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Ultrasonic Phased Array Evaluation of Control Rod Drive Mechanism (CRDM) Nozzle Interference Fit and Weld Region NDE Results and Destructive Analysis


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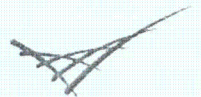
Greg Oberson, NRC Program Manager


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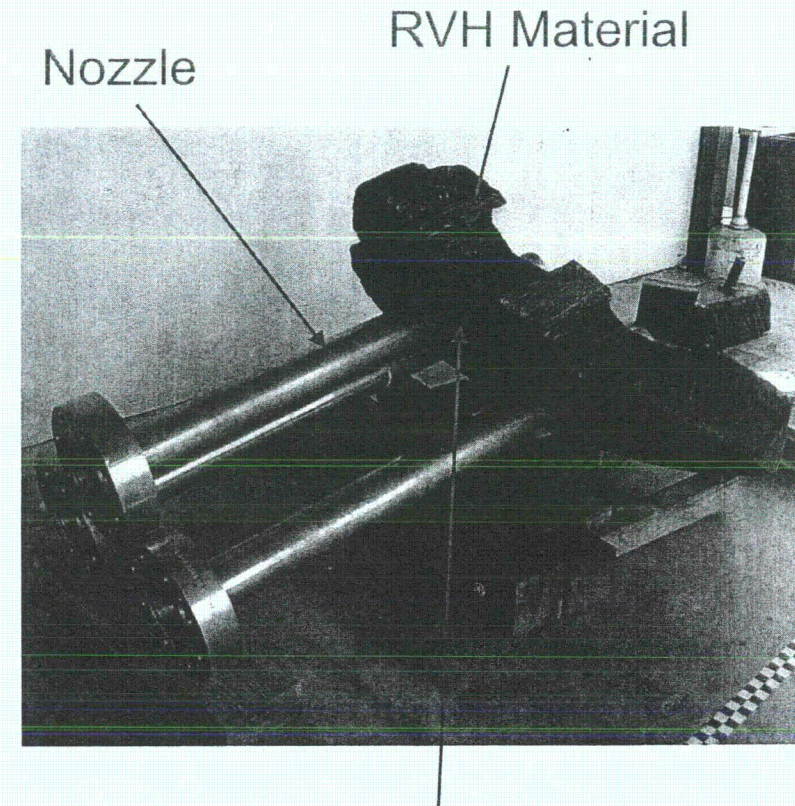
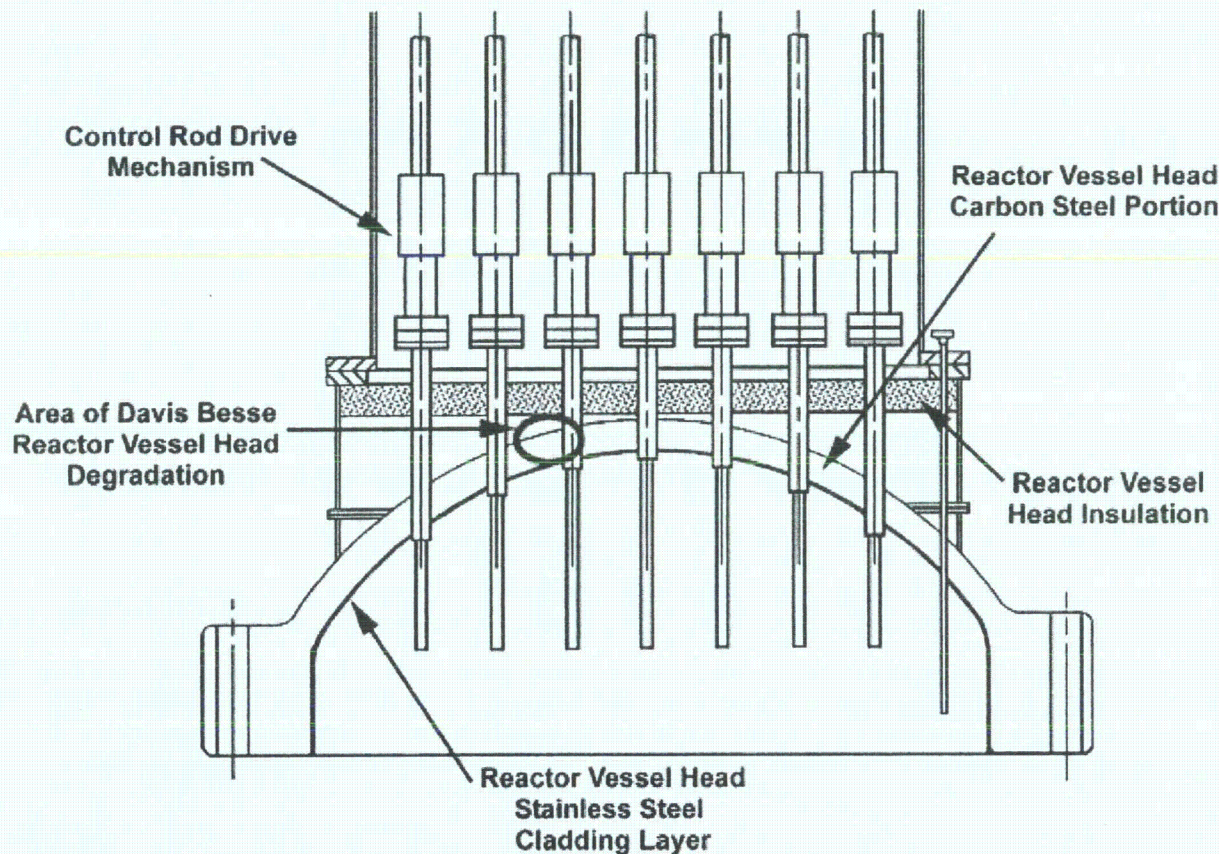
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Topics of Discussion

- ▶ CRDM Nozzles
- ▶ Objectives of the Current Study (Nozzle 63)
- ▶ Mock-up Calibration Specimen
- ▶ Evaluation of UT-Phased Array Inspection Approach
 - Ultrasonic probe and phased array system
 - Probe modeling of sound fields
 - Data acquisition and analysis
- ▶ Destructive Analysis (Nozzle 63)
 - Leak Path Assessment
 - Boric Acid/Corrosion Product Assessment
- ▶ Summary of Results/Conclusions
- ▶ Questions



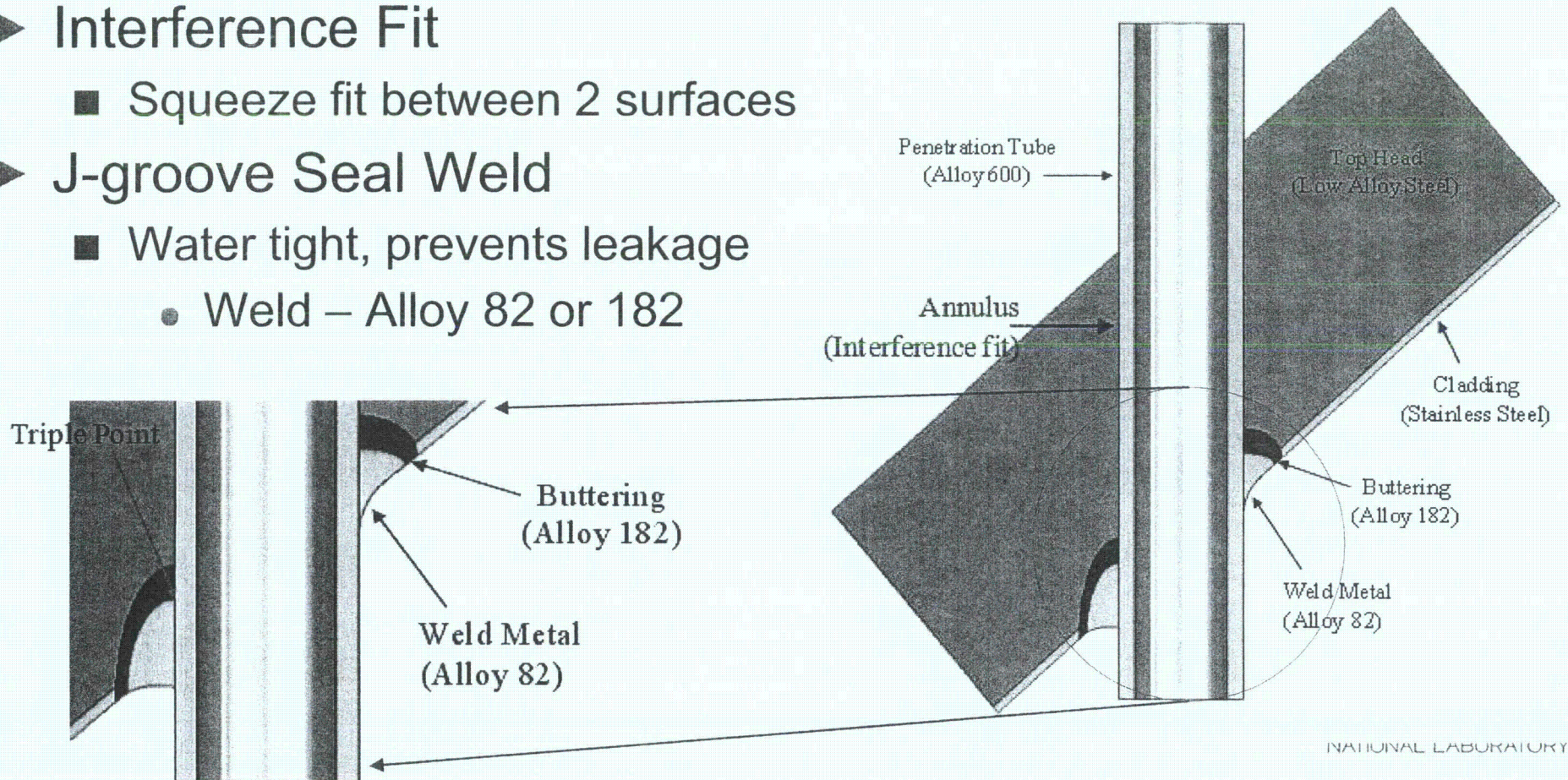
CRDM Nozzle Usage



- ▶ Pressurized Water Reactors (PWR)
- ▶ Facilitate control of a nuclear reactor
 - Raise and lower control rods through nozzle

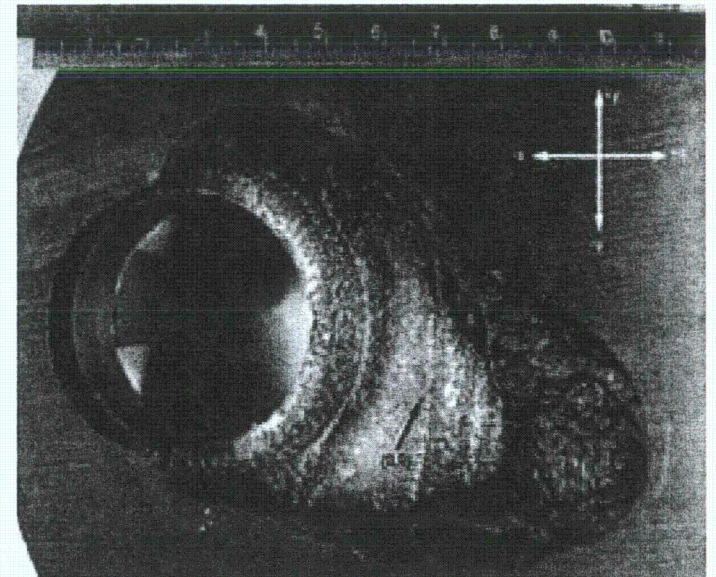
CRDM Nozzle/Fit/Weld Design

- ▶ Vessel Head Penetration (VHP) nozzle
 - Nickel-based alloy, Alloy 600 (Inconel) tube
 - Low Alloy Steel Reactor Vessel Head (RVH)
 - Interference fit and J-groove weld hold nozzle in place
- ▶ Interference Fit
 - Squeeze fit between 2 surfaces
- ▶ J-groove Seal Weld
 - Water tight, prevents leakage
 - Weld – Alloy 82 or 182



CRDM Nozzle/Fit/Weld Vulnerabilities and Concerns

- ▶ Nickel-Based alloys - susceptible to primary water stress corrosion cracking (PWSCC)
 - Cracking in J-groove weld or Inconel tube could lead to leakage of borated water into the fit region
- ▶ Leakage related concerns
 - Hot, pressurized borated water erodes/corrodes low alloy RVH material and ultimately escapes the reactor vessel
 - Loss-of-coolant accident (LOCA)
 - Worst case: Borated water erodes a significant amount of the carbon steel RVH
 - Provided circumferential cracking
 - Results in ejection of nozzle
- ▶ Corrosion example: Davis-Besse Plant



Objectives of the Current Study

- ▶ The objective of this work was to conduct ultrasonic nondestructive tests to assess a reported leak path in the annulus of a removed-from-service nozzle
 - Design and build a mock-up CRDM nozzle specimen
 - Conduct ultrasonic phased array (PA) volumetric inspections
 - Evaluate NDT equipment resolution and characterization properties
 - Conduct ultrasonic PA volumetric inspections on a removed-from-service specimen, North Anna 2 Nozzle 63
 - Use mock-up data to correlate known response signals to Nozzle 63 data
 - Verify the ultrasonic PA data with the destructive analysis of Nozzle 63



Nozzle 63

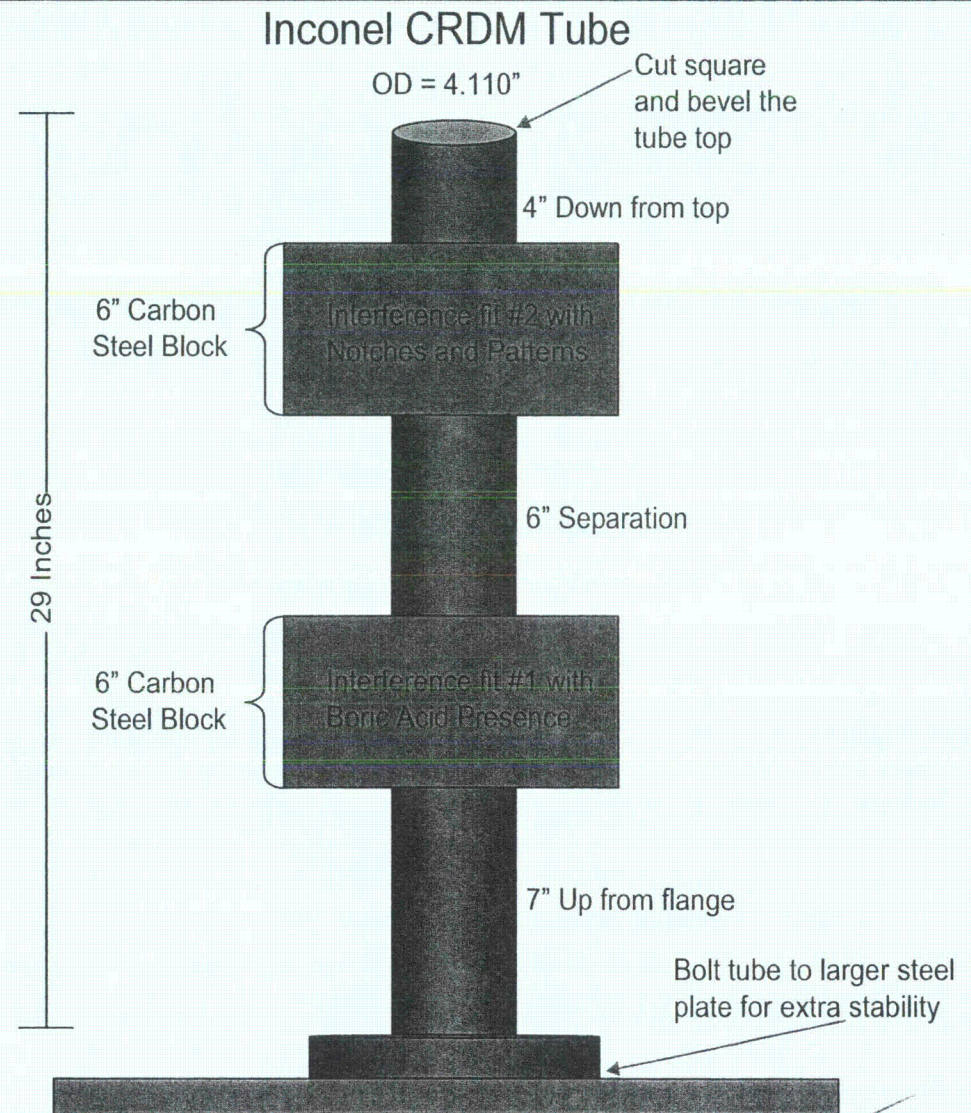
- ▶ Obtained from the original North Anna Unit-2 Nuclear Power Plant (NPP)
- ▶ In the 2001 refueling outage, Nozzle 63 was repaired
- ▶ In the 2002 outage, significant flaw indications and weld cracks resulted in the decision to replace the entire RVH
- ▶ Nozzle 63 was cut from the RVH and saved for research
- ▶ Previous Nozzle 63 characterizations (Industry)
 - Bare metal visual (BMV) results were inconclusive (masked)
 - Volumetric NDT revealed a probable leak path



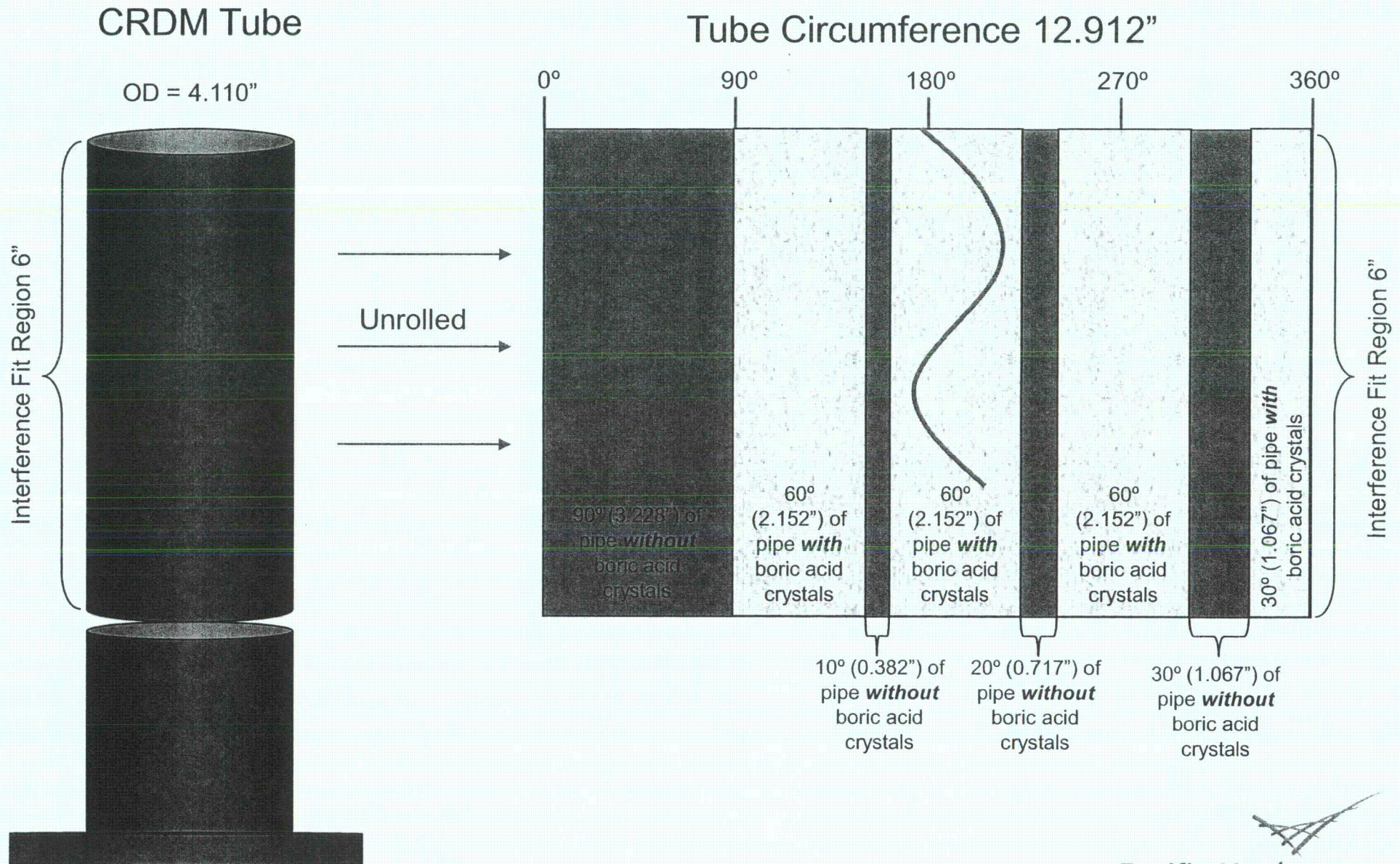
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Mock-up Calibration Specimen Design

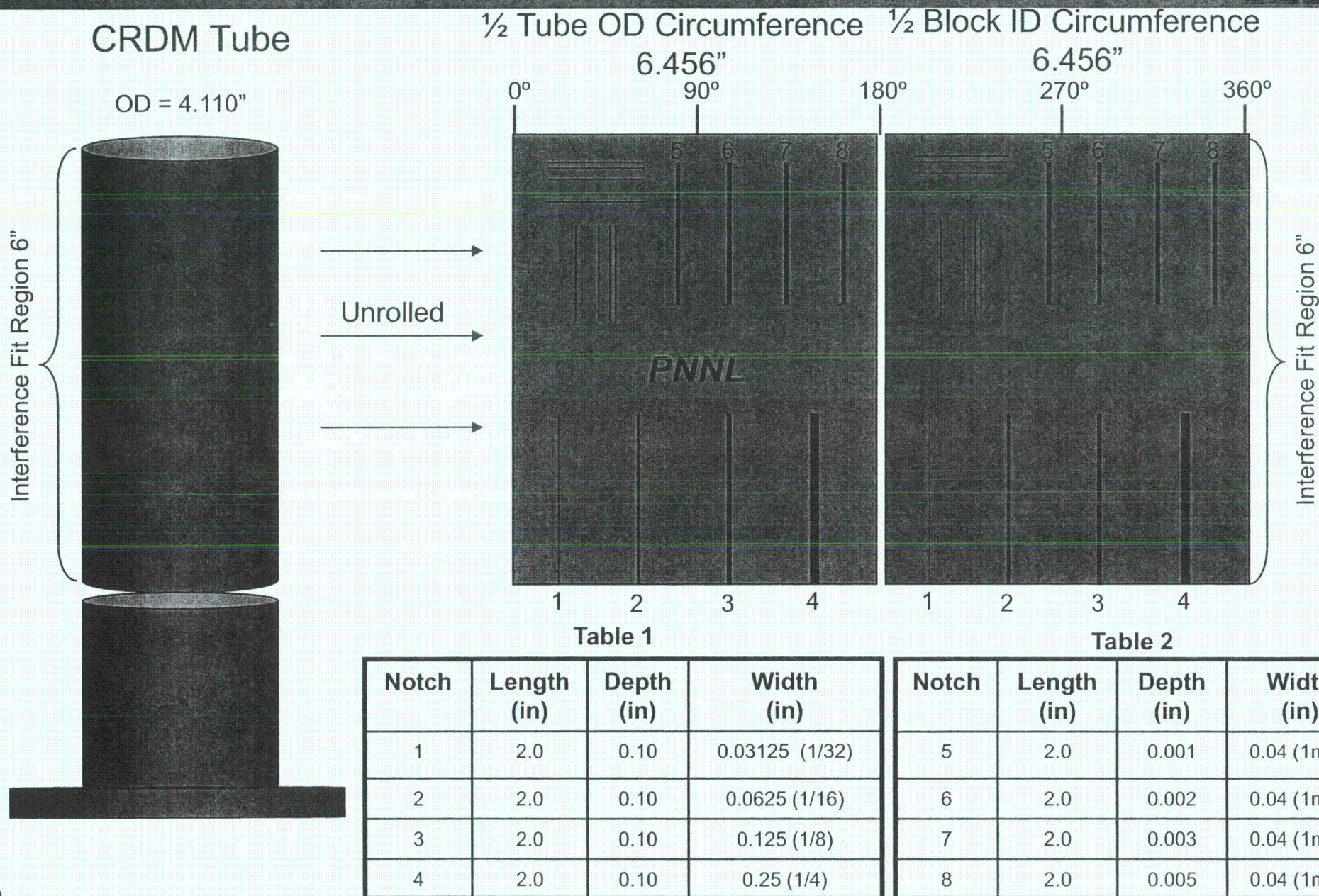
- ▶ Goal: Mimic actual field interference fits
 - Inconel tubing and RVH material
 - Used similar assembly procedures
 - 3 mil fit
- ▶ Components:
 - Inconel tube (OD = 4.110")
 - Two 6" thick carbon steel blocks
 - Machined holes (D = 4.107")
- ▶ Created 2 fit regions
 - Boric acid presence
 - Precision EDM notch presence
- ▶ Designed for specific signal responses
 - Inspection resolution
 - Leak path characteristics



Interference Fit #1: Boric Acid Presence Layout

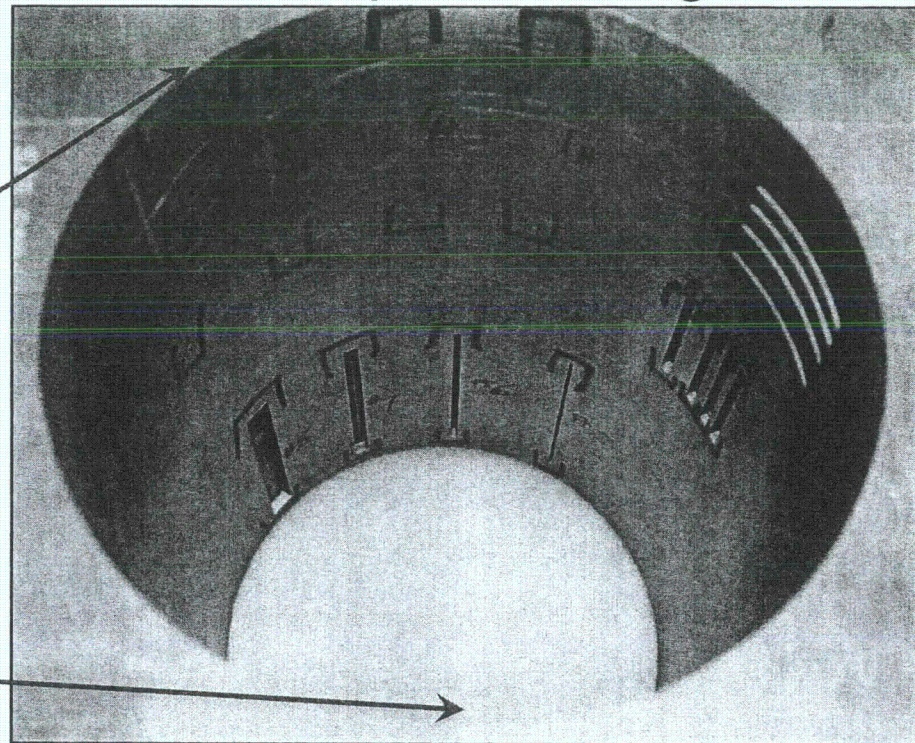
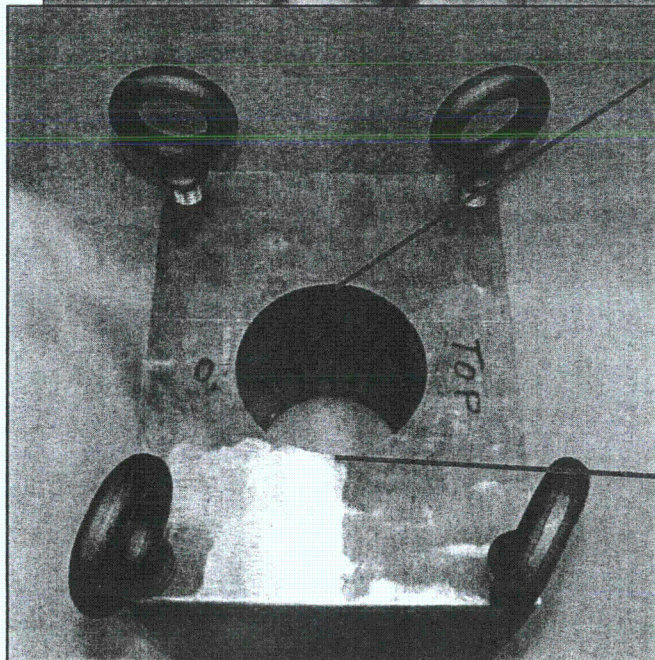
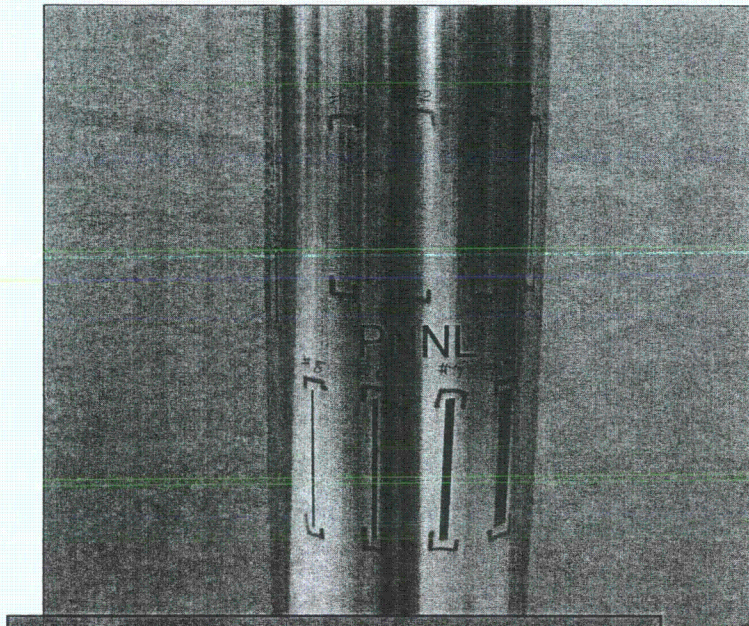


Interference Fit #2: Notches and Patterns



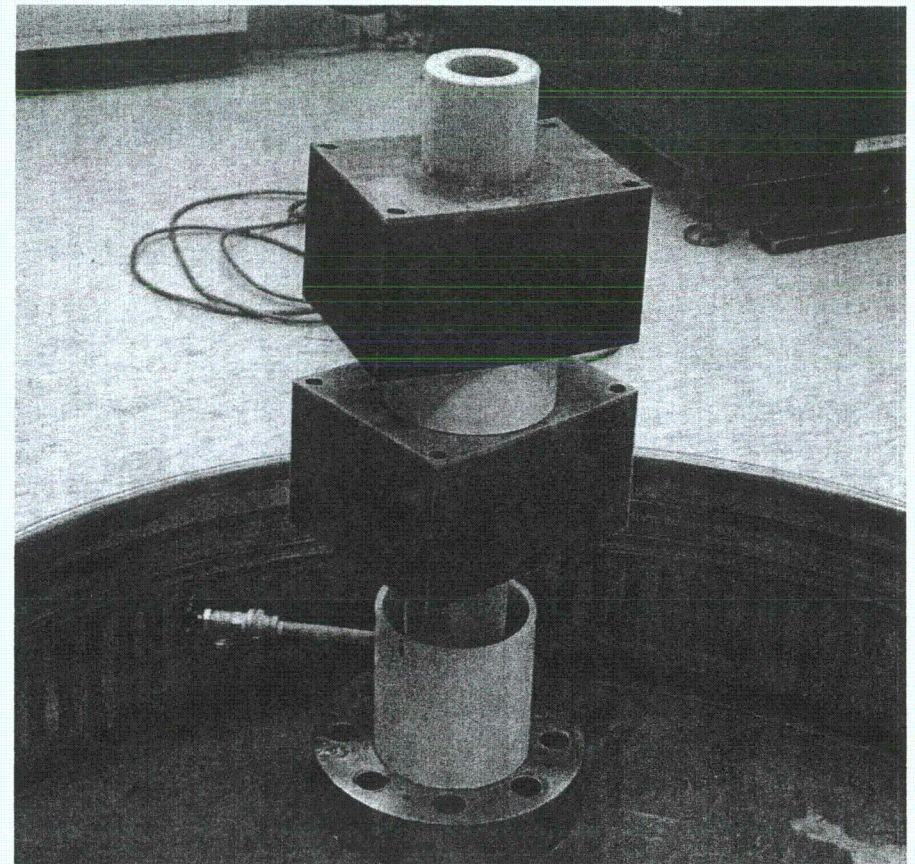
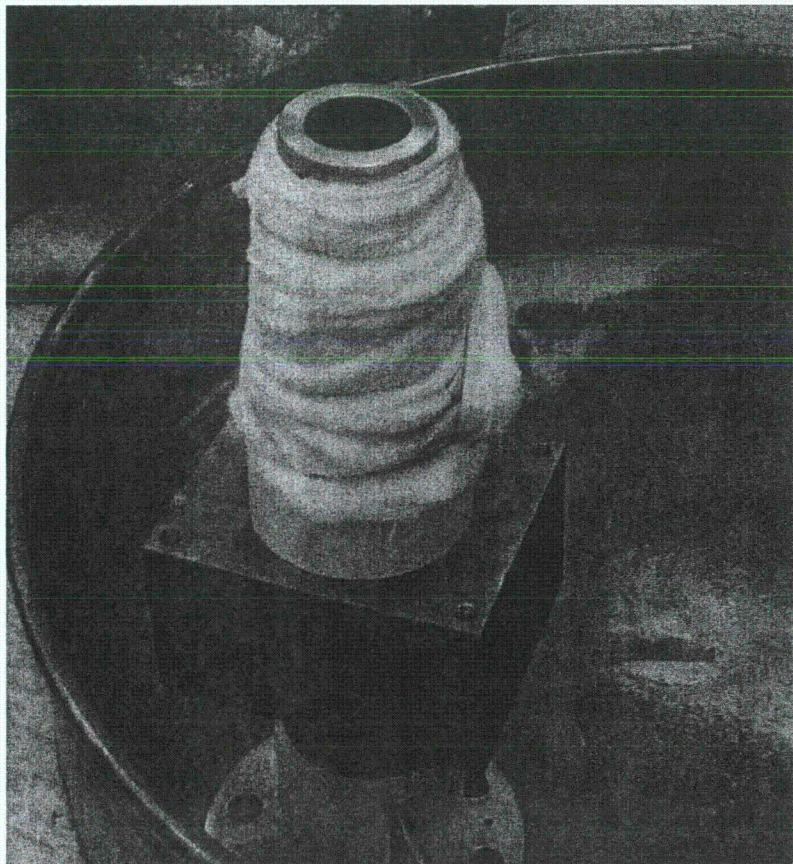
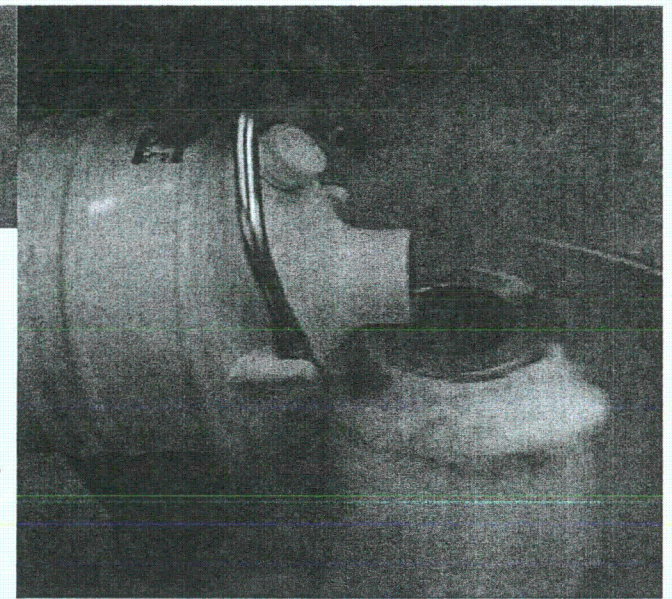
Notches and Patterns

- ▶ Precision EDM notches
- ▶ Machined in two materials
 - Inconel tube OD
 - Carbon steel block ID
- ▶ 'PNNL' pattern engraved



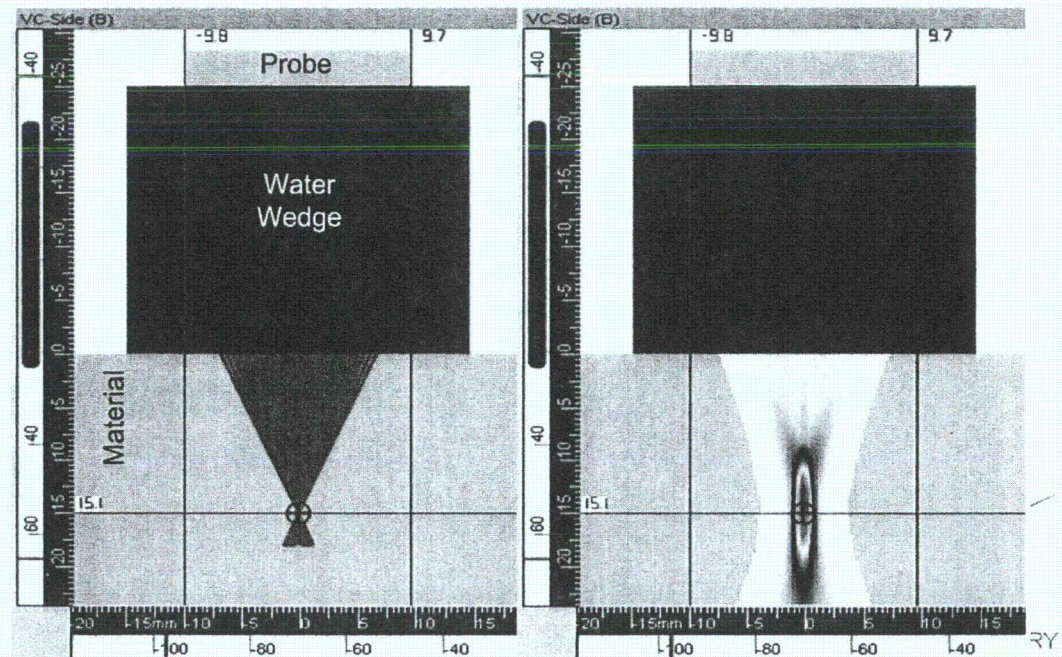
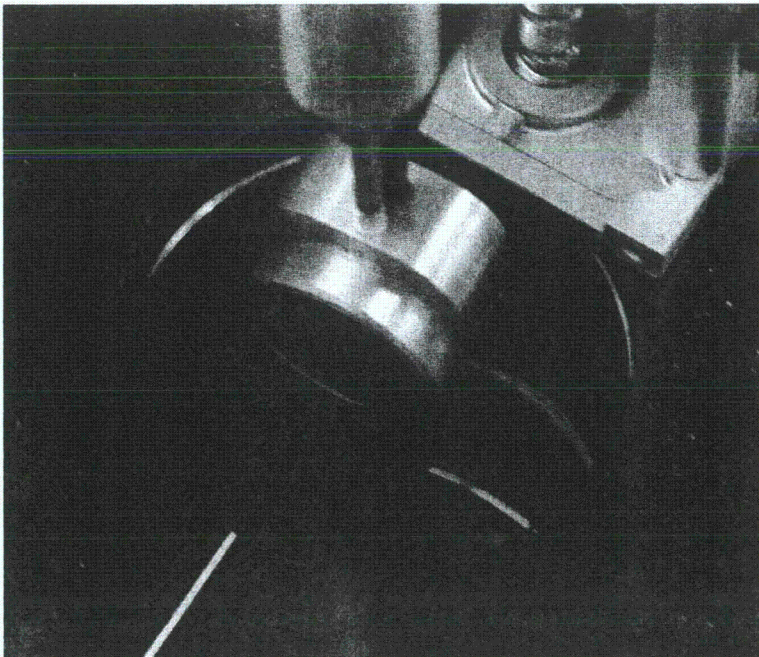
Mock-up Assembly

- ▶ Shrunk Inconel tube to allow assembly
 - Filled tube with liquid nitrogen
 - Monitored tube diameter during cooling process
- ▶ Lowered carbon steel blocks into position



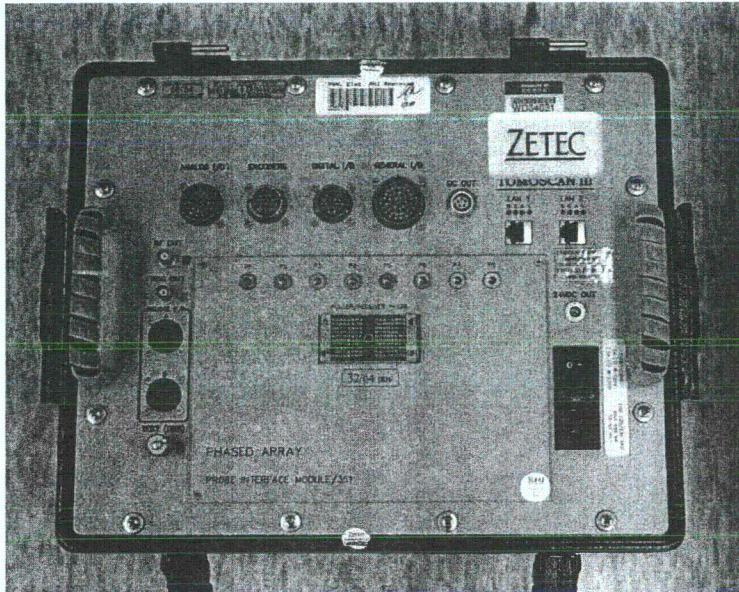
Ultrasonic Phased Array Probe

- ▶ Custom pulse-echo (PE) immersion phased array probe
 - Center frequency – 5 MHz
 - 1-D annular Fresnel configuration
 - 8 elements
 - Element radii from 3 to 9.72 mm
 - 296.81 mm² total aperture
- ▶ Designed for variable depth focusing capabilities



Phased Array System and Scanner

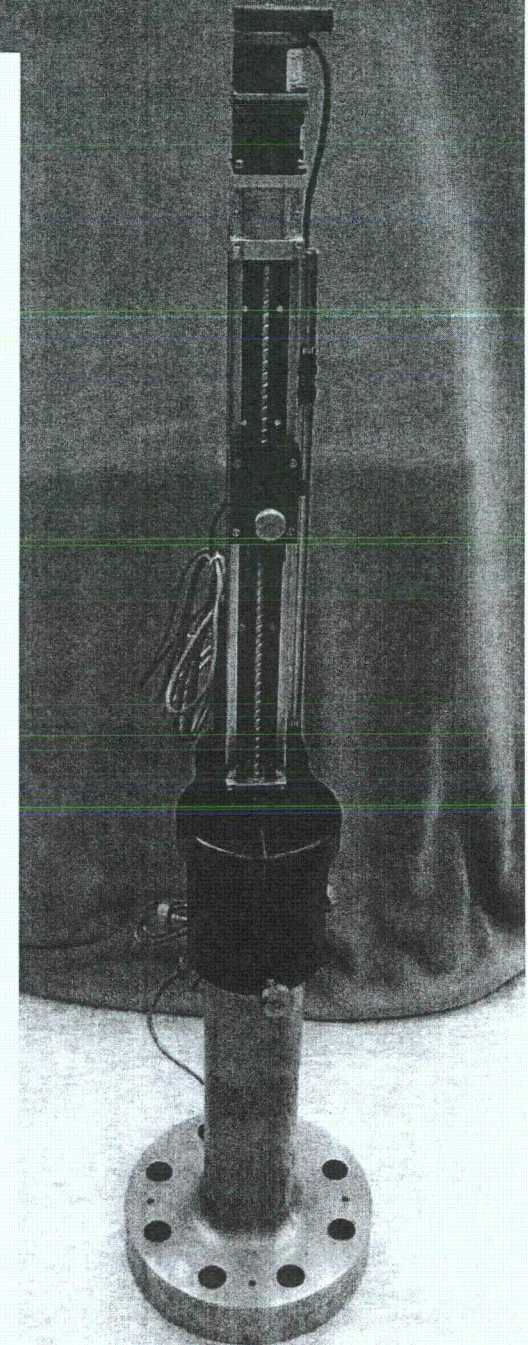
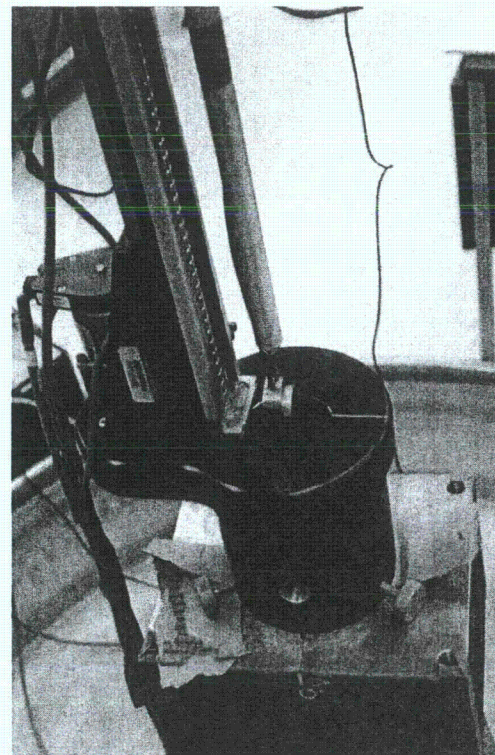
Tomoscan III PA System 0.7 – 20 MHz



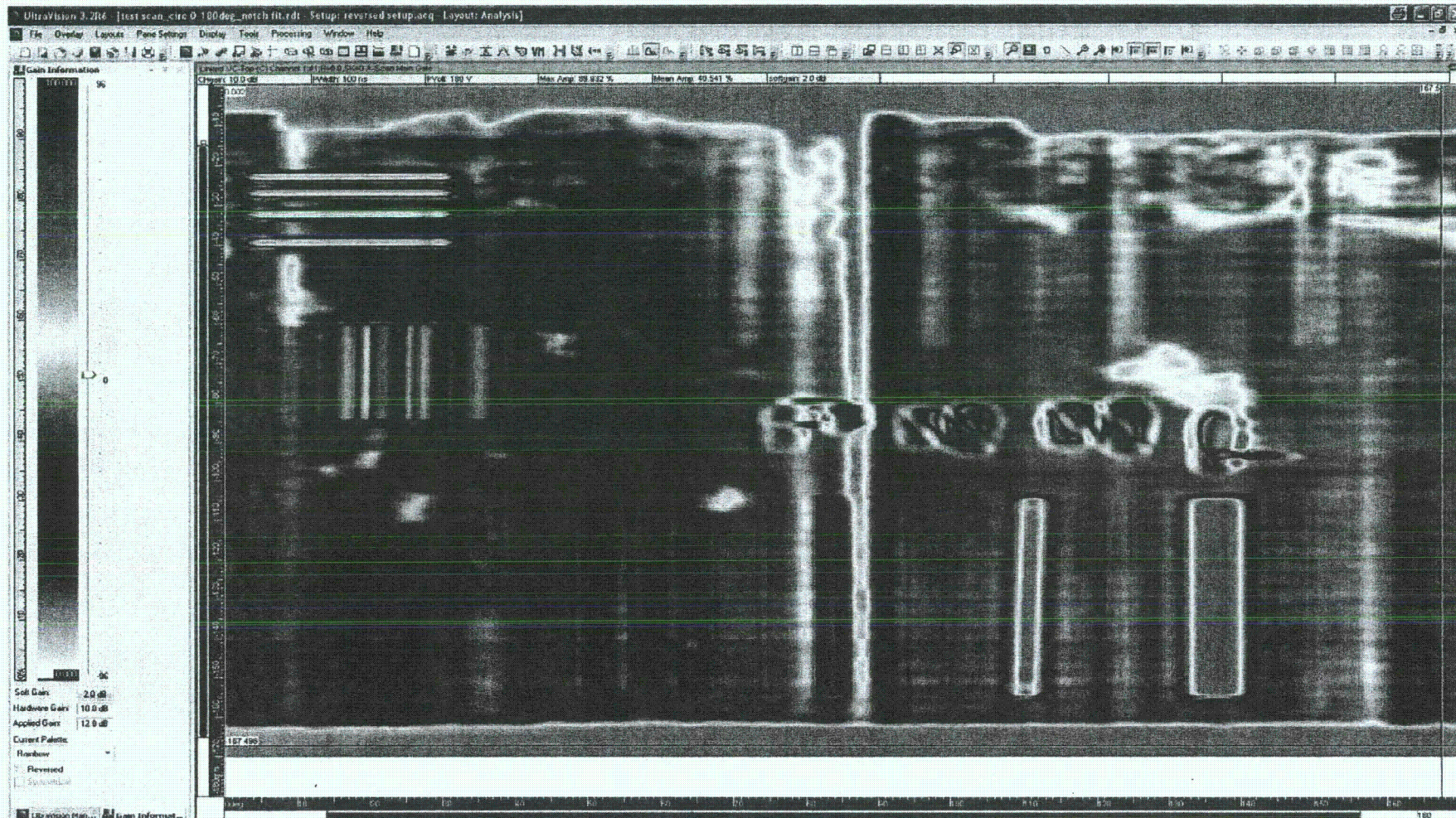
- ▶ Accommodates a maximum of 64 channels
- ▶ Controlled by UltraVision 1.2R4 software
- ▶ Accepts multiple axis positional information

Custom Pulse Motor Scanner

- ▶ 2 axes of motion
 - Axial 0 - 18"
 - Circumferential 0 - 360 degrees
- ▶ Mounts directly on nozzle



Ultrasonic Data: Mock-up Notches



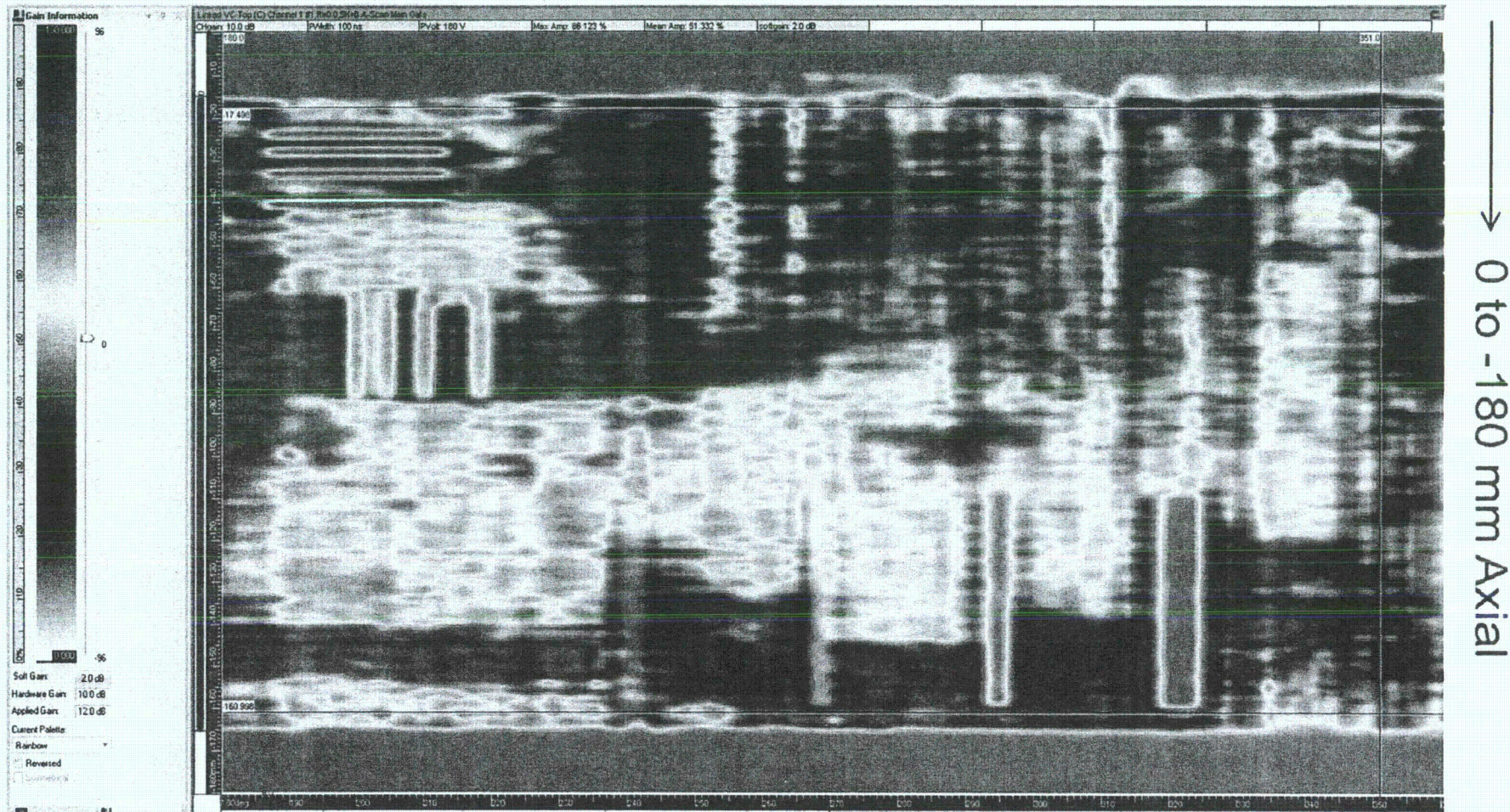
0 to 170 deg. Circumference

► C-Scan view: Calibration notches in the Inconel tube



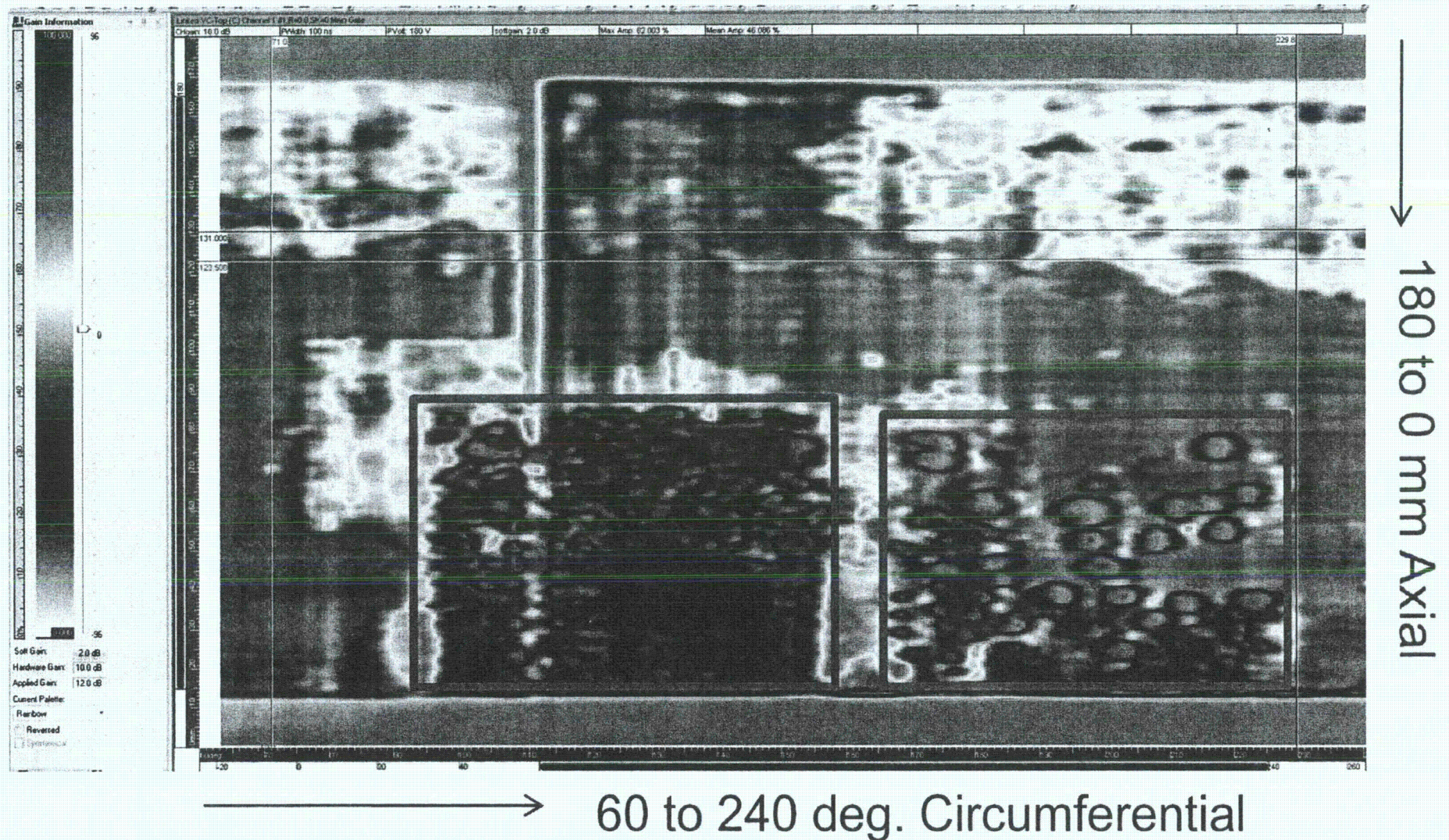
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Ultrasonic Data: Mock-up Notches



- C-Scan view: Calibration notches in the carbon block

Ultrasonic Data: Mock-up Boric Acid

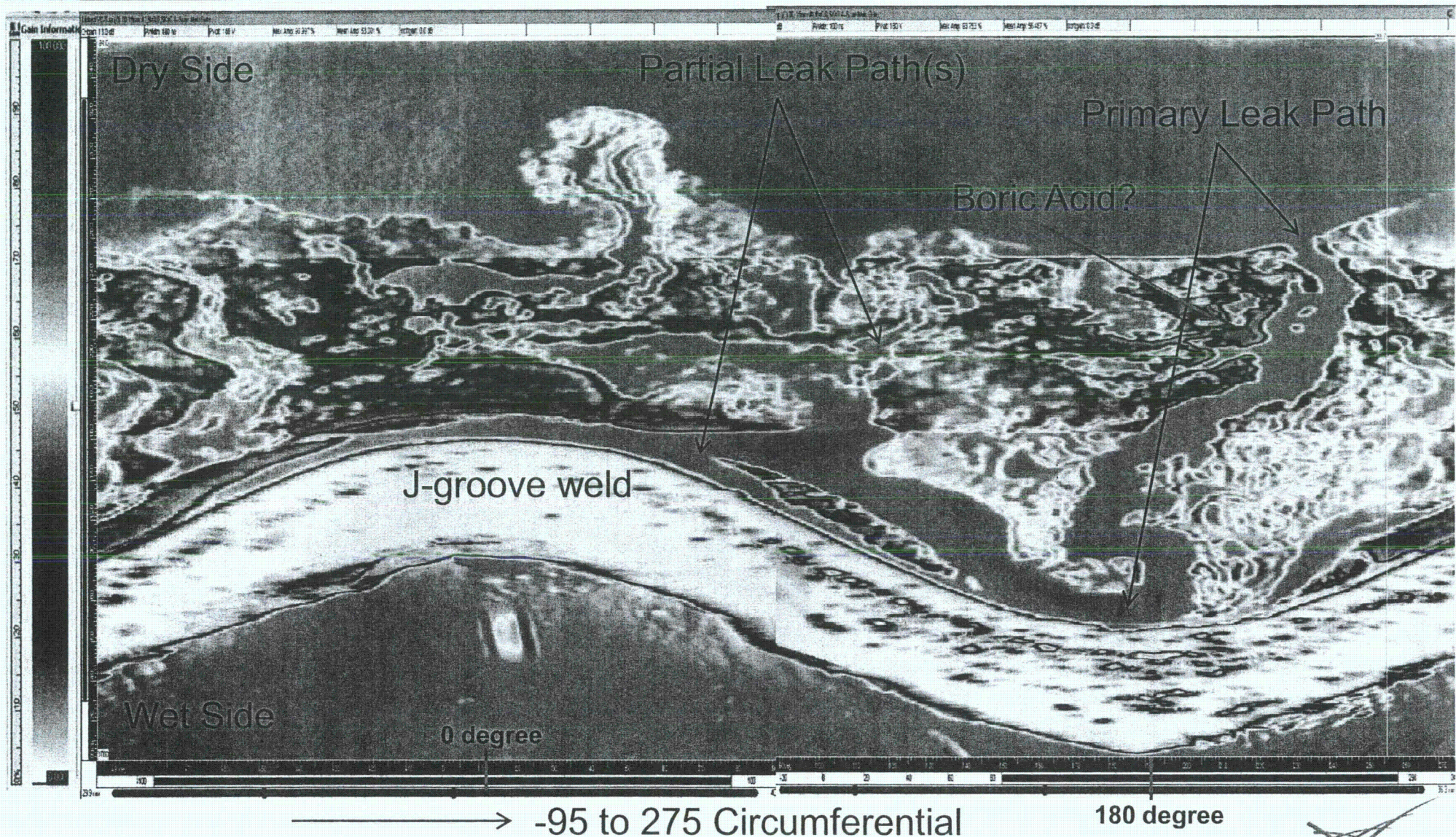


- C-Scan view: Boric acid presence in fit region

Mock-up Characterization Summary

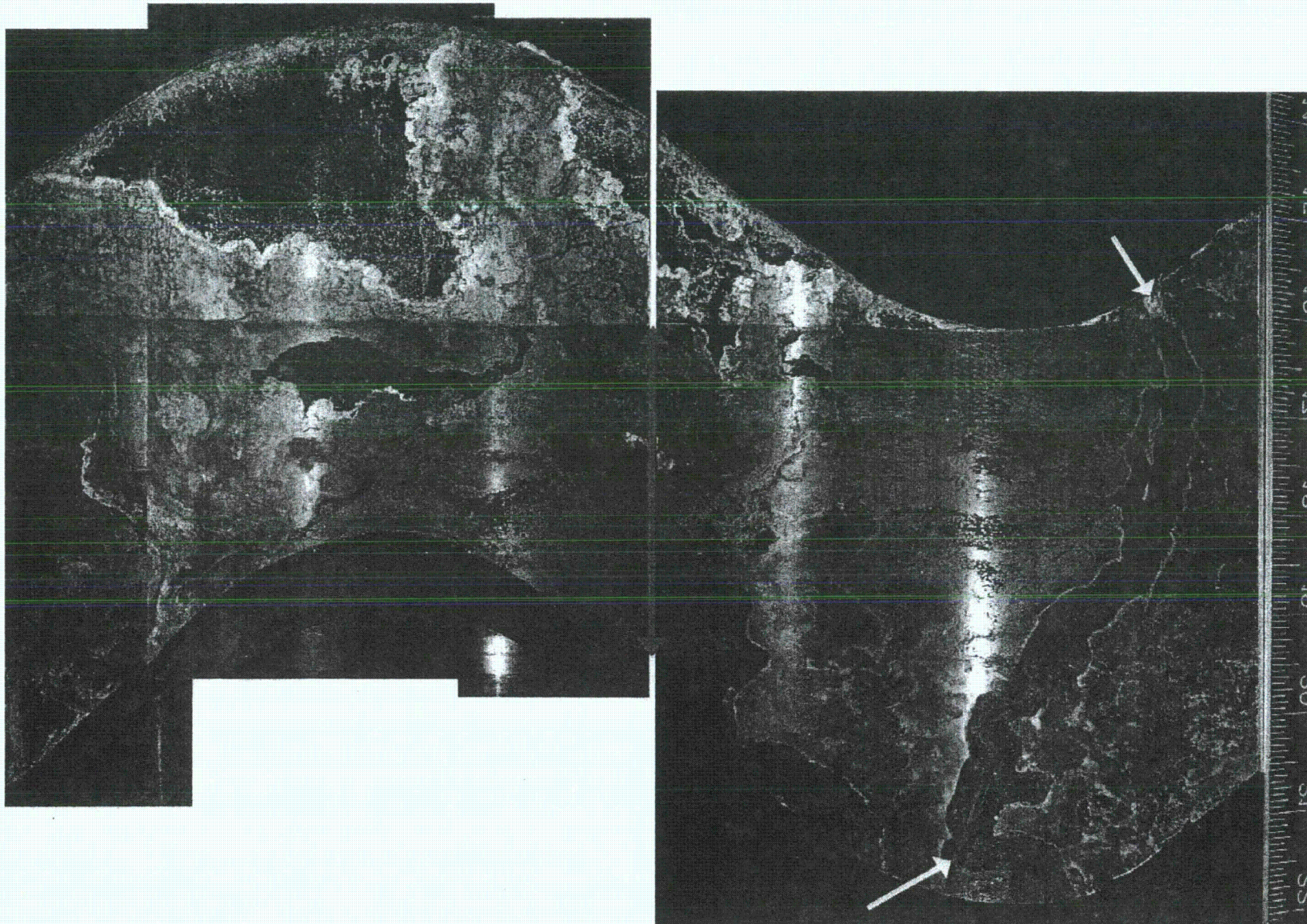
- ▶ All EDM notches were detected
 - Difficult to depth size the 'depth variation notches'
 - Both resolution sets (axial and circumferential) were detected and clearly distinguishable in both Inconel and carbon steel
 - Width variation notches sized within 1 mm
- ▶ Boric Acid presence was easily detected with ultrasound
 - Acid presence created regions of low ultrasonic reflection at the interference fit zone
 - Served as a couplant medium for ultrasonic energy

Ultrasonic Data: Nozzle 63



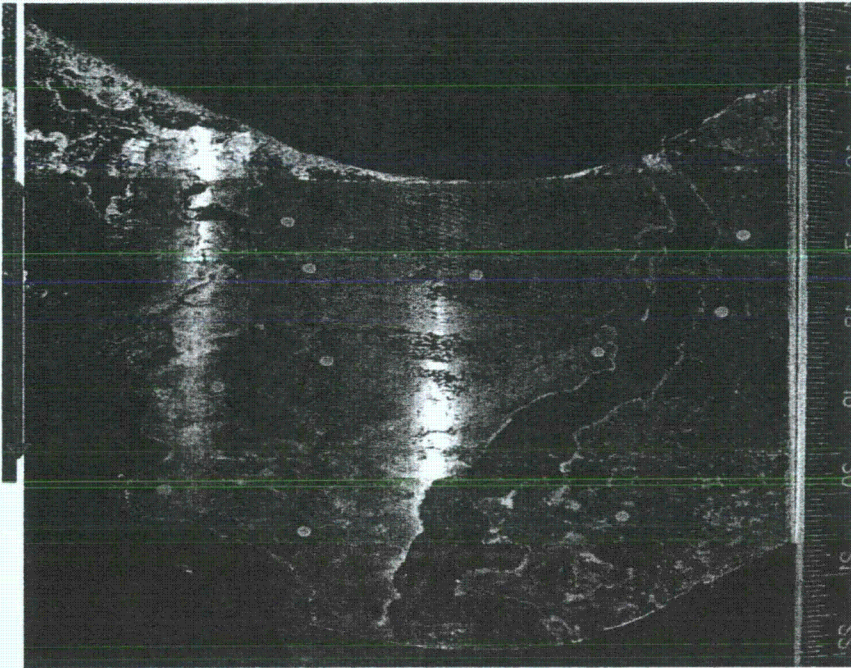
19 ► C-Scan view: Full weld and fit region

Destructive Verification

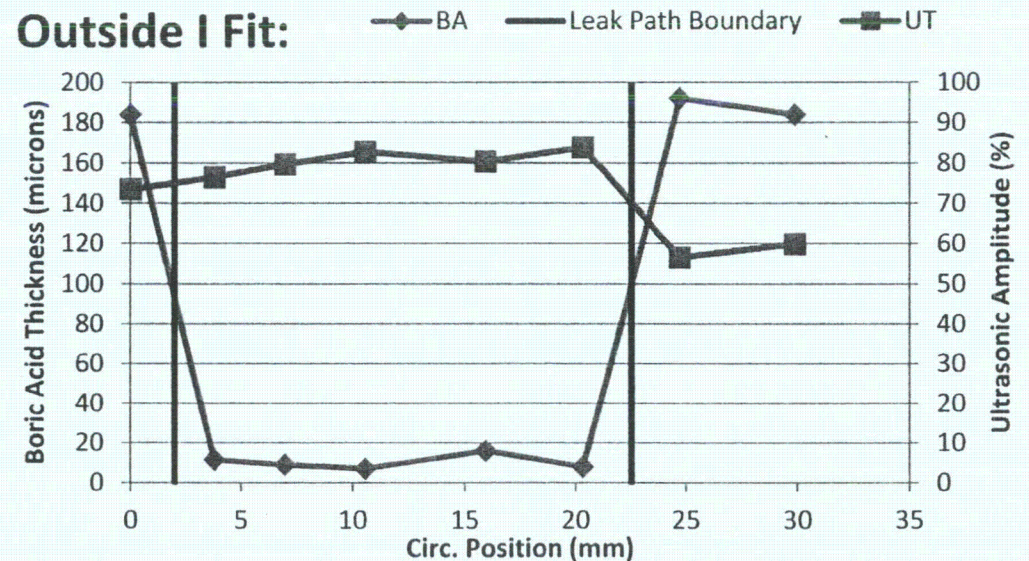
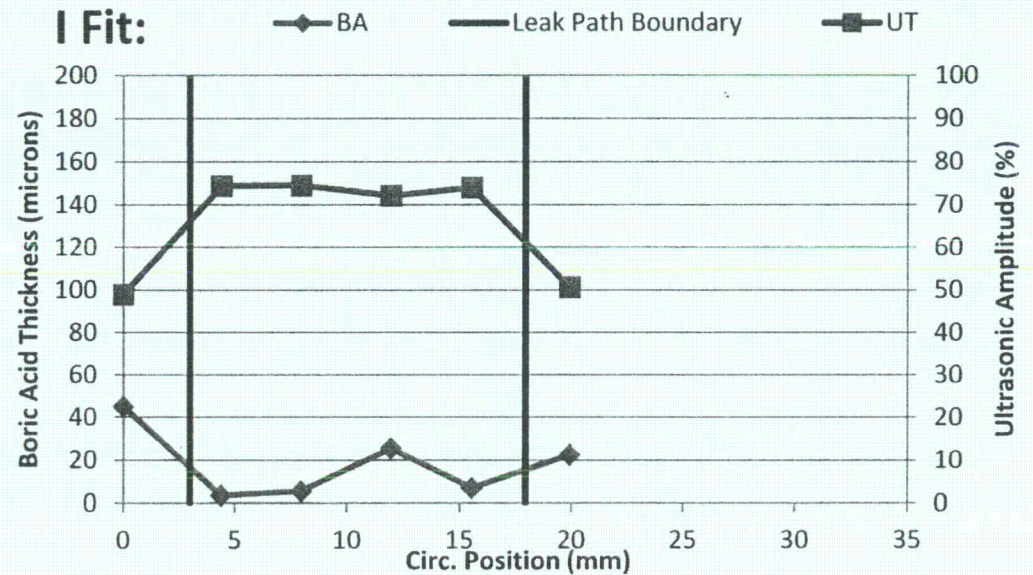


► RVH annulus view montage

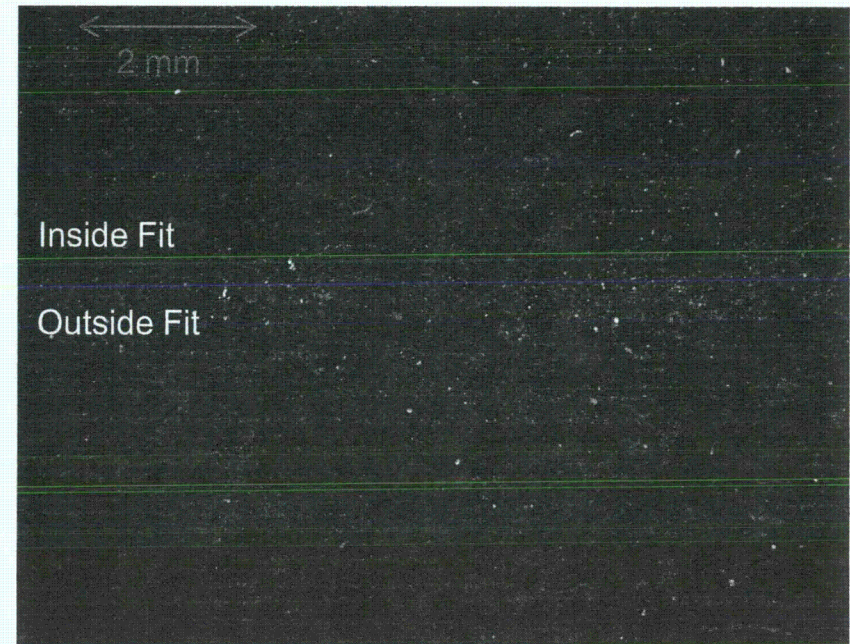
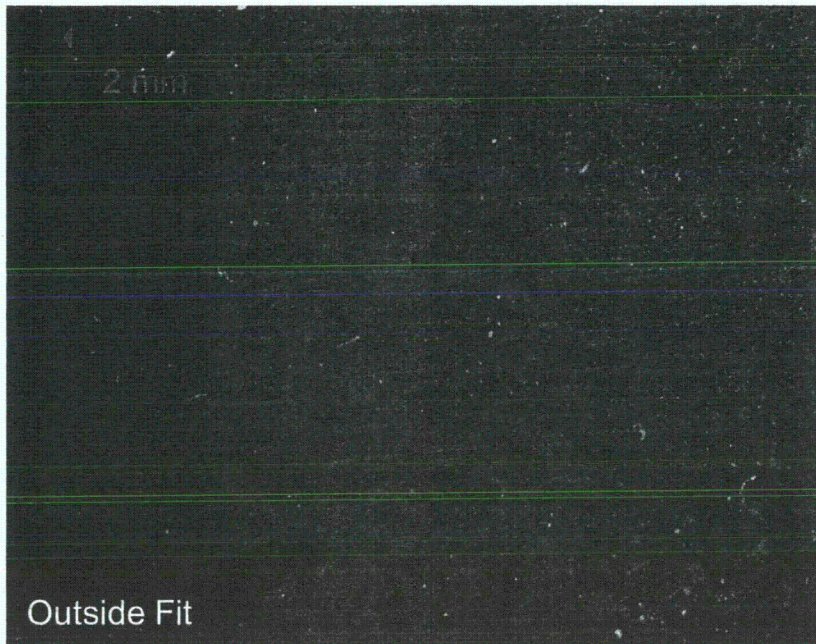
Boric Acid/Corrosion Product Assessment (Leak Path Region)



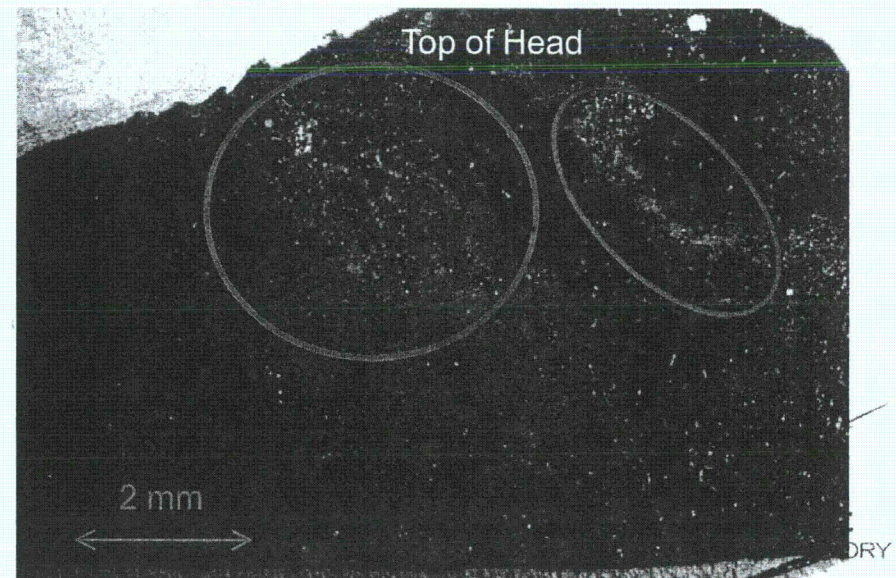
- ▶ Eddy current point probe
 - Accurate to 2.5 microns
 - Measure boric acid/ corrosion product layer thickness
- ▶ Inverse relationship with ultrasonic response



Microset Analysis



- ▶ Replicas made on RPV annulus main leak path region
- ▶ Machining striations present
 - Minimal corrosion/wastage
- ▶ Minor Corrosion visible at top of head region
 - Leak exit point



Results/Conclusions

► Mock-up Specimen

- All calibration notches were detected
 - Most notches sized favorably with true state
 - Shallow notch detection showed sensitivity of UT method
- Boric acid regions were detected
 - Greater ultrasonic transmission in boric acid regions

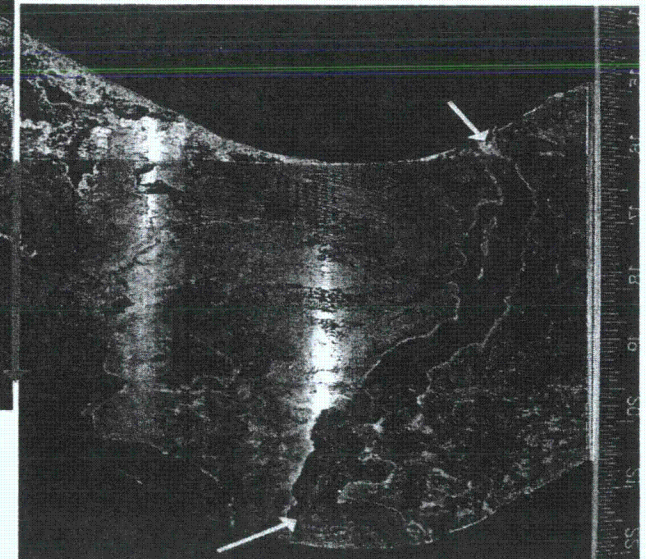
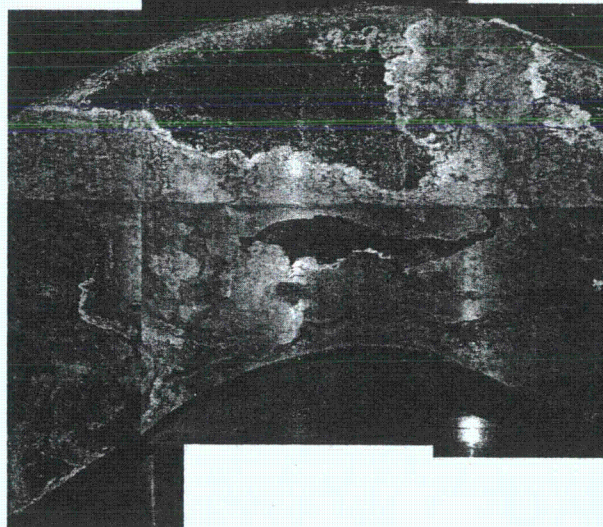
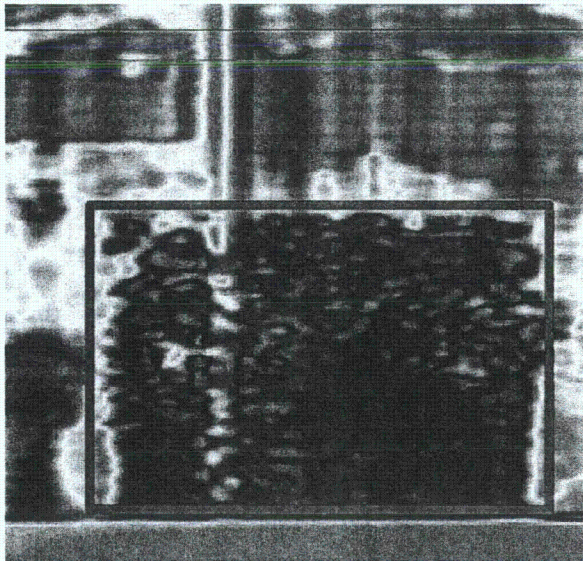
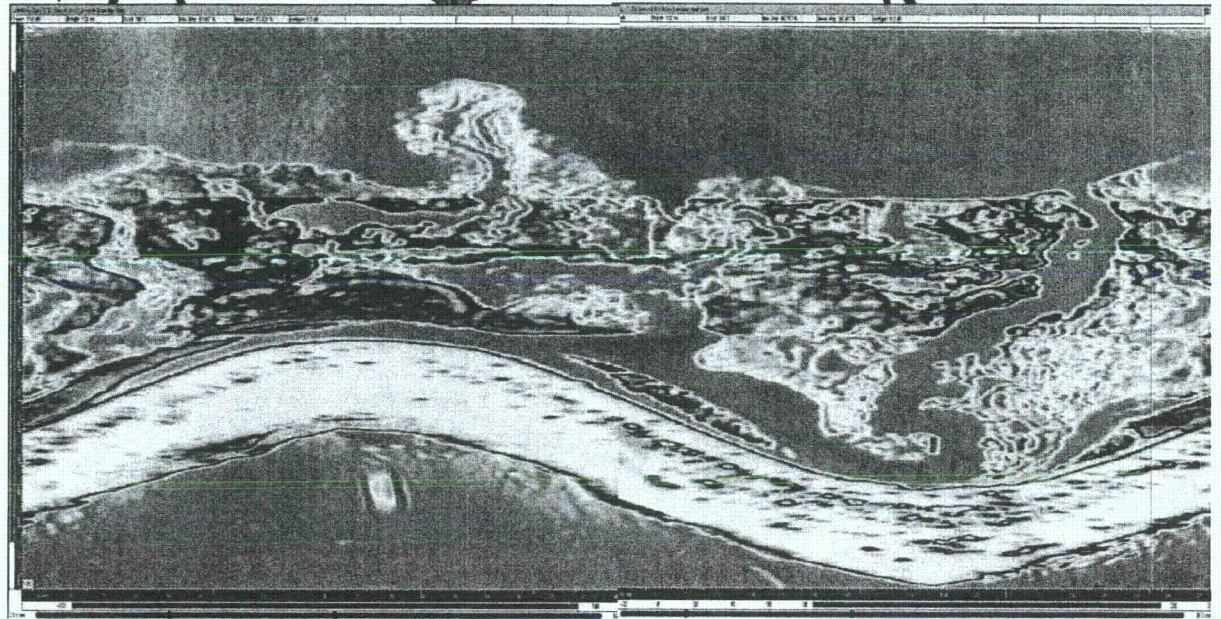
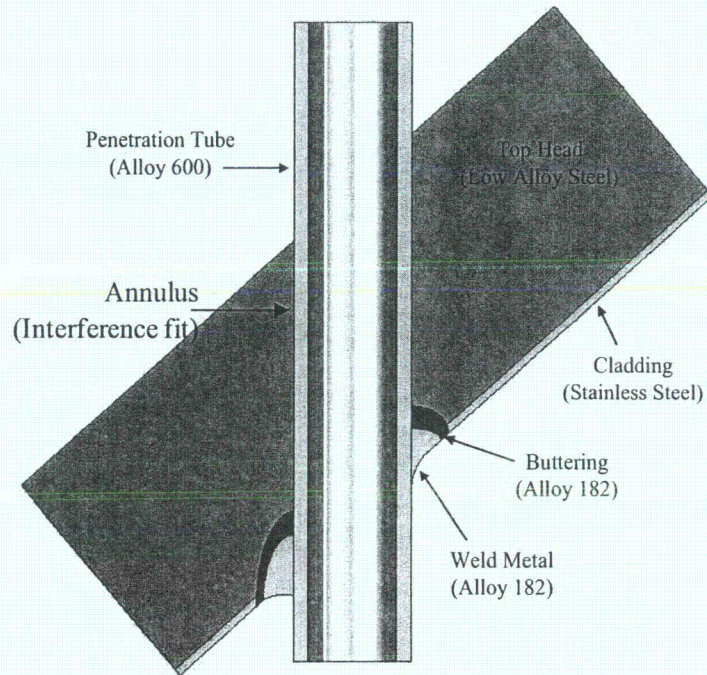
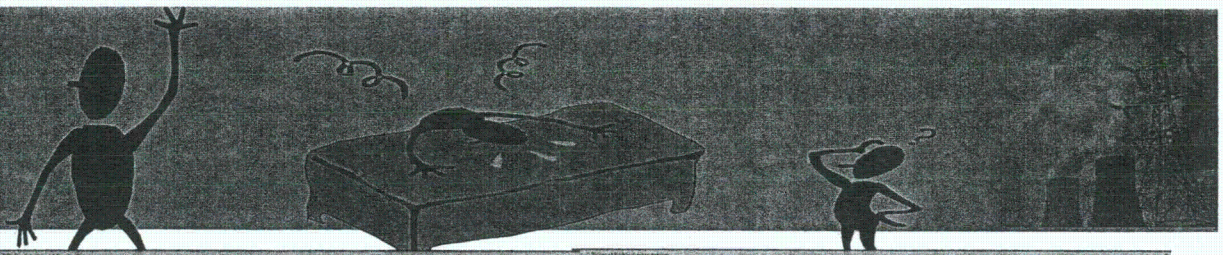
► A leak path was identified in Nozzle 63

- A strong reflection pattern extended from the weld region through the interference fit
- Corresponded to the previous industry assessment
- Surrounding regions showed enhanced ultrasonic transmission
 - Indicative of boric acid trapped in the fit region

► The Leak path in Nozzle 63 was confirmed via destructive analysis



Thank You! Questions?

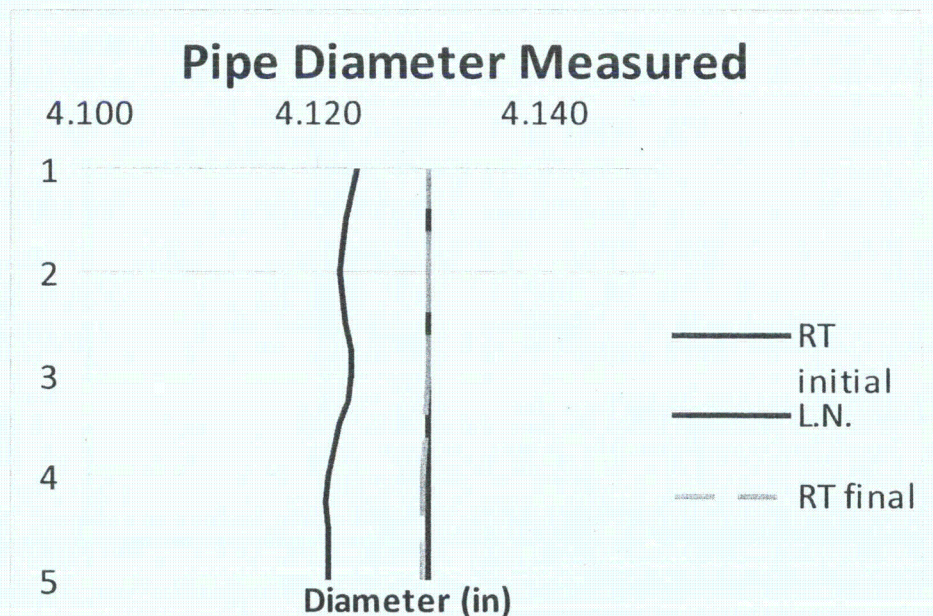
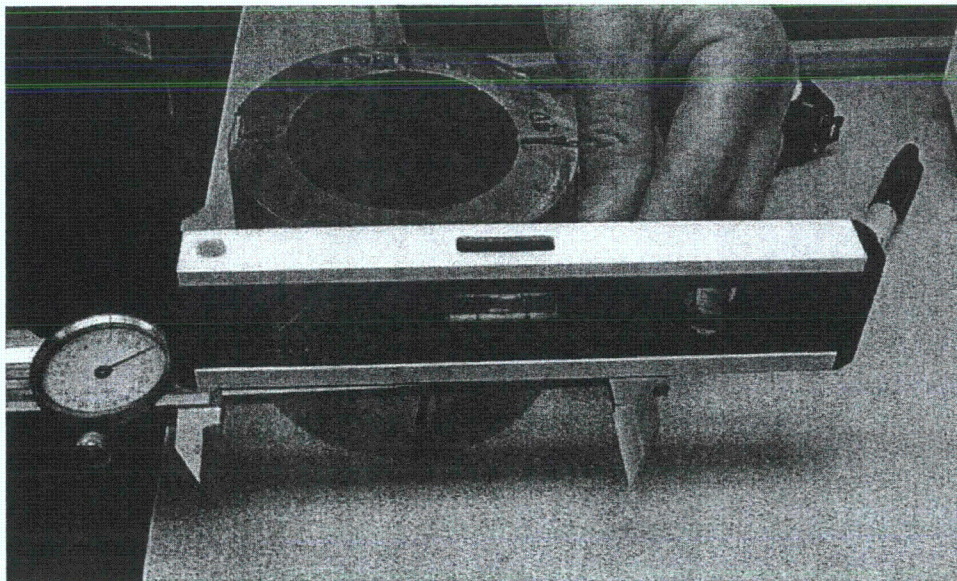


Supplemental Slides Beyond This Point

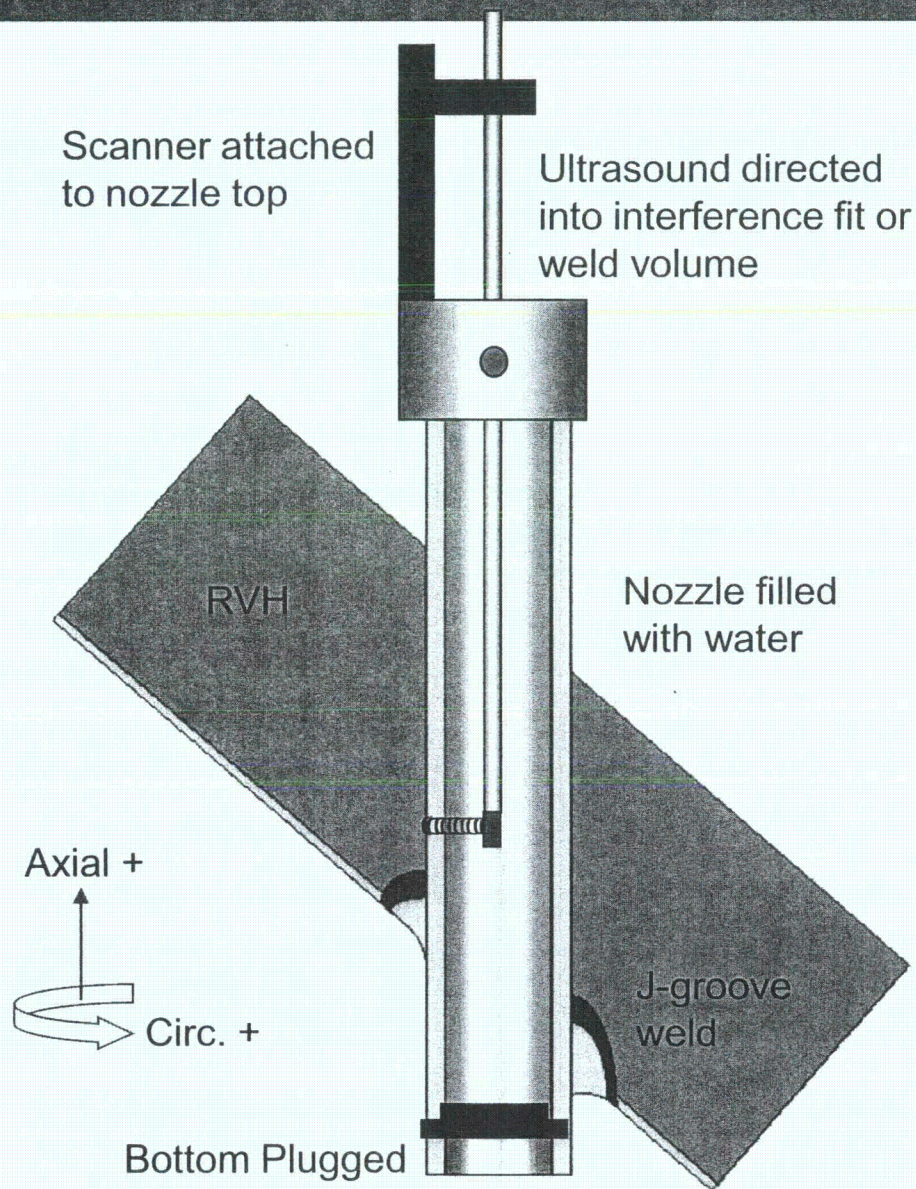


Mock-up Assembly: Inconel Shrinkage

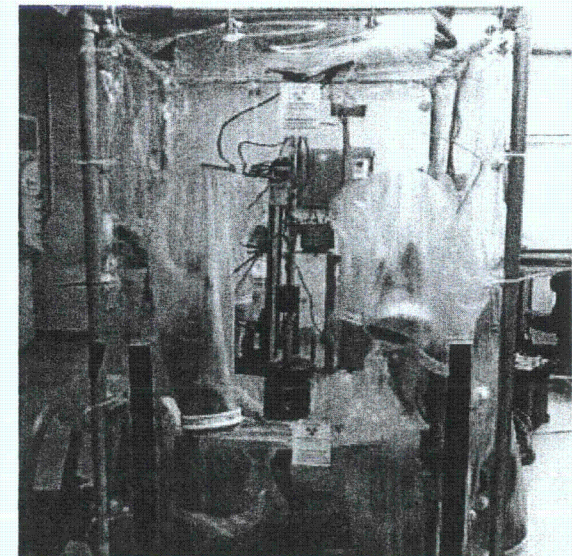
- ▶ Test Inconel tube achievable shrinkage
 - Theory predicts 9 mils
- ▶ Use representative Inconel tube section
 - Measure initial room temperature (RT) diameter (5 axial locations)
- ▶ Cool tube in liquid nitrogen (LN) (77.2°K)
 - Measure diameter at cryogenic temperature
- ▶ Natural equilibration to room temperature
 - Important that tube diameter returns to initial state



Ultrasonic Data Acquisition



- ▶ Multiple depth focal laws implemented
 - Tube ID
 - Tube OD/interference fit region
- ▶ Raster scan protocol
 - 'Scan' in circumferential direction
 - 'Index' in axial direction
- ▶ Resolution
 - 0.5° in scan by 0.5 mm in index
- ▶ Positional information relayed via shaft encoders

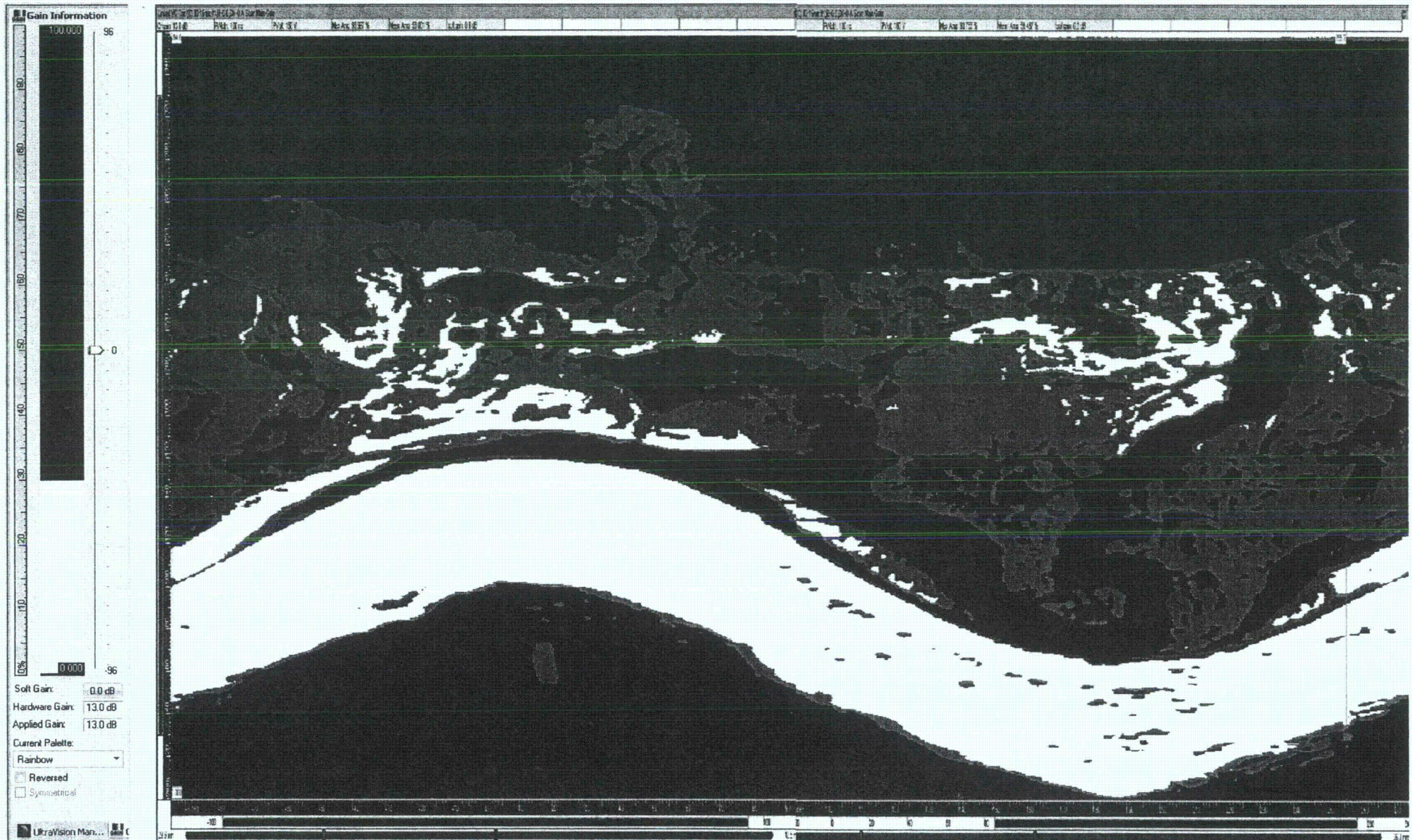


Ultrasonic Data: Nozzle 63 (cont'd)

60-100%

30-60%

0-30%



28 ► C-Scan view: Custom color bar

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Supplemental: Destructive Cutting

