PNNL-SA-131575

Update on Progress in CASS Research at PNNL

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Pacific Northwest
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Outline

- Manoir specimen wrap-up
- Flaw signal persistence
- End-of-Block signal dropout
- EPRI CASS Round Robin analysis
- NUREG/CR summary

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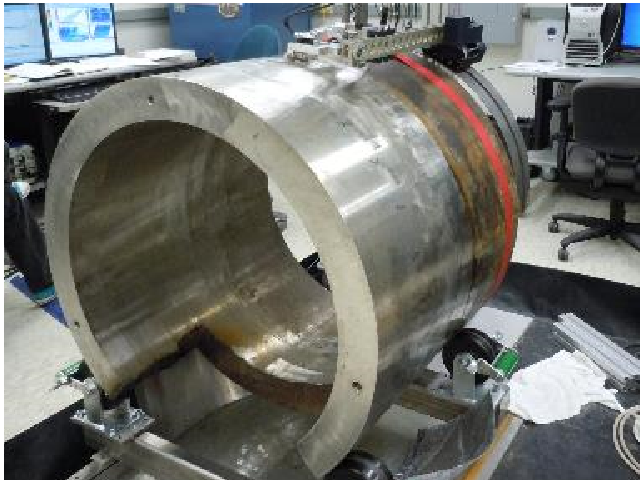
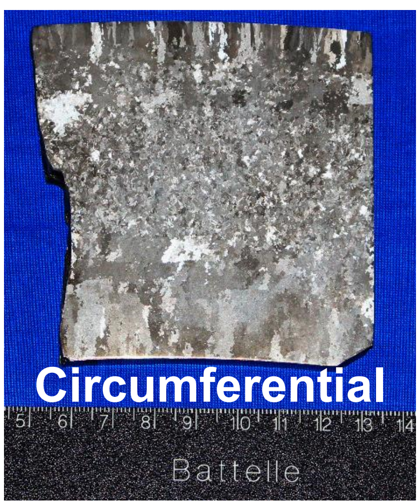
Description of Manoir Specimen

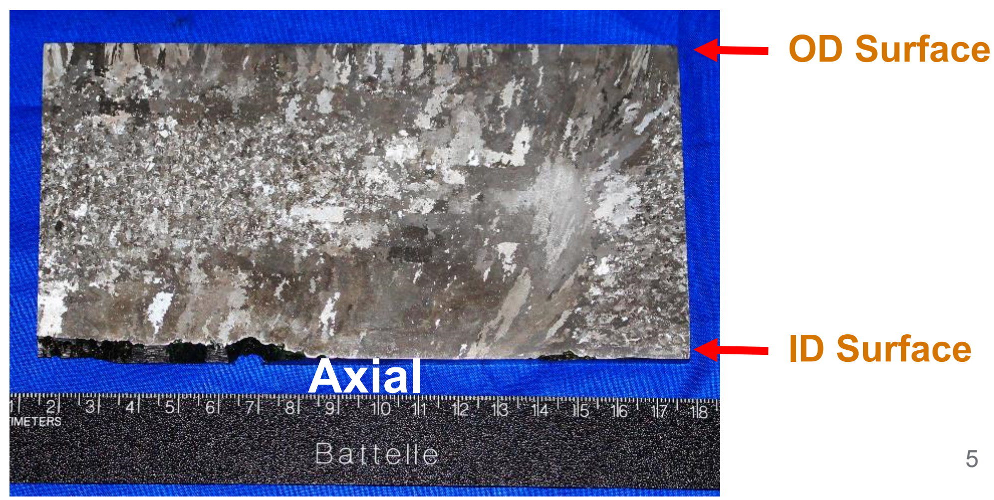
- Thick-walled reactor coolant pump (RCP) carbon steel nozzle-to-CASS safe-end mockup
- Vintage CASS material from the Manoir Foundry in France
- Specimen size
  - OD = 36.63 in. (930.5 mm)
  - ID = 29.96 in. (760.9 mm)
  - Wall thickness = 3.34 in. (84.8 mm)
- Dissimilar metal weld (carbon steel to CASS)
  - SA-516 Grade 70 carbon steel with 308/309 stainless steel cladding
  - SA-351 CF8M stainless steel
  - Inconel 182/82 weld and butter
- Data were acquired in 2015 and 2016
- For more information, see presentation from 2017 NDE Meeting (ADAMS ML17013A628)



Final Observations

- Grain structure in this CASS specimen was consistent with other coarse-grained materials studied previously.
- Flaws in a large-bore, dissimilar metal weld joint were readily detected from the CASS side with low-frequency phased array.
  - Through-wall depth as small as 10% without depth sizing (circ flaw).
  - Far-side flaw with 16% through-wall depth (circ flaw).
  - Length as small as 19 mm (0.75 in.) (two axial flaws).
- Axial flaws were readily detected by raster-scanning across the weld region (no weld crown).





Final Observations – Probe Frequency

- The 500 kHz PA probe generally provided ~3 dB higher SNR than the 800 kHz PA probe.
  - Potentially better detection sensitivity.
- Less signal drop-out was observed with the 500 kHz probe.
- The 800 kHz PA probe was more effective at detecting tip-diffracted signals and allowed for more accurate depth sizing.
  - RMSE depth sizing for the 800 kHz probe was within ASME Code Section XI, Appendix VIII, Supplement 2 and 10 performance demonstration standards.
  - RMSE depth sizing for the 500 kHz probe was outside the standards.
- 500 kHz and 800 kHz probes provided comparable length sizing.
  - RMSE length sizing for both 500 kHz and 800 kHz probes was within Supplement 2 and 10 performance demonstration standards.
- The 500 kHz probe resulted in fewer artifacts.
  - Potentially fewer false calls.
- Note: Small number of data points in this analysis, but results are consistent with trends from previously published work.

Best Practices/Recommendations

- Use phased array probes.
  - Better SNR.
  - Better length and depth sizing.
  - Full sweep of angles in a single scan.
  - Helps combat the unpredictable location and severity of drop-out.
- Use low frequency (~500 kHz) probes for detection.
  - Fewer artifacts (false calls).
  - Better SNR.
  - Less drop-out.
- Use higher frequency (~800 kHz) for sizing.
- Remove weld crowns when possible to assure full coverage.
  - Axial flaws can be detected.
  - Lower refraction angles can be used.
- Use line scans for detection and raster scans for characterization.
- True-depth and Half-path focusing performed comparably.

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What is Flaw Signal Persistence?

Flaw signal persistence (in this context) is defined as:

The time-duration that an ultrasonic flaw signal response remains above a specified amplitude threshold (in terms of signal-to-noise ratio – SNR) for the purposes of detection, as a function of scan speed.

Why Evaluate Flaw Persistence?

- **Motivation**: To addess whether non-encoded, real-time, conventional examination approaches are viable for CASS materials, where typical SNRs are low and flaw detection/discrimination is challenging

- **Objective**: To better understand and quantify the impact of flaw persistence on flaw detection in CASS materials, in terms of inspection parameters

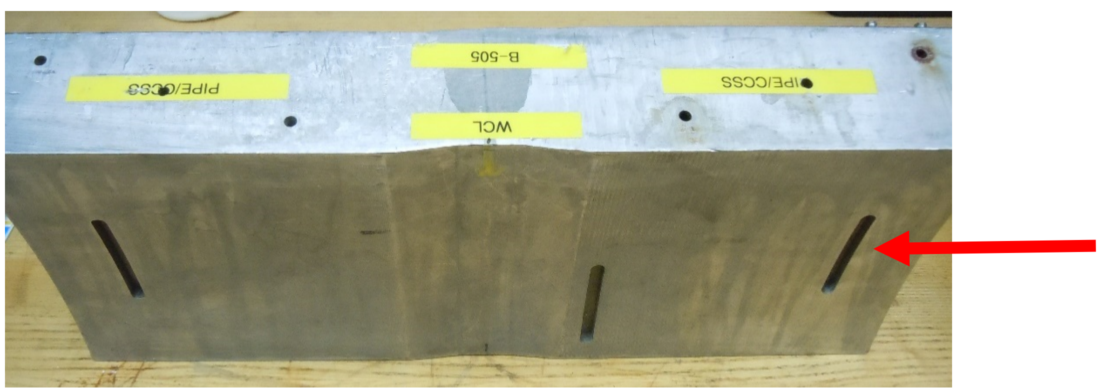
- **Inspection Parameters**: **Scan speed, SNR,** probe type/ characteristics, frequency/wavelength, scan orientation relative to the flaw orientation, CASS material properties, and flaw type/size/ morphology

How “Conventional” is Defined Here

- Use of single- or dual-element, pulse-echo or transmit-receive transducer configurations operating at frequencies at or above 1.0 MHz.
- Ultrasonic sound fields having a “dead zone” in the near field with more linear beam characteristics in the far field
  - Reduction of sound field intensity
  - Beam divergence
- Typically employ only a single fixed angle for each transducer configuration
- May or may not be spatially encoded
- Scanning may be done manually or by using automated fixtures

Data Acquisition

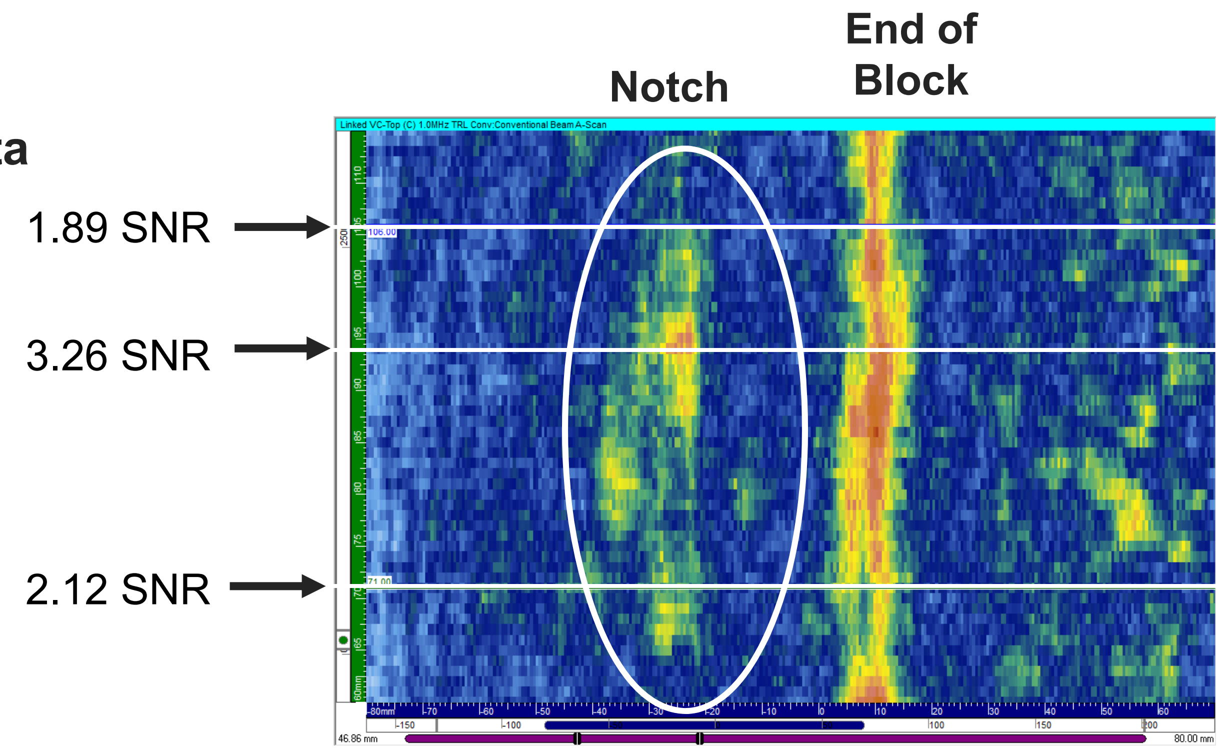
- Conventional dual probe used for manual inspections in the field
  - 1.0 MHz nominal frequency (0.98 MHz center frequency, 49.95% BW at -6 dB)
  - 0.75 x 1.0 in. (19.05 x 25.4 mm) element dimensions
  - Dual-element, 45° longitudinal (pitch-catch configuration)
  - Designed for 2.0 in. (50.8 mm) crossover depth point in steel (zone focus)
- Data were collected using automated, encoded scanning
  - 0.6 in./sec (15.2 mm/sec)
  - Scan resolution 0.02 x 0.04 in. (0.5 x 1.0 mm)
- Specimen details
  - Small-to-medium size columnar grained structure (equiaxed on opposite side of weld)
  - 2.35 in. (59.7 mm) wall thickness
  - 10% deep, 0.25 in. wide (6.33 mm) notch (red arrow)



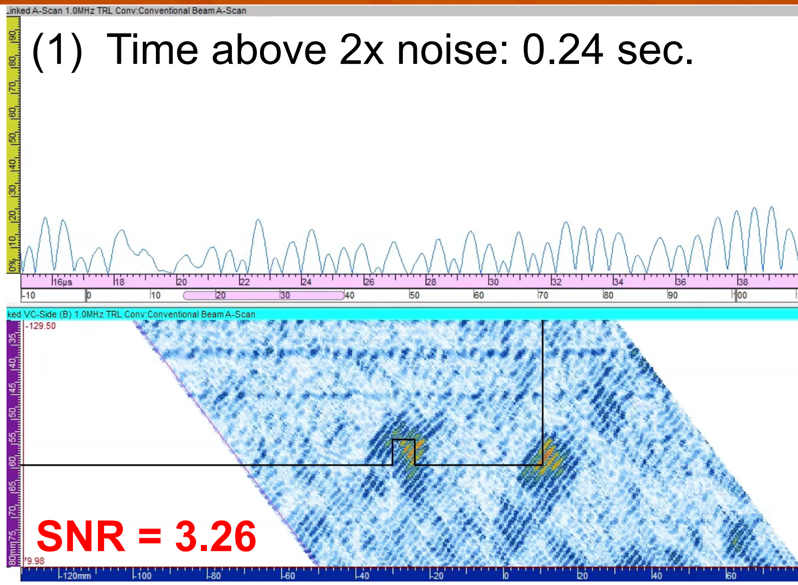
Data Analysis

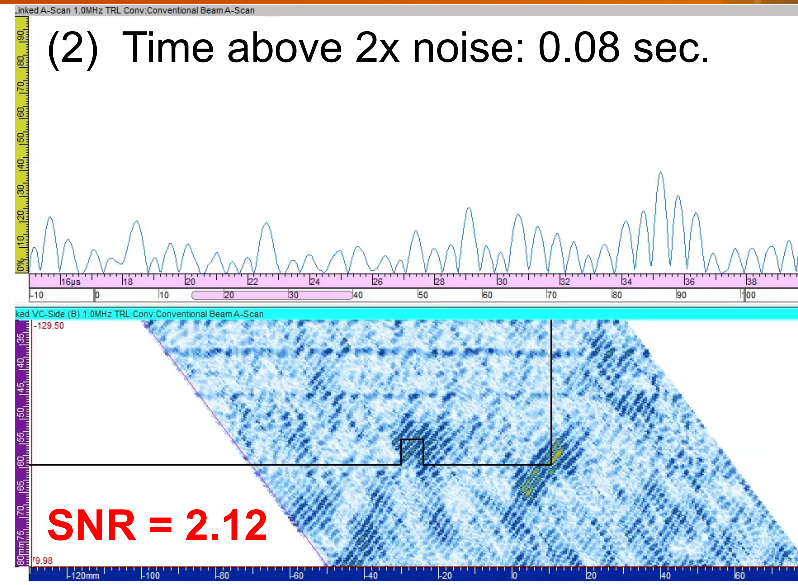
- Three slices were taken through the notch signal representing three different peak signal levels.
- A-scans of these three slices were analyzed as a function of time, to simulate moving a probe across that slice at 1 in./sec and 2 in./sec
- The duration of signal persistence above the noise level in these slices was calculated for the two different scan rates.

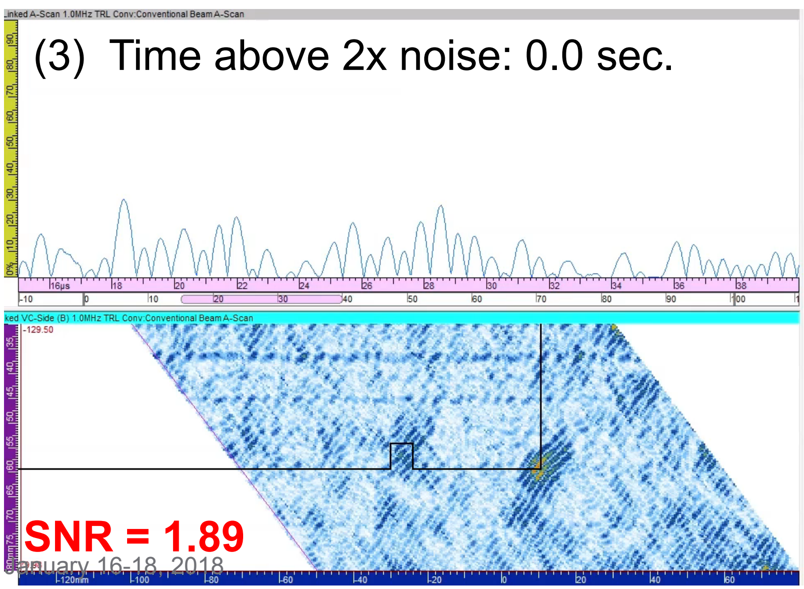
C-scan of Encoded Data



Signal Persistence (at 2 in./s)

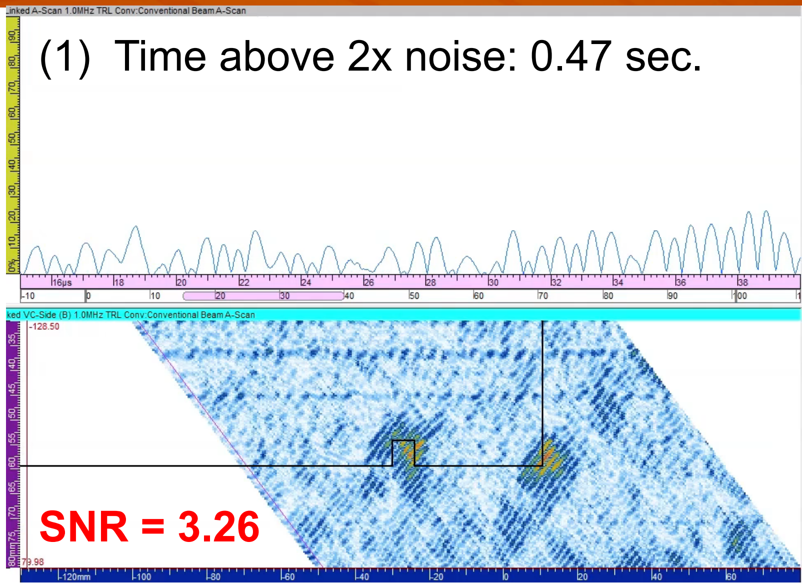


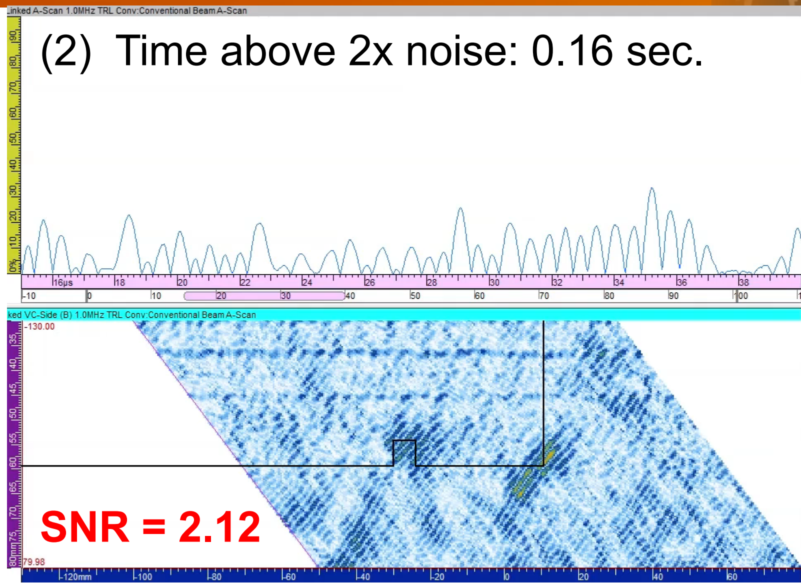


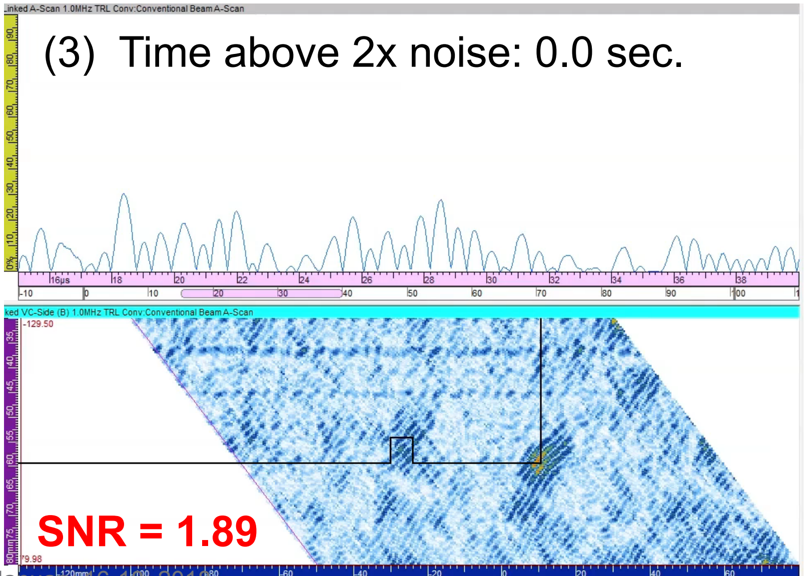


Machined Reflector: 0.25 in. wide, 10% through-wall notch in CASS mockup with small-grained columnar microstructure

Signal Persistence (at 1 in./s)







Machined Reflector: 0.25 in. wide, 10% through-wall notch in CASS mockup with small-grained columnar microstructure

CASS Signal Persistence Summary

- The detection of a large, machined reflector represents a best-case-scenario for detection as opposed to actual crack detection
- Signal persistence for peak observed signal (3.26 SNR):
  - 0.24 sec at 2 in./sec
  - 0.47 sec at 1 in./sec
- Signal persistence for nominal observed signal (2.12 SNR):
  - 0.08 sec at 2 in./sec
  - 0.16 sec at 1 in./sec
- Detection in CASS using non-encoded, conventional, real-time methods is not feasible due to short signal persistence in the presence of high noise levels
  - The notch was readily detected using encoded data
  - Detection is very challenging or impossible when signal was at or below the 2:1 SNR level, regardless of scan speed

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What is Signal Dropout?

Signal dropout (in this context) is defined as:

The amplitude dip of an ultrasonic end-of-block signal response below a specified amplitude threshold (in terms of signal-to-noise ratio – SNR) for the purposes of detection, as a function of circumferential spatial position and incident angle.

Why Evaluate Signal Dropout?

- **Motivation**: To address whether use of a discrete incident angle is viable for the effective examination of CASS materials – where microstructural variability is unpredictable, typical SNRs are low, and flaw detection/discrimination is challenging – and confirm the range of search unit angles as described in the conditions for CC N-824

- **Objective**: To better understand and quantify the prevalence and impact of signal dropout on the detection of the “end-of-block” geometry (essentially a 100% through-wall flaw) in CASS mockups, in terms of key inspection parameters

- **Key Inspection Parameters**: SNR, probe type/characteristics, frequency/wavelength, scan orientation to the end of block, and CASS material properties/dimensions

Grain Structure and Probe Frequency: PA-UT Sound Field Mapping in CASS

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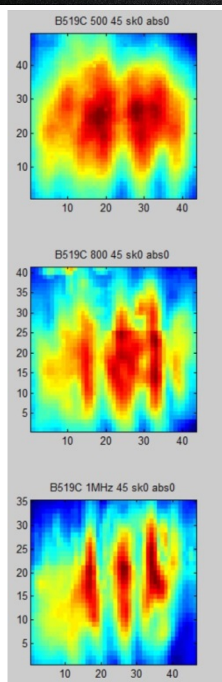
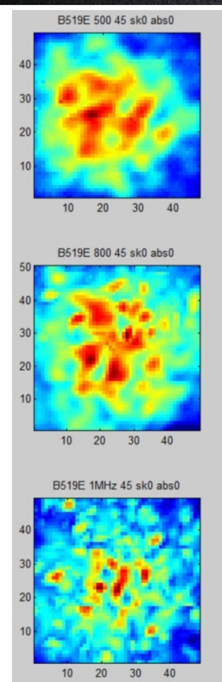
Columnar	Equiaxed	Coarse-grained mix	
			**Fine grained wrought SS**

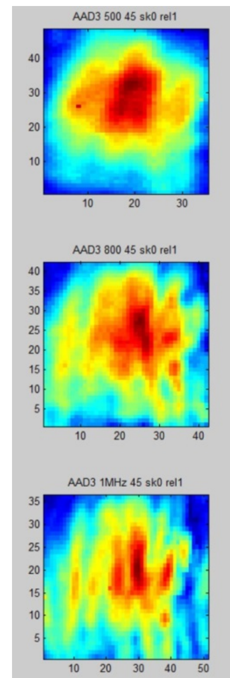


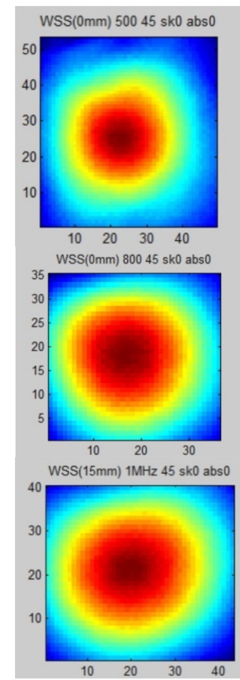
500 kHz

800 kHz

1.0 MHz



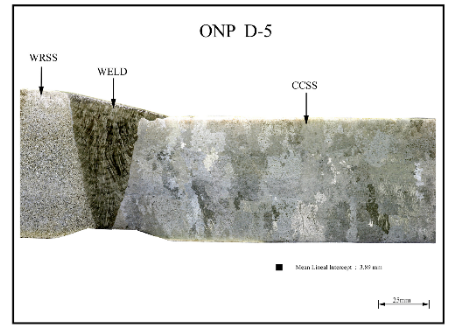


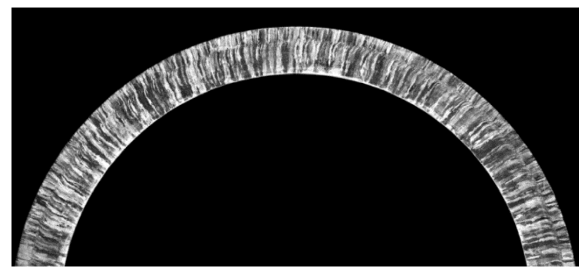


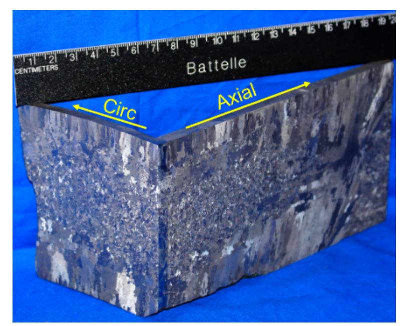
Phased Array Ultrasonic Sound Field Mapping in Cast Austenitic Stainless Steel (ML14155A165)

Methods

- Measured the amplitude of the signal response from the end-of-block on CASS specimens with a range of known grain structures
  - Small-grain equiaxed (Manoir) – 75 mm thick
  - Coarse-grain equiaxed (ONP-D-5) – 64 mm thick
  - Columnar (Westinghouse) – 64 mm thick
  - Mixed/banded (Manoir, 14C-146) – 85 mm thick
  - Wrought specimen, control – 64 mm thick
- Encoded phased array, TRL, TD focus at ID
  - 500 kHz, 10x5 elements, 64x34 mm aperture
  - 800 kHz, 10x5 elements, 43x21 mm aperture
  - 1.0 MHz, 10x5 elements, 40x20 mm aperture
- Angle range 20-70 deg., 5 deg. steps
- Raster scans
  - 2.0 mm index resolution
  - 0.5 mm scan resolution
- Scanned as much of each specimen as was accessible

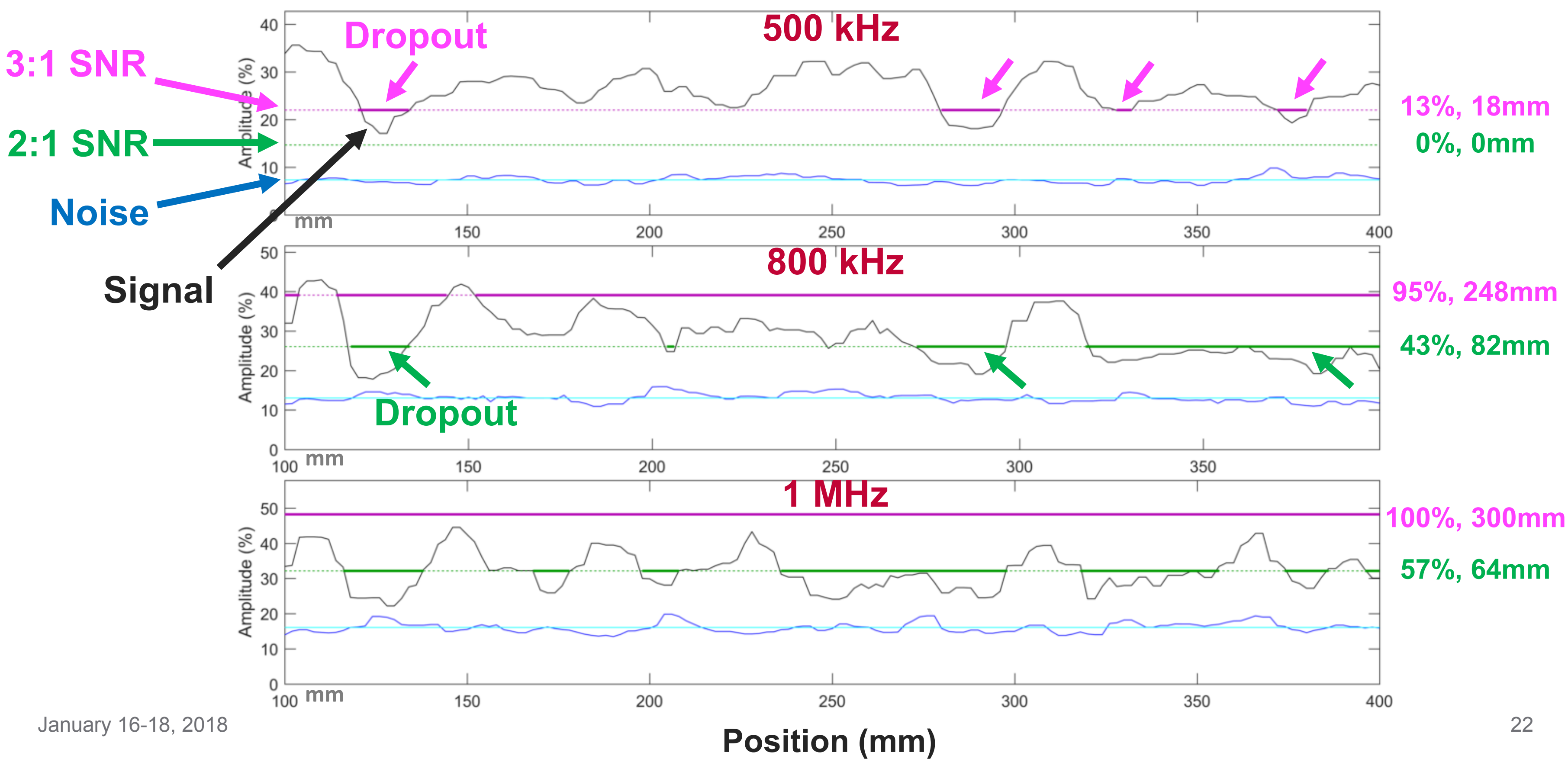




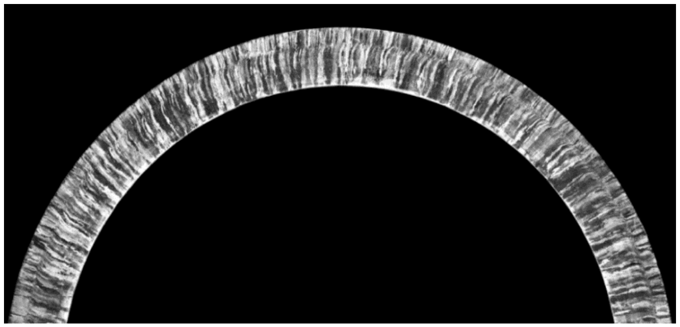


Analysis

- Data exported from UltraVision. Fully automated analysis in MATLAB.
- Measured corner signal intensity and mean noise at same metal path for all frequencies and all angles
- Identified regions where signal dropped below 3:1 SNR and 2:1 SNR (note that noise increases with frequency)
- Calculated % dropout and longest continuous dropout



Data Example: Columnar

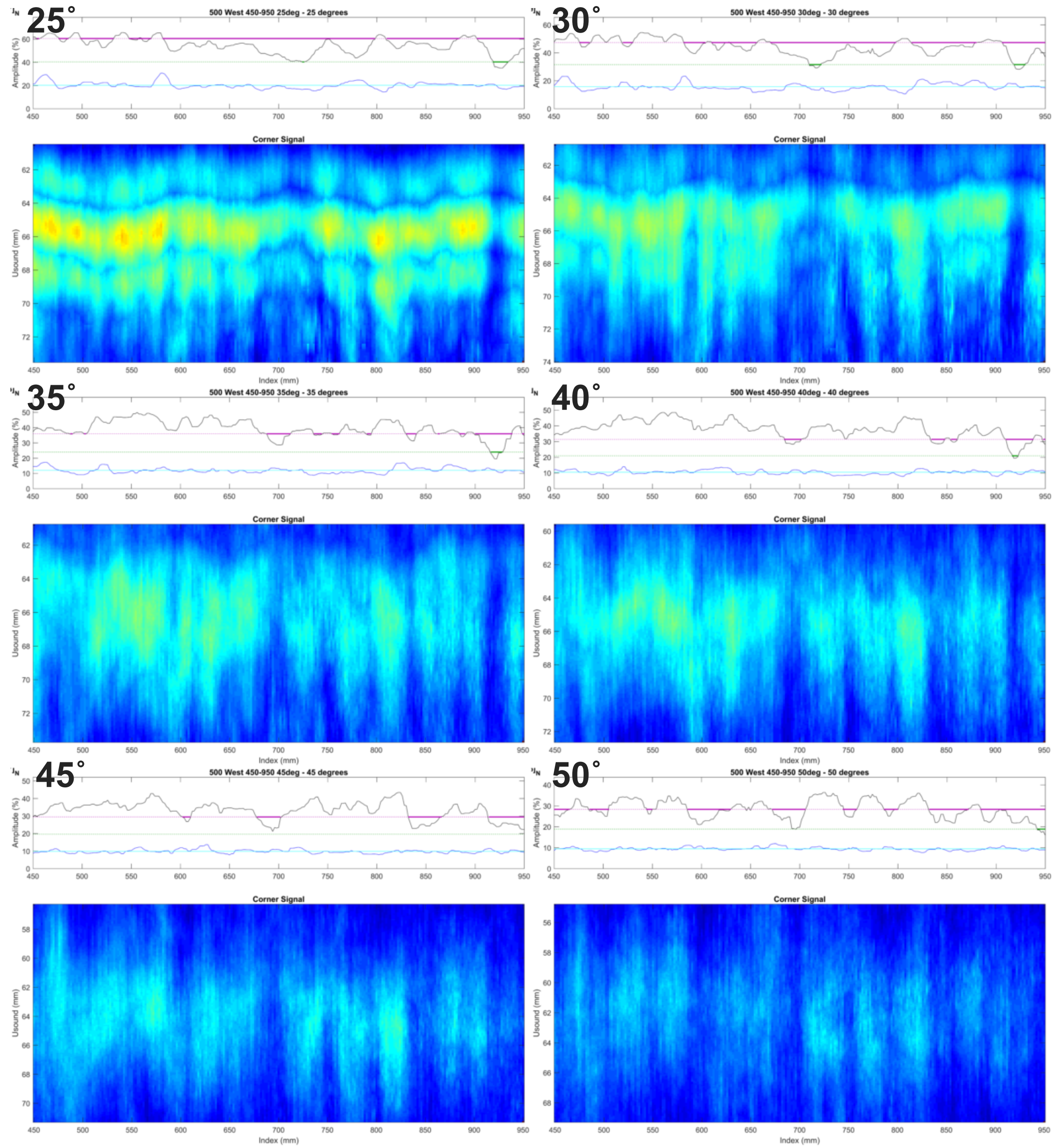


2:1 SNR at 500 kHz

Angle	% Dropout	Max Dropout
20	15	46
25	4	18
30	6	14
35	3	14
40	2	8
45	0	0
50	2	10
55	10	16
60	49	36
65	49	44

Percentage of scan range where signal dropped below threshold.

Maximum continuous dropout length (mm).



2:1 SNR Dropout Comparison at Different Frequencies

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- 500 kHz (top), 800 kHz (middle), and 1 MHz (bottom)

Small Grained Equiaxed

500 kHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	0	0
25	0	0
30	0	0
35	0	0
40	0	0
45	0	0
50	0	0
55	0	0
60	35	88
65	–	–

800 kHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	0	0
25	0	0
30	0	0
35	0	0
40	0	0
45	0	0
50	0	0
55	11	26
60	35	46
65	–	–

1 MHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	0	0
25	0	0
30	0	0
35	0	0
40	0	0
45	2	8
50	19	26
55	49	60
60	73	76
65	–	–

Coarse Grained Equiaxed

500 kHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	96	170
25	87	160
30	50	64
35	29	50
40	6	12
45	11	16
50	26	32
55	86	82
60	–	–
65	–	–

800 kHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	100	200
25	98	166
30	91	128
35	68	90
40	56	48
45	38	32
50	65	30
55	–	–
60	–	–
65	–	–

1 MHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	98	162
25	100	200
30	85	122
35	68	58
40	59	52
45	71	48
50	83	84
55	–	–
60	–	–
65	–	–

Columnar

500 kHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	15	46
25	4	18
30	6	14
35	3	14
40	2	8
45	0	0
50	2	10
55	10	16
60	49	36
65	49	44

800 kHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	88	200
25	43	52
30	20	38
35	8	16
40	4	12
45	6	12
50	31	36
55	74	74
60	98	264
65	–	–

1 MHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	89	92
25	55	44
30	21	38
35	8	16
40	13	16
45	21	28
50	55	42
55	95	148
60	–	–
65	–	–

Mixed/Banded

500 kHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	0	0
25	0	0
30	0	0
35	0	0
40	0	0
45	0	0
50	17	14
55	37	22
60	36	24
65	–	–

800 kHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	0	0
25	0	0
30	0	0
35	10	10
40	43	82
45	48	84
50	67	84
55	90	98
60	–	–
65	–	–

1 MHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	6	8
25	25	20
30	46	42
35	47	46
40	57	64
45	83	68
50	95	156
55	99	250
60	–	–
65	–	–

Wrought

500 kHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	0	0
25	0	0
30	0	0
35	0	0
40	0	0
45	0	0
50	0	0
55	0	0
60	0	0
65	0	0

800 kHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	0	0
25	0	0
30	0	0
35	0	0
40	0	0
45	0	0
50	0	0
55	0	0
60	0	0
65	0	0

1 MHz, 2x SNR		
Angle	% Dropout	Max Dropout
20	0	0
25	0	0
30	0	0
35	0	0
40	0	0
45	0	0
50	0	0
55	0	0
60	0	0
65	0	0

End-of-block Dropout Summary

- Significant signal dropout is observed in CASS, even with an ideal smooth, planar, 100% through-wall reflector
  - Dropout from actual flaws is anticipated to be considerably more significant
  - Dropout may make accurate flaw sizing in CASS problematic
- Range of least affected angles was unpredictable
  - The range of least affected angles was not consistent between 2:1 and 3:1 SNR
  - Higher angles were universally bad
  - Grain geometry and structure are critical factors but are usually unknown
- The 500 kHz probe consistently had the least dropout and lowest noise levels

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- Manoir specimen wrap-up
- Flaw signal persistence
- End-of-Block signal dropout
- Analysis of EPRI's CASS Round Robin
- NUREG/CR summary

Scope and Objectives of PNNL’s Round Robin Analysis

Scope:

PNNL’s assessment focused on evaluating all aspects of the EPRI CASS round robin, including round robin protocols, mockups, data, and other relevant factors.

Objectives:

- Determine POD/FCP for the collective set of all participants’ data
- Assess the flaw distribution, locations, and dimensions, and whether flaws seem to be too easy or too difficult to detect
- Assess whether the specimens seem to be representative of field conditions – especially in regard to weld root, weld crown, and counterbore
- Assess the impact of data acquisition and analysis protocols used in the RR
- Determine if single-sided examinations are reasonable for CASS components

Overview of PNNL Preliminary Analysis – Considerations

- PNNL developed grading criteria based on independent examination of the data with consideration of the impact of CASS material properties
- Detection rates and false call rates only – no length or depth sizing analysis
  - A breakdown of detection data by flaw depth was not considered
- Determine the effects of geometry on false call rates
- PNNL focused solely on raster scan data for this analysis
- Single-sided only
  - Upstream and downstream data from a given specimen were treated as independent data sets

Comparison of Key Detection Grading Criteria

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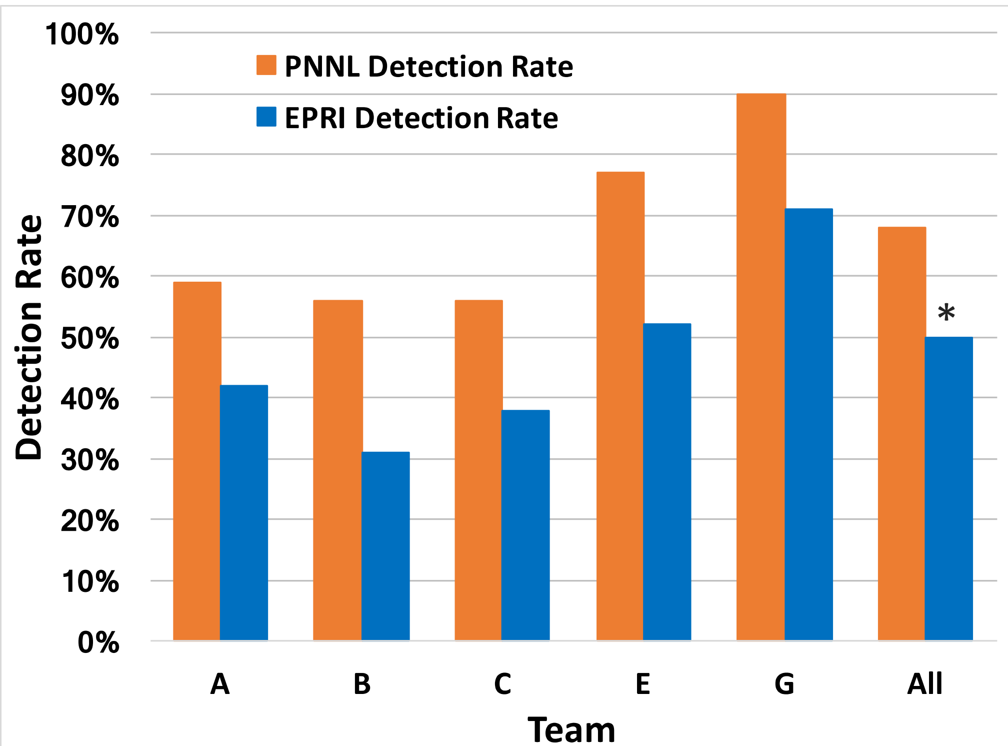
PNNL Grading Criteria	EPRI Grading Criteria
A reported flaw must overlap circumferentially by any amount with the true flaw position	
No axial grading units	
If a reported flaw overlaps with one or more geometrical feature and/or a true flaw, a center-to-center proximity test was used to determine which feature the reported flaw represented	No distinguishing between geometrical feature calls and flaw calls
No length criteria were used	The reported flaw length must be at least 50% of the true flaw length but not more than 2x longer than the true flaw (or no more than 2 inches longer for flaws shorter than 2 inches)
Each reported flaw was counted only once: as a true call, a false call, a geometry call, or ignored.	Reported flaws that span multiple unflawed grading units may count as multiple false calls.

These two grading criteria were responsible for most of the differences between the PNNL and EPRI detection rates and false call probabilities.

Detection Rates

- PNNL's detection rates were higher than EPRI's.
  - The flaw length grading criterion was the major difference, accounting for about 90 additional detections for PNNL.



*Note: EPRI "All" includes Candidates D and F. PNNL does not. Teams D and F performed comparably to Teams E and G, respectively.

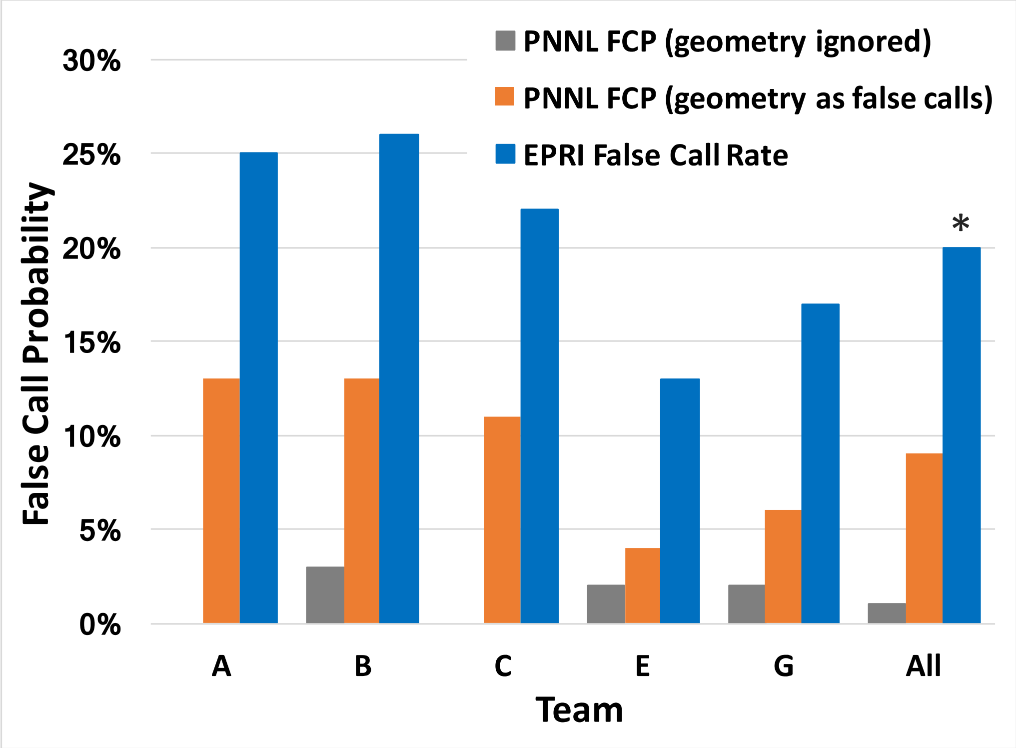
36" Specimens

Team	PNNL POD	PNNL POD with 50% criteria	EPRI mean POD*
A	68%	32%	29%
B	74%	13%	16%
C	66%	29%	29%
E	84%	37%	37%
G	87%	58%	58%
A,B,C,E,G	76%	34%	34%
A,B,C only	69%	25%	25%
E,G only	86%	47%	47%

*Approximate, as calculated from results in EPRI's report

False Call Probabilities

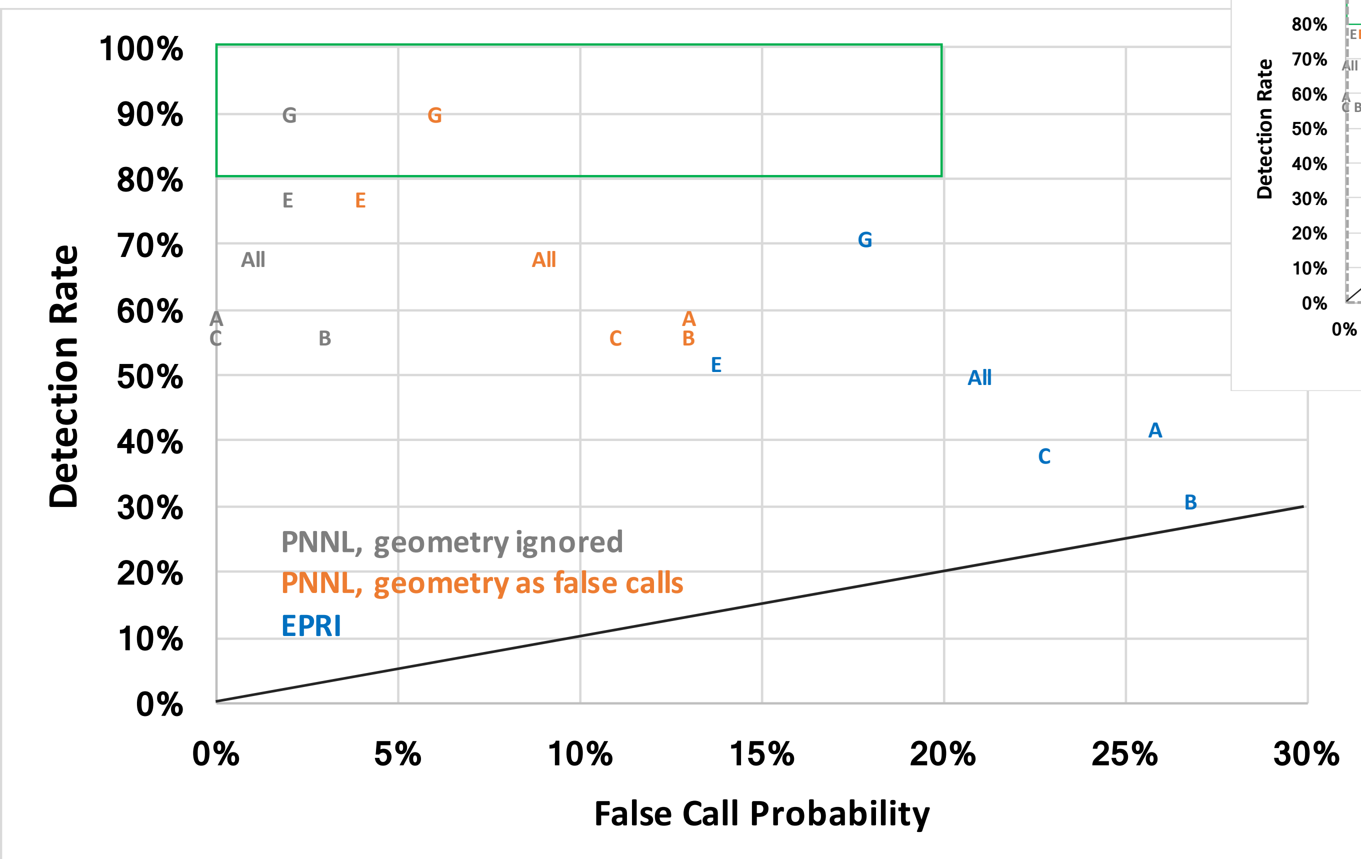
- PNNL's false call probabilities were lower than EPRI's.
  - The different methods of counting reported flaws across grading units was the major difference.
  - Effects of microstructure – highlighted by "ignoring" geometry – shows that microstructure was not the primary source of false calls in these specimens.

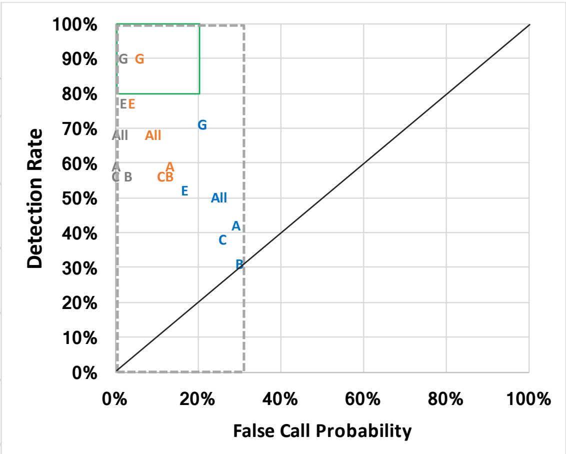


*Note: EPRI "All" includes Teams D and F. PNNL does not.

Detection Rates vs. False Call Probabilities

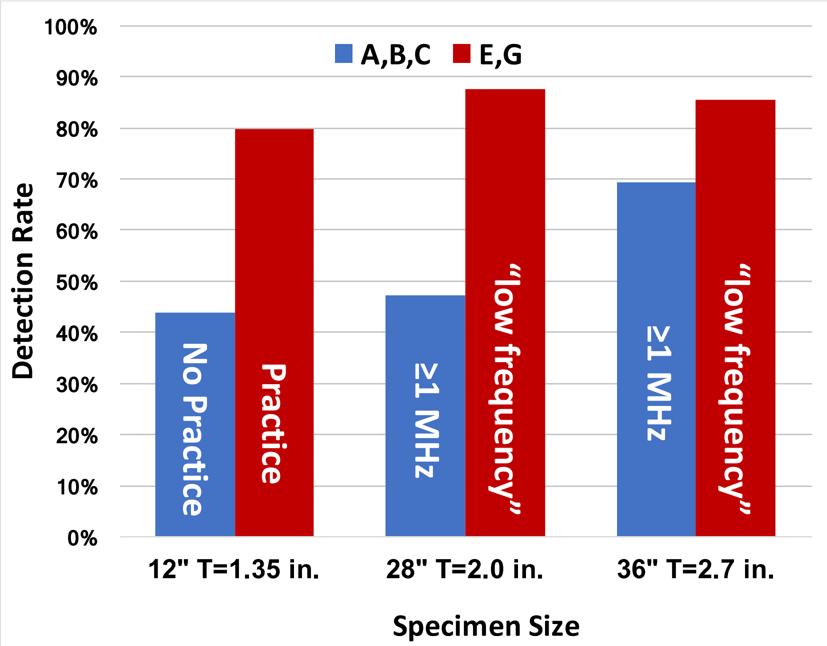
- PNNL results showed all teams below the 20% false call probability threshold and one team above the 80% detection threshold.





Detection Rates by Specimen Group

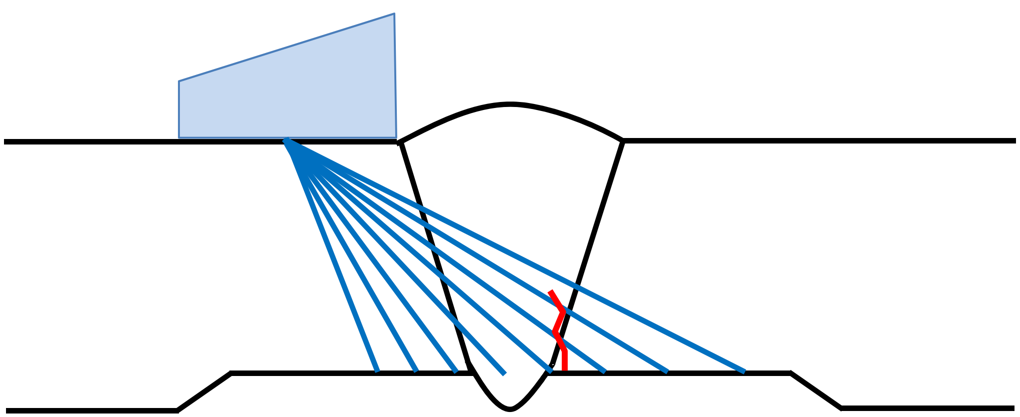
- Teams A, B, and C
  - Used “non-low frequency” PA-UT (≥1 MHz) for all scans
  - Practiced on 28” only or did not practice
- Teams E and G
  - Used “low frequency” PA-UT for 36” scans and 28” scans
  - Practiced on 12” and 28” specimens
- Observations based on PNNL’s grading criteria
  - Practice likely helped teams E and G perform better on the 12” specimens
  - Specimen thickness did not appear to be a factor for teams E and G
  - Results support the condition for CC N-824 requiring 500 kHz for specimens >1.6 in.



(Note: 36” specimens had greater access over weld)

Access Limitations

- Most effective examination angle (PNNL data only)
  - Average angle was 40º in specimens without OD geometry (e.g., weld crowns)(range: 32º - 50º)
  - Average angle was 55º in specimens with OD geometry (e.g., weld crowns) (range: 41º - 62º)
  - Based on end-of-block signal dropout results, angles ≥50º are not favorable for detection in most CASS specimens



In the presence of OD geometry (e.g., weld crowns), higher examination angles are required, particularly for far-side examinations.

PNNL's Key Observations

- Average detection rate with application of PNNL's grading criteria
  - Significantly higher when length-based detection criteria are not used
  - Nearly 70% for all teams
  - Over 80% for low-frequency teams
- Average false call rate with application of PNNL's grading criteria
  - About 1% when ignoring geometry calls
  - Less than 10% with geometry calls as false calls
  - Teams that used low frequency had lower false call rates
- Length-based detection criteria may not be appropriate for CASS
  - Signal dropout is unpredictable in CASS at any frequency
  - Signal dropout can be a major problem in thick-wall CASS at frequencies above about 500 kHz (several teams used ≥1 MHz for all scans)
  - Noise levels in CASS are generally higher than in fine-grained materials

PNNL's Key Observations (continued)

- Grading criteria have a profound effect on the detection rates and false call rates.
  - It should be determined whether PDI-based grading criteria appropriate for detection in other materials are appropriate for CASS
- Geometry conditions (weld root, counterbore) were strong confounders for some teams.
- When PNNL's grading criteria is applied to the data for the thick-wall specimens, both teams that used low frequency probes had detection rates >80%.

Outline

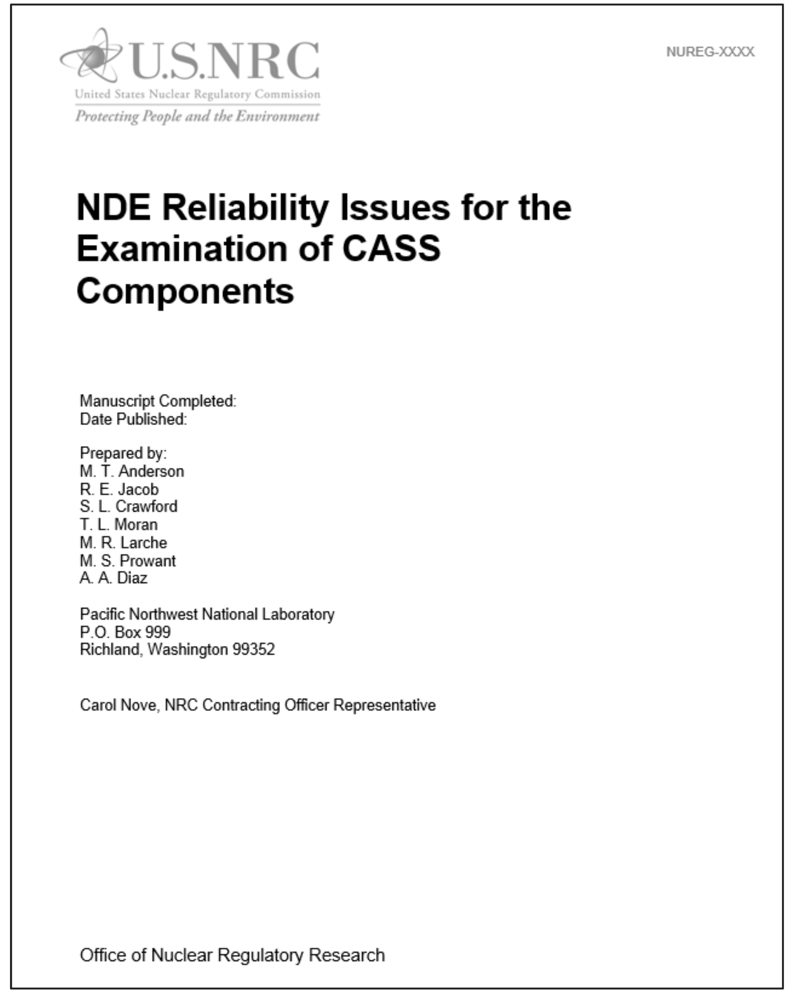
- Manoir specimen wrap-up
- Flaw signal persistence
- End-of-Block signal dropout
- EPRI CASS Round Robin analysis
- NUREG/CR summary

CASS NUREG/CR

Scope:

- Summary of past and current work documenting the latest research sponsored by the NRC and conducted at PNNL to evaluate the effectiveness and reliability of NDE methods for the inspection of CASS weldments.

- Encompasses CASS weldments located within the primary pressure boundary of LWRs.



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NUREG-XXXX

NDE Reliability Issues for the Examination of CASS Components

Manuscript Completed:
Date Published:

Prepared by:
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CASS NUREG/CR

Objectives:

- To determine the potential reliability of current inservice inspection (ISI) techniques,
- Assess the viability of using advanced NDE methods for examining CASS,
  - Develop recommendations to ensure a suitably high inspection reliability if fully implemented.
- Provide a technical foundation to support NRC rulemaking activities and provide guidelines and a solid technical basis for supporting the development of performance demonstration requirements via a Section XI, Appendix VIII, Supplement 9.

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CASS NUREG/CR
Key Attributes for Effective CASS Exams

- **Adequate sound field**
  - Selecting appropriate UT frequencies, propagation angles, and beam forming methods for establishing effective sound fields to detect, then characterize, flaws in varied coarse-grained CASS microstructures
- **Spatial encoding and volumetric ultrasonic image analysis**
  - The importance of using encoded data with off-line imaging and analyses for the discrimination between cracks, geometrical reflectors, and material noise inherent in CASS
- **Understanding probe performance, sound field dimensions, propagation characteristics, and the material being examined**
  - The use of UT modeling to optimize examinations, providing preliminary validation of search unit design, theoretical sound field intensities, and potential for adequate volumetric coverage
- **Effective training**
  - Indoctrinating examiners through specialized training in CASS microstructures that may be encountered, resultant sound field effects, and methods to discriminate between flaws, geometry, and other coherent noise in CASS configurations

CASS NUREG/CR Conclusions

- Low frequency, PA-UT allows for acquisition of multiple angles in rapid fashion and provides improved focusing over conventional UT
- For CASS piping with wall thickness > 41 mm (1.6 in.), 500 kHz PA-UT is necessary for detection
  - Higher frequencies (up to 1 MHz) may be applied after a flaw is detected, for characterization
- For CASS piping with wall thickness ≤ 41 mm (1.6 in.) 800 kHz PA-UT is necessary for detection
  - Higher frequencies (1.5 to 2.0 MHz) may be applied after a flaw is detected, for characterization
- Only LF-PA techniques should be used to examine CASS weldments, and PA focal laws should be modeled effectively and applied to ensure robust sound field intensities in the proper areas of interest. It is necessary to have a sufficiently large active array aperture in order for robust sound fields to be produced in the targeted regions of material.

CASS NUREG/CR Conclusions – continued

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- A minimum range of inspection angles from 30°– 55°, with increments no larger than 3°, be applied to enhance flaw detection in CASS materials
- Real-time, non-encoded scans should not be employed for CASS components, however, spatial encoding, coupled with off-line post-processing and imaging techniques, should be used for all CASS piping examinations
- Modeling can provide important insight. Even simple models, which only provide theoretical beam projections, are beneficial to examiners in facilitating choices for array probe design by defining active aperture sizes, to assist focal law development, to ensure appropriate beam intensities, and to optimize steering within the components being inspected. More sophisticated (including reflected signal response) simulations are encouraged to provide information on expected flaw detection capabilities and volumetric coverage.

CASS NUREG/CR Conclusions – continued

- Requirement for fundamental knowledge and skills by field examiners, to include:
  - Casting processes that result in the unpredictable and highly variable microstructures, along with how these are expected to affect UT propagation in CASS,
  - Best practices need to be developed to help examiners distinguish between coherent energies and varied modes returned from the coarse grains or geometrical features, and similar reflections from flaws, to enhance these examinations,
  - Access to suitable realistic CASS mockups with simulated service-induced flaws (cracks) for hands-on practice, and
  - Formal classroom training and hands-on practice is paramount if effective and reliable examinations are to be performed on CASS.

Questions

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