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Comparison of an Ultrasonic Phased Array Evaluation with Destructive Analysis of a Documented Leak Path in a Nozzle Removed from Service

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ABSTRACT

Non-destructive and destructive testing methods were employed to evaluate a documented boric acid leakage path through an Alloy 600 CRDM penetration from the North Anna Unit 2 reactor pressure vessel head that was removed from service in 2002. A previous ultrasonic examination of this nozzle (Nozzle 63), conducted during an in-service inspection (ISI) prior to the head removal, identified a probable leakage path in the interference fit between the penetration tube and the vessel head. Nozzle 63 was examined using phased array (PA) ultrasonic testing with a 5.0-MHz, eight-element annular array; immersion data were acquired from the nozzle inner diameter (ID) surface. A variety of focal laws were employed to evaluate the signal responses from the interference fit region. These responses were compared to responses from a previously evaluated mockup specimen that was used to determine detection limits and characterization capabilities for wastage and boric acid presence in the interference fit region. Nozzle 63 was destructively examined after the completion of the ultrasonic nondestructive evaluation (NDE) to visually assess the leak paths. These destructive and nondestructive results compared favorably.

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INTRODUCTION

The United States Nuclear Regulatory Commission (NRC) has funded the Pacific Northwest National Laboratory (PNNL) to assess the effectiveness and reliability of advanced NDE methods including the ultrasonic PA technique for the evaluation of control rod drive mechanism (CRDM) nozzles [1, 2]. Nickel-based alloy primary pressure boundary components are plagued by susceptibility to primary water stress corrosion cracking (PWSCC). This degradation mechanism may pose a safety concern due to the potential for reactor pressure boundary leaks, the associated potential for boric acid corrosion of low-alloy steels, and the development of flaws in the piping and welds. Alloy 82 and 182 were used in the North Anna plant piping welds. Other super alloys have since been developed, such as Alloy 690 and its associated weld metals, Alloy 52 and 152, to improve the pressurized water reactor (PWR) components' resistance to PWSCC [3, 4].

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In the 2002 refueling outage at North Anna Unit 2, a significant number of J-groove welds in the CRDMs had flaw indications and cracking. It was estimated that in excess of 40 of these welds would require repair; instead, the utility decided to replace the reactor head. The Electric Power Research Institute (EPRI) sponsored the extraction of several nozzles from the removed head to be used for research. Previous ISI inspections of Nozzle 63 revealed a probable leak path and axial indications on the outside diameter of the nozzle tube. Surface examinations of the J-groove weld identified flaw indications. It was of interest to conduct additional nondestructive assessments to confirm and further

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characterize the leak path. This was to be followed by destructive analysis and a comparison to the nondestructive examination.

ULTRASONIC PHASED ARRAY PROBE~~, AND SETUP~~

A calibration mockup specimen and Nozzle 63 were examined with a pulse-echo (PE) longitudinal phased-array probe with a nominal center frequency of 5 MHz operating in an immersion mode. The PA probe was designed in a 1-D annular configuration using eight elements. The eight elements were arranged in a Fresnel radius pattern starting with a radius of 3 mm (0.12 in.) and ending with an element radius of 9.72 mm (0.38 in.). Thus, the total aperture was 296.81 mm^2 (0.46 in.^{2}). The probe exhibited a 72% bandwidth at −6 decibels (dB). This particular design was chosen for enhanced depth focusing capabilities. Its beam-forming potential was modeled to show excellent insonification of the interference fit region of interest. Figure 1 shows an example of simple ray tracing for the probe on the left and the sound field density mapping on the right for a 15-mm (0.59-in.) focal depth in the nozzle material. It should be noted that this simulation is performed in isotropic material; the longitudinal acoustic velocity of sound is constant for any angle.

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State the purpose of the NRC to do this work: NR regulations require a surface or volumetric leak p for upper head penetration nozzles. Industry has expressed interest in using UT methodology. Th purpose of this work is to demonstrate the efficac the ultrasonic leak path assessment methodology performing the UT then comparing to destructive analysis.

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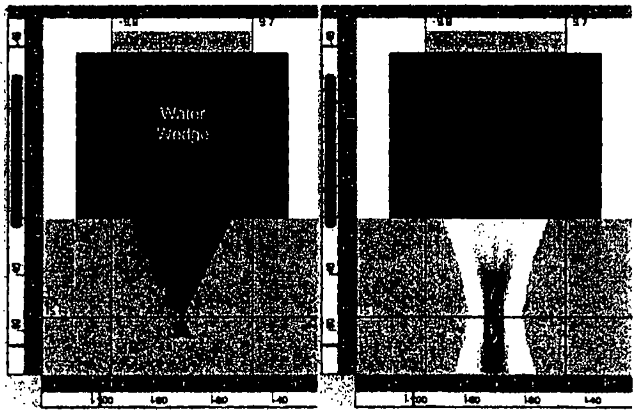

Figure 1 – Side views: ray trace on the left and sound field simulation on the right at a depth focus of 15 mm (0.59 in.).

Data acquisition on the mockup specimen and Nozzle 63 was accomplished with a custom, slave-encoded scanner mounted on the nozzle. The scanner had two stepper motors that controlled circumferential and axial (vertical) motion. It was attached to the nozzle by sliding the scanner over the top of the specimen and equally tightening three set screws to align the PA probe head in the center of the tube. The setup is shown in Figure 2 with the scanner on the calibration specimen. The probe was mounted on the extension arm that was adjustable along the pipe axis allowing probe positioning in the region of interest.

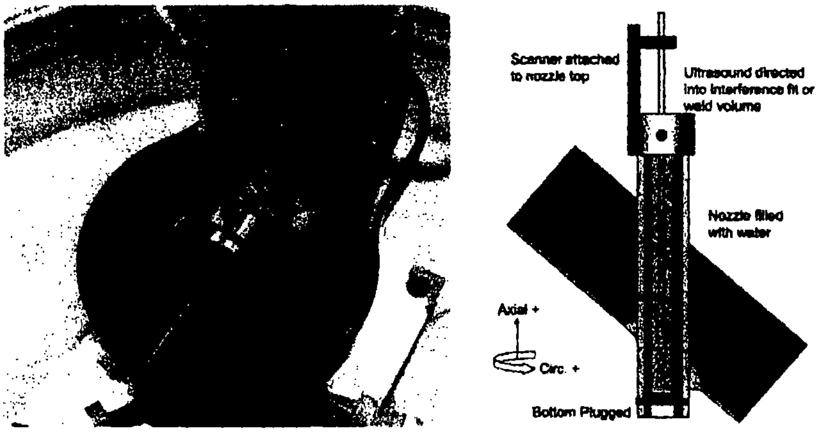

Figure 2 – Left: Scanner on calibration specimen. Right: Inspection schematic.

The nozzle was filled with enough water to immerse the regions of interest. Data were acquired with the ZETEC Tomoscan III system running UltraVision 1.2R4 software. Phased-array data were acquired over a range of inspection depths from 1–15 mm (0.039–0.59 in.) at a normal or 0° angle of inspection. Raster data were acquired at 0.25-degree increments in the scan axis (circumferential) and at 0.5-mm (0.019-in.) increments in the index axis (vertical or nozzle axial direction) on the calibration specimen, and 0.5 degree in the scan and 0.5-mm (0.019-in.) increments in the index for Nozzle 63.

CRDM MOCKUP SPECIMEN

A calibration mockup specimen was fabricated with two interference fit regions [5]. One region contained electro-discharging machined (EDM) notches separated by various surface distances and at varying depths. One set of notches was placed in the Inconel tube and the other in the steel head material. The other region contained boric acid regions in a known pattern. Data were acquired on the mockup specimen with the ultrasonic PA probe on both the notches and the boric acid regions. Figure 3 is a top view or C-scan image that displays the resolution notches in the upper left portion of the image, circled in red. The variable depth notches on top and variable width notches on bottom are also seen and are circled in red. An image from the lower interference fit region containing boric acid deposits is displayed in Figure 4. The boric acid regions are outlined in red. The full detailed analysis of the calibration specimen can be found in the proceedings of the 2011 ASME Pressure Vessel and Piping Conference [5]. In summary, the presence of an air gap in the interference fit resulted in a strong ultrasonic reflection. This can be seen in Figures 3 and 4 by the red and orange colors. The presence of a tight fit was shown in the regions containing boric acid and resulted in a weak ultrasonic reflection. These two areas are noted by the blue and white colors. The nominal interference fit region contained a mixture of mid-range reflections, noted by the green and yellow colors. Thus the mockup interference fit specimens provided the expected range of conditions thought to be present in Nozzle 63. Furthermore, the ultrasonic evaluation validated the capabilities of the system to distinguish between the different nozzle conditions.

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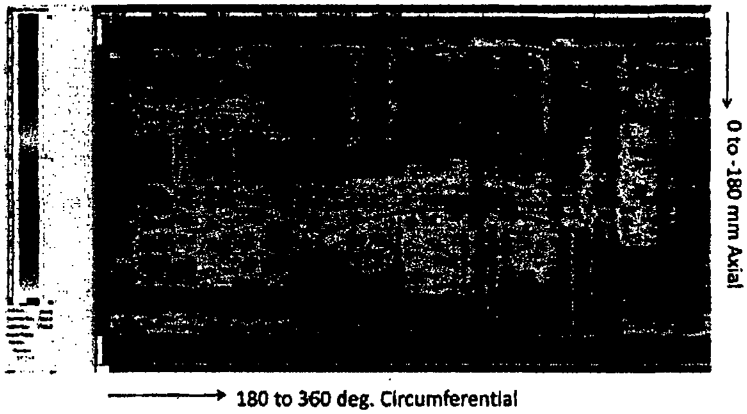

Figure 3 – Top view, plan view or C-scan ultrasonic image of the interference fit region containing calibration notches in the carbon steel head.

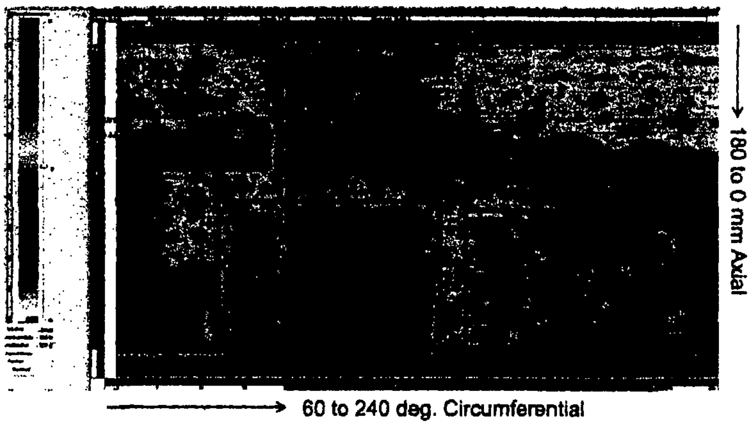

Figure 4 – C-scan plan view of the boric acid deposits in the interference fit region. The horizontal axis represents the circumferential range of 60–240 degrees.

INDUSTRY IN-SERVICE INSPECTION DATA

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Standard ultrasonic evaluation techniques used by ISI vendors include time-of-flight diffraction (TOFD) for detecting cracks in both the circumferential and axial orientation and zero-degree PE for an interference fit examination. An examination conducted by ISI vendor, WesDyne International (data supplied by John P. Lareau), discovered a probable leak path in Nozzle 63 during the 2002 outage. The data acquired with an industry-standard 5.0-MHz probe are shown in Figure 5. The data set indicates a leak path at the downhill position, traveling upward through the interference fit and is marked by the two black arrows in the figure.

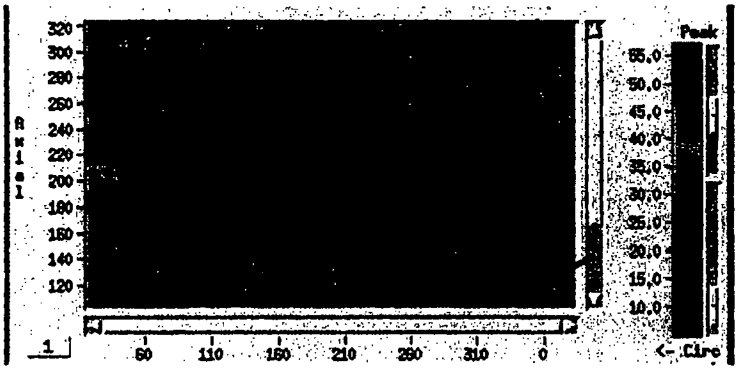

Figure 5 – Ultrasonic Data from Nozzle 63 as Obtained by WesDyne International (courtesy of John P. Lareau). The image was acquired with a 5-MHz probe. The horizontal axis represents the nozzle circumference in units of degrees. The vertical axis represents the nozzle axis in units of millimeters. The leak path is indicated by the black arrows.

NOZZLE 63 DATA AND ANALYSES

Ultrasonic data were acquired on Nozzle 63 in a radiologically controlled laboratory at PNNL. Destructive examinations (DE) were conducted by Babcock and Wilcox Technical Services Group (B&W) at the Lynchburg, Virginia~~, facility~~. Following these two separate activities the data were compared and showed a high degree of correlation between the NDE and DE findings.

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Ultrasonic data

Scanning commenced on Nozzle 63 using setup and data acquisition methods similar to those used for the calibration specimen. High-resolution scans were conducted with 0.5-degree resolution in the scan and 0.5-mm (0.020-in.) resolution in the index axes over regions of −94 to 94 degrees and 86 to 274 degrees. Scans extended in the axial direction a distance of 0 to 360 mm (0 to 14.2 in.). Each region was scanned twice to observe repeatability. A composite 360-degree scan of the interference fit region is shown in Figure 6 and shows the fit region of interest as well as the J-groove weld. The J-groove weld is identified as the white to light-blue oscillating band in the lower third of the figure. High ultrasonic transmission (low reflection) is signified by the white and light-blue colors in the figure. The color-bar scale is seen in the left of the figure. ~~Many potential volumetric fabrication flaws were observed in the weld region.~~

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The investigation of the interference fit region on Nozzle 63 shows a large variety in the reflected ultrasonic responses. Some responses are strong in amplitude, indicating an air gap and noted as red-orange in color, while others are weak in reflected amplitude, indicating a tight interference fit and noted as white-blue. A search in the data image for a high-amplitude river pattern connecting the weld to the top of the interference fit region reveals the primary leak path. This leak path originates at approximately the 180-degree location (downhill point on the nozzle) and is marked in Figure 6. The lower amplitude

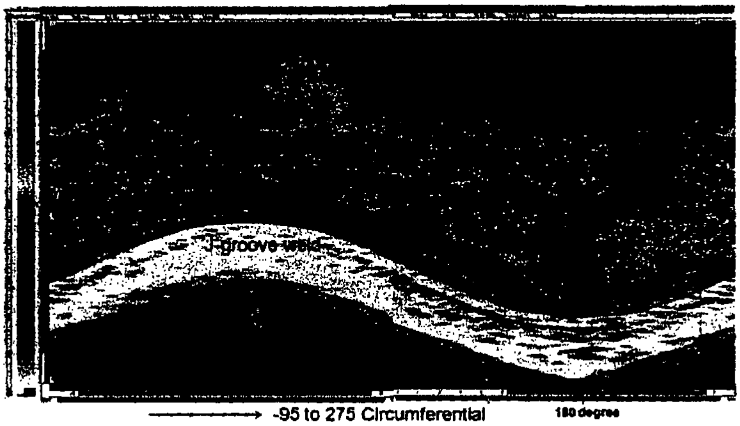

Figure 6 – A composite 360-degree ultrasonic data image from Nozzle 63. The vertical axis represents 360 mm (14.17 in.)

(blue) cluster regions near the leak path in the interference fit indicate the potential presence of boric acid as was observed in the calibration specimen. Boric acid deposits have been noted in actively leaking nozzles [1, 2].

Nozzle 63 destructive analysis

Confirmatory destructive testing was performed on Nozzle 63, by B&W, to validate the ultrasonic characterizations of the leak path(s) and other areas of interest as described above. This activity required dismantling the interference fit region with full separation of the Alloy 600 tube from the reactor vessel head material to reveal true-state information regarding the leak path(s), boric acid deposits, and wastage regions.

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Ultrasonic data correlation to destructive analysis

The exposed reactor pressure vessel (RPV) head was photographed and the composite image is displayed in Figure 7. The main leak path (yellow arrows) and other features observed in the ultrasonic images are clearly evident. Boric acid deposits are visible in white and corrosion products in the rust color. The interference fit band is apparent in the photograph and is marked with the red line. For comparison to the ultrasonic data, refer to Figure 6. The ultrasonic features well match the features seen visually on the RPV head annulus. Clearly, the main leak path was precisely imaged and other partial leak paths are evident.

RPV boric acid and corrosion analysis with comparison to ultrasonic data

Attempts were made to measure the thickness of the combined boric acid and corrosion layer deposits in the annulus as well as the extent of corrosion of the RPV head. These measurements were then compared to the ultrasonic data. The layer thicknesses were first

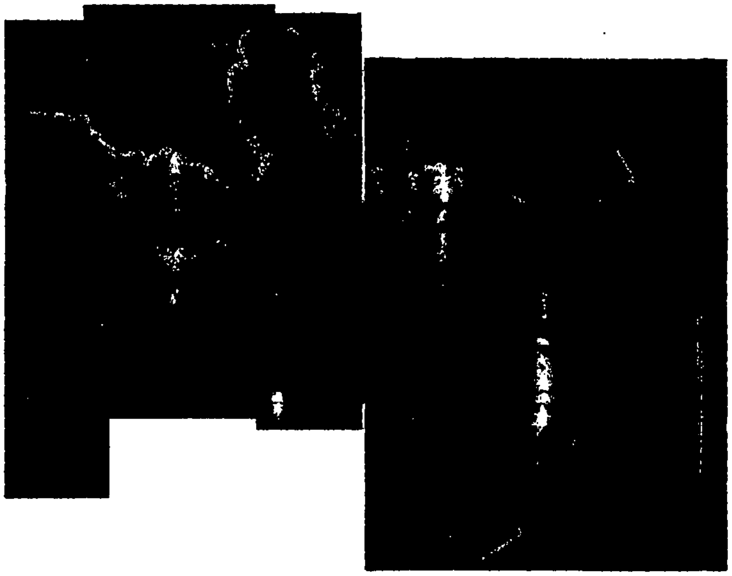

Figure 7 – RPV head surface. The red line marks the interference fit region and the two yellow arrows identify the main leak path.

measured at specific points using an eddy current thickness gage. Next, the RPV head surface in the region of the primary leak path was replicated with a Microset material, and layer thickness measurements were made on cross-sectional slices of the replica to validate several of the eddy current measurements. Finally, the replicated sections were examined with a stereomicroscope to provide an indication of the corrosion extent.

The separation of the Alloy 600 tube from the low-alloy steel of the RPV and ensuing point measurements of the boric acid and corrosion layer thicknesses allowed confirmation of the ultrasonic findings. Particular interest was placed on the main leak path area and the region immediately adjacent to it. Boric acid and corrosion layer thickness values were acquired along lines traversing the leak path inside of the interference fit and outside (below) the interference fit. Within the leak path there was no evidence of boric acid deposits, only a thin corrosion layer. This is indicative of a continual flushing of any potential deposits during plant operation. The corrosion layer was measured at 10 microns (0.79 mils) or less while the high ultrasonic responses were nominally greater than 60–70%. Outside of the leak path, to either side, the ultrasonic responses decreased while the boric acid deposit layer increased. Ultrasonic responses were typically less than 50% in the interference fit and greater than 50% outside the interference fit. Boric acid deposits were 15 to 75 microns (0.59 to 2.95 mils) thick in the interference fit and 130 to 190 microns (5.12 to 7.48 mils) thick outside the interference fit. The interference fit region would reflect less energy and also contain a thinner boric acid layer as compared to the larger gap in the annulus above and below the interference fit in the presence of a counter bore. This counter bore could potentially fill with boric acid deposits in a leaking nozzle. Furthermore, the deposits appear less compacted as noted by the larger amplitude of the ultrasonic signals. In summary, an inverse relationship between the ultrasonic responses and boric acid and corrosion layer deposits was seen across a line traversing the primary leak path. The leak path is characterized by a high ultrasonic response and low layer values while the regions on either side of the leak path are characterized by a lower ultrasonic response and higher layer thickness.

Lastly, replicated surfaces were viewed with a stereomicroscope to better document the surface conditions and to attempt to quantify the corrosion or erosion of the low-alloy steel in the annulus region. The replica of the main leak path is displayed on the left in Figure 8. Machining marks were observed on the replicated surfaces indicating minimal corrosion, erosion, or wastage throughout the leak path region. Piece 4 obtained at the transition from below the interference fit to the interference fit shows the surface machining marks still present as seen on the right in Figure 8. It was estimated that the finish within the interference fit region was equivalent to a turned finish of 1.6 micrometers (63 µin.) while the finish below the interference fit was equivalent to a milled 1.6 micro-meter- (63 µin.-) finish. A noted corroded area was visible at the exit point of the main leak path at the top of the head. It covered an area approximately 12.7 by 1.6 mm (0.5 by 0.06 in.) and had a depth of 0.25 mm (0.01 in.). These replica observations indicated a low flow rate through the annulus during plant operation.

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Figure 8 – Replicated leak path on the left and piece 4 on the right with machining marks evident. The red line on the right represents 2.0 mm (0.80 in.) in length.

CONCLUSIONS

Nozzle 63 from the North Anna Unit 2 Nuclear Power Plant had showed signs of leaking through the annulus region and a suspected leak path was detected during in-service inspections. PNNL was able to ultrasonically evaluate the nozzle at PNNL after the head was replaced and several nozzles were made available for further study. To first evaluate the ultrasonic phased array system detection capabilities, a calibration/resolution mockup specimen was built. It was fabricated with one interference fit containing machined notches to simulate wastage and another with boric acid deposits. The ultrasonic system was able to detect and size the notches and to distinguish between areas with and without boric acid deposits. Wastage or voids were identified by a high-amplitude response, typically greater than 60%, indicating a strong reflection. Boric acid deposits were identified by a low-amplitude response, less than 30%, indicating good energy transfer through the interference fit region.

The evaluation of Nozzle 63 revealed the previously identified leak path as well as other partial leak paths as high ultrasonic responses. Potential boric acid deposits were noted in areas surrounding the leak paths as lower ultrasonic responses. Destructive evaluation validated the ultrasonic findings and confirmed the relationship between ultrasonic response and the two conditions of voids (or wastage) and boric acid deposits. A layer thickness composed of boric acid and corrosion products was measured with an eddy current probe at points traversing the main leak path. The data showed a minimal layer thickness in the main leak path, where conversely the ultrasonic response was high. On either side of the leak path, the layer thickness increased while the ultrasonic response diminished. Inside the interference fit, the boric acid deposits were in the 20–40 micron range where a tight fit was expected. Outside the interference fit, the layer deposits were in the 180–200 micron range; thicker deposits were due to a looser fit in the counter bore region. Machining marks on the low-alloy steel head and only one small area of noted wastage were indicative of a low flow through the annulus during plant operation.

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