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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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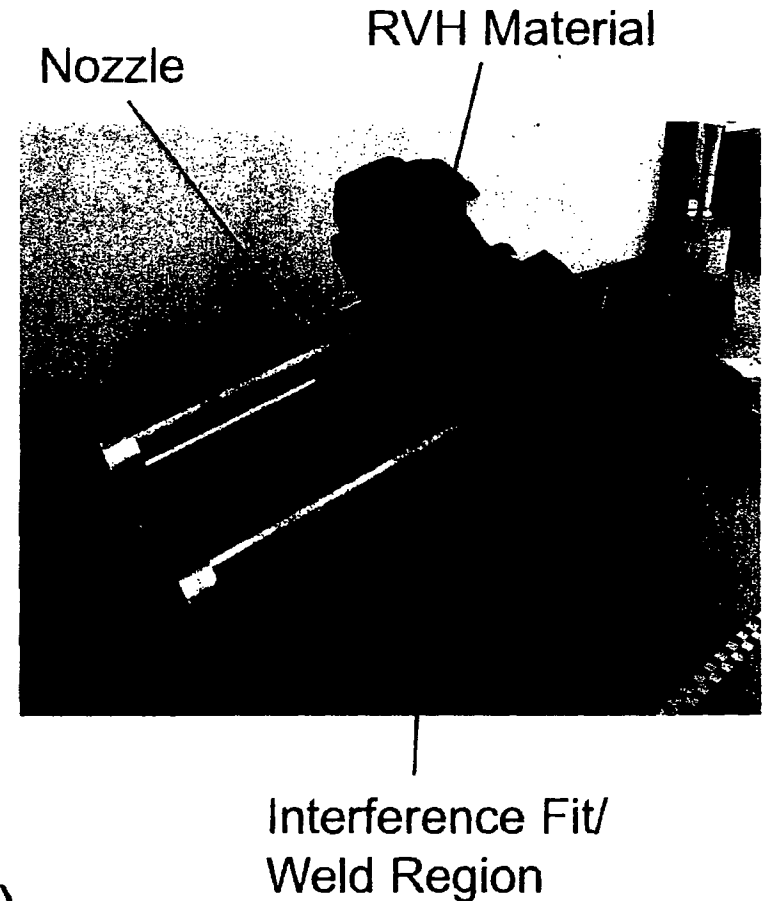
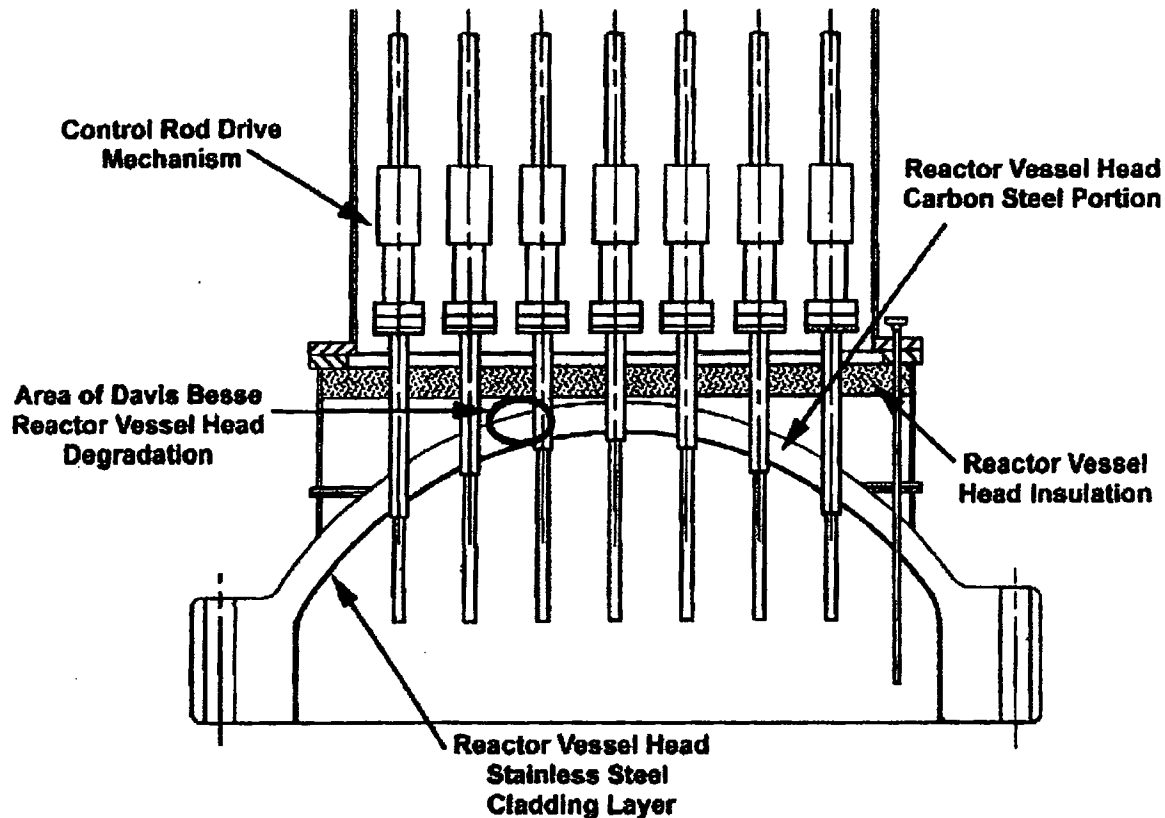
**Greg Oberson, NRC Program Manager**

  
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# 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

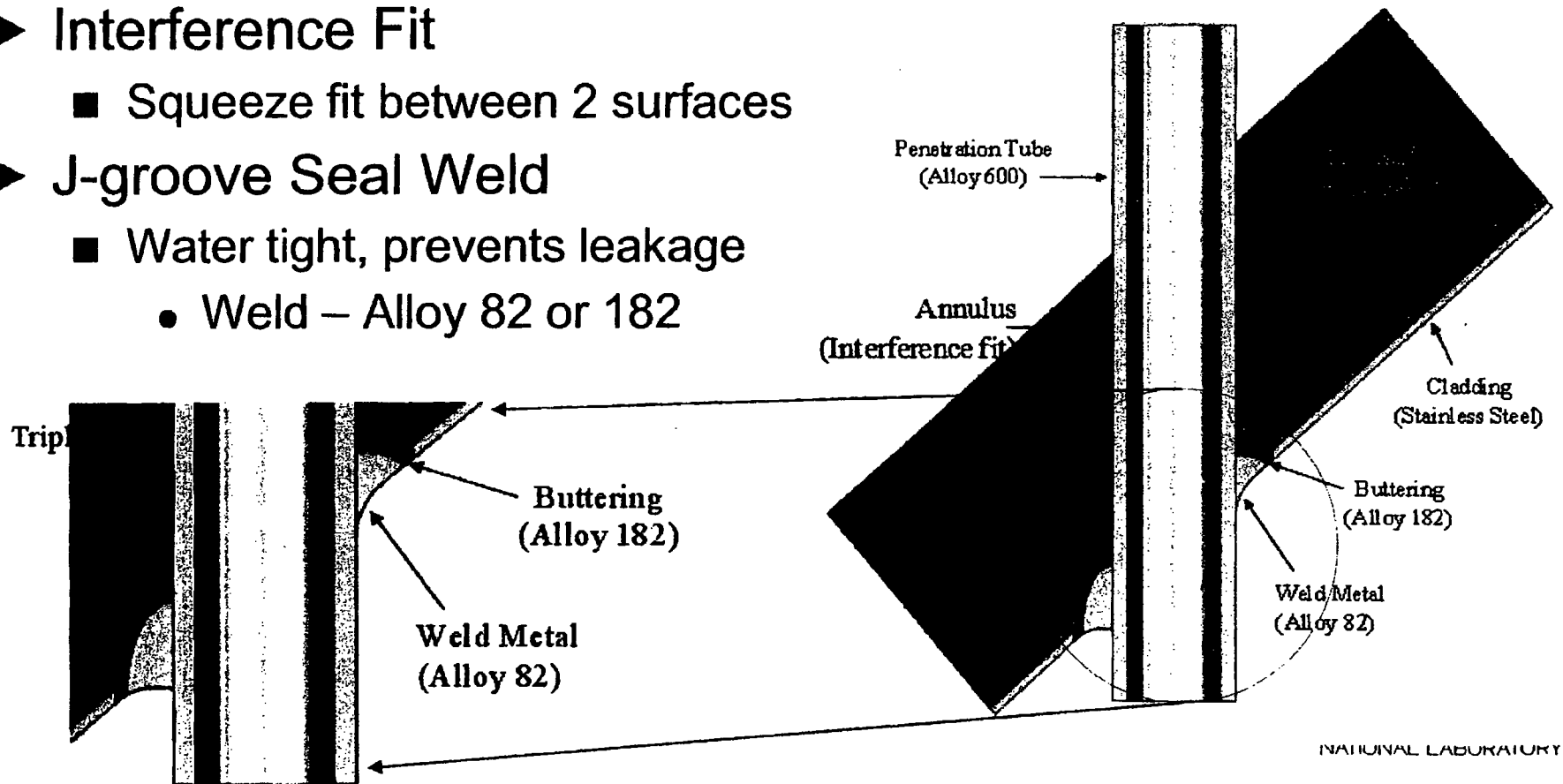
# CRDM Nozzle Usage



- ▶ 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



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# Nozzle 63

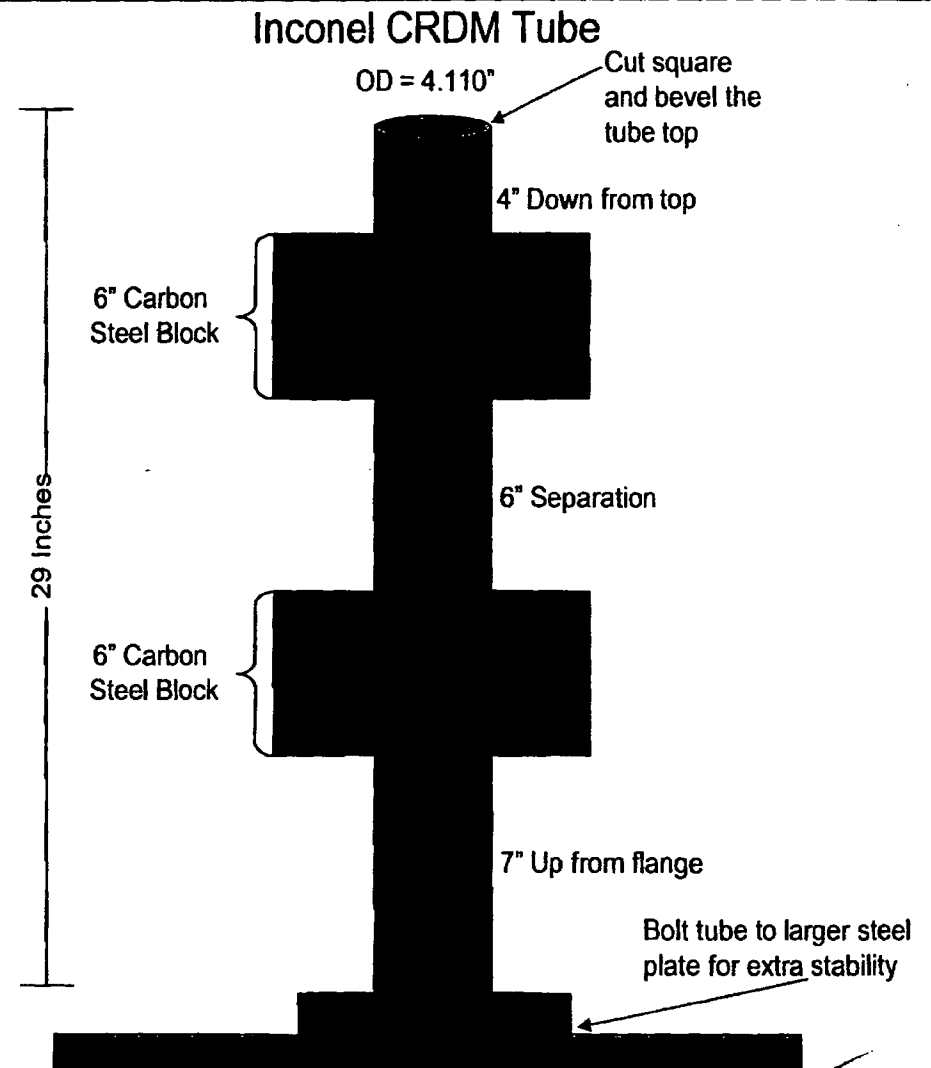
- ▶ Obtained from the original North Anna Unit-2 Nuclear Power Plant (NPP)
- ▶ In the 2001 refueling outage, Nozzle 63 was repaired
- ▶ In the 2002 outage, significant flaw indications and weld cracks resulted in the decision to replace the entire RVH
- ▶ Nozzle 63 was cut from the RVH and saved for 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

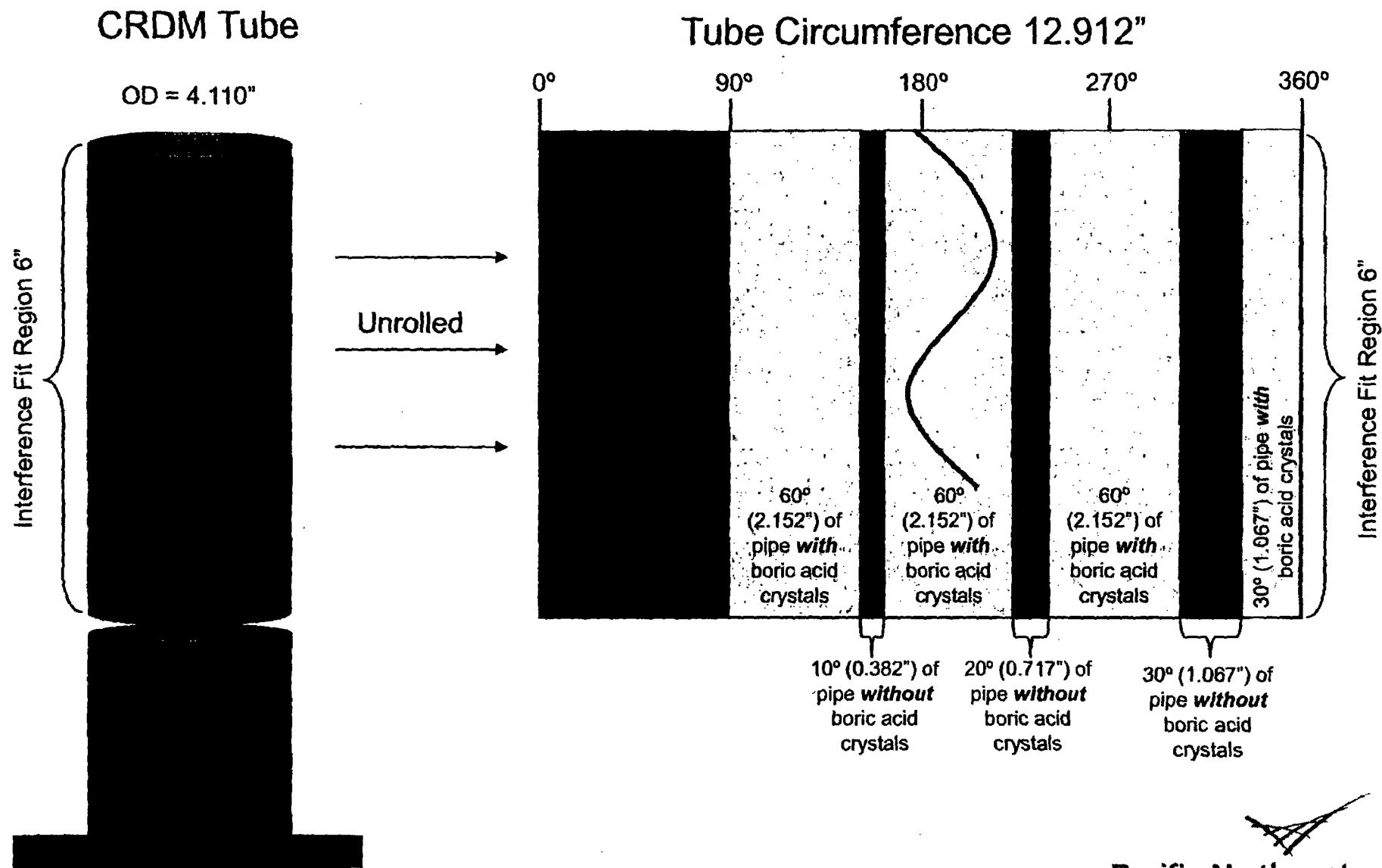
- ▶ **Goal: Mimic actual field interference fits**
  - Inconel tubing and RVH material
  - Used similar assembly procedures
    - 3 mil fit
- ▶ **Components:**
  - Inconel tube (OD = 4.110")
  - Two 6" thick carbon steel blocks
    - Machined holes (D = 4.107")
- ▶ **Created 2 fit regions**
  - Boric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



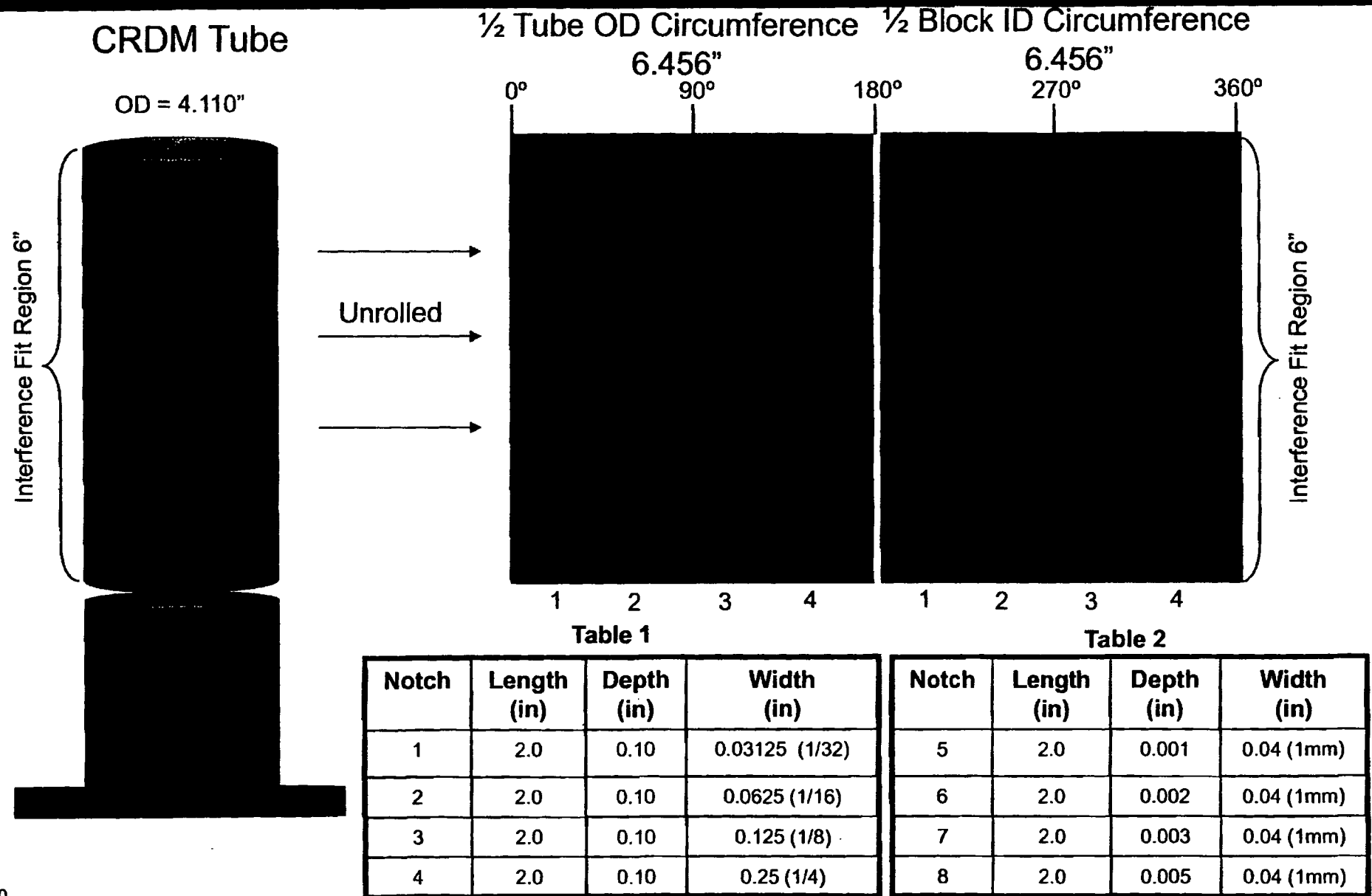
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# Interference Fit #1: Boric Acid Presence Layout

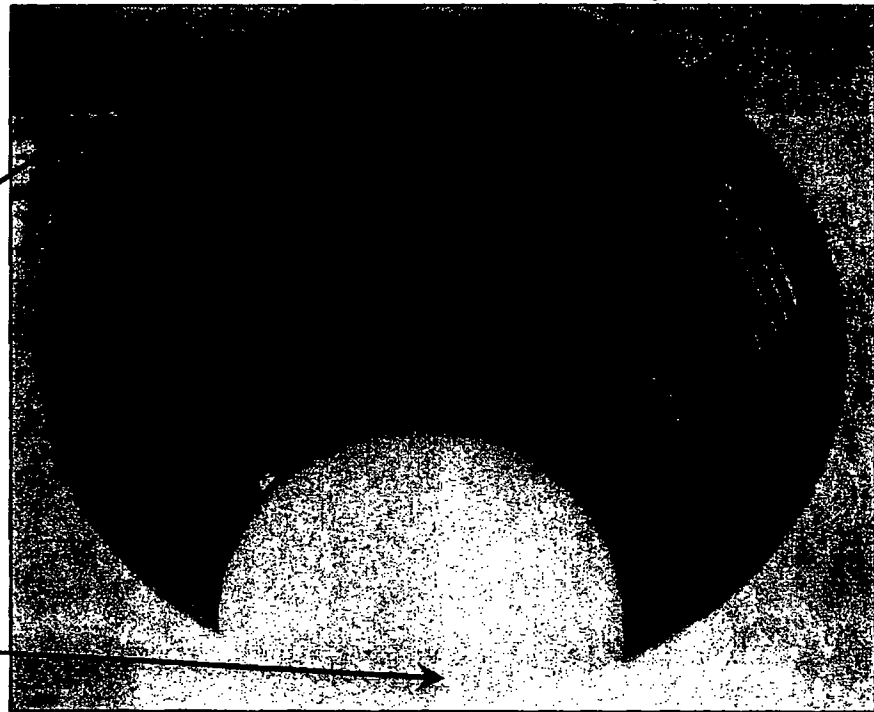
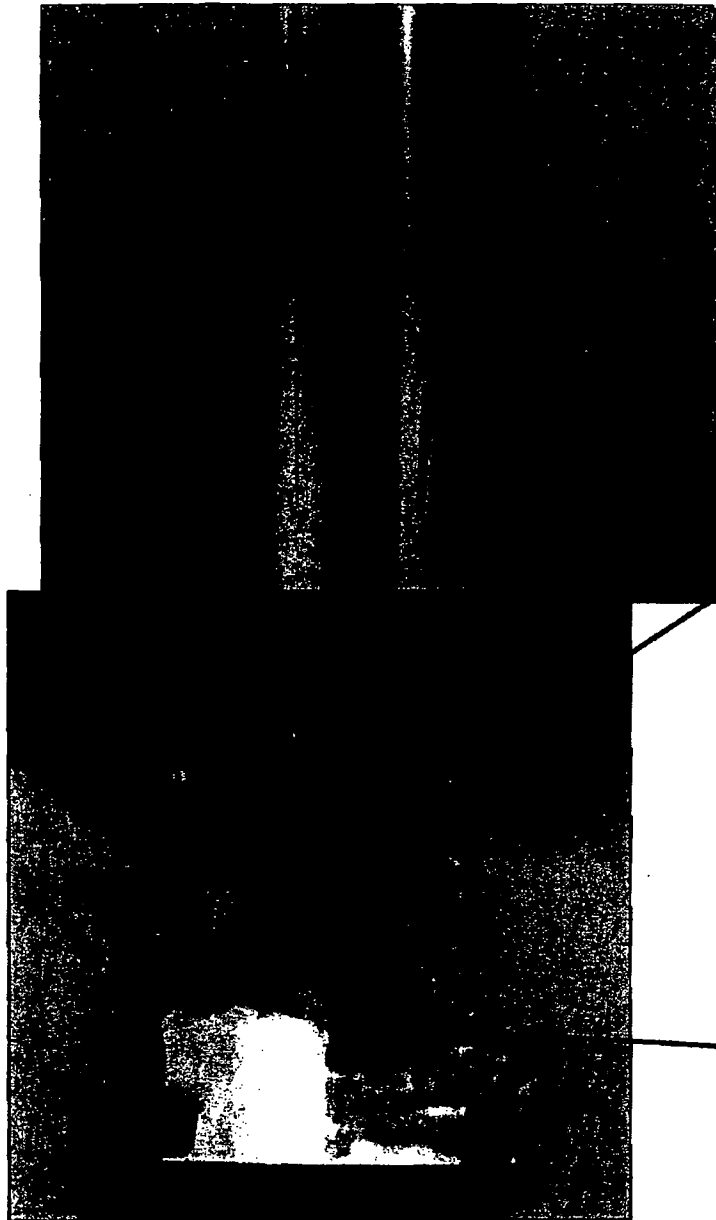


# Interference Fit #2: Notches and Patterns



# Notches and Patterns

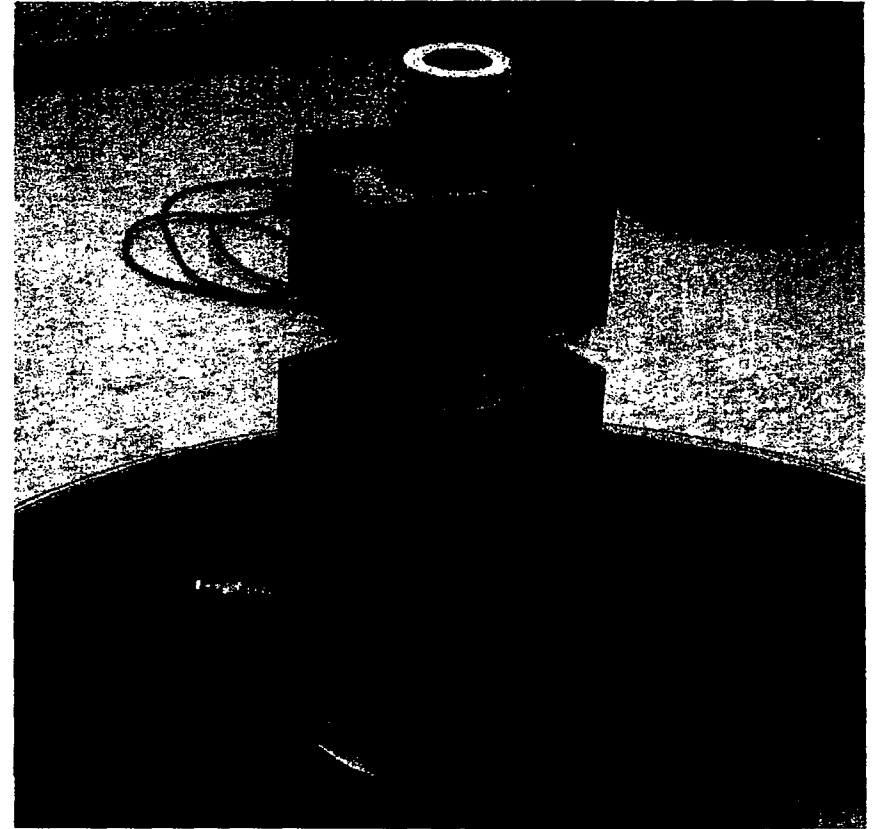
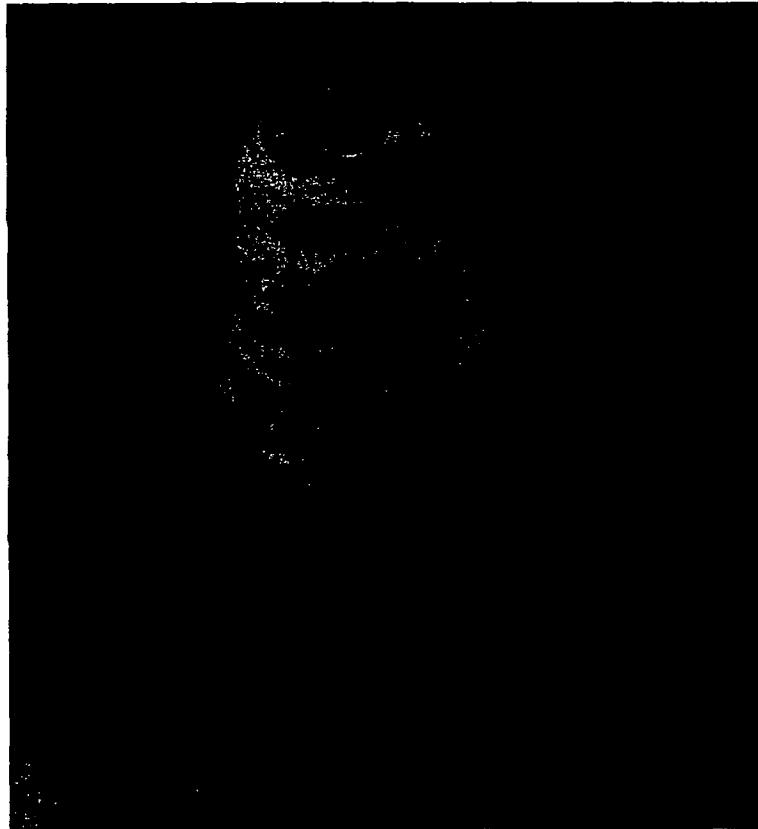
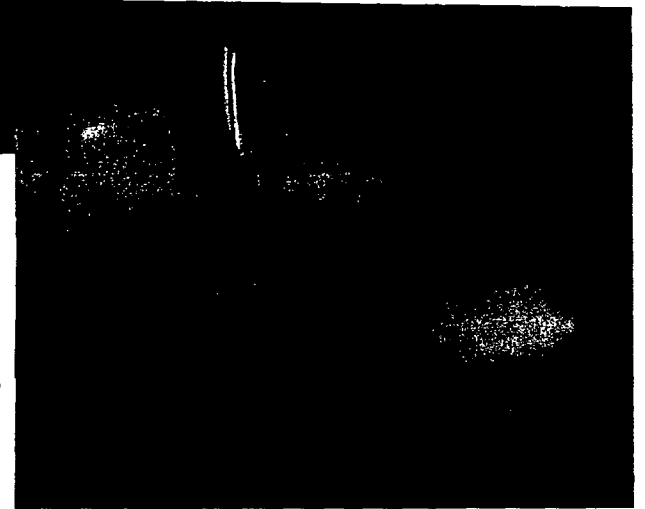
- ▶ Precision EDM notches
- ▶ Machined in two materials
  - Inconel tube OD
  - Carbon steel block ID
- ▶ 'PNNL' pattern engraved



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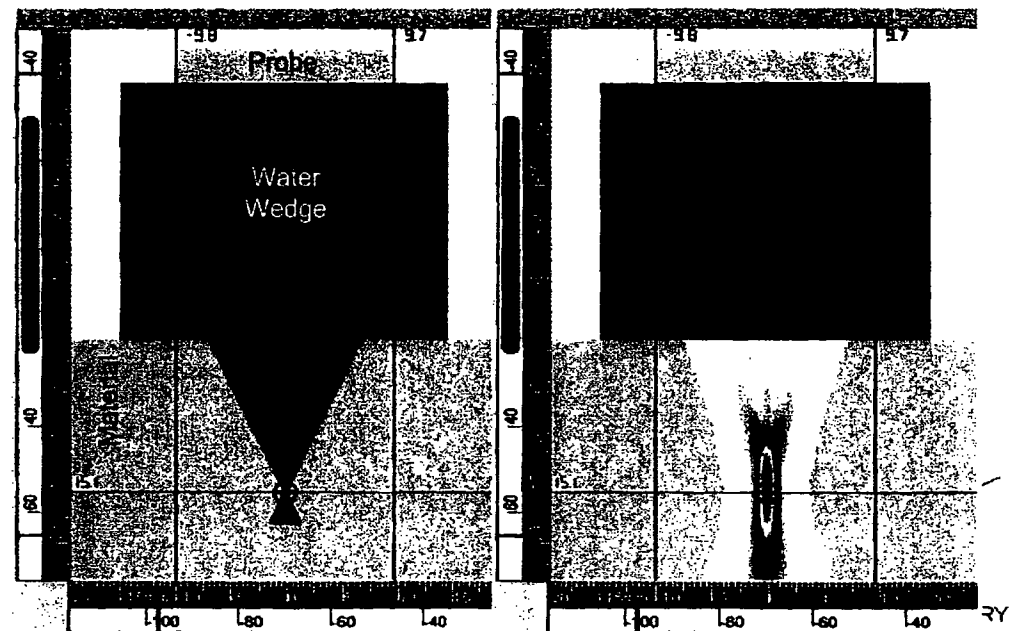
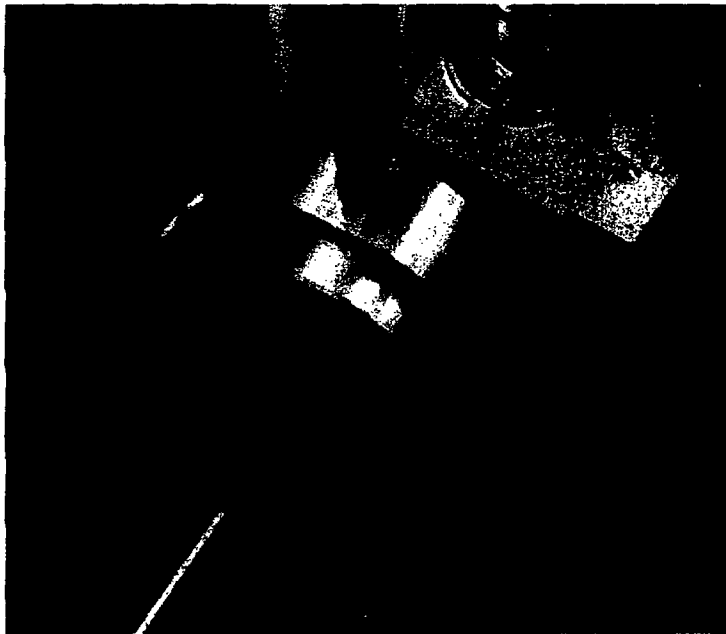
# Mock-up Assembly

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



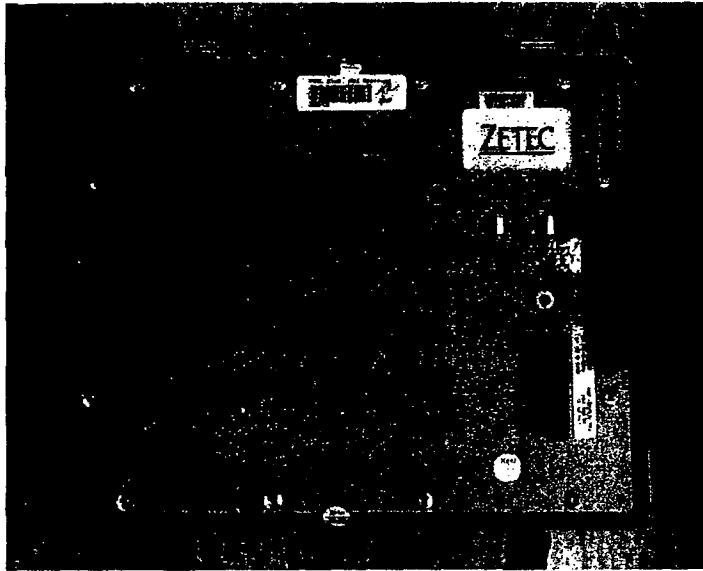
# Ultrasonic Phased Array Probe

- ▶ 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 mm<sup>2</sup> total aperture
- ▶ Designed for variable depth focusing capabilities



# Phased Array System and Scanner

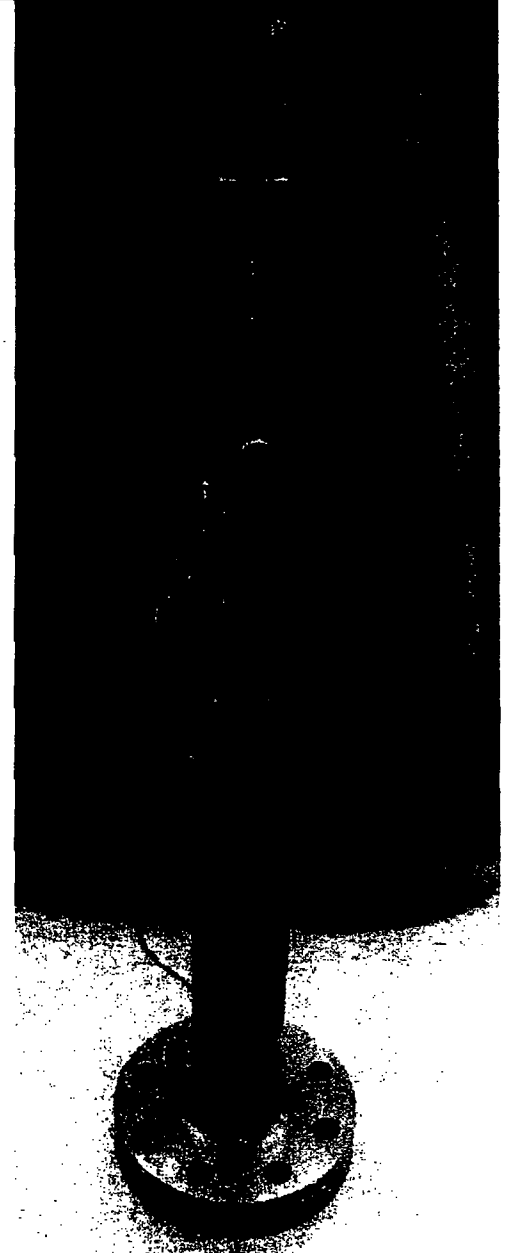
## Tomoscan III PA System 0.7 – 20 MHz



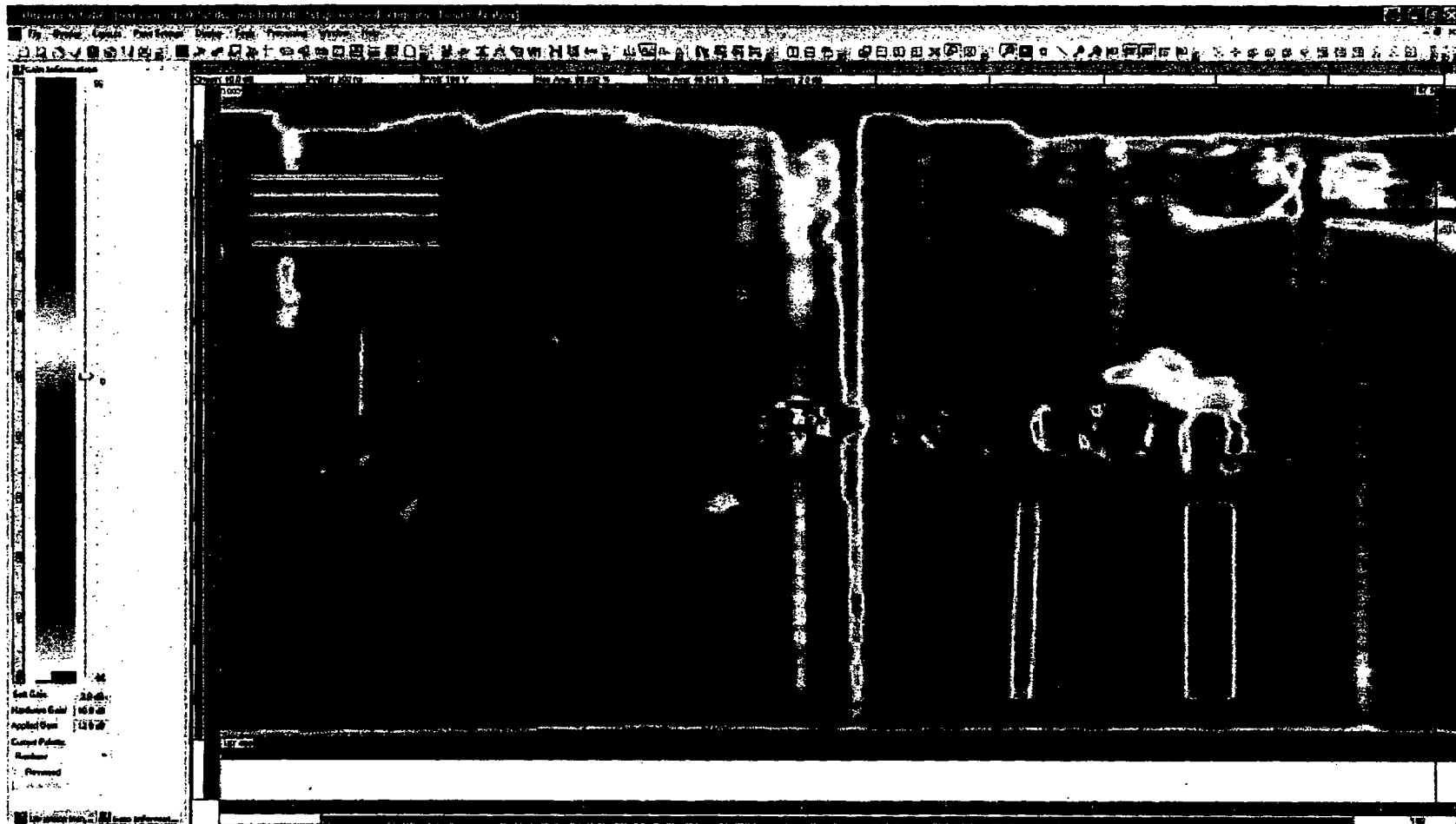
- ▶ Accommodates a maximum of 64 channels
- ▶ Controlled by UltraVision 1.2R4 software
- ▶ Accepts multiple axis positional information

## Custom Pulse Motor Scanner

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



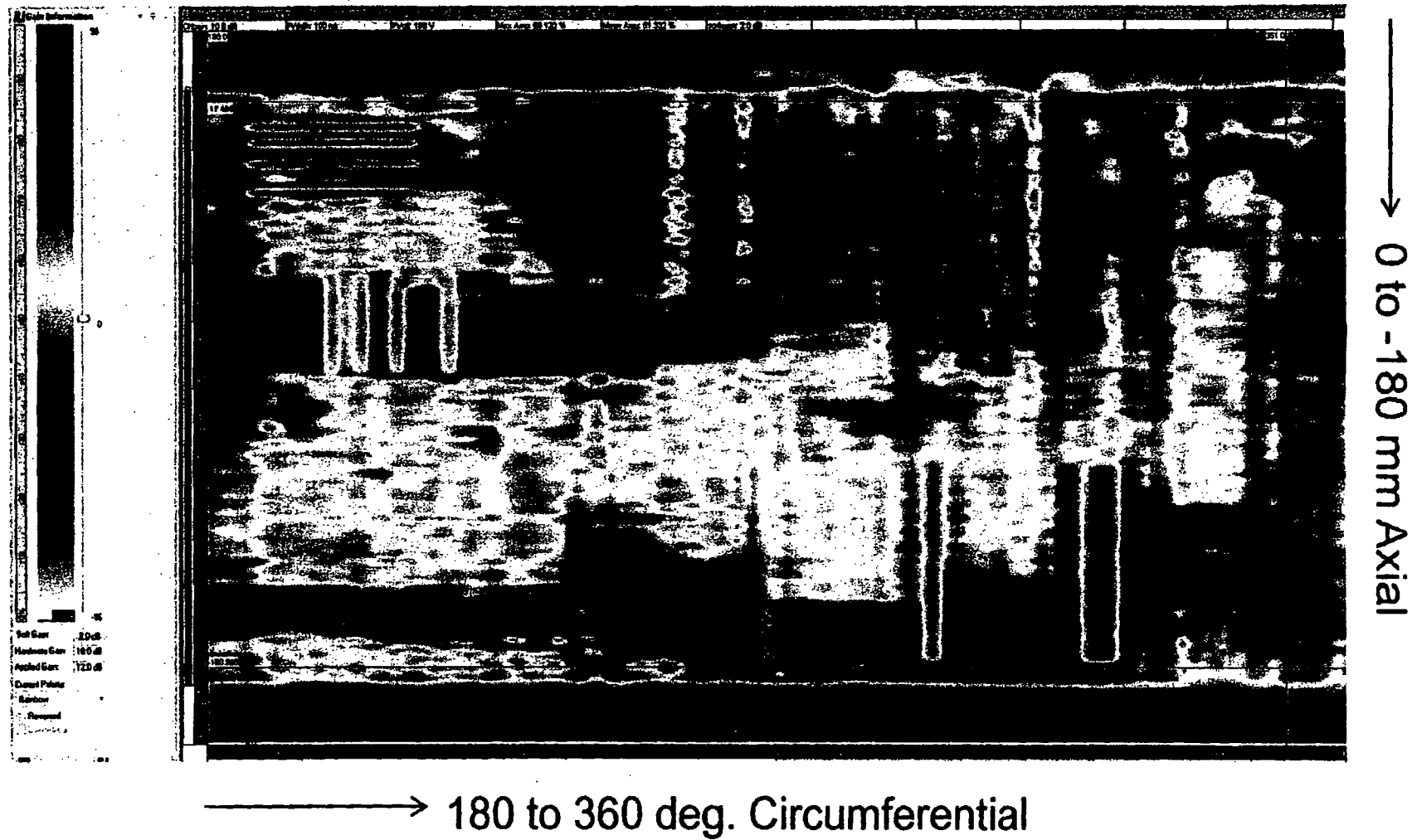
# Ultrasonic Data: Mock-up Notches



0 to 170 deg. Circumference

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

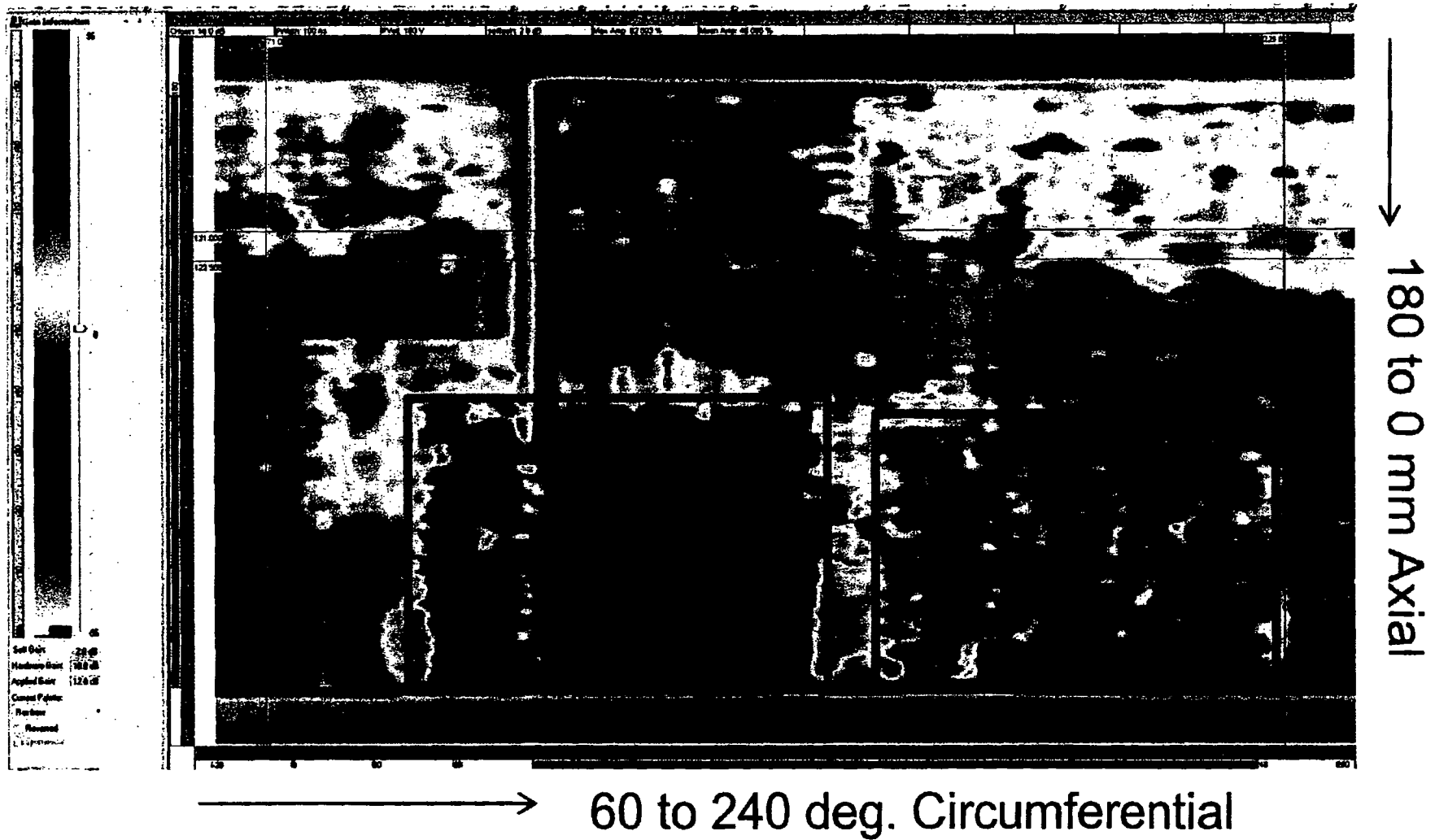
# Ultrasonic Data: Mock-up Notches



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



# Ultrasonic Data: Mock-up Boric Acid

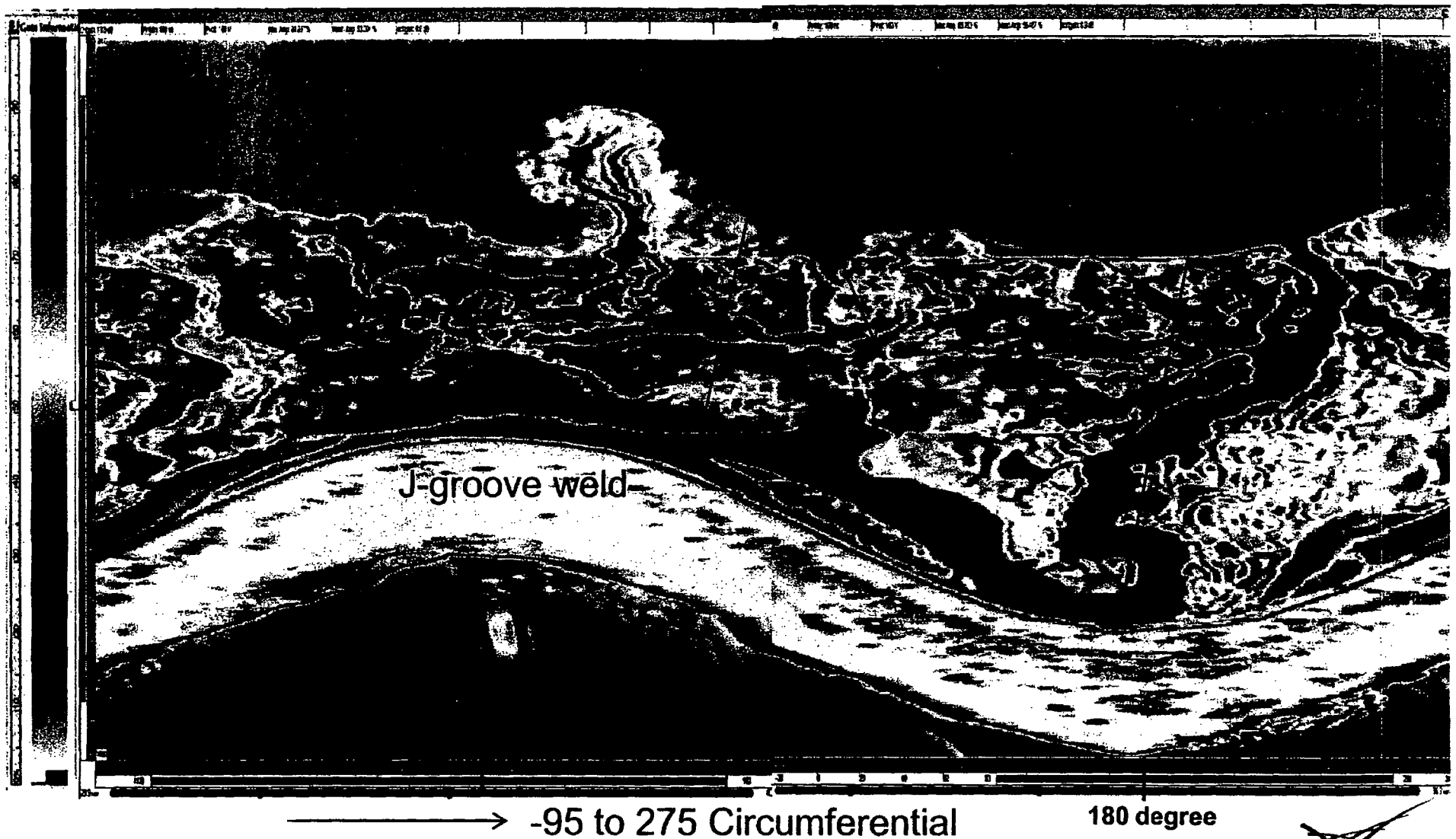


► C-Scan view: Boric acid presence in fit region

# 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

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# Destructive Verification



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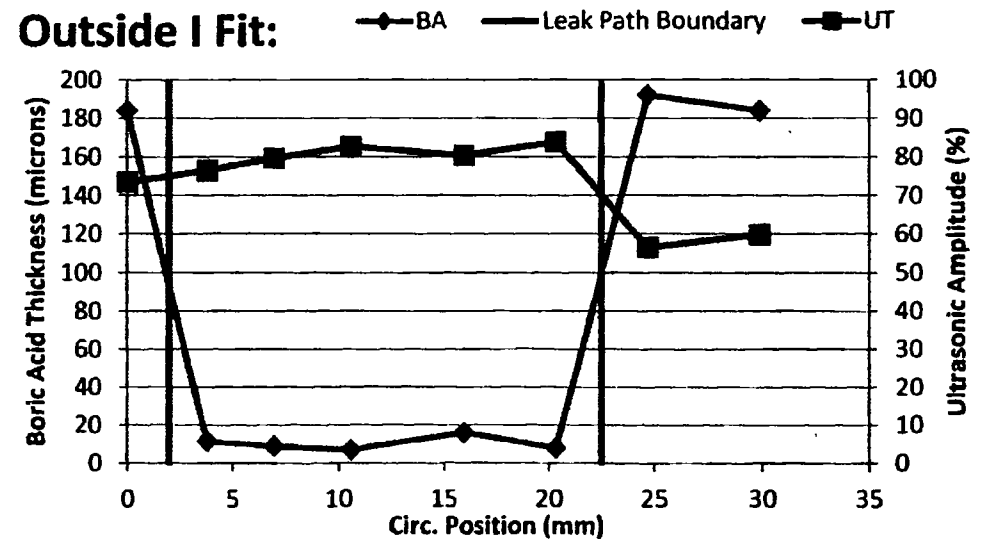
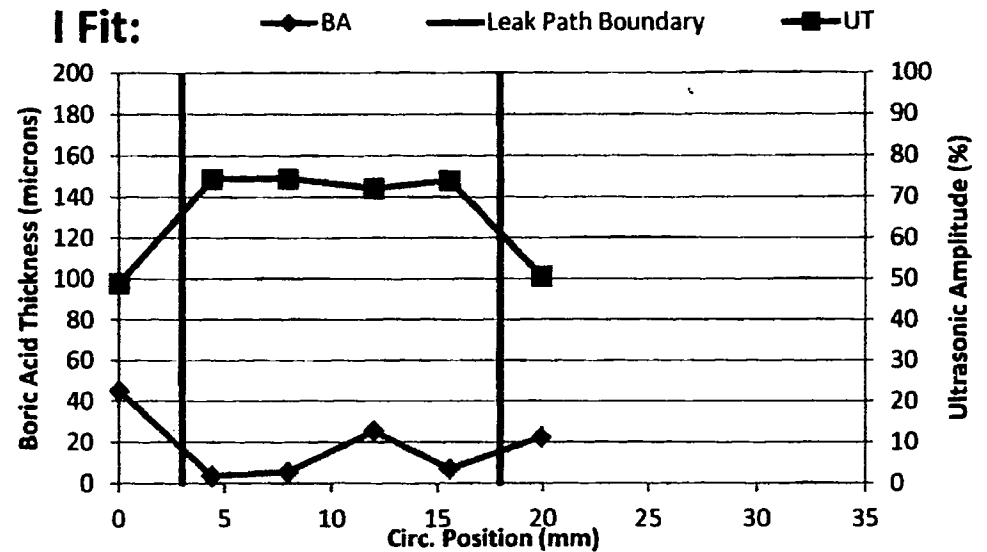
► RVH annulus view montage

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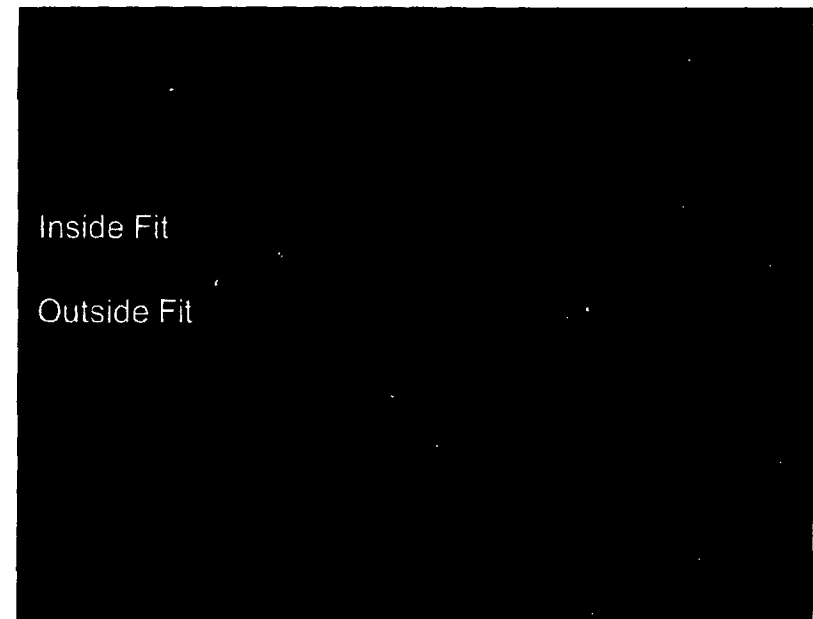
# Boric Acid/Corrosion Product Assessment (Leak Path Region)



- ▶ 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



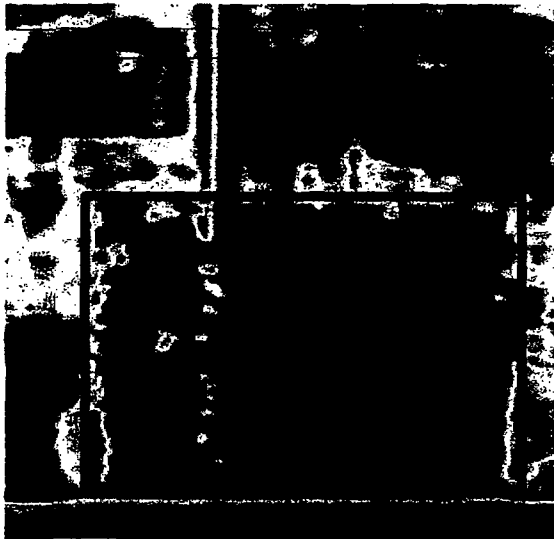
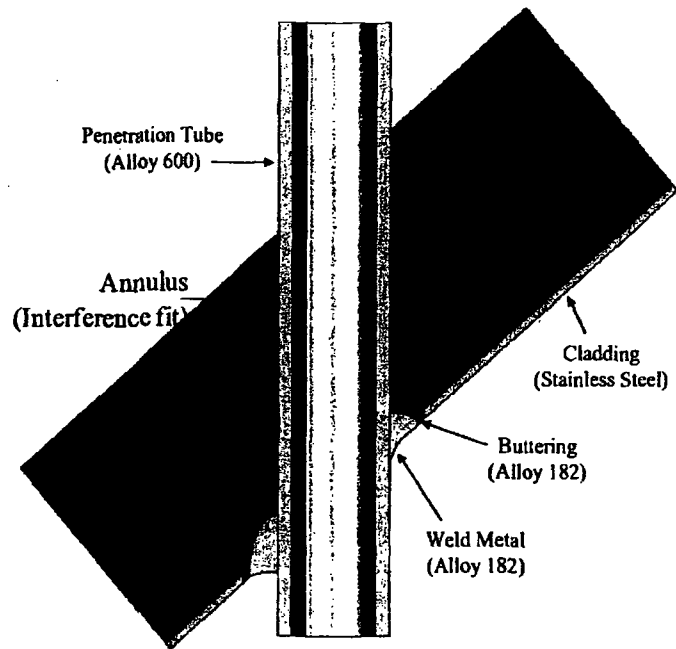
# Results/Conclusions

- ▶ 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



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# Thank You! Questions?

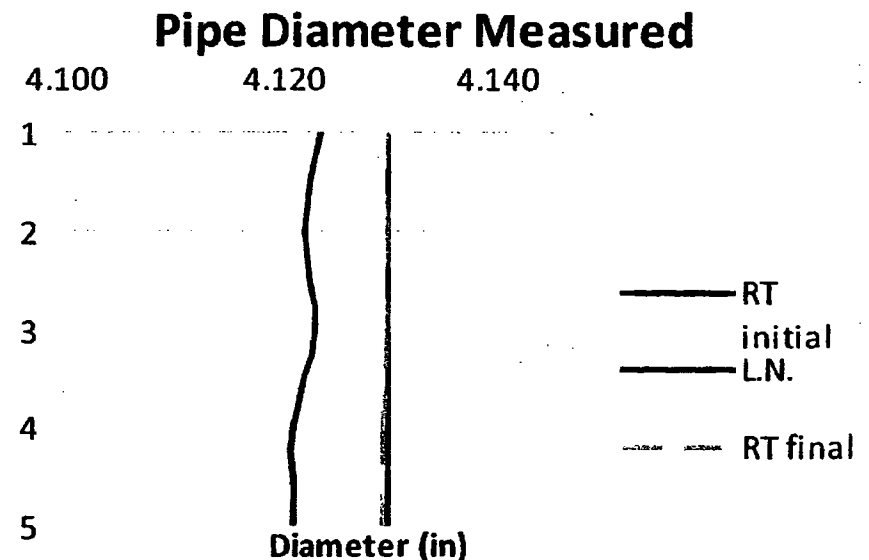
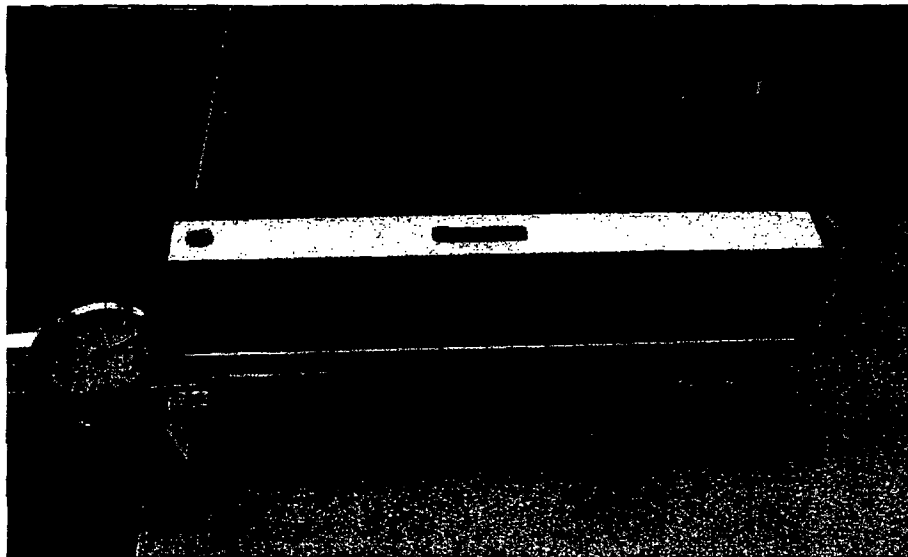




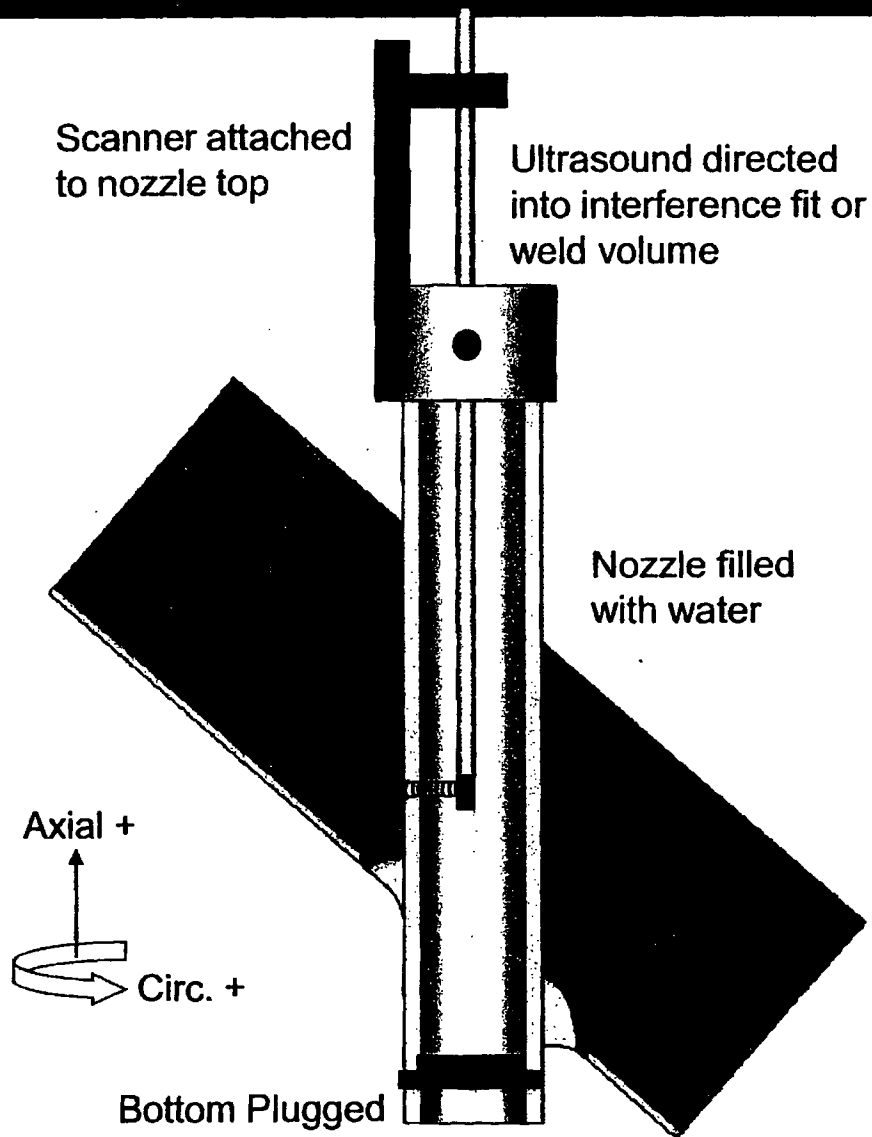
# Supplemental Slides Beyond This Point

# 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
  - $0.5^\circ$  in scan by 0.5 mm in index
- ▶ Positional information relayed via shaft encoders



0-30%



# Supplemental: Destructive Cutting

