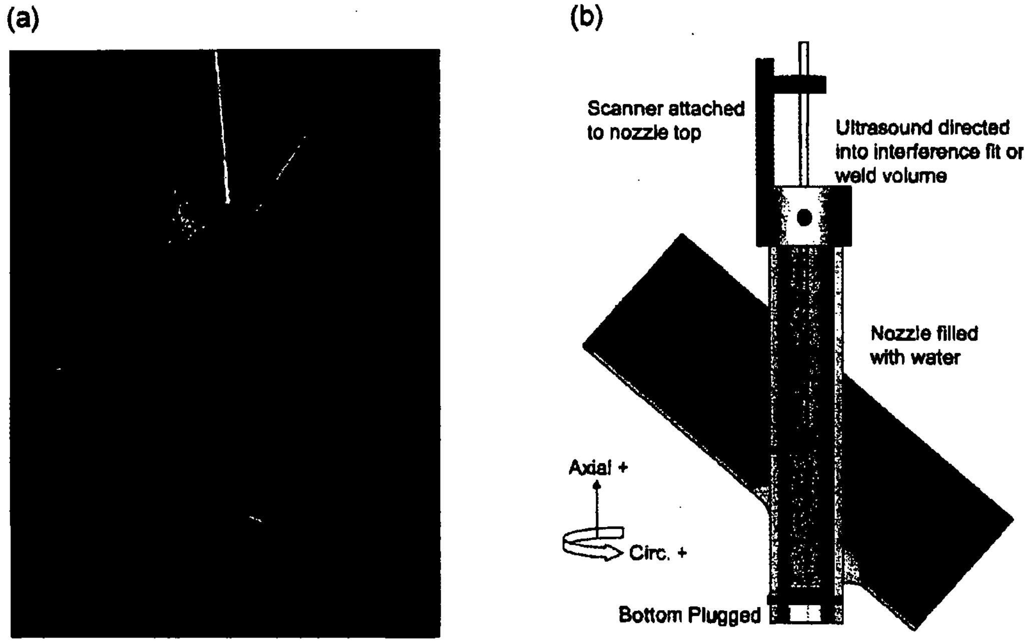

Figure 2. (a) CRDM nozzle 63 used for this investigation, (b) Schematic illustration of ultrasonic scanning setup for Nozzle 63.

scanner could move vertically along the length of the nozzle and rotate around the nozzle circumference. For acquiring data from Nozzle 63, the nozzle was put in a vertical orientation, plugged with a water tight seal in the bottom end, and then filled with distilled water. In immersion scanning, water serves as both the wedge material and the ultrasonic couplant material. The probe was manually lowered to the bottom of the interference fit region and the data collected while indexing the probe upwards.

2.2 Interference Fit Mockup

Before acquiring the UT data for Nozzle 63, an interference fit mockup was constructed to assess the capability of the test system to detect features could indicate leakage. The mockup consisted of an Alloy 600 tube with similar dimensions as the CRDM nozzle and two carbon steel blocks with machined bores of slightly smaller diameter than the tube. The tube was shrunk with liquid nitrogen and the carbon steel blocks were fit onto it to create two interference fits once the tube returned to room temperature, as shown in Figure 3. For the top interference fit, machined notches with various orientations and dimensions were placed on the outer diameter (OD) surface of the tube and the inner diameter (ID) surface of the hole in the block to determine the capability of the UT probe to detect cracks or air gaps between the nozzle and RPV head that could indicate a leakage path. For the bottom interference fit, simulated boric acid deposits were made between the tube and the other carbon steel block. A thin boric acid-methanol paste was applied to the tube before the block was placed on, which left dried boric acid after the methanol evaporated.

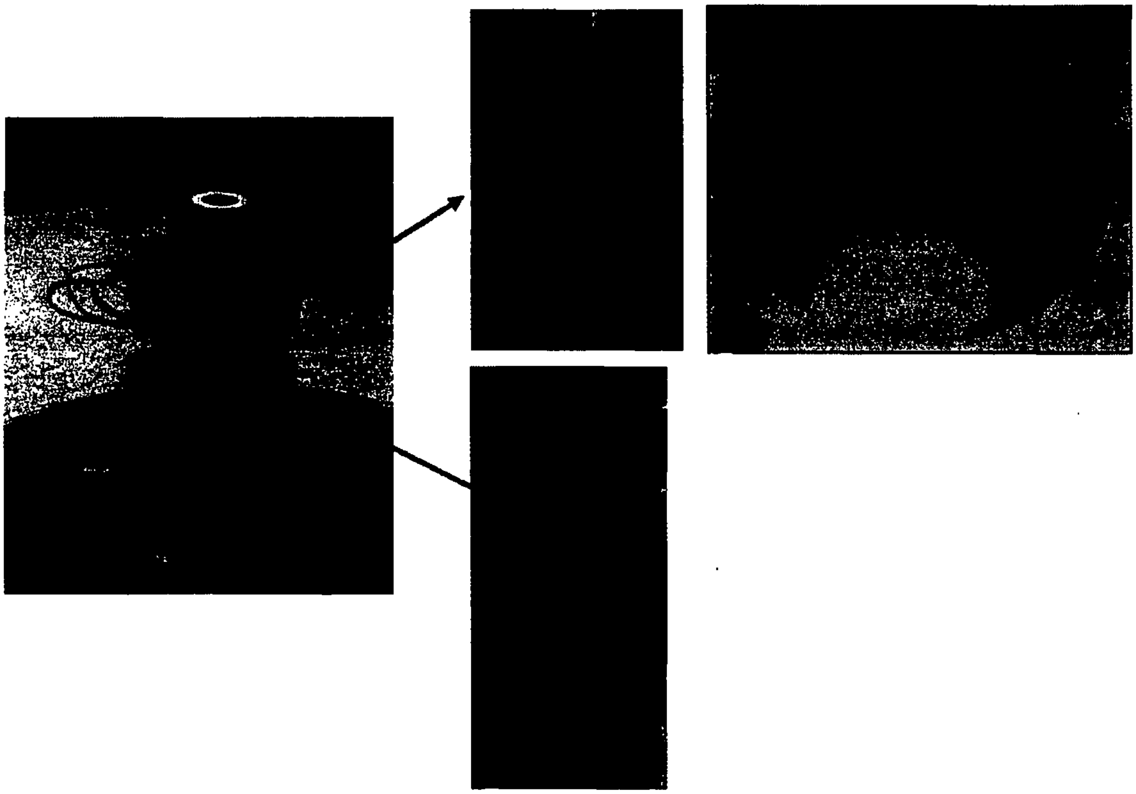

Figure 3. Interference fit mockup on left showing two carbon steel blocks fit onto Alloy 600 tube. Top interference fit has notched machined into the OD of the tube and ID of the bore in the block. Simulated boric acid deposits were placed on the OD of the tube for the lower interference fit.

The UT image for the upper interference fit with notches in the tube is shown in Figure 4(a). The colors of blue to green represent a relatively low amplitude ultrasonic signal response, meaning that much of the acoustic energy is transmitted from the tube to the block and does not return to the detector. This indicates a tight fit between the tube and block. The notches appear as yellow to orange in the images, which represents a relatively high amplitude ultrasonic signal response. The air gap between the tube and the block created by the notches reflects much of the acoustic energy from the interface back to the detector. This suggests that a leak path between a nozzle penetration and the RPV head may be identified by a high amplitude ultrasonic response. The UT image for the lower interference fit with boric acid deposits in the annulus between the tube and carbon steel block is shown in Figure 4(b). The regions with the boric acid deposits appear blue, indicating a lower amplitude signal response or greater acoustinc energy transmission compared to regions with no deposits. The boric acid deposits may serve to couple the tube and block, facilitating a more efficient transfer of acoustic energy. This indicates that deposits left by primary water leakage between the nozzle and RPV head may be identified by a low amplitude ultrasonic response. Additional details on the mockup examination and system calibaration are found in in Cinson *et al* [8].

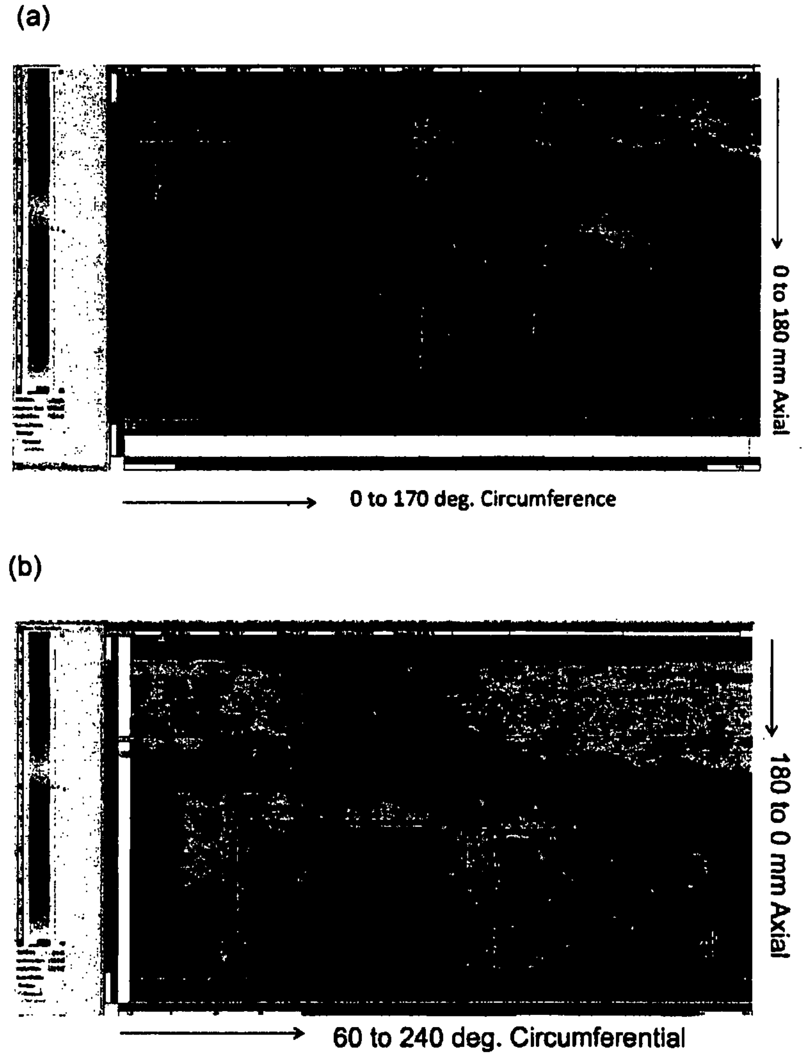

Figure 4. Ultrasonic images for the interference fit mockup. (a) shows the response for the interference fit where there are notches in the OD of the Alloy 600 tube. Notches are circled and the word "PNNL" which was inscribed into the tube is also visible. (b) shows the response for the interference fit where there are boric acid deposits between the tube and blocks. The regions with boric acid deposits are boxed.

3. Results

3.1 UT Leak Path Assessment

The ultrasonic image from the scan of Nozzle 63 is shown in Figure 5. This image shows the full 360° circumference of the nozzle. The light blue region toward the bottom of the figure is the J-groove weld. The portion of the figure above the weld represents the annulus between the nozzle and the RPV head. Based on the known response from the mockup, it was assumed that the green-to-yellow colors indicated regions of the annulus with metal-to-metal contact between the nozzle and RPV head and that the orange color indicates a metal-to-air interface. Following this interpretation, the box in Figure 5 indicates a region of the annulus where there is an air gap or potential leakage path between the nozzle and the RPV head. This would be on the downhill side of the penetration. Other partial leakage paths are visible in orange towards the uphill side of the nozzle. The mockup response also indicated that boric acid deposits left by primary water leakage would appear blue in the ultrasonic image. Thus, the UT response indicates potential deposits throughout the annulus.

Figure 5. Ultrasonic image of the interference fit for Nozzle 63. The boxed region indicates a potential leakage path between the nozzle and the RPV head.

3.2 Destructive Examination of Nozzle 63

Following acquisition of the UT data at PNNL, Nozzle 63 was sent to Babcock and Wilcox Technical Services Group for destructive visual examination. The nozzle was separated from the RPV head to expose the annulus, thereby allowing confirmation of the features identified by UT. The nozzle and attached RPV were first bisected along the tube length direction, and then the J-groove weld was removed from each half. After the weld was removed, the nozzle pieces freely separated from the RPV head. Figure 6(a) shows the exposed annulus surface of the RPV head along with the UT image to the same scale in Figure 6(b) for comparison. The arrows indicate the vertical span of the interference fit. The appearance of the surface correlates will with the UT data. The leak path is visible in the same location indicated by UT and the pattern of deposits on the annulus surface is also similar to that shown by UT.

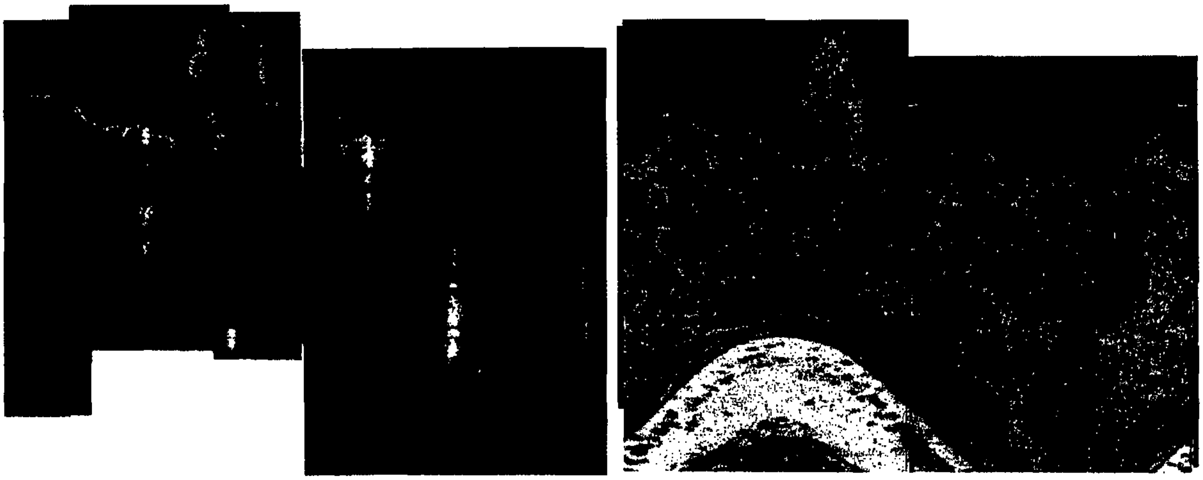

Figure 6. (a) Exposed annulus surface for the RPV head. (b) UT image of the annulus to same scale as (a). Red arrows show the vertical span of the interference fit..

3.3 Surface Deposit Thickness Measurements

The thickness of deposits on the annulus surface of the RPV head were measured to determine if these had any correlation with the amplitude of the UT response. The deposit thicknesses were measured using a DeFelsko PosiTector 6000 Series eddy current coating thickness gage. It was assumed that the deposits could be crystalline boric acid left by primary water or corrosion products from degradation of the RPV head, such as iron oxides. In the eddy current probe, a coiled wire sets up an alternating current on the probe tip. When brought into proximity of a surface with a coating or surface deposit, the probe creates eddy currents in the base material. The deposit thickness affects the magnitude of the eddy currents, which create an electromagnetic field that is measured by a second coil. The probe had a point contact area of 1 mm in diameter and is calibrated for coating thicknesses in the range of 0 to 1.14 mm. Thickness measurements were made across the leakage path and at a number of other locations in the annulus, both inside and outside the vertical span of the interference fit.

Figure 7 shows the surface deposit thickness measurement and amplitude of the UT response at a number of points across the leak path. The series of measurements across the leak path in the vertical span of the interference fit, (designated "I Fit") in Figure 7, shows that there is minimal deposit thickness within the leak path and the amplitude of the UT response, given as a percentage of full screen height, is relatively high. Outside the leak path, on both sides, the deposits are thicker and the amplitude of the UT response decreases. A similar pattern holds for the measurements across the leak path below the span of the interference fit (designated "Outside I Fit"), though the deposits are somewhat thicker. This response can be explained if it is assumed that the active flow of primary water prevents the formation of deposits directly in the leak path and that the deposits would tend to accumulate to the sides. Because there are no deposits in the leak path, an air gap is maintained between the nozzle OD and the RPV head which gives a high amplitude UT response. Outside the leak path, the deposits serve to couple the nozzle and RPV head, allowing greater transmission of ultrasonic energy, and thus a lower amplitude UT response.

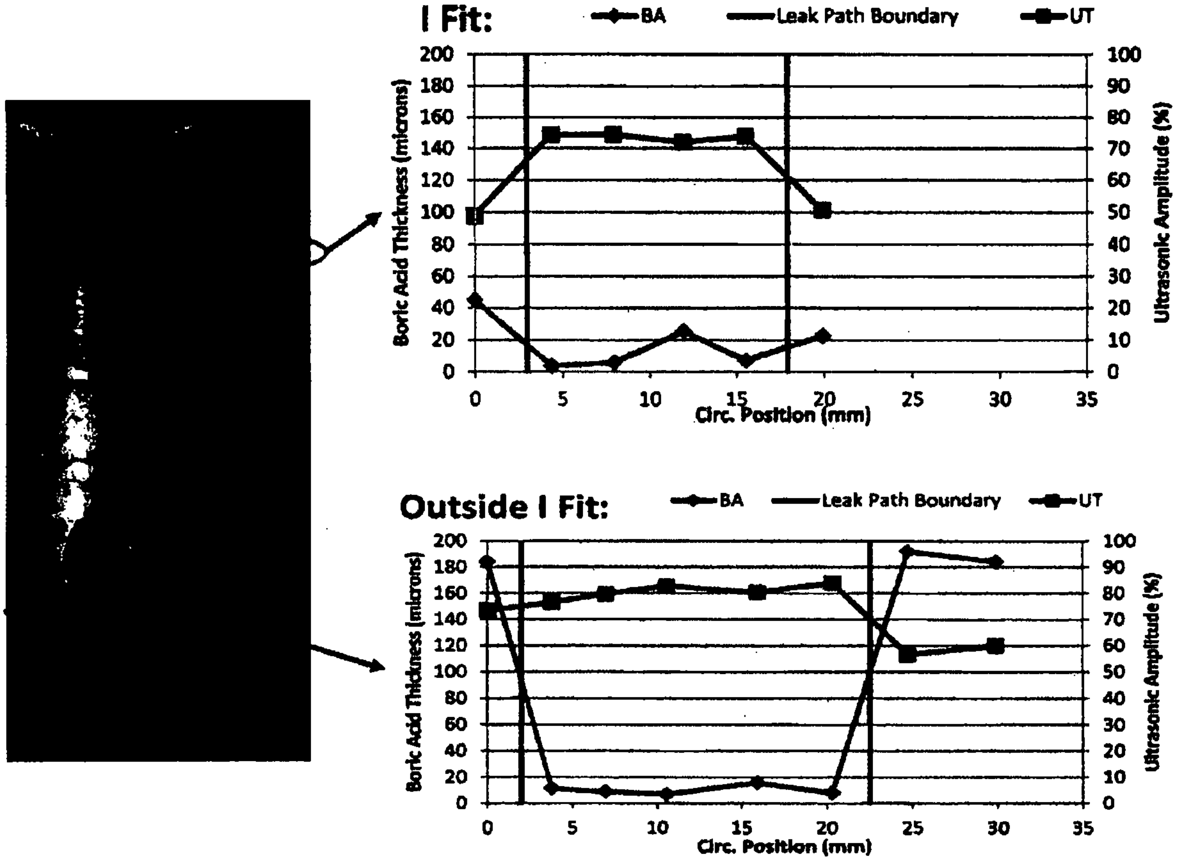

Figure 7. Measurements of the surface deposit thickness (BA) and amplitude of the UT response (UT) across the leak path for locations in the vertical span of the interference fit (I Fit) and below the interference fit (Outside I Fit). The vertical black lines on the graphs represent the side boundaries of the leak path.

The deposit thicknesses were also measured for various other locations in the annulus, both within and outside the vertical span of the interference fit. The correlation between the deposit thickness and the amplitude of the UT response is shown in Figure 8. The data pattern indicates that within the span of the interference fit, the deposits tend to be thinner, with the locations giving a relatively low amplitude UT response. Outside the span of the interference, the deposits are generally thicker, with locations giving higher amplitude UT response. From these responses, it is postulated that at reactor operating temperature, a gap may open in the annulus between the nozzle and RPV head because of differing thermal expansion coefficients. If leakage occurs, primary water may flow throughout the annulus by the path of least resistance. As the reactor cools down, the gap between the nozzle and RPV head will close, trapping primary water that will leave deposits as it evaporates. It is likely that in the span of the interference fit, the gap between the nozzle OD and the RPV head is narrower than outside, which would significantly compact any deposits left behind. Thus deposits in the span of the interference will tend to be thin and dense relative to deposits outside. The thin and dense deposits should more efficiently couple the nozzle and RPV head allowing greater transmission of ultrasonic energy and a lower amplitude UT response.

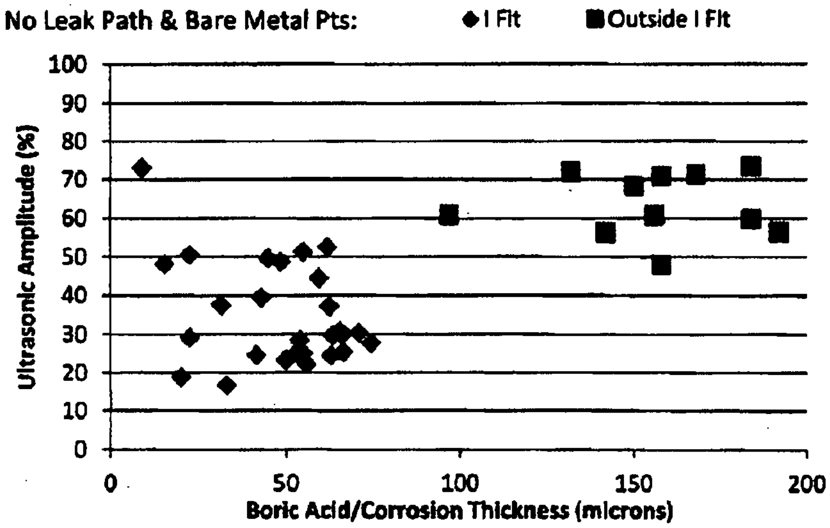

Figure 8. Measurements of the surface deposit thickness and amplitude of the UT response for points inside and outside the span of the interference fit (I Fit).

3.4 Surface Replication

Following measurement of the surface deposit thickness with the eddy current probe, the leakage path on the RPV head side of the annulus was analyzed by surface replication with Microset to determine if any loss of material or wastage could be detected. On viewing with a stereomicroscope, machining marks were visible on the replicated surfaces, as shown in Figure 9. This indicates minimal loss of material, and likely a relatively low leakage flow rate during plant operation.

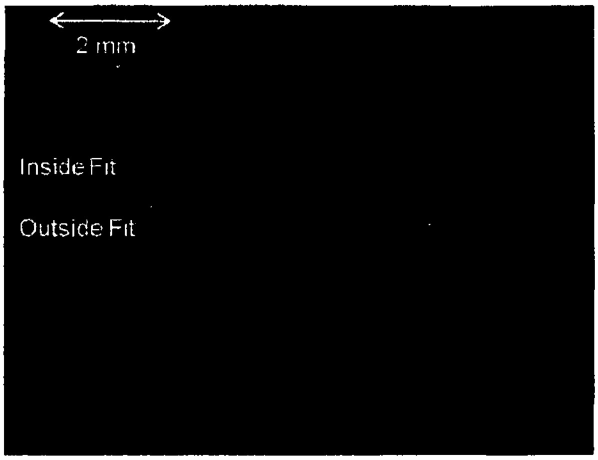

Figure 9. Image of surface replication for leakage path on RPV had surface showing transition from outside to inside span of interference fit. Machining marks are visible.

4. Conclusions

The efficacy of UT for leak path assessment of upper RPV head penetrations in PWRs was evaluated using Nozzle 63 that was removed from service at North Anna Unit. Ultrasonic examination of Nozzle 63 using a PA probe indicated the presence of a leakage path and scattered boric acid deposits in the annulus between the nozzle penetration and the RPV head. These features were identified by comparing with data acquired from an interference fit mockup. A gap or leak path between the nozzle and RPV head was characterized by a high amplitude UT response whereas deposits in the annulus of the interference fit gave a low amplitude UT response.

Following acquisition of UT data, Nozzle 63 was destructively examined by separating the nozzle from the RPV head to allow visual examination of the annulus region. Visual examination confirmed the presence of the leak path and the pattern of surface deposits in the regions indicated by UT. Measurements were taken of the surface deposit thicknesses using an eddy current probe and correlated to the UT response. There is minimal deposit thickness within the leak path and the amplitude of the UT response is relatively high. Outside the leak path the deposits are thicker and the amplitude of the UT response drops off. This suggests that the flow of primary water prevents the formation of deposits directly in the leak path and that the deposits would tend to accumulate to the sides. The lack of deposits in the leak path allows an air gap between the nozzle OD and the RPV head which gives a high amplitude UT response. Outside the leak path, the deposits serve to couple the nozzle and RPV head, allowing greater transmission of ultrasonic energy, and thus a lower amplitude UT response.

Measurements of the deposit thicknesses elsewhere in the annulus of the interference fit showed that within the span of the interference fit, the deposits tend to be thinner, with the locations giving a relative low amplitude UT response. Outside the span of the interference, the deposits are generally thicker, with locations giving higher amplitude UT response. It is postulated that the narrower gap between the nozzle penetration and the RPV head in the span of the interference fit leads to the compact deposits that more efficiently transmit acoustic energy.

Finally, surface replication of the leak path on the RPV head surface revealed that machining marks were still visible. This indicates that minimal corrosion or wastage of the RPV head surface was needed for the leak path to develop.

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