3/7/2012

SPIE Smart Structures/NDE 2012

San Diego, California, USA

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

AD Cinson, SL Crawford, PJ MacFarlan,
BD Hanson, and RA Mathews
Pacific Northwest National Laboratory, Richland, WA, USA

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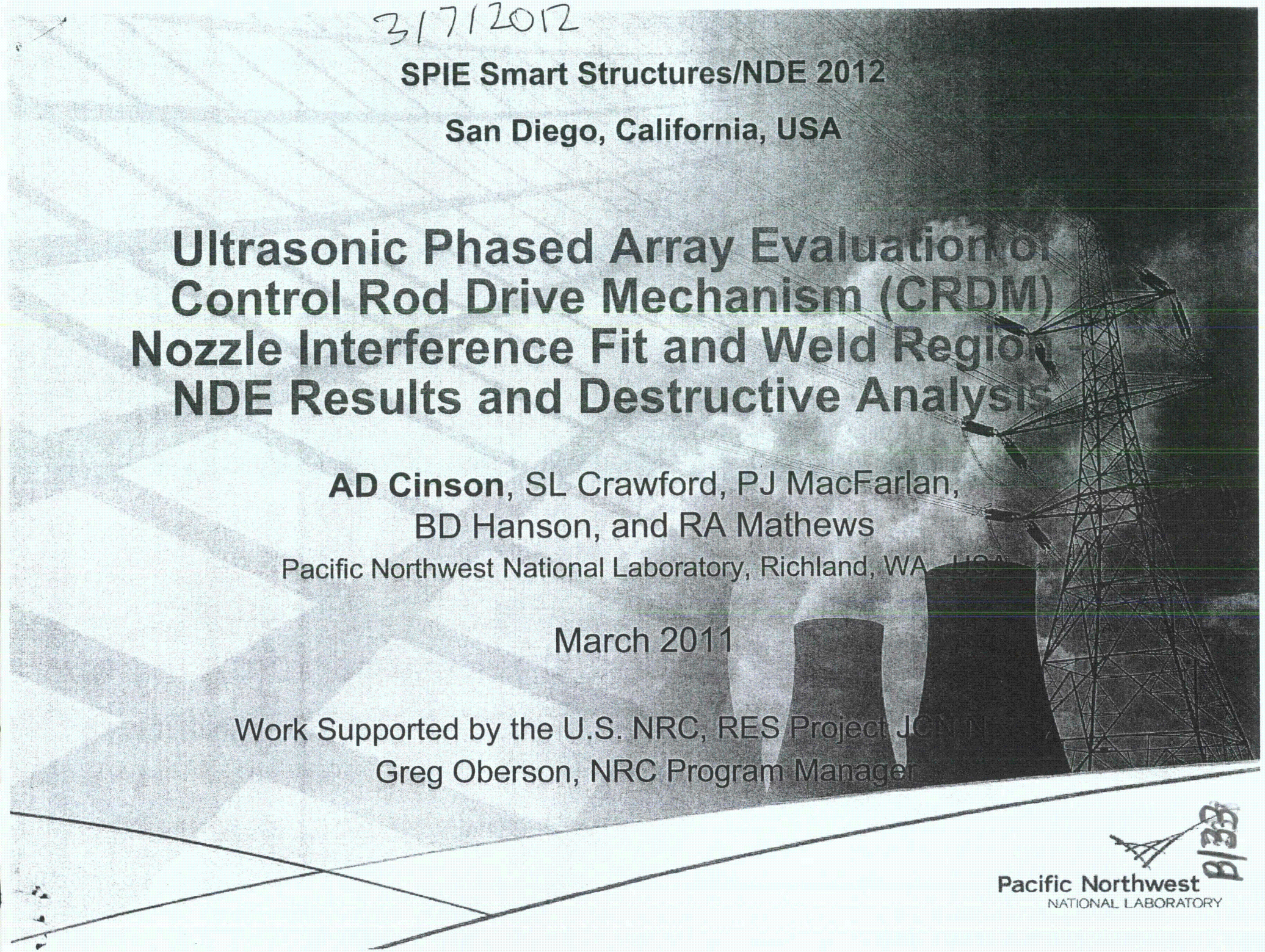
Work Supported by the U.S. NRC, RES Project JCN [illegible]
Greg Oberson, NRC Program Manager



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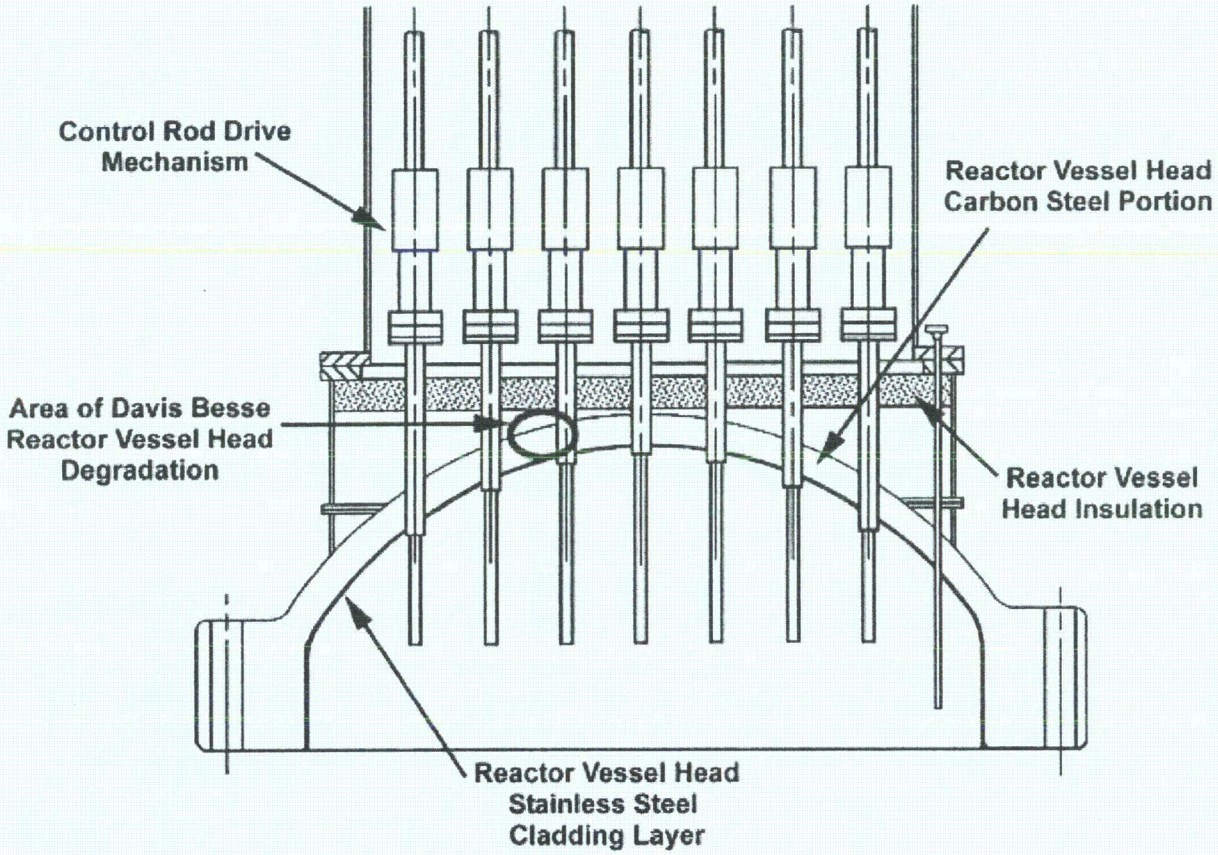
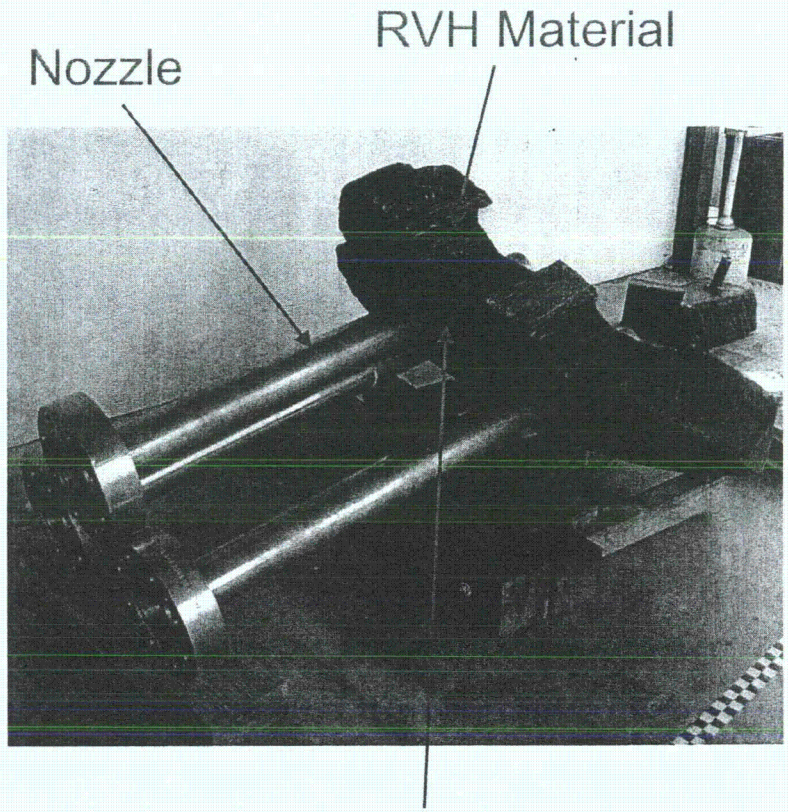
Topics of Discussion

- 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

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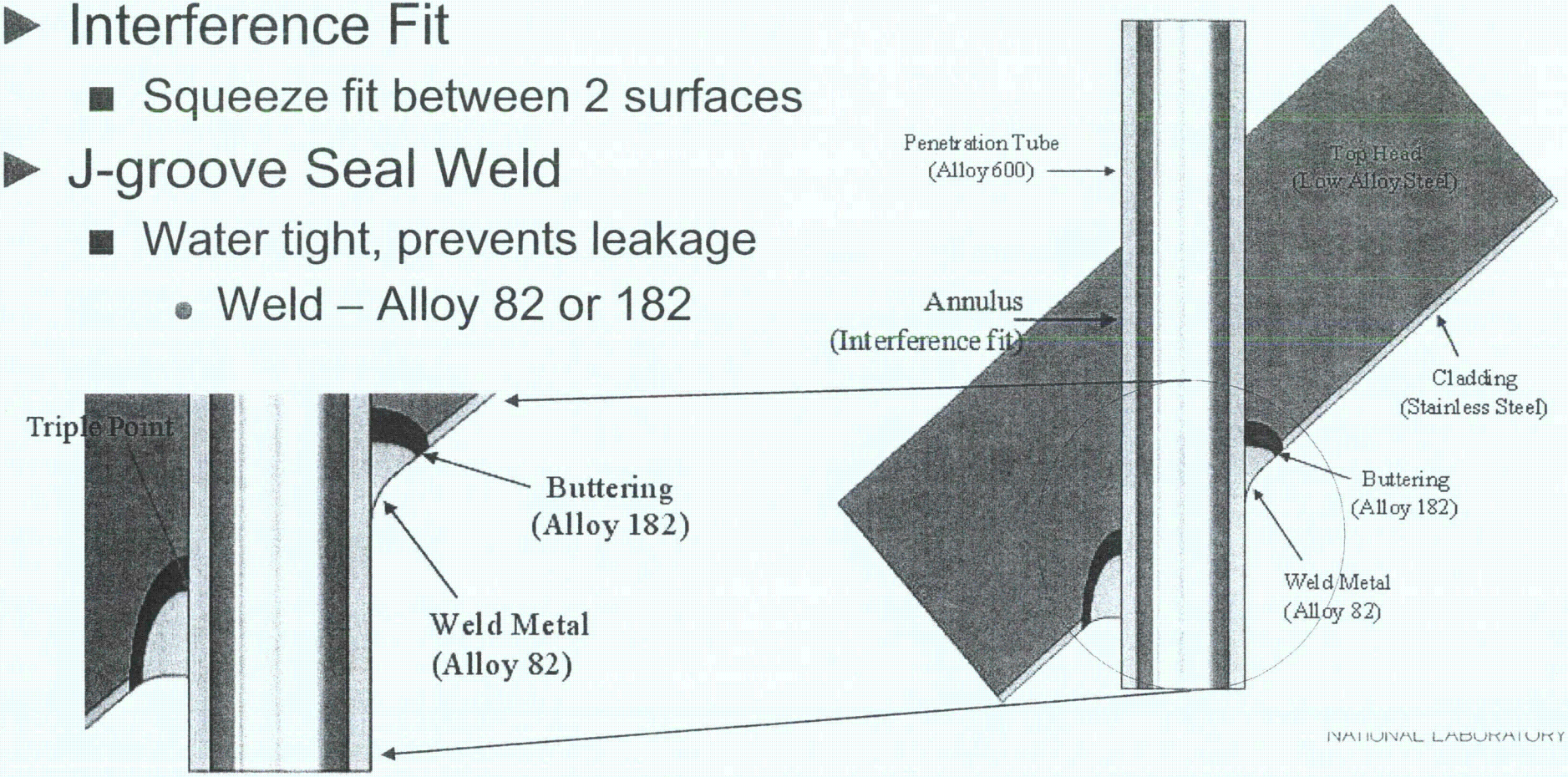
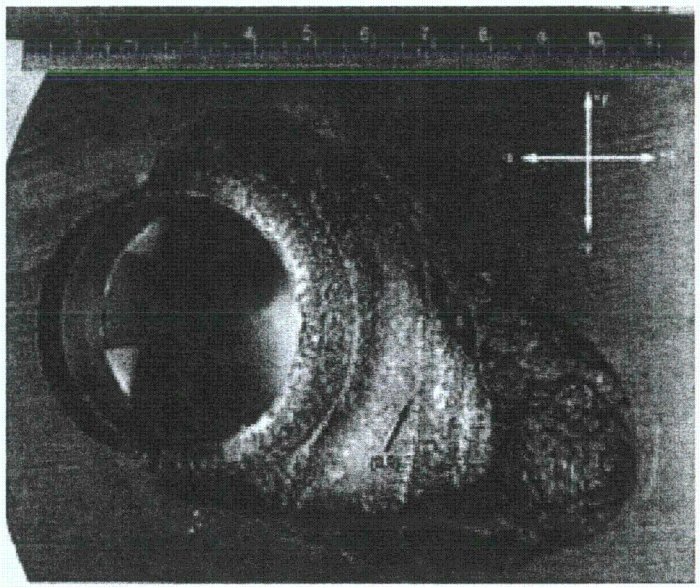
CRDM Nozzle/Fit/Weld Design

- 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

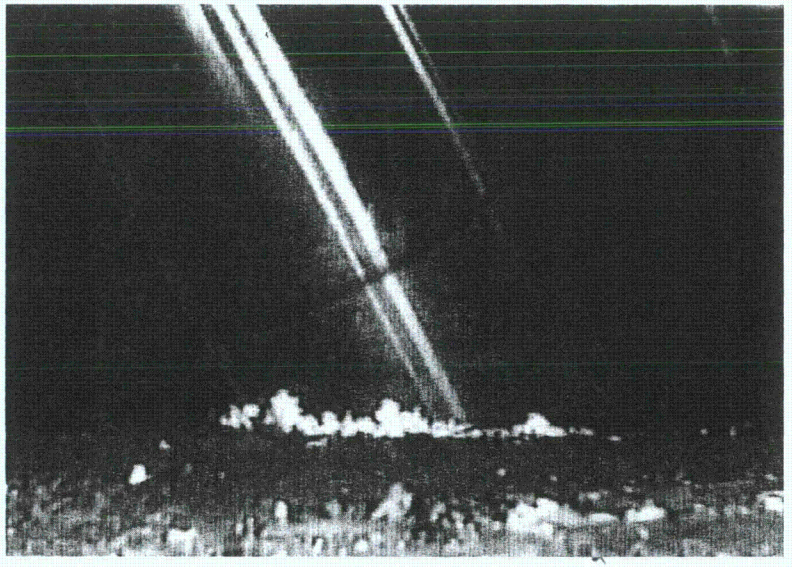


Objectives of the Current Study

- 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

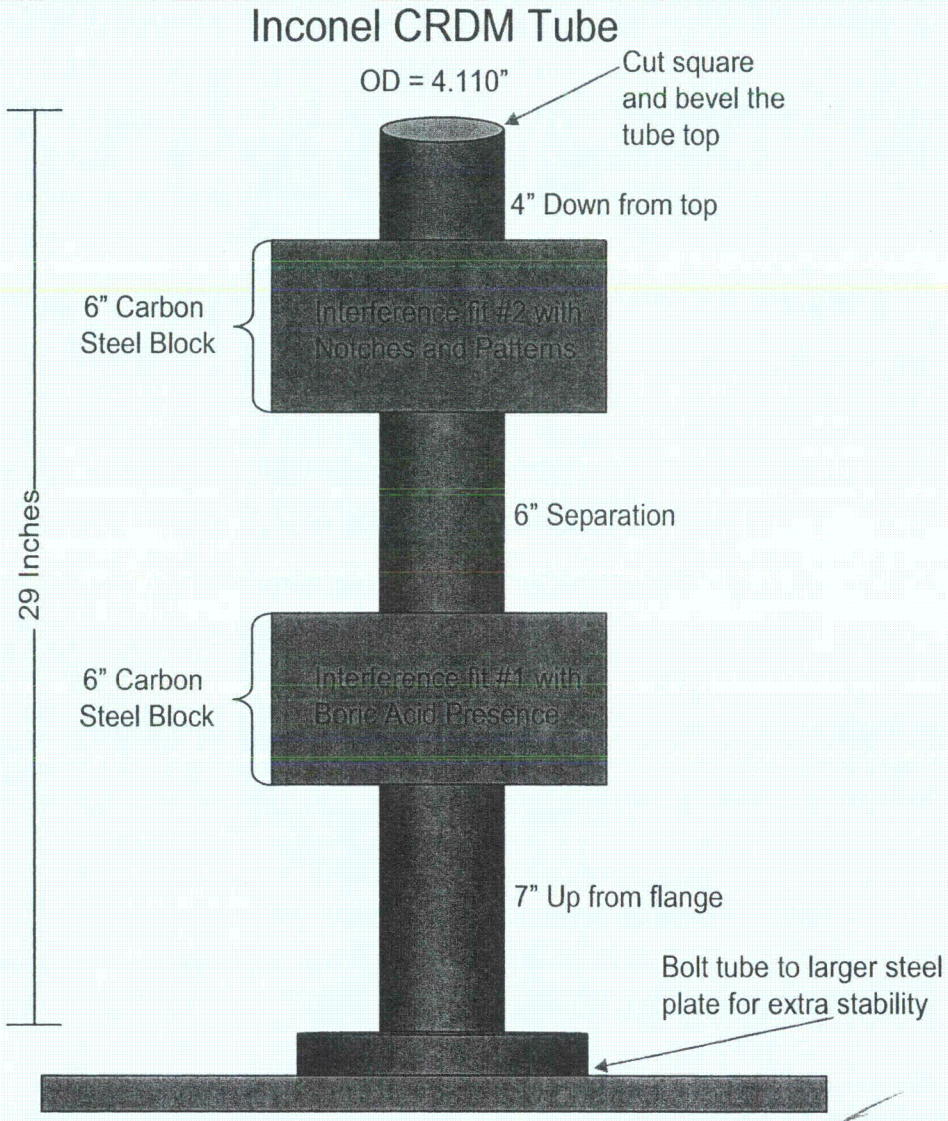
Nozzle 63

- 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



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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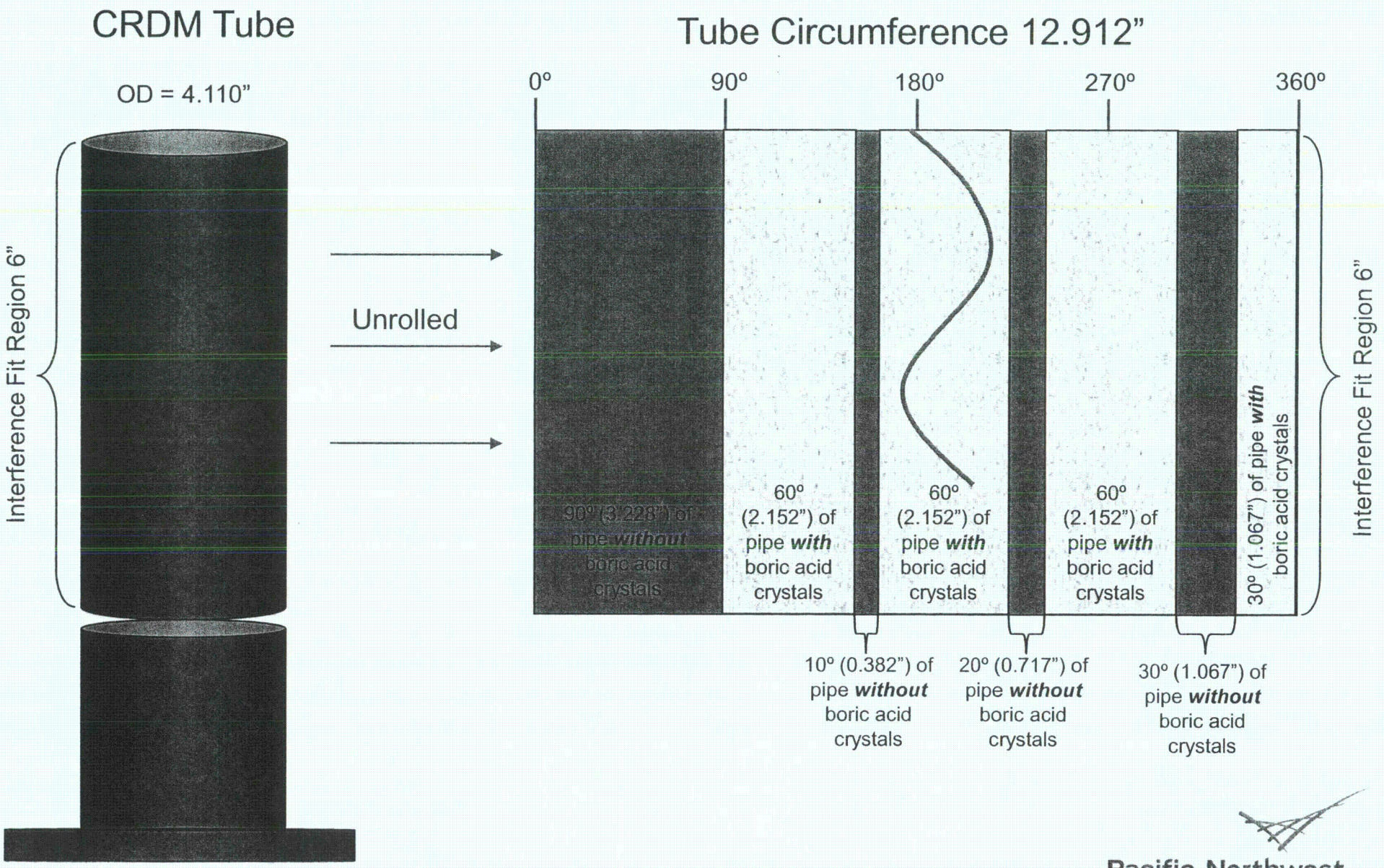
Interference Fit #1: Boric Acid Presence Layout



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Interference Fit #2: Notches and Patterns

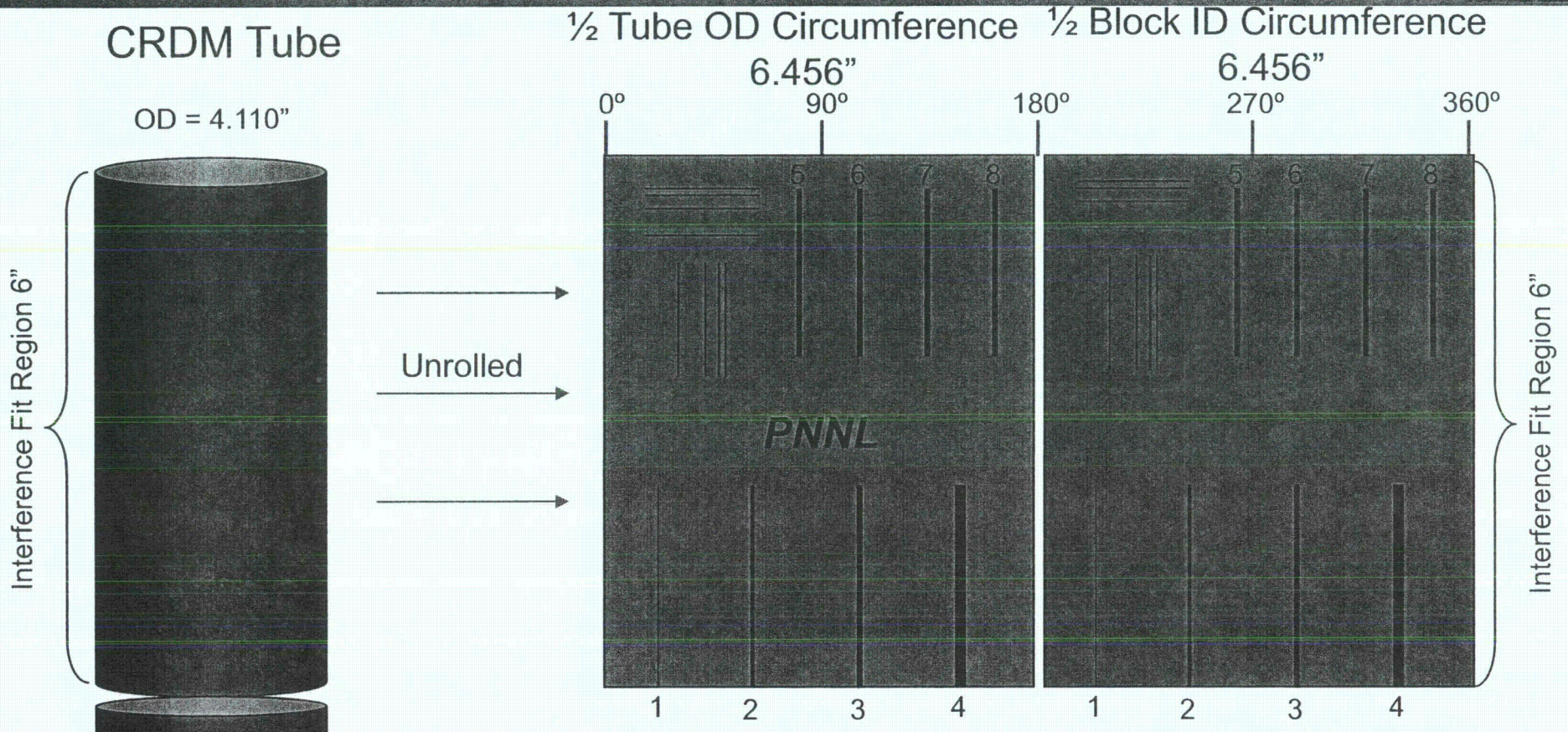


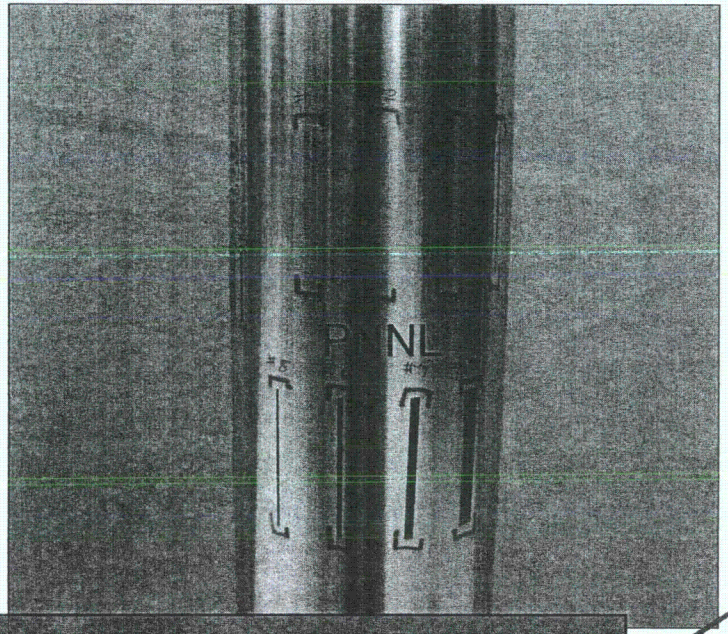
Table 1

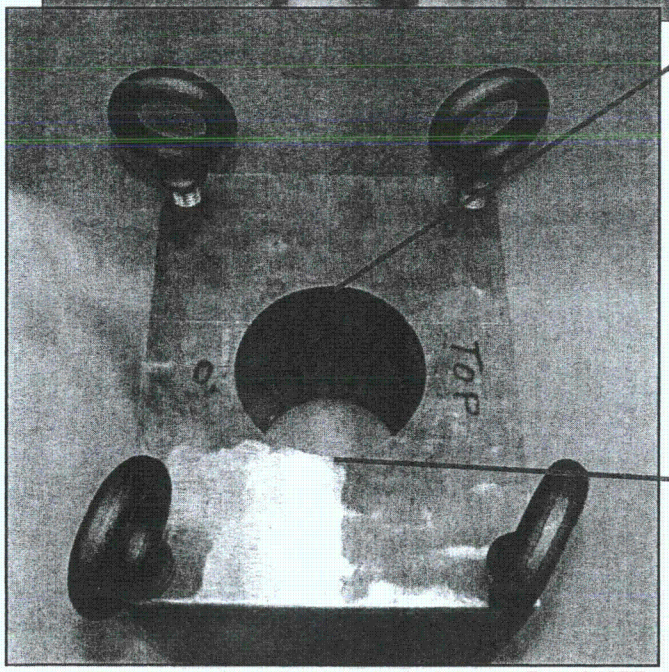
Notch	Length (in)	Depth (in)	Width (in)
1	2.0	0.10	0.03125 (1/32)
2	2.0	0.10	0.0625 (1/16)
3	2.0	0.10	0.125 (1/8)
4	2.0	0.10	0.25 (1/4)

Table 2

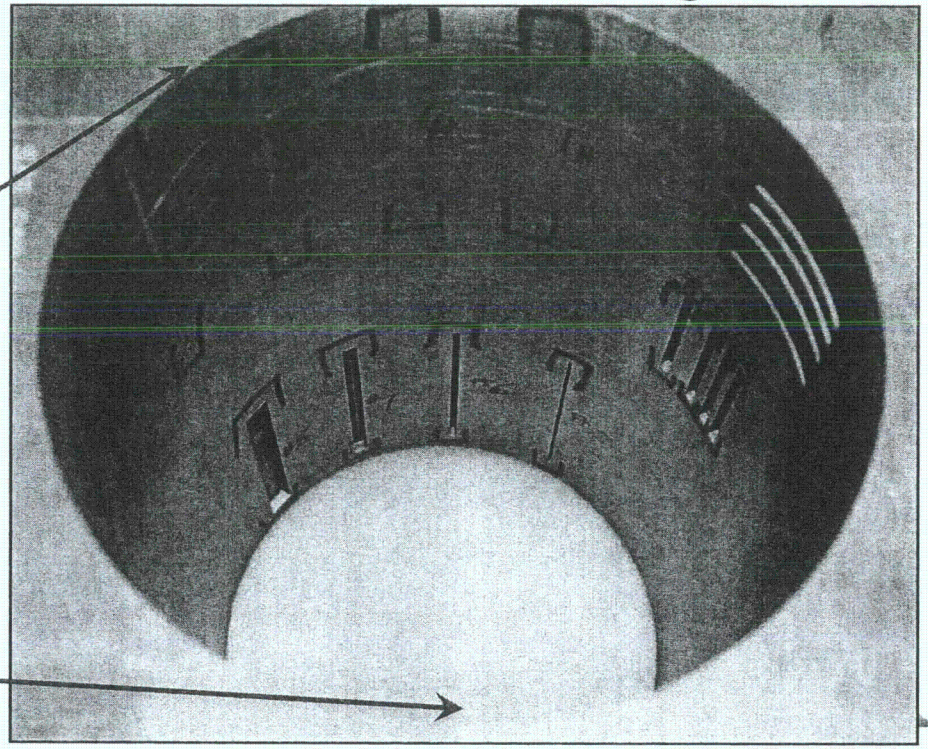
Notch	Length (in)	Depth (in)	Width (in)
5	2.0	0.001	0.04 (1mm)
6	2.0	0.002	0.04 (1mm)
7	2.0	0.003	0.04 (1mm)
8	2.0	0.005	0.04 (1mm)

Notches and Patterns

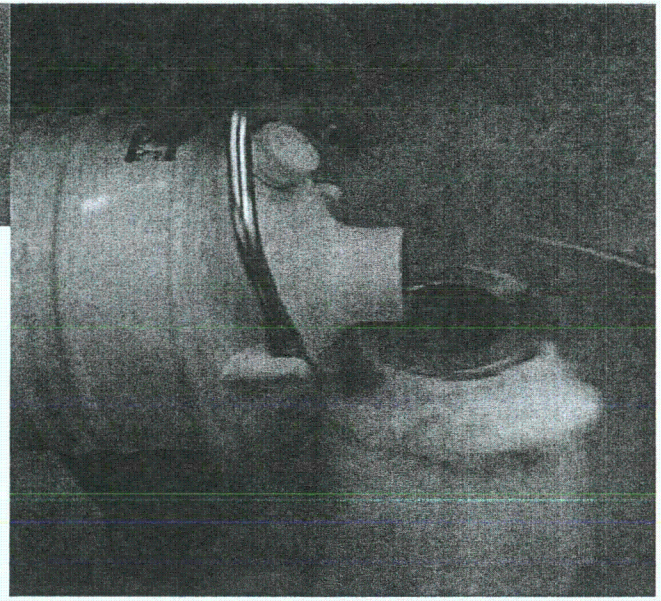




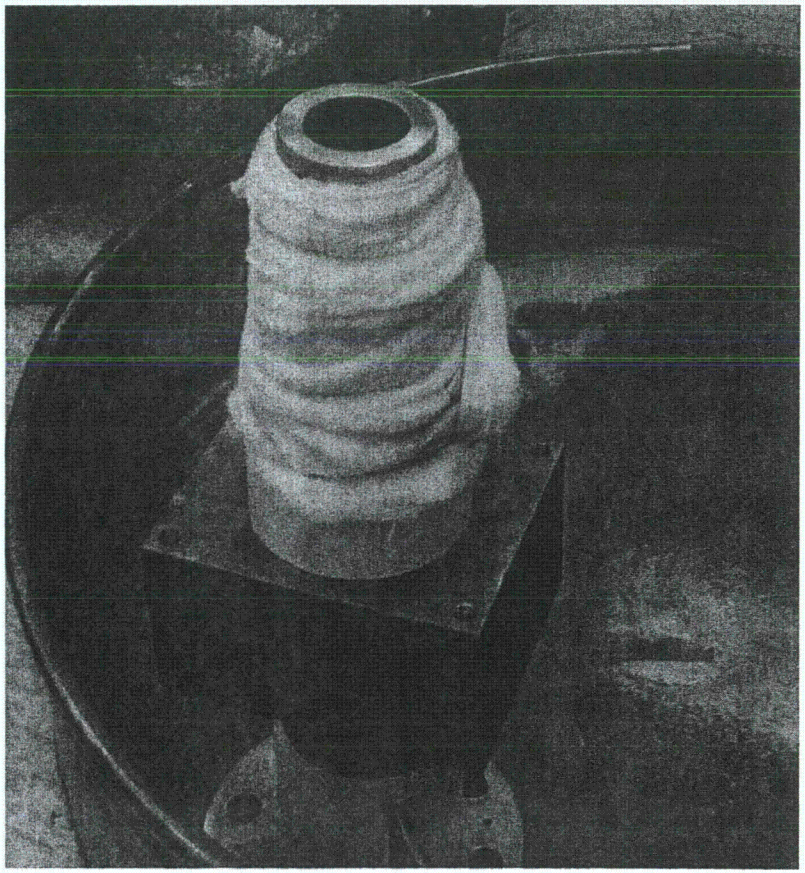
- Precision EDM notches
- Machined in two materials
  - Inconel tube OD
  - Carbon steel block ID
- 'PNNL' pattern engraved

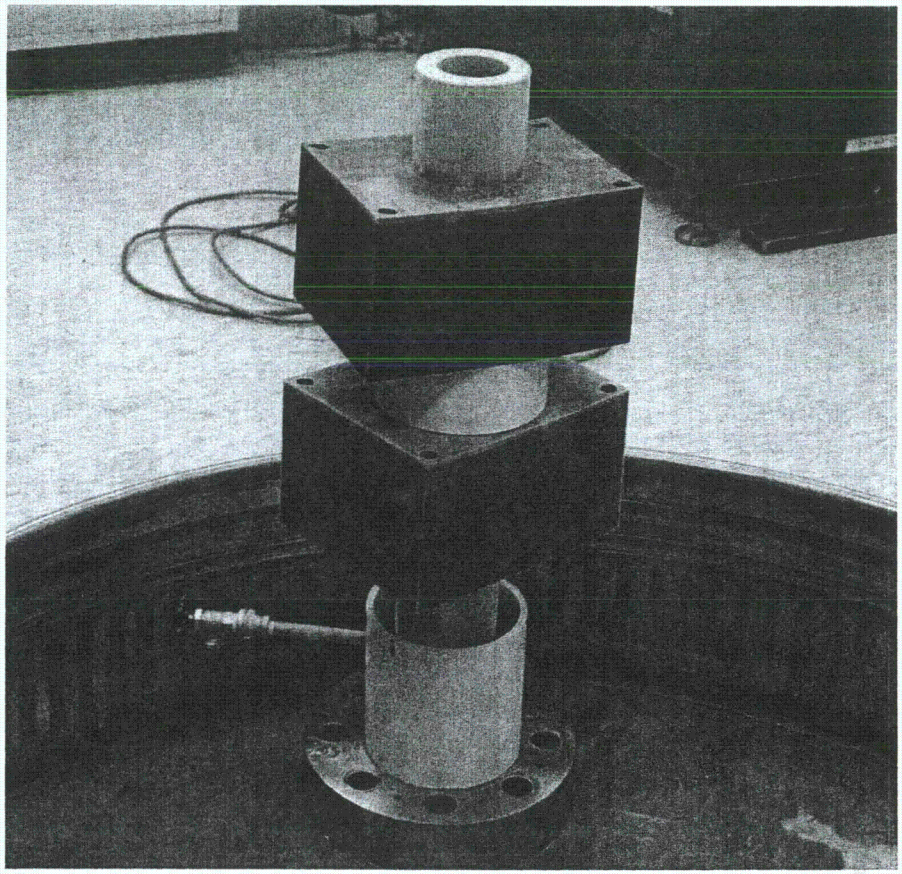


Mock-up Assembly



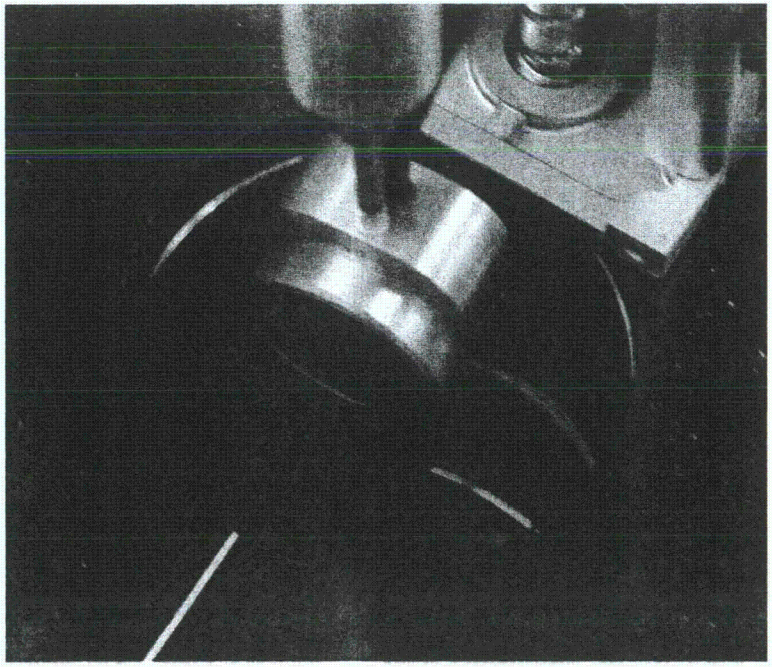
- Shrunk Inconel tube to allow assembly
  - Filled tube with liquid nitrogen
  - Monitored tube diameter during cooling process
- Lowered carbon steel blocks into position

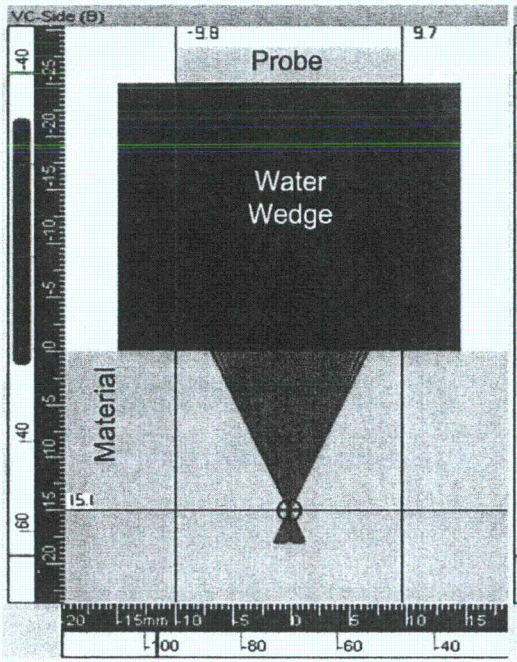


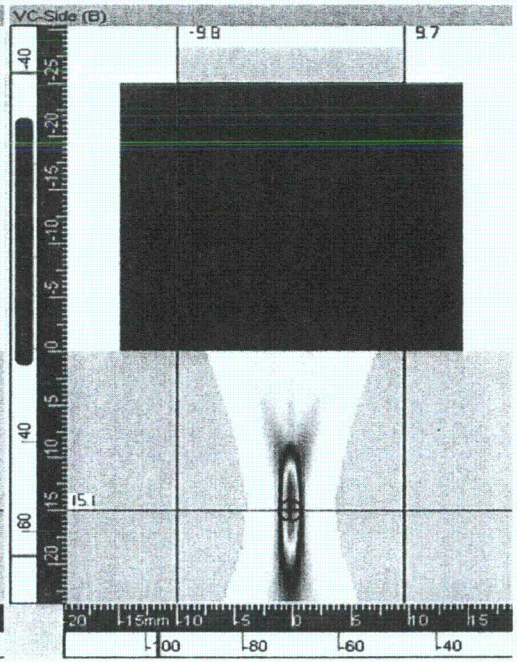


Ultrasonic Phased Array Probe

- 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 mm^2 total aperture
- Designed for variable depth focusing capabilities

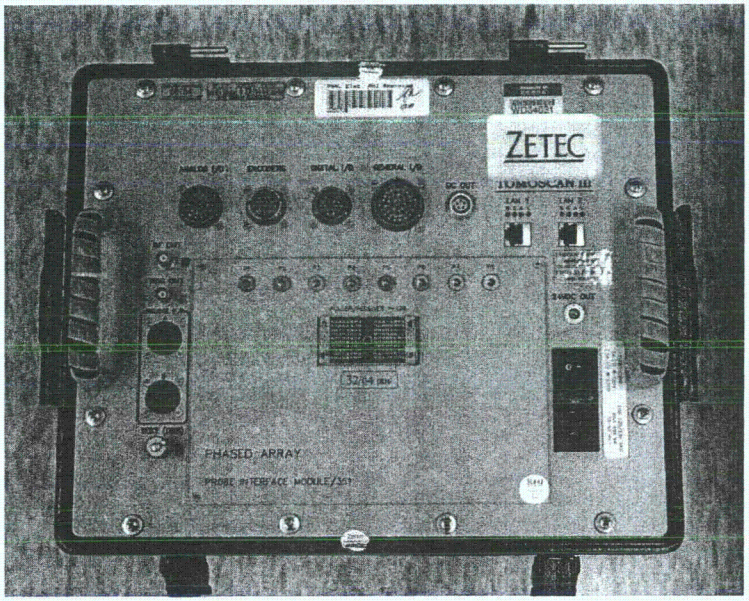






Phased Array System and Scanner

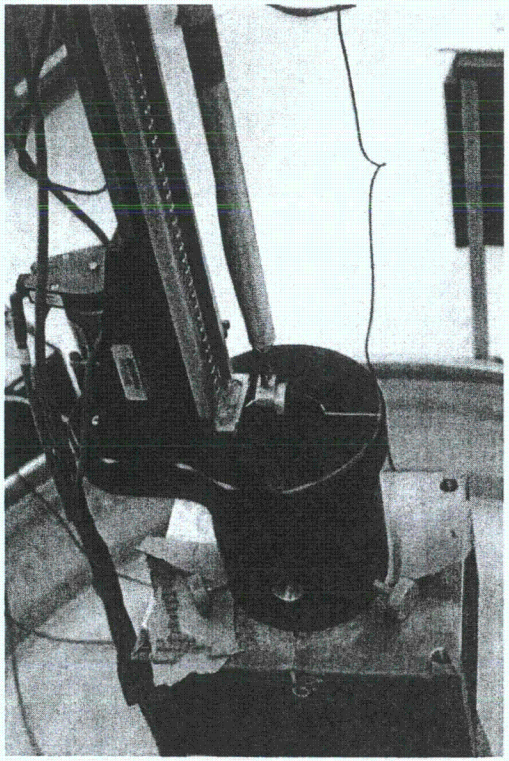
Tomoscan III PA System
0.7 – 20 MHz

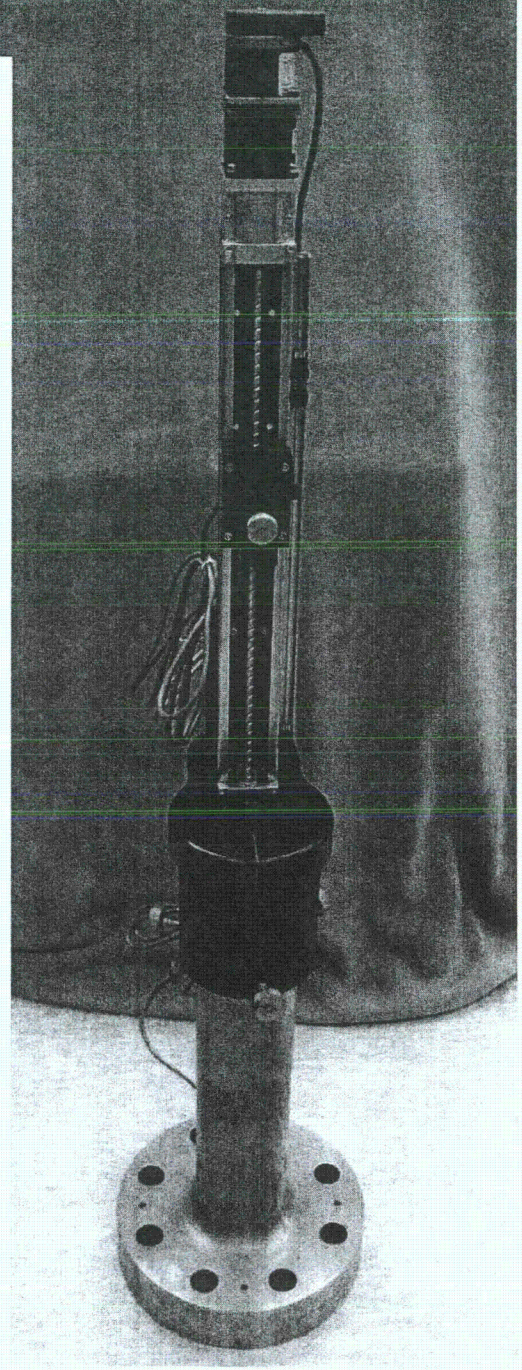


- Accommodates a maximum of 64 channels
- Controlled by UltraVision 1.2R4 software
- Accepts multiple axis positional information

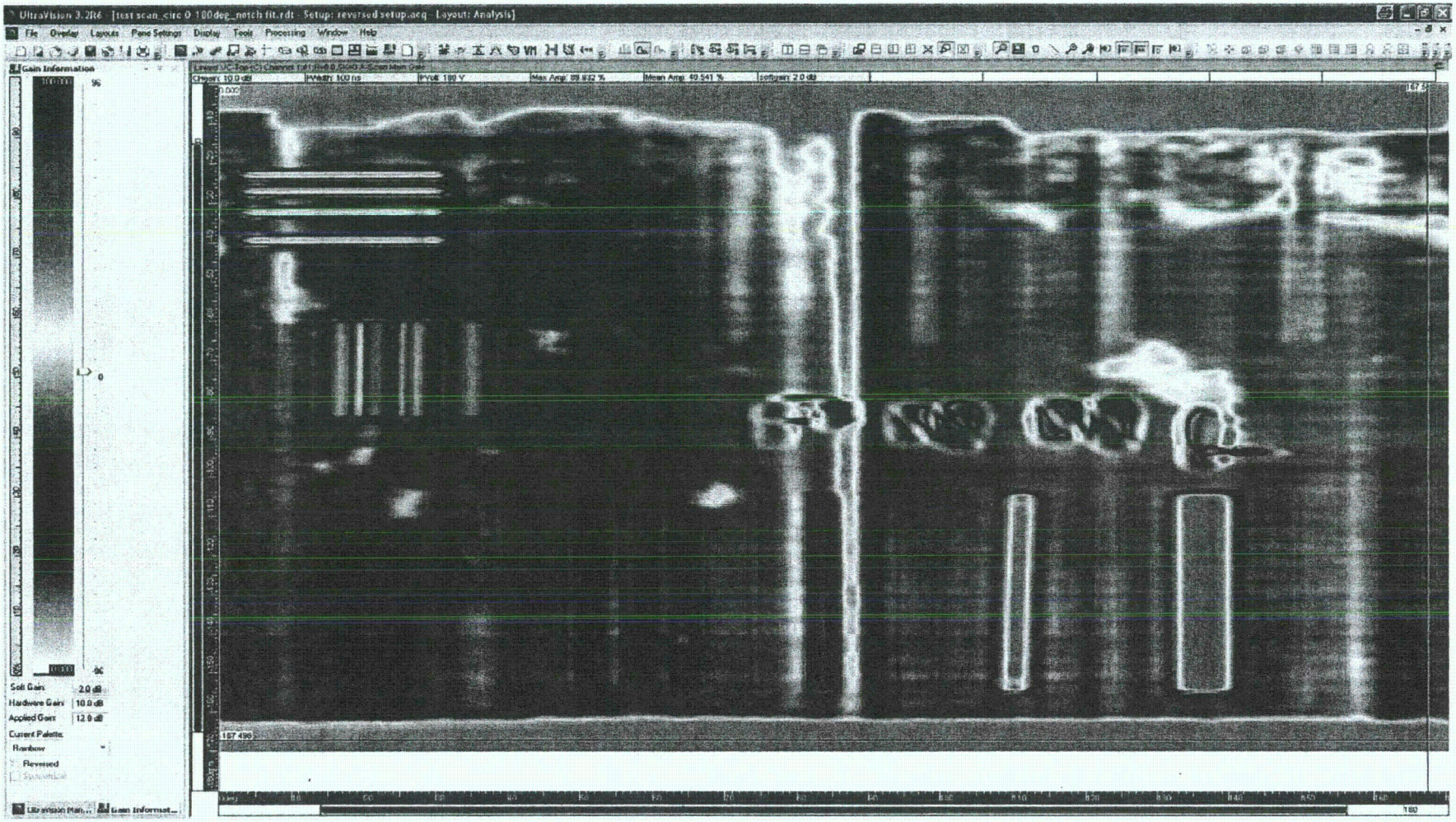
Custom Pulse Motor Scanner

- 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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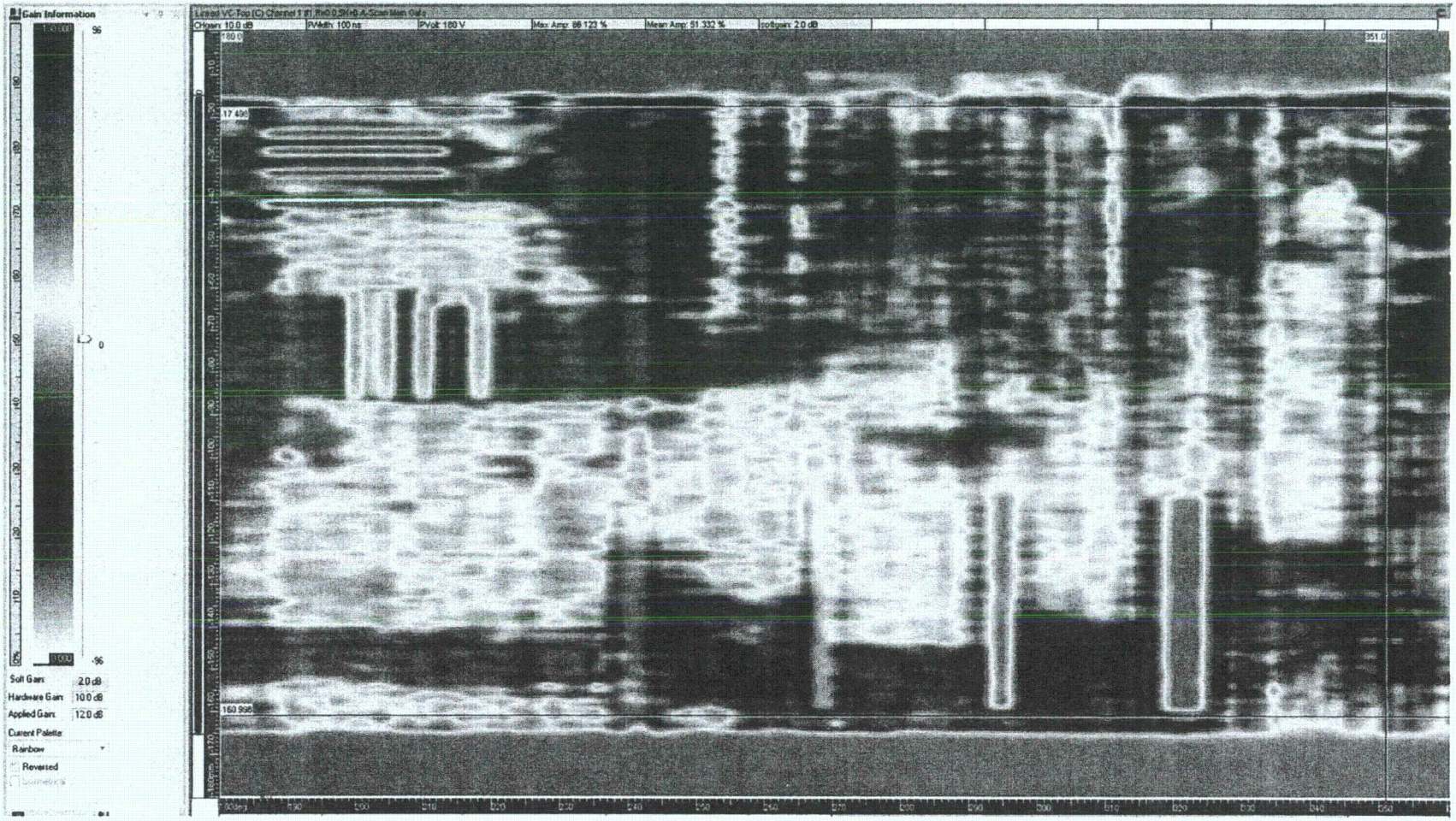
Ultrasonic Data: Mock-up Notches



0 to -180 mm Axial

180 to 360 deg. Circumferential

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

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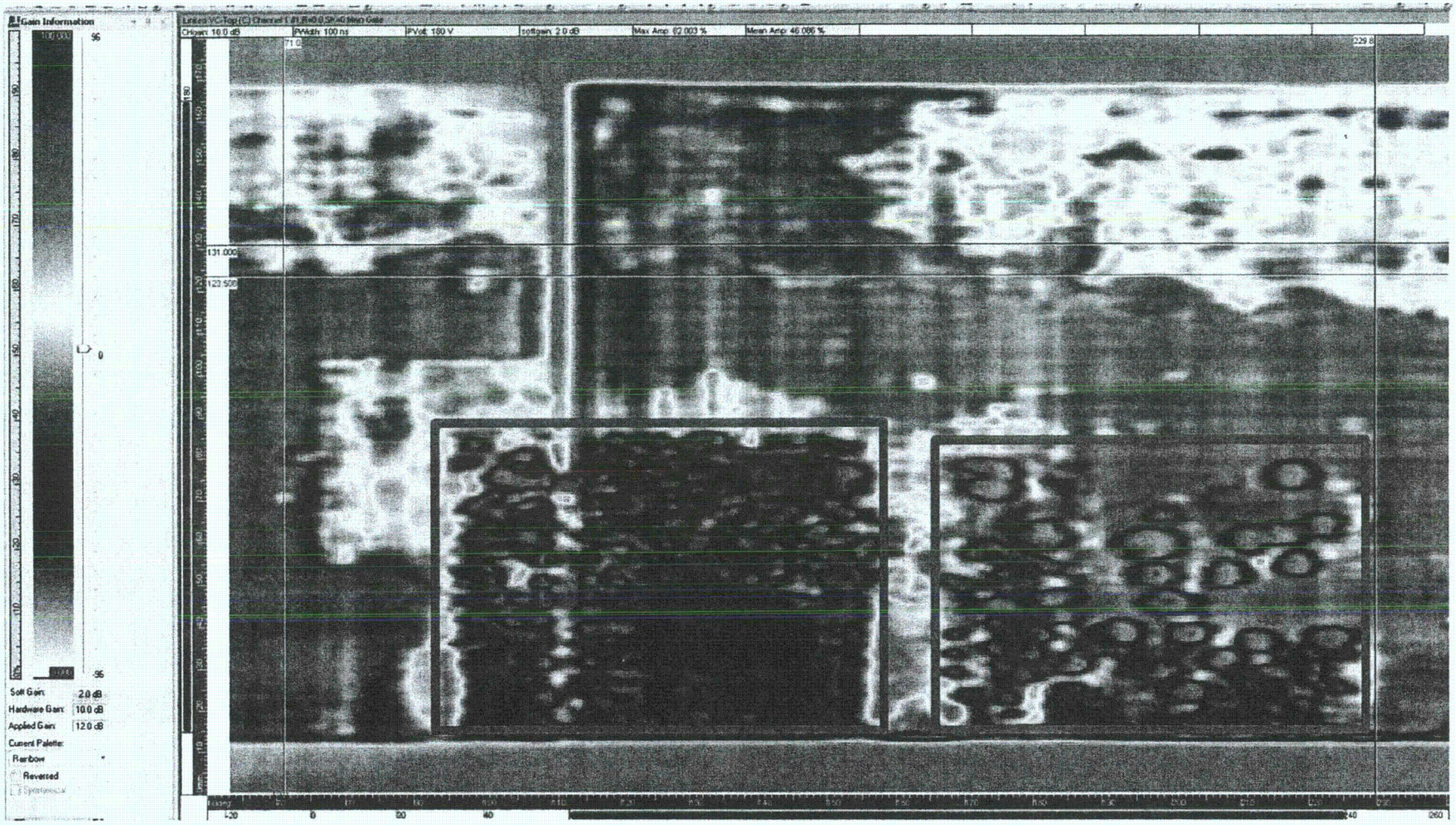
Ultrasonic Data: Mock-up Boric Acid



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

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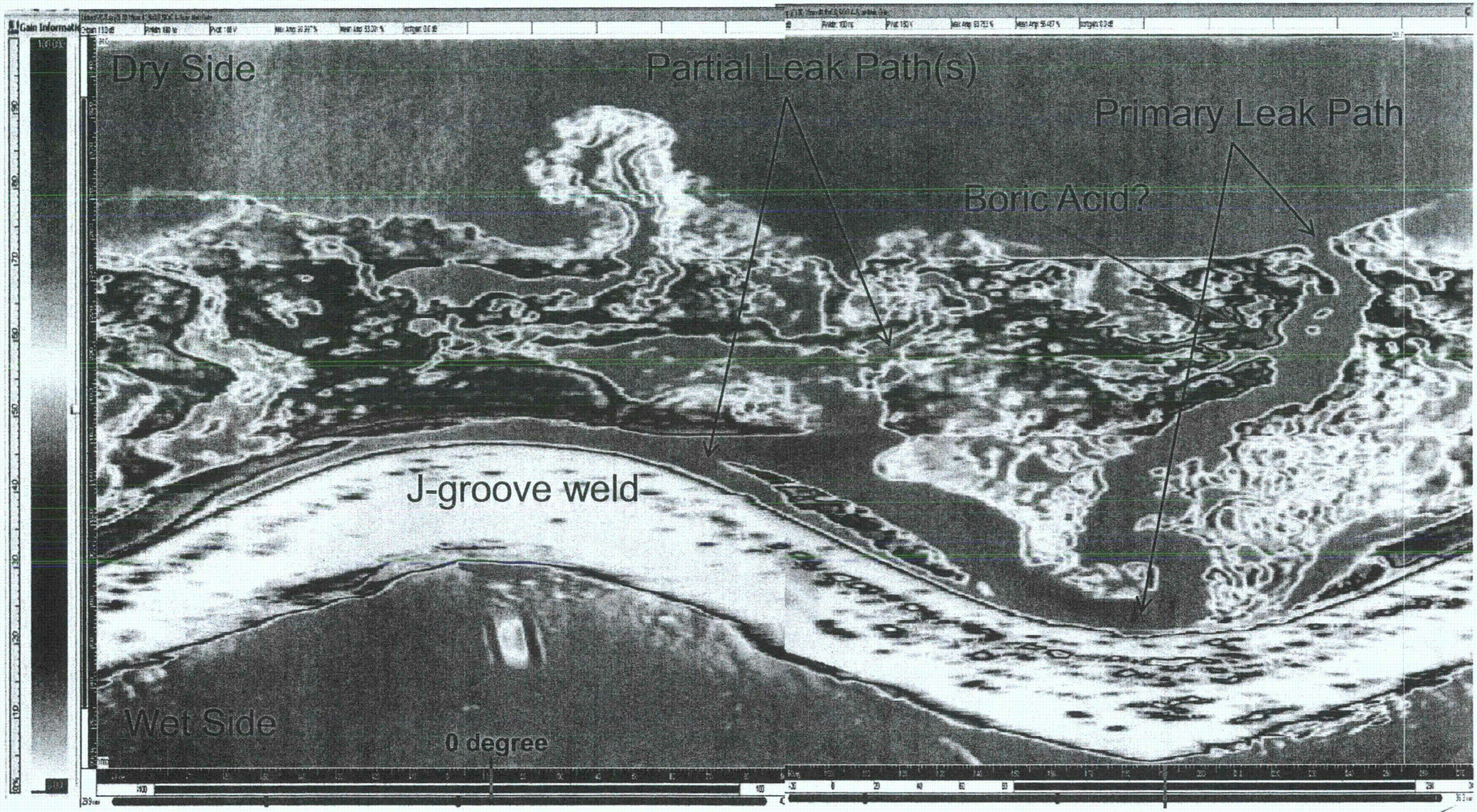
Mock-up Characterization Summary

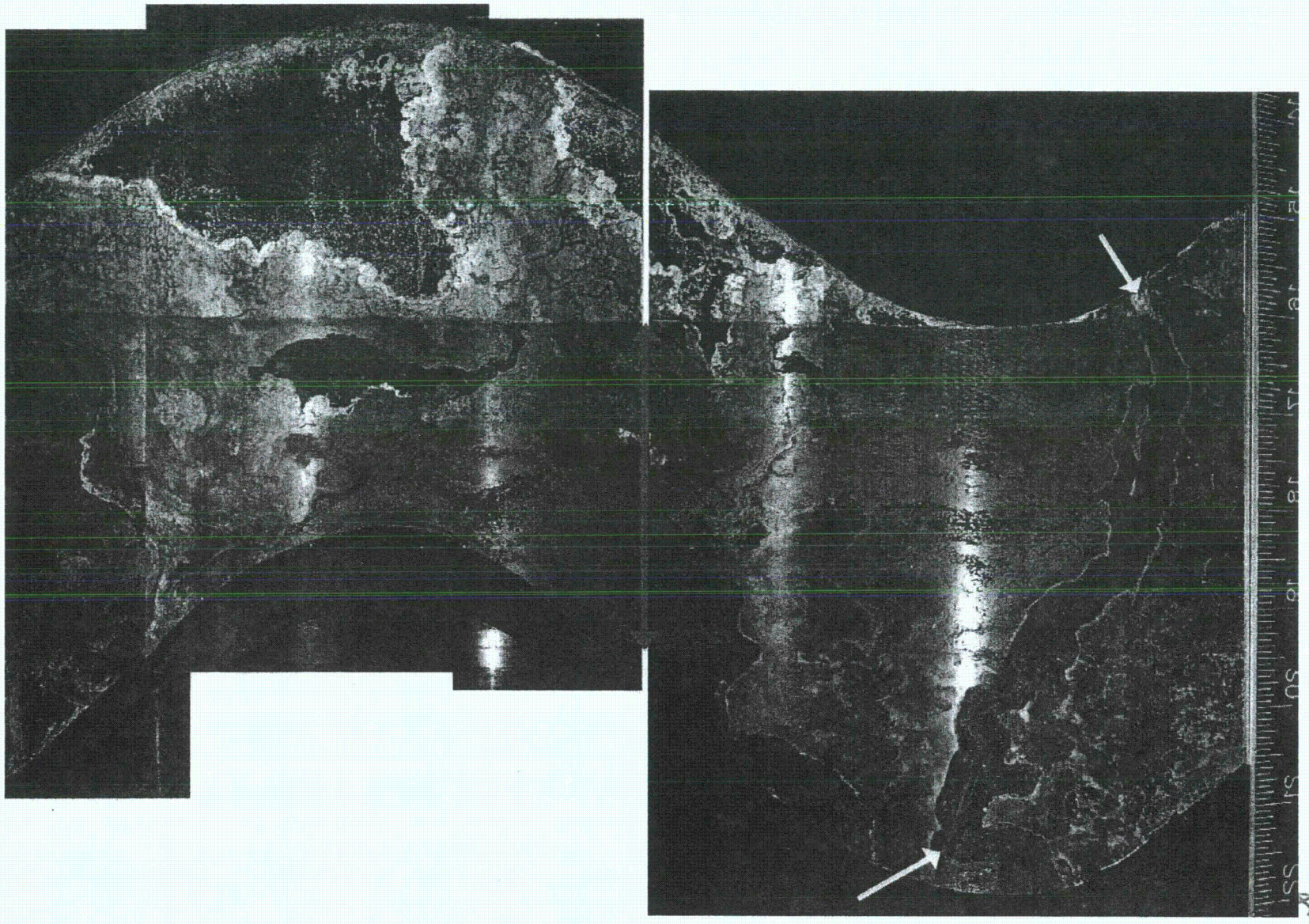
- All EDM notches were detected
  - Difficult to depth size the 'depth variation notches'
  - Both resolution sets (axial and circumferential) were detected and clearly distinguishable in both Inconel and carbon steel
  - Width variation notches sized within 1 mm
- Boric Acid presence was easily detected 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



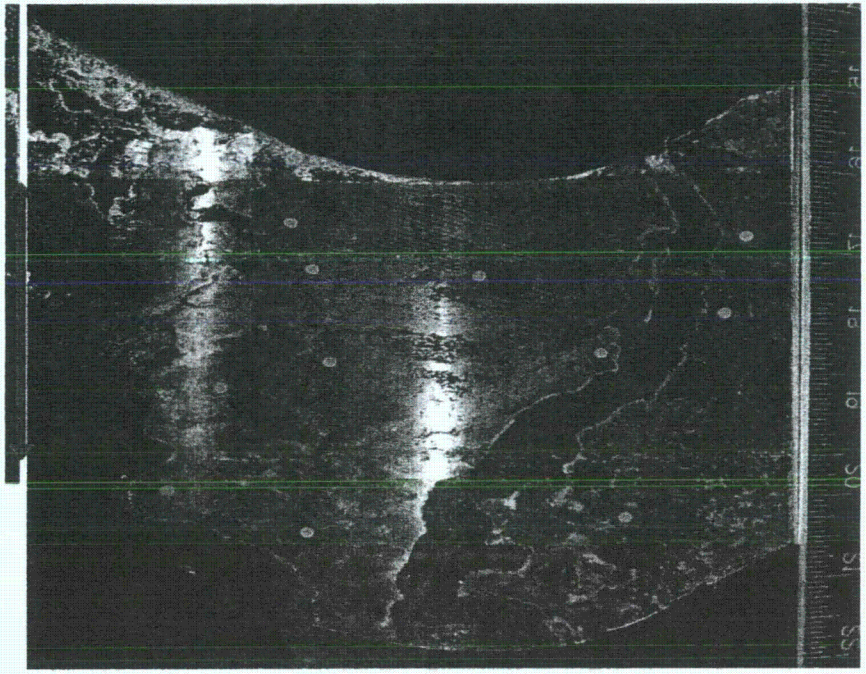
- C-Scan view: Full weld and fit region

Destructive Verification

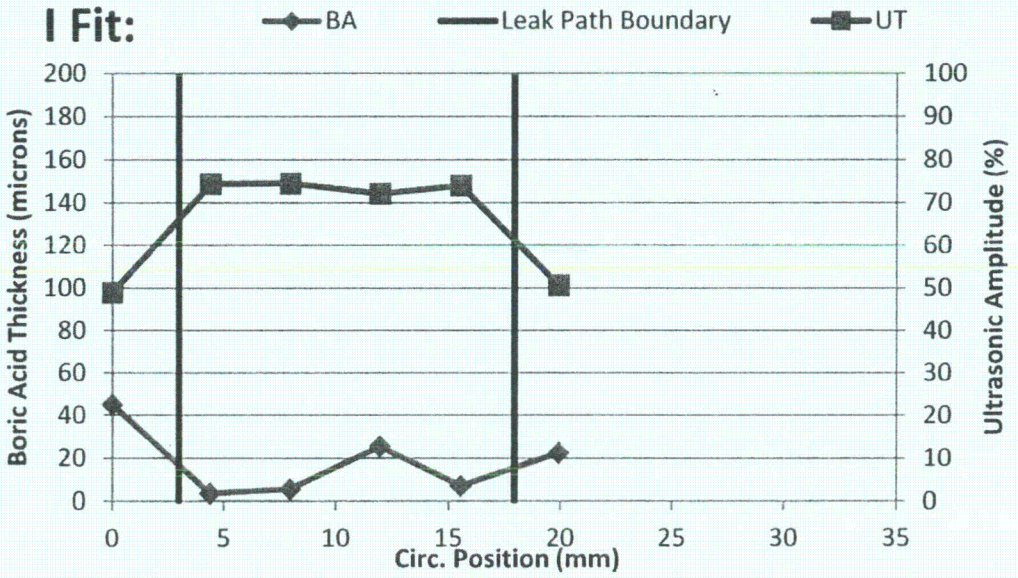


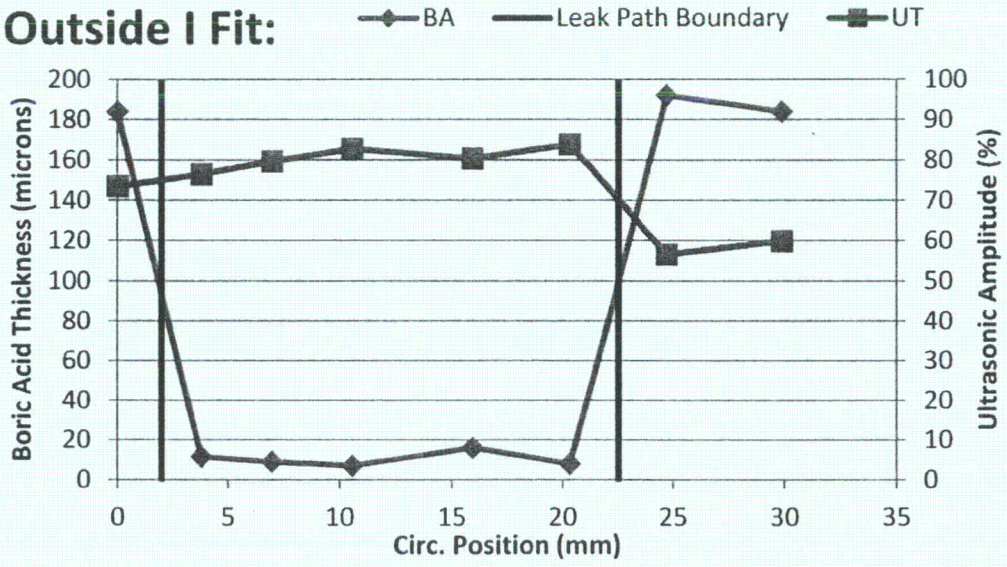
- RVH annulus view montage

Boric Acid/Corrosion Product Assessment (Leak Path Region)

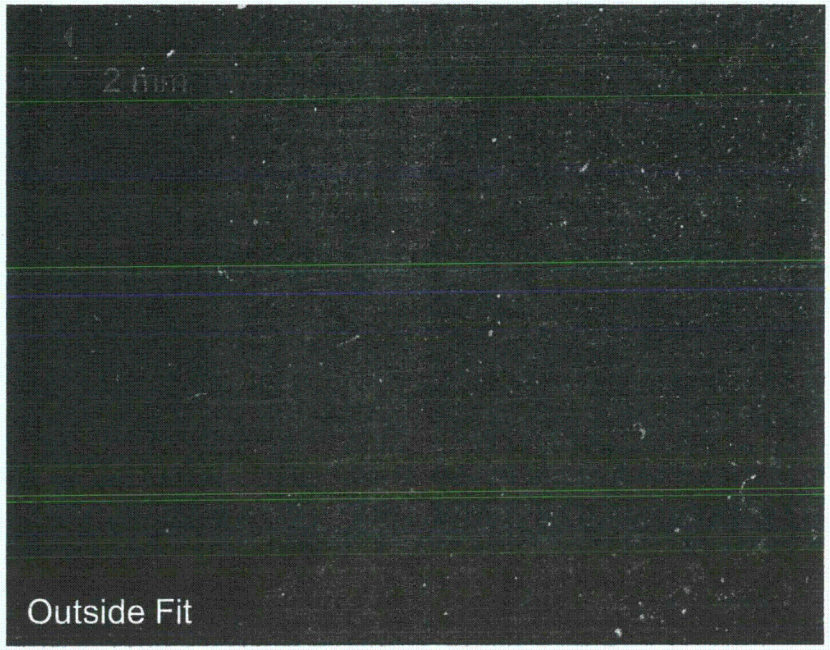


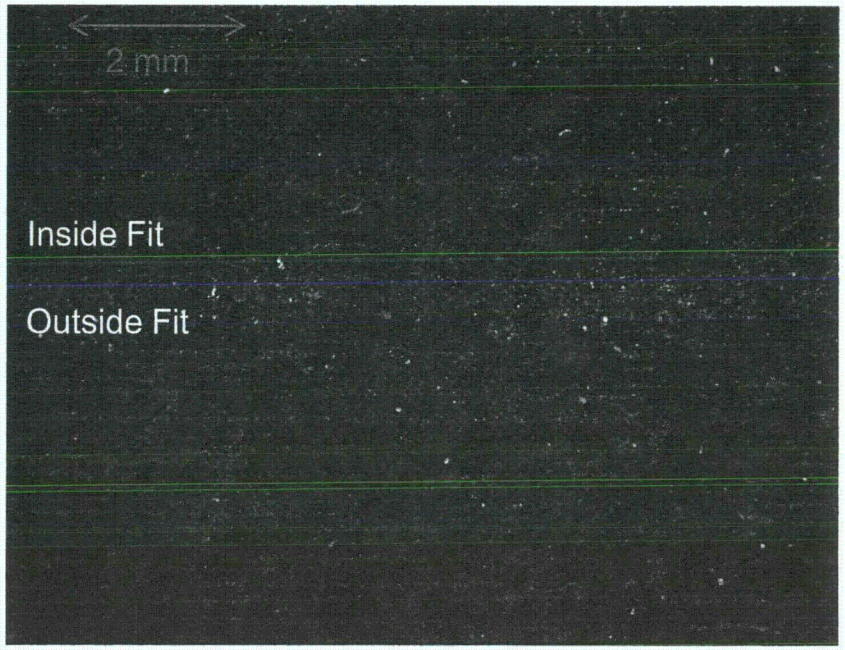
- Eddy current point probe
  - Accurate to 2.5 microns
  - Measure boric acid/ corrosion product layer thickness
- Inverse relationship with ultrasonic response



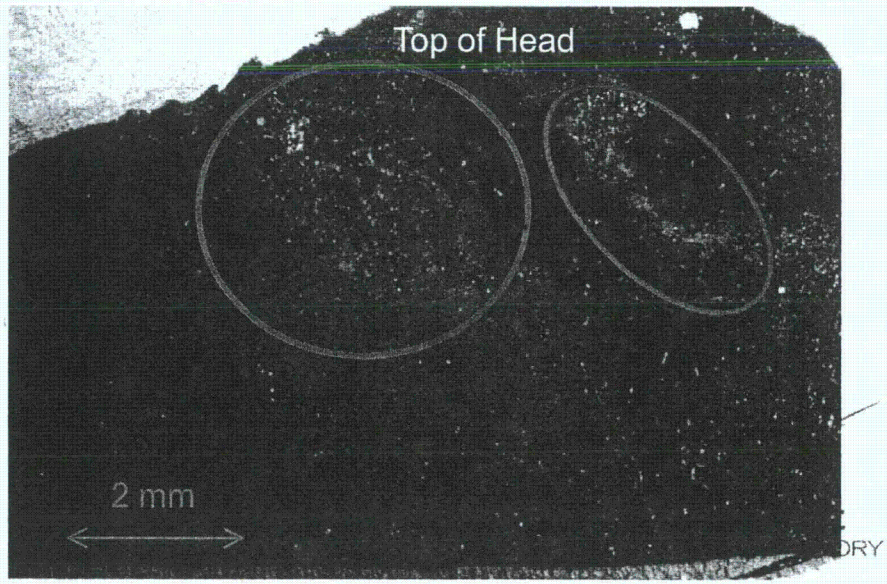


Microset Analysis





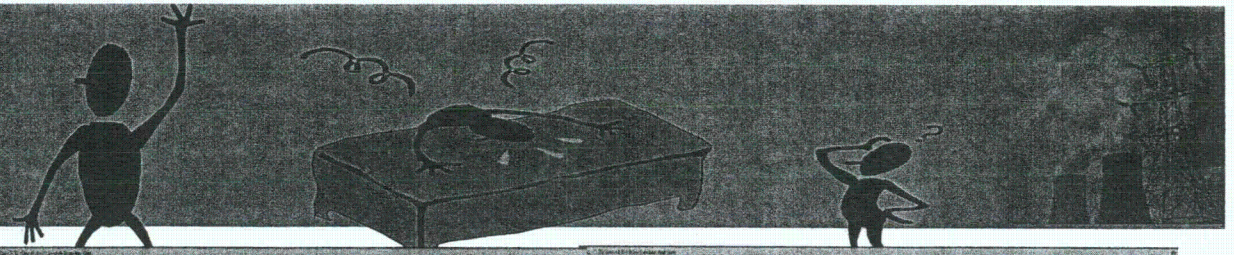
- Replicas made on RPV annulus main leak path region
- Machining striations present
  - Minimal corrosion/wastage
- Minor Corrosion visible at top of head region
  - Leak exit point

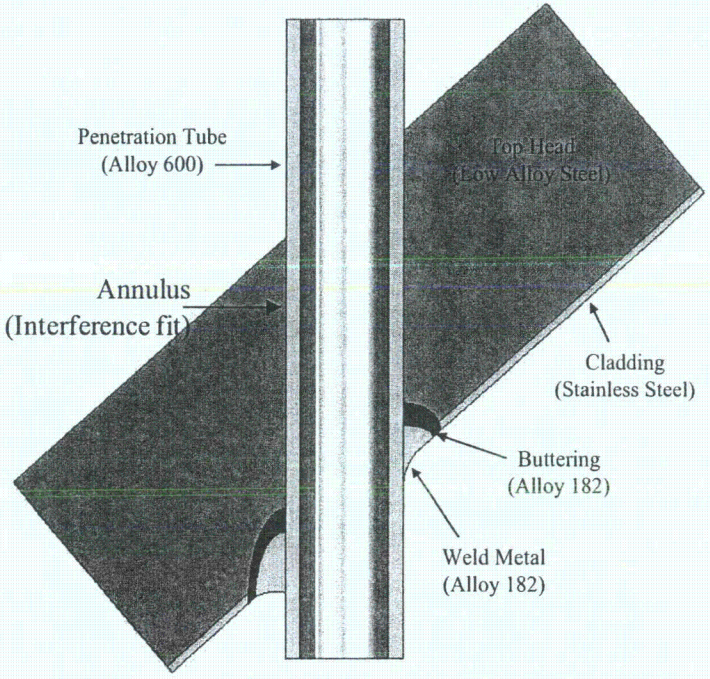


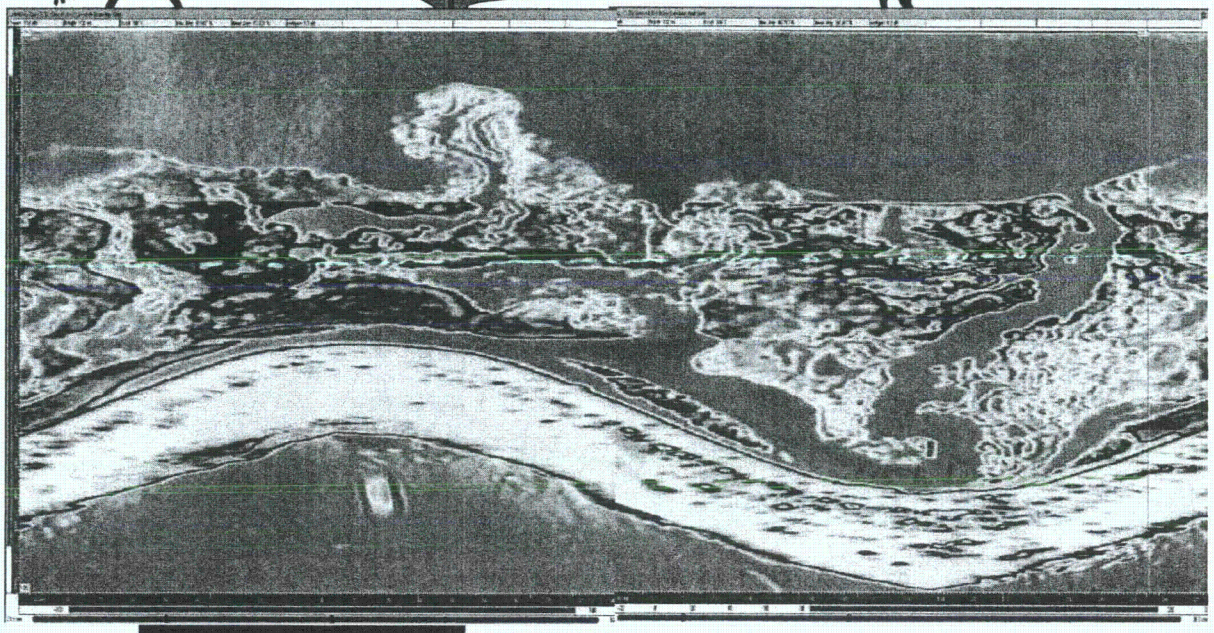
Results/Conclusions

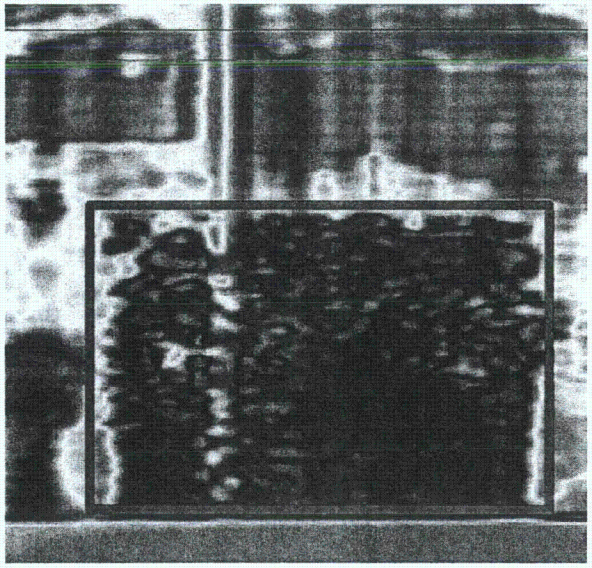
- Mock-up Specimen
  - All calibration notches were detected
    - Most notches sized favorably with true state
    - Shallow notch detection showed sensitivity of UT method
  - Boric acid regions were detected
    - Greater ultrasonic transmission in boric acid regions
- A leak path was identified in 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

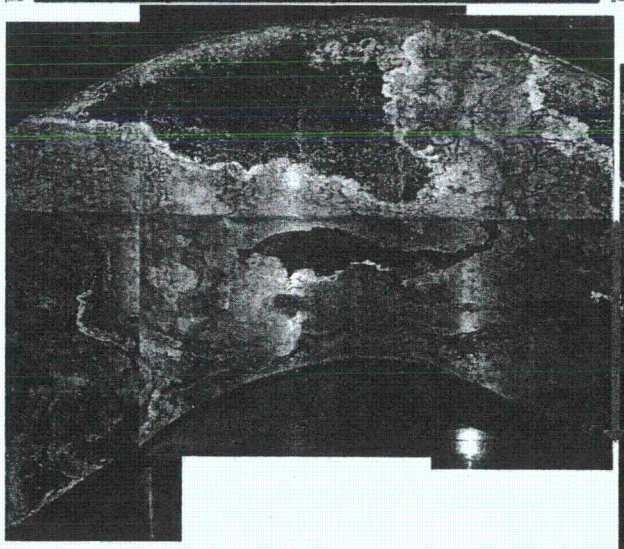
Thank You!
Questions?

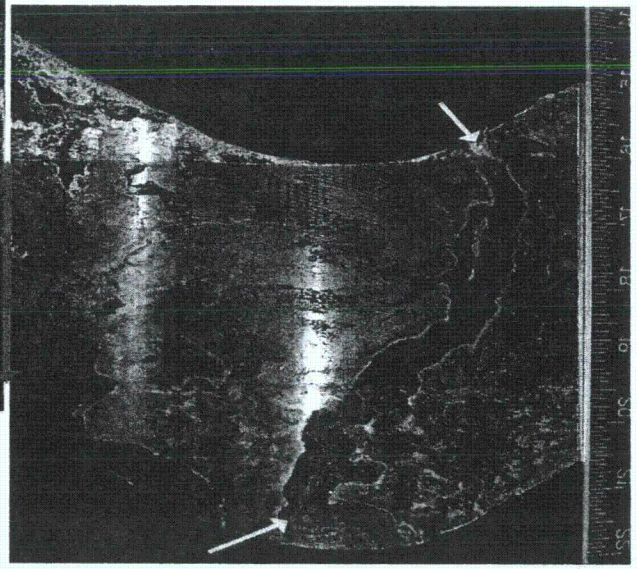








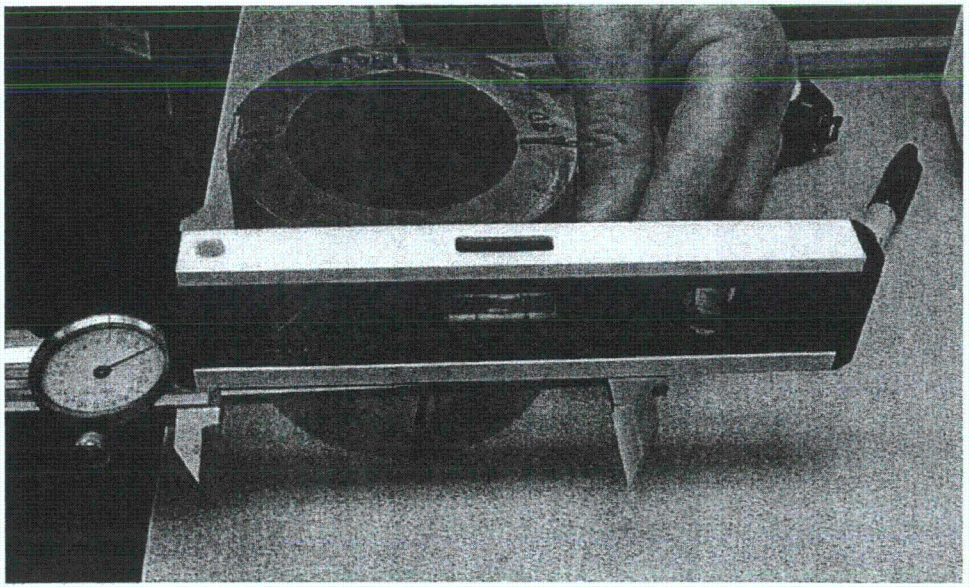


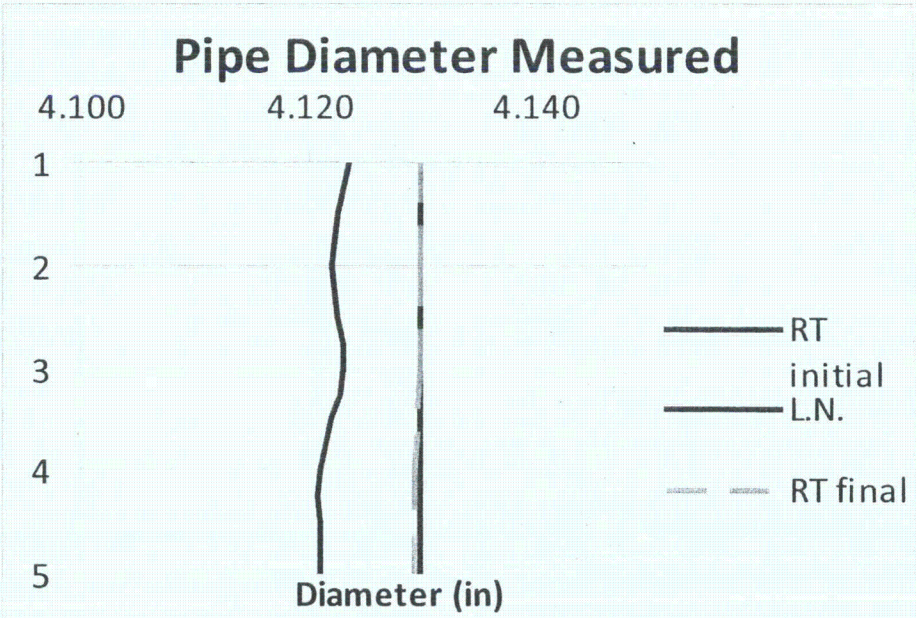


Supplemental Slides Beyond This Point

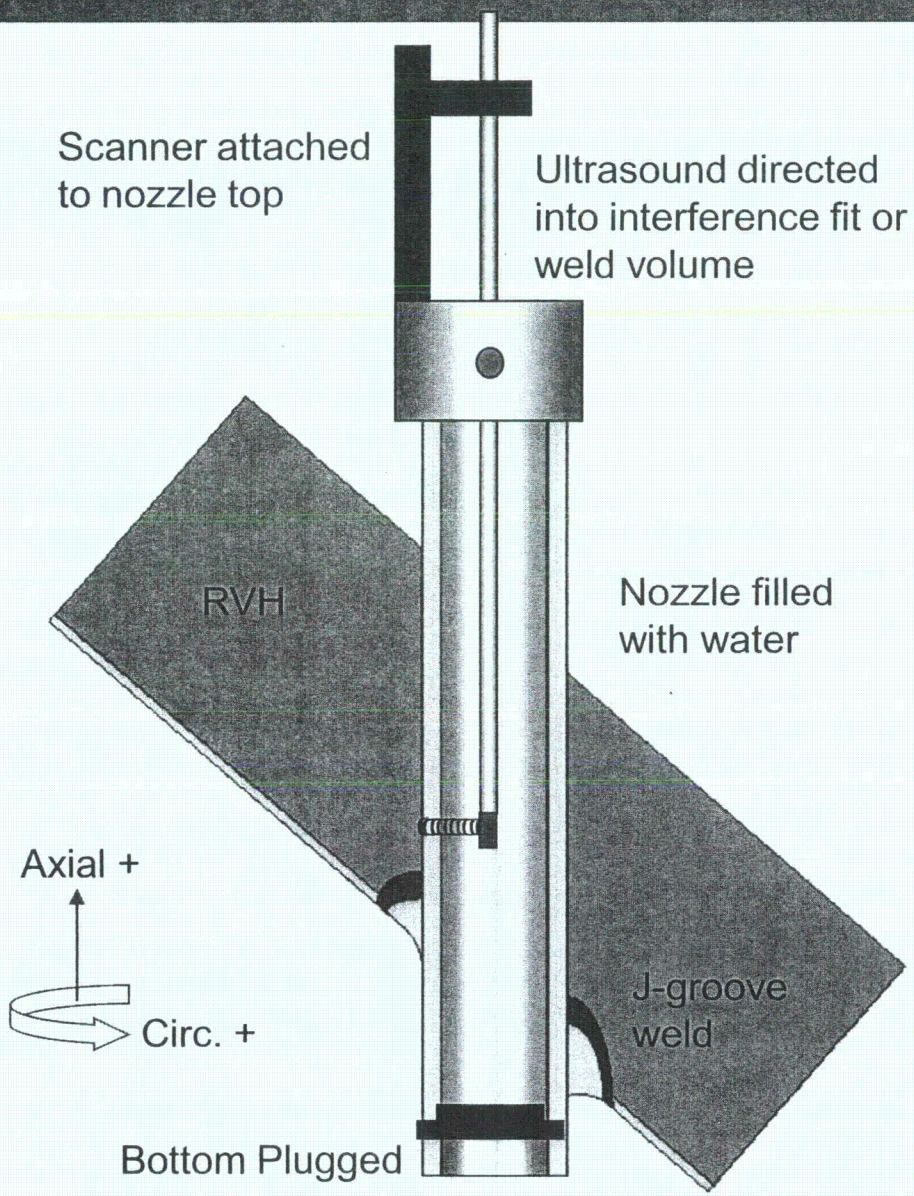
Mock-up Assembly: Inconel Shrinkage

- 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

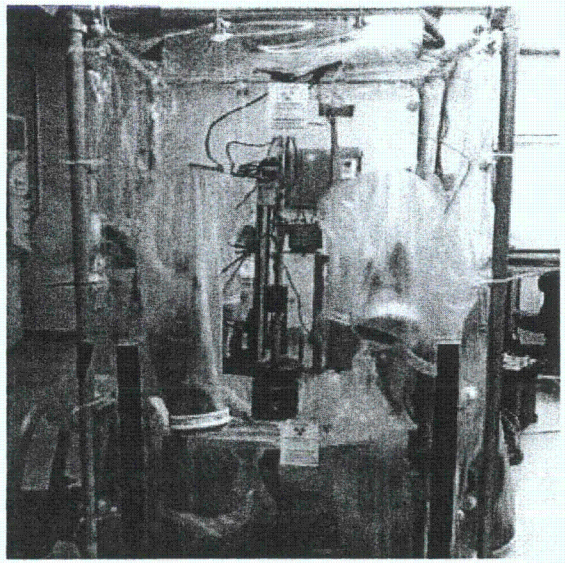




Ultrasonic Data Acquisition

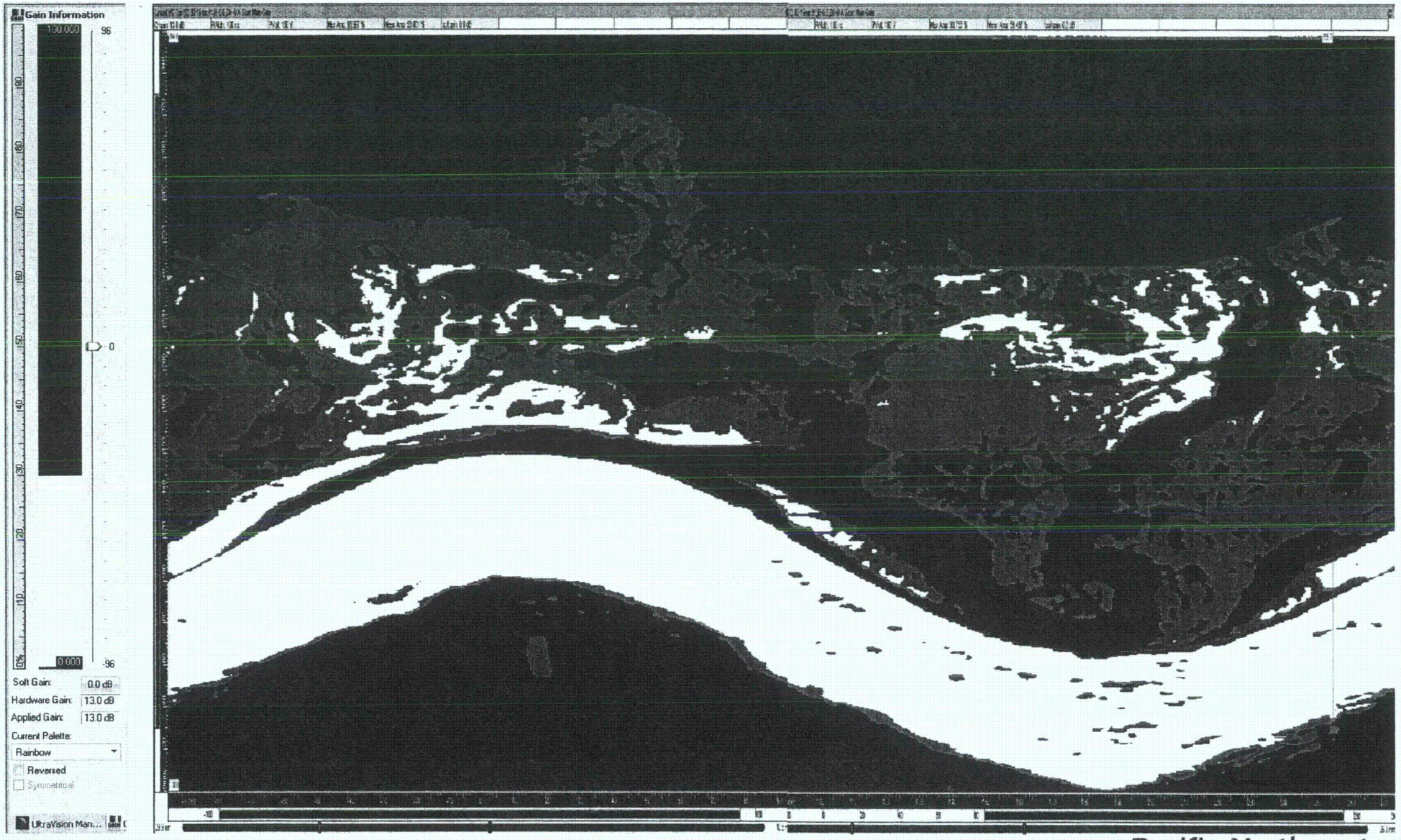


- Multiple depth focal laws implemented
  - Tube ID
  - Tube OD/interference fit region
- Raster scan protocol
  - 'Scan' in circumferential direction
  - 'Index' in axial direction
- Resolution
  - 0.5º in scan by 0.5 mm in index
- Positional information relayed via shaft encoders



Ultrasonic Data: Nozzle 63 (cont'd)

60-100%
30-60%
0-30%



C-Scan view: Custom color bar

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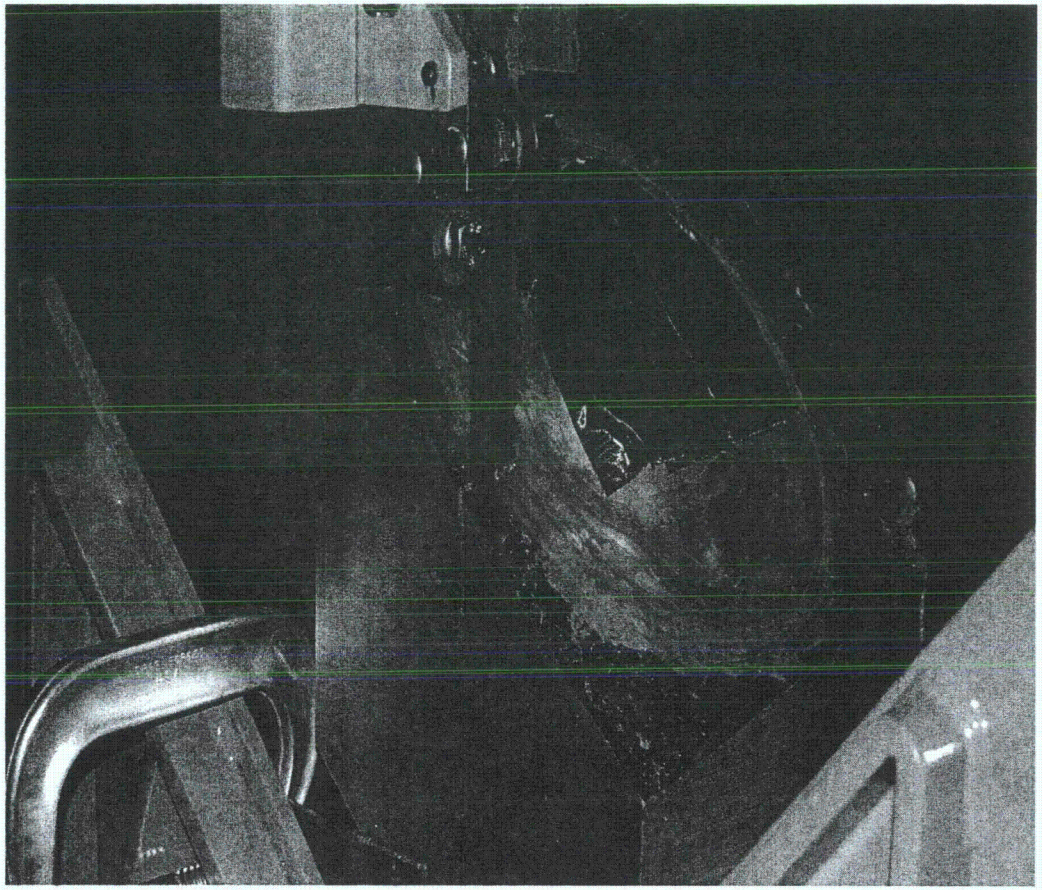
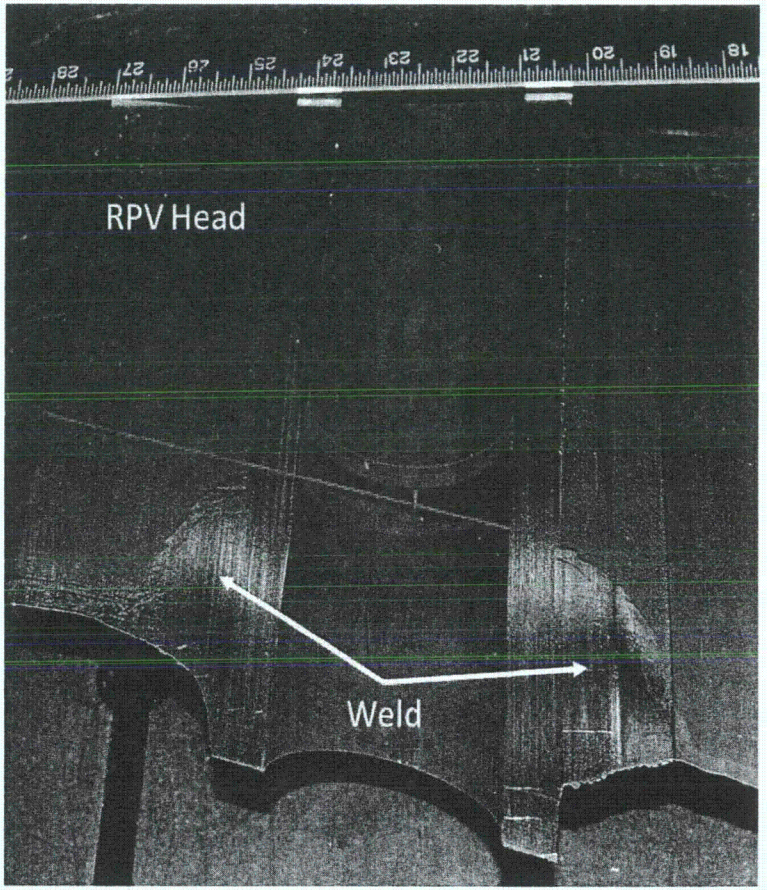
Suplemental: Destructive Cutting





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