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PNNL-SA-150349

Assessment of Eddy Current Testing for PWSCC Susceptible Materials

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Carol Nove, NRC COR

Presentation Outline

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- NRC Expectations
- Purpose and Objectives
- ET Surface Exam Acceptable Flaw Length and Depth
- ET Probes, Mockups and Data Acquisition Configuration used in the Study
- Results
- Observations
- Unresolved Issues

NRC Expectations

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In 2015, the NRC communicated their expectations to industry for ET inspections of peened, inlayed, and onlayed DMWs.* The focus was to ensure a better understanding of detection performance and sensitivity of ET techniques to support the development of:

- "Eddy current acceptance standards that have a technical basis given the sizes and depths of flaws that can challenge a peened surface and/or an Alloy 52 inlay or onlay"
- "Eddy current qualification requirements that provide confidence that the procedure can reliably detect shallow and near-surface flaws and be able to discriminate between shallow flaws and scratches and weld passes"
- "Alternate inspection methods or programs to determine if the mitigation process is functioning as intended."
- "Include or refer to these standards in N-770-X."

***** Cumblidge SE. 2015. "NRC Expectations for Eddy Current Inspections of Peened, Inlayed, and Onlayed Dissimilar Metal Welds." Presented at *Industry/NRC NDE Technical Information, Exchange Public Meeting*, January 13-15, 2015, Bethesda, MD. ADAMS Accession ML15013A279.

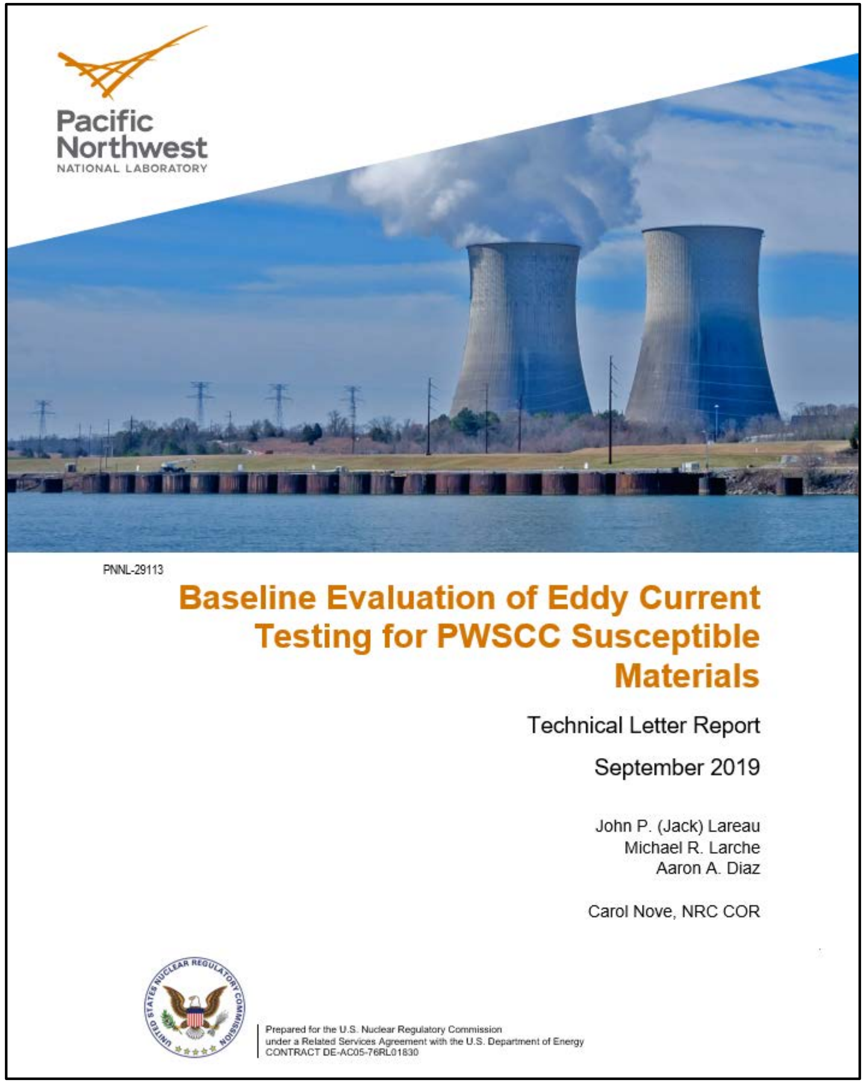
Purpose and Objectives

Goal of this Research: To inform NRC regarding detection performance and sensitivity of ET for surface examinations in the context of recommended NRC criteria for ET inspections of peened, inlayed, and onlayed dissimilar metal welds (DMWs)

This presentation summarizes the ET research to develop a better understanding of detection performance and sensitivity of ET techniques to support the development of:

- A technical foundation regarding detection and sizing limits
- Effective ET qualification requirements
- The focus is on the inspection of weld metal. Base metal ET is not discussed.
- Effective alternate inspections or programs for evaluating PWSCC mitigation processes
- ET acceptance standards that can be referenced in the appropriate ASME B&PV Section XI Code Case (N-770-X).

PNNL Report on ET Assessments



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PNNL-29113

Baseline Evaluation of Eddy Current Testing for PWSCC Susceptible Materials

Technical Letter Report

September 2019

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ML19267A240

ET Surface Exam Acceptable Flaw Length

ET surface exams are described in Section XI, Appendix IV, with qualification requirements for piping and vessel exams being found in Supplement 2.

- Supplement 2 specifies a cal notch (EDM) of 0.5 mm (0.02 in.) deep and < 0.25 mm (0.01 in.) wide; or a compressed notch 1.02 mm (0.04 in.) deep.
- IWB-3514.1 does allow wetted surface planar flaws detected by preservice volumetric inspection and specifically includes PWSCC susceptible materials.
- Table IWB-3514-2 specifies allowable flaw lengths, allowing surface connected flaws < 6.35 mm (0.25 in.) for wall thicknesses ≥ 50.8 mm (2.0 in.).

- One could argue that 6.35 mm (0.25 in.) is the de facto allowable flaw length using surface ET

ET Surface Exam Acceptable Flaw Depth

ET surface exam preservice acceptance standards - solely based on length and do not address depth.

- Depth can be addressed indirectly (as a detection threshold) but cannot be evaluated quantitatively
- Section XI, Appendix IV, Supplement 2 specifies a cal notch (EDM) of 0.5 mm (0.02 in.) deep and < 0.25 mm (0.01 in.) wide; or a compressed notch 1.02 mm (0.04 in.) deep.
- While an EDM notch is a non-conservative representation of PWSCC, ET detection sensitivity associated with this notch has been shown to be suitable for detecting actual PWSCC that has been confirmed by DT.*
- There is a large body of SG tube data that supports a detection threshold of 0.25 mm (0.01 in.) depth based on 20% of a typical tube wall thickness. Detecting defects less than this depth would be questionable in weld material.

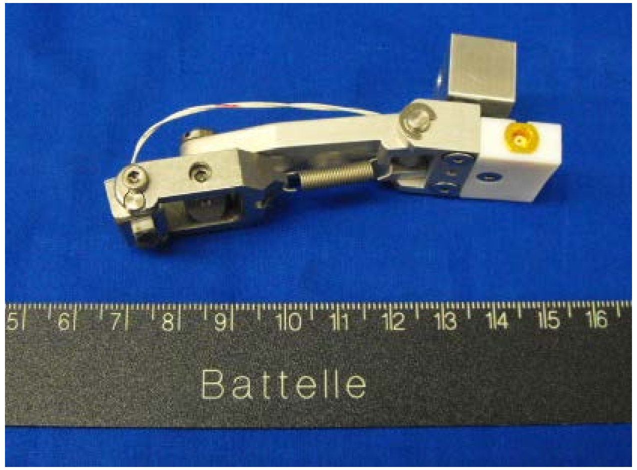
- More work is required for establishing flaw depth acceptance standards for ET surface exams in PWSCC susceptible materials.

* References provided in PNNL report 29113; ADAMS Accession #: ML19267A240

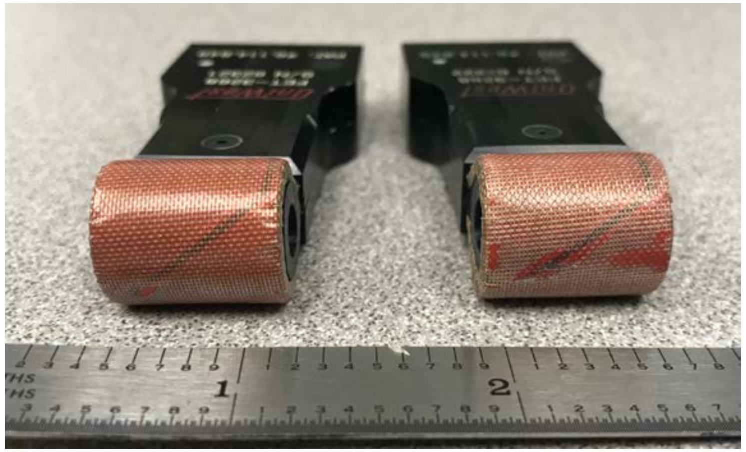
ET Probes

Probe	Model	Type	Excitation Frequency Range (MHz)
UniWest Flex Coil	FET-3427	Cross-wound coil in circumferential direction on flexible probe body for improved surface compliance near J-groove weld	0.2–2.0
UniWest Flex Coil	FET-3268	Cross-wound coil in helical direction on flexible probe body for improved surface compliance near J-groove weld	0.2–2.0
WesDyne “Grooveman”		+ Point probe on articulating body for improved compliance with examination surface	0.2–0.4

Flex Probe with Coils Wound in the Circumferential Direction



WesDyne Grooveman Probe with Articulating Body



Flex Probes with Coils Wound in Helical Direction

ET Mockups (CRDM Mockups)

Head Assembly of Unused WNP-1 RPV

Photograph Capturing an Iron Worker Cutting Segments Containing CRDM Penetration Nozzle Assemblies from the Actual WNP-1 RPV Head

ET Mockups (CRDM Mockups)

Photograph Showing Partitioning and Locations for Cutting and Extraction of CRDM Penetration Nozzle Assemblies from the WNP-1 Segment of the RPV Head

Photograph Showing WNP-1 Segment of the RPV Head Containing 16 CRDM Penetration Nozzle Assemblies

ET Mockups (CRDM Mockups)

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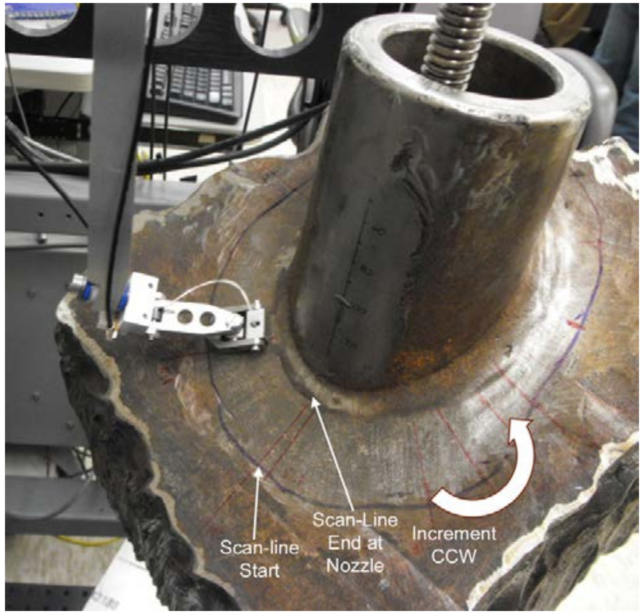

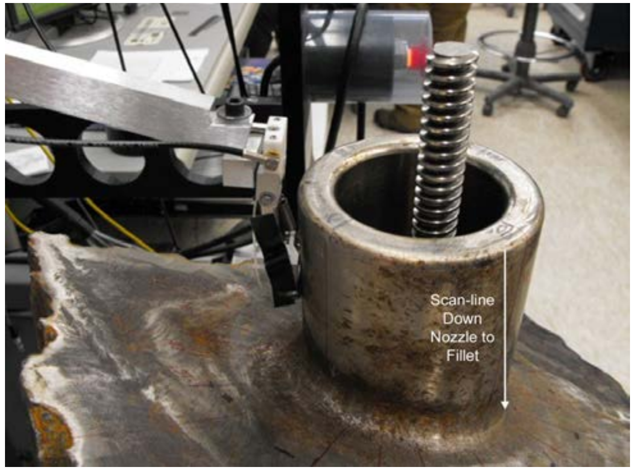

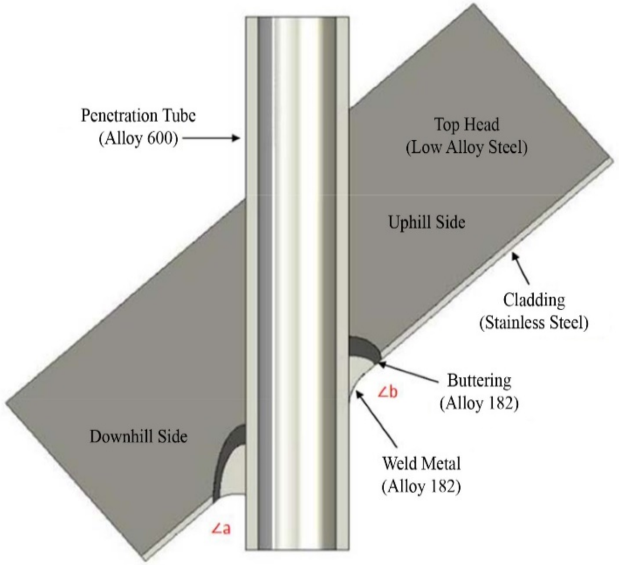

	CRDM Penetration-Nozzle Assembly Measurements															RPV Head Cut-Out Measurements			Total Specimen
	Inside Surface of RPV Head "Wetted Side"								Outside Surface of RPV Head										
Mockup Number	Top Angle ∠b	Bottom Angle ∠a	90° - ∠a	Top Length (mm)	Bottom Length (mm)	ID (mm)	OD (mm)	Wall Thickness (mm)	Top Angle	Bottom Angle	Top Length (mm)	Bottom Length (mm)	ID (mm)	OD (mm)	Wall Thickness (mm)	X-Axis (mm)	Y-Axis (mm)	Z-Axis (mm)	Weight (kg)
CRDM #3	131.1°	43.8°	46.2°	157	38	69	102	16.5	51.8°	128.2°	258	340	69	105	18	300	313	198	181.3
CRDM #4	120.6°	59.4°	30.6°	163	66	69	102	16.5	56.7°	123.3°	265	337	69	105	18	356	318	203	140.6
CRDM #6	121.3°	58.7°	31.3°	157	69	69	102	16.5	56.2°	123.8°	277	335	69	105	18	284	269	203	136.1
CRDM #7	131.1°	48.9°	41.1°	157	71	69	102	16.5	55.4°	124.6°	366	305	69	105	18	320	305	198	174.6
CRDM #9	109.3°	70.7°	19.3°	140	107	69	102	16.5	73.0°	107.0°	277	244	69	105	18	290	328	198	154.2
CRDM #12	99.2°	80.8°	9.2°	72	58	69	102	16.5	86.4°	93.6°	295	283	69	105	18	271	285	195	127

ET Mockups (Calibration Plate Mockups)

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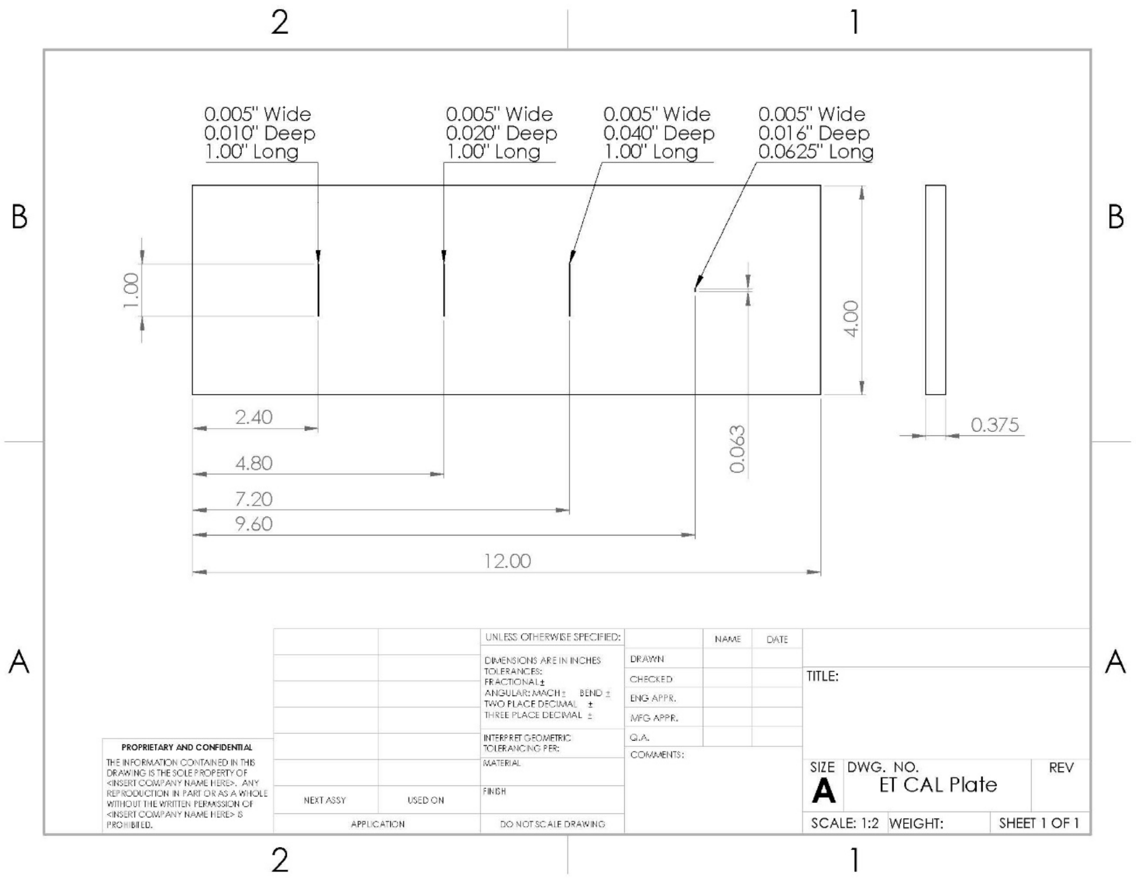

Design Drawing of EDM Notches Fabricated in SS and Inconel 600 Calibration Plates

Material	Notch Dimensions in inches (Length × Width × Depth), mm (in.)	Measured Length,(a) mm (in.)	Measured Width,(b) mm (in.)	Measured Depth,(c) mm (in.)
SS	25.4 × 0.13 × 0.25 (1.00 × 0.005 × 0.010)	25±0.13 (0.985±0.005)	0.15 (0.006)	0.20 (0.008)
SS	25.4 ×0.13 × 0.5 (1.00 × 0.005 × 0.020)	25.3±0.18 (0.996±0.007)	0.18 (0.007)	0.43 (0.017)
SS	25.4 × 0.13 × 1.02 (1.00 × 0.005 × 0.040)	25.43±0.23 (1.001±0.009)	0.18 (0.007)	0.94 (0.037)
SS	1.6 × 0.13 × 0.4 (0.0625 × 0.005 × 0.016)	1.70±0.13 (0.067±0.005)	0.23 (0.009)	0.36(d) (0.014)
Inconel	25.4 × 0.13 × 0.25 (1.00 × 0.005 × 0.010)	25.45±0.15 (1.002±0.006)	0.15 (0.006)	0.15 (0.006)
Inconel	25.4 × 0.13 × 0.5 (1.00 × 0.005 × 0.020)	25.65±0.23 (1.010±0.009)	0.18 (0.007)	0.04 (0.0017)
Inconel	25.4 × 0.13 × 1.02 (1.00 × 0.005 × 0.040)	25.35±0.13 (0.998±0.005)	0.2 (0.008)	0.91 (0.036)
Inconel	1.6 × 0.13 × 0.4 (0.0625 × 0.005 × 0.016)	1.68±0.08 (0.066±0.003)	0.25 (0.010)	0.36(d) (0.014)

(a) Length was measured using the average of five manual caliper measurements.
(b) Notch width was determined using the average of ten feeler gauge measurements.
(c) Depth measurements were acquired using the optical technique reported earlier. The measured depth represents the average of five depth measurements spread over the length of the notch.
(d) Only three measurements were used for the average due to the short length of the notch.

Summary of True-state Measurements for SS and Inconel Calibration Plates

ET Mockups (Other Plate Mockups)

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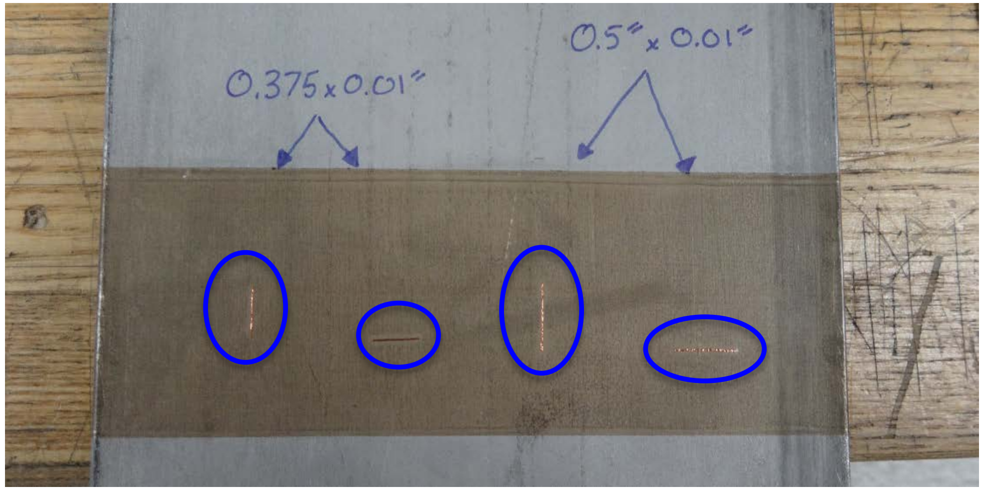
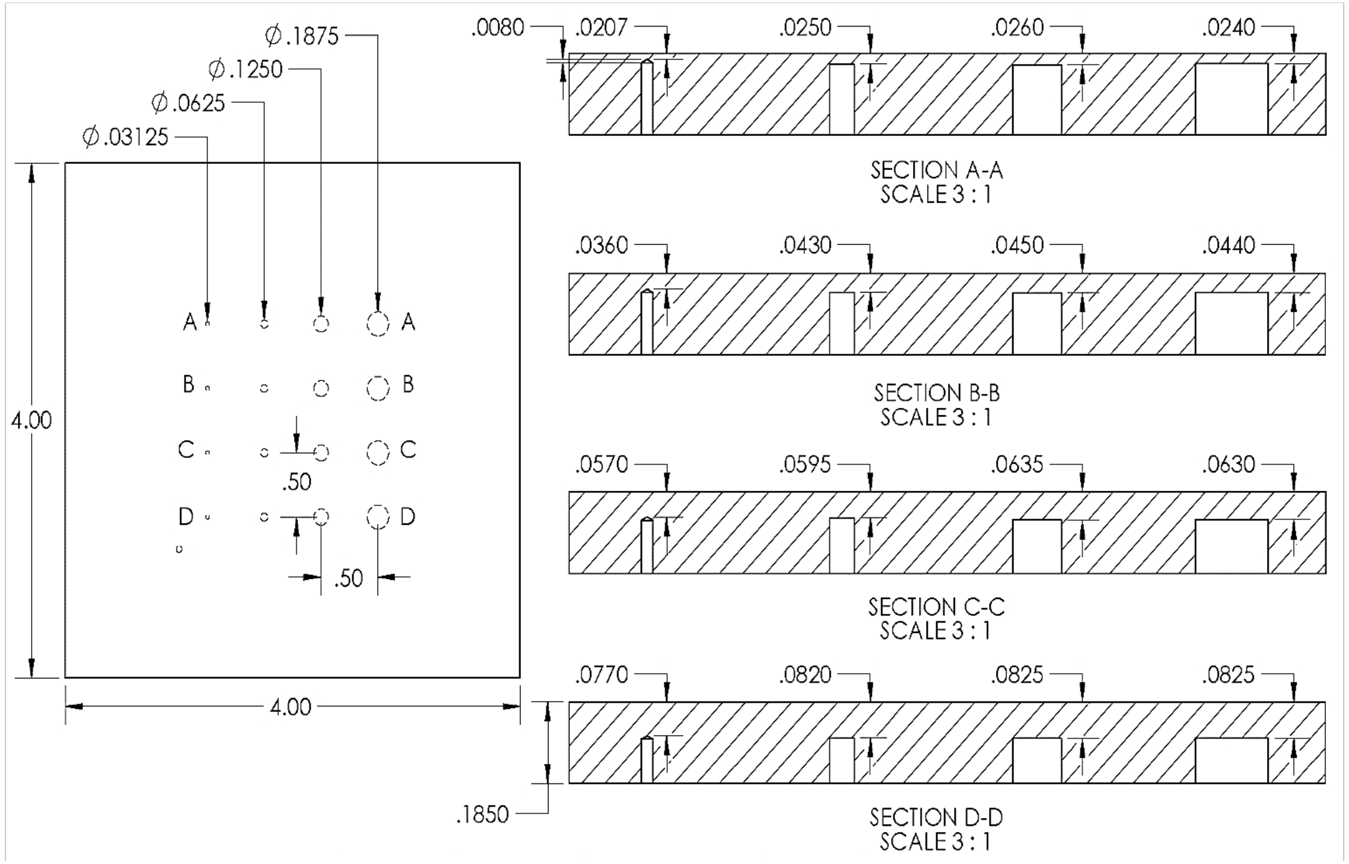
Stainless Steel Plates with Copper Reflector Strips



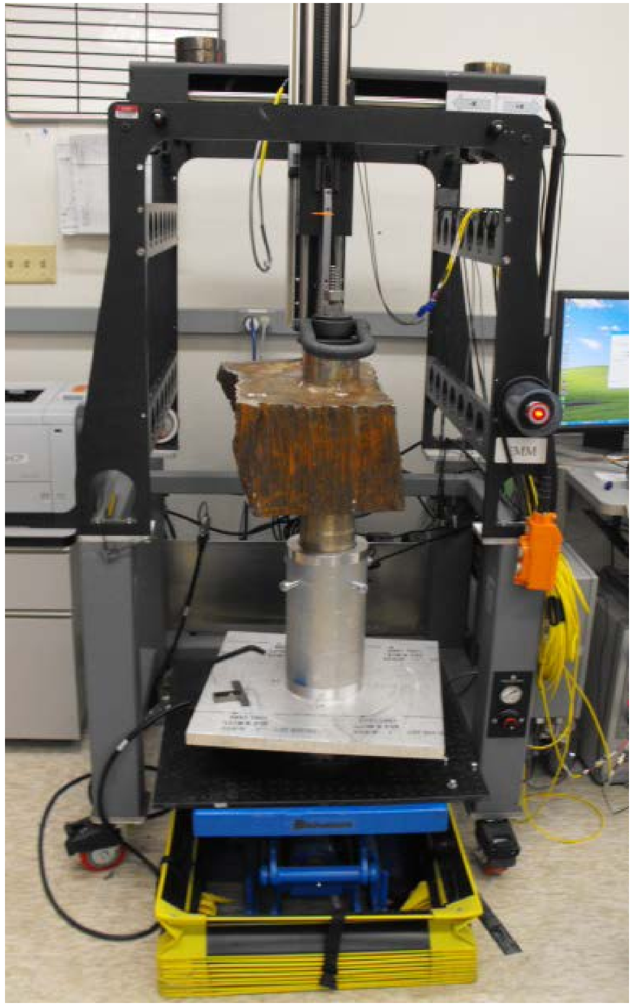
Simulate reference notches in an Inconel 600 calibration plate using narrow copper strips with an adhesion backing for placement on an examination surface

Bottom-Drilled Hole Standard

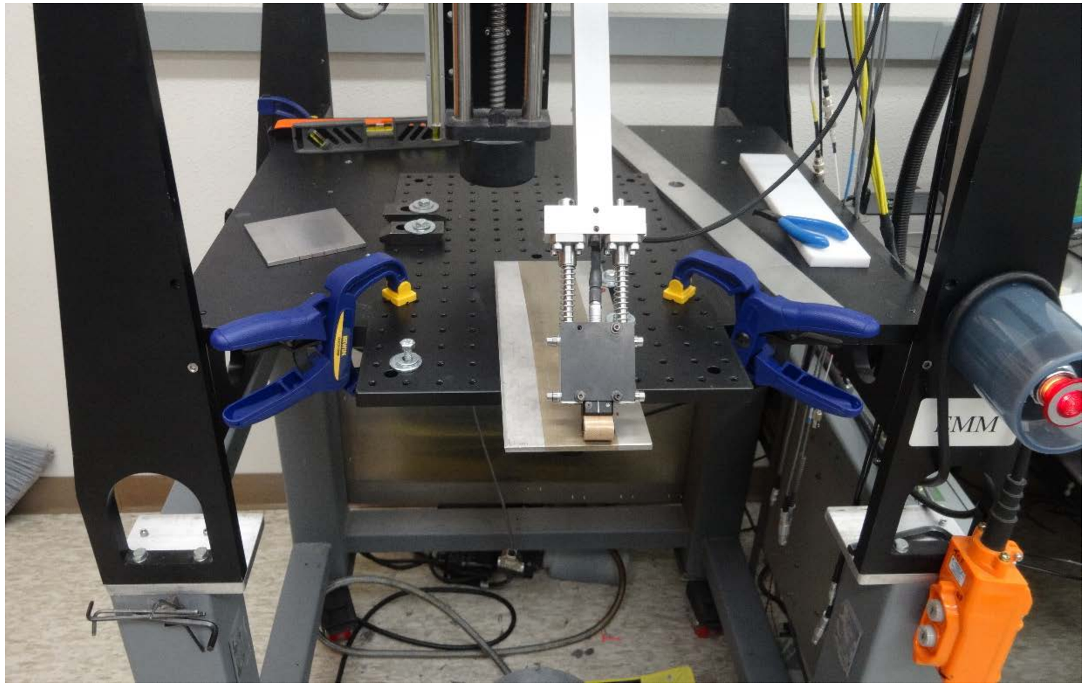


Design Drawing of the Bottom-Drilled Hole Plate with As-built Dimensions Showing Remaining Ligament

Data Acquisition Setup



Translation Stage Capable of Motion in Four Axes (X, Y, Z, rotation) Used for ET Exams

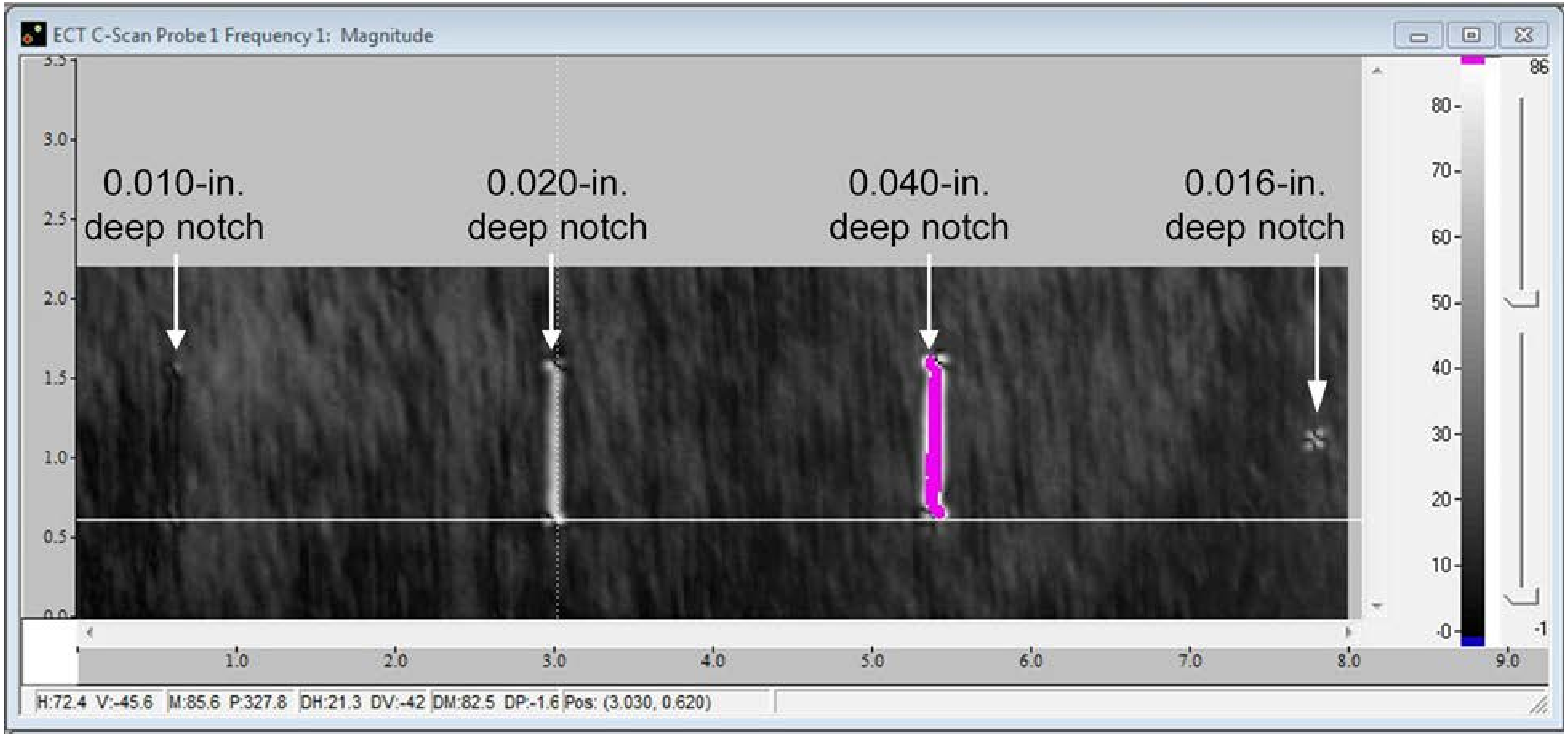


Translation Stage with Table Insert for Acquiring Data on Flat Specimens

WesDyne IntraSpect Eddy Current Examination System

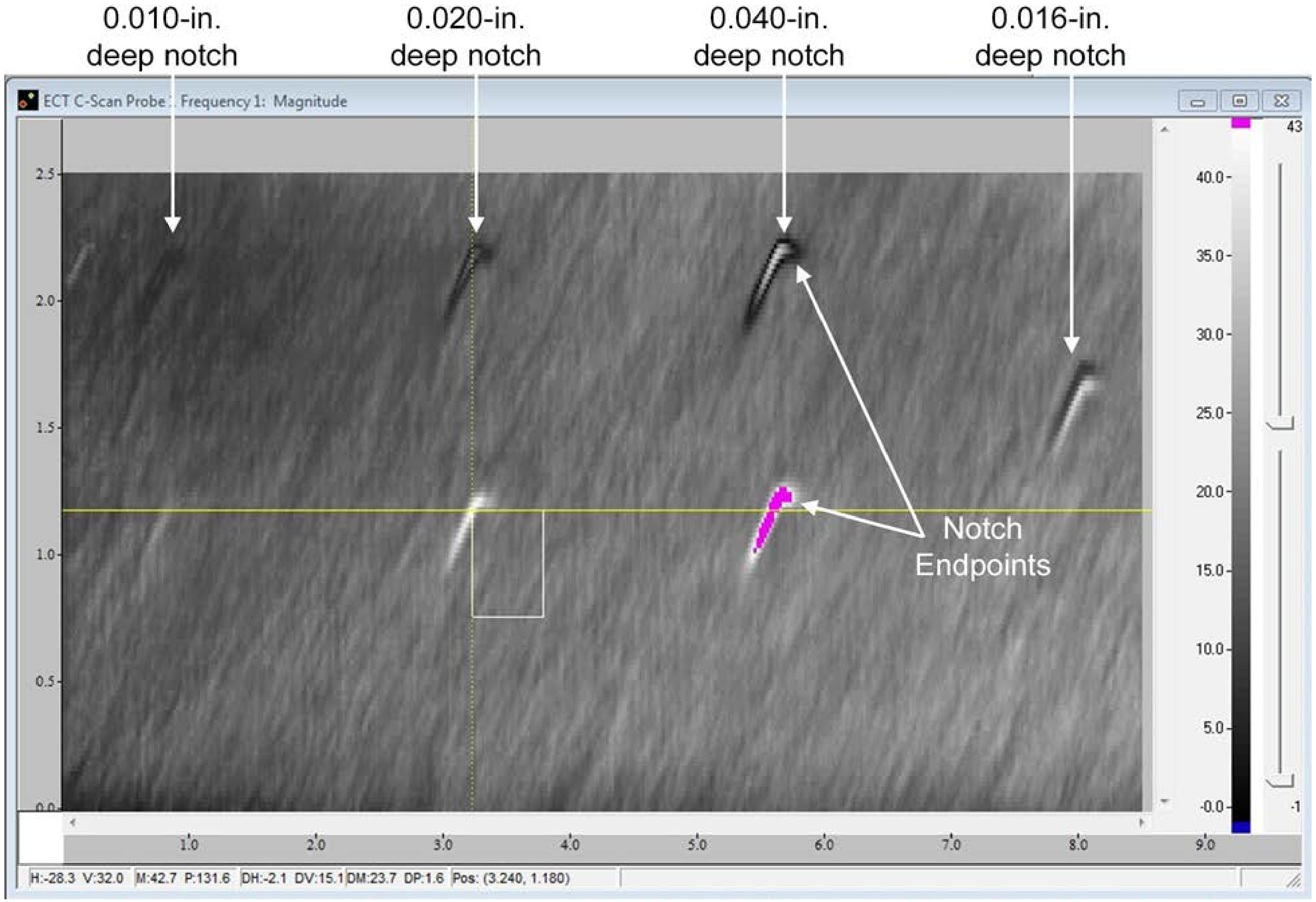
Results (Calibration Plate)

Magnitude ET Response of the Inconel 600 Calibration Plate Collected at 400 kHz with the Grooveman ET probe.



Results (Calibration Plate)

Magnitude ET Response of the Inconel 600 Calibration Plate Collected at 700 kHz with the UniWest FET-3268 Flex Probe, with a helical coil.



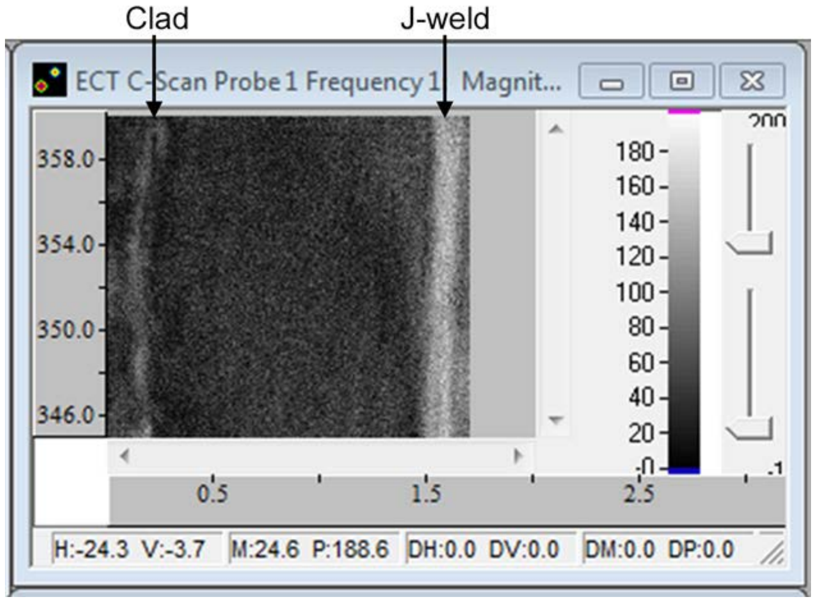
The edges of the notches are the only features that appear in the ET data. This is caused by the orientation of the coils in the ET probe relative to the notch orientation. The responses from the notch endpoints are tilted at 45° because of the helical orientation of the probe coils.

The circumferentially wound flex probe was next to be scanned before the project was ended.

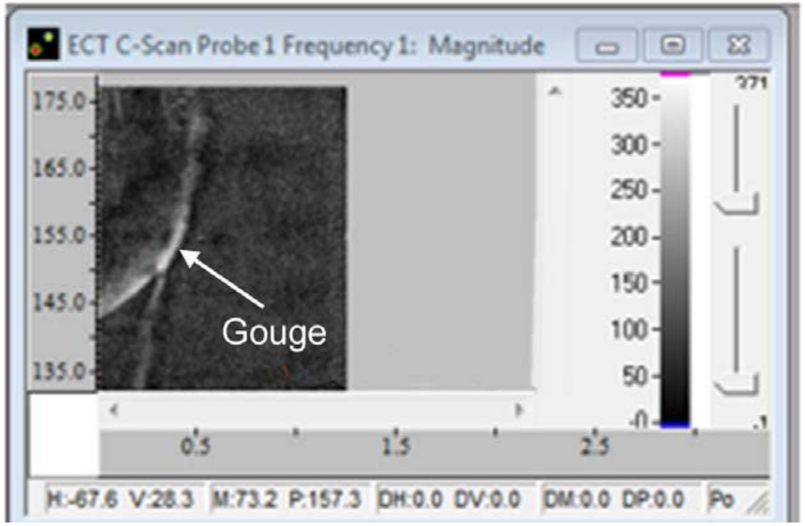
Results (CRDM Mockups)

Degrees of Exam Coverage of Each CRDM Sample with Grooveman Probe

Sample 3	Sample 6	Sample 9	Sample 12
150–180	90–100	2–23	6–9
180–210	94–115	21–42	5–22
210–225	100–115	40–55	20–35
225–240	113–134	53–74	33–48
237–250	114–142	72–93	46–61
	132–177	91–106	59–74
	135–180	104–125	72–87
	175–220	123–144	85–100
	218–233	142–163	98–113
	231–246	161–182	111–126
	244–259	180–201	124–139
	257–272	199–220	137–152
	270–291	215–230	150–165
		228–243	163–178
		241–256	177–192
		254–269	190–205
		267–282	203–218
		280–295	241–256
		293–309	254–269
		306–321	267–282
		319–334	280–295
		332–347	293–308
		345–360	306–321
			319–334
			332–347
			345–360



Grooveman probe ET data from #9 at 345°–360° using 400 kHz showing Magnitude C-scan. Cladding response shown at scan start on left and J-groove weld is shown at end of each scan line on right.



Grooveman probe ET data from #6 at 132°–177° using 400 kHz showing Magnitude C-scan. Cladding response shown at scan start on left and J-groove weld is shown at end of each scan line on right.

Results (Bottom-Drilled Hole Plate Mockup)

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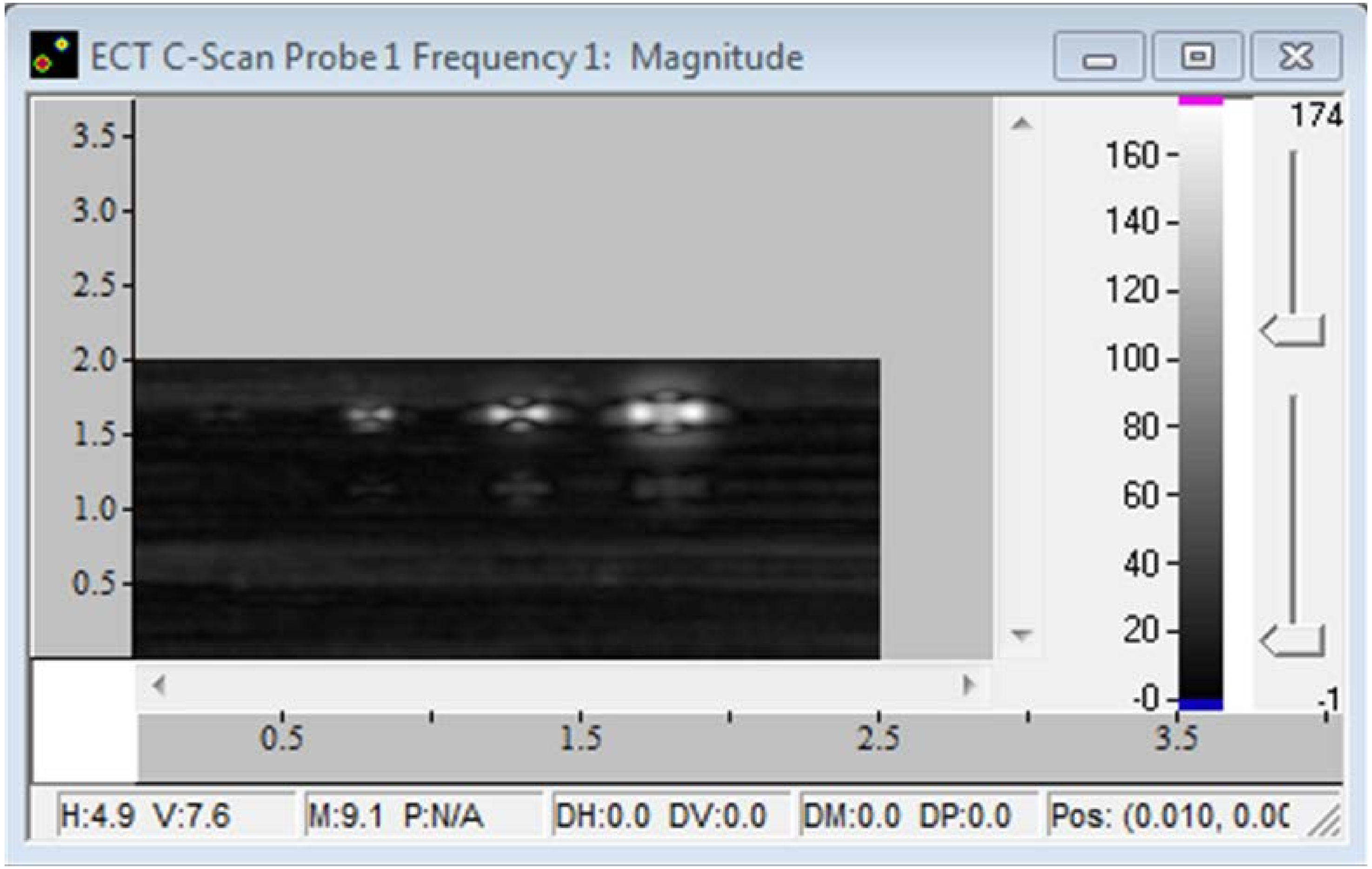
Row	Hole Diameter, mm (in.)	Remaining Ligament, mm (in.)	Grooveman Probe, 400 kHz
A	0.79 (0.03125)	0.51 (0.02027)	Detected
A	1.6 (0.0625)	0.64 (0.0250)	Detected
A	3.18 (0.125)	0.66 (0.0260)	Detected
A	4.76 (0.1875)	0.61 (0.0240)	Detected
B	0.79 (0.03125)	0.91 (0.036)	Not Detected
B	1.6 (0.0625)	1.09 (0.043)	Detected
B	3.18 (0.125)	1.14 (0.045)	Detected
B	4.76 (0.1875)	1.12 (0.044)	Detected
C	0.79 (0.03125)	1.45 (0.057)	Not Detected
C	1.6 (0.0625)	1.51 (0.0595)	Not Detected
C	3.18 (0.125)	1.61 (0.0635)	Not Detected
C	4.76 (0.1875)	1.60 (0.063)	Not Detected
D	0.79 (0.03125)	1.96 (0.077)	Not Detected
D	1.6 (0.0625)	2.08 (0.082)	Not Detected
D	3.18 (0.125)	2.10 (0.0825)	Not Detected
D	4.76 (0.1875)	2.10 (0.0825)	Not Detected

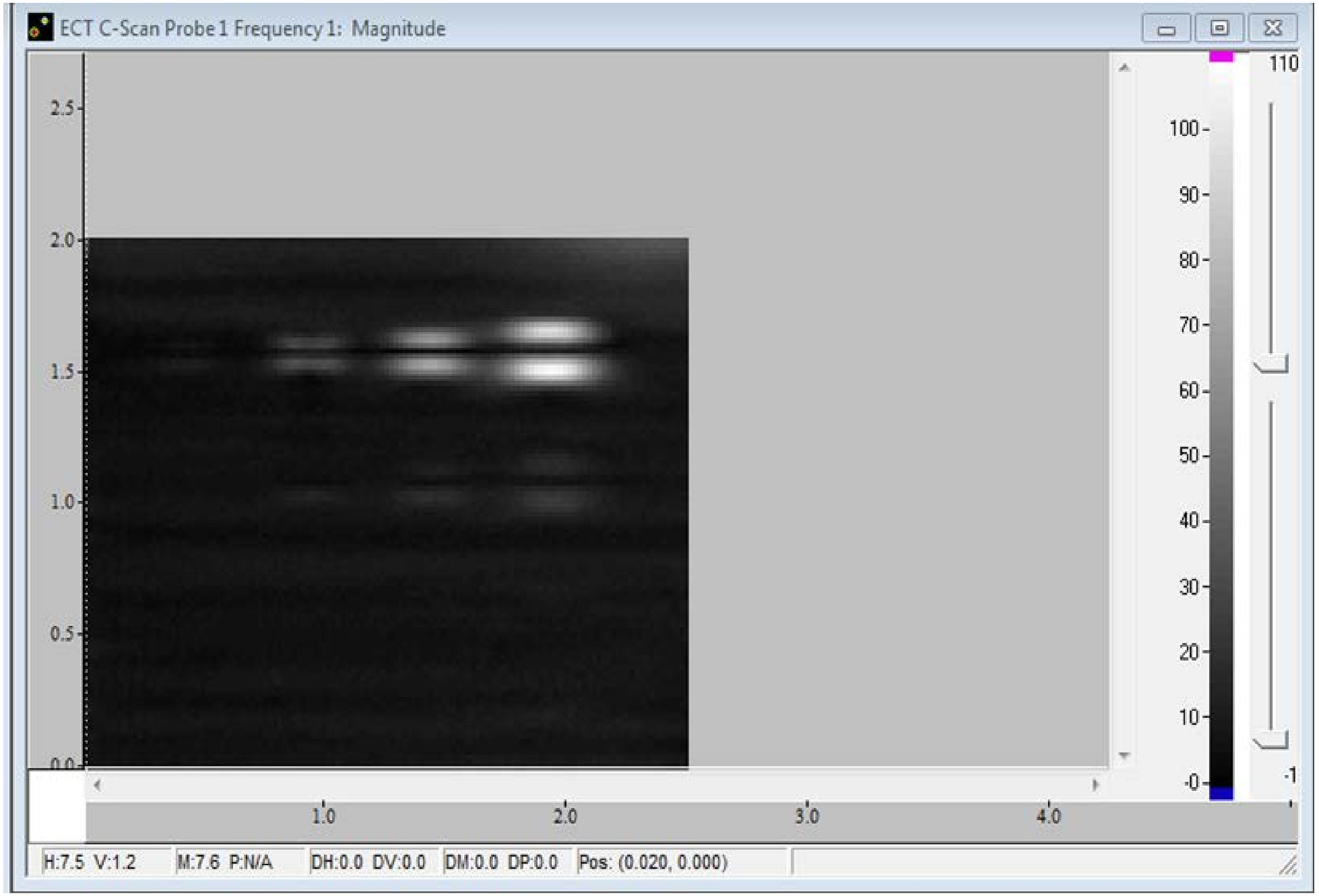
400 kHz C-Scan Magnitude ET responses for Row A – Grooveman Probe



Results (Bottom-Drilled Hole Plate Mockup)

Row	Hole Diameter, mm (in.)	Remaining Ligament, mm (in.)	FET 3427 (400 kHz) SN 65966	FET 3427 (400 kHz) SN 65967
A	0.79 (0.03125)	0.51 (0.02027)	Detected	Detected
A	1.6 (0.0625)	0.64 (0.0250)	Detected	Detected
A	3.18 (0.125)	0.66 (0.0260)	Detected	Detected
A	4.76 (0.1875)	0.61 (0.0240)	Detected	Detected
B	0.79 (0.03125)	0.91 (0.036)	Not Detected	Not Detected
B	1.6 (0.0625)	1.09 (0.043)	Detected	Detected
B	3.18 (0.125)	1.14 (0.045)	Detected	Detected
B	4.76 (0.1875)	1.12 (0.044)	Detected	Detected
C	0.79 (0.03125)	1.45 (0.057)	Not Detected	Not Detected
C	1.6 (0.0625)	1.51 (0.0595)	Not Detected	Not Detected
C	3.18 (0.125)	1.61 (0.0635)	Not Detected	Not Detected
C	4.76 (0.1875)	1.60 (0.063)	Not Detected	Not Detected
D	0.79 (0.03125)	1.96 (0.077)	Not Detected	Not Detected
D	1.6 (0.0625)	2.08 (0.082)	Not Detected	Not Detected
D	3.18 (0.125)	2.10 (0.0825)	Not Detected	Not Detected
D	4.76 (0.1875)	2.10 (0.0825)	Not Detected	Not Detected

400 kHz C-Scan Magnitude ET responses for Row A – UniWest Flex Probe



Observations

Based on ET data from domestic and international field results, as well as laboratory studies, including a removed CRDM weld from North Anna Unit 2, PINC and PARENT Programs, the following observations are made:

- The ASME Code does not have an acceptance standard for ET surface examinations of high nickel-alloy welds. However, there are numerous documented field results where ET has been demonstrated through confirmatory testing as a reliable detection technique for both service-induced PWSCC and hot tears.

- Laboratory studies at PNNL demonstrated detection of flaws 1.5 mm (0.06 in.) long by 0.4 mm (0.015 in.) deep in plate material.* However, there were no welded surfaces with flaws available for evaluation. ASME Code Section XI, Appendix IV guidelines require flaws in the base metal, HAZ, weld edge, and weld surface for demonstration.

* References provided in PNNL report 29113; ADAMS Accession #: ML19267A240

Observations (continued)

- ET probes were demonstrated capable of detecting near-subsurface voids/inclusions comparable to those identified as the root cause of failure in J-groove welds at the South Texas and Palo Verde plants. Subsurface voids were simulated using holes drilled from the back side of plates with various diameters and ligaments.
  - Conventional probe designs were not capable of coupling adequately at the toe of the weld, especially on the downhill side, due to geometric obstructions. However, a special UniWest flexible design bobbin probe detected these subsurface conditions and was able to couple onto the toe of the J-groove weld on the downhill side with very little lift-off noise.
  - These results show promise for a detection method in this region.
- PNNL laboratory work on removed nozzles from North Anna Unit 2 showed that DT confirmed ET calls that were not detected by PT. Given the small sample size, it is difficult to draw any firm conclusions.

Unresolved Issues

- Study is needed to assess performance capabilities of ET versus PT on surface breaking flaws in PWSCC susceptible materials/welds that include a variety of flaw characteristics, dimensions and locations.
  - As a subset of this, an evaluation of ET detection performance on PWSCC susceptible welds with near-subsurface flaws should shed light on the current state-of-the-art for ET capabilities.
- Assess advanced ET probe designs and quantify their impact on detection sensitivity and performance for J-groove welds.

Thank you

- Questions?