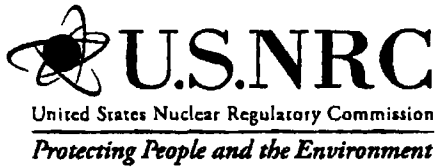


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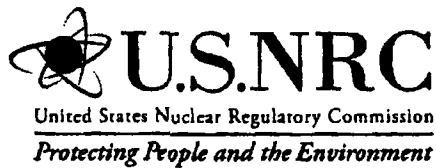


NUREG/CR-XXXX  
PNNL-XXXXX

**Ultrasonic Phased Array  
Assessment of the Interference  
Fit and Leak Path of the  
North Anna Unit 2 Control Rod  
Drive Mechanism Nozzle 63 with  
Destructive Validation**

Office of Nuclear Regulatory Research

B/20



NUREG/CR-XXXX  
PNNL-XXXXX

# **Ultrasonic Phased Array Assessment of the Interference Fit and Leak Path of the North Anna Unit 2 Control Rod Drive Mechanism Nozzle 63 with Destructive Validation**

Manuscript Completed: January 2012  
Date Published:

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## **Abstract**

In this investigation, nondestructive and destructive testing methods were employed to evaluate potential boric acid leakage paths through an Alloy 600 control rod drive mechanism (CRDM) penetration, Nozzle 63, from the North Anna Unit 2 power plant that was removed from service in 2002. A previous ultrasonic examination of this nozzle, conducted during an in-service inspection (ISI) prior to the head removal, identified a probable leakage path in the interference fit between the penetration and the vessel head. Subsequently, Nozzle 63 was made available for independent testing. Nozzle 63 was examined using phased-array ultrasonic testing with a 5.0-MHz, eight-element annular array; Immersion data were acquired from the nozzle inner diameter surface. Responses from a mock-up specimen were initially evaluated to determine detection limits and characterization capability of the probe as well as to identify and assess differences in ultrasonic responses with and without the presence of boric acid in the interference fit region. The ultrasonic evaluation of Nozzle 63 found a primary leak path as well as other partial leak paths. Following the nondestructive examination, Nozzle 63 was destructively examined to visually assess the leak paths. Additional thickness measurements were made on the boric acid deposits on the reactor pressure vessel head. These destructive and nondestructive results are compared and the results are presented. The results of this investigation may be used by the NRC to evaluate licensees' volumetric leak path assessment methodologies and to support regulatory inspection requirements.

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## **Foreword**

(To be written by Greg - NRC.)

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## Executive Summary

Research is being conducted for the U.S. Nuclear Regulatory Commission (NRC) at the Pacific Northwest National Laboratory (PNNL) to assess the effectiveness and reliability of advanced nondestructive examination (NDE) methods for the detection and characterization of flaws in nuclear power plant components. One area of concern is in primary water stress corrosion cracking (PWSCC) in the nickel-base alloys used in primary pressure boundary components in pressurized water reactors (PWRs). Nickel-based alloys exposed to reactor coolant in PWRs may experience a form of degradation known as PWSCC. One PWR component that has an operational history of PWSCC is the control rod drive mechanism (CRDM) nozzle. The CRDM nozzles are cylindrical penetrations in the upper reactor pressure vessel (RPV) head that allow for the insertion and removal of control rods. The penetration tube is held in place with an interference fit, and is seal-welded to the vessel head with a J-groove weld. Cracking in the nozzle or weld metal can allow borated water to leak to the top of the RPV head. Corrosion of the RPV head is a concern, as was discovered at Davis Besse, as well as nozzle ejection in the presence of extensive circumferentially oriented cracking. In response to the repeated occurrence of RPV head leakage, licensees were directed to perform a "demonstrated" surface or volumetric leak path assessment of all J-groove welds in the RPV head.

The original construction materials for the CRDM nozzles at North Anna 2 were Alloy 600 base metal and Alloy 82/182 weld metal. During the Fall-2001 refueling outage, coolant leakage was noted near Nozzle 63. NDE showed crack-like indications near the J-groove weld and butter layer in the nozzles and shallow axial cracking on the inner diameter. The leaking welds were repaired with Alloy 52/152 material, thought to have higher PWSCC resistance than Alloy 82/182. Subsequent visual examination of the RPV head in the Fall-2002 outage again revealed leaking nozzles. The head was replaced and several nozzles including Nozzle 63 became available for study. The purpose of this investigation was to confirm features previously identified by industry in an ultrasonic evaluation with an equivalent or better examination and to validate the findings by opening the nozzle assembly to reveal the annulus surfaces.

This study resulted in a successful ultrasonic examination of the interference fit region of control rod drive mechanism Nozzle 63 from the North Anna Unit 2 power plant. A phased-array ultrasonic system was calibrated on a mockup specimen containing two interference fit regions. The probe spot size at the interference fit was modeled at 1.2 by 1.2 mm (0.04 by 0.04 in.) at the -6 dB level. Ultrasonic data from notches in the carbon steel material from one of the mockup interference fit regions showed system resolution at nominally 4 mm (0.16 in.) in both the axial and circumferential directions. Notches as shallow as 0.028 mm (0.0011 in.) were detected as well as notches as narrow as 0.80 mm (0.10 in.) in the circumferential direction. The second interference fit mockup contained regions with boric acid deposits. These regions were ultrasonically imaged and suggested that the ultrasonic responses could be segmented into three categories: 1) good interference fit, 2) interference fit with boric acid, and 3) leak path or gap.

Ultrasonic data were acquired on Nozzle 63 and clearly showed a variation of responses throughout the annulus region. The primary leak path at the downhill position of the nozzle was imaged and definitively spanned the annulus region, thus providing a path for borated water to

reach the top of the head. Partial leak paths were also identified. The normal beam inspection, while not optimum for crack detection, also detected two axial cracks in the nozzle. These cracks were previously found by industry with an eddy current examination conducted during an in-service inspection. One of the cracks was below the weld at the uphill position. The other axial crack was located above the weld at the downhill position, which also places it in the main leak path. A comparison of the PNNL ultrasonic images to data obtained by industry showed similar results, but the PNNL data had better resolution, data registration, and focusing. Finally, a supplemental evaluation of the weld, which was again not optimized for crack detection, failed to detect any weld cracking but did detect numerous near-surface fabrication flaws.

After sectioning of the nozzle assembly to reveal the interference fit and photographing the exposed surfaces, the primary leak path was confirmed. Also confirmed was the excellent agreement of the ultrasonic images and revealed features on the annulus surfaces.

Additional measurements were made to quantify the thickness of the boric acid deposits or corrosion layer on the RPV head. It was reasonable to assume that any gap in the annulus could fill with boric acid deposits. As the gap between Alloy 600 tube and low-alloy steel head varied so too did the boric acid thickness. The leak path or bare metal corrosion layer throughout the annulus was 16 microns (0.63 mils) or less with ultrasonic responses greater than 65%. Boric acid apparently did not deposit in the leak path due to the constant flow of borated water through the area, and the ultrasonic response indicates an air gap was present. The boric acid deposits in the counter bore regions above and below the interference fit were in the 132 to 192 micron (5.2 to 7.6 mils) range with ultrasonic responses between 48 and 83%. These two regions, leak path and counter bore, are clearly distinct from each other in both boric acid thickness but overlap in ultrasonic response. The interference fit region with a narrower annulus had boric acid deposits in the 16 to 75 micron (0.63 to 3.0 mils) range, in between the leak path and counter bore values. There was not a direct correlation between the RPV head boric acid measurements in the interference fit region and the ultrasonic responses. This is not unexpected as the ultrasound was influenced by additional physical conditions that were not measured such as the deposits on the outside of the Alloy 600 tube surface and the density of any of the deposits.

Lastly, the leak path region of the RPV head was replicated and limited confirmatory measurements made on the replica for boric acid thickness. The replica surfaces were imaged with a stereomicroscope and showed minor evidence of corrosion product streaking and little or no corrosion or wastage. Machining marks were clearly evident across the main leak path. Two small areas with minor corrosion were found above the main leak path with depths of 0.25 mm (0.01 in.). Attempts to remove the boric acid deposits on the RPV head to determine wastage underneath were unsuccessful, but dental pick probing indicated that all areas were sound. Therefore, in this leaking nozzle assembly, there was minimal corrosion or wastage occurring on the low-alloy steel RPV head.

## **Acknowledgments**

The work reported here was sponsored by the U.S. Nuclear Regulatory Commission (NRC) and conducted under NRC Job Code Number N6783. Greg Oberson is the NRC project manager. The Pacific Northwest National Laboratory (PNNL) would like to thank Dr. Oberson, Mr. Darrell Dunn and Mr. Jay Collins for their guidance throughout the course of this effort.

The authors acknowledge and thank J. W. Hyres, et al. at Babcock & Wilcox Technical Services Group in Lynchburg, Virginia, for cutting the nozzle assembly, for acquiring additional measurements on the head material, and for excellent photography and documentation of their work. A special thanks to Jim for his flexibility and willingness to try new approaches to obtain requested data is due.

The authors acknowledge and thank John P. (Jack) Lareau from WesDyne International for providing information on in-service inspections (ISI) and nozzle fabrication as well as data from an ISI on Nozzle 63.

The authors also thank Kay Hass for her diligence and patience in editing and preparing the manuscript.

PNNL is operated by Battelle for the U.S. Department of Energy under Contract DE-AC05-76RL01830.

## Acronyms and Abbreviations

ASME	American Society of Mechanical Engineers
BW	bandwidth
B&W	Babcock and Wilcox Technical Services Group
CASS	cast austenitic stainless steel
CCSS	centrifugally cast stainless steel
CFR	Code of Federal Regulations
COD	crack opening dimension
CRDM	control rod drive mechanism
CWD	constant wedge delay
dB	decibels
EDM	electric discharge machining
EPRI	Electric Power Research Institute
FSH	full screen height
ID	inner diameter
IR	infrared
ISI	inservice inspection
LN	liquid nitrogen
LWR	light water reactor
NDE	nondestructive examination
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
OD	outer diameter
PA	phased array
PA-UT	phased array ultrasonic testing
PDI	performance demonstration initiative
PE	pulse-echo
PNNL	Pacific Northwest National Laboratory
PT	liquid penetrant testing
PWR	pressurized water reactor
PWSCC	primary water stress corrosion cracking
PZR	pressurizer
RMSE	root mean square error
RPV	reactor pressure vessel
RT	room temperature
RVH	reactor vessel head
SNR	signal-to-noise ratio



TLR	technical letter report
TOFD	time-of-flight diffraction
TRL	transmit-receive longitudinal
UT	ultrasonic testing

## 1 Introduction

Research is being conducted for the U.S. Nuclear Regulatory Commission (NRC) at the Pacific Northwest National Laboratory (PNNL) to assess the effectiveness and reliability of advanced nondestructive examination (NDE) methods for the detection and characterization of flaws in nuclear power plant components. One area of concern is in primary water stress corrosion cracking (PWSCC) in the nickel-base alloys used in primary pressure boundary components in pressurized water reactors (PWRs). Nickel-based alloys exposed to reactor coolant in PWRs may experience a form of degradation known as PWSCC. One PWR component that has an operational history of PWSCC is the control rod drive mechanism (CRDM) nozzle. As shown in Figure 1.1, the CRDM nozzles are cylindrical penetrations in the upper reactor pressure vessel (RPV) head that allow for the insertion and removal of control rods. The penetration tube is held in place with an interference fit, represented as the area between the two horizontal dashed lines in the figure labeled 'shrink fit zone', and is seal-welded to the vessel head with a J-groove weld. Counter bore regions are not designed to be compression-fit zones between the nozzle and RPV head and are shown exaggerated in the drawing. Most CRDM nozzles originally placed into service in PWRs were fabricated from the nickel-based alloy referred to as Alloy 600, along with the Alloy 82 and 182 weld metals. PWSCC of a CRDM nozzle in a PWR was first identified in the Bugey Unit 3 plant in France during an over-pressurization test in 1991 (Economou et al. 1994). The crack initiated in the Alloy 600 base metal and propagated into the Alloy 182 weld metal. In late 2000 and early 2001, reactor coolant leakage to the RPV head from axial through-wall cracks in CRDM nozzles was identified at Arkansas Nuclear One Unit 1 and Oconee Unit 1 (Grimmel 2005). Follow-up inspections at Oconee Units 2 and 3 in 2001 identified axial and circumferentially oriented cracks. The circumferentially oriented cracks were of particular concern because of the possibility of nozzle ejection.

Leakage of borated water to the RPV head may occur as cracks initiate on the J-groove weld surface, propagate through the weld to the triple point, and allow water into the annulus region between the nozzle outer diameter (OD) and the RPV head. The triple point is diagrammed in Figure 1.2 and is the point at which the RPV head, butting, and Alloy 600 CRDM tube meet. Once the boundary formed by an intact J-groove weld is compromised, there is the potential for a leakage path through the interference fit allowing reactor coolant to reach the outer surface of the RPV. The coolant can flash to steam, leaving boric acid deposits on the head and in the interference fit region around the leakage path. Additionally, a steam-cut leakage path through the interference fit and annulus may also be produced at operating temperature and pressure in a plant when a gap in the carbon steel RPV head at the uphill and downhill positions opens due to material expansions.

In response to the discovery of the CRDM cracks at Oconee Unit 3, in August 2001, the NRC issued Bulletin 2001-01, "Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles." PWR licensees were directed to evaluate the susceptibility of head penetration nozzles to PWSCC and to provide inspection plans to detect potential cracking. Thereafter, CRDM cracking was identified at additional PWRs including Davis Besse (Bennetch et al. 2002) and North Anna Unit 2 (NRC 2002). At Davis Besse, reactor coolant leakage led to significant wastage of carbon steel in a portion of the RPV head, leaving only a layer of stainless steel cladding at the pressure boundary. In response to the repeated occurrence of RPV head

leakage, in 2004 NRC issued EA-03-009 for PWR licensees requiring additional periodic inspections and evaluation of boric acid deposits as they pertain to the reasonable assurance of plant operational safety. The requirements of EA-03-009 were superseded by the adoption of American Society of Mechanical Engineering (ASME) Section XI Code Case N-729-1 by rulemaking in Title 10 of the Code of Federal Regulations (10 CFR) Part 50.55(a)(g)(6)(ii)(D)(1). As a condition in 10 CFR 50.55(a)(g)(6)(ii)(D)(3), licensees are directed to perform a "demonstrated" surface or volumetric leak path assessment of all J-groove welds in the RPV head.

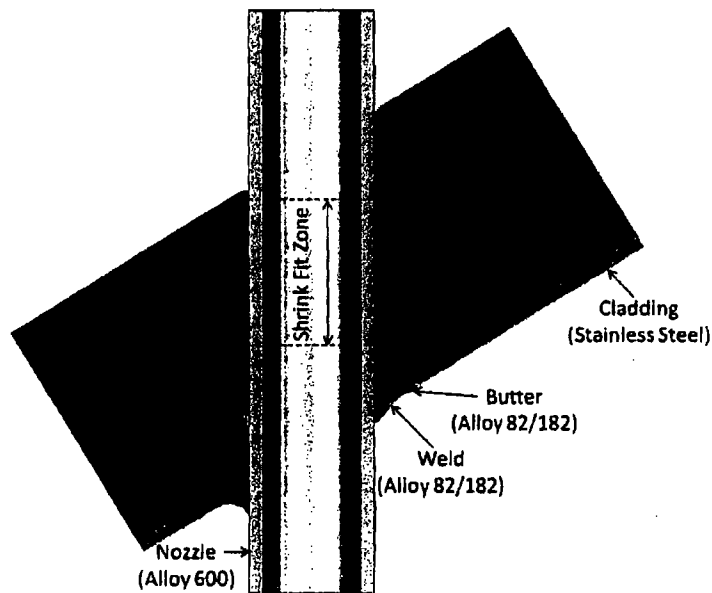
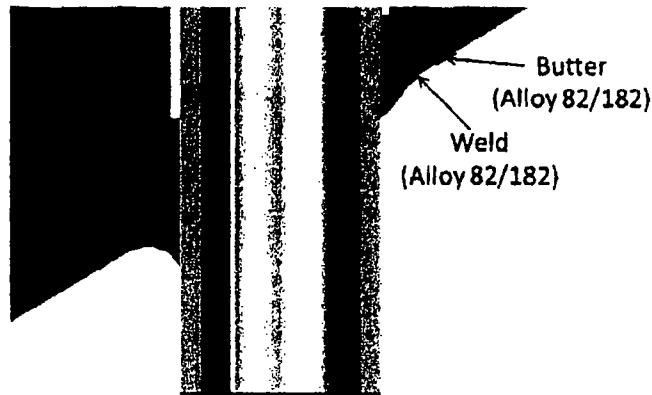


Figure 1.1 CRDM J-groove Weld Schematic

Comment [PG03]: Why doesn't the shrink fit go down to the top of the J-groove weld?



**Figure 1.2 The Triple Point in the Assembly Where the Alloy 600 Nozzle, RPV Head, and Buttering Material Meet**

A leak path assessment involves the use of an NDE technique, such as ultrasonic testing (UT), to determine whether a flow path exists through the interference fit that would allow reactor coolant to access the outside of the RPV head. The ultrasonic response from the interference fit examination will likely detect a leak path and may additionally detect corrosion or loss of material as well as the presence of boric acid in the annulus region. Industry groups, such as the Electric Power Research Institute (EPRI), are participating in programs to generically demonstrate the volumetric leak path assessment. As part of this initiative, EPRI obtained CRDM nozzles removed from operational service at the North Anna Unit 2 plant for further analysis and testing. North Anna Unit 2 is a three-loop Westinghouse PWR that was placed into service in 1980. The materials of construction for the original CRDM nozzles were Alloy 600 base metal and Alloy 82/182 weld metal.

Visual inspection of the outer surface of the North Anna Unit 2 RPV head during the Fall-2001 refueling outage indicated reactor coolant leakage in the proximity of penetrations 51, 62, and 63 as evinced by the presence of boric acid crystals (EPRI 2005). NDE of the nozzles showed crack-like indications near the J-groove weld/butter layer in the nozzles and shallow axial cracking on the inner diameter. The leaking welds in these nozzles were repaired using a temper bead repair technique with nickel-based Alloys 52 and 152, which are thought to have higher PWSCC resistance than Alloy 182. Subsequent visual examination of the RPV head during the Fall-2002 outage revealed 6 CRDM nozzles that were suspected of leaking and 21 that were masked to the extent that their status could not be determined. Eddy current and ultrasonic examinations showed numerous axial and circumferential indications in the nozzles, including those repaired during the previous outage. Given the extensive degradation of the RPV head, the utility made the decision to replace the head during the 2002 outage and make it available for further examination and study. EPRI took possession of six CRDM nozzles from the removed head including nozzles 10, 31, 51, 54, 59, and 63, which were transferred to

PNNL. Several of these nozzles were subsequently studied by EPRI and the NRC including nozzles 10, 31, 54, and 59 (EPRI 2006; Cumblidge et al. 2009).

The subject of this report is a leak path assessment of Nozzle 63 from North Anna Unit 2. This nozzle is of additional interest because of the Alloy 52/152 weld repair during the Fall-2001 outage. The purpose of this investigation is to determine whether features identified by a UT examination of the nozzle, including leak paths, voids, and the presence of boric acid in the interference fit, are confirmed by destructive analysis. The UT process is assumed to be equivalent to or better than that used in industry examinations. The radiological and mechanical steps taken to configure the nozzle for the ultrasonic evaluation are discussed in Section 2. Section 3 presents technical information on the ultrasonic transducer, the system electronics, and mechanical scanner. The calibration mockup specimen is described in Section 4 and consists of a notched specimen and a specimen with boric acid in the interference fit. Ultrasonic data on the mockup specimens are presented and system resolution and flaw detection capabilities are discussed. The ultrasonic evaluation of Nozzle 63 and corresponding results are presented in Section 5. Section 6 documents the cutting activities on the nozzle assembly to reveal the interference fit. Initial views of the annulus region are shown. Section 7 compares the ultrasonic findings to the visual evaluation of the interference fit. An ultrasonic weld examination for fabrication flaws and cracking was conducted and is described in Section 8. Section 9 contains additional measurements on the RPV head including boric acid thickness measurements in the annulus and Microset replica measurements of the primary leak path region. Lastly, a summary of the finding is presented in Section 10 and conclusions that can be drawn at this time. Section 11 gives references cited in this report.

## 2 Nozzle Preparation

When received at the Pacific Northwest National Laboratory (PNNL), the control rod drive mechanism (CRDM) Nozzle 63 from the North Anna Unit 2 reactor consisted of a flame cut section of the upper reactor pressure vessel (RPV) head and a full length Alloy 600 penetration tube, as shown in Figure 2.1. The CRDM was removed from its storage box and a radiologic survey performed. The flame cut edges of the CRDM were then painted with two coats (the first yellow, the second red) of a flexible air dried plastic coating from Plasti Dip® to reduce the risk of workers being cut while handling the CRDM (see Figure 2.2). An expandable 3-in. plug was inserted in the wetted-side of the penetration tube so the tube could be filled with water. In retrospect, it would have been better to cut the nozzle prior inserting the plug. This may have reduced some of the debris that first coated the ultrasonic scanner (see Section 5.2). With the plug inserted, the nozzle was wrapped in plastic (see Figure 2.3) and bagged to contain contamination during the nozzle cutting. The nozzle was then secured on a wheeled cart that was modified to allow the penetration tube to be kept vertical during the testing, as seen in Figure 2.4.



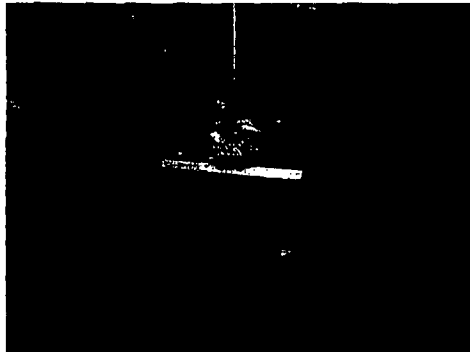
Figure 2.1 As-Received Condition of Nozzle 63.



**Figure 2.2**    **Nozzle 63 with Painted Edges.**



**Figure 2.3**    **Nozzle 63 Wrapped in Plastic for Contamination Control**



**Figure 2.4 Nozzle 63 on Modified Cart**

In order to better fit in a glovebag for contamination control purposes and to facilitate connection of the scanner, approximately two feet of the penetration tube had to be removed. A catch pan was first fitted around the penetration tube below where the cut was to be made, approximately 12 in above the RPV steel. A hydraulic rotary pipe cutting tool was then fitted around the penetration tube as shown in Figure 2.5. The penetration tube and catch tray were wrapped in plastic to provide contamination control. The hydraulic cutting tool was connected and the first attempt at cutting the tube was made (see Figure 2.6). A "hard spot" was encountered within the nozzle and two cutting heads broke before the decision was made to attempt a new cut approximately 1 in above the previous cut attempt. Cutting proceeded without any other issues in this new location. The removed section of the penetration tube was placed in a 55 gallon drum for storage.



**Figure 2.5 Nozzle 63 with Hydraulic Rotary Pipe Cutting Tool**



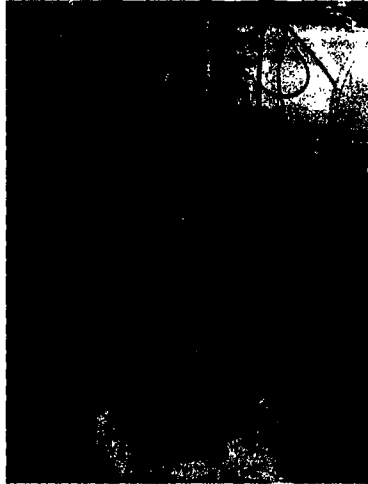


**Figure 2.6 Cutting of Nozzle 63 Penetration Tube.**

After cutting, the CRDM was completely wrapped in plastic to prevent the spread of contamination. The CRDM was then transported to RPL/33 where a containment glovebag had been assembled to house the nozzle. The cart with the nozzle was wheeled into the glovebag as shown in Figure 2.7. Once the nozzle was properly positioned, the two-axis scanner with attached ultrasonic phased array probe was lowered through an upper access port and centered onto the penetration tube. The scanner was secured to the penetration tube using three set screws. The main door and the upper access port were sealed and the control cables secured to the upper frame. Approximately 1.5 liters of distilled water was added to the penetration tube. The final configuration of the scanner in the glovebag is shown in Figure 2.8.



**Figure 2.7 CRDM Installed in Containment Glovebag.**



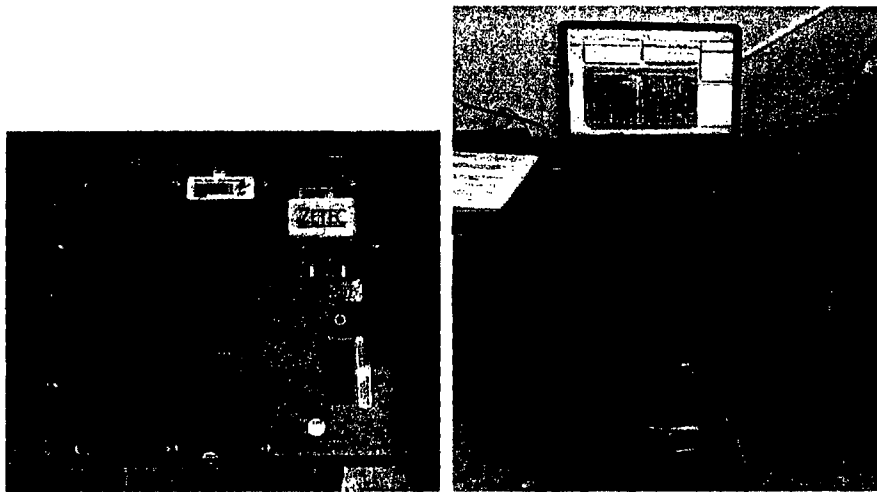
**Figure 2.8** Final Configuration of CRDM Nozzle 63 for Examination

### 3 Ultrasonic Testing Equipment for Nozzle 63 Examination

The nondestructive leak path assessment of Nozzle 63 was performed at the Pacific Northwest National Laboratory (PNNL) with an ultrasonic phased array (PA) probe. A PA probe has multiple individual elements that are electronically fired at prescribed time delays to form a coherent and focused beam at a specified depth in the material under test. The equipment used for this investigation was selected because it is similar to or better than equipment used by industry for in-service inspections of nozzle penetrations in pressurized water reactors (PWRs). A detailed description of the equipment is provided in this section.

#### 3.1 Phased Array Electronics

Ultrasonic data acquisition for Nozzle 63 was accomplished using the ZETEC Tomoscan III phased array system to control the PA probe employed in this study. This commercially available system was equipped to accommodate a maximum of 64 channels of data from PA probes and was operated with UltraVision 1.2R4 software. Its frequency pulsing electronics can drive probes in the 0.7–20 MHz range. The system is capable of accepting multiple axis positional information from external encoders to map ultrasonic data to spatial location on a specimen. The data acquisition system is shown in Figure 3.1.



**Figure 3.1** Data Acquisition System and Laboratory Workstation. Left: Tomoscan III phased array data acquisition system. Right: Laboratory workstation/laptop computer for both data acquisition and data analysis, with the Tomoscan III system below.

### 3.2 Phased Array Probe and Software Simulations

Nozzle 63 was examined with a pulse-echo (PE) longitudinal-wave immersion phased-array probe with a center frequency of 5 MHz, as shown in Figure 3.2. The PA probe was designed in a 1-D annular configuration using eight elements. The probe contained elements in a Fresnel radius pattern starting with a radius of 3 mm (0.12 in.) up to the final element radius of 9.72 mm (0.38 in.). Thus, the total aperture was 296.81 mm<sup>2</sup> (0.46 in.<sup>2</sup>). As characterized by the manufacturer, Imasonic, the probe exhibited an overall 71% bandwidth at -6 decibels (dB) with all eight elements and an overall central frequency of 5.4 MHz. This design was chosen for enhanced depth focusing capabilities. Its beam-forming capabilities showed a satisfactory insonification of the interference fit region of interest as well as the ability to propagate a coherent ultrasonic beam deep into the weld region. Figure 3.3 shows the probe attached to the scanning arm.

Before the PA probe was used for the examination, a set of focal laws was produced to control the firing of individual elements. The focal laws were inputs to the UltraVision control software, which determined specific elements to excite at specific times to allow for proper beam-forming in the material. The focal laws may also contain details about insonification angles, the focal depth of the sound field, the delays associated with the wedge and electronics, and the orientation of the probe. For this investigation, a software package contained in the UltraVision software program suite, known as the ZETEC Advanced Focal Law Calculator 1.2R4, was used to produce the focal laws. The software program generated focal laws and simulated the ultrasonic field produced by the probe when using the generated laws. The user entered the physical information about the PA probe and wedge into the program, including the number and size of probe elements, and the wedge angle and size. After the desired angles and focal distances were entered, the software generated the needed delays for each element to produce the desired beam steering and focusing in the material. The software beam simulation produced a simple ray-tracing image of the probe, wedge, and material under evaluation, as well as a density mapping of the modeled sound field. The sound field mapping enabled the user to see how well the sound field was formed with the given input parameters. The probe was also evaluated for the generation of grating lobes that may be detrimental to the examination. It should be noted that the software simulation was performed using an isotropic material assumption; namely, that the velocity of sound is maintained throughout any angle for a particular wave mode. The simulations enabled the user to estimate sound field parameters and transducer performance to optimize array design and focal law development.

Typical control rod drive mechanism (CRDM) nozzles made from Alloy 600 have a tube wall thickness on the order of 15–17 mm (0.59–0.67 in.). The targeted area of interest in this study was the interference fit in the annulus between the nozzle and low alloy steel vessel material. It was important to design a phased array probe capable of depth focusing into this region. Prior to probe fabrication, sound field simulations were conducted using the Phased Array Calculator 1.2R4 software program and the design parameters to simulate a projected sound field into an isotropic material with acoustic properties of Alloy 600. Figure 3.4 shows a side view representation of the focal laws generated on the left and a sound field simulation on the right for a target depth focus of 15 mm (0.59 in.). The gray regions represent the Alloy 600 material and the dark blue regions represent water. In this immersion scanning setup, water was used

as the 'wedge' material. The red horizontal line at 15.1 mm (0.59 in.) represents the target focal region. The simulation showed a favorable sound field density at the desired focal depth.

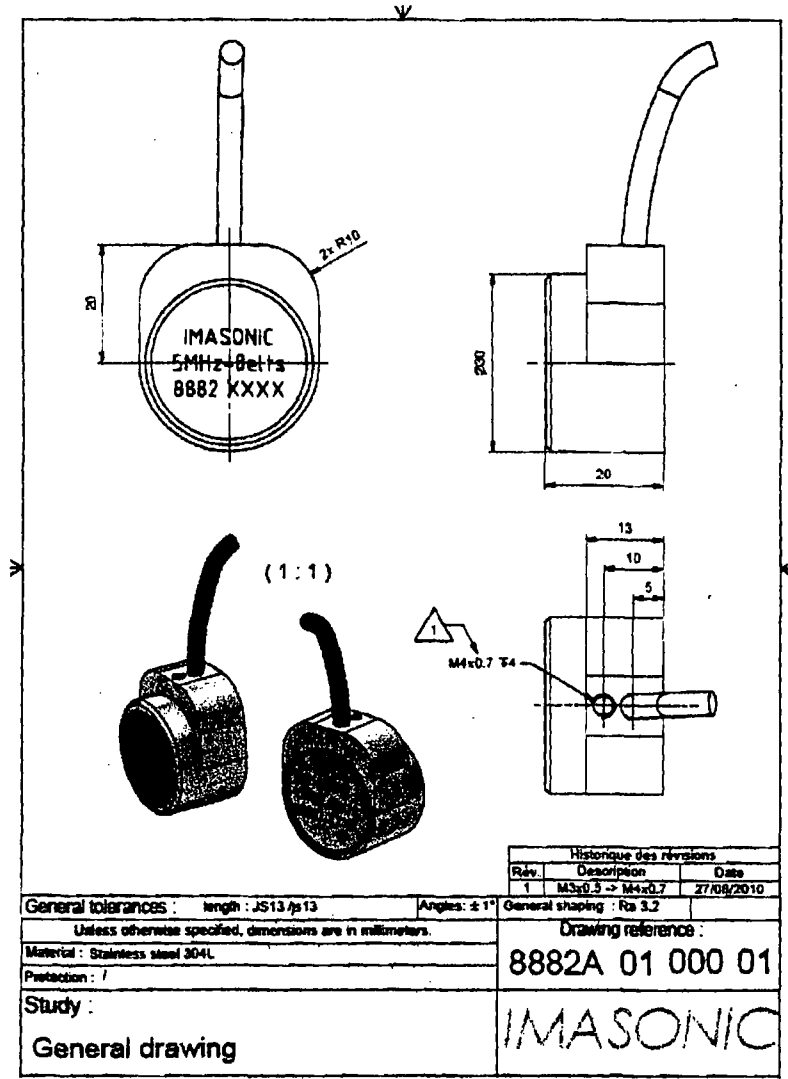


Figure 3.2 5.0-MHz Phased Array Probe

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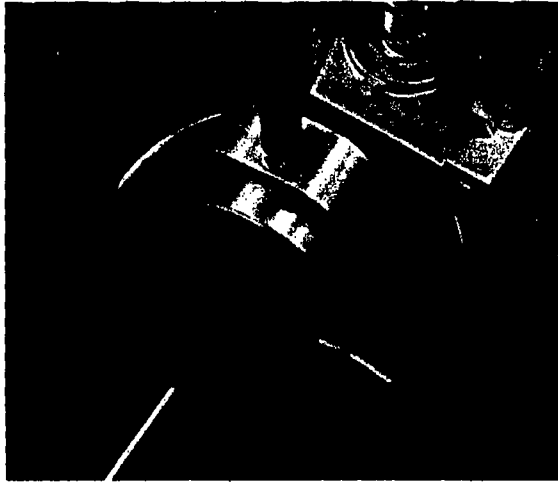


Figure 3.3 Annular Phased Array Probe Attached to Scanner Arm

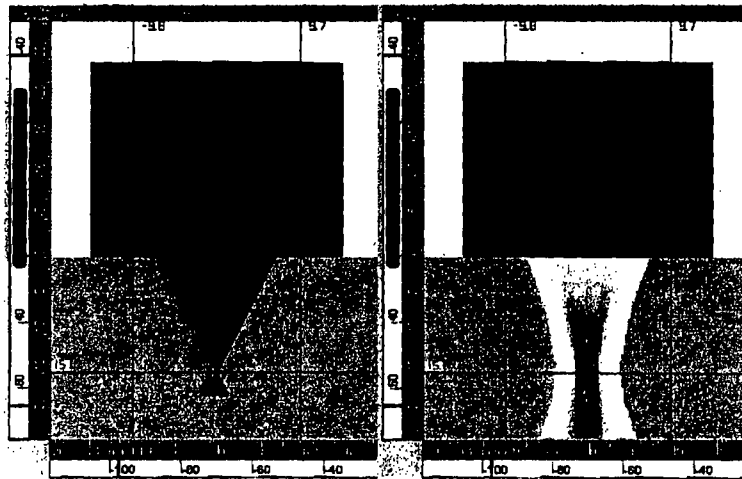


Figure 3.4 Laser Formation and Round Field Simulation for a Depth Focus of 15 mm

Comment [PG05]: Where is probe in this figure?

The simulations viewed from the top or C-scan view gave information on the overall spot size in the scan and index axes of the formed beam at a particular depth. As seen in Figure 3.5, the predicted -6 dB (50%) and -3 dB (70.7%) spot sizes for the phased array probe focused at a

depth of 15 mm (0.59 in.) in Alloy 600 material were  $1.2 \times 1.2$  mm ( $0.047 \times 0.047$  in.) and  $1.0 \times 1.0$  mm ( $0.04 \times 0.04$  in.), respectively. Additional sound field simulations were modeled at 1 mm (tube inner diameter [ID]) and 30 mm (15 mm into the J-groove weld region). The -6 dB spot size for depth focuses of 1 and 30 mm were  $0.6 \times 0.6$  mm ( $0.024 \times 0.024$  in.) and  $2.0 \times 2.0$  mm ( $0.079 \times 0.079$  in.), respectively. The -3 dB spot sizes were  $0.4 \times 0.4$  mm ( $0.016 \times 0.016$  in.) and  $1.4 \times 1.4$  mm ( $0.055 \times 0.055$  in.), respectively.

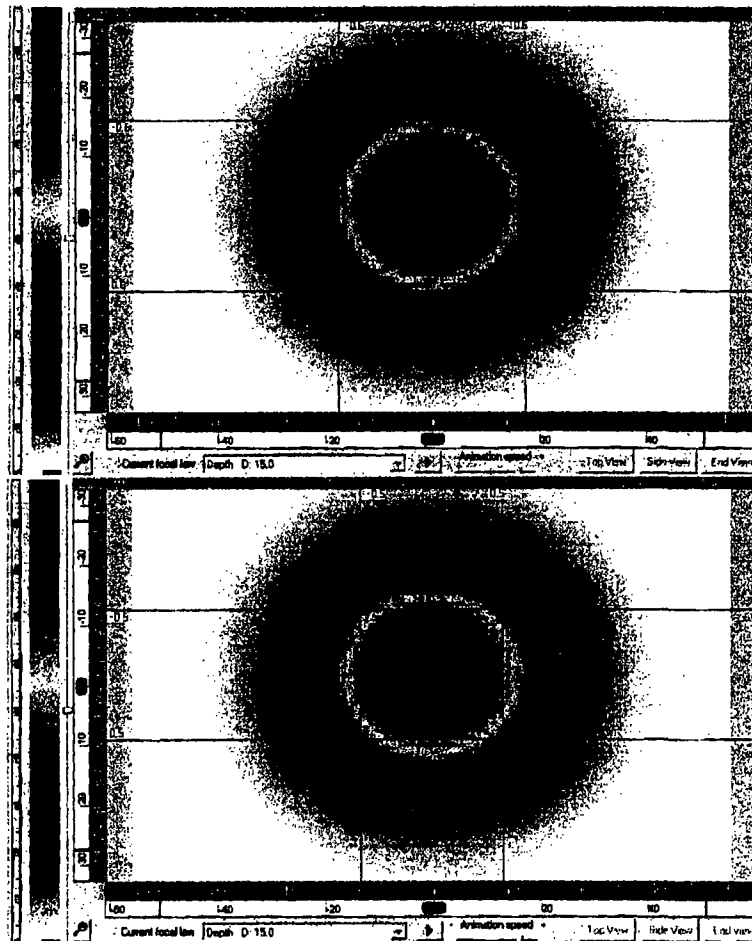


Figure 3.5 C-Scan View at a Depth Focus of 15 mm. Top: -6 dB spot size. Bottom: -3 dB spot size.

Comment [PG06]: What is significance of *r* and blue lines?

### 3.3 Scanner

The theta-Z scanning apparatus for examining the annulus region of the nozzle from the ID of the penetration tube was constructed by Brockman Precision Machine and Design located in Kennewick, Washington. The ID scanner was designed for inner-surface scanning with ultrasonic probes but could be adapted and used with other sensor technologies. The scanner system was built to attach directly and securely onto the nozzle, centered by three setscrews spaced evenly around the collar of the scanner. Figure 3.6 shows photographs of the scanner sitting on a nozzle mockup specimen. The scanner had a linear, Z or vertical axis for movement along the length of the nozzle and a rotational or theta axis for rotation around the nozzle ID. Motion of the scanner was controlled by two pulse-counter or stepper motors. Optical eye shaft encoders with a sensitivity of 2500 counts per revolution were attached to each motor. The calibrated positional information attained via the slave encoders was routed directly into the ultrasonic system and correlated with the ultrasonic testing (UT) data. The maximum range of motion along the nozzle length was 457.2 mm (18 in.). The rotational motion was continuous with no fixed limits, but was practically constrained to approximately 1.5 revolutions by the cables attached to the motor drivers, encoders, and the PA probe.

The scanner system was controlled using a custom-designed software program interfaced with a pulse-counter motor control system. A menu in the program allowed the user to 'jog' the scanner to a desired position. This feature was useful for setup, mapping the desired scan bounds as well as calibrating the UT signal response at certain locations. The customizable scanning sequence menu allowed the user to specify the scan and index range and resolution settings. Additionally, speed settings were tailored to acquire data with consistency and within the UT data acquisition system limits.

Prior to scanning, the nozzle was arranged in a vertical position, 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 water was given 24 hours or more to degas/de-bubble. Next, the ID of the nozzle specimen was gently brushed to remove bubbles that formed and attached to the ID wall region. Because air bubbles have a strong ultrasonic impedance mismatch to water or steel, it was important to remove them from the ID surface prior to scanning to minimize reflection or distortion of the ultrasonic energy.

The scanner was lowered onto the top of the nozzle specimen, centered, and secured by uniformly tightening the three set screws in the collar. Centering the scanner apparatus allowed the transducer arm to be positioned at the center of the nozzle tube so that a constant sound path was maintained during a circumferential scan sweep to reduce signal walk. The phased array probe was then affixed to the 762-mm (30-in.) scanner arm using an M4 threaded rod running directly into the transducer housing and attached to the vertical axis via a set screw, as shown in Figure 3.7. The transducer face was orientated such that the ultrasonic beam was propagating radially outward towards the annulus or weld region. Using a set screw to hold the scanner arm enabled manual positioning the probe in the vertical axis for increased versatility.





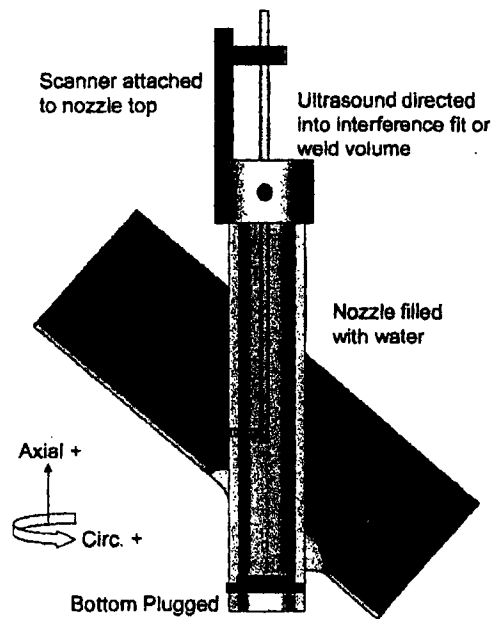
**Figure 3.6 Scanner on Mockup Nozzle Specimen. Left: Scanner alone. Right: Scanner with PA probe attached sitting on the calibration mockup specimen.**



**Figure 3.7 Transducer Attachment**

The scanning sequence used the rotational or circumferential direction as the scan axis and the vertical direction as the index axis. The positive scan direction was established to be counter clockwise and the positive index was defined as vertically upwards. Positional resolutions were set to 0.25 degrees in the scan and 0.5 mm (0.02 in.) in the index directions for scanning the calibration mockup specimen. For output file size management, Nozzle 63 scanning protocol used 0.5 degrees by 0.5-mm (0.02-in.) resolutions in the scan and index directions, respectively. Figure 3.8 shows a detailed scanning setup schematic on a CRDM nozzle assembly.

Due to the radiation contamination concerns surrounding Nozzle 63, a custom glove bag (details discussed in Section **Error! Reference source not found.**) was constructed to reduce radiation contamination to persons or equipment. Setup in the glove bag required modifications to the glove bag so that scanner and phased array cables and equipment could be passed in while maintaining connection to vital equipment such as the phased array electronics and motor control units. Figure 3.9 depicts the scanner system fully assembled in the protective glove bag environment.



**Figure 3.6 Scanning Setup Orientation Schematic**

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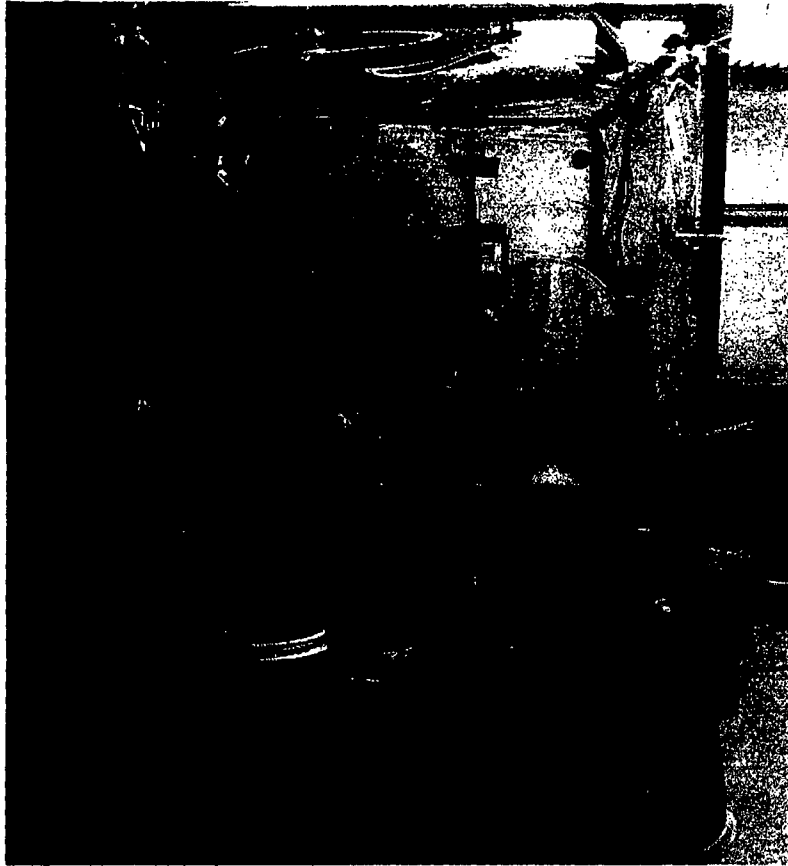


Figure 3.9 Scanner System on Nozzle 53 in the Custom Glove Bag

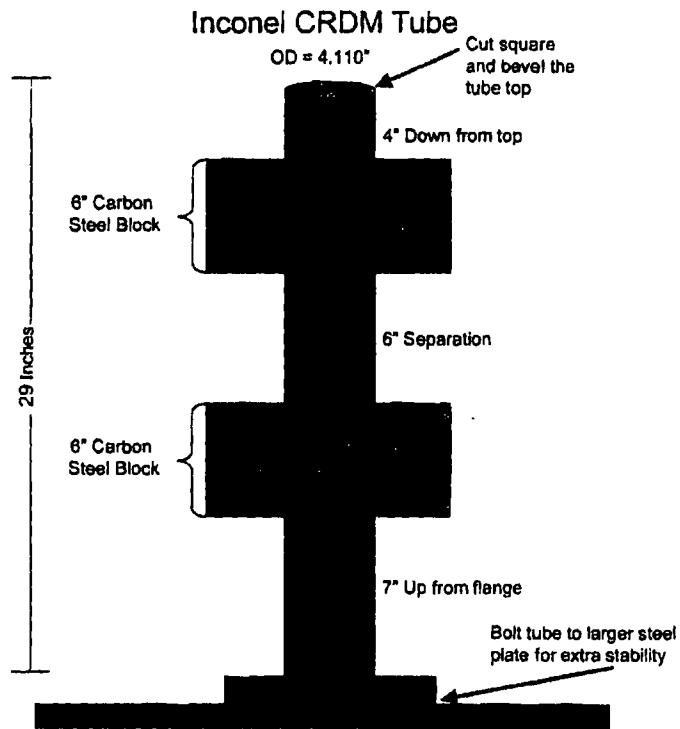
Comment [PG08]: Same as figure 5.2.

## **4 Calibration Mockup**

Prior to performing the non-destructive leak path assessment of Nozzle 63, a control rod drive mechanism (CRDM) mockup was constructed at Pacific Northwest National Laboratory (PNNL) for calibration of the ultrasonic testing equipment and to assess its capability to identify features associated with primary water leakage. These include crystalline boric acid in the interference fit region, wastage or corrosion of the low alloy steel reactor vessel head material, and cracking or degradation of the Alloy 600 nozzle material. A description of the mockup and testing is presented in this section.

### **4.1 Mockup Design and Fabrication**

The CRDM mockup was made from an Alloy 600 tube fitted with two 6-in.-thick carbon steel blocks. The mockup was designed to simulate the interference fit between the CRDM nozzle and the reactor vessel head (RVH) material in a pressurized water reactor (PWR), using similar materials and fabrication techniques. The mockup had two interference fit regions as shown in Figure 4.1. In the top interference fit, notches were made in the tube and carbon steel blocks with electric discharge machining (EDM) to simulate cracking, wastage, and degradation of the materials. In the bottom interference fit, crystalline boric acid was placed between the tube and the carbon steel blocks to simulate deposits left by primary water leakage. Due to safety concerns (tipping) regarding specimen weight and center of mass, the flange end of the tube was bolted to a larger plate for increased stability.



**Figure 4.1 Assembled CRDM Interference Fit Mockup Specimen**

#### **4.1.1 Simulated Boric Acid Deposits**

The lower interference fit on the CRDM nozzle mockup contained crystalline boric acid deposits in the region between the Alloy 600 tube and the carbon steel block. Boric acid deposits in the interference fit of an operating plant could indicate leakage of borated primary water through the J-groove seal weld. In-service-inspection data show that the presence of boric acid creates a unique ultrasonic transmission and reflection patterns in the fit regions (Cumblidge et al. 2009). The boric acid fit of the mockup was designed so that PNNL could evaluate and quantify this ultrasonic transmission and reflection phenomenon.

The lower interference fit mockup region was designed to have both regions where boric acid deposits were present and bare metal regions without boric acid, as shown in Figure 4.2. Ideally, the contrast of the two regions in the ultrasonic data would reveal differences in ultrasonic transmission and reflection. The process of creating the boric acid deposit regions began with masking off regions with tape on the Alloy 600 tube outer diameter (OD) where boric

acid was unwanted, as shown in the left hand side of Figure 4.3. The boric acid was prepared for application by mixing a small amount of boric acid in solid form with a small amount of methanol. The two components were then sonicated into a paste with medium to high viscosity. The application of the acid involved spreading a thin and even coat of the paste with a compatible brush over the localized region on the OD of the tube between the masked-off sections. Upon evaporation of the methanol and solidification of the boric acid, the masking tape was removed. A snake-like pattern was scraped into one of the boric acid regions as indicated with the blue line in Figure 4.2 and the arrow in the right hand side of Figure 4.3.

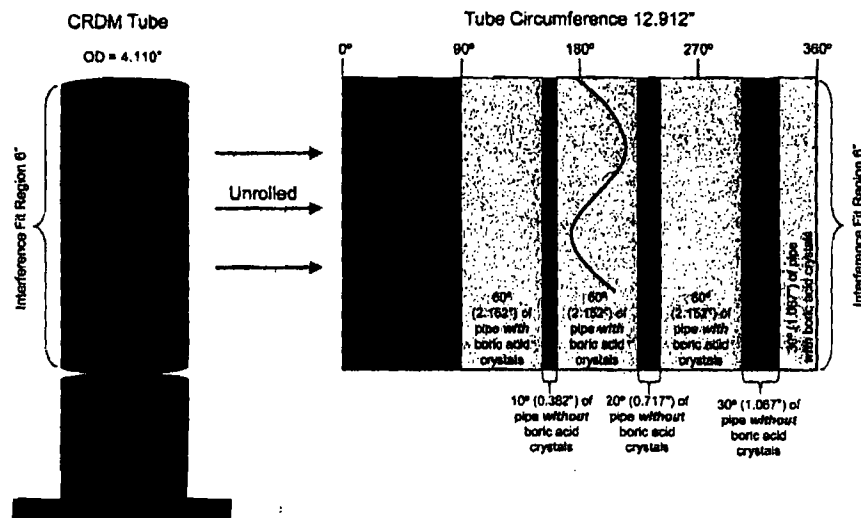
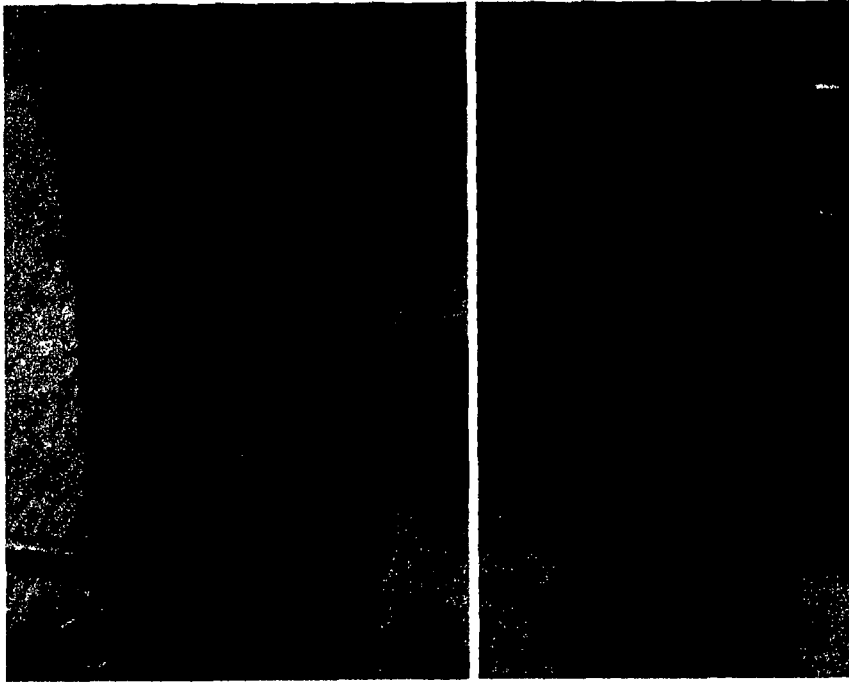


Figure 4.2 Boric Acid Pattern Conceptual Design



**Figure 4.3 Boric Acid Application**

**Comment [P809]:** State that in the image on the left the blue tape indicates masked regions and that the arrow on the right indicates the path where the boric acid was scraped off.

#### **4.1.2 Simulated Cracking, Cutting and Wastage**

The upper interference fit in the CRDM nozzle mockup contained various precision-crafted EDM notches to create a small void region between the tube and the carbon steel block. This was intended to simulate regions in the assembly where a void was created by wastage of the carbon steel RVH material or by anomalies in the CRDM tube such as machining marks, cracking, and steam cutting. The notches were machined by Western Professional, Inc., with the pattern shown in Figure 4.4, to provide ultrasonic detection limits and characterization information for voids in the interference fit region.

As shown in Figure 4.4, notches were put in both the Alloy 600 tube, which is the silver-colored region in the figure, and the carbon steel block, which is the brown/orange colored region. The tube and the carbon steel block had the same notch pattern, with the first 180 degrees of the mockup having the notches cut into the tube OD, and the area from 180 to 360 degrees having the notches cut into the carbon steel block inner diameter (ID). The notches were oriented horizontally and vertically to assess probe resolution in the circumferential and axial directions. A theoretically determined spot size using the 5-MHz phased-array probe at the interference fit region is 1.0 mm (0.04 in.) in both theta and Z directions (circumferential and axial directions).



For reference, the theoretical wavelength ( $\lambda$ ) in the Alloy 600 tube material at 5 MHz is 1.1 mm (0.043 in.).

The probe resolution in both the circumferential and axial directions was measured by acquiring data on a series of notches 2-mm wide  $\times$  2-mm deep  $\times$  25-mm long (0.079-in.  $\times$  0.079-in.  $\times$  1.0-in.) that were spaced 2, 3, and 5 mm (0.079, 0.12, and 0.20 in.) apart (approximately 2, 3, and 5  $\lambda$ ), respectively. One set of these notches was orientated circumferentially and the other was oriented axially, as represented by blue lines in Figure 4.4. To measure width detection sensitivity, axial notches labeled 1–4 in Figure 4.4 were placed equidistant from each other and had a constant depth, while the widths varied from 0.7938 to 6.35 mm (0.03125 to 0.25 in.). The third set of notches was used to assess depth sensitivity, with axially oriented notches placed equidistant from each other. These notches are labeled 5–8 in Figure 4.4 and had constant lengths and widths but varied in depth. Figure 4.5 shows additional detailed notch dimensions. Complete as-built dimensional details for all of the notches can be found in Appendix A.

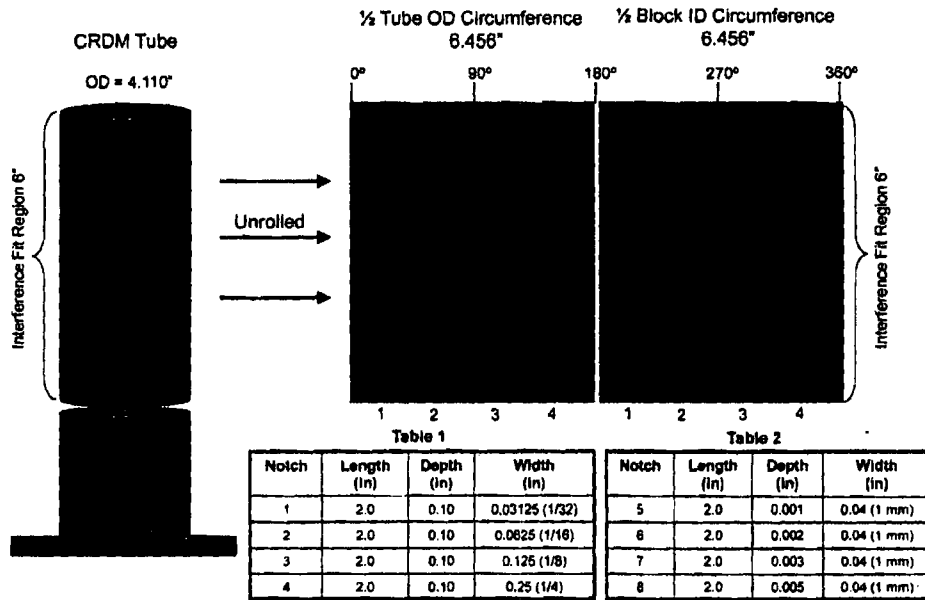


Figure 4.4 Interference Fit #2; Notch and Pattern Conceptual Design

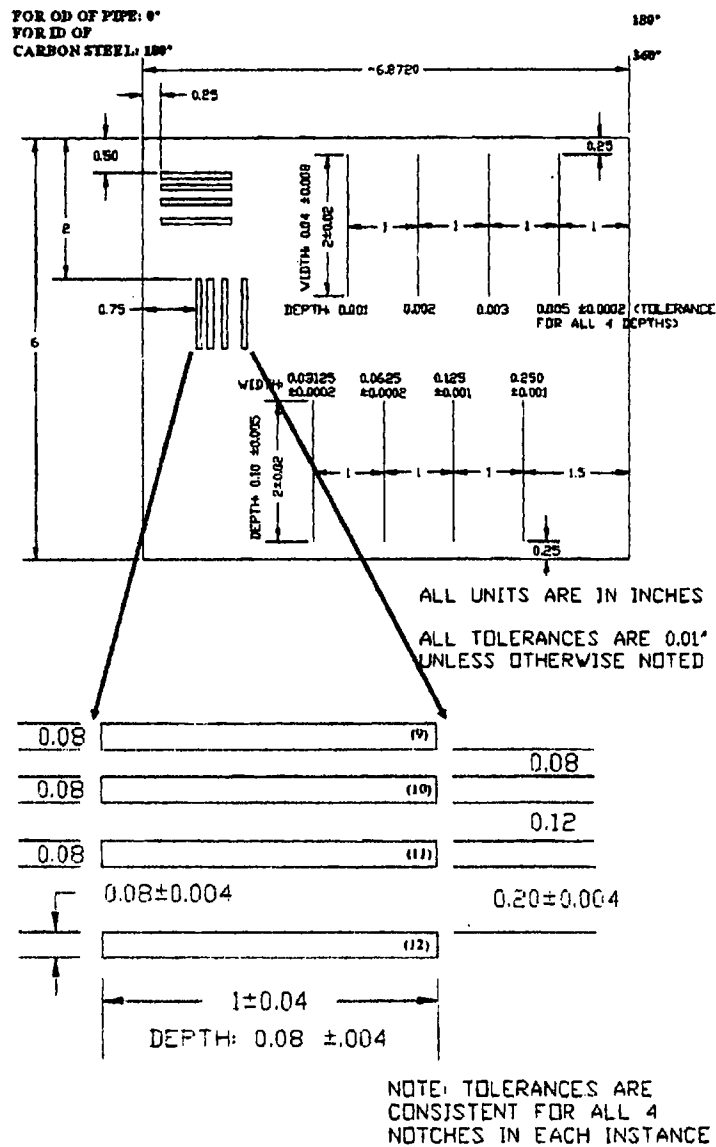
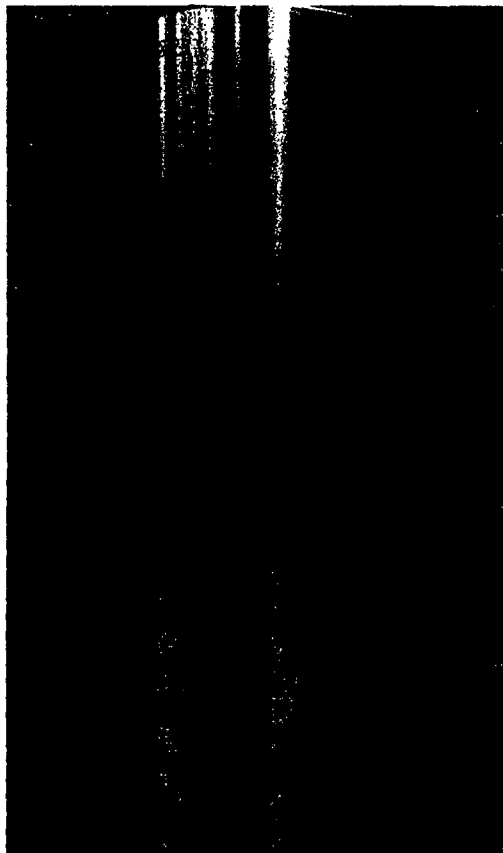


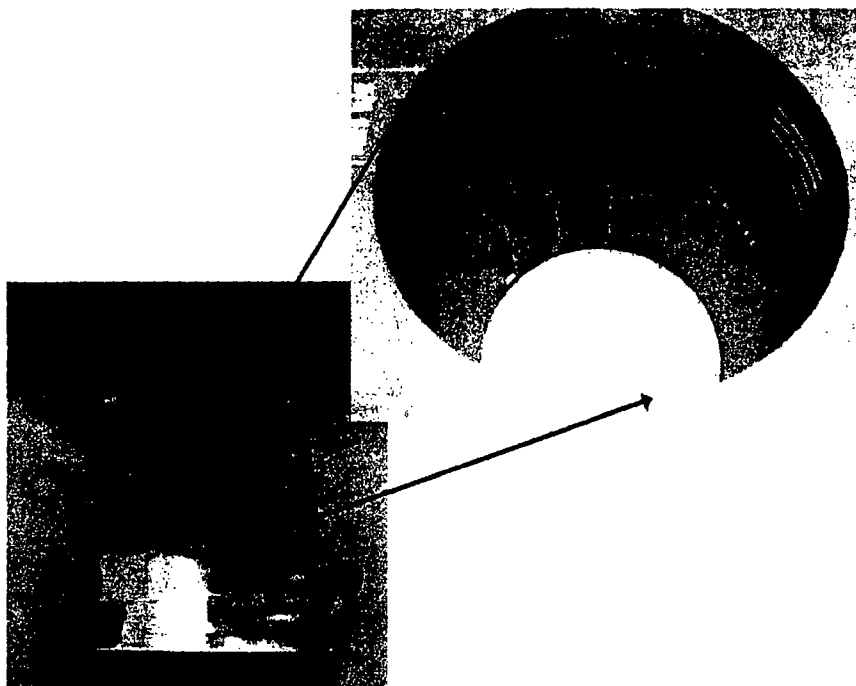
Figure 4.5 Notch Pattern in the CRDM Calibration Mockup Specimen Upper Interference Fit. All units are inches. Above: General notch layout with detail. Below: Circumferentially orientated resolution notch detail.

Comment [PG010]: Can this be in appendix? Do you need here?

The three sets or groupings of notches did not overlap, but were separated so that ultrasonic observations could be made independently on the ability to resolve two closely spaced indications, as well as width and depth sensitivity. The acronym 'PNNL' was also notched on the OD of the tube to provide an indication of off-axis sensitivity. Figures 4.6 and 4.7 show the EDM notch patterns as cut into the Alloy 600 tube and carbon steel block.



**Figure 4.6 EDM Notches in Alloy 600 Tube**



**Figure 4.7 EDM Notches on Carbon Steel Block**

#### **4.1.3 Mockup Assembly**

An interference fit is made by either heating the low alloy steel reactor pressure vessel (RPV) head or cooling the Alloy 600 nozzle, or both. PNNL choose to cool the nozzle. The other parameter considered was the size of the interference fit diameter. A suggested maximum fit was 0.102 mm (0.004 in.) (Gorman et al. 2009). Reported industry interference fit ranges were listed as 0.030 to 0.102 mm (0.0012 to 0.004 in.) (Hunt and Fleming 2002). PNNL decided to fabricate nominal 0.0762-mm (0.003-in.) interference fits.

The nozzle was lightly machined to remove any minor surface irregularities and its outer diameter was measured. Then the carbon steel blocks were machined with a hole that was 0.0762 mm (0.003 in.) in diameter smaller than the OD of the tube at room temperature of 22°C (72°F). The assembly of the CRDM mockup involved temporarily cold-shrinking the Alloy 600 tube with liquid nitrogen, so that it could be fitted with the carbon steel blocks. This created an interference fit of 0.0762 mm (0.003 in.) after all components returned to room temperature.

To determine if the interference fit was attainable, the expected thermal shrinkage for the nozzle at liquid nitrogen temperature was calculated. Thermal expansion coefficients are generally



liquid nitrogen (LN) bath for approximately 2.5 minutes. The chilled tube section was promptly removed from the LN bath and the diameter of the tube was again measured at the same locations. The temperature of the tube upon removal from the LN bath was unattainable as it surpassed the low end capability of the IR thermometer ( $-32$  to  $760$  degrees C/ $-25$  to  $1400$  degrees F). The theoretical temperature of LN is  $-195.95$  degrees C/ $-320.71$  degrees F. At cold temperatures, the average diameter of the tube was  $104.699$  mm ( $4.122$  in.). The tube section was allowed to re-equilibrate to room temperature and additional diameter measurements were made. These showed that the average nozzle diameter returned to  $104.902$  mm ( $4.130$  in.). A full set of diameter data can be viewed in Table 4.1, where data were acquired in descending order from position 5 to 1. Figure 4.6 shows the tube diameter at the three stages of this experiment as a function of axial position. Room temperature initial (RT initial), after LN, and room temperature final (RT final). The results from this test indicated that the Alloy 600 tube material shrank an average of  $0.203$  mm ( $0.008$  in.) in diameter when chilled with LN and then was restored to its original size after returning to room temperature. The CRDM calibration specimens were designed and machined for a  $0.076$  mm ( $0.003$  in.) diameter interference fit. Tube shrinkage of an additional  $0.127$  mm ( $0.005$  in.) provided the necessary room for slipping the machined carbon steel blocks over the tube during mockup assembly. Moreover, it was equally important that the tube return to its original size (at room temperature) in order to create the tight interference fit. This successful preliminary test proved that both necessary requirements could be achieved.



Figure 4.6 Diameter Measurements Acquired at Room Temperature Using a Calliper

Table 4.1 Alloy 600 Tube Shrinkage Measurements at Various Temperatures

Temp (°F)	Room Temp		Liquid Nitrogen		Return to Room Temp	
	0-180	90-270	0-180	90-270	0-180	90-270
Diameter (in.)	1	4.120	4.120	4.120	4.120	4.120
	2	4.120	4.120	4.122	4.120	4.120
	3	4.120	4.120	4.122	4.120	4.120
	4	4.120	4.120	4.122	4.120	4.120
	5	4.120	4.120	4.122	4.120	4.120
Average:		4.120	4.122		4.120	

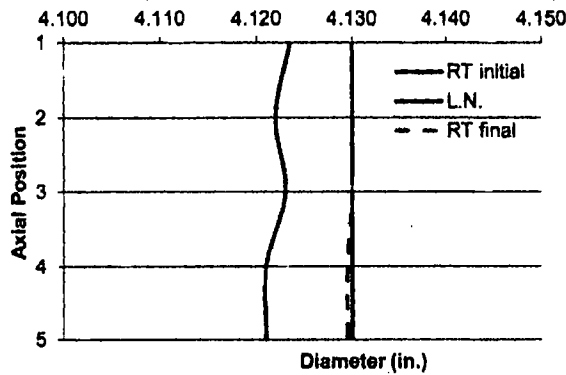
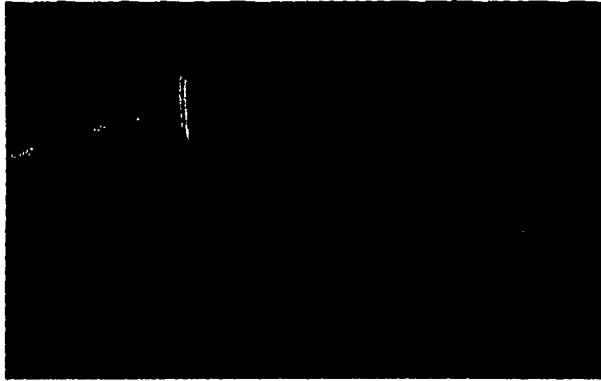


Figure 4.9 Tube Shrinkage Measurements

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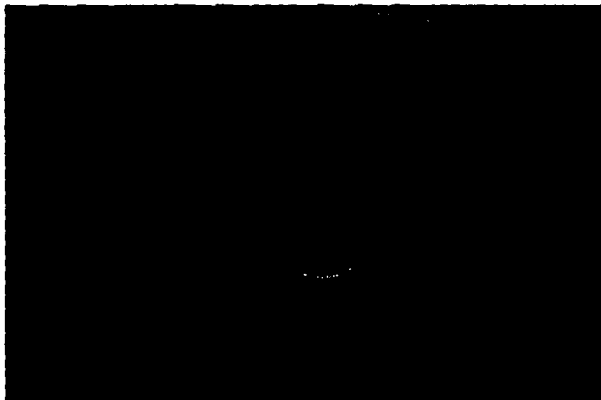
To assemble the mockup, LN was used to shrink the 736.6-mm (29-in.) long Alloy 600 tube. As the tube rested vertically in a stainless steel secondary containment trough, LN was added in the tube to within 101.6 mm (4 in.) below the top, as shown in Figure 4.10. The LN was contained solely within the tube. A permanent end cap was seal welded at the flange end of the tube to prevent leakage of any LN. Towels were used to assist in insulating the tube to prevent unwanted heat transfer and/or ice formation on the OD of the tube. Once the tube cavity was full of LN, the OD of the tube was monitored until the maximum shrinkage level was achieved. As measured at the top of the tube, a diameter-shrinkage of 8 mills (0.20 mm) was achieved.

Comment [PG012]: Global comment: please check all measurements (English in parentheses).



**Figure 4.10 Filling Alloy 600 Tube with Liquid Nitrogen**

The first fit to be made was the lower one with simulated boric acid deposits. Oversized polyvinyl chloride (PVC) piping was cut to length and fitted over the Alloy 600 tube and served as a hard stop for the carbon steel block to rest on while the specimen returned to room temperature, as seen in Figure 4.11. Next, the insulation towels were removed and the machined carbon steel block was hoisted over top of the tube and aligned accordingly. The block was lowered rapidly and slid down the Alloy 600 tube, but came to rest approximately 63.5 mm (2.5 in.) above the targeted resting place. Thus, the boric acid deposits were only under the bottom half of the carbon-steel block. Upon return to room temperature, the PVC piping was no longer needed and was removed.



**Figure 4.11 PVC Spacer Shown at Bottom of Specimen**



The second interference fit with machined notches was created following a similar protocol. For this fit, it was critical to align the zero degree point of the carbon steel block with the zero degree point stamped on the Alloy 600 tube so as to not overlap the notch patterns created in the two materials. The assembly of this fit went according to plan using the PVC piping separator during assembly to maintain separation between the two fit regions. Figure 4.12 shows the completed and assembled calibration specimen.



**Figure 4.12 Assembled Calibration Specimen**

## **4.2 Ultrasonic Evaluation of Mockup**

The CRDM nozzle mockup was examined with the annular ultrasonic phased-array probe described in Section 2. The results of the mockup examination are presented in the following sections.

#### 4.2.1 Alloy 600 Tube Notches

The machined notches in the Alloy 600 tube of the CRDM nozzle mockup simulated potential cracks or degradation of the nozzle penetration. The notched area shown in Figures 4.4 and 4.5 was scanned over approximately a 0 to 170 degree range in the circumferential direction (horizontal axis) and 0 to 180 mm (7.1 in.) in the axial direction (vertical axis) with the data image shown in Figure 4.13. This top view, plan view, or C-scan image shows the resolution notches in the upper-left portion of the image. The variable depth and width notches are also seen as well as the letters "PNNL." The color scale is displayed on the left with lowest amplitudes at the bottom represented by white and the highest amplitude at the top of the color bar represented by red. In this pulse-echo data, the low amplitude signals (blue and green) indicate good transmission or low reflection of the ultrasonic energy at the interface of the tube to the carbon steel. Conversely, the high-amplitude signals (yellow and red) represent poor transmission or large reflection at the interface. A large reflected signal would be generated at a tube-to-air interface as would be seen above and below the interference fit region or in the presence of a notch with large enough dimensions.

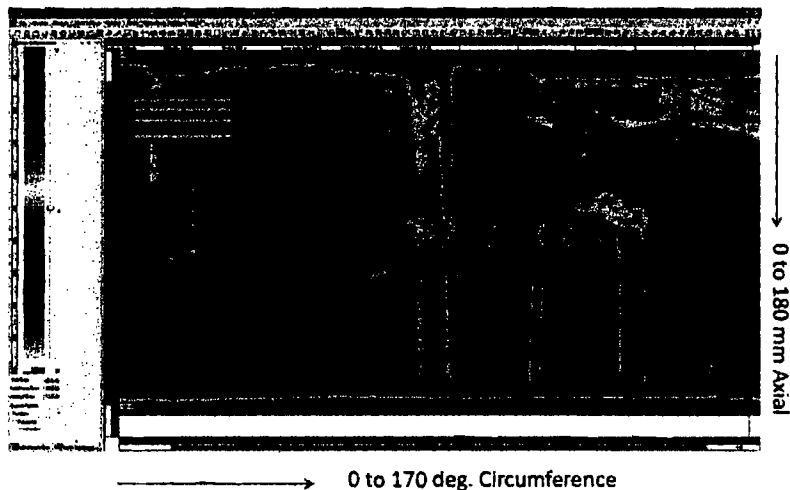
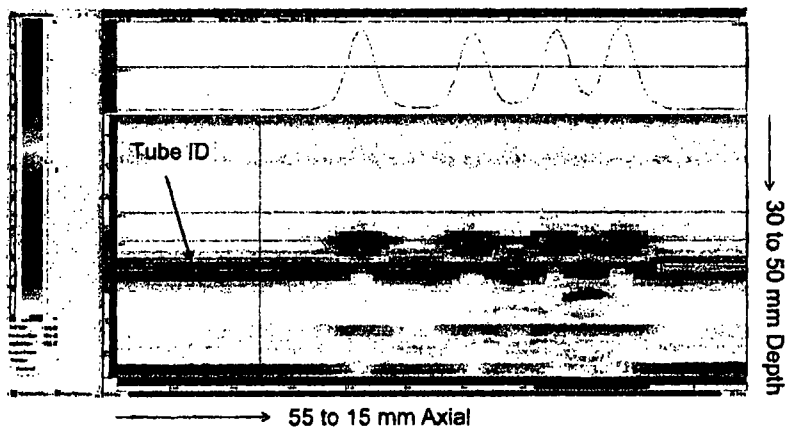


Figure 4.13 Top View, Plan View, or C-scan Ultrasonic Image of the Upper Interference Fit Region Containing Calibration Notches in the Alloy 600 Tube

Comment [PG013]: Please state in the figure caption what is circled

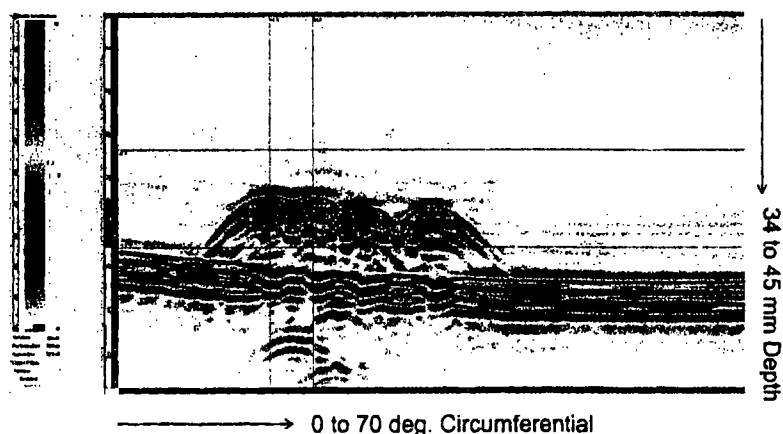
The data analysis software allowed electronic gating of signals in the time or depth dimension as well as positional dimensions Z and theta (axial and circumferential, respectively). The axial resolution notches were first gated or selected for analysis. An enlarged D-scan end view, as depicted in Figure 4.14 was used to measure the center-to-center spacing of the notches. This image was taken as viewed from the left edge of the image in Figure 4.13 and depicts depth into the material (along the sound path) in the vertical axis and the scanner index or nozzle axial

direction in the horizontal axis. From this end view, an "echodynamic" curve or profile was generated along the red horizontal line drawn through the responses from the notches, and was plotted above the image. The measured notch widths, from left to right, as measured at the half-amplitude points, were 2.0, 2.0, 2.5, and 2.5 mm (0.08, 0.08, 0.10, and 0.10 in.), respectively. This represents only 4 or 5 pixels with each pixel equal to 0.5 mm (0.02 in.). The actual notch widths were 2.08, 2.06, 2.16, and 2.11 mm (0.082, 0.081, 0.085, and 0.083 in.), respectively. Notch depths were measured as 2.06, 2.06, 2.03, and 2.03 mm (0.081, 0.081, 0.080, and 0.080 in.), respectively. Actual depths were 2.06, 1.95, 2.00, and 2.00 mm (0.081, 0.077, 0.079, and 0.079 in.), respectively. The data suggested that cracks as small as approximately 1 mm (0.04 in.) in depth could be accurately measured. Also, the notches could be clearly distinguished from each other, providing an indication of lateral probe resolution in the nozzle axial direction. In this set of notches, the actual center-to-center separations were 7.11, 5.08, and 4.06 mm (0.28, 0.20, and 0.16 in.), respectively. The measurements from the ultrasonic data gave separations of 7.0, 5.5, and 4.0 mm (0.28, 0.22, and 0.16 in.), respectively. These highly correlated data values and the data image indicated that an axial resolution of better than 4.0-mm (0.16-in.) was achievable.



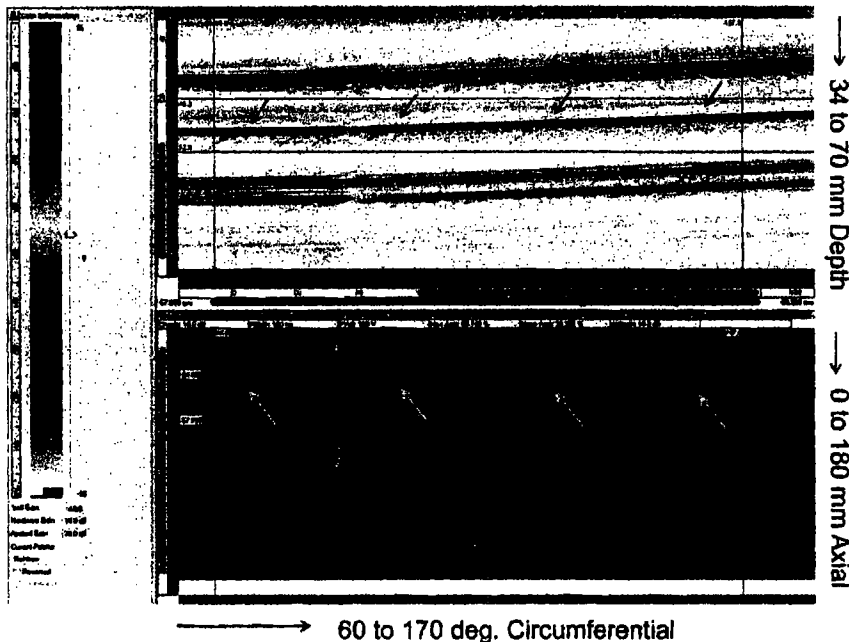
**Figure 4.14 D-scan End View of the Axial Resolution Notches in the Inconel Tube**

The gated circumferential resolution notch set is shown in Figure 4.15. This image was taken as viewed from the bottom edge in Figure 4.13. Notice that the closely spaced two notches on the left are overlapping but they are still resolvable. Peak-to-peak values gave measured notch separations of 4.36, 5.18, and 6.82 mm (0.17, 0.20, and 0.27 in.), respectively. The actual separations were 4.06, 5.08, and 7.11 mm (0.16, 0.20, and 0.28 in.), respectively. This is greater error than was observed for the axial direction. This test demonstrated a circumferential probe resolution of approximately 4.4 mm (0.17 in.).



**Figure 4.15 B-scan Side View of the Circumferential Resolution Notches in the Inconel Tube**

The set of notches in the upper right portion of the scanned image in Figure 4.13 varied in depth but had constant width. These very shallow notches were recognized because their shape and location were known, but they could have been missed based on amplitude response alone. Machining marks on the tube as well as variations in the interference fit produced a non-uniform background response for the fit region, complicating the detection. The center-to-center separations of these notches as ultrasonically measured were 23.84, 24.29, and 23.61 mm (0.939, 0.956, and 0.930 in.), respectively, whereas the actual spacing was 25.4 mm (1.0 in.) between each notch. Flaw depth information was not discernable in the first interference fit echo, but the second echo gave some indication of a flaw tip as noted by the red arrows in the upper part of Figure 4.16. This image represents the B-scan side view of the data while the lower image is a C-scan top view. A higher inspection frequency could have better resolved the small depth variations in these notches. The current second-echo ultrasonic data showed an approximate depth of 0.15 mm (0.006 in.) for all four notches, whereas the actual depths were 0.028, 0.051, 0.76, and 0.13 mm (0.001, 0.002, 0.003, and 0.005 in.), respectively. While these very shallow notches each presented a discontinuity that was ultrasonically detected, their depths were below the system depth or range resolution. For a greater than 50% bandwidth probe, the range resolution is on the order of one wavelength, which in Alloy 600 is approximately 1.1 mm (0.043 in.) at a 5-MHz inspection frequency.

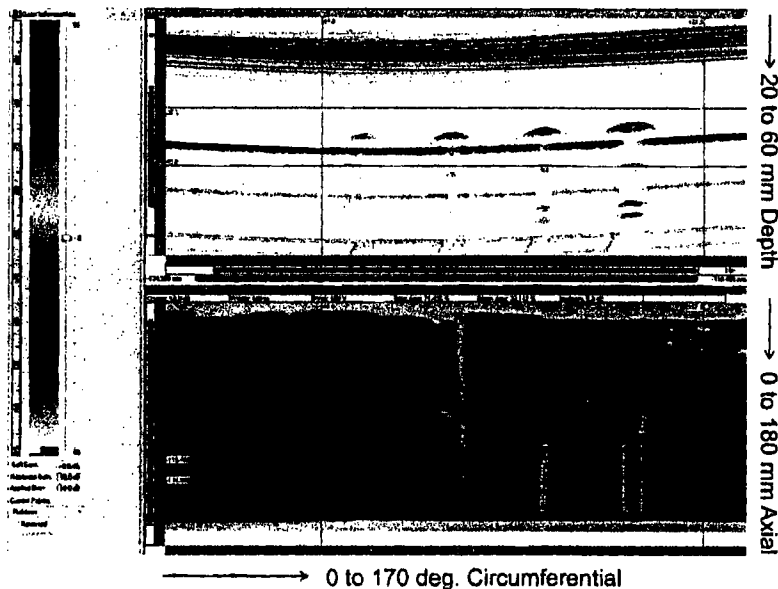


**Figure 4.16 The Second Echo is Gated in the Side View Image in the Top of Figure with the Horizontal Lines. The corresponding Scan in the Side View is displayed in the bottom image. This second echo captures a disturbance in the back-wall echo showing some depth information, noted by the red arrows at top.**

**Comment (PG024):** Show what arrows are pointing to in bottom image.

The final set of notches contained width variations and are shown in Figure 4.17. These flaws were ultrasonically measured with depths of 2.2, 2.5, 2.7, and 2.9 mm (0.09, 0.10, 0.11, and 0.11 in.), respectively, left to right in the image, while the actual depth was 2.53 mm (0.10 in.) for all notches. The measured center-to-center spacings were 23.1, 24.8, and 23.8 mm (0.91, 0.98, and 0.94 in.), respectively, while actual spacings were all 24.5 mm (1.00 in.). Finally, the widths of the flaws were measured in two ways. The first method used the width of the upper part of the flaw response, and the second method used the width of the loss of back-wall signal. The loss of back-wall signal technique was more accurate with measured widths of 3.91, 3.36, 5.00, and 8.82 mm (0.099, 0.126, 0.154, and 0.298 in.), respectively. Actual widths were 0.80, 1.61, 3.24, and 6.42 mm (0.031, 0.063, 0.127, and 0.253 in.), respectively. When measured from the second ultrasonic back-wall echo, the loss of signal measurements gave notch widths of 1.36, 2.73, 3.82, and 7.00 mm (0.054, 0.107, 0.150, and 0.276 in.), which were closer to the actual values. The probe spot size when focused at the interference fit, or 15 mm (0.59 in.) into the Alloy 600, was modeled at 1.2 x 1.2 mm (0.047 x 0.047 in.) at the -6 dB points. Flaw width sizing values are typically oversized by the probe spot size so these measured width values were well within the error expected with this probe.

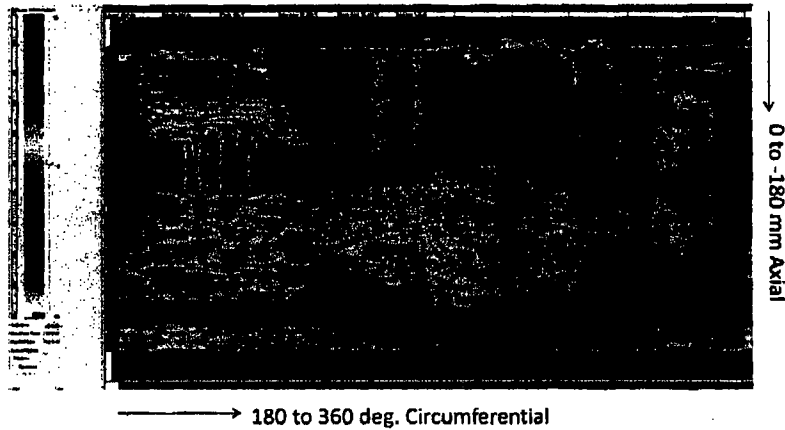
In summary, the system resolution for defects as represented by notches in the Alloy 600 tube was better than 4 mm (0.16 in.) in the axial direction and 4.4 mm (0.17 in.) or greater in the circumferential direction. The depth or range resolution notches, as small as 0.028 mm (0.0011 in.), were beyond the system limits for depth sizing but the notches were detected. Range resolution was estimated at 1 mm (0.039 in.). Notches as narrow as 0.80 mm (0.031 in.) in the circumferential direction were detected and sized but the limits were somewhat dependent on the machining marks and other anomalies in the materials and interference fit that also gave ultrasonic indications.



**Figure 4.17 B-scan Side View on Top and C-scan Plan View on Bottom of the Width Varying Notches in the Inconel Tube**

#### **4.2.2 Carbon Steel Notches**

The 180–360 degree portion of the upper fit region in the CRDM mockup contained notches in the carbon steel block to simulate degradation or wastage of the RPV head material. These notches were on the far side of the interference fit relative to the location of the probe. Because the interference fit was not uniform, the notch responses were not as clear as those for notches in the tube, as evident in Figure 4.18.



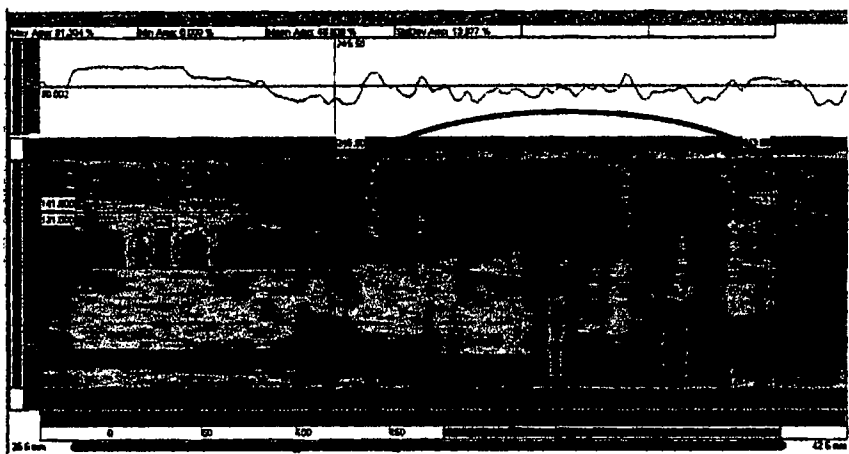
**Figure 4.18** C-scan Plan View of the Notches in the Carbon Steel from the First Ultrasonic Echo

Comment: [PG 18] State what is circled.

The axial resolution notches in the top left of the figure were resolved, but the lower notch was on the edge of a high-amplitude region. The measured center-to-center spacings were 3.90, 4.58, and 6.88 mm (0.15, 0.18, and 0.27 in.), respectively, while actual spacings were 4.06, 5.08, and 7.11 mm (0.16, 0.20, and 0.28 in.), respectively. Axial resolution was therefore approximately 4 mm (0.16 in.) or better.

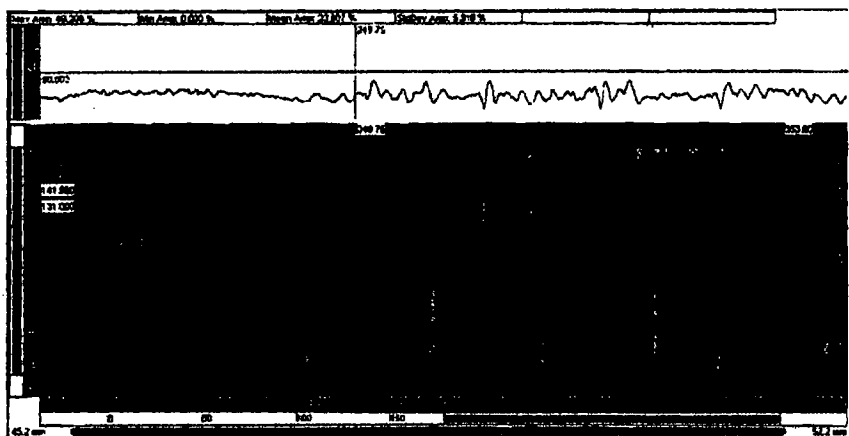
Measurements from the circumferential resolution notch pattern showed center-to-center spacings of 3.82, 5.00, and 7.54 mm (0.15, 0.20, and 0.30 in.), respectively, with actual spacings of 4.06, 5.08, and 7.11 mm (0.16, 0.20, and 0.28 in.). Circumferential resolution was also approximately 4 mm (0.16 in.) or better.

The variable depth notches in the top right of Figure 4.18 were detected but depths could not be measured. First and second echo images are shown in Figures 4.19 and 4.20, respectively. Center-to-center spacing was ultrasonically measured at 23.9, 22.4, and 24.4 mm (0.94, 0.88, and 0.96 in.), respectively, with an actual spacing of 25.4 mm (1.00 in.) for all notches.



**Figure 4.19 C-scan Plan View of the Depth Notches in Carbon Steel, on the Upper Right.**  
 This image was acquired from the first ultrasonic echo.

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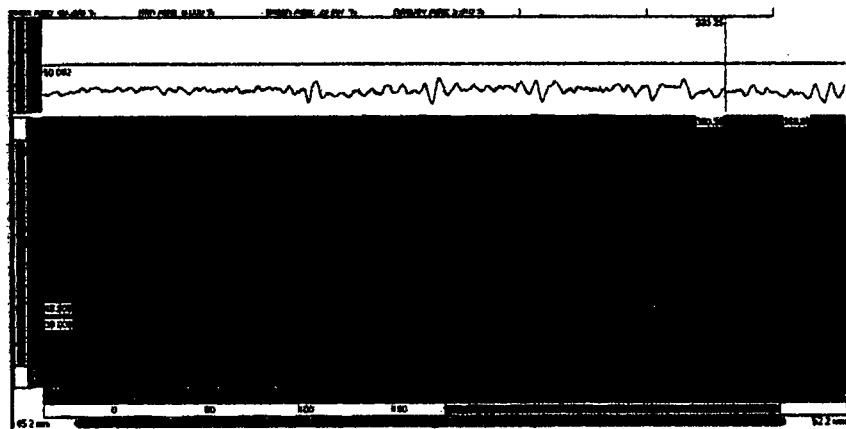
**Figure 4.20 C-scan Plan View of the Depth Notches in Carbon Steel, on the Upper Right.**  
 This image was acquired from the second ultrasonic echo.

Comment [PG017]: Say what arrows are pointing to.

The set of notches with variable widths is shown in Figure 4.21 with the notches marked by red arrows at the bottom of the image. This image represents the second echo. The center-to-center spacing measurements were 25.4, 23.2, and 25.0 mm (1.00, 0.91, and 0.98 in.), respectively, left to right, with actual spacing of 25.4 mm (1.00 in.). Measured notch width



values were 1.82, 2.27, 4.27, and 6.82 mm (0.072, 0.089, 0.168, and 0.268 in.), respectively, with actual values of 0.80, 1.59, 3.18, and 6.39 mm (0.032, 0.062, 0.13, and 0.25 in.), respectively. The notch widths were also measured from the first echo (refer to Figure 4.18, a first ultrasonic echo image) with slightly poorer results.



**Figure 4.21 C-scan Plan View of the Width Notches in Carbon Steel, on the Bottom. This image was acquired from the second ultrasonic echo.**

Comment: (PG 014) Say what arrows are pointing to.

In summary, the system resolution for defects as represented by notches in the carbon steel was better than 4 mm (0.16 in.) in both the axial and circumferential directions. The depth or range resolution notches, as small as 0.028 mm (0.0011 in.), were beyond the system limits for sizing but the notches were detected. In general, the notch depth into the carbon steel is not measureable because the sound beam is reflected at the first tube-to-air interface and does not travel through the air gap to the back of the cavity in the steel. Notches as narrow as 0.80 mm (0.10 in.) in the circumferential direction were detected.

#### 4.2.3 Simulated Boric Acid Deposits

The top view, C-scan images from the mockup with boric acid deposits in the interference fit region are displayed in Figures 4.22 and 4.23. The first image represents the 60 to 240 degree circumferential region and the second image represents the 240 to 60 degree circumferential region, both as captured by the first echo. The boric acid regions were readily detected as lower amplitude response and are outlined with red boxes. Again, notice machining marks and non-uniformity in the interference fit response. The amplitude relevance is discussed in the next section.

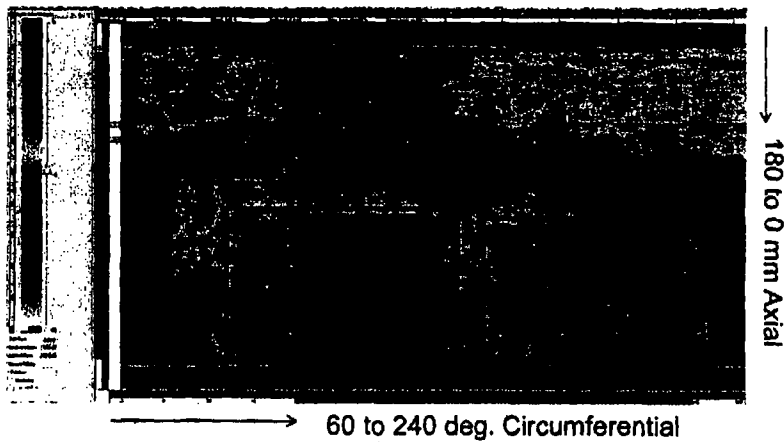


Figure 4.22 C-scan Plan View of the Boric Acid Deposits in the Lower Interference Fit Region. The horizontal axis represents the circumferential range of 60–240 degrees. ~~This image is from the first ultrasonic echo.~~

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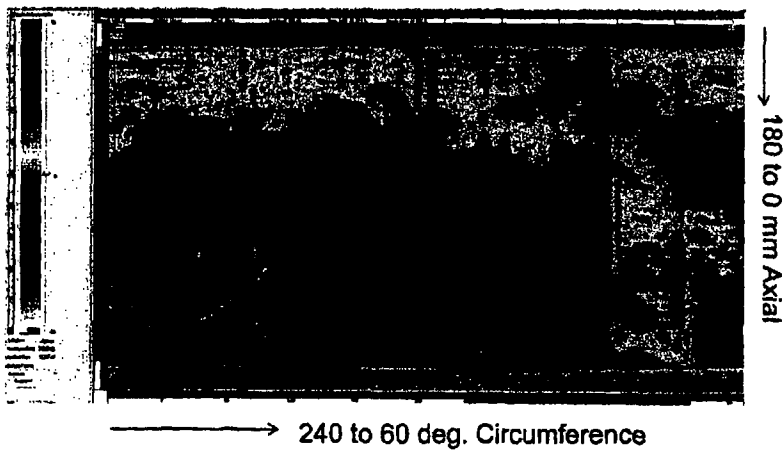
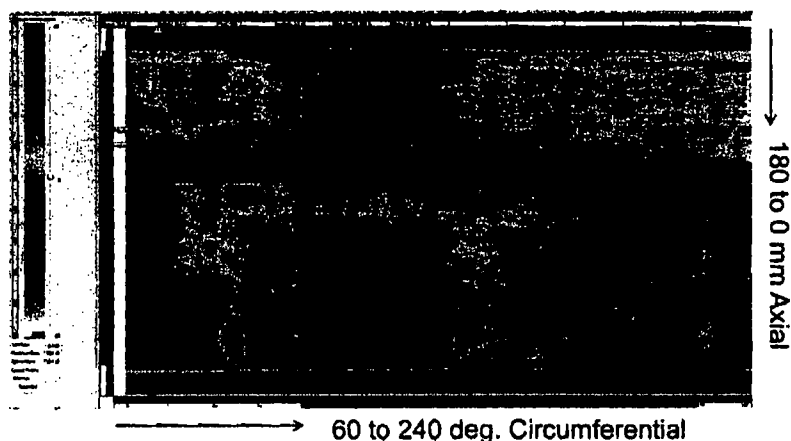


Figure 4.23 C-scan Plan View of the Boric Acid Deposits in the Lower Interference Fit Region. The horizontal axis represents the circumferential range of 240–60 degrees. ~~This image is from the first ultrasonic echo.~~

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#### 4.2.4 Amplitude Response

In addition to characterizing the notch response data for probe spatial and range resolution and flaw detection capability, an analysis of the acoustic response from the different regions was performed based on the reflected signal strength in the lower boric acid mockup section. The three categories represented in the data were the interference fit region where no boric acid was present, the interference fit region where boric acid was present, and the tube region outside of the interference fit area. These areas are represented in Figure 4.24 for the 60 to 240 degree boric acid image. The portion of the image outlined with the red box represents the interference fit region where boric acid deposits were present, the black dashed boxes represent the tube regions above and below the interference fit, and the black dotted boxes represent regions in the interference fit without boric acid deposits. The mean and peak amplitudes were measured in each of these boxed areas from the C-scan image. Similar measurements were also acquired for the 240 to 60 degree boric acid image.

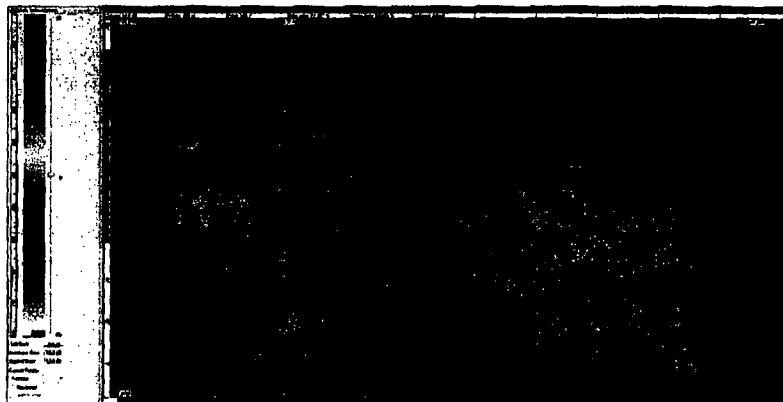


**Figure 4.24 The Interference Fit Region Containing Boric Acid is Subdivided into Three Regions. The red box represents the presence of boric acid in the interference fit region, the black dashed boxes represent the tube region, and the black dotted boxes represent the interference fit region.**

The data images were analyzed with a total image gain of 12 dB. This represented 10 dB of hard gain applied during acquisition and 2 dB of soft gain applied during analysis. The mean responses from the interference fit regions without boric acid deposits were in the range of 40 to 55 percent of full-screen amplitude. This range of values was due to the variability in the fit itself. Some regions of the fit were tight, giving lower reflected amplitude and more transmitted energy. This condition is represented by the green color in the image. Other regions of the fit showed higher reflected energy (not tight), thus less transmitted energy, and this state is represented by the yellow-to-orange colors. Machining marks were evident and also lead to

response variability. The mean responses of the interference fit regions with boric acid deposits were in the range of 24 to 30 percent range of full-screen height (FSH). This shows more energy transmitted (less reflected) through the interference fit region with the presence of boric acid than in the regions without boric acid. The boric acid crystals filled gaps in the fit and efficiently coupled the ultrasonic energy into the carbon steel material. Finally, the mean responses of the tube regions above or below the interference fit were 60 to 75 percent of FSH, demonstrating greater reflectance of energy at the outside tube surface-to-air interface. These measurements established a baseline for the Alloy 600 tube-to-air interface reflectivity level. It also indicated that orange-colored regions in the interference fit represented an air gap. These mockup data images showed that interference fit region where no boric acid is present, the interference fit region where boric acid is present, and the tube region above or below the interference fit area are distinguishable by their mean ultrasonic response.

A final study was conducted as a result of discussions with John P. Lareau of WesDyne International on industry-style CRDM inspections and practices. He reported that the presence of boric acid was simulated with clay on a nozzle mockup specimen and gives an ultrasonic response that is 2 dB lower than the nozzle without clay. To evaluate the PNNL inspection system under a similar scenario, putty was placed on the outside of a blank nozzle specimen. The results are displayed in Figure 4.25 and clearly show that the system detects the putty as displayed by the yellow flower and butterfly characters in the C-scan image. The mean response from the putty region was measured at 64.8 percent of FSH and the clean nozzle response was 72.0 percent. This represents a 0.9 dB drop in amplitude. This smaller response difference is possibly due to the type of clay used in the WesDyne testing as compared to the putty used at PNNL.



**Figure 4.25** Putty on a Nozzle Outer Surface is Detected. The horizontal axis represents 250 mm (9.8 in.) and the vertical axis represents 90 mm (3.5 in.).

Comment [PG021]: Please don't show this figure, it is distracting. Do you have an image with different shapes or can we describe with words only.

## 5 Nozzle 63 Nondestructive Leak Path Assessment

After calibration and testing on the control rod drive mechanism (CRDM) mockup, the phased array ultrasonic equipment was transported to the Radiochemical Processing Laboratory (RPL/33) for the examination of Nozzle 63. The results of the examination are presented in this section.

### 5.1 Scanner Setup

A CRDM nozzle was used to assess the functionality of the probe, scanner, and electronics after they were moved to RPL/33 where Nozzle 63 was housed. A simple scan on the nozzle was performed in the ultrasonic laboratory where the mockup was tested and then in RPL/33 after transporting and reassembling all of the equipment. Data images before and after transport are displayed in Figure 5.1. These images represent C-scan top views with 150 degrees on the horizontal axis and 50 mm (1.97 in.) on the vertical axis. The maximum and mean amplitude responses were measured in a region approximated by the box in each top view. The maximum responses at 77.4 and 79.4 full scale were within 0.23 dB of each other while the mean responses at 54.5 and 55.0 full scale differed by 0.079 dB. Typically calibration data that fall within  $\pm 2$  dB of each other are acceptable so the equipment functionality was validated.



**Figure 5.1** Calibration Data on the Blank Nozzle Piece Before (left) and After (right) Transport to RPL/33. The horizontal axis represents 150 degrees of circumference and the vertical axis represents 50 mm (1.97 in.) in the axial direction in each image.

Comment [PG022]: Don't need all the description and figure. Just can say that the scanner functionality was validated after moving.

After equipment verification, the scanner was placed on Nozzle 63 in the glove bag as depicted in Figure 5.2 and diagrammed in Figure 5.3. The wetted side of the nozzle assembly was facing down. A plug was inserted in the wetted side of the nozzle several months earlier. At that time the nozzle was removed from storage and the length of nozzle extending above the reactor pressure vessel (RPV) head material (dry side) was shortened to give easier access to the interference fit region and for easier maneuvering of the nozzle/head assembly. Water was added several days prior to mounting the scanner on the nozzle. With the scanner in place, the glove bag was examined for any leakage points in the bag walls and glove ports. No leaks were

found and the glove bag was sealed. Any materials entering the glove bag from this point forward were passed through an access port in the bag wall.

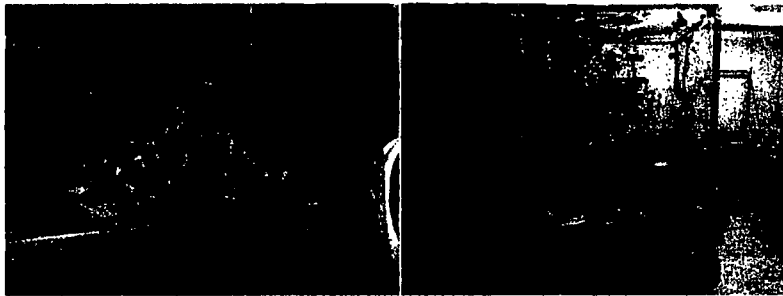


Figure 5.2 Dry Side of Nozzle 63 Prior to Scanner Mounting (left); Scanner Mounted on the Nozzle in the Glove Bag (right)

Comment [PG023]: Same as Figure 3.9

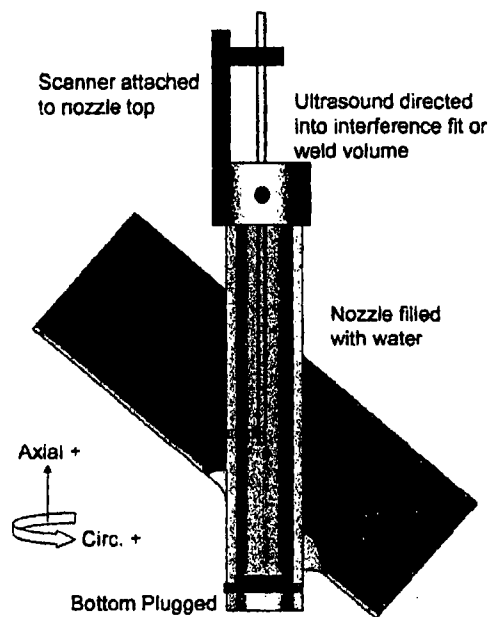


Figure 5.3 Schematic of Nozzle Assembly and Ultrasonic Evaluation of the Interference Fit

Comment [PG024]: You have already used this image (Fig. 3.8). Do not repeat it. Reference previous figure if necessary.

## 5.2 Data Acquisition

Before the start of a scan, the probe was manually lowered to the bottom of the interference fit region and the data were collected while indexing the probe upwards. Two data channels were recorded during acquisition—one with a focus at the front surface (1 mm or 0.04 in.) and the other focused at the interference fit interface (15 mm or 0.59 in.). The front surface reflection represented the interface between the water inside the tube and the Alloy 600 tube inner diameter (ID), and provided an indication of the surface condition of the tube. This data would reveal bubbles, pitting, and other surface anomalies, if present. The second data channel recorded the reflection from the interface between outer diameter (OD) of the Alloy 600 tube and the carbon steel RPV head material, and represented the interference fit region. The first coarse scan data showed the need to laterally adjust the scanner to more accurately center the phased-array probe in the nozzle. Results from data acquired towards the top of the tube before and after centering the scanner are displayed in Figure 5.4. The horizontal axes in each image represent a circumferential distance from -90 to +90 degrees. The vertical axes represent approximately 20 mm (0.79 in.) of travel in depth or distance from the probe. Before centering the scanner, the front surface signal travel or difference from high to low point was measured at 10 mm (0.39 in.) on the left image. After centering, the signal travel was only 1 mm (0.04 in.) with the data displayed on the right of Figure 5.4. In addition to showing centeredness of the probe, the coarse scans also verified that the areas of interest were captured in the data file.



Figure 5.4 Alloy 600 Tube ID Response Before (left) and After (right) Centering the Scanner on the Nozzle. The horizontal axis represents approximately 180 degree and the vertical axis 20 mm (0.79 in.).

Once the areas of interest were bounded, the scanner step sizes were reduced for more detailed imaging. A resolution of 0.5 degree in the circumferential (scan) direction and 0.5 mm (0.02 in.) in the axial (index) direction were selected. The ZETEC UltraVision software limits the data files to 1 gigabyte in size. Working within this constraint, data in a file were collected over a range of approximately 180 degrees circumferentially and 380 mm (14.96 in.) axially. A previous examination of Nozzle 63 by industry indicated a leakage path at the low point or downhill side of the nozzle, which is the 180-degree location on the coordinate system established for this investigation. Therefore, data were acquired over an approximate -90 to +90 degree region and a 90 to 270 degree region to capture the possible leakage path in the center of an image. The actual circumferential scan regions were slightly larger than 180 degrees to provide some overlap in the data.

The first data covering the 90 to 270 degree area are shown in Figure 5.5. The front surface echo is displayed on the top and the interference fit echo on the bottom. These C-scan top view images show approximately 180 degrees across the horizontal axis and 360 mm (14.17 in.) on the vertical axis. The color bar on the left shows low-amplitude signals in blue/white, which represent good transmission or poor reflectance. High-amplitude signals in orange/red conversely represent poor transmission and good reflectance. The weld region is shown in the white-to-light-blue color at the bottom of the interference fit image. The interference fit or shrink-fit zone is located between the counter bore regions as was shown in Figure 1.1. The data above the interference fit (dry-side annulus region) represent a tube-to-air interface and should provide a strong and uniform reflection. Such a strong reflection was only evident in the orange-colored regions in the right side of the images. The tube OD-to-air interface is a good reflector, so a uniform orange color would be expected across the top of the image. Therefore, the lack of uniformity across the upper portion of the image (tube OD) was unexpected. The lack of uniformity across the entire front surface echo (upper image in the figure) was also unexpected.

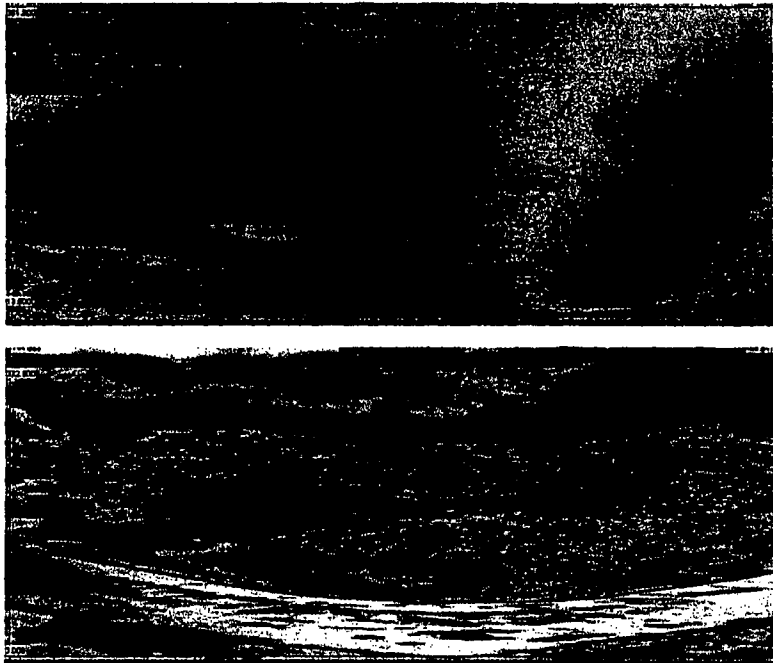


**Figure 5.5** First PA Ultrasonic Data from Nozzle 63. The front surface or nozzle ID echo is on the top and the interference fit echo on the bottom. The horizontal axis represents the 90 to 270 degree area and the vertical axis represents 360 mm (14.17 in.). The color scale is represented on the far left.

Comment [PG027]: Remove figure



After the first scanning attempt, the probe was lifted above the water line and found to be dirty. The probe face was carefully wiped with a dry cloth. It was also suspected that bubbles on the ID tube surface could be partly responsible for the degraded image. Since the presence of bubbles in the tube could not easily be visually confirmed, a metal rod was swiped around the ID surface in an attempt to dislodge and remove any bubbles. Thereafter, the next set of data, given in Figure 5.6, were acquired and showed an improvement in the uniformity of the OD tube echo above the interference fit, as seen in the lower image. A possible leakage path was also detected starting at the weld near the 180 degree or low position and extending upwards and to the right. Bubbles on the ID tube surface were still suspected in the front surface data shown in the top image. These were confirmed in data acquired from the front surface echo over a small region. The data are displayed in Figure 5.7 with multiple bubbles noted and the lack of uniformity in amplitude response still evident.



**Figure 5.6** PA Ultrasonic Data from Nozzle 63 Acquired After Cleaning the Probe Face. The front surface or nozzle ID echo is on the top and the interference fit echo on the bottom. The horizontal axis represents the 86 to 274 degree area and the vertical axis represents 360 mm (14.17 in.).

Comment [PG025]: Remove figure



**Figure 5.7** Bubbles are Detected on the ID of the Nozzle, some of which are indicated by Arrows. The vertical axis represents 25 mm (0.98 in) and the horizontal axis represents 180 degrees.

Comment [PG022]: Remove figure.

After this second scan attempt, it was decided to brush the tube ID surface to remove bubbles but to do it carefully to minimize or avoid introducing new bubbles. The top photo in Figure 5.8 shows the brush being inserted past the probe and into the nozzle. The bottom photo is another view of the manual brushing process. The data acquired after brushing are shown in Figure 5.9 with the front surface echo on top and the interference fit data on the bottom. Several days later the tube ID was brushed again and data acquired to show repeatability of the data and to attempt to remove any remaining bubbles. These results are depicted in Figure 5.10. As expected, the interference fit image (bottom image) showed nearly uniform amplitude response from the tube OD above the interference fit (orange region at top of image). More bubbles were removed during the second brushing as evidenced by the smoother front surface image on the top in Figure 5.10 as compared to Figure 5.9.

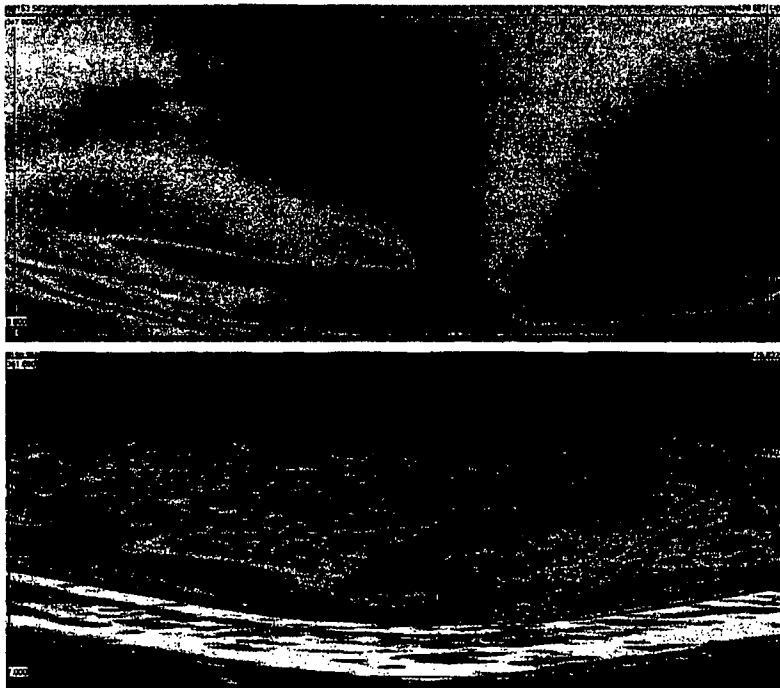


Figure 5.8 Brush Used to Remove Surface Bubbles (top); Pushing in Progress (bottom)

Comment [PG030]: Remove figure



**Figure 5.9** PA Ultrasonic Data from Nozzle 63 Acquired After First Brushing of the Nozzle ID. The front surface or nozzle ID echo is on the top and the interference fit echo on the bottom. The horizontal axis represents the 86 to 274 degree area and the vertical axis represents 360 mm (14.17 in.).



**Figure 5.10 PA Ultrasonic Data from Nozzle 63 Acquired After Second Brushing of the Nozzle ID. The front surface of nozzle ID echoes on the top and the interference fit echo on the bottom. The horizontal axis represents the 66 to 274 degree area and the vertical axis represents 360mm (14.17in).**

Commentary G0813: Remove figure

Data acquired after the first brushing from the two scans were pieced together to form the composite image of the interference fit region in Figure 5.11. This image displays a full 360-degree representation of the weld and interference fit region with -90 degrees at the left and 270 degrees at the right. The suspected leakage path at the low point, near 180 degrees, is marked with arrows. Also observed from the weld region response are suspected inclusions or fabrication flaws. Several of these indications are circled in red in the figure.



Figure 5.11 PA Ultrasonic Data from the interference fit in Nozzle 51 Acquired After the First Brushing of the Nozzle ID. The horizontal axis represents the full 360-degree area and the vertical axis represents 360 mm (14.17 in.).

Comment [PG032]: This is the important figure. Everything in this chapter up to this can be described by a few paragraphs of text at most.

Comment [PG033]: Say that the arrows indicate the main leakage path. Don't circle the indications. Leave those for the section on the weld analysis. Maybe identify 90 on left and 270 on right for reference.

### 5.3 Amplitude Analysis

An analysis based on amplitude responses was conducted on the data images. The first such analysis was conducted on the 90 to 270 degree data acquired after the first brushing. The image was segregated into regions as depicted in Figure 5.12. The peak and mean amplitude responses were measured in each boxed region. Regions 1 through 6 are suspected leakage path zones. Regions 7 through 10 represent the interference fit and lower counter bore areas. Regions 11 through 15 represent the tube above the interference fit, and regions 16 through 18 represent the interference fit with suspected boron acid present. The same procedure was used on the 0 to 90 degree data with the boxed regions shown in Figure 5.13. Finally, the mean amplitudes within each boxed region were plotted against the box numbers with results in Figure 5.14. The suspected leakage path and tube responses all were in the range of 60 percent of full screen height and greater. At the other extreme, the regions with suspected boron acid deposits had mean amplitudes 25 percent and below. Finally, the interference fit/counter bore region mean amplitudes were in the 43 to 58 percent range. A proposed segregation of the regions is denoted by the yellow, green, and blue colored zones in the plot. The data suggest that 30 percent mean amplitude or less indicates the presence of boric acid in the interference fit while greater than 60 percent represents an air gap and possible leakage path if connected all the way through (top to bottom) the interference fit. Note that the same analysis

Comment [PG034]: Make clear that the justification for suggesting that Region 1-6 is leakage path; Region 7-10 is interference fit, etc., is from the mockup results. Say that these suggestions need to be confirmed by destructive analyses.

was performed on the data acquired after the second brushing, to remove bubbles, and produced similar results. In a direct comparison of data values, the difference was 2 percent or less in mean response, indicating the data are similar in response amplitudes from the segregated zones.



**Figure 5.12 Interference Fit Data Image After Final Brushing** The horizontal axis represents approximately 90 to 270 degrees. The vertical axis represents 360 mm (14.17 in.).

Comment (PG035): Say that the bones correspond to regions for the amplitude analysis.



Figure 5.13 [PG036] [See comment above] The horizontal axis represents approximately -90 to +90 degrees. The vertical axis represents 360 mm (14.17 in.).

Comment [PG036]: See comment above.

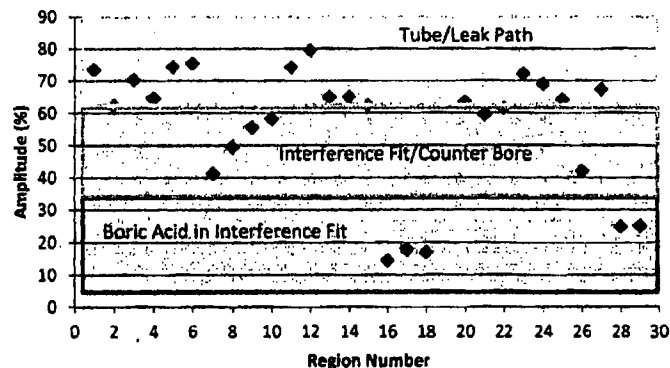


Figure 5.14 Mean Amplitude Responses from the Regions Indicated in Figures 5.12 and 5.13

Comment [PG037]: This plot needs to be changed to better display the data. At a glance it looks like a random scatter of points because the region number has no correspondence to the amplitude. For example, it might display better if Regions 1-5 were selected as low amplitude locations, Regions 6-12 were selected as intermediate amplitude, etc.

In summary, the mean amplitude responses from the different regions in the data image were measured. Based on this analysis, the regions are separable and compare favorably to the responses measured previously on the calibration mockup specimen. A comparison of the responses is presented in Table 5.1. Note that the Nozzle 63 data were acquired with 1 dB more gain (13 dB as opposed to 12 dB) than the calibration mockup data and this difference was accounted for in the analysis.

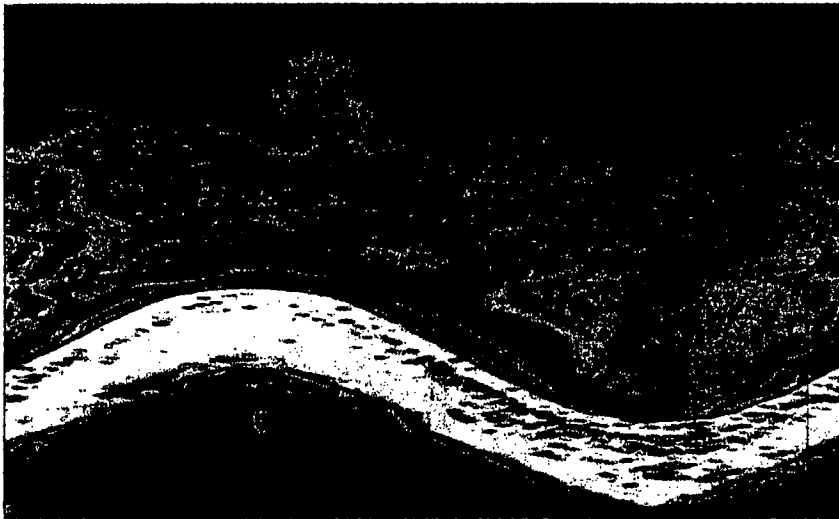


**Table 5.1 Mean Amplitude Responses (%)**

Region	Calibration Mockup	Nozzle 63
Tube/Leak Path	60-75	60-79
Interference Fit/Counter Bore	40-55	41-58
Interference Fit - with Boric Acid	24-30	14-25

In a color-coded qualitative sense, the C-scan image analysis is also divided into three categories. The orange color implies that an air gap exists in the interference fit or counter bore response and presents a large reflected signal. Orange also represents the tube response outside of the interference fit region. The interference fit and counter bore regions with some contact between the tube OD and the low alloy steel are represented by the green-to-yellow colors and the interference fit region with greater contact is represented by the blue-to-white colors. This greater contact is assumed to be due to the presence of boric acid. Destructive analyses are needed to confirm these results.

A composite view of the data acquired after the second brushing is presented in Figure 5.15. This is the best representation of the interference fit region and from this data a cut was selected for destructive evaluation.



**Figure 5.15 Nozzle 63 Interference Fit Data After Second Brushing. The horizontal axis represents -95 to 275 degrees. The vertical axis represents 360 mm (14.27 in.).**

Based on the amplitude analyses conducted, the data were also plotted with a tri-level color bar to represent the three categories previously discussed. The tri-level color bar implementation is shown in Figure 5.16. White represents the less than 30% amplitude range and indicates good transmission such as in the weld or possible boric acid in the interference fit region. Light blue represents the 30 to 60% amplitude range and indicates the interference fit and counter bore regions. Dark blue represents the above 60% amplitude range and indicates poor transmission such as in the tube above the interference fit or an air gap in the interference fit and counter bore regions. A leakage path exists if a gap in the interference fit region extends fully through the interference fit connecting the weld and annulus region immediately above the weld to the dry side of the tube. From this image as well as the rainbow color-coded images, one clear leakage path is visible. The leakage path starts in the vicinity of 180 degrees circumferentially, or the low point of the nozzle, and meanders upwards and toward the right in the image. Other leakage paths are also evident but may not connect all the way through to the dry side of the assembly. Destructive analyses are needed to confirm the cause of these regions of differing reflectivity.



Figure 5.16 A Tri-Color Representation of the Interference Fit Data

Comment [PG028]: You may state what the 3 colors represent.

#### 5.4 Industry Standard Nondestructive Evaluations

Standard ultrasonic evaluation techniques used by in-service inspection (ISI) vendors include time-of-flight diffraction (TOFD) for detecting cracks in both the circumferential and axial orientation and zero-degree pulse echo for an interference fit examination. Blade probes (low profile) and solid-probe head configurations are deployed depending on the access conditions of the CRDM assembly (EPRI 2005; IAEA 2007, and discussions with JP Lareau, WesDyne International). An examination conducted by ISI vendor, WesDyne International (data supplied by JP Lareau), discovered a probable leak path in Nozzle 63. The data acquired with industry-standard 5.0- and 2.25-MHz probes are shown in Figures 5.17 and 5.18, respectively. The 2.25-MHz image in Figure 5.18 has a lower resolution than the 5.0-MHz image in Figure 5.17 as expected, but both data sets detect the leak path observed at the low point (industry's zero-degree position) of the interference fit region.

The Figure 5.17 image can be compared to the PNNL's results in Figure 5.15. Both data sets were acquired with probes having nominal center frequencies of 5 MHz and they show the main leak path as a high-amplitude signal. In the WesDyne data, this is represented by the magenta color. Both data images capture other partial leak paths and show similar areas of high and low reflectivity. The PNNL data however possess better data registration in the odd and even scan lines as well as improved resolution and focusing. These images demonstrate that PNNL was successful in achieving a better evaluation of the interference fit as compared to a qualified industry procedure.

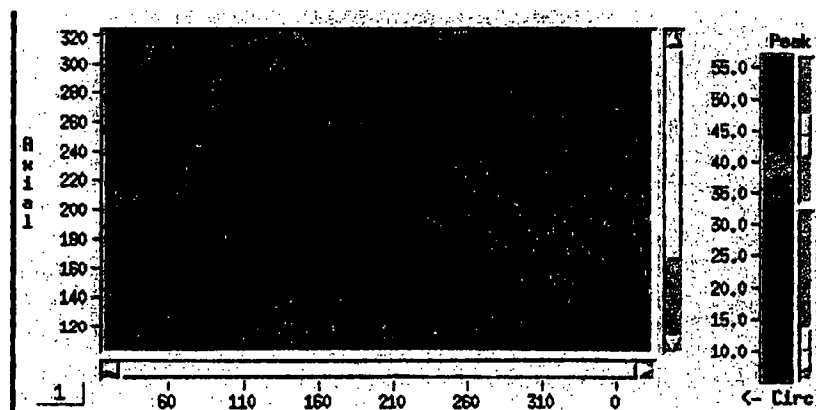


Figure 5.17 Ultrasonic Data from Nozzle 63 as Obtained by WesDyne International. The image was acquired with a 5-MHz probe. The horizontal axis represents the nozzle circumference in units of degrees. The vertical axis represents the nozzle axis in units of millimeters.

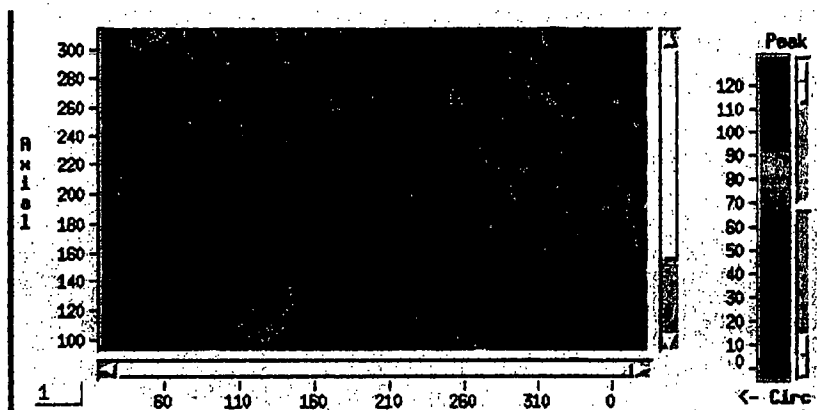


Figure 5.18 Ultrasonic Data from Nozzle 63 as Obtained by WesDyne International. The image was acquired with a 2.25-MHz probe. The horizontal axis represents the nozzle circumference in units of degrees. The vertical axis represents the nozzle axis in units of millimeters.

Additionally, an eddy current inspection conducted by WesDyne International detected two axial flaws. These were found at the locations shown in Figure 5.19 (data supplied by JP Lereau). The specific circumferential locations were noted at 172 and 360 degrees with 0 or 360 degrees representing the downhill position. The axial length for flaw 1, below the weld, was 25.4 mm (1.0 in.) and for flaw 2, above the weld and in the main leak path, was 19.3 mm (0.76 in.). These cracks were ID surface connected and reported as shallow flaws.

While PNNL did not specifically perform an evaluation for axial cracking in the Alloy 600 tube, the two axial cracks noted by industry were detected. The zero-degree PNNL inspection was not optimized for crack detection as an axial crack presented only a knife-edge profile to the ultrasonic beam and did not reflect much energy. Nevertheless, the cracks were visible in the interference fit response, and on further analysis also marginally detected in the water-to-Alloy 600 tube reflection (ID surface of the tube). Figure 5.20 shows the uphill images for the ID tube and interference fit responses. Similarly Figure 5.21 shows the responses for the downhill images. Both flaws appear to be ID surface connected as they were detected in the data acquired at the ID surface of the Alloy 600 tube. These two flaws are also evident in the image in Figure 5.15. The ultrasonic data did not provide any depth-sizing information.

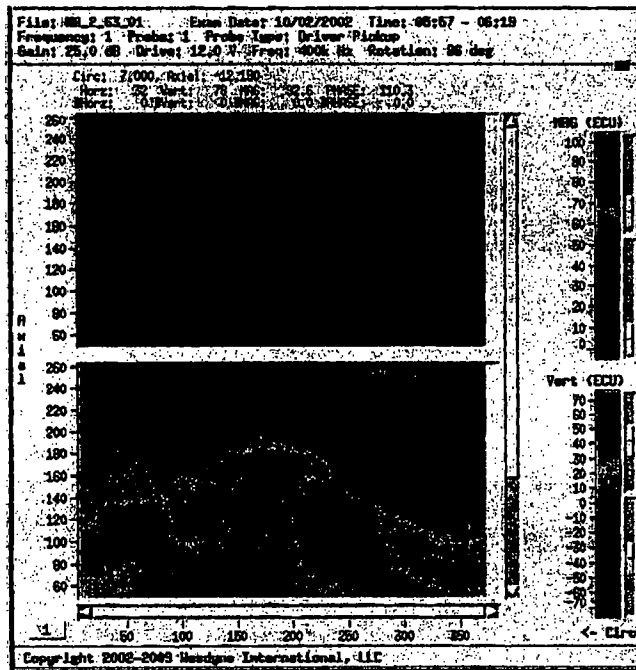


Figure 5.19 Eddy Current Data (Wesdyn International) Showing Two Axial Flaws. The horizontal axis represents the nozzle circumference in degrees. The vertical axis represents the nozzle axis in millimeters.

Comment: (P-6042) What is the difference between the top and bottom image?



Figure 5.20 Uphill Nozzle 10 Response on the Left and Interference Fit Response on the Right with the Axial Flaw Indication Circled. The horizontal axes represent 189 degrees and the vertical axes represent 360 mm (14.2 in.).



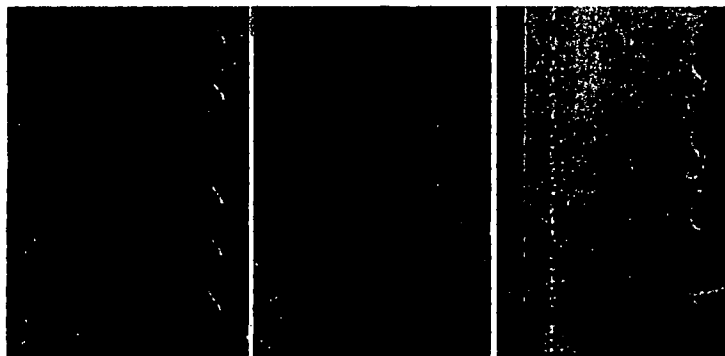
**Figure 5.21** Downstream Nozzle Flow Response on the Left and Interference Flow Response on the Right with the Axial Flow Indication Overlay. The horizontal axes represent 180 degrees and the vertical axes represent 165 mm (6.1 in).

**Comment [P8043]:** All discussion of eddy current flow analysis should be removed.

## 6 Destructive Validation of Nozzle 63

Confirmatory destructive testing was necessary on Nozzle 63 to validate the ultrasonic characterizations of the leak path(s) and other areas of interest as described in Section 5. The destructive testing activity was conducted by Babcock and Wilcox Technical Services Group (B&W) located at the Lynchburg, Virginia, facility. This activity required the dismantling of the interference fit region with full separation of the Alloy 600 tube from the reactor vessel head (RVH) material to reveal true-state information with regard to the leak path(s), boric acid deposit regions, and wastage regions. Pacific Northwest National Laboratory (PNNL) personnel were on site during the critical sectioning activities to identify proper cutting locations. Additionally, the J-groove weld region was preserved and returned to PNNL for storage in anticipation of future work.

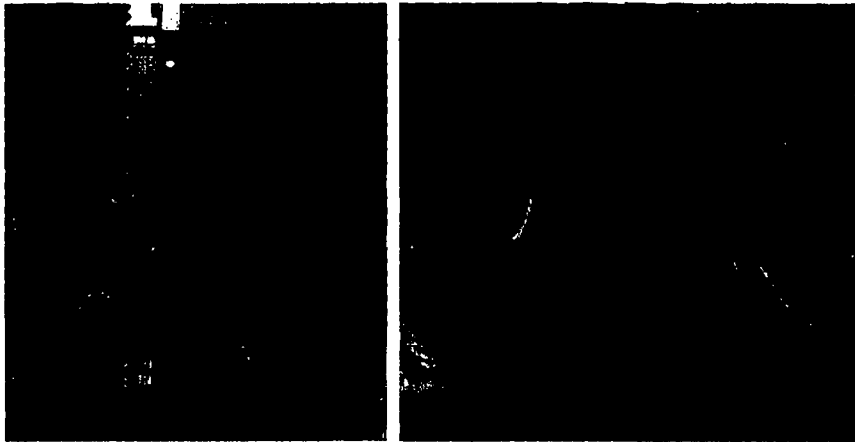
SAW used an industrial 19-ft Cobra Abundant and Genie saws with 203- $\phi$ PHD with 16-tooth Strike and shaper blades. The blade width for all cutting was 203 mm (8 in). The destructive activity trials saw was equipped with a 55-hp motor and a 12.5-hp generator. The saw was capable of cutting pieces measuring 60.3 cm (24 in) wide by 152.4 cm (60 in) in the vertical position and 60.3 cm (24 in) wide by 55.9 cm (22 in) high in the horizontal position. The 16-tooth blades were acquired from Scary and Sharp Toolage in Idaho. Two coarse tooth (2-3 tooth per inch) and three fine tooth (4-5 tooth per inch) blades with positive rake, variable pitch, and variable tooth were used. Additionally, one carbide grit abrasive blade was also used. In general, coarse tooth blades were used for thicker section cutting (20.3 cm (8 in) and larger) and the fine tooth blades were used for thinner cutting (material under 20.3 cm (8 in) in thickness). The carbide grit abrasive blade was used when the bi-metallic blades were ineffective. Figure 6.4 shows the three blade types used. All cuts in this activity were conducted without lubrication or coolant to minimize disturbance to the interference-fit region.

[illegible]

**Figure 6.1** Three Blade Types were Utilized to Section the RPM Head and CRDM Nozzle. From left, fine tooth blade, coarse tooth blade, and carbide grit blade.

**Comment [PGD45]:** Remove this figure.

The initial size reduction cuts were performed on the Nozzle 63 specimen using one of the coarse toothed blades prior to the arrival of PNNL staff. Non-essential material was removed to reduce weight and to facilitate proper blade placement on the specimen during critical cuts. Figure 6.2 shows images from the size reduction activity.

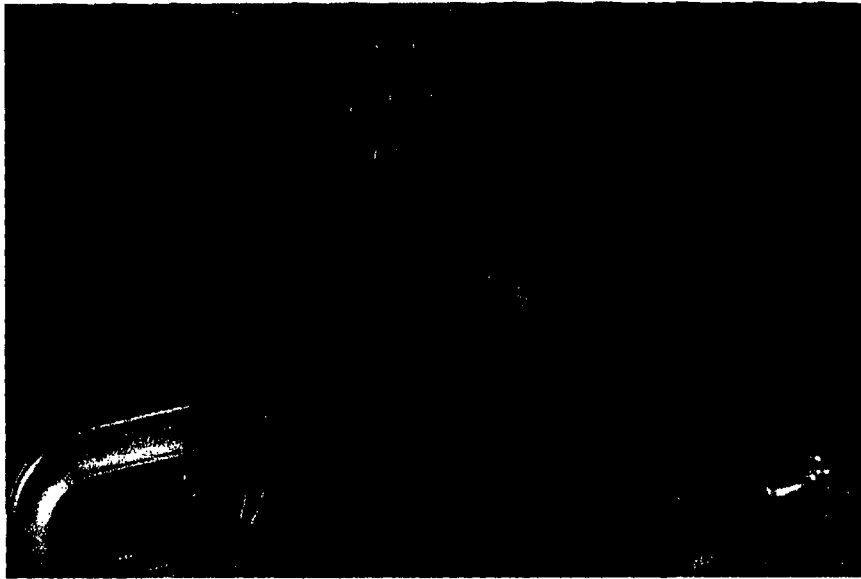


**Figure 6.2: Size Reduction/Cutting Activity**

Comment [PG046]: Can keep this figure.

After size reduction, the nozzle assembly was prepared for the dissection cut that separated the high and low sides of the assembly. The cut line was selected to start at approximately the 95-degree mark (Figure 6.3), and follow through to the 275-degree mark. The line placement was based on the ultrasonic data and chosen to preserve the primary leak path previously identified in the ultrasonic images.





**Figure 6.3 Start of the Dissection Cut**

**Comment (PGO47):** Keep this figure.

Dissection cutting began with the coarse-toothed blade. The cut progressed for approximately 20 minutes until an unidentified 'hard spot' was reached at the outer edge of the Alloy 600 nozzle region and stopped the cutting progression. A slower feed rate with a faster blade speed was attempted, but did not traverse the hard spot. The cause of the hard spot was not fully investigated, but a likely cause was from a cold-worked region of material within the heat-affected zone of the J groove weld adjacent to the nozzle outer diameter (OD). The coarse-cut blade was exchanged with a fine-toothed cutting blade and the cut was attempted again without success. Finally, the carbide blade was employed to abrasively grind through the hard spot. This blade required a greatly reduced feed rate, thus lengthened the cutting time. Further, the ~~kerf~~ of the carbide blade was thicker than the cutting blades, requiring the cut to be restarted at the initial cut path. The carbide grit abrasive blade is shown in Figure 6.4. The cut through this hard spot required approximately 2 hours to complete.

**Comment (PGO48):** What is the term?



Figure 6.4 Abrasive Carbide Blade Progressing Through the Hard Spot

Comment (PG049): Remove this figure.

After cutting through the first side of the nozzle, the carbide blade was exchanged with the fine-toothed cutting blade and the dissection cutting continued. Another hard spot was incurred in the J-groove weld region. Again, the carbide blade was used to cut through the hard spot with a slow feed rate. Finally, the fine-toothed blade was re-engaged and the dissection cut completed. From the exposed surfaces, the triple point was identified along with the weld and butter regions as shown in Figure 6.5.

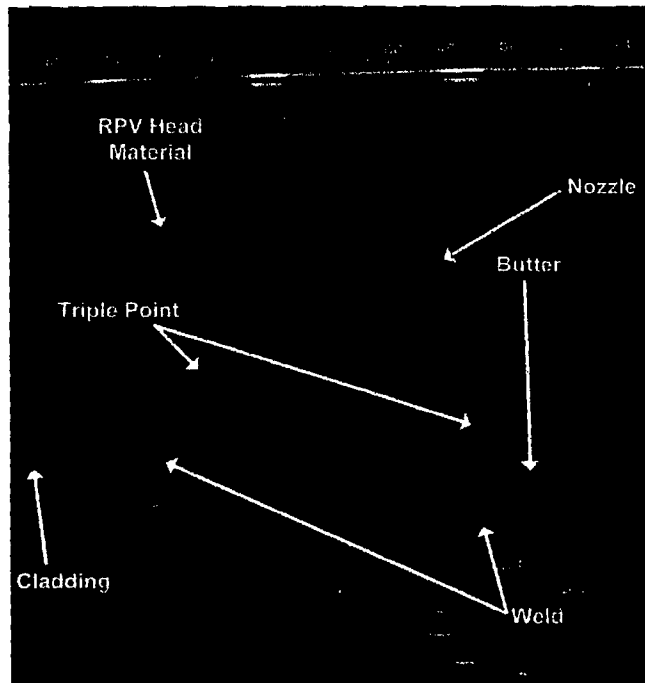


Figure 6.6 Nozzle Assembly Cut Direction Plan

Copyright 2000. Keep this figure  
 removed from all reports except RPV head and weld.  
 Draw a line on this figure to show where the  
 weld removal cut was made.

The cut to remove the J-groove weld was made 6.35 mm (0.25 in.) above the butter/triple point region in the reactor pressure vessel (RPV) head as seen in Figure 6.6. The high or uphill side half-portion was selected for the first cutting. As previously stated, the 'high' side has several potential leak paths whereas the 'low' or downhill side had the primary leak path as identified in the ultrasonic data. The specimen was secured and the band saw tilted to an approximate 43-degree angle to match the angle between the nozzle and head as shown in Figure 6.7. Cutting at this angle maximized the annulus region that was exposed while keeping the weld and butter regions intact for future evaluation. As the cut was designed to pass only through the low-alloy RVH material, the fine toothed cutting blade was selected for use. During the J-groove weld removal cut, another hard spot was encountered near the outside of the nozzle. Attempts were made to continue cutting with the fine-toothed blade until abrasive wear on one side of the blade resulted in the cut veering away from the desired cut line. Blades were exchanged and the carbide blade was used to cut through the hard spot and also to finish the cut. Before the cut broke through the inside of the tube, a vacuum equipped with a high-efficiency particulate air (HEPA) filter was added to collect and capture any radioactive oxide particles that were discharged from the cut as pictured in Figure 6.8.

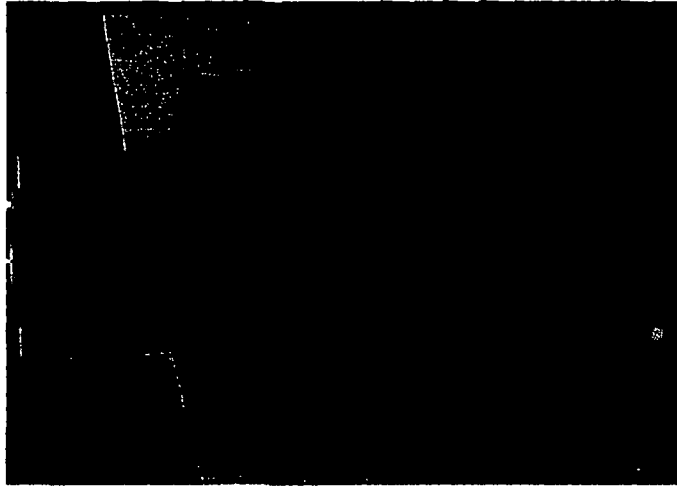


Figure 6.6 J-groove Weld Removal Cut Line Placement

Comment [PG051]: Remove this figure.



Figure 6.7 J-groove Weld Cut on the High Side

Comment [PG052]: Remove this figure.

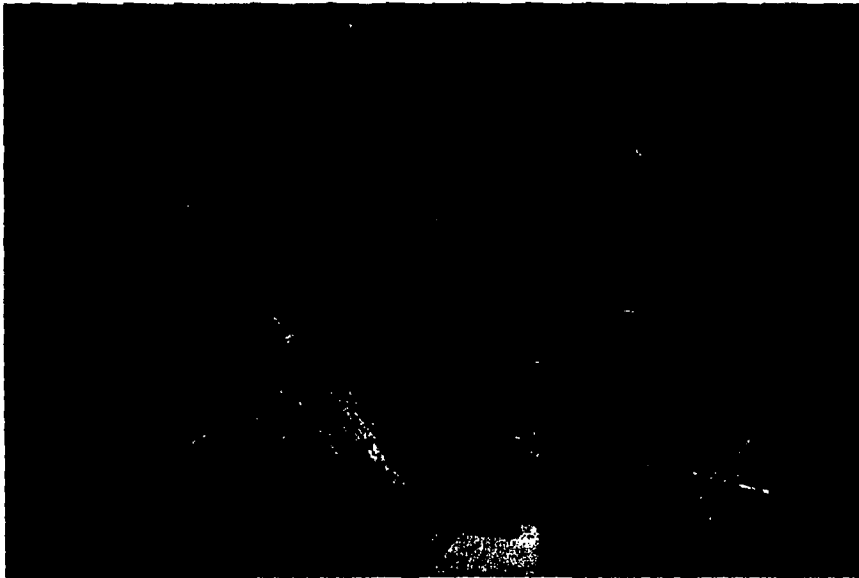
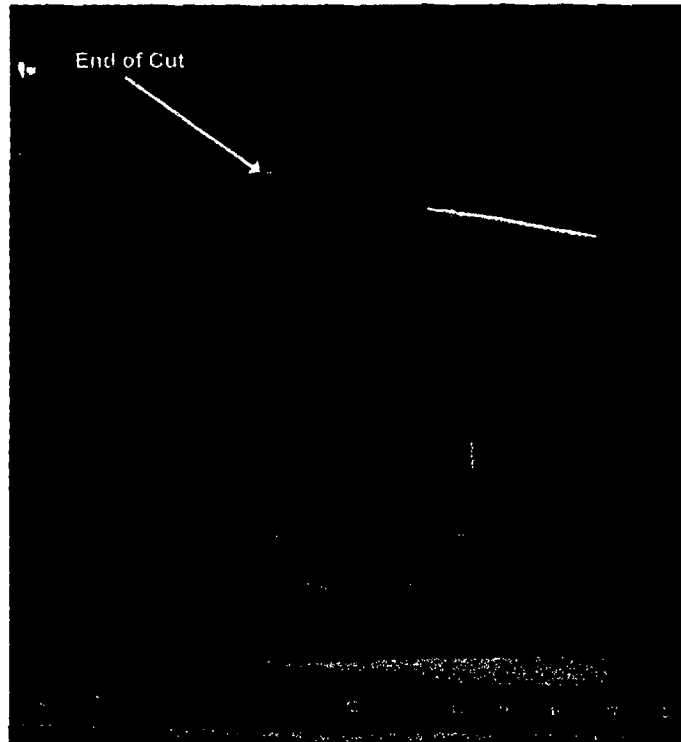


Figure 6.8 Abrasive Blade Cutting through the Nozzle with a J-groove Nozzle

Comment [PG053]: Remove this figure.

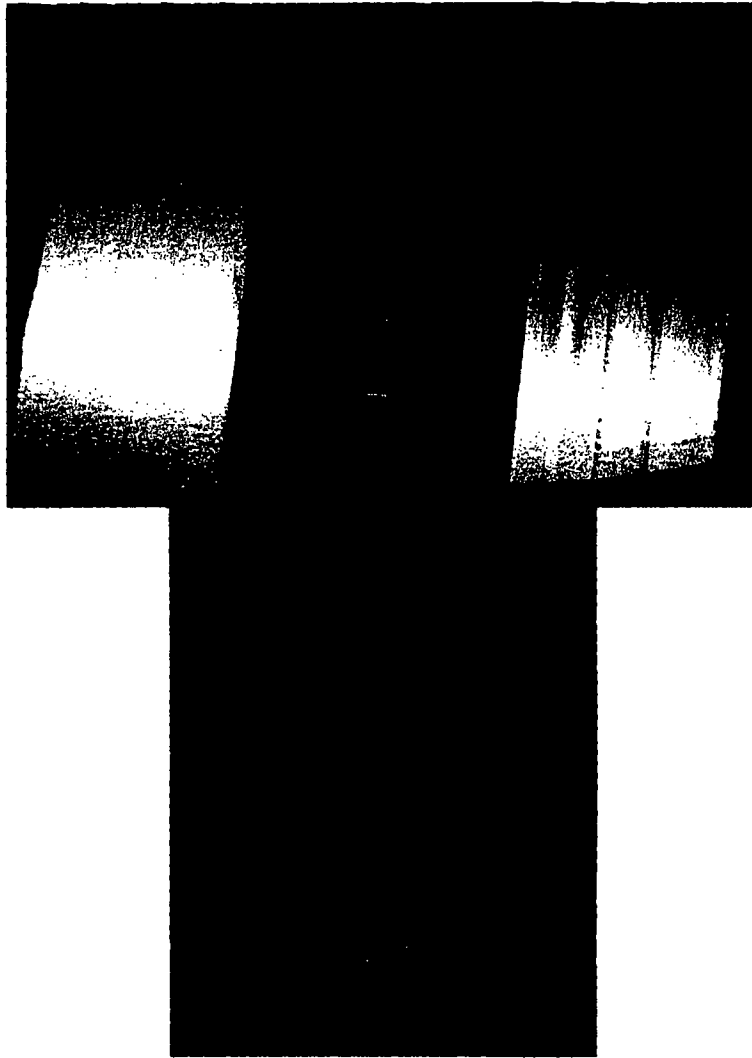
The cutting continued until the entire nozzle was separated from the J-groove weld region as pictured in Figure 6.9. At this point, the nozzle region above the weld was freely released from the RPV head material. Removal of the nozzle exposed the annulus region of the high-side section as shown in Figure 6.10. At this point all available blades were exhausted. Replacement blades were ordered to finish the cut and complete removal of the J-groove weld region. A Nikon D40x camera was used to acquire high-resolution photographic documentation of the annulus region. This activity was provided by B&W. A subsequent cut was conducted on the low-side section to expose its annulus region containing the primary leak path (Figure 6.11). The nozzle freely released from this portion as well.



**Figure 6.9 End of J-groove Weld Removal Cut**



**Figure 6.10 Exposed RPV Head and Nozzle from High Side Section**

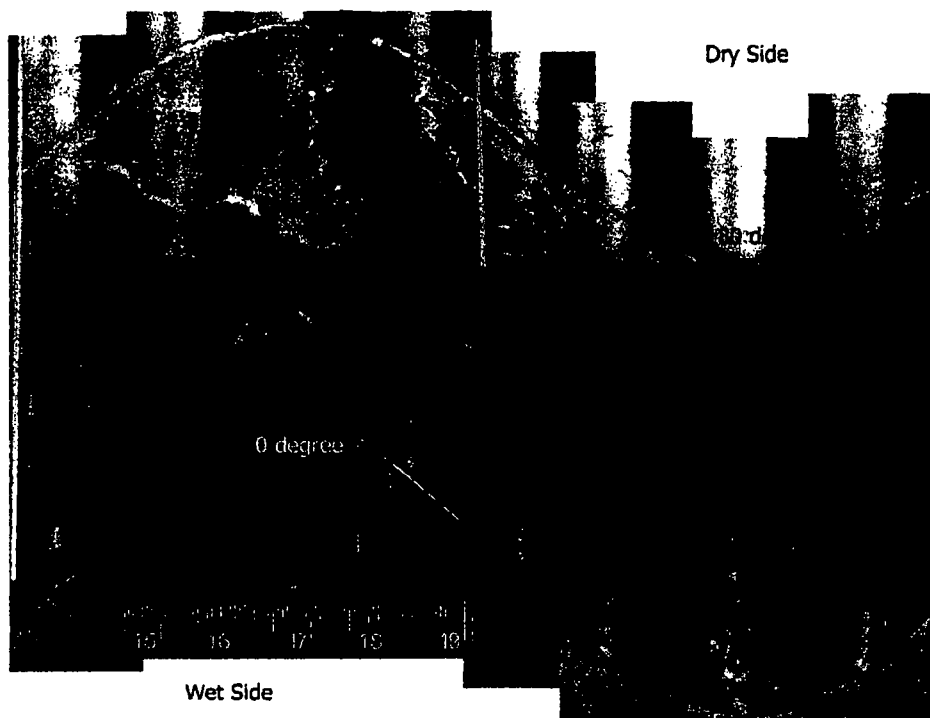


**Figure 6.11 Exposed RPV Head and Nozzle from Low-Side Section**



## 7 Correlation of Ultrasonic and Destructive Results

This section compares the phased-array ultrasonic results to the visual results obtained by cutting through the nozzle assembly to reveal the interference fit surfaces. The nozzle outer diameter surface was photographed in 45-degree increments with the individual photographs cropped and stitched together to form the montage image in Figure 7.1. Some evidence of thin boric acid deposits is visible in the white regions while a thin corrosion layer is seen in the rust-colored regions. The red line marks the interference fit region.



**Figure 7.1 Nozzle Surface. The red line marks the interference fit region.**

Similarly, the exposed reactor pressure vessel (RPV) head was photographed and the stitched image is displayed in Figure 7.2. The drain leak path and other features seen in the ultrasonic images are clearly evident. Boric acid deposits are visible in white and corrosion products in the rust color. The interference fit region is evident in the photograph and is marked with the red line.

Comment: (PAC) If you may identify the leak path with an arrow on something on the figure

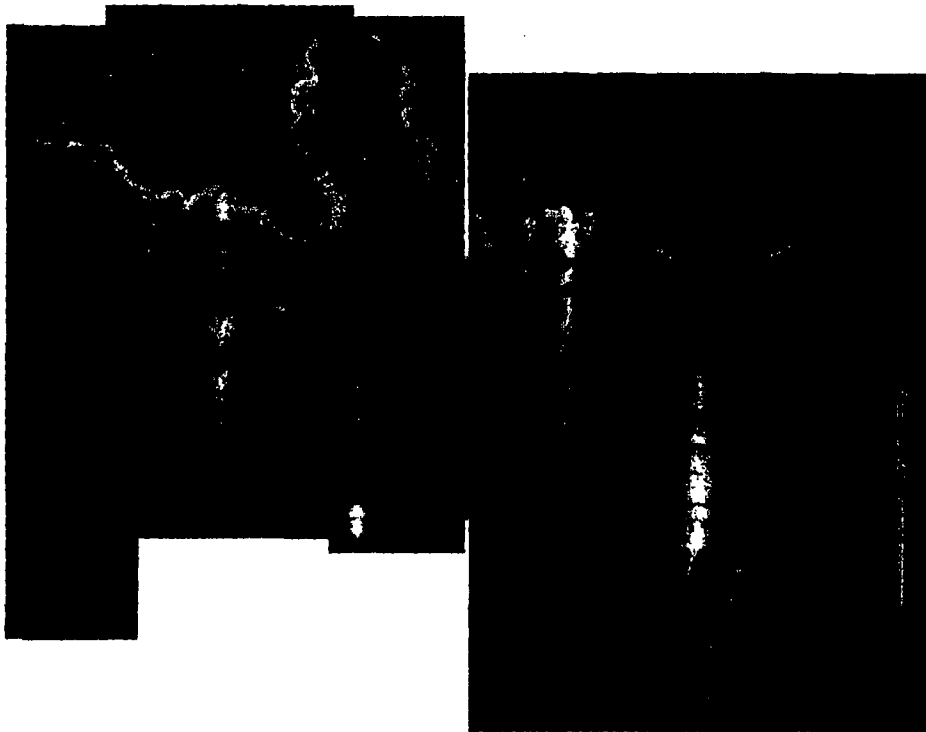


Figure 7.2 RPV Head Surface Stretched Image of the Head Annulus Direction

Comment: 160551: See comment on Figure 7.3. This figure should be on the same page as the UT data so that they can be easily compared.

A comparison of the ultrasonic and visual images is next presented. The ultrasonic data is overlaid on the RPV head montage photograph in a series where the opacity of the ultrasonic data is varied from 10 to 60%, in increments of 10%. Figure 7.3 displays the results with increasing opacity from left to right, top to bottom. The ultrasonic image was stretched to best fit the visual data but the match is not perfect due to the curved surfaces. Nevertheless, 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 as well.

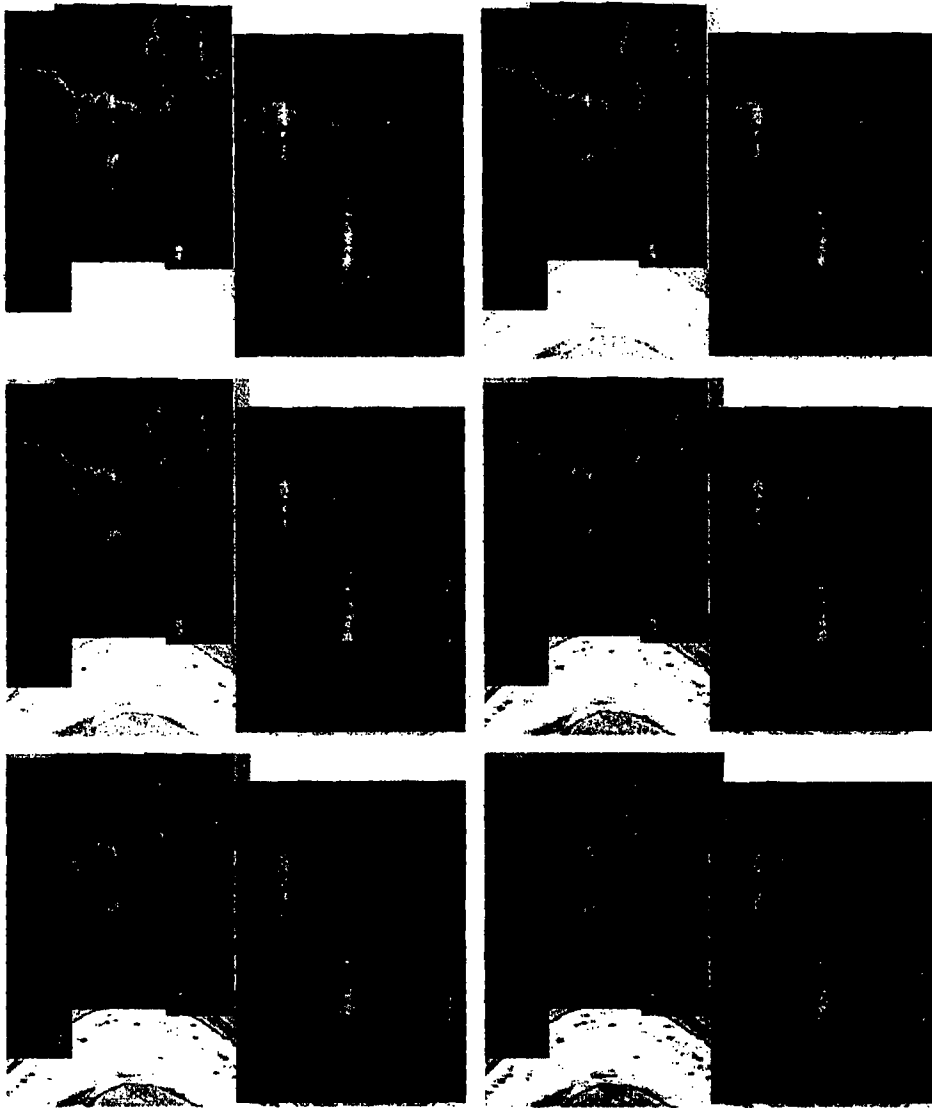


Figure 7.3 Ultrasonic Data Overlaid on RPV Head Photograph with Opacity Varying from 10 to 80%, Top to Bottom

Comment: (P6056) you don't need all the overlaid angles. We do need on the same: Figure 7.3 and the OT data in the same to scale next to each other, be one on top of the other.

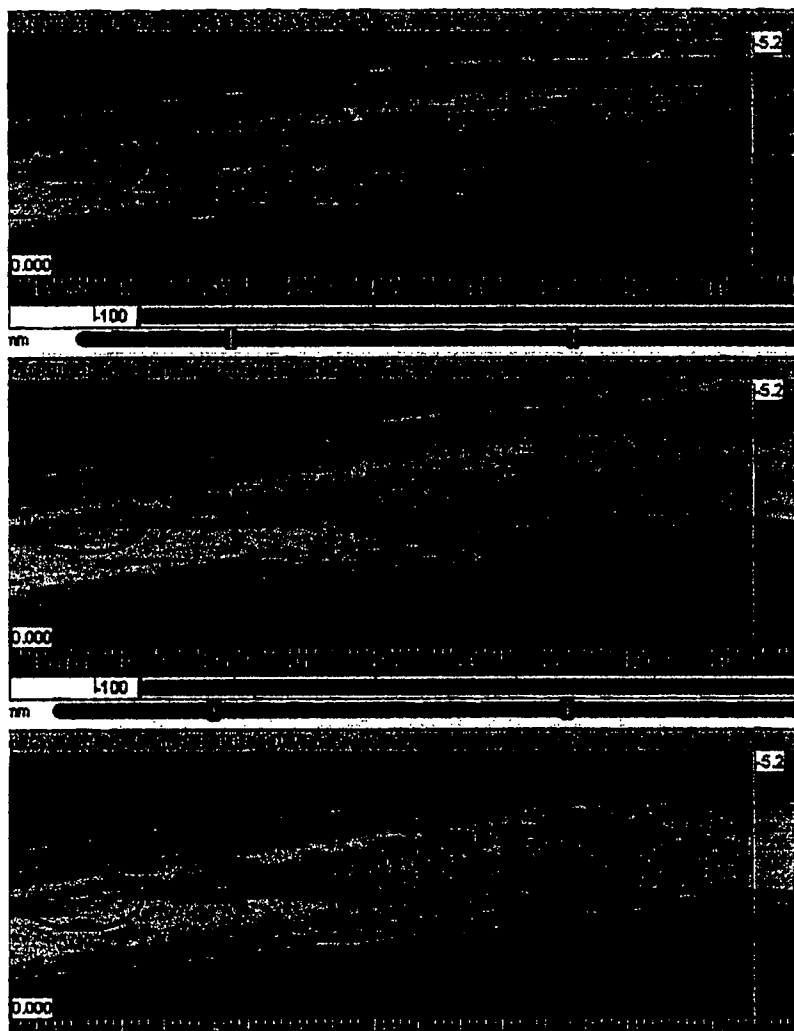
## 8 J-groove Weld Examination

Comment (R02057): This section should be removed from the document.

As a supplemental evaluation, a J-groove weld examination was attempted using the same equipment as was used on the interference-fit evaluation. Ideally, a goniometer would have been included in the setup and thus allowed angled-beam inspections. Without a goniometer, the probe angle was fixed at zero degrees or normal to the inner diameter (ID) surface of the Alloy 600 tube. The zero-degree inspection of the weld was not ideal for detecting axial or circumferential cracks in a single elevation plane as any such crack presented only a knife edge view rather than a preferred side view. The evaluation was attempted on a best-effort basis.

Data were acquired in a single scan at probe focal depths of 20, 30, and 40 mm (0.79, 1.18, and 1.56 in.) to attempt to focus the beam into the weld material at different depths. All of the detected indications were located at the near surface of the weld, along the Alloy 600 tube-to-weld interface. As a result, these indications were better focused at the 20- and 30-mm (0.79- and 1.18-in.) depths as can be seen by comparing the circled indications in the three images in Figure 8.1. The top or 20-mm (0.79-in.) image has the largest amplitude response and resolves the two indications in the circled region. At the other extreme, the 40-mm (1.56-in.) focal depth image at the bottom shows a lower amplitude and blurred response from the same two indications.

A composite view of the ultrasonic indications in the weld are presented in the C-scan top view or plan view images in Figures 8.2 and 8.3 for the uphill and downhill halves of the weld, respectively. Each figure represents approximately 150 mm (5.91 in.) in the vertical or axial direction and 180 degrees in the horizontal or circumferential direction. The indications were generally all located at the Alloy 600 tube-to-weld interface, or near surface, as will be discussed in more detail below. These indications appear to be volumetric in shape, indicative of fabrication flaws and assumed to be welding anomalies. The types of fabrication flaws expected would include incomplete or lack of fusion between individual weld beads, inclusions, voids, etc. Notice that the downhill image contains more indications. This is not unexpected due to the more difficult configuration at this position in the nozzle assembly. One would be welding upside down, in a deeper cavity, and with limited access at this location; and therefore more likely to introduce imperfections in the weld. A connected string of indications following the curvature of the weld are observed in Figure 8.3—likely a lack of fusion between weld bead passes. These indications are noted by the red arrow in the figure.



**Figure 8.1** Weld Images with Focal Depths at 20, 30, and 40 mm (0.79, 1.18, and 1.56 in.) from Top to Bottom, Respectively. The horizontal axis represents approximately 90 degrees and the vertical axis represents approximately 150 mm (5.9 in.). A 20-mm (0.79-in.) focus provided the best resolution in this data.



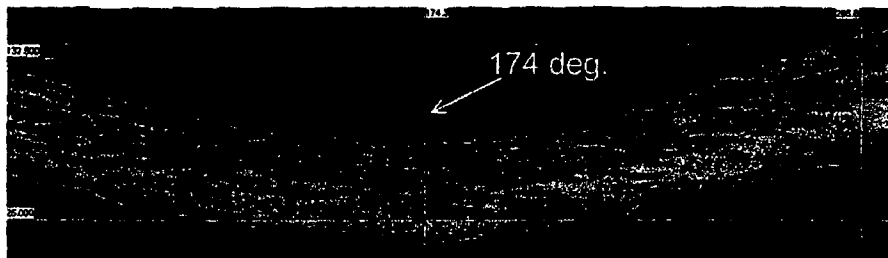
**Figure 8.2 Uphill Half of the Weld.** The horizontal axis represents approximately 180 degrees and the vertical axis represents approximately 150 mm (5.9 in.).



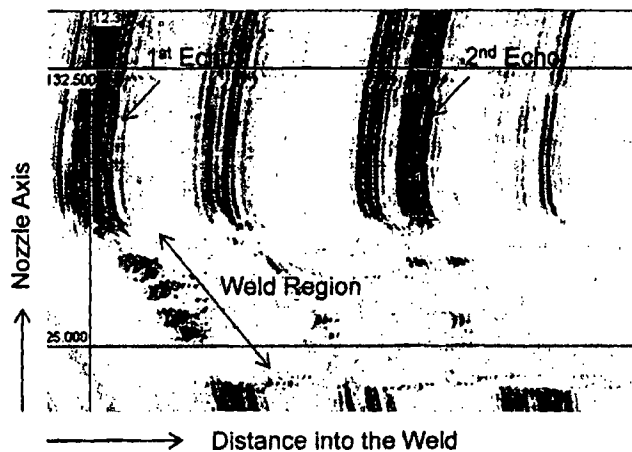
**Figure 8.3 Downhill Half of the Weld.** The horizontal axis represents approximately 180 degrees and the vertical axis represents approximately 150 mm (5.9 in.).

The ultrasonic indications were evaluated for flaw-depth position or distance into the weld material, and all responses appeared to be at or just below the surface with the surface representing the Alloy 600 tube-to-weld or butter interface. Figure 8.4 shows the composite top view of the downhill half of the weld with a vertical line drawn through the 174-degree position. A single plane or slice of data taken at the 174-degree position is displayed in Figure 8.5 and this figure represents a B-scan side view of the data. The horizontal axis in the side-view image represents depth or distance into the material. The first and second ultrasonic echoes are noted and represent reflections from the tube-to-weld interface. The scanner index or nozzle axis is shown in the vertical direction. The profile shape follows the front surface or inside of tube profile displayed in Figure 8.6. The distortion or deviation from vertical is due to the weld heating and subsequent cooling in the material and was measured at approximately 2 mm (0.08 in.). The distortion is magnified in the image due to the velocity difference between water and the Alloy 600 tube. Water velocity is nearly four times slower than the metal, assuming a water velocity of 1483 m/sec (58.4 in./msec) and 5820 m/sec (229.1 in./msec) for the metal. The side-view plots (Figures 8.5, 8.6, and 8.8) display the horizontal axis in units of distance

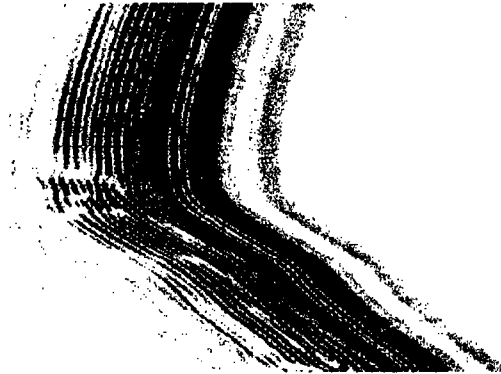
calculated with a metal velocity rather than in units of water velocity or time. During the data acquisition, a constant water path is assumed. As the water path varies due to the tube distortion, the difference is magnified by a factor of four on this metal scale. However, signals are correctly plotted relative to each other on the horizontal axis. For example, the first and second echoes are separated by a nominal distance of 17 mm (0.67 in.), which represents the tube wall thickness.



**Figure 8.4** Location of Single Slice Shown in Figure 8.5. The horizontal axis represents 180 degrees approximately and the vertical axis 145 mm (5.7 in.).

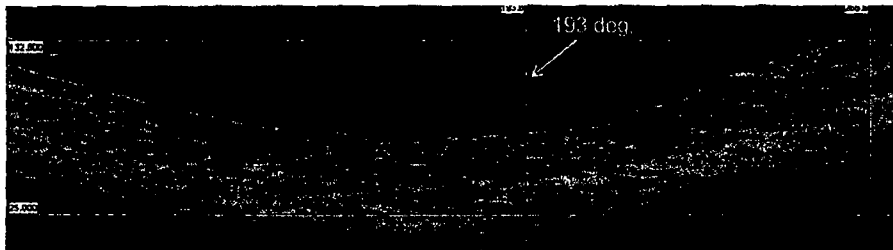


**Figure 8.5** B-scan Side View at the 174-Degree Circumferential Position. Near-surface indications are visible in the weld material. The horizontal axis represents approximately 40 mm (1.6 in.) in metal and the vertical axis 155 mm (6.1 in.).



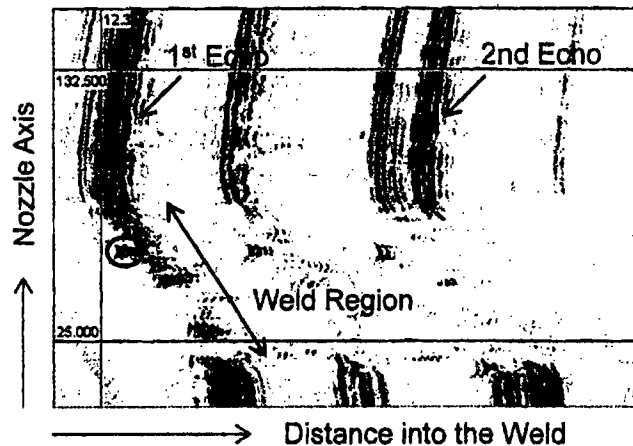
**Figure 8.6 B-scan Side View of the Front Surface Echo Showing Surface Profile Distortion Due to Welding and Cooling at the 174-Degree Circumferential Position. The horizontal axis represents approximately 20 mm (0.8 in.) in metal and the vertical axis 155 mm (6.1 in.).**

The weld region was evaluated for anomalies throughout the full 360-degree circumference. The indications fell along the Alloy 600 tube-to-weld interface at all but one circumferential position. At the 193-degrees position as noted in Figure 8.7, an indication appeared earlier in time than the other indications. The corresponding B-scan side view is shown in Figure 8.8 with the early indication circled. This earlier indication would plot into the tube material and could possibly be from a gouge in the tube and improper or no weld fill or repair. The indication displacement is shallow at approximately 1 mm (0.04 in.) in depth. No indications of circumferential cracking across or along weld beads were detected.



**Figure 8.7 Location of Single Slice Shown in Figure 8.8**

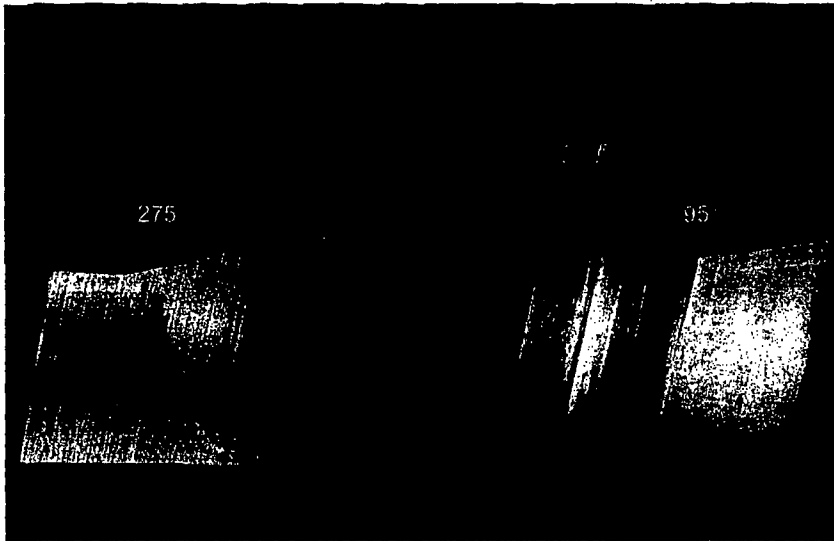




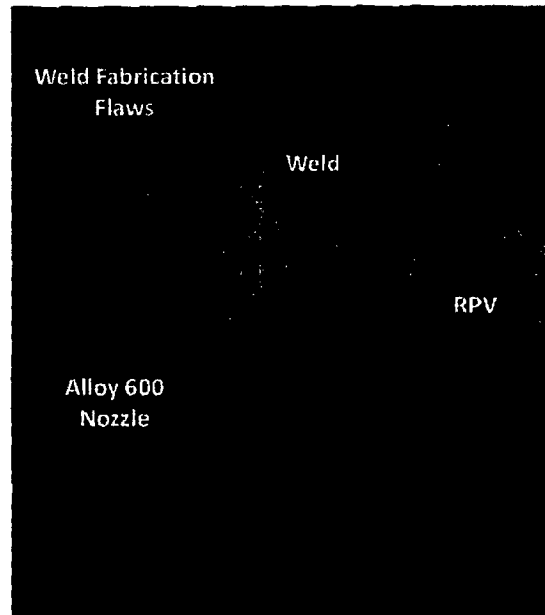
**Figure 8.8 B-scan Side View at the 193-Degree Circumferential Position. Near-surface indications and one indication, circled in red, occurring earlier in time are visible. The horizontal axis represents approximately 40 mm (1.6 in.) in metal and the vertical axis 155 mm (6.1 in.).**

A visual glimpse of several weld anomalies was made possible during the destructive evaluation conducted by Babcox & Wilcox. After making the dissection cut at approximately 95 and 275 degrees on the nozzle assembly, the exposed surfaces at 95 and 275 degrees were photographed with results shown in Figure 8.9 for the downhill half of the nozzle assembly. An enlarged version of the right side, or 95-degree position, is shown in Figure 8.10 and displays two flaws at the Alloy 600 nozzle-to-weld interface.

A comparison between the cut surface and ultrasonic data was made. It was observed that the 180-degree or low point on the weld was found to be located at 171 degrees in the ultrasonic image. Therefore, the ultrasonic data was shifted by 9 degrees to account for this offset. By this reasoning, the 95-degree cut surface corresponds to the 86-degree position in the ultrasonic data and the 275 cut surface corresponds to the 266-degree position ultrasonically. Again, note that these positions and the positions of the cut surfaces are estimated. The corresponding ultrasonic positions are noted in the ultrasonic C-scan top view image in Figure 8.11 with the left red vertical line at 87 degrees (on the left edge of the image) and the right blue vertical line at 266 degrees. The image did not extend to the 86-degree position so the 87-degree position is noted instead. The two indications marked by arrows at the 87-degree position in Figure 8.11 correlate to the two indications noted in Figure 8.10. An indication is also marked on the right side at the 266-degree position.



**Figure 8.9** Cut Surfaces of the Nozzle Assembly at 95 Degrees on the Right and 275 Degrees on the Left. The scale is in inches.

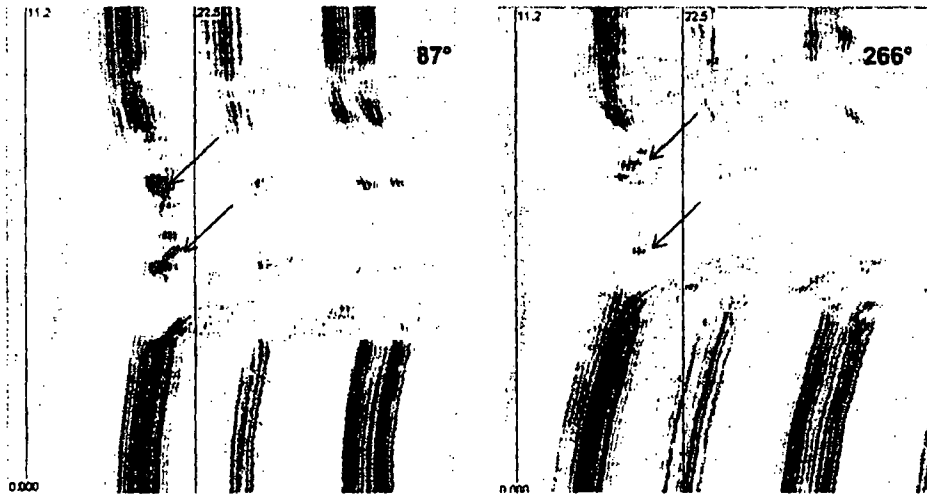


**Figure 8.10 The 95-Degree Surface Shows Two Fabrication Flaws at the Alloy 600 Tube-to-Weld Interface**



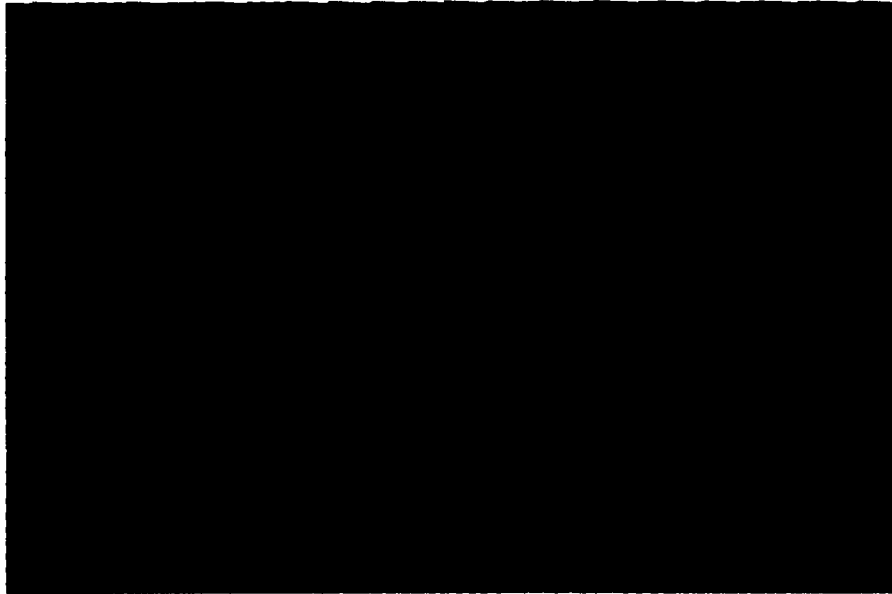
**Figure 8.11 C-scan Top View of the Downhill Section of the Weld with the Left Edge Red Line and Right Side Blue Line Slicing through the Image at Locations Corresponding to the Cut Surfaces in Figure 8.9. The horizontal axis represents 180 degrees and the vertical axis 155 mm (6.1 in.) approximately.**

B-scan side view images are displayed in Figure 8.12 for the 87- and 266-degree positions from Figure 8.11. The left side view image in Figure 8.12 at the 87-degree circumferential position shows the two defects with anomalous signals in between. The right image at the 266-degree position shows two possible defects with much lower signal amplitude, indicating smaller flaws.



**Figure 8.12 B-scan Views of the Data at 87 Degrees on the Left and 266 Degrees on the Right, Corresponding to the Cut and Exposed Surfaces in Figure 8.9. The horizontal axis in each image represents 40 mm (1.6 in.) in metal and the vertical axis represents 155 mm (6.1 in.) approximately. Flaw indications in the Alloy 600 tube-to-weld interface are noted with arrows.**

The presence of these flaws was further confirmed by the dye penetrant test results on the cut surfaces shown in Figure 8.13. The two flaws at the 95-degree and two at the 275-degree cut surfaces are marked with arrows. Furthermore, two additional flaws in the weld material are circled on the 95-degree surface. These weld flaws were not evident in the ultrasonic data for two likely reasons. First, the beam possibly did not focus well at those depths. Second, any flaws occurring earlier in time (depth) would return or reflect the ultrasonic energy causing a shadow region beyond or later in time (depth) that would not be insonified.



**Figure 8.13 Dye Penetrant Test Results on the Downhill Dissection Cut Surface. The scale is in inches.**

In summary, a J-groove weld examination was conducted with the probe oriented normal to the Alloy 600 tube inner surface. This was the same configuration used in the interference fit evaluation and was the only easily available option for a weld inspection. Inspections at several focal depths were made to attempt to fully insonify the weld material. The normal orientation was not ideal for detecting cracks as the beam was oriented toward an expected flaw edge rather than broadside to the flaw. The evaluation did not find any crack-like indications. Many fabrication flaws or weld anomalies were found with a higher concentration noted at the downhill side of the weld. The flaws mapped to the tube outer surface-to-weld interface region. Dye penetrant results validated four flaws at the tube-to-weld interface but also revealed two possible flaws in the weld that were not found ultrasonically. The larger of these two indications was in a shadow region caused by an earlier indication.

## 9 Additional Physical Measurements on the Reactor Pressure Vessel Head

As part of a supplemental study, attempts were made at measuring the boric acid thickness in the annulus as well as the extent of corrosion of the reactor pressure vessel (RPV) head. These measurements were then compared to the ultrasonic data. The boric acid thicknesses were first measured at specific points using an eddy current thickness gage. Next the RPV head surface was replicated with a Microset material, and boric acid thickness measurements were made on cross-sectional slices through the replica in the main leak path area. Finally, the replicated sections were examined with a stereomicroscope providing an indication of the corrosion extent. Best-effort attempts within limited budget and time constraints were made to remove the boric acid deposits in order to then measure corrosion or material wastage under the deposits. This effort was unsuccessful, but replica observations indicated minimal corrosion and wastage of the low-alloy steel head.

### 9.1 Boric Acid Measurements – Thickness Gage

In addition to the comparison of the interference fit region photographs with the ultrasonic images, a further study was conducted to obtain boric acid thickness measurements on the RPV head in the annulus region and to compare these results to the ultrasonic data. This was done while recognizing that the ultrasonic response in terms of reflected ultrasonic amplitude from the interference fit region would likely not correlate solely to the boric acid thickness measurements on the RPV low-alloy steel material. The boric acid on the RPV head material was only part of the contribution to the ultrasonic response. Also contributing to the ultrasonic response was the boric acid on the nozzle material (refer to Figure 7.1), and this contribution was not measured. Additional factors not measured or investigated were the density of the boric acid deposits and the low-alloy steel corrosion products which were visible in the photographs and could reflect or transmit ultrasonic energy differently than boric acid alone. Nevertheless, a best-effort attempt was undertaken to quantify the boric acid in the annulus region and relate these measurements to the ultrasonic data.

An eddy current probe was selected (DeFelsko PosiTector 6000 Series coating thickness gage) to measure the boric acid deposit thickness at selected points in the annulus region on the RPV head material. The probe had a point contact area of 1 mm (0.040 in.) in diameter and spanned a measureable coating thickness range of 0 to 45 mils (0 to 1.14 mm). The selected measurement sites were chosen to represent the differing ultrasonic amplitudes in the interference fit that included the main leak path, other partial leak paths, the interference fit with and without suspect boric acid present, and areas outside of the interference fit. A total of 70 points were selected by both Pacific Northwest National Laboratory (PNNL) and U.S. Nuclear Regulatory Commission (NRC) personnel and are displayed in Figure 9.1 for the photographed uphill and downhill halves of the RPV head. Figure 9.2 shows the ultrasonic data with a low opacity level superimposed on the photograph. A tri-color amplitude scale previously developed during the mockup study was used in the ultrasonic image and is displayed in the figure. Areas of interest were selected from the three color regions and represented a segmentation of ultrasonic responses. These specific points are associated with the green dots.

Comment [PG038]: Is there a standard or some calibration information that we can use support the resolution of the probe.

The red dots were selected to represent the main leak path and other partial leak paths or bare metal regions. Lastly, the yellow dots were additional data points chosen for further verification, such as the two pairs on either side of the uphill interference fit.

Comment [PG058]: This needs to be updated because it is confusing as written. Particularly because the photo image used shows both blue and white to distinguish the regions. Should the caption be: Red dots represent measurement sites in and around the main and suspected leakage paths. Yellow dots represent measurement sites. Green dots represent measurement sites.

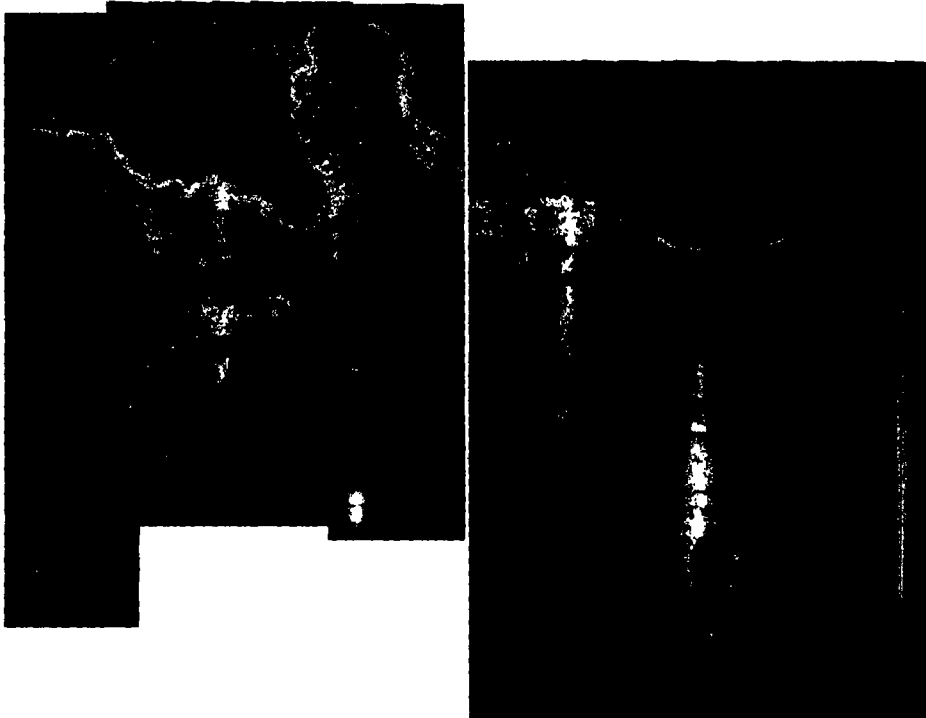


Figure 9.1 Photograph of the RPV Head Material with Boric Acid Measurement Points

Comment [PG060]: State what the dots are and the significance of the color scheme. Make the span of the interference fit.



Figure 9.2 Ultrasonic Data with Boric Acid Measurement Points

Each of the 70 data points was numbered and the boric acid measurements were entered into a spreadsheet. The thickness measurements in microns are displayed adjacent to the data points in Figure 9.3. Some general observations were:

- 1) Boric acid values above and below the interference fit region outside of leak path and bare metal or nearly bare metal regions are nominally in the 130 to 200 micron (5.1 to 7.9 mils) range.
- 2) The two pairs of data (yellow dots) on either side of the interference fit on the uphill section show boric acid values of 156 and 150 microns (6.1 and 5.9 mils) above the fit region and 62 and 74.5 micron (2.4 and 2.9 mils) in the fit region.
- 3) Leak path and bare metal or nearly bare metal points have a thin surface corrosion layer, not visible boric acid deposits, with deposits at 16 microns (0.63 mils) or less.

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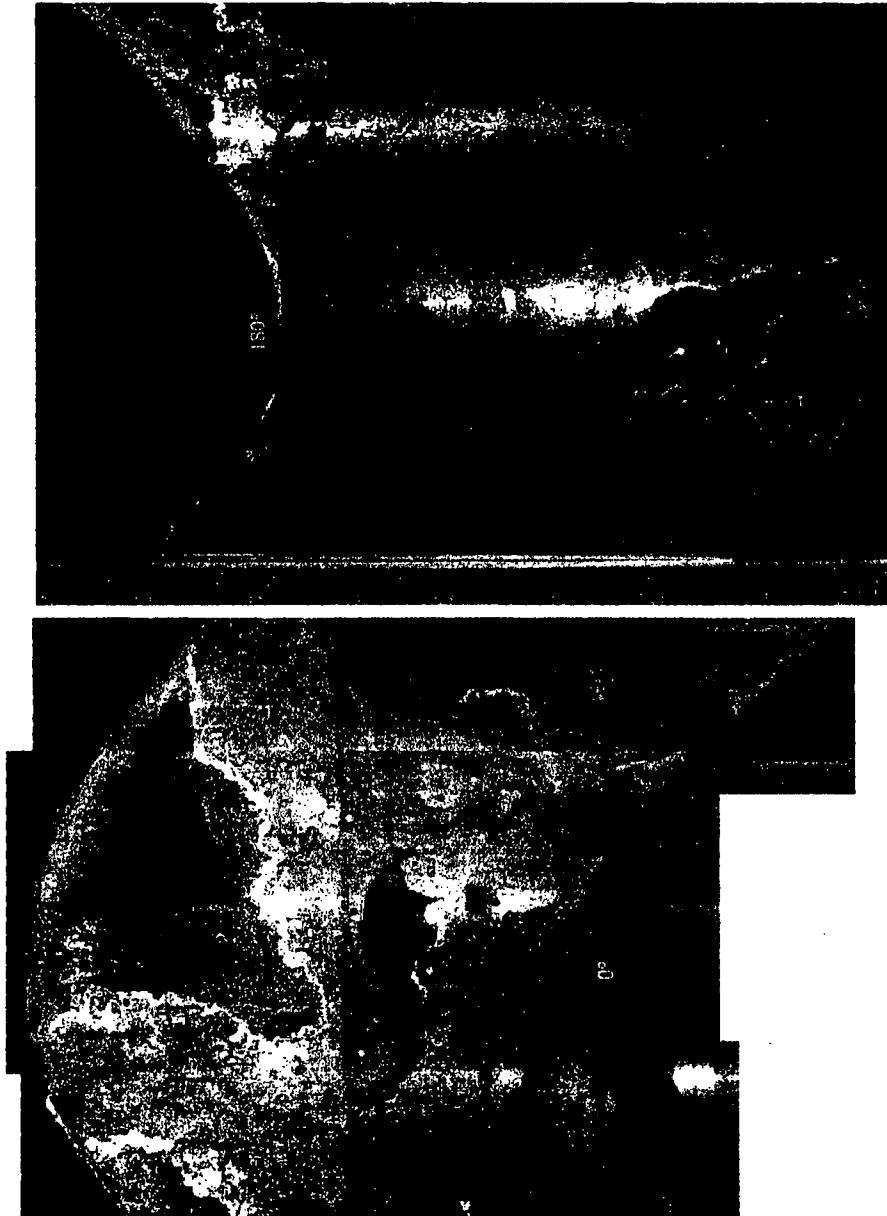


Figure 9.3 Boric Acid Thickness Values in Microns

Comment [PG083]: The numbers are small and hard to read. Is there a way to make larger?

The relationship, if any, between the ultrasonic response values and boric acid values are displayed in graphical form in Figures 9.4 and 9.5. In the first graph, shown in Figure 9.4, the ultrasonic data are displayed as a function of the boric acid values for measurement points in the interference fit region. The points circled in the upper left corner represent bare metal or nearly bare metal points and point from the leak path. These points cluster separately from the remaining data and have ultrasonic values greater than 65% of full screen height and coating layer values less than or equal to 9 microns (0.35 mils). Furthermore, these points represent a strong ultrasonic response such as one associated with a reflection from a gap or void in the interference fit region. There was not close contact between the Alloy 600 tube outer diameter (OD) and the RPV head inner diameter (ID) materials at these locations and minimal or no boric acid or corrosion products were present. The points outside of the circled region represent the rest of the data and show no correlation between the ultrasonic response and the boric acid or coating thickness. The region is, however, bounded by boric acid deposits in the 16 to 75 micron (0.63 to 3.0 mils) range, while the ultrasonic responses almost cover the full range, spanning from 10 to 80% of full screen height.

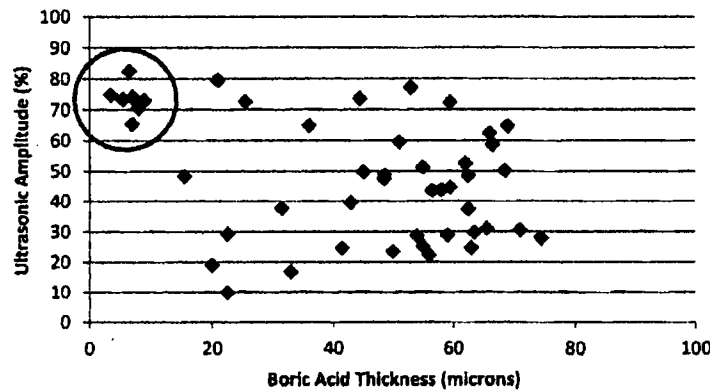
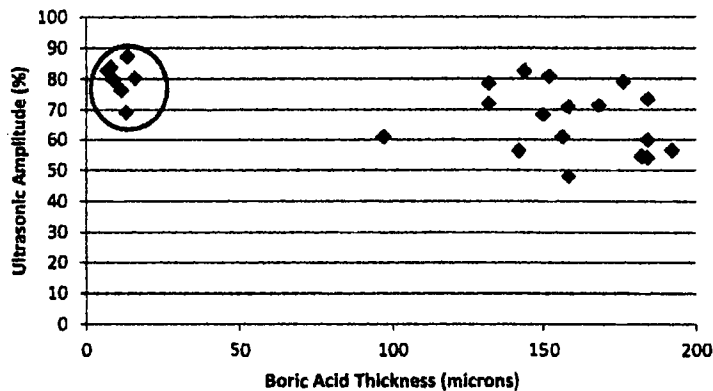


Figure 9.4 Ultrasonic Amplitude as a function of Boric Acid Thickness from Points in the Interference Fit Region

Comment: [PG064]: Remove figure.

The data above and below the interference fit are displayed in Figure 9.5. The leak path or bare metal points are circled and have ultrasonic values between 69 and 87% and boric acid or corrosion thickness values of 16 microns (0.63 mils) or less. Outside of this circled cluster and the one isolated data point in the middle, the remaining data have boric acid thickness between 132 and 192 microns (5.2 and 7.6 mils) and ultrasonic amplitudes between 48 and 83%. The one outlier point is from the dry side on the uphill half and is towards the edge of a boric acid patch with a center-of-patch (0.7 in. or 17.8 mm to the center) thickness of 176 microns (6.9 mils).



**Figure 9.5** Ultrasonic Amplitude as a Function of Boric Acid Thickness (Low Points Above and Below the Interference Fit Region)

Comment [PG065]: Remove figure.

If this outlier or transitional point from Figure 9.5 is excluded, all of the boric acid measurements can be segmented into three categories. The leak path or bare metal regions have approximately less than 16 microns (0.63 mils) of boric acid/corrosion products. The interference fit points contain between 16 and 75 microns (0.63 to 3.0 mils) of boric acid, and the annulus region above and below the interference fit contain 132 to 192 microns (5.2 to 7.6 mils) of boric acid. These numbers are assumed to depend on the geometry of the particular control rod drive mechanism (CRDM) assembly and more specifically on the size of the interference fit and counter bore regions outside of the interference fit. It is reasonable to assume that with a leak, any interference fit or counter bore gap could fill with boric acid and corrosion products.

Attempts to correlate the ultrasonic data to the RPV head boric acid data are again simplistic. The ultrasonic responses were sensitive to the entire interaction at the Alloy 600 tube-to-steel RPV head interface including metal-to-metal contact or lack of contact, boric acid and corrosion product presence, and the density of these materials. The earlier proposed tri-level segmentation of ultrasonic responses based on the mockup specimen was inadequate. It was proposed from the ideally machined mockup with well-mated surfaces. In an actual nozzle, the contact area could be as low as 5% at operating temperatures due to out-of-roundness, not straight components, and surface roughness (Hunt and Fleming 2002). Furthermore, the mockup did not contain a counter bore region. Less-than-perfect data registration also likely contributed to error in the correlation between the ultrasonic and boric acid values. The ultrasonic images show large variations between points located in close proximity to each other. Small positional errors in the boric acid measurement could have led to an incorrect matching of the data. An overlay of the ultrasonic data on the RPV head with the 70 measurement points is shown in Figure 9.6 with the multilevel color scheme for reference. The ultrasonic responses in the leak path and bare metal regions are greater than 65%, while interference fit data are in the 10 to 80% range and counter bore data are in the 48 to 83% range. High values, large

reflectance, indicate an interface with a large impedance mismatch such as metal to air. Low values indicate good transmission at the interface due to similar materials tightly bonded. Bare metal and leak path points show large ultrasonic reflectance with a minimal corrosion layer. These data points cluster well. The interference fit data does not. Approximately two-thirds of the interference fit ultrasonic data are below the 50% response level and cluster with boric acid values in the 16 to 75 micron range (0.63 to 3.0 mils). The remaining one-third of the ultrasonic data has response levels in common with the counter bore data. Because a full investigation of the multiple factors affecting the ultrasonic responses was beyond the scope of this project, the data are at best bounded but do not show a direct correlation to the boric acid measurements on the RPV head.

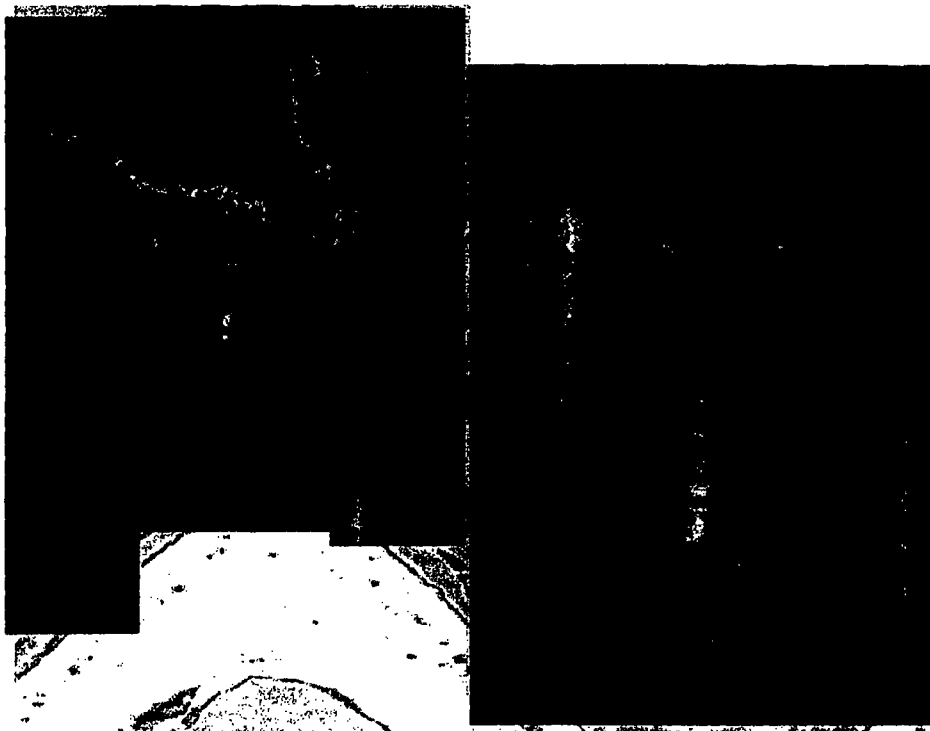


Figure 9.6 Overlay of Ultrasonic image on the 20 Measurement Points

Comment [PG056]: Remove figure.

## 9.2 Boric Acid Measurements – Microset Cross Sections

Confirmatory boric acid measurements were also visually made on Microset replicas of the RPV annulus in the main leak path region. This replicating material has better than 0.1 micron (0.004 mils) resolution. ~~These areas of interest are in the main leak path as shown in Figure 9.7 and are related to the boric acid interference fit region measurements.~~ The sliced and annotated replica is shown in Figure 9.8. ~~Replicated cross sections were made to the edges of the slices with the white arrows showing the low surfaces that were measured. Several of the measurement values obtained by these surface cross sections were compared to the thickness gage measurements. While only a few data points were compared and these measured at thicknesses of approximately 40 and 120 microns, the data showed good agreement as Figure 9.9 shows. Ideally, comparisons in the range of distances nominally 120 microns would have been made as well. However, for this test effort with several measurements were validated.~~

Comment [P0067]: State that these include the locations of the measurement locations. (This is the way it is indicated in the previous section.)

Comment [P0068]: Do you have any of the profile pictures?

## 9.3 Replicated Surfaces – Stereomicroscope

Lastly the replicated surfaces from Figure 9.8 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. Machining marks were observed on the replicated surfaces indicating minimal corrosion, erosion, or wastage throughout the leak path region. Interesting areas are discussed.

Comment [P0069]: Rephrase this to say that the comparisons were done for the measurements that were the leak path.

Comment [P0070]: Do not say this.

Comment [P0071]: This is not possible for this section. Machining marks were evident in the images that showed the low surface conditions.

Figure 9.10 shows replica pieces 2 and 3 in the main leak path in the region below the interference fit. Both pieces show double streaks from corrosion product staining but no or minimal actual corrosion or wastage. The machining marks are intact across the images.

The transition from below the interference fit to the interference fit region is captured in Figure 9.11 on piece 4. Machining marks are clearly evident and were observed in most of the bare areas examined on the RPV head surface. The surface finish within the interference fit region was approximately equivalent to a turned finish of 63 microns. The finish below the interference fit region was approximately equivalent to a milled 68 finish.

Comment [P0072]: What does this mean?

Piece 5 contained an angular feature or anomaly with an approximate length of 2.3 mm (0.090 in.) and is shown in Figure 9.12. The right image is at a twice the magnification as the image on the left and shows more detail. This feature appeared to be more of a dent or scrape and not corrosion. Piece 5 lies in the interference fit region.

The only corrosion observed in the replicated surfaces was in the region above the interference fit in piece 9. The piece is shown in Figure 9.13 with the two areas of interest circled. The circled region on the left was in the main leak path and covered an area of approximately 6.4 mm (0.25 in.) in diameter with a depth of 0.25 mm (0.01 in.). The corroded area on the right was approximately 12.7 by 1.6 mm (0.5 by 0.06 in.) with a depth of 0.25 mm (0.01 in.).

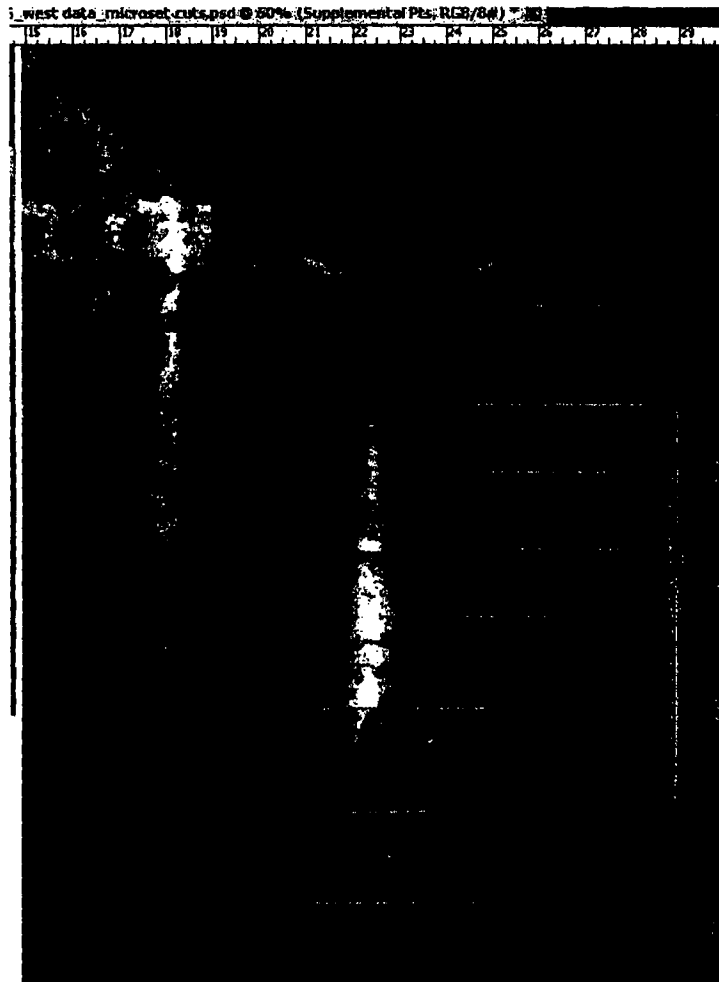
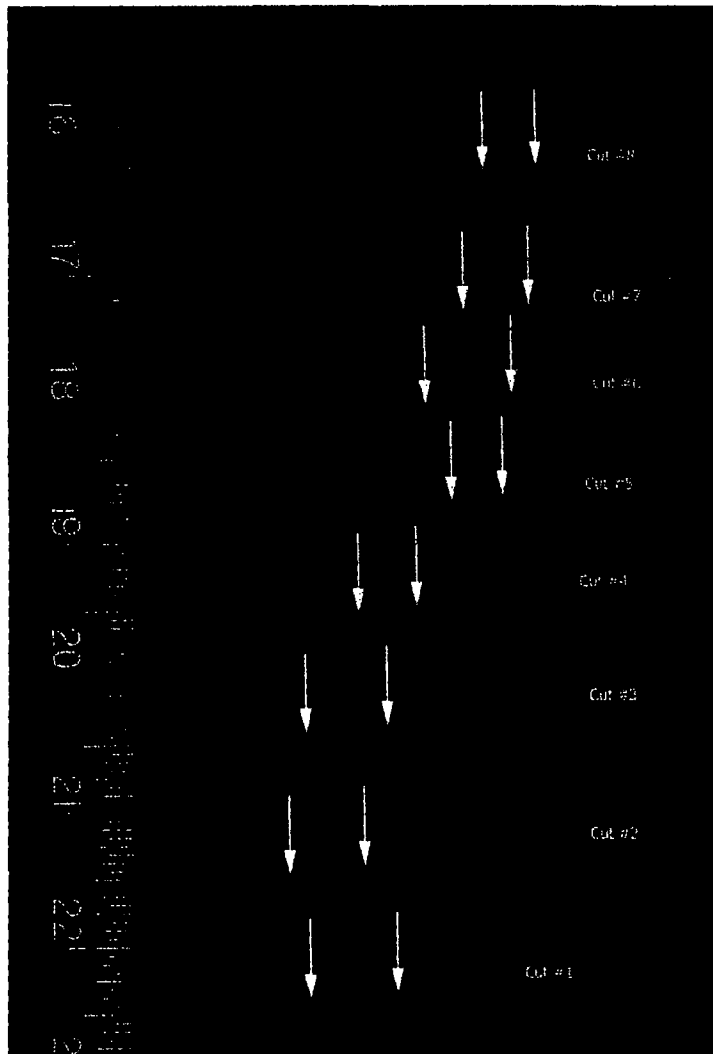
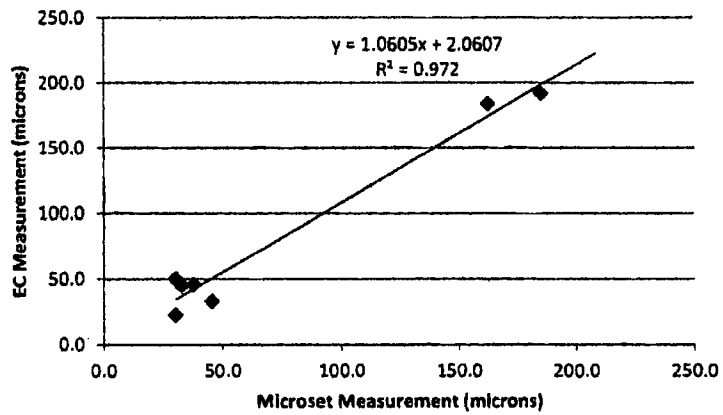


Figure 9.7 Eight Areas Selected for Bone Acid Thickness Measurements on Cross-Sectional Slices of Microcast Replica

Comment [PG073]: Remove dots from fit except those for the horizontal line measurements.



**Figure 9.8 Leak Path Replica with Cuts and Pieces Identified. The interference fit region is noted with the black line and is contained in pieces 4 through 9.**



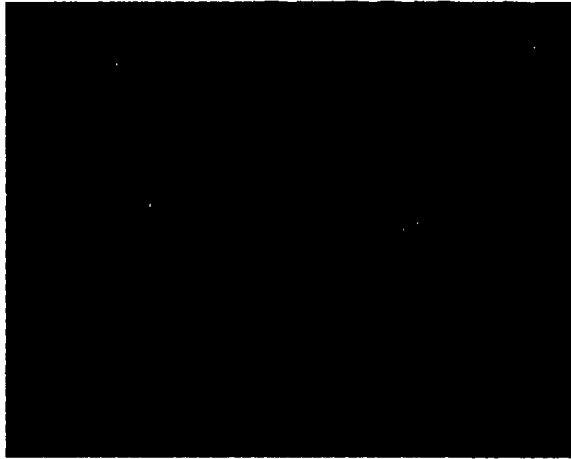
**Figure 9.9 Eddy Current Thickness Gage and Microset Thickness Measurements of Boric Acid Comparison**

Comment (P6074): Use a table to compare the measurements instead of plot.



**Figure 9.10 Staining Streaks in the Leak Path Below the Interference Fit from Replica Pieces 2 and 3, Left and Right, Respectively. The red line represents 2.0 mm (0.80 in.) in length.**





**Figure 9.11 Transition from Below the Interference Fit to the Interference Fit Region. Machining marks are evident in this replica piece 4. The red line represents 2.0 mm (0.80 in.) in length.**



**Figure 9.12 Piece 5 from the Interference Fit Region Shows an Indication of a Scrape. In the left image the red line represents 2.0 mm (0.80 in.) in length. The image on the right at twice the magnification of the left shows more detail.**



**Figure 9.13 Corrosion Areas Observed Above the Interference Fit Region. The red line represents 2.0 mm (0.80 in.) in length.**

In summary, a limited boric acid thickness measurement study was conducted on the RPV head material. Boric acid deposits were found throughout the interference fit region as well as above and below this region. Larger boric acid thickness values were found in the counter bore regions above and below the interference fit and ranged from approximately 132 to 192 microns (5.2 to 7.6 mils). In the interference fit region itself, the boric acid values were in the 16 to 75 micron (0.63 to 3.0 mils) range. The leak paths and bare metal regions had a measureable corrosion layer of 16 microns or less. Finally, the ultrasonic measurements were sensitive to the entire interaction at the tube-to-RPV head interface so a simplistic comparison of boric acid thickness on the RPV head to ultrasonic response showed only a partial correlation.

## 10 Summary and Conclusions

In summary, a successful ultrasonic examination of the interference fit region of control rod drive mechanism Nozzle 63 from the North Anna Unit 2 power plant was conducted. A phased-array ultrasonic system was calibrated on a mockup specimen containing two interference fit regions. The probe spot size at the interference fit was modeled at 1.2 by 1.2 mm (0.04 by 0.04 in.) at the -6 dB level. Ultrasonic data from notches in the carbon steel material from one of the mockup interference fit regions showed system resolution at nominally 4 mm (0.16 in.) in both the axial and circumferential directions. Notches as shallow as 0.028 mm (0.0011 in.) were detected as well as notches as narrow as 0.80 mm (0.10 in.) in the circumferential direction. The second mockup interference fit contained regions with boric acid deposits. These regions were ultrasonically imaged and suggested that the ultrasonic responses could be segmented into three categories: 1) good interference fit, 2) interference fit with boric acid, and 3) leak path or gap.

Ultrasonic data were acquired on Nozzle 63 and clearly showed a variation of responses throughout the annulus region. The primary leak path at the downhill position of the nozzle was imaged and definitively spanned the annulus region thus providing a path for borated water to reach the top of the head. Partial leak paths were also identified. The normal beam inspection, while not optimum for crack detection, also detected two axial cracks in the nozzle. These cracks were previously found by industry with an eddy current examination conducted during an in-service inspection. One of the cracks was below the weld at the uphill position. The other axial crack was located above the weld at the downhill position, which also places it in the main leak path. A comparison of the Pacific Northwest National Laboratory (PNNL) ultrasonic data to that obtained by industry showed similar results but the PNNL data had better resolution, data registration, and focusing. Finally, a supplemental evaluation of the weld, which was again not optimized for crack detection, failed to detect any weld cracking but did detect numerous near-surface fabrication flaws.

After sectioning of the nozzle assembly to reveal the interference fit and photographing the exposed surfaces, the primary leak path was confirmed. Also confirmed was the excellent agreement of the ultrasonic images and exposed features on the annulus surfaces.

Additional measurements were made to quantify the thickness of the boric acid deposits or corrosion layer on the reactor pressure vessel (RPV) head. It was reasonable to assume that any gap in the annulus could fill with boric acid deposits. As the gap between Alloy 600 tube and low-alloy steel head varied so too did the boric acid thickness. The leak path or bare metal corrosion layer throughout the annulus was 16 microns (0.63 mils) or less with ultrasonic responses greater than 65%. Boric acid apparently did not deposit in the leak path due to the constant flow of borated water through the area, and the ultrasonic response indicates an air gap was present. The boric acid deposits in the counter bore regions above and below the interference fit were in the 132 to 192 micron (5.2 to 7.6 mils) range with ultrasonic responses between 48 and 83%. These two regions, leak path and counter bore, are clearly distinct from each other in both boric acid thickness but overlap in ultrasonic response. The interference fit region with a narrower annulus had boric acid deposits in the 16 to 75 micron (0.63 to 3.0 mils) range, in between the leak path and counter bore values. There was not a direct correlation

Comment: (R2075) This needs to be revised and presented as a table for roughly as follows:

1. Nozzle 63 showed evidence of leaking in annulus and was imaged from the North Anna Unit 2 power plant.

2. The nozzle was imaged and showed evidence of leaking in annulus and was imaged from the North Anna Unit 2 power plant.

3. The nozzle was imaged and showed evidence of leaking in annulus and was imaged from the North Anna Unit 2 power plant.

4. The nozzle was imaged and showed evidence of leaking in annulus and was imaged from the North Anna Unit 2 power plant.

5. The nozzle was imaged and showed evidence of leaking in annulus and was imaged from the North Anna Unit 2 power plant.

6. The nozzle was imaged and showed evidence of leaking in annulus and was imaged from the North Anna Unit 2 power plant.

7. The nozzle was imaged and showed evidence of leaking in annulus and was imaged from the North Anna Unit 2 power plant.

8. The nozzle was imaged and showed evidence of leaking in annulus and was imaged from the North Anna Unit 2 power plant.

9. The nozzle was imaged and showed evidence of leaking in annulus and was imaged from the North Anna Unit 2 power plant.

10. The nozzle was imaged and showed evidence of leaking in annulus and was imaged from the North Anna Unit 2 power plant.

Please modify as you see necessary.

between the RPV head boric acid measurements in the interference fit region and the ultrasonic responses. This is not unexpected as the ultrasound was influenced by additional physical conditions that were not measured such as the deposits on the outside of the Alloy 600 tube surface and the density of any of the deposits.

Lastly, the leak path region of the RPV head was replicated and limited confirmatory measurements made on the replica for boric acid thickness. The replica surfaces were imaged with a stereomicroscope and showed minor evidence of corrosion product streaking and little or no corrosion or wastage. Machining marks were clearly evident across the main leak path. Two small areas with minor corrosion were found above the main leak path with depths of 0.25 mm (0.01 in.). Attempts to remove the boric acid deposits on the RPV head to determine wastage underneath were unsuccessful, but dental pick probing indicated that all areas were sound. Therefore, in this leaking nozzle assembly, there was minimal corrosion or wastage occurring on the low-alloy steel RPV head.

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## **Appendix A**

### **Precision EDM Notch Information**

## **Appendix A**

### **Precision EDM Notch Information**

Precision square-edged electrical discharge machining (EDM) notches were an essential aspect of the CRDM nozzle mockup specimen. As described in the calibration specimen design section, a variety of notches were chosen for the mockup specimen and allowed for a multitude of ultrasonic calibrations to be made. Understanding the phased-array probe resolution and detection characteristics allowed for a more thorough leak-path assessment to occur on North Anna Unit 2 removed-from-service Nozzle 63.

This appendix highlights the exact as-built dimensions and locations for all notches used in the mockup assembly specimen as provided by Western Professional, Inc., the EDM notch subcontractor. Page A-2 lists the as-built dimensions for the 16 EDM notches placed in the carbon steel material representing the RPV head. Page A-3 lists the as-built dimension for the 16 EDM notches placed in the outer diameter of the Alloy 600 tube. Page A-4 shows the requested placement and size of the notches on the Alloy 600 tube outer diameter. Page A-5 shows the requested placement and size of notches 9–12. Page A-6 shows the requested placement and size of notches 13–16. Page A-7 shows the requested notch layout and sizing for the carbon steel material inner diameter.





WESTERN PROFESSIONAL, INC.  
DBA WESTPRO LAB  
3460 BRADY COURT NE  
SALEM, OR 97303  
(503)585-6263

Electrical Discharge Machining  
Reference Standard Manufacturing  
Optical Dimensioning System  
Non Destructive Evaluation  
RT, UT, MT, PT

CUSTOMER: BATTELLE STANDARD: BLOCK STANDARD S/N 5381  
DRAWING #: CUSTOMER DRAWING P.O. #: 135771  
MATERIAL: CARBON STEEL SIZE: 4.102" Ø HOLE  
DATE: 11-11-10 SPEC(S): PER CUSTOMER DRAWING INSTRUCTIONS

**BLOCK STANDARD S/N 5381**

DEFECT DIMENSIONS (IN INCHES)				LOCATION	ORIENTATION
NO.	DEPTH	LENGTH	WIDTH		
1	.0011"	2.0017"	.0384"	I.D.	LONGITUDINAL
2	.0020"	2.0048"	.0379"	I.D.	LONGITUDINAL
3	.0029"	1.9974"	.0377"	I.D.	LONGITUDINAL
4	.0049"	2.0046"	.0372"	I.D.	LONGITUDINAL
5	.1000"	1.9991"	.0316"	I.D.	LONGITUDINAL
6	.1004"	1.9929"	.0624"	I.D.	LONGITUDINAL
7	.1007"	2.0067"	.1251"	I.D.	LONGITUDINAL
8	.1002"	1.9968"	.2514"	I.D.	LONGITUDINAL
9	.0786"	1.0061"	.0833"	I.D.	TRANSVERSE
10	.0789"	1.0011"	.0828"	I.D.	TRANSVERSE
11	.0786"	1.0015"	.0834"	I.D.	TRANSVERSE
12	.0811"	1.0004"	.0827"	I.D.	TRANSVERSE
13	.0811"	1.0009"	.0807"	I.D.	LONGITUDINAL
14	.0789"	1.0028"	.0821"	I.D.	LONGITUDINAL
15	.0805"	1.0011"	.0828"	I.D.	LONGITUDINAL
16	.0805"	1.0007"	.0810"	I.D.	LONGITUDINAL

SEE ATTACHED DRAWING FOR NOTCH LOCATIONS

NOTE: ALL DEPTH AND WIDTH MEASUREMENTS ARE BASED ON AN AVERAGE OF FOUR OR MORE READINGS.

ALL DIMENSIONS ARE MEASURED WITH DIMENSIONAL EQUIPMENT WHICH IS CERTIFIED AND TRACEABLE TO NIST (#706) #2343033 AND NIST (#783183) #3881145. NUCLEAR REGULATORY COMMISSION RULES AND REGULATIONS 10 CFR PART 21 APPLIES TO THIS ORDER. ALL NOTCHES MANUFACTURED PER WESTPRO PROCEDURE WQC-IV.

CERTIFIED BY: S. CHAMBERLAIN

APPROVED BY: *S. Chamberlain*



WESTERN PROFESSIONAL, INC.  
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SALEM, OR 97303  
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Electrical Discharge Machining  
Reference Standard Manufacturing  
Optical Dimensioning System  
Non Destructive Evaluation  
RT, UT, MT, PT

CUSTOMER: BATTELLE STANDARD: PIPE STANDARD S/N 5382  
DRAWING #: CUSTOMER DRAWING P.O. #: 135771  
MATERIAL: STAINLESS STEEL, SIZE: 4.112" Ø X .6837" AWT  
HT# L215S  
DATE: 11-11-10 SPEC(S): PER CUSTOMER DRAWING  
INSTRUCTIONS

PIPE STANDARD S/N 5382

DEFECT DIMENSIONS (IN INCHES)					
NO.	DEPTH	LENGTH	WIDTH	LOCATION	ORIENTATION
1	.0011"	1.9978"	.0367"	O.D.	LONGITUDINAL
2	.0020"	1.9961"	.0366"	O.D.	LONGITUDINAL
3	.0030"	1.9971"	.0370"	O.D.	LONGITUDINAL
4	.0050"	1.9994"	.0371"	O.D.	LONGITUDINAL
5	.0980"	1.9945"	.0314"	O.D.	LONGITUDINAL
6	.1002"	2.0004"	.0632"	O.D.	LONGITUDINAL
7	.1012"	2.0066"	.1274"	O.D.	LONGITUDINAL
8	.1009"	1.9971"	.2526"	O.D.	LONGITUDINAL
9	.0795"	1.0007"	.0826"	O.D.	TRANSVERSE
10	.0797"	1.0000"	.0851"	O.D.	TRANSVERSE
11	.0806"	1.0018"	.0807"	O.D.	TRANSVERSE
12	.0806"	1.0007"	.0822"	O.D.	TRANSVERSE
13	.0804"	1.0004"	.0818"	O.D.	LONGITUDINAL
14	.0840"	1.0015"	.0816"	O.D.	LONGITUDINAL
15	.0780"	1.0020"	.0818"	O.D.	LONGITUDINAL
16	.0809"	1.0012"	.0828"	O.D.	LONGITUDINAL

SEE ATTACHED DRAWING FOR NOTCH LOCATIONS

\*NOTCH #10 WIDTH IS .001" OVER MAXIMUM TOLERANCE.

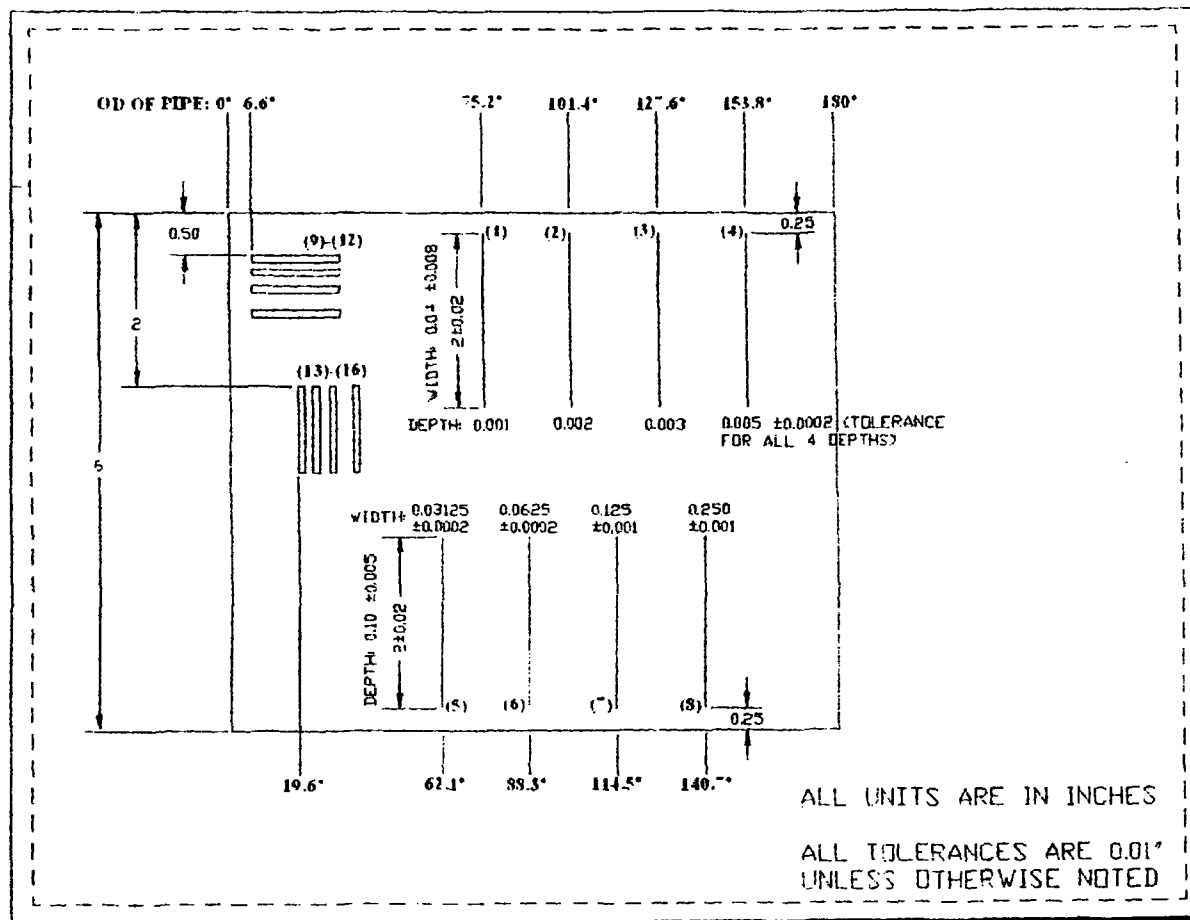
NOTE: ALL DEPTH AND WIDTH MEASUREMENTS ARE BASED ON AN AVERAGE OF FOUR OR MORE READINGS

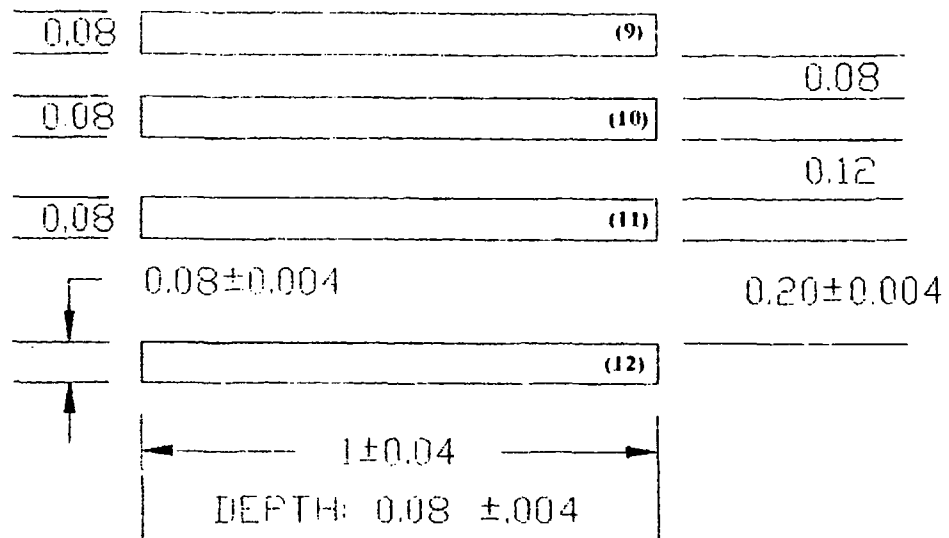
ALL DIMENSIONS ARE MEASURED WITH DIMENSIONAL EQUIPMENT WHICH IS CERTIFIED AND TRACEABLE TO NIST #708) #2343033 AND NIST (#763183) #3681145. NUCLEAR REGULATORY COMMISSION RULES AND REGULATIONS 10 CFR PART 21 APPLIES TO THIS ORDER. ALL NOTCHES MANUFACTURED PER WESTPRO PROCEDURE WQC-IV.

CERTIFIED BY: S. CHAMBERLAIN

APPROVED BY: *S. Chamberlain*

A-4





NOTE: TOLERANCES ARE  
CONSISTENT FOR ALL 4  
NOTCHES IN EACH INSTANCE

