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PNNL-SA-131574

Ultrasonic Modeling and Simulation

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CAROL NOVE, NRC COR
Industry-NRC NDE Technical Information Exchange Meeting
Rockville, Maryland
January 16-18, 2018

Outline

- Modeling and simulation
  - Objectives
  - Approach and examples of results to date
  - Key takeaways
  - Next steps
- Limited coverage
  - Objectives
  - Approach
  - Key takeaways
  - Next steps

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Modeling and Simulation: Objectives

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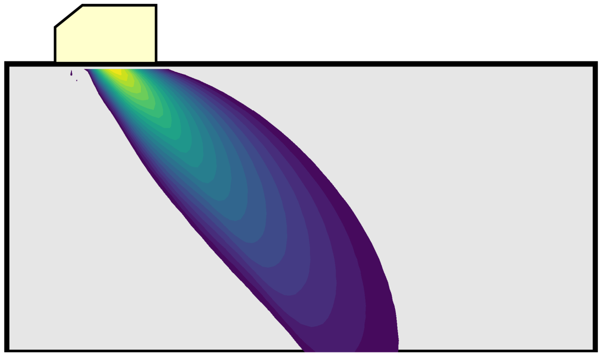
- Quantify the effectiveness of beam models with respect to coverage and flaw detection capability
  - Quantify effects of component geometries, material properties, probe specifications, and other parameters on sound field characteristics and detection capability
  - Quantify effect of input parameter uncertainties in simulation results
- Identify gaps in common software tools for 2D and 3D simulation of ultrasonic inspection.
- Develop guidance for use and interpretation of simulation models for conveying information on effectiveness of inspections.

Coverage area for beam within -6 dB



Coverage area for beam within -20 dB

Foundation for confirming solid technical basis for conducting, interpreting, and applying ultrasonic modeling to assess the effectiveness of inspections of NPP components

Approach

- Leveraging, when possible, prior work at PNNL and elsewhere
  - Verification and validation of simulation tools
  - Variability of calculated flaw amplitudes; initial methods for noise incorporation in simulations
  - Sensitivity of calculated flaw amplitudes to parameter uncertainties
  - Metrics for comparing simulation and experimental results

- This phase of research
  - Compare and contrast ultrasonic beam calculations from commonly used ultrasonic NDE simulation tools
  - Determine if correlations between sound fields and flaw amplitudes may be inferred
  - Quantify sound field and flaw amplitudes as a function of several parameters that are hypothesized to influence ultrasonic amplitudes
  - Define techniques to include noise in simulation results - SNR
  - Quantify uncertainty in simulation results and its impact on interpretability

Key Takeaways to Date from Modeling Studies

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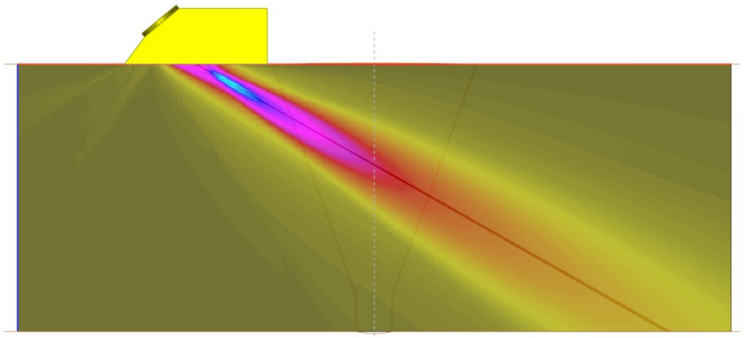
- Some software tools have limited ability to simulate beam propagation through complex materials (welds, coarse grained, or anisotropic base material)

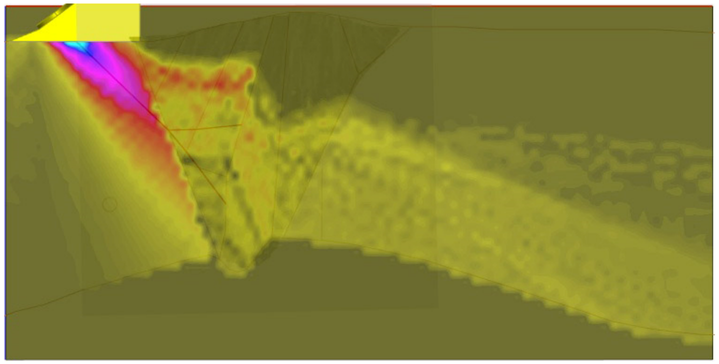
- Software tools evaluated for ultrasonic beam modeling show some differences in beam coverage estimates in isotropic materials

- Comparisons of simulation results and interpretation will require calibration (normalization) of calculated ultrasonic flaw amplitudes

- Beam models show limited correlation with calculated and measured amplitudes from flaws
  - Flaw amplitudes are a complex function of beam energy as well as a number of other parameters



Simulated Ultrasonic Beam in Isotropic Material



Simulated Ultrasonic Beam Through a Weld

Assumptions and Limitations of Research

- Industry-accepted standards and guidance for UT examinations used to develop bounding cases (geometry, probe, flaw parameters)
  - Limit conditions and inform test matrix development
- Focus is on developing guidance for:
  - Interpreting model results for applicability to coverage and detection capability
  - Identifying and documenting variables impacting coverage and detection calculations
  - Quantifying uncertainty in calculated values of sound field coverage and detection ability
  - Assessing the value of 2D and 3D simulations
- Focus of effort is **NOT** on assessing ability to discriminate between responses from flaws and non-flaws

Parameters Influencing Ultrasonic Simulation Results

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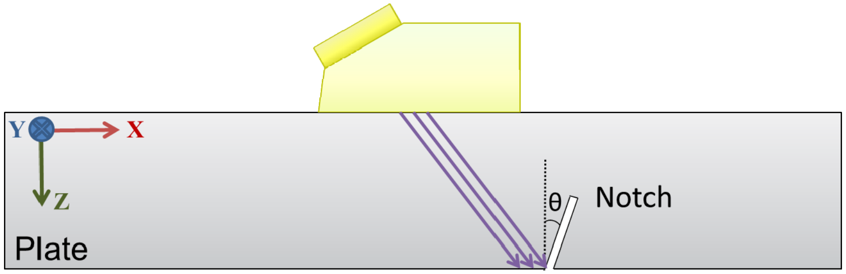
- Parameters include probe, coupling, wedge, material, flaw, and data acquisition system parameters
- Many of these parameters cannot be specified with sufficient precision for modeling purposes
  - Add uncertainty in the simulation results



Aleatory	Epistemic	Bias
• Specimen moduli • Specimen density • Specimen thickness • Flaw height • Flaw length • Flaw tilt • Flaw skew • Probe shape • Wedge dims • Wedge moduli • Wedge density	• Probe squint • Probe orientation • Specimen surface • Grain noise • Grain boundaries • Flaw morphology	• Element coupling • Wedge coupling • Material attenuation • Electronics • Piezoelectric element transfer function

A Brief Summary of Prior Results

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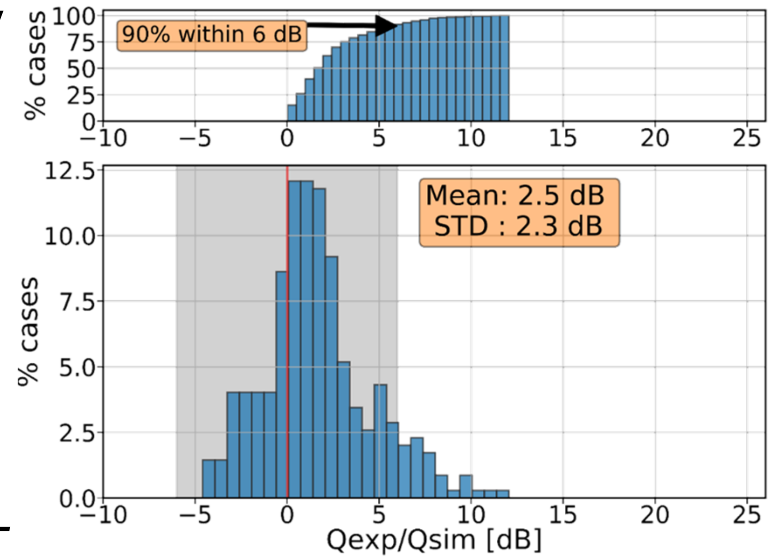
- Prior (Phase I) efforts: assessing variability in simulated flaw amplitudes
  - Sensitivity of calculated amplitudes to key parameters
  - Metrics for comparing simulation and experiment, in the presence of noise
  - Results documented in ML17082A190: *Validation of Ultrasonic Nondestructive Examination (NDE) Computational Models - Phase 1,* PNNL-26336 (2017)
- Differences attributed to
  - Inability to precisely quantify experimental factors (uncertainty)
  - Approximations inherent in models



Histogram of 358 different angle beam inspections

Flaw amplitude from simulation results and experiments appear to compare reasonably well under ideal conditions (isotropic materials), although noise and uncertainty in input parameters can limit simulation fidelity.

Normalization of Beam Amplitudes Enable Comparison Across Probes and Software Tools

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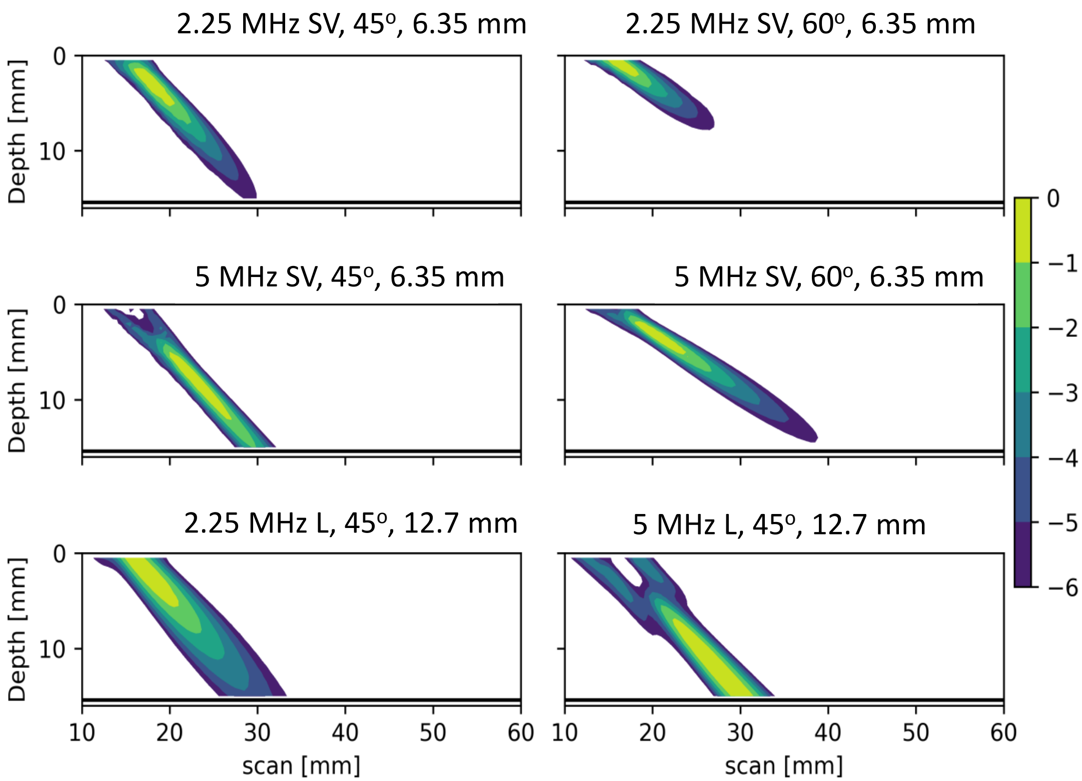
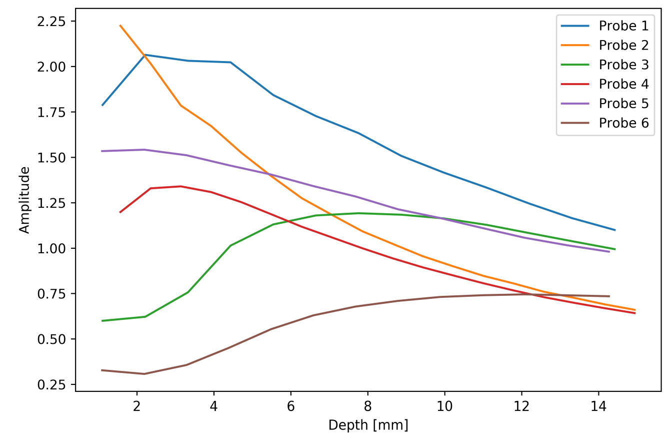
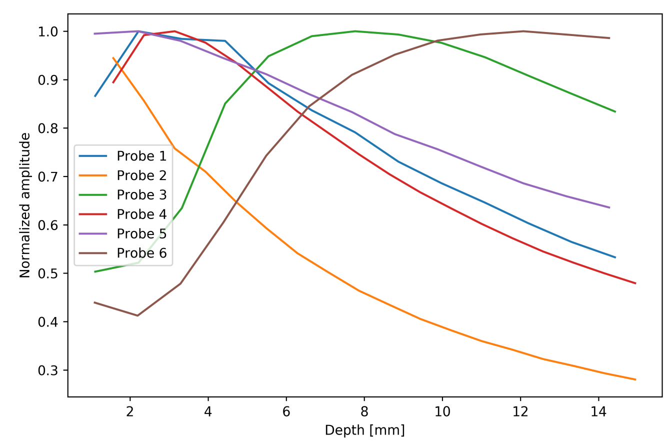


Beam Simulations for Six Ultrasonic Probes



Unnormalized Beam Amplitude vs. Distance from Probe



Normalized Beam Amplitude vs. Distance from Probe

Note: Beam amplitude profiles were obtained along the probe axis.

Sound Field Simulations Examples

Shear wave probes

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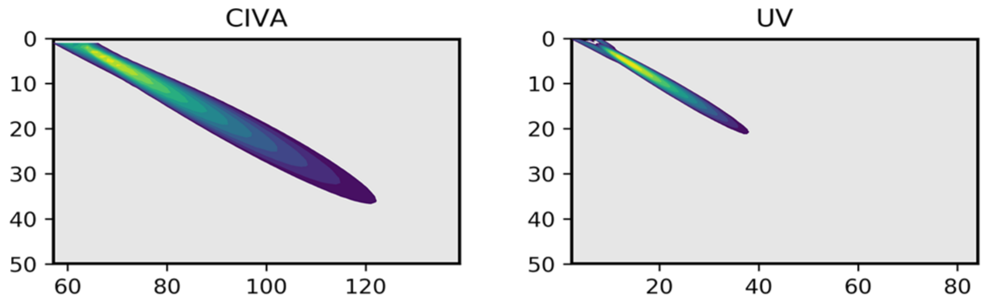
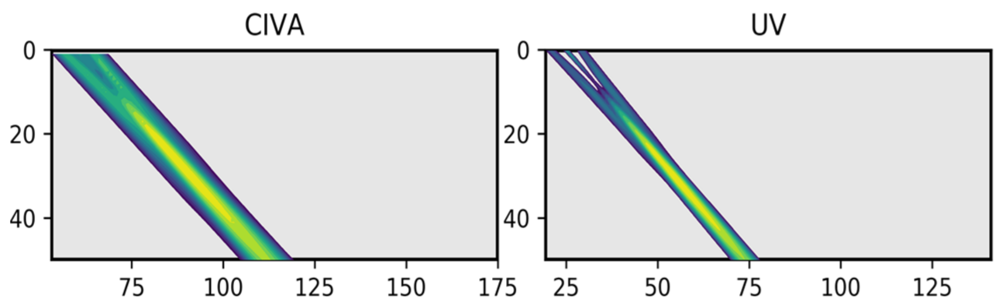
<u>Refracted Shear Wave Inspection Using Single Element Probe</u>

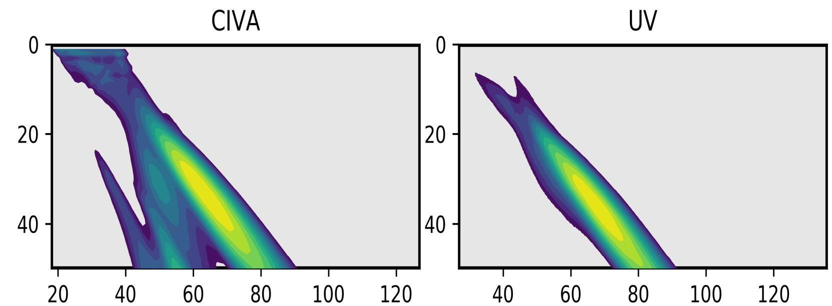


5 MHz, 60°, 6.35 mm (1/4”)

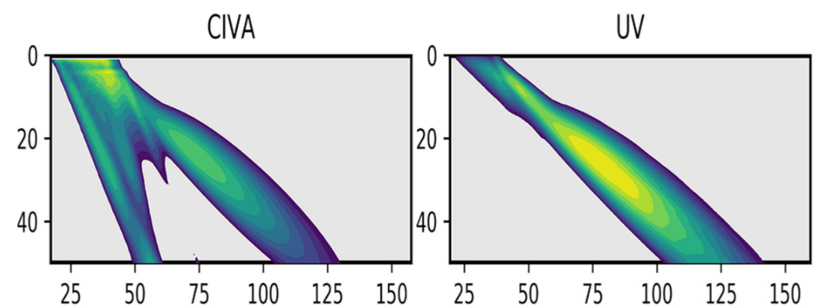


5 MHz, 45°, 12.7 mm (1/2”)

<u>Refracted Longitudinal Wave Inspection Using TRL Probe</u>



2 MHz, 45°, 15x25 mm



2 MHz, 60°, 15x25 mm

Software tools evaluated for ultrasonic beam modeling show some differences in beam coverage estimates in isotropic materials.

Note: Figures show beam shapes with a -12 dB cutoff.

Beam Simulations Summary

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Probe #	Type	Element Shape	Frequency (MHz)	Size (mm)	Angle	Wave Mode	UltraVision (%)	CIVA (%)	Difference (%)
1	Single	Circular	1.00	6.35	45	shear	1.2	10.0	8.8
2	Single	Circular	1.50	6.35	45	shear	2.0	12.1	10.1
3	Single	Circular	2.25	6.35	45	shear	3.1	15.9	12.8
4	Single	Circular	5.00	6.35	45	shear	12.2	29.8	17.6
5	Single	Circular	1.00	6.35	60	shear	0.0	6.4	6.4
6	Single	Circular	1.50	6.35	60	shear	0.0	7.4	7.4
7	Single	Circular	2.25	6.35	60	shear	1.2	9.2	8.0
8	Single	Circular	5.00	6.35	60	shear	5.5	18.3	12.8
9	Single	Circular	1.00	12.7	45	shear	9.8	26.3	16.5
1[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]5
1[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]6
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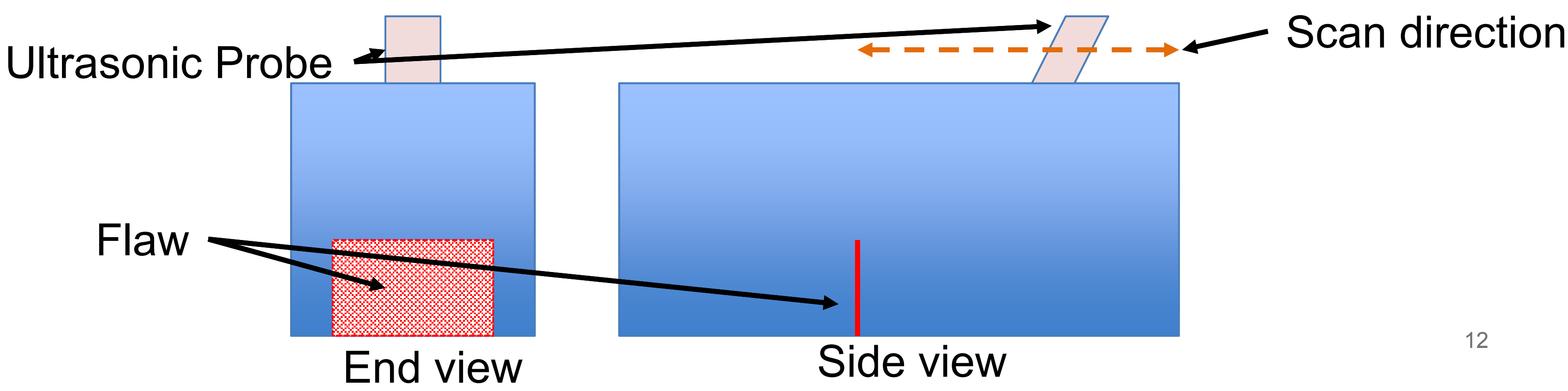
14	Single	Circular	1.50	12.7	60	shear	7.5	20.0	12.5
15	Single	Circular	2.25	12.7	60	shear	14.1	28.6	14.5
16	Single	Circular	5.00	12.7	60	shear	52.9	60.0	7.1
101	Dual	Rectangular	2.00	20x34	45	Long	69.4	79.0	9.6
102	Dual	Rectangular	2.00	20x34	60	Long	82.0	73.6	-8.4
103	Dual	Rectangular	1.00	20x34	45	Long	54.1	57.3	3.2
104	Dual	Rectangular	1.00	20x34	60	Long	51.0	26.4	-24.6
105	Dual	Rectangular	2.00	15x25	45	Long	79.2	74.1	-5.1
106	Dual	Rectangular	2.00	15x25	60	Long	52.5	31.6	-20.9
107	Dual	Rectangular	1.00	15x25	45	Long	44.3	37.8	-6.5
108	Dual	Rectangular	1.00	15x25	60	Long	28.6	9.3	-19.3

Both simulation tools appear to be capable of providing similar ultrasonic beam amplitudes in isotropic materials. Experimental data is needed to confirm observed trends from simulation results.

Note: Beam amplitude computed at 50 mm depth relative to maximum overall beam amplitude.

How Does Beam Coverage Relate to Flaw Detection?

- Software: CIVA
  - Commonly used in nuclear industry for simulating ultrasonic NDE processes
  - Capable of simulating the interaction of ultrasonic energy with a flaw
- Flaws: Reference flaw (10 mm x 20 mm, rectangular flaw) in a 50 mm thick stainless steel specimen
- Metric: Flaw amplitude
  - Generally used for detection
  - Maximum amplitude in B-scan used as metric in this study
  - Complex function of flaw parameters (depth, length, orientation, tilt, morphology) and other parameters that influence incident sound field
- Beam metric: Maximum beam amplitude at the ID of the specimen
  - One of many possible metrics for representing sound fields



Flaw Amplitudes vs. Beam Amplitudes

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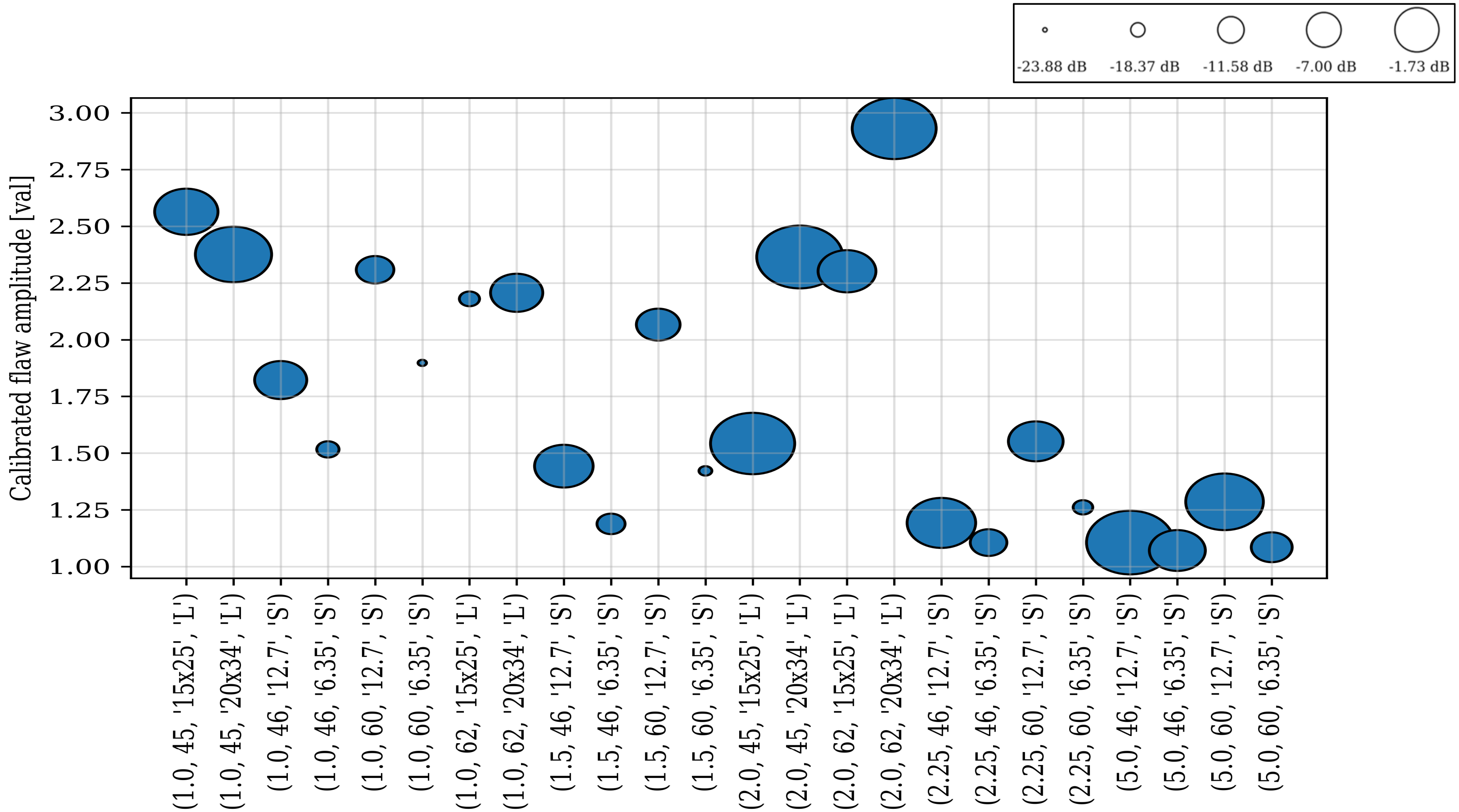

Inferring flaw amplitudes from ultrasonic beam amplitudes alone is challenging. Knowledge of additional parameters and physics of ultrasound is critical.

For a Given Flaw, Flaw Amplitudes Are a Function of Several Parameters

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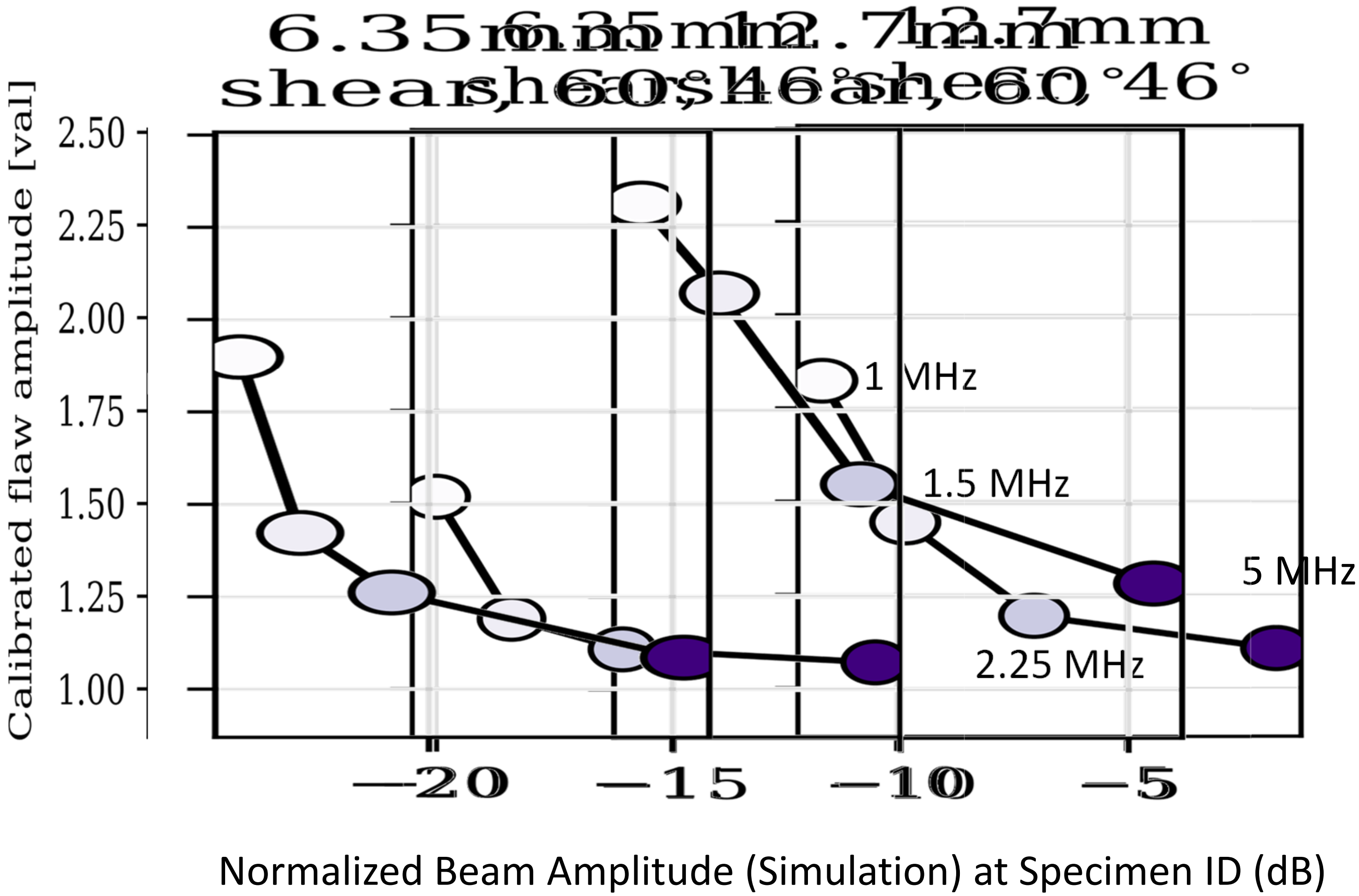
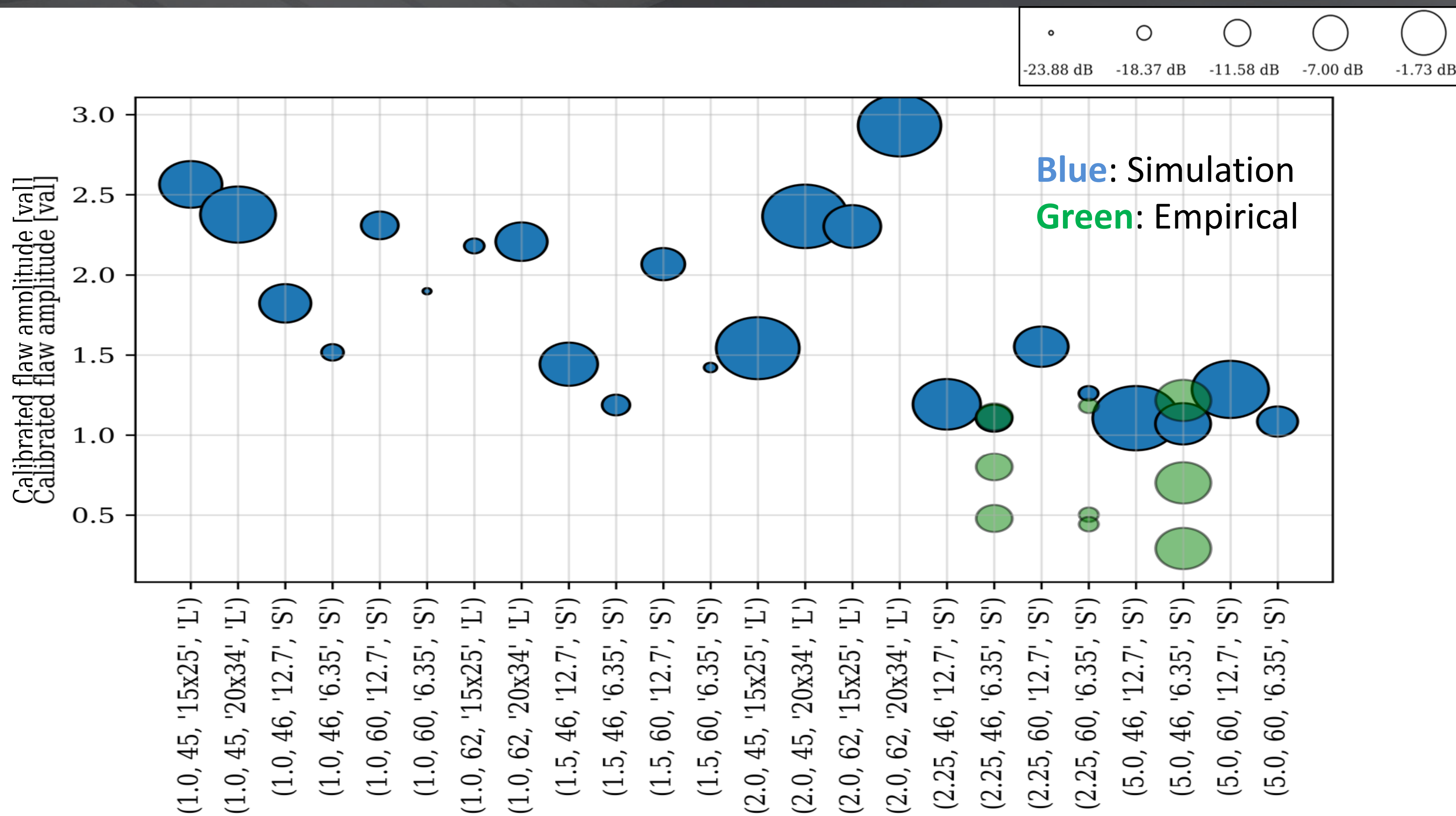


All data in plots are from refracted shear wave inspection simulations, with a 20 mm x 10 mm rectangular flaw.

Flaw Amplitudes vs. Beam Amplitudes



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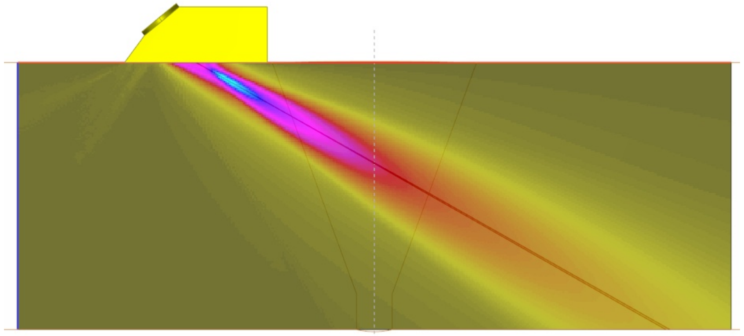

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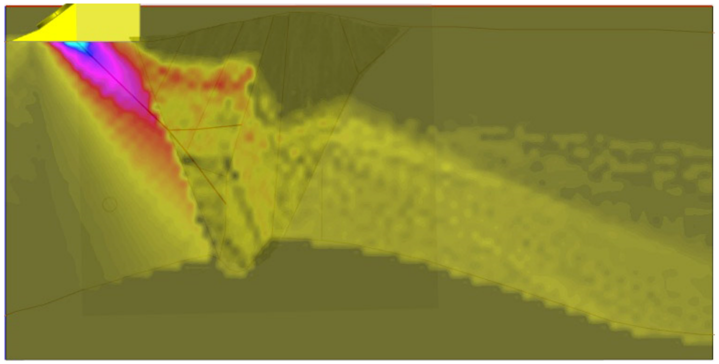
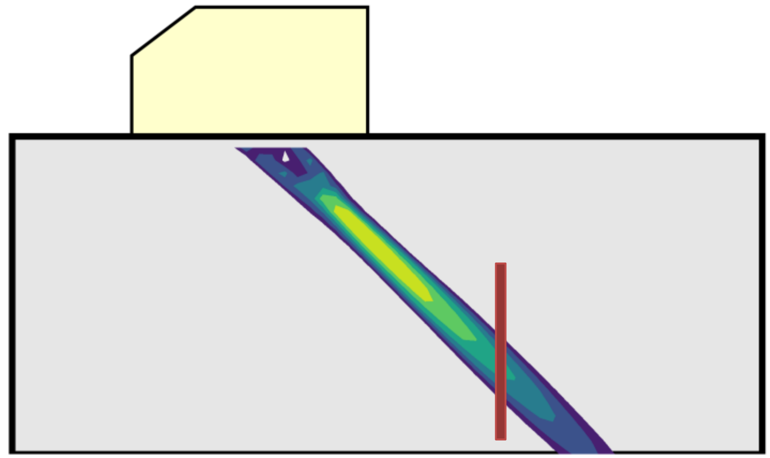
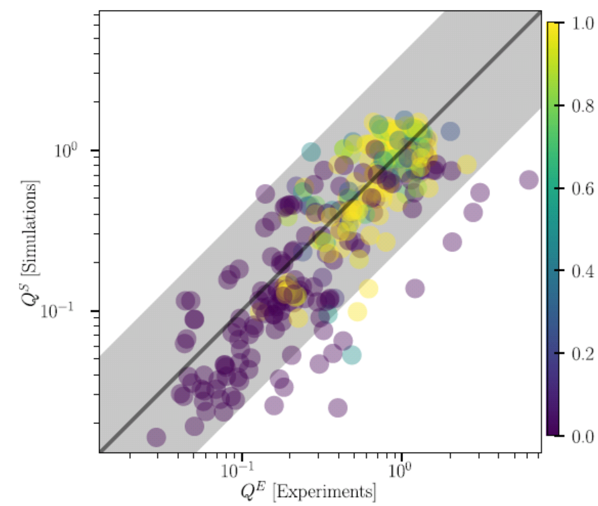


Simulated Ultrasonic Beam Through a Weld

Next Steps: Modeling and Simulation

- Modeling beam propagation through welds
  - Appropriate techniques to model welds due to anisotropy and weld dendrites.
  - Investigate extents of beam redirection/change in expected coverage when compared to homogeneous isotropic assumptions.
- Approaches for incorporating noise (material noise, measurement noise) in simulation results
  - SNR estimates, flaw detection ability
- Quantification of uncertainty in simulation input parameters
  - Uncertainty propagation
  - Empirical measurements
- Evaluate effects of limited insonification of flaw (no corner response, flaw at periphery of beam)
  - Limited coverage





Effects of Noise on Fidelity of Simulation Results

Simulation and Modeling: Activities under NRC RES-EPRI Memorandum of Understanding (MOU)

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- Efforts at PNNL parallel efforts in modeling and simulation at EPRI

- To date, focus under MOU activities have been on
  - Reviewing technical reports
  - Sharing key findings

- Future coordinated research plan under NRC RES-EPRI MOU is currently under development
  - Sharing data (empirical and simulation)
  - Sharing simulation models
  - Identifying and sharing best practices for modeling and simulation
  - Exchanging specimens for independent data acquisition
  - Looking for other ideas, where research activities can be coordinated, data from the activities can be independently assessed, and conclusions can be independently drawn

Outline

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  - Objectives
  - Approach and examples of results to date
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- Limited coverage
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Modeling and Simulation Also Supports Assessment of Limited Coverage

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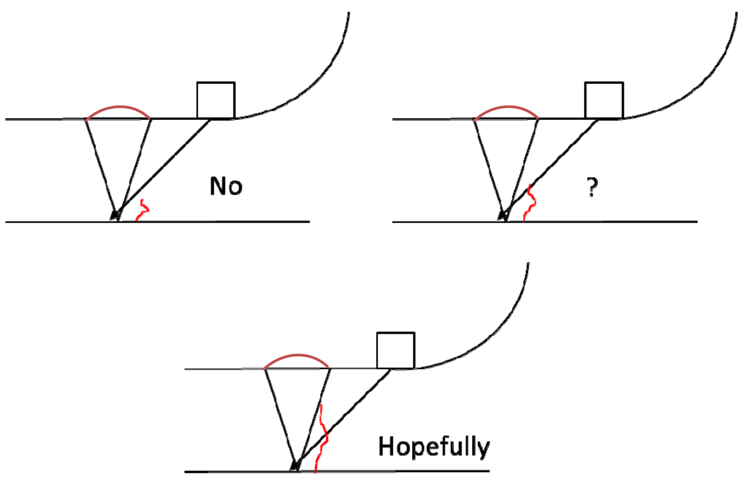
- Establish a basis to determine how far a flaw would have to emanate from an uninspectable region into an inspectable region before it can be reliably detected with UT
  - Austenitic welds
  - Less than 100% coverage due to access limits
    - Weld tapers or transitions
    - Permanent item blocking coverage
    - Material such as CASS with no qualified single-sided procedures



Limited Coverage: Objectives

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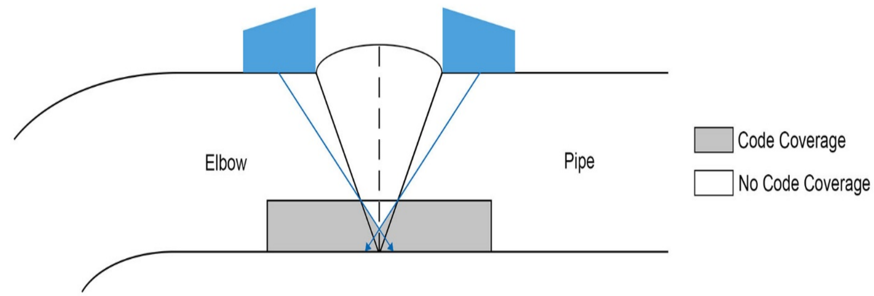
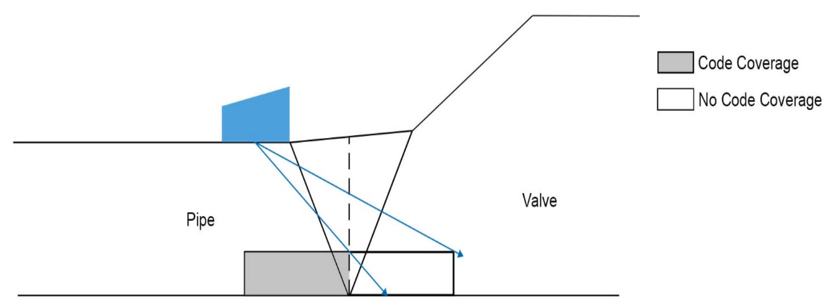
- Develop methods for ascertaining the largest flaw that may be missed given a specified beam coverage (less than 100%) in austenitic welds
- Assess the impact of materials in limited coverage examinations (ferritic steel, stainless steel, cast stainless steel)
- Identify important factors that govern flaw detectability and sizing in limited coverage examinations
- Quantify flaw detection rates in limited coverage examinations as a function of important factors



Example of SS Elbow to SS Pipe where Dual-Sided Access was Obtained and Partially Limited due to Weld Geometry



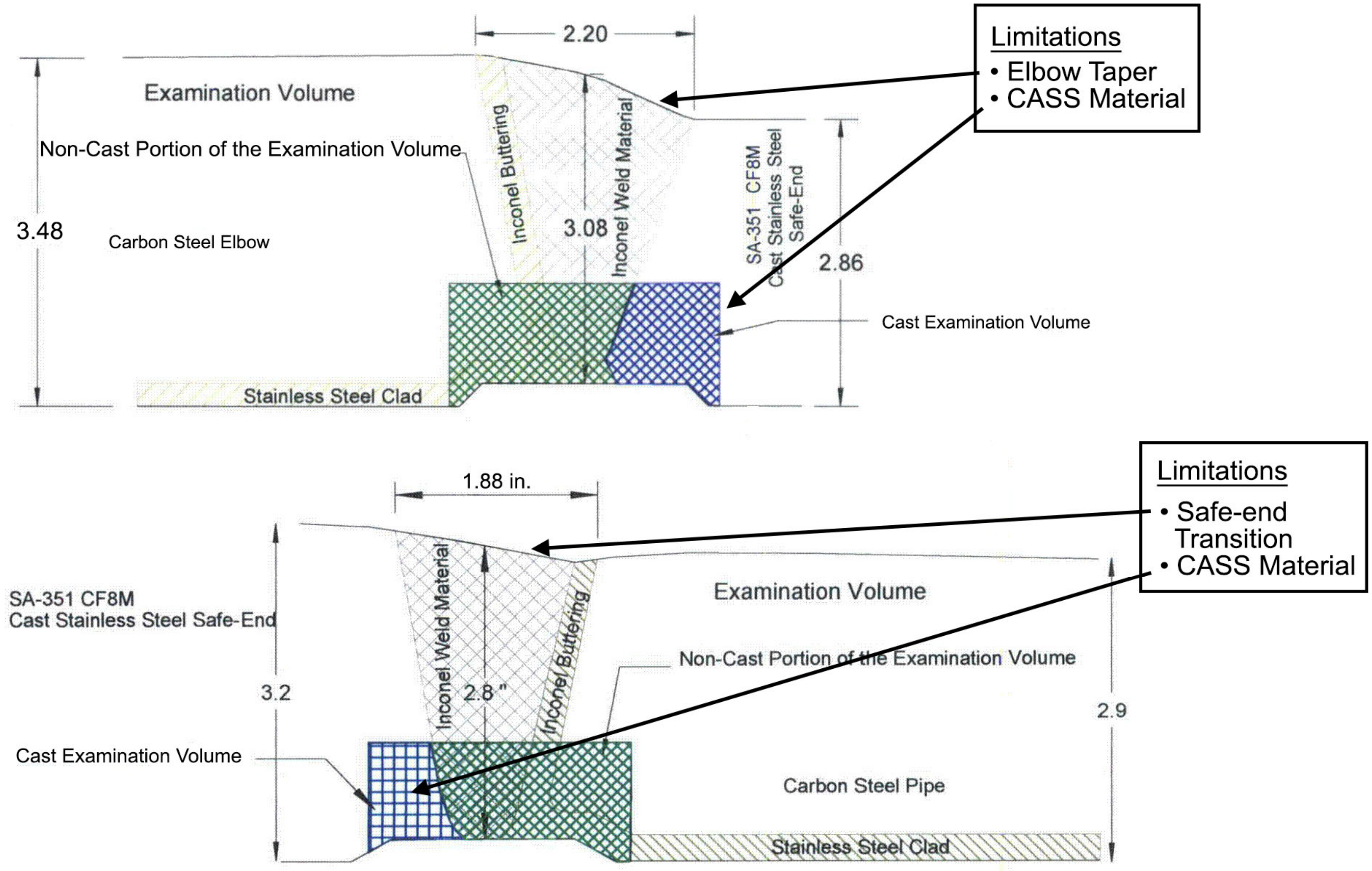
Example of SS Pipe to SS (or CASS) Valve where Only Single-Sided Access was Obtained due to Limitation Caused by Valve Taper and SS/CASS Material

Examples of Limited Coverage Welds (PWRs) Based on Relief Requests

Component Description	Number of Welds	Examination Description	Percent Coverage Claimed	Range of Diameters, inches	CASS Material	No Single Sided Procedure	Weld taper	Nozzle taper	Valve taper	Component taper	Proximity to adjacent component/ structure	Safe-end width	Weld geometry
RCP nozzle CASS safe–end-to-CS elbow[(b)]	16	Single-sided from CS elbow side	(a)	30	16			16					
RCP nozzle CASS safe–end-to-CS elbow[(b)]	8	Single-sided from CS elbow side		36	8			8					
RCP nozzle CASS safe–end-to-CS pipe[(b)]	16	Single-sided from CS pipe side	(a)	30	16			16			6		
RCP nozzle CASS safe–end-to-CS pipe[(b)]	8	Single-sided from CS pipe side		36	8			8					
CASS safe–end-to-CS nozzle[(b)]	18	Single-sided from CS nozzle side	(a)	12	18		17						
CS nozzle-to-SS safe-end with SS weld	1	Single-sided from SS safe-end side	26 to 75	4			1				1		
CS nozzle-to-SS safe-end with SS weld	1	Single-sided from SS safe-end side		14				1					1
CS nozzle-to-SS safe-end with Alloy 52 weld	4	Single-sided from SS safe-end side	24 to 26	(c)				4				4	
CS nozzle-to-SS safe-end with Alloy 52/152	2	Axial scan from nozzle side. Circumferential scan from safe-end side.	40.5 and 42	38			2					2	
CS nozzle-to-CASS elbow with SS weld	3	Single-sided from CASS elbow side	49 to 65	34	3			3		3			
CS nozzle-to-CASS elbow with SS weld	3	Single-sided from CASS elbow side		38	3			3		3			
CS nozzle-to-SS safe-end with Inconel weld	4	Single-sided from SS safe-end side	75	42				4				4	
CASS safe–end-to-CS nozzle[(b)]	4	Two sided	(a)	12	4		4						
CS nozzle to SS safe-end with Alloy 82/182 weld with Alloy 52 inlay[(b)]	1	Two sided	(a)	29				1					
CS nozzle to SS safe-end with Alloy 82/182 weld with Alloy 52 inlay[(b)]	1	Two sided		31				1					
CS nozzle-to-SS safe-end with SS weld	3	Two sided	37 to 86	6				3				1	2
CS nozzle-to-SS safe-end with SS weld	1	Two sided		15				1			1	1	

Limited Coverage Examples in PWRs

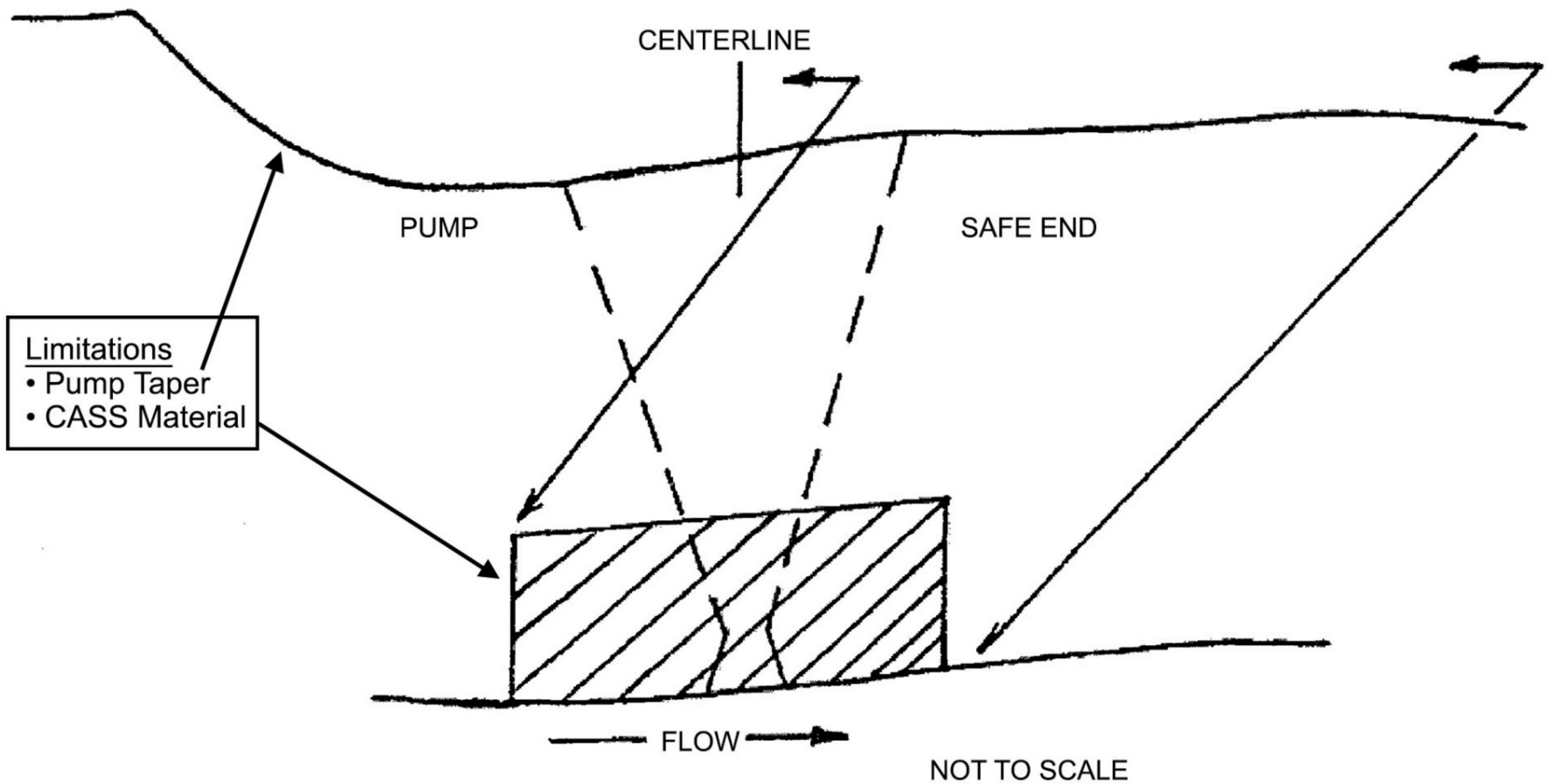
RCP CASS Nozzle-to-CASS Safe-End-to (top) CS Elbow (bottom) CS Pipe



From Sartain 2014, ML14051A109

Limited Coverage Examples in PWRs

RCP CASS Pump-to-CASS Safe-End-to with Single Sided Access Only



From Katzman 2009, ML090430304

Overall Approach to Addressing Limited Coverage

- Identify the most common and problematic weld configurations
- Develop a statistics-based design of experiments (DoE) to inform an optimized test matrix
- Data gaps will be filled in by modeling and simulation activities
- Develop metrics for assessing flaw detection capability under limited coverage conditions
- Assess detection capability for flaws in limited coverage situations.

Limited Coverage Assessments are Using Design of Experiments Approach

- Construct Design of Experiments (DoE) to identify the set of experiments (empirical and simulation) necessary to quantify the effectiveness of UT under limited coverage conditions
  - Define the parameters likely to affect flaw detection
  - Design specimens that can provide the necessary data for the evaluation
  - Develop the test matrix (parameter combinations) for the experiments

- Inputs to DoE
  - Insights from physics of ultrasonic testing and modeling results to date
  - ML17318A118: Summary of Literature Search of Relief Requests on ASME Code, Section XI, Volumetric Examination Coverage Requirements for Piping Butt Welds, PNNL-26157, Rev. 1 (2017)
  - ML12011A130: An Assessment of Ultrasonic Techniques for Far-Side Examinations of Austenitic Stainless Steel Piping Welds, NUREG/CR-7113, PNNL-19353 (2011)
  - Generic inspection procedures
  - ASME Boiler and Pressure Vessel Section XI and Code Case N770-1

Design of Experiments: Factors and Levels

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- Factor levels based on typical conditions in the field
- Conditions limiting coverage include taper (weld and/or component), physical access restrictions, weld geometry, and material microstructure (CASS)
- Metrics for quantifying coverage along with uncertainty bounds are being developed

Factors	Number of levels	List of levels	Notes
Materials	3	CASS–CS CASS –SS SS – SS	
Wall Thickness	3	Thin, Medium, Thick	Assumed correlation between wall thickness and pipe diameter
Weld Root Condition	1	None	Using best case scenario of no weld root.
Probe Aperture	2	Small, Large	
Probe Type	3	Single Element, Phased Array, TRL	
Refracted Angle	4	30^o ,45^o ,60^o ,70^o	All angles for Phased Array, Conventional -45^o ,60^o ,70^o , TRL – 30^o ,45^o ,60^o ,70^o
Wave Mode	2	Shear, Longitudinal	Shear is only applicable for conventional probe
Probe Frequency	4	1 MHz, 2 MHz, 2.25 MHz, 5 MHz	Conventional – 1 MHz, 2.25 MHz, 5 MHz Phased Array – 1 MHz, 2 MHz TRL – 1 MHz, 2.25 MHz, 5 MHz
Flaw Parameters	Ongoing assessment with respect to size distributions, aspect ratio, location, orientation, and tilt. Other factors may also be included as assessment progresses.		

Key Takeaways to Date (Limited Coverage Research)

- DoE significantly reduces the number of specimens and experiments needed
  - Recommended number of experiments reduced from 1836 (full factorial design) to 118
  - The actual numbers may change a little based on allowable flaw parameters, and allowable probe-frequency combinations
- Specimens under consideration are welds between
  - CS – CASS
  - SS – CASS
  - SS – SS
- Specimen fabrication needs can be identified from DoE results
  - Fabrication needs based on available specimens and flaw dimensions, and configurations that can be evaluated in simulation
- Number of flaws per specimen expected to range from 6-16 depending on size of the specimen, and length, orientation, and depth of the flaw.

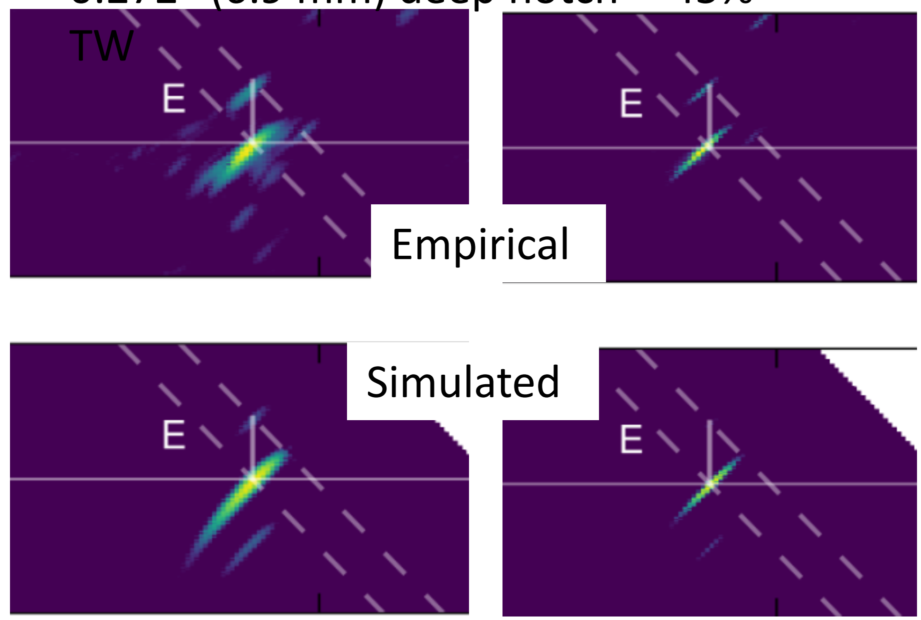
Mockup Designs

- Leverage available specimens
  - Mockups of primary coolant headers in a BWR recirculation system, austenitic stainless steel welds
  - Flaws include implanted thermal fatigue cracks, saw cuts, and notches
  - Flaw depths range from 10% to 64% TW deep
  - Other dissimilar weld mockups available
- Planned 1-2 additional mockups to accommodate combinations of factors and flaws
  - Limited coverage can be real as determined from weld crown or root presence, or simulated by restricting axial scan position
  - Flaw size and location are being finalized

Next Steps

- Complete mockup design and fabrication
- Develop metrics for assessing flaw detection capability under limited coverage conditions
- Complete flaw response measurements and simulations
  - Empirical measurements from mockups
  - Simulations of flaws of interest in test matrix that are not part of mockups
- Assess detection capability for flaws in limited coverage situations.

0.272” (6.9 mm) deep notch -- 45% TW



2.25 MHz, 45° shear 5.0 MHz, 45° shear

Summary

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- Ongoing research on limited coverage examinations will include both simulation and empirical studies
- Design of experiments can assist in targeted evaluation of configurations, significantly reducing the test matrix size

- Specimens that may be applicable to evaluating limited coverage examinations
- Insights into limited coverage constraints in a field setting

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