PNNL-SA-123305

Evaluation of Ultrasonic Phased-Array for Detection of Planar Flaws in High-Density Polyethylene Butt-Fusion Joints

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Outline

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- Phased Array Ultrasonic Testing (PAUT) Examination of HDPE Butt-fusion Joints
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  - Results Summary
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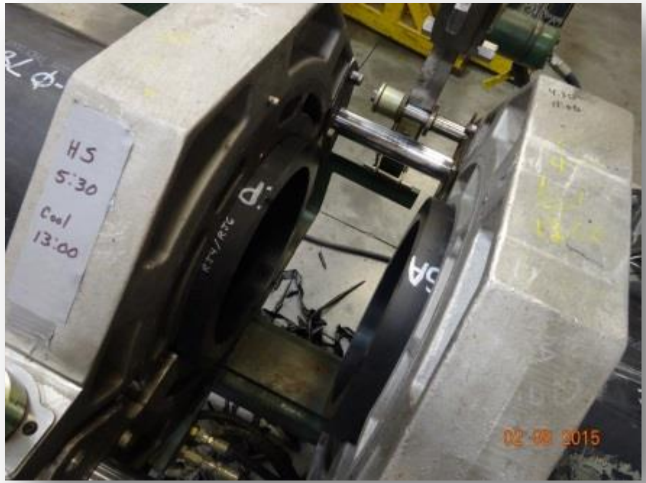
- Outcomes and Conclusions
- Recommendations

Introduction

- PNNL is conducting a review/assessment of volumetric nondestructive examination (NDE) methods identified in ASME Code/Section III for HDPE joints to ensure high-quality product enters service and structural integrity is maintained during service
- Focus of PNNL 'NDE of HDPE' work:
  - Evaluating the reliability of PAUT in the detection of surrogate fabrication flaws in butt-fusion joints using different PAUT probe apertures
- PNNL had conducted a preliminary assessment of NDE of HDPE focused on lack of fusion in butt-fusion joints (NRC Job Code N6398, 2007-2012)
  - Testing was performed with PE3408 HDPE Material
  - NUREG/CR-7136, *Assessment of NDE Methods on Inspection of HDPE Butt Fusion Piping Joints for Lack of Fusion*

Motivation

- Butt-fusion is the primary HDPE pipe joining method
- PAUT is the primary examination technique, transmit-receive longitudinal (TRL) most effective configuration for flaw detection
- HDPE butt-fusion joint fabrication flaws of concern are:
  - Planar flaws
  - Cold fusion/lack of fusion caused by out-of-spec temperature/pressure during fabrication or the introduction of fine particulate contamination
- Assess reliability of PAUT NDE for detection of fabrication flaws in HDPE



HDPE Specimens

- The reliability of PAUT-TRL was evaluated for HDPE butt-fusion joints
- 12-in. dia. DR11 pipe produced with PE4710 bi-modal Code-conforming resin
  - Same commercial-dedicated pipe used for EPRI slow crack growth rate studies
- Fabricated butt-fusion joints without and with surrogate flaws:
  - Planar flaws (SS discs), 0.8-2.2 mm diameter
  - *Attempted* cold fusion/lack of fusion from particulate contamination (tungsten powder)
  - *Attempted* cold fusion/lack of fusion from out-of-spec pressure applied during heat soak period or shortened duration of heat soak

Specimens, *Pre-Fabrication*

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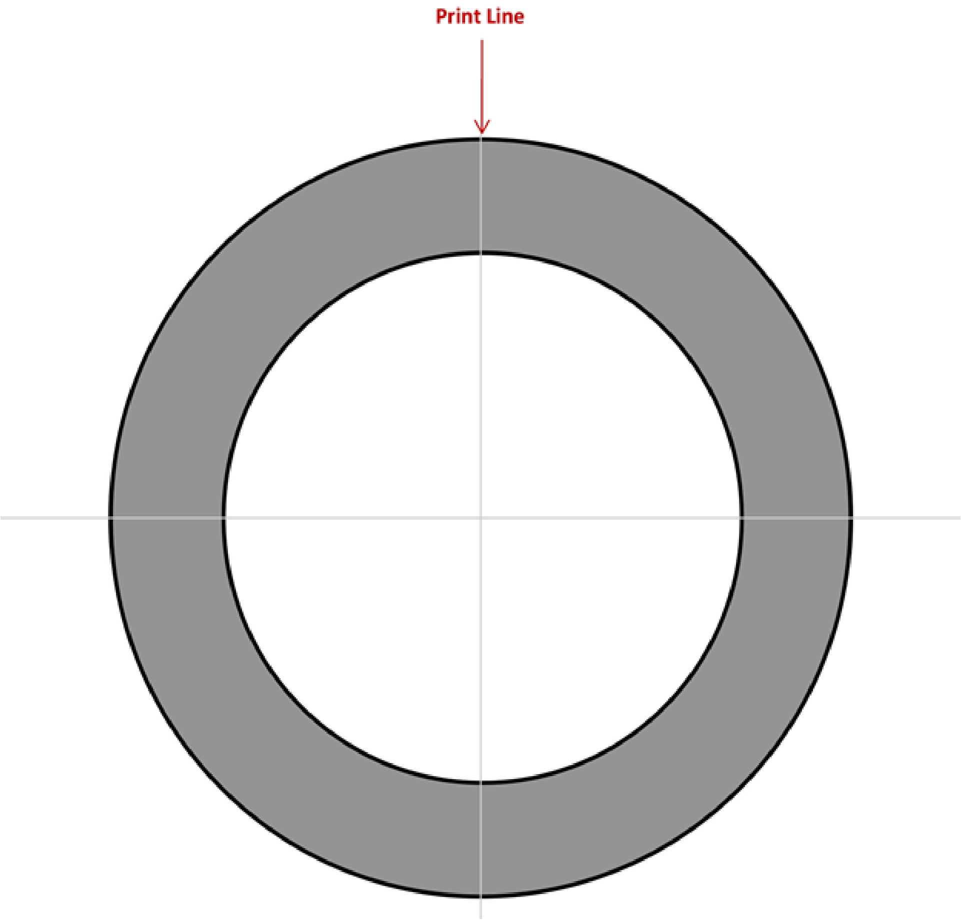
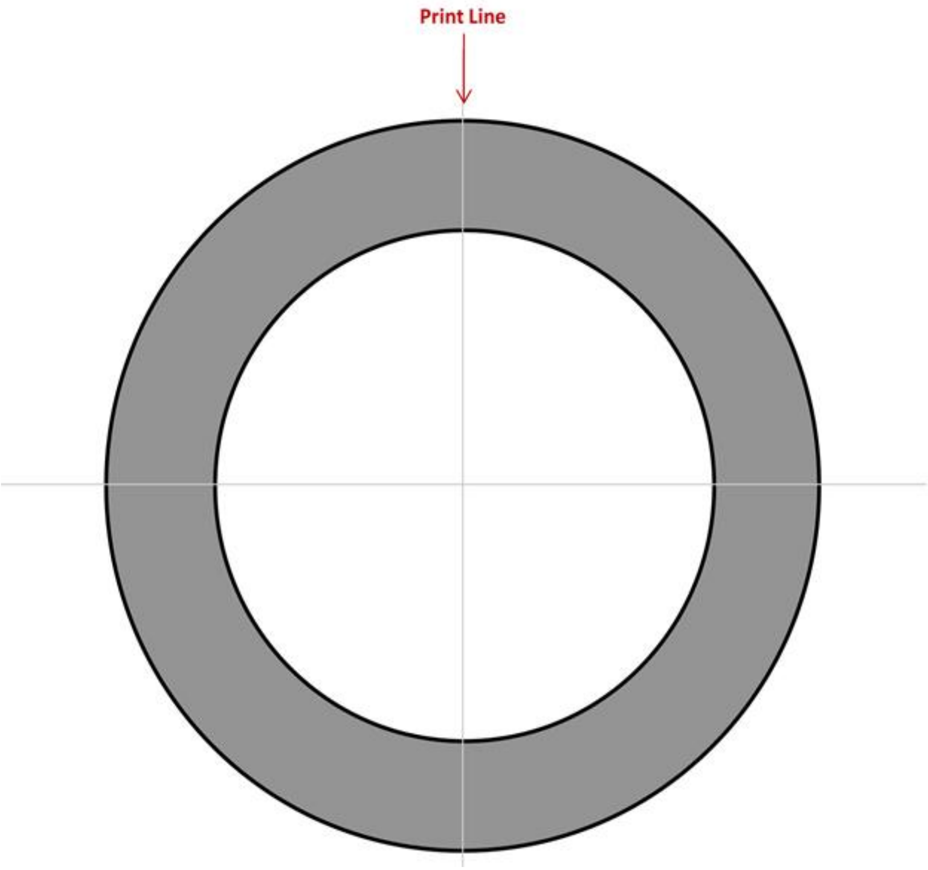
Specimen J-28 (baseline; no implanted flaws)
Fabrication: TR-33

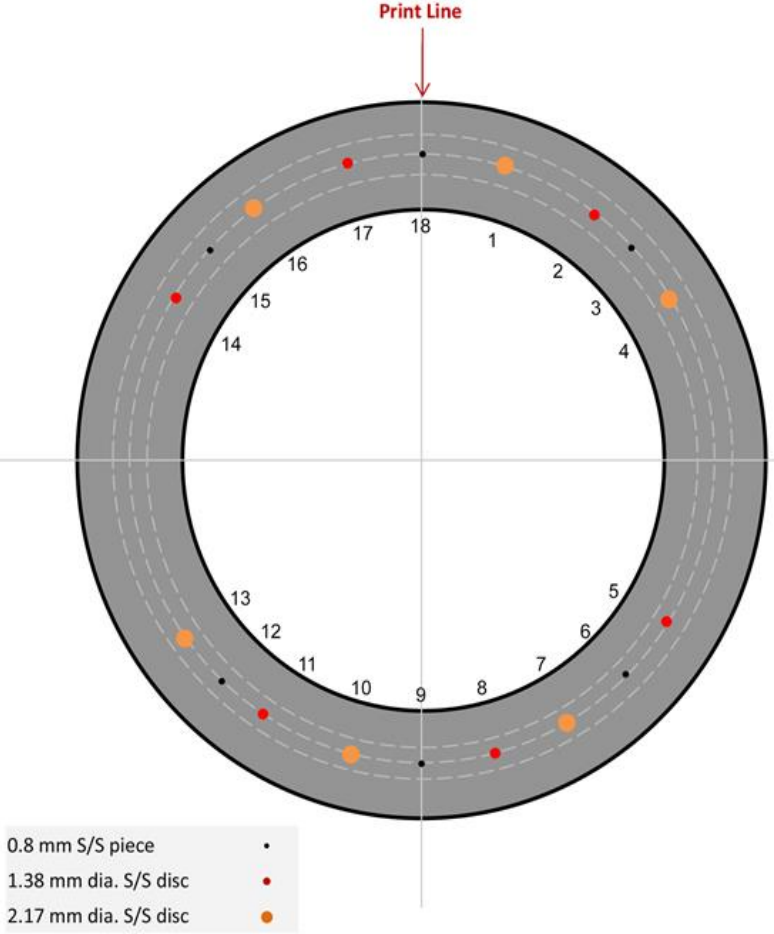


Specimen J-31 (cold fusion attempt; no planar flaws)
Fabrication: TR-33 **violation** with 75 psi (5.2E+2 kPa) interfacial pressure during heat soak

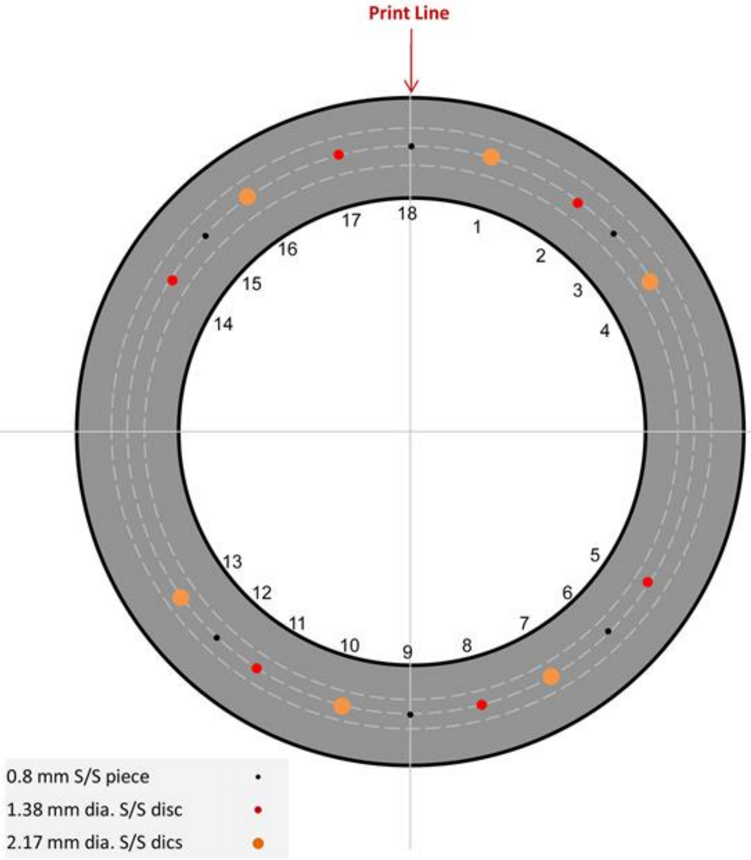


Specimens, *Pre-Fabrication*

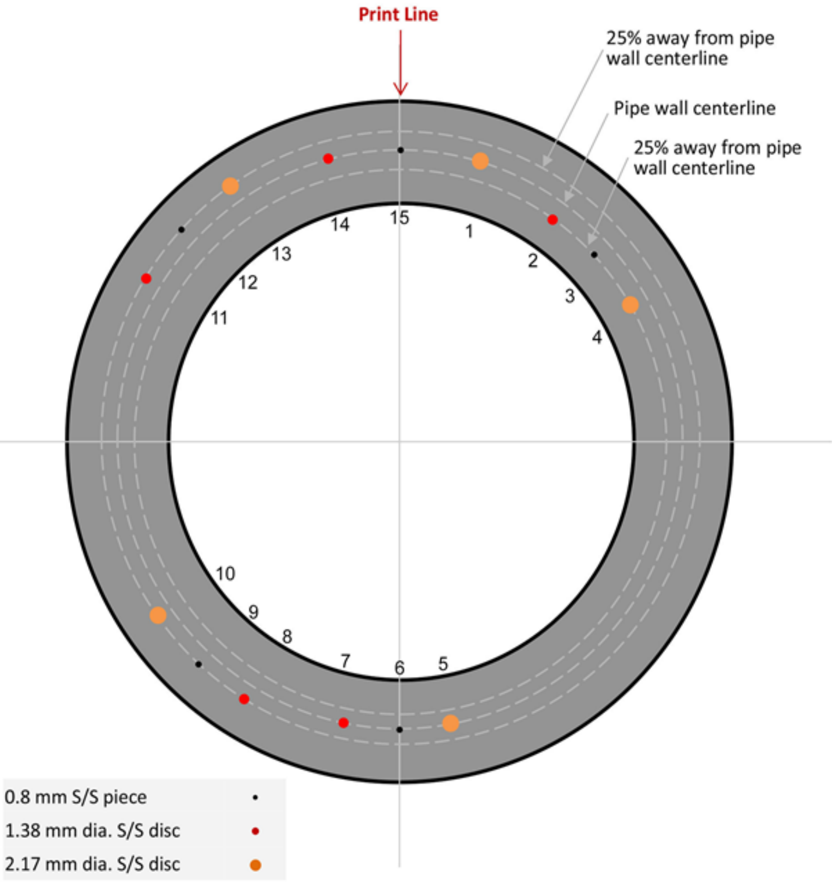
Specimen RJ4/RJ6-2 (planar flaws)
Fabrication: TR-33



Specimen RJ-8 (cold fusion attempt with planar flaws)
Fusion Procedure: TR-33 **violation** with 2-minute heat soak



Specimen RJ4/RJ6 (planar flaws)
Fabrication: TR-33



Specimens, *Pre-Fabrication*

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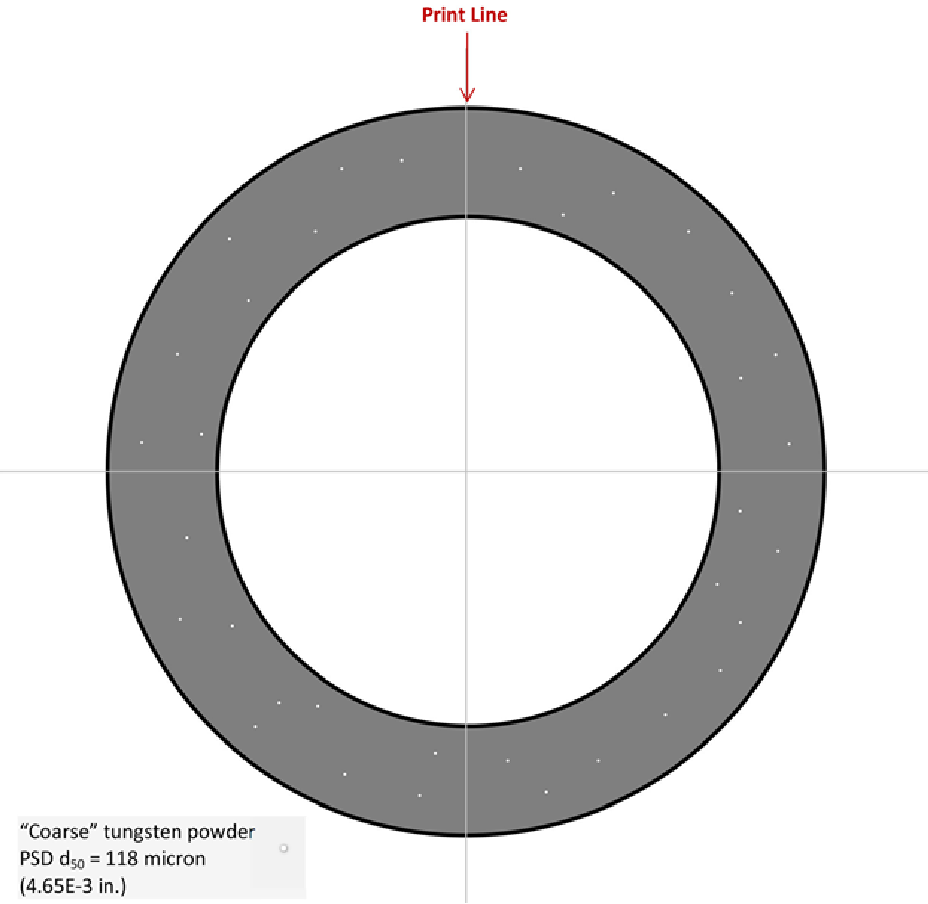
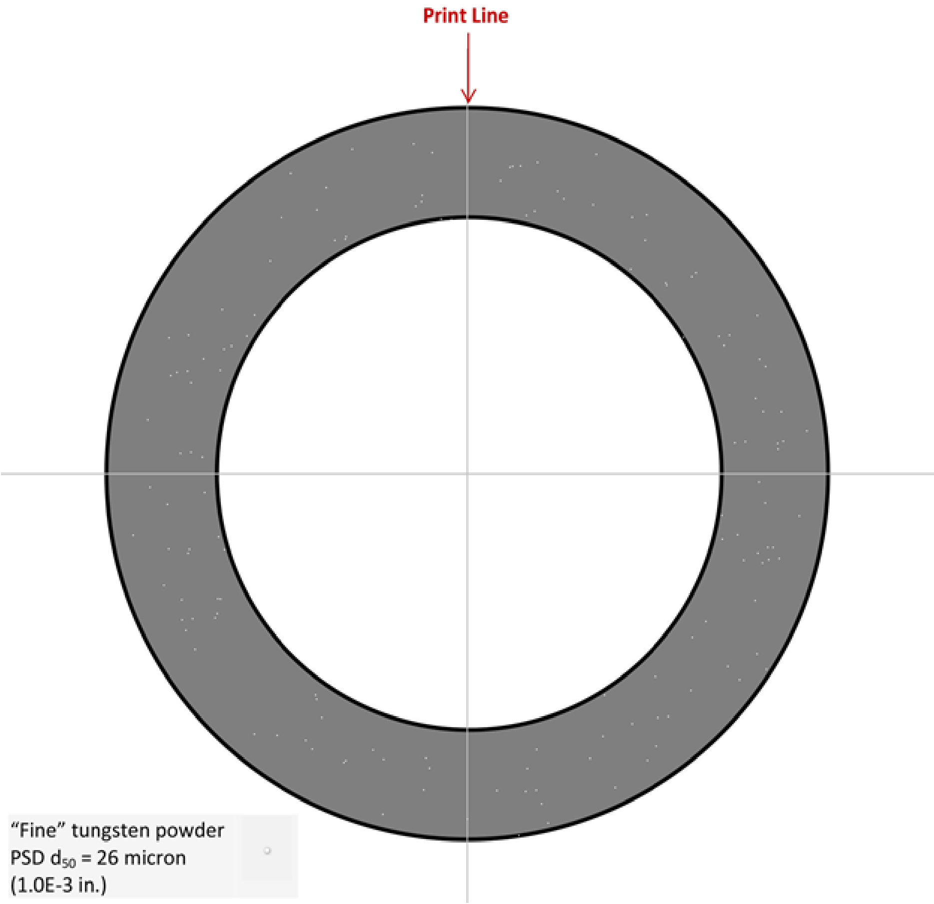
Specimen J-29 (“coarse” particulate contamination)
Fabrication: TR-33

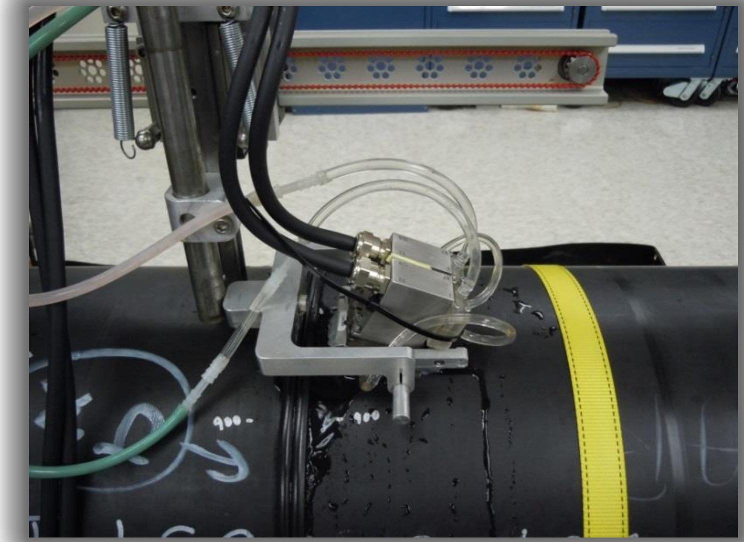


Specimen J-30 (“fine” particulate contamination)
Fabrication: TR-33



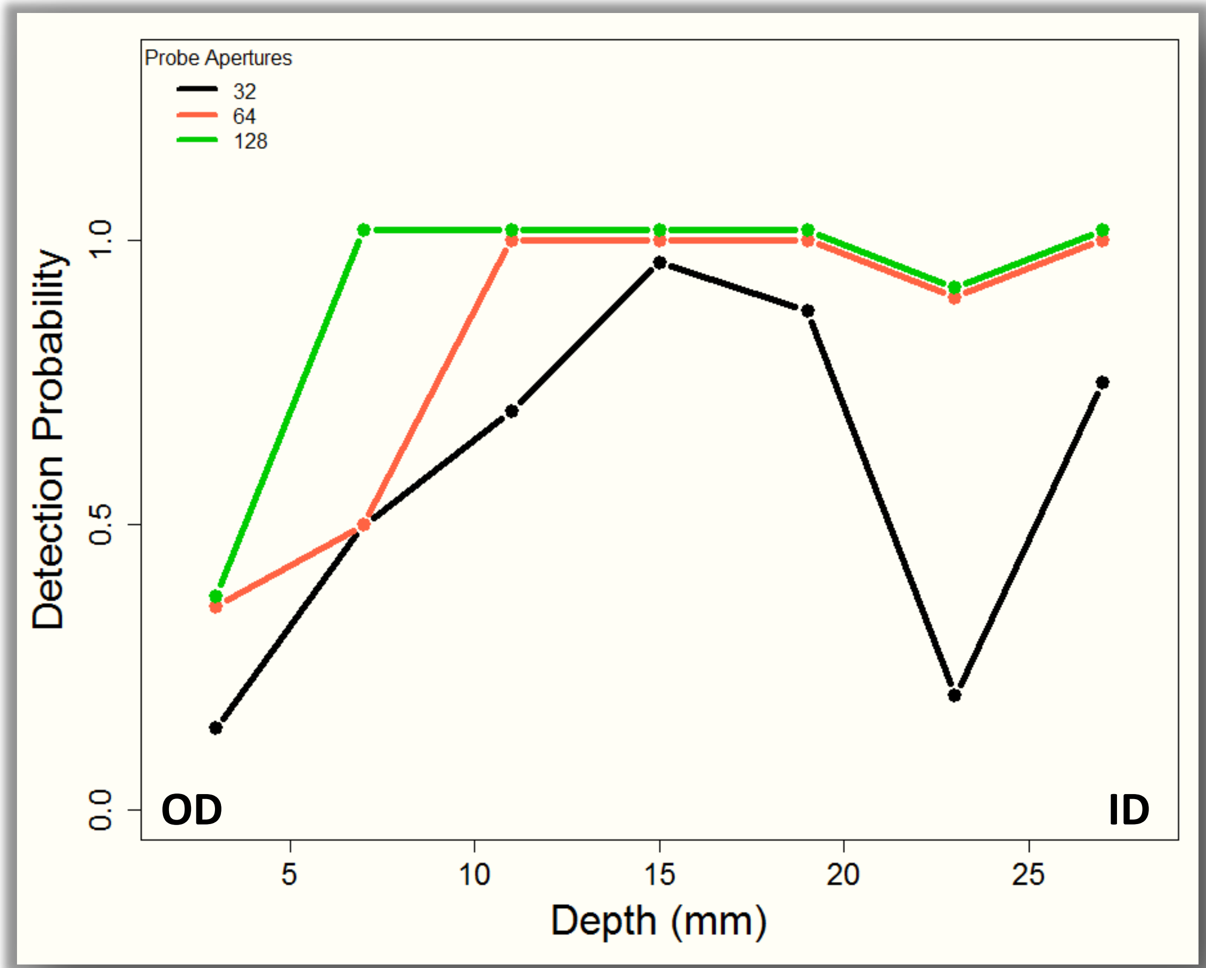
Examination

- True state of post-fabrication planar flaw size, position verified with RT (see supplemental slides)
  - 51 discs implanted before fabrication
  - 38 remained in the weld after fabrication
- Butt-fusion joints examined by PAUT-TRL
  - Examined with weld beads intact
  - Three different apertures:
    - 128E – represented best possible
    - 64E – represented reasonable mid-point
    - 32E – minimum specified in ASME Code



Probability of Detection (POD)

- Completed evaluation of PAUT-TRL for HDPE weld joints containing planar flaws, with weld beads intact
- Detection depends primarily on through-wall (radial) position of discs
  - Discs near OD difficult to detect by all apertures
  - 128E and 64E similar in detection performance
  - 32E had lowest detection rate overall
  - Sharp changes in plot are exaggerated – due to a limited number of data points at that through-wall depth
- Work illustrates volumetric coverage using PAUT-TRL



POD for Each Probe Aperture as a Function of Radial Disc Position. POD based on 38 discs.

Percent Detection with Different Apertures

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Probe Aperture	*Planar Flaw Diameter*		
	0.8 mm	**1.38 mm**	**2.17 mm**
128E	80.77 %	76.92 %	95.83 %
64E	80.77 %	80.77 %	87.50 %
32E	42.31 %	65.38 %	79.17 %

- Overall detection of the discs using the 128E and 64E were comparable
  - Above 75% for these two apertures on all discs
  - Undetected discs were located near the OD of the specimen (~2 mm deep “blind spot”)
- Detection using a 32E aperture was significantly lower
  - Only the 2.17 mm discs were detected with a certainty above 75%

Single vs. Double Sided Inspections

- Detection not guaranteed if examination performed from only one side of weld
  - Better detection from skew 180° side than skew 0° side (skew 180° side is the pipe end onto which discs were attached prior to fusion, not perfectly flat)
  - Detection percentage improves by over 5% for all 3 apertures when both skews are used to identify flaws within the weld region
- Overall detection is similar between the 128E and 64E apertures
  - Both show 18.4% improved detection of defects over the 32E aperture

Detection Percentages by Probe Aperture and Examination Rigor

Probe Aperture	Scanning from One Side	Scanning from Both Sides
32E	61.84 %	71.05 %
64E	82.89 %	89.47 %
128E	84.21 %	89.47 %

PAUT-TRL Examination of Planar Flaws

Same specimen, same flaws: RJ4/RJ6-2, Flaws 1, 2, and 3 (skew 180°)

128E Aperture

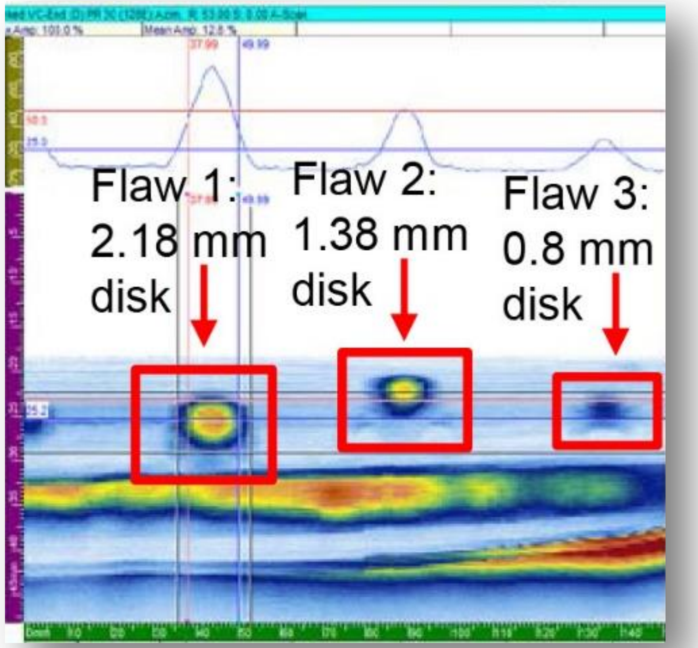
- 2.17 mm → 20.6 dB SNR
- 1.38 mm → 18.1 dB SNR
- 0.80 mm → 11.6 dB SNR

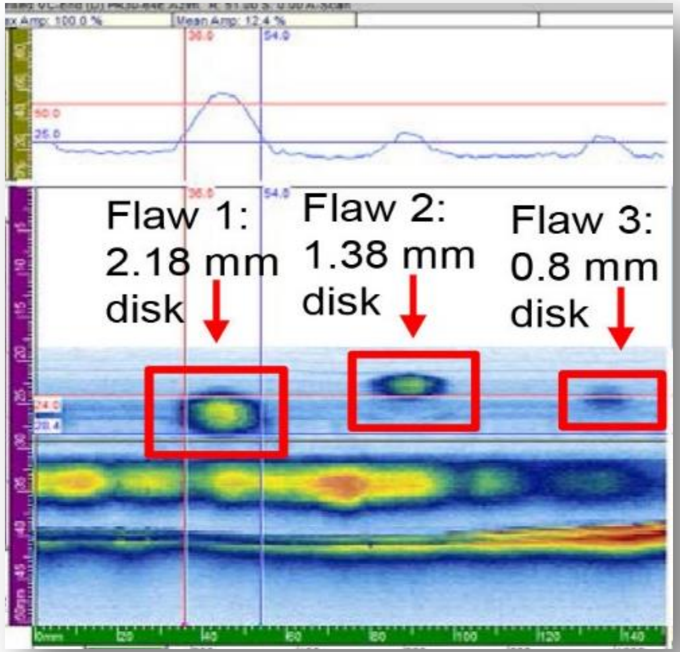
64E Aperture

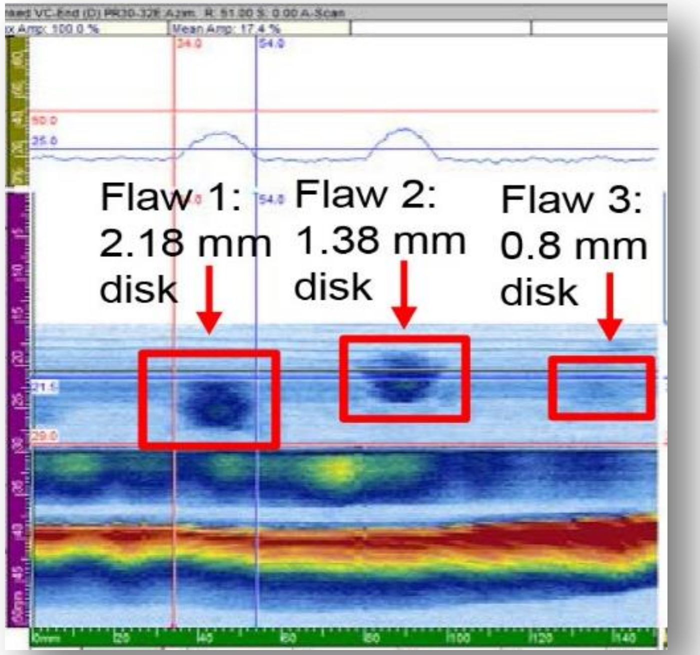
- 2.17 mm → 15.3 dB SNR
- 1.38 mm → 15.3 dB SNR
- 0.80 mm → 11.2 dB SNR

32E Aperture

- 2.17 mm → 11.3 dB SNR
- 1.38 mm → 10.8 dB SNR
- 0.80 mm → < 9.5 dB (marginal detection)







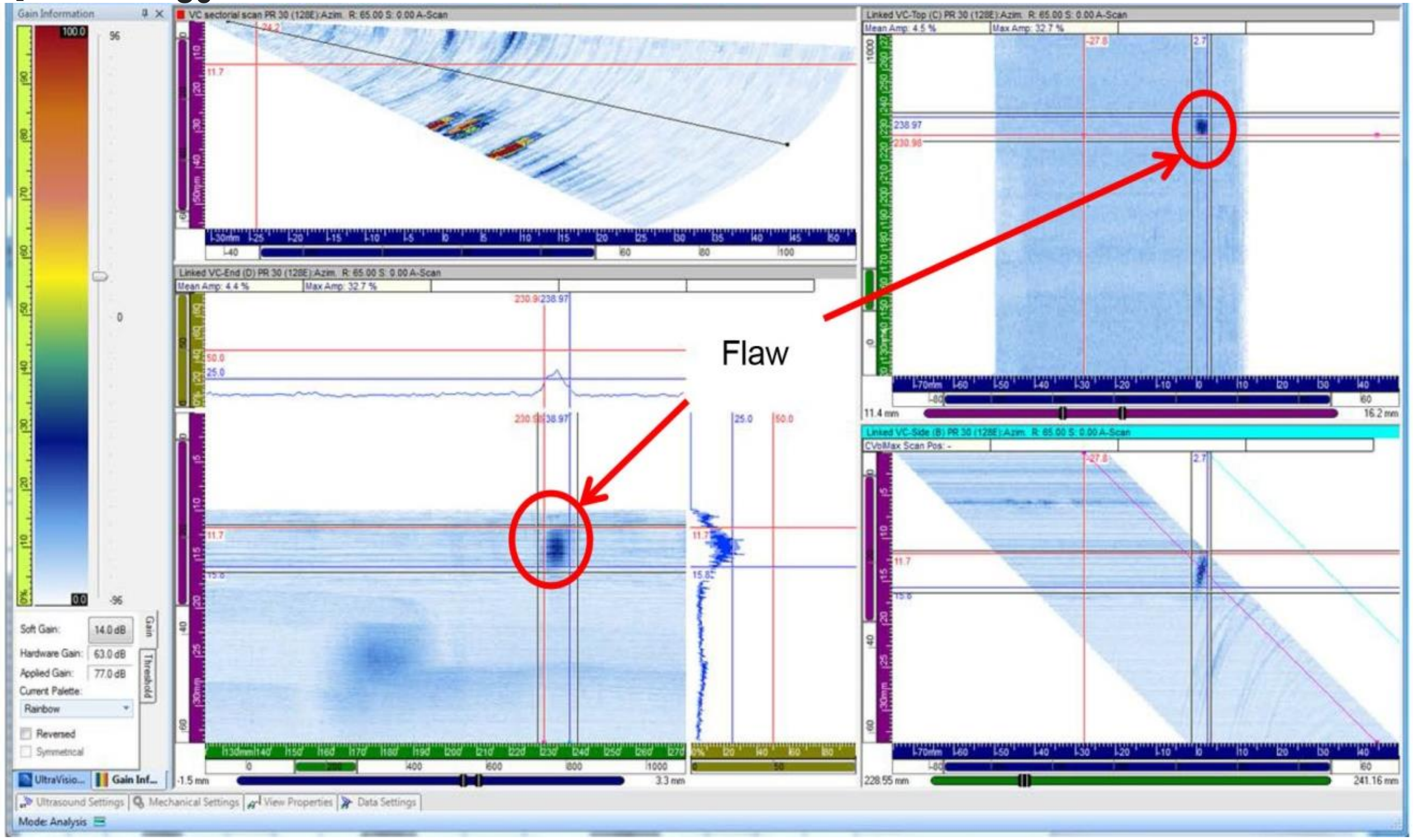
Other Flaw Types

- The successful embedment of fine particulate and cold fusion/lack of fusion flaws must be confirmed (requires destructive testing) before PAUT-TRL results and conclusions are reported
- Other potential “flaws” that warrant investigation are parent material inclusions; these were not implanted but resulted in significant ultrasonic indications
  - Large signal-to-noise ratios
  - High spatial frequency, and thus high potential to enter fusion joint
  - Potentially un-melted resin pellet, other inclusion or high concentration of carbon black

Particulate Detection (Preliminary)

- **Results are preliminary. The distribution of tungsten powder has yet to be confirmed.**

Specimen J-29 with coarse tungsten powder (PSD d_{50} = 118 micron

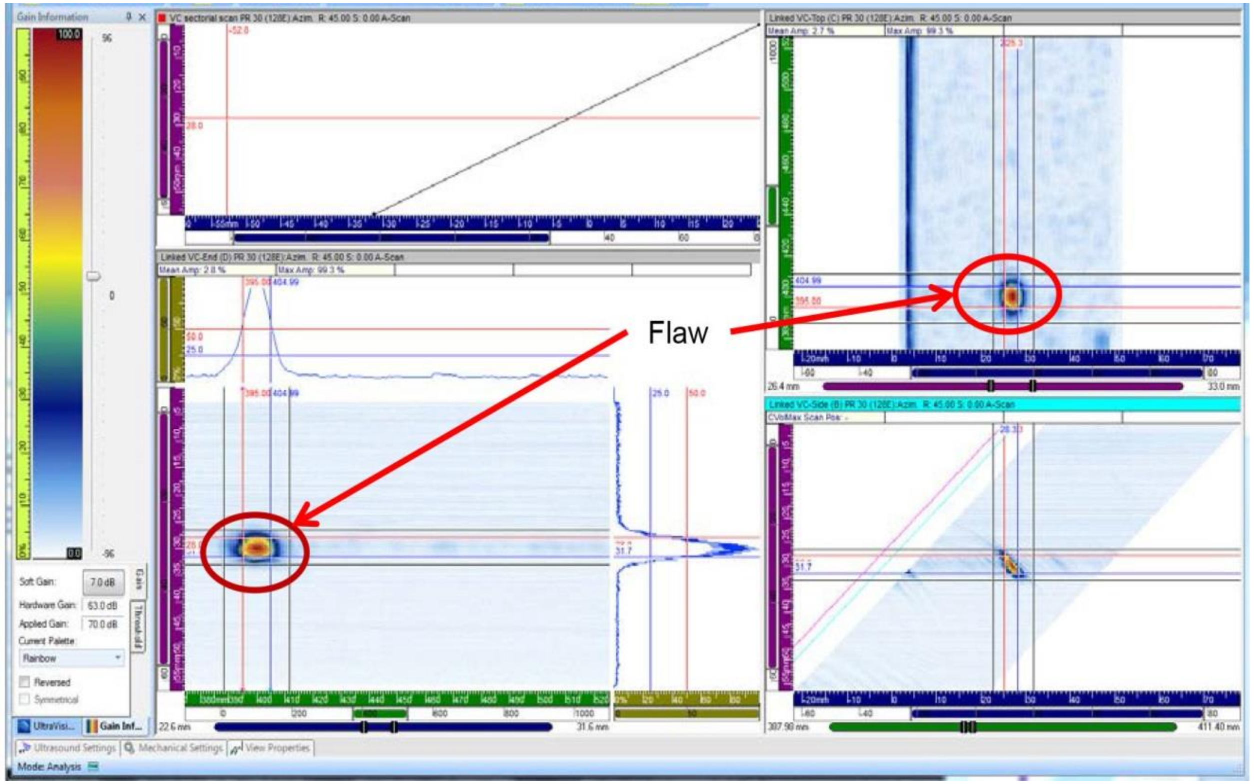


Example from Specimen J-29, 128E, Skew 0 (Flaw 4, 231–239 mm)

No flaws detected by PAUT-TRL in weld of Specimen J-30 with fine tungsten powder (PSD d_{50} = 26 micron)

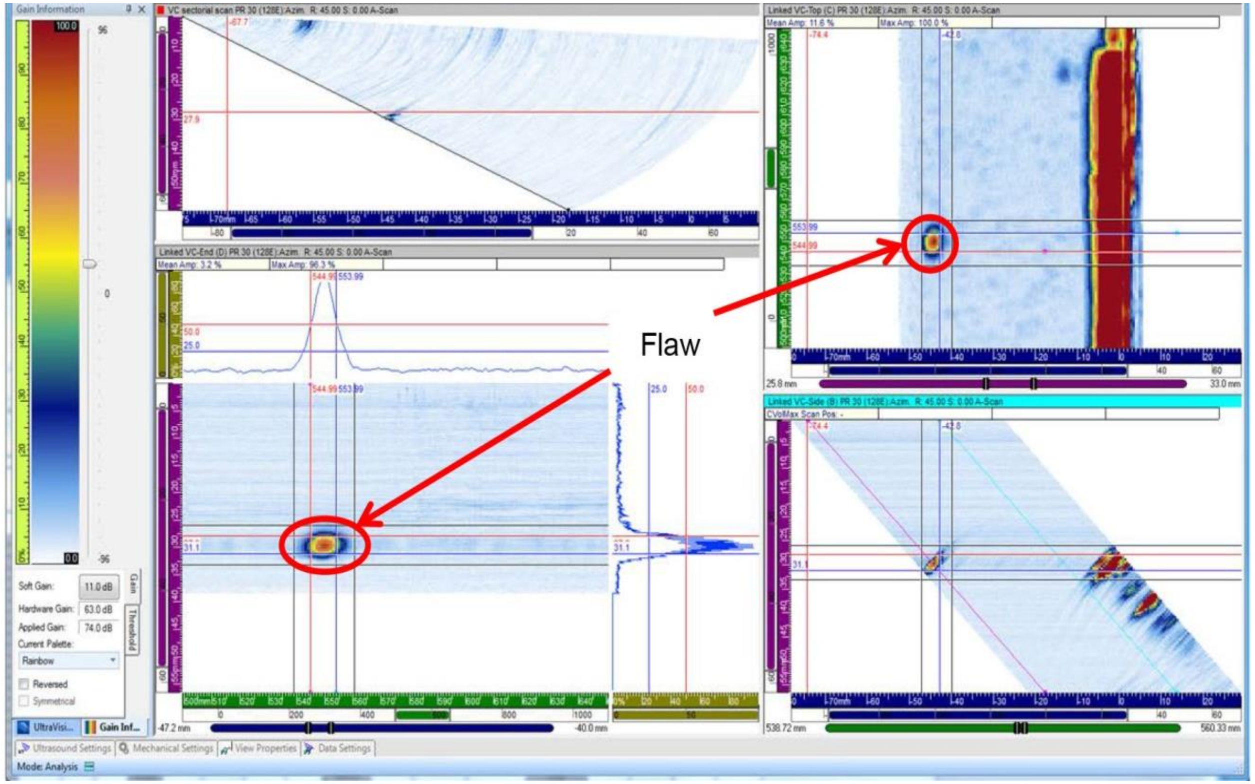
Parent Material Indications

Parent material indications with signal-to-noise ratios (SNRs) greater than those for the discs



Example from Specimen J-31, 128E, Skew 180

“Flaw” PM21 (395–405 mm) with **SNR 30.4**



Example from Specimen J-29, 128E, Skew 0

“Flaw” PM7 (545–554 mm) with **SNR 27.9**

Parent Material Indications

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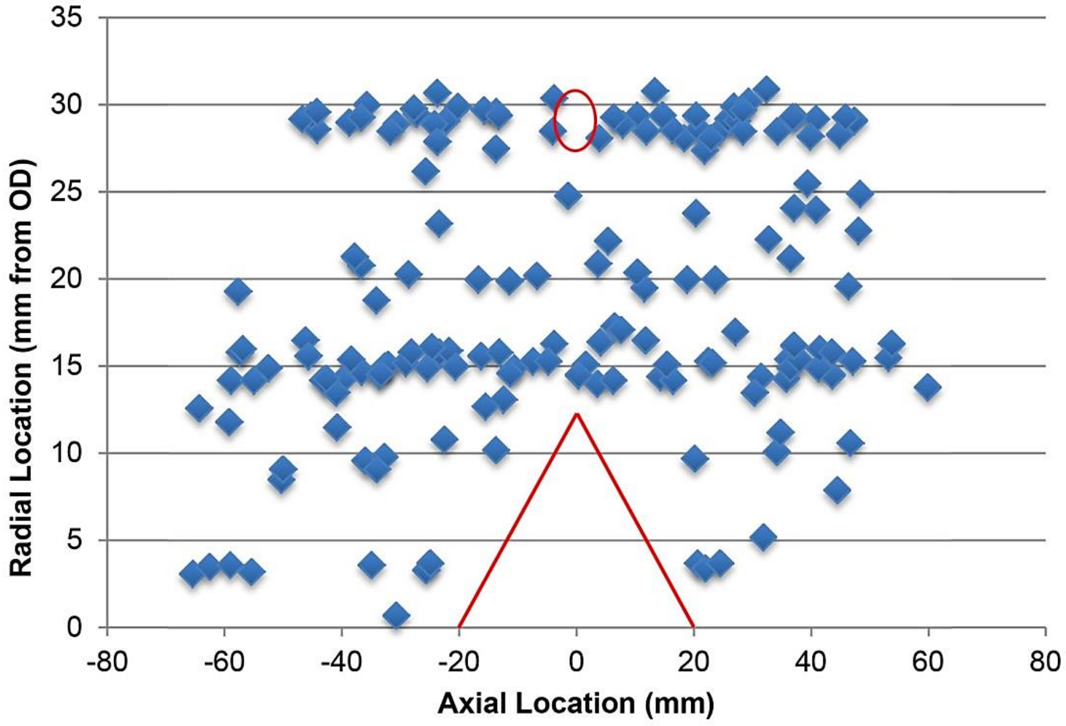
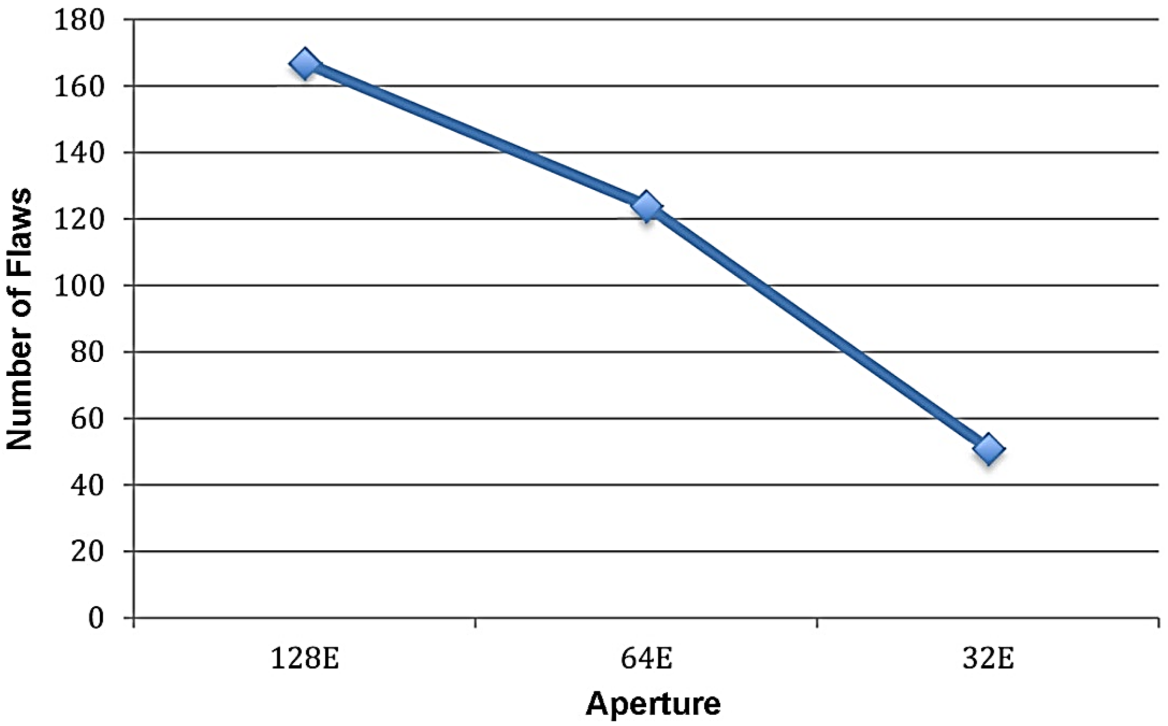
- Parent material inhomogeneities detected from OD to ID, except in blind spots identified by red outlines (shown for 128E)



- Quantity of parent material inhomogeneities detected as a function of aperture



Conclusions

<u>Planar Flaws</u>

- Detection improves with increasing probe aperture
  - OD blind spot decreases as probe aperture increases - improved beam steering and energy
- Detection improves by >5% when examinations are performed on both sides of weld
- 128E and 64E are comparable in terms of probability of detection (POD), and both have a significantly higher POD than 32E
  - 32E has difficulty detecting discs near the ID-bead as well as the OD-bead
  - 32E is the minimum specified in Code
- POD may improve with removal of the OD weld beads prior to scanning
  - All UT scanning to date was performed with the weld-bead attached to the pipe
- **Planar flaw PODs illustrate PAUT-TRL coverage**
  - **No flaw would be detectable outside the coverage volume (i.e., in a “blind spot”)**

Recommendations

- **Complete reliability evaluation for PAUT-TRL with the planar flaws**
  - Remove OD weld beads and re-scan discrete regions where OD discs were missed
    - Determine whether improved probe access improves detection probability and coverage
  - Evaluate other Code-accepted NDE techniques, e.g., tandem PAUT and microwave

- **Obtain true-state information on joints with attempted fine particulate contamination and cold fusion/lack of fusion**
  - Perform RT or high-resolution CT examination of particulate-contaminated joints with incidence normal to fusion plane
  - Destructive testing of weld joints (attempted cold fusion with/without particulate)
  - Reconcile these true-state data with PAUT data

Recommendations (cont'd)

- **Turn research focus to evaluate impact of parent material inhomogeneities**
  - Parent material inhomogeneities may be the cause of inexplicable butt-fusion joint failures during mechanical testing and service, and affects integrity of research results
  - Reconcile NDE results with "forensic" and mechanical test results
    - Sample voxels of pipe wall containing "flaws" and perform "forensics" to identify reflectors
    - Mechanical testing on "flawed" parent material and "flawed" fusion joints to evaluate impact
  - Pre-inspection of parent to qualify before fusing may be appropriate

Supplemental Information and Data

Specimen Matrix

ID No.	Pipe Number	Distance between Joints, in.	Joining Protocol	Flaw Type & Material	Flaw Size	Pre-fabrication Implanted Flaw Location
J-28	32	~ 12	ASME Code	None	None	None
RJ4/ RJ6	32	~ 12	ASME Code	Planar flaws, all discs fabricated from 0.02 mil thick SS shim stock	2.17 mm (0.0854 in.), 1.38 mm (0.0543 in.), and ~0.8 mm (0.0315 in.)	Mid-wall and ±25% of mid-wall
RJ4/ RJ6-2	32	~ 12	ASME Code	Planar flaws, all discs fabricated from 0.02-mil thick SS shim stock	2.17 mm (0.0854 in.), 1.38 mm (0.0543 in.), and ~0.8 mm (0.0315 in.)	Mid-wall only
RJ-8	32	~ 12	Violated ASME Code – limited to 2-minute heat soak	Planar flaws, all discs fabricated from 0.02-mil thick SS shim stock; attempted cold fusion	2.17 mm (0.0854 in.), 1.38 mm (0.0543 in.), and ~0.8 mm (0.0315 in.)	Mid-wall only
J-29	33	~ 12	ASME Code	Coarse particulate contamination (tungsten particles)	118 micron (4.65E-3 in.) dia. (d_{50})	ID to OD, all quadrants
J-30	33	~ 12	ASME Code	Fine particulate contamination (tungsten particles)	26 micron (1.0E-3 in.) dia. (d_{50})	ID to OD, all quadrants
J-31	32	~ 12	Violated ASME Code – excess interfacial pressure applied during heat soak	Attempted cold fusion	N/A	N/A

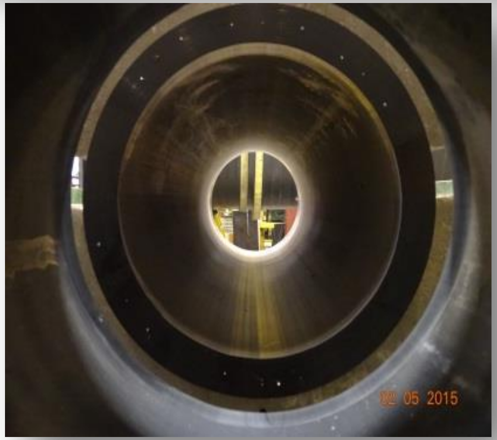
Specimen Fabrication

Base Material

- 12 in., DR11
- Bi-modal PE4710
  - Code-conforming resin
- Commercially-dedicated by EPRI
  - Same pipe used in EPRI slow-crack growth rate studies led by Doug Munson

Implanted Flaws

- Surrogate planar flaws (SS discs)
  - 0.8 mm, 1.38 mm, 2.17 mm diameters
- 0.05 mm thickness
- Attached to the side designated skew 180°

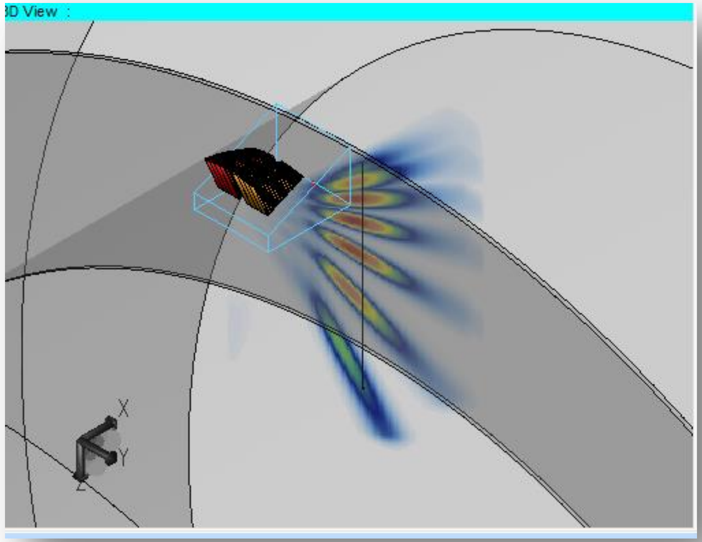


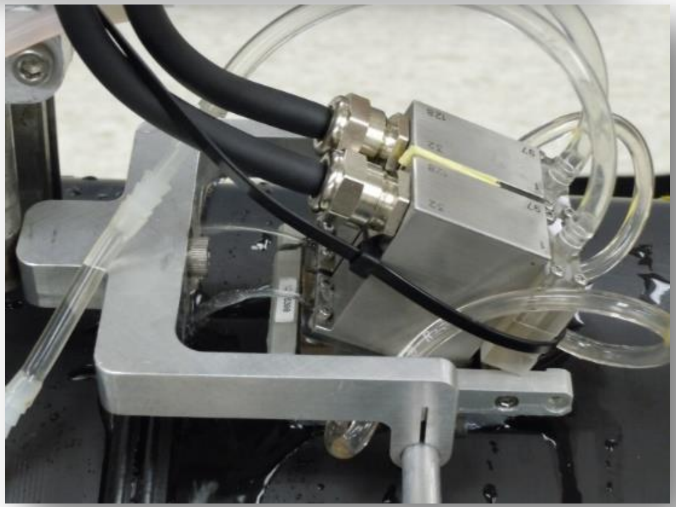
Specimen Fabrication (cont'd)

- Fabrication (February 2015)
  - Thermally butt-fused per and intentionally outside ASME Code standard fusing procedure (ASTM F2620, PPI TR-33)
  - 12-in., DR11: Minimum 5.25-minute heat soak; minimum 13-minute cooling period
  - Fusion performed by technician with >20 years experience
  - Calibrated equipment with data logger

PAUT Inspection of Weld Joints

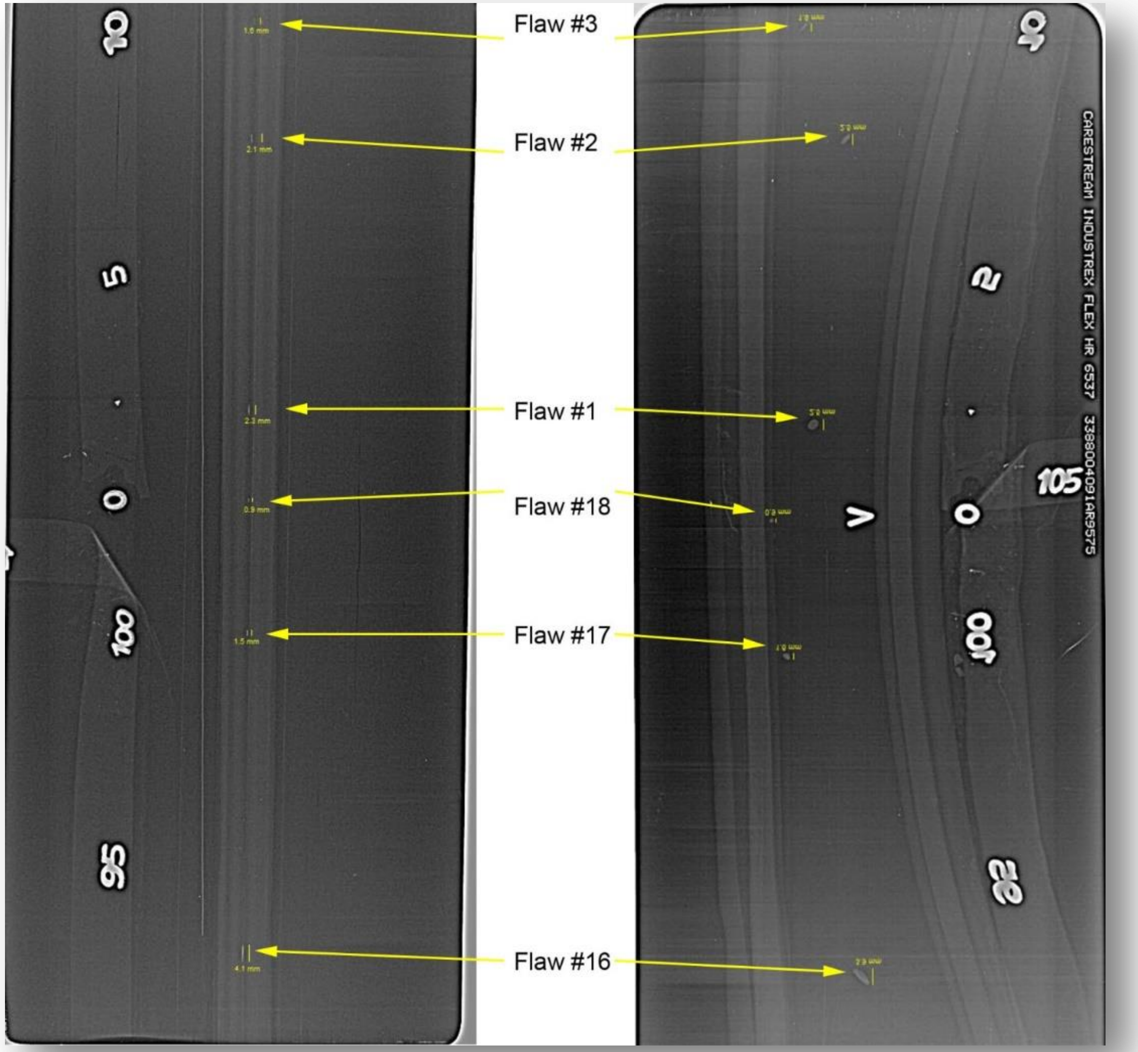
- Inspection performed with two 2.0-MHz PAUT probes
  - Probe was modeled/designed to function in 1”-4” HDPE wall thickness
  - 128-elements available in each probe
  - Operated in a TLR configuration
- Effect of aperture size on flaw detection was evaluated
  - 128E (2x[32x4]-element)
  - 64E (2x[32x2]-element)
  - 32E (2x[16x2]-element)
- Beam was focused on a vertical-plane 30 mm in front of the wedge
  - Probes were models and beams simulated to validate the ability of the probe to focus energy into the weld plane





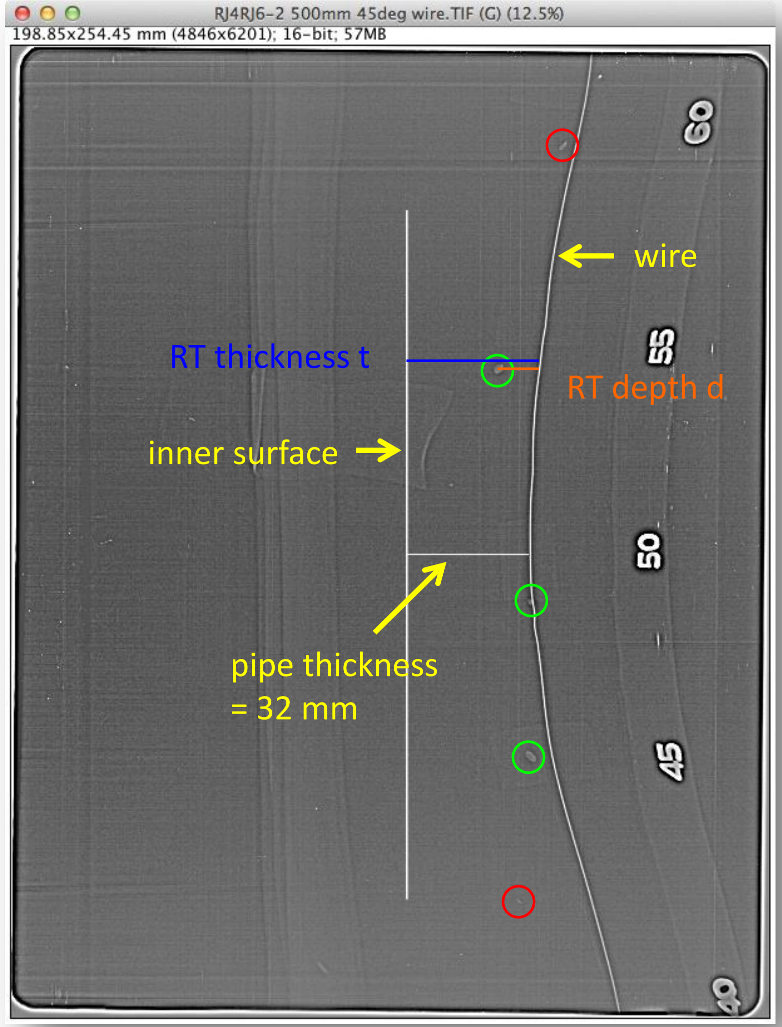
Data Example:
RT Detection of Planar Flaws

- X-ray radiography can illuminate SS discs within the weld joint
  - 8:1 density difference between steel and HDPE
- RT was performed at normal and angled-incidence to obtain disc locations within the weld
  - Discs moved with melt during fusion
  - Less motion in RJ8 due to less melt/flow
- Through-wall location difficult to determine with weld beads intact

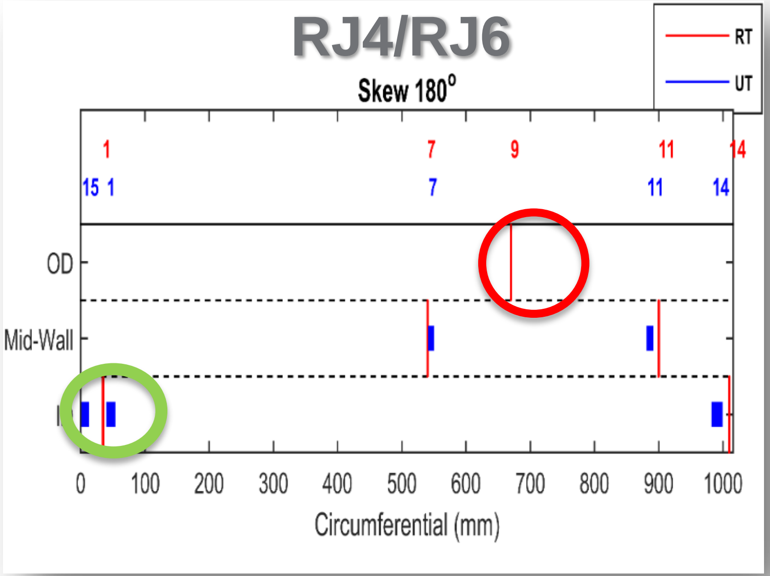


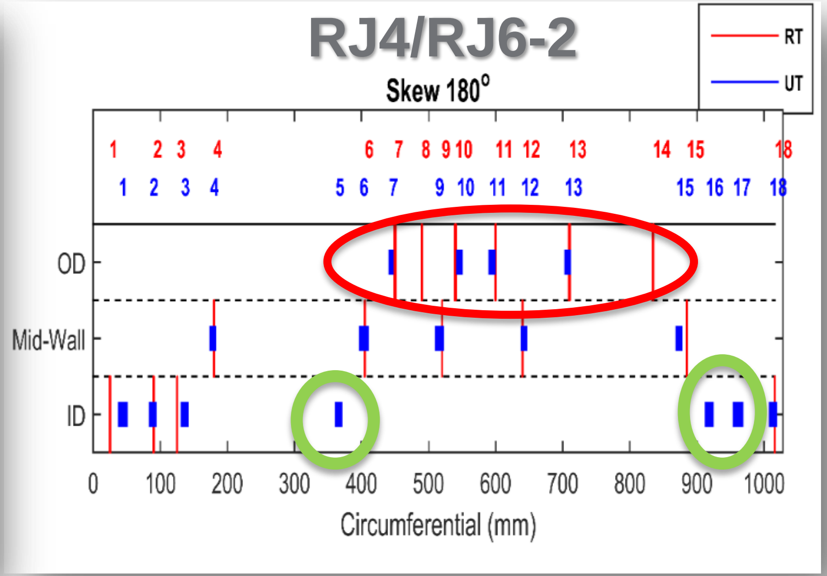
Bead Removal and RT-Verification

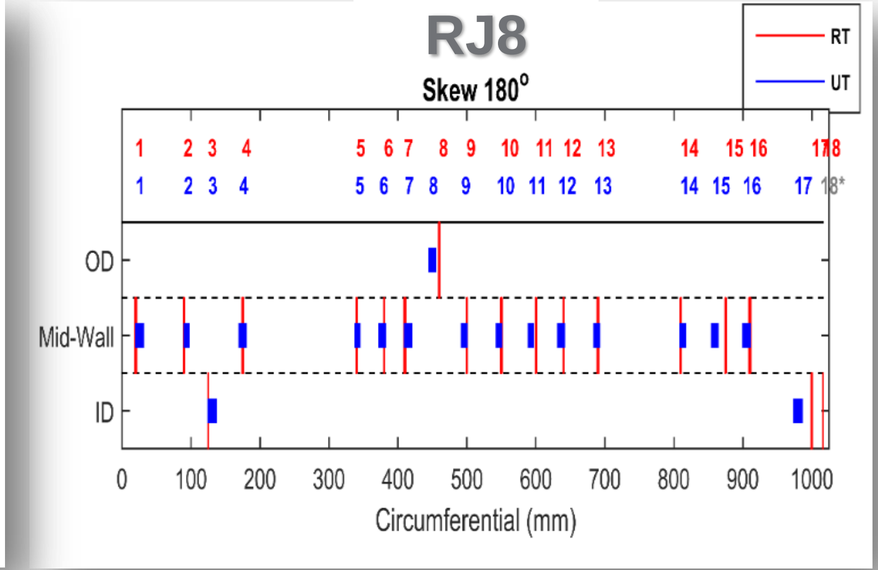
- ID and OD beads were removed on both RJ4/RJ6 and RJ4/RJ6-2
  - RT images were generated of both the weld and removed beads
  - All implanted discs were accounted for prior to bead removal
  - 2 discs were lost during bead removal, and were determined to be in the transition material and thus outside the weld
- A small section of the OD weld bead was removed on RJ8
  - Radial position of most discs could be determined with the weld beads intact
- Radial positions were measured using 45° angled-incidence RT images



PAUT and RT Detection of Discs (128E)



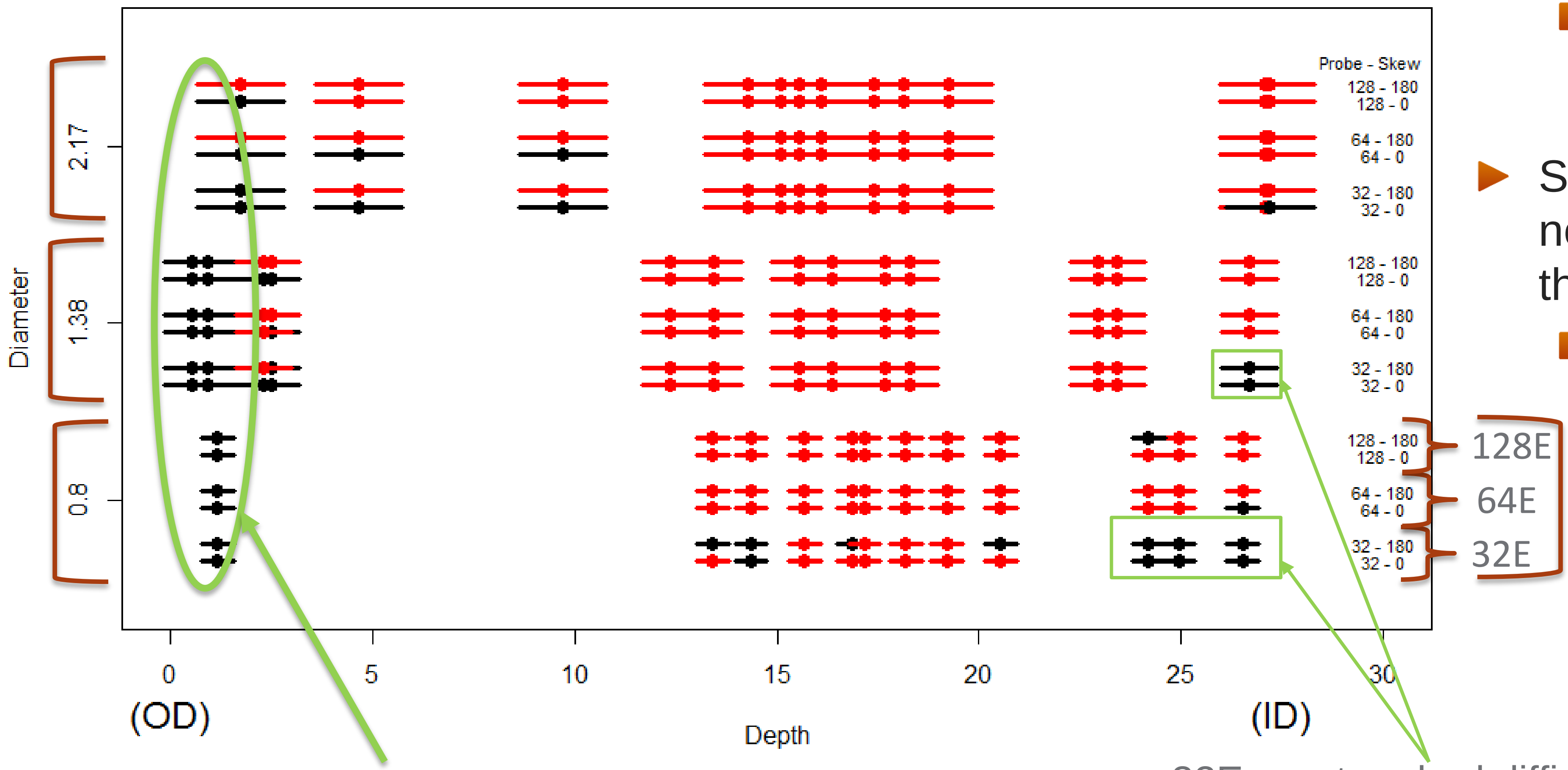




- Majority of discs verified within the weld joints were detected by PAUT
  - Most missed were near the OD
- Some discs within the ID transition-region or ID-bead were detected before bead removal
  - Example: Disc in transition region of RJ4/RJ6 detected by 128E and 64E apertures

Detection of Discs (across all welds)

● = Detected ● = NOT Detected



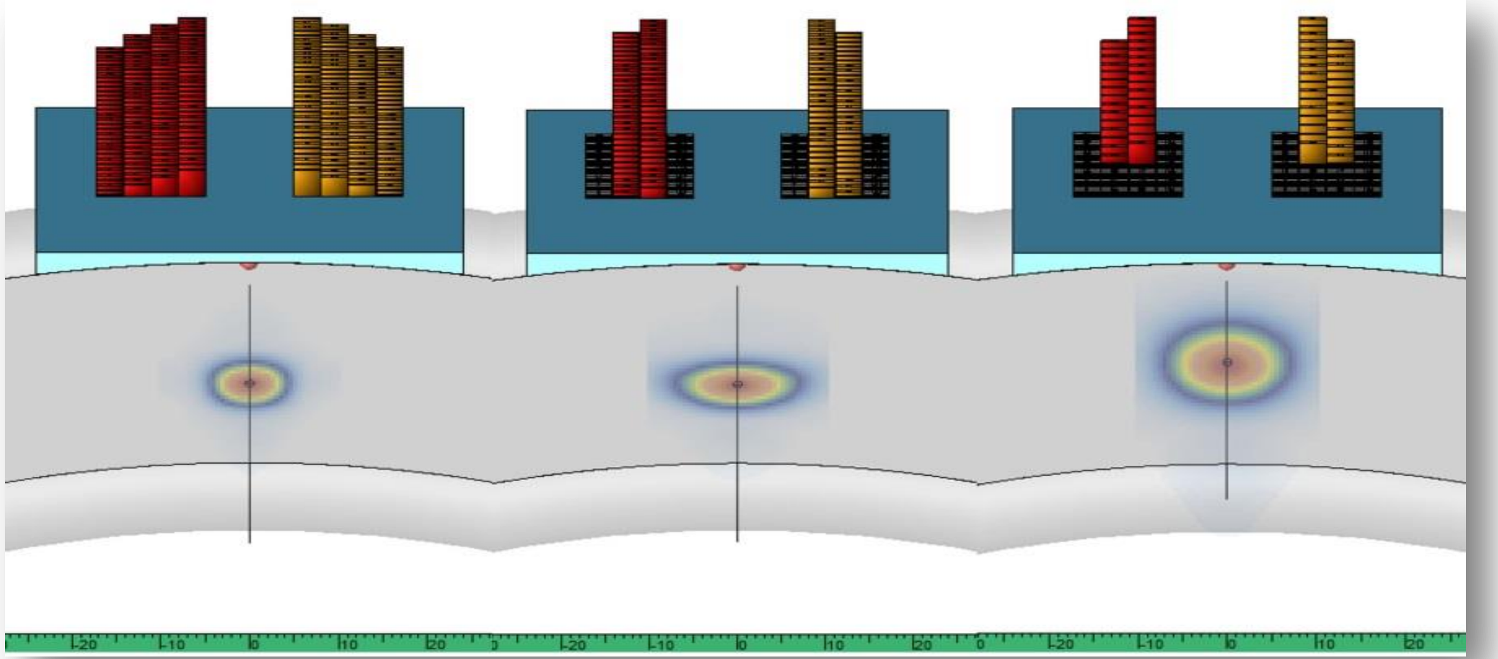
- Sorted by disc diameter
  - Detection was divided based on aperture and inspection direction
- Some regions contained no discs between the three joints
  - Movement of the disc during fusion

Discs located near the OD were consistently missed (blind-spot due to presence of bead)

32E aperture had difficulty distinguishing discs from the ID bead

Modeling results of beam spot-size on the focal plane

128E (32x4) 64E (32x2) 32E (16x2)



Acronyms

ASME	American Society of Mechanical Engineers
CT	computed tomography
DE	destructive examination
EPRI	Electric Power Research Institute
HDPE	high-density polyethylene
ID	inside/inner diameter
NDE	nondestructive examination
NRC	U.S. Nuclear Regulatory Commission
OD	outside/outer diameter
PAUT	phased array ultrasonic testing
PNNL	Pacific Northwest National Laboratory
POD	probability of detection
RT	radiography testing
SBT	side-bend test
SS	stainless steel
TRL	transmit-receive longitudinal