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PNNL-SA-140480

Status of Ultrasonic Modeling and Simulation at PNNL

RICHARD E. JACOB, GERGES DIB, MICHAEL R. LARCHE, PRADEEP RAMUHALLI, MATTHEW S. PROWANT, AARON A. DIAZ

Pacific Northwest National Laboratory

NRC-Industry NDE Technical Information Exchange Meetings
Rockville, MD
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Purpose

Goal of this Research: Provide a solid technical basis for conducting, interpreting, and applying ultrasonic modeling to assess the effectiveness of inspections of NPP components.

This presentation will focus on PNNL's work to:

- Evaluate the effectiveness of beam models and flaw response models with respect to quantifying volumetric coverage and flaw detection capability.
- Identify key variables in typical simulation models that influence coverage extent and flaw detection capability.

PNNL Reports on Modeling and Simulation

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Validation of Ultrasonic Nondestructive Examination (NDE) Computational Models – Phase 1

March 2017

G Dib
SL Crawford
RE Jacob
MS Prowant
AA Diaz

Prepared for the U.S. Nuclear Regulatory Commission
under a Related Services Agreement with the U.S. Department of Energy
CONTRACT DE-AC05-76RL01830

U.S. DEPARTMENT OF ENERGY

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Ultrasound Modeling and Simulation: Status Update

December 2018

Gerges Dib
Michael R. Larche
Matthew S. Prowant
Richard E. Jacob
Pradeep Ramuhalli
Aaron A. Diaz

Prepared for the U.S. Nuclear Regulatory Commission
under a Related Services Agreement with the U.S. Department of Energy
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U.S. DEPARTMENT OF ENERGY

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Approach

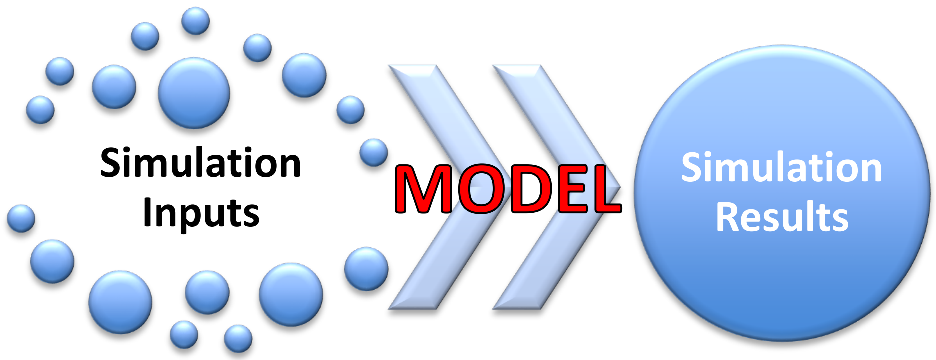
- Leverage prior work at PNNL and elsewhere.
  - Verification and validation of simulation tools
  - Variability of calculated flaw amplitudes; initial methods for noise incorporation
  - Sensitivity of calculated flaw amplitudes to parameter uncertainties
  - Metrics for comparing simulation and experimental results

- During this phase of research:
  - Quantify sound field and flaw amplitudes as a function of parameters that are hypothesized to influence ultrasonic amplitudes
  - Determine the effects of uncertainty in model inputs on simulation results
  - Quantify uncertainty in simulation results and its impact on interpretability
  - Define techniques to include realistic noise in simulation results

- Identify best practices for managing uncertainty and interpreting results.

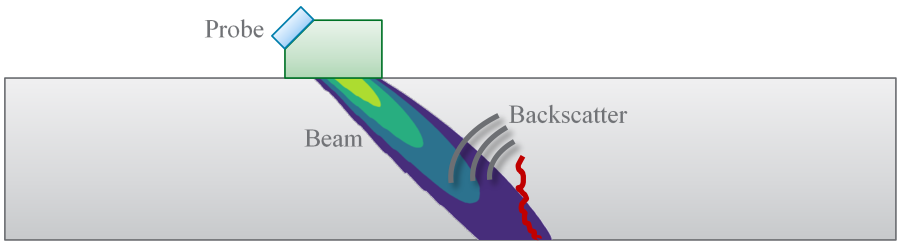
Key Concept Definitions

- Models provide the framework for performing simulations.
- "Beam models" are used to simulate ultrasonic beam characteristics.
- "Flaw response models" are used to simulate the response from an insonified flaw.

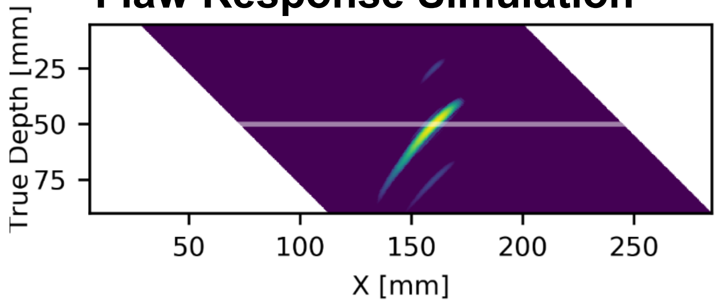


- CIVA is a UT software package with both beam and flaw response models.
- UltraVision is a data acquisition and analysis tool that includes a beam model application.

Beam Simulation



Flaw Response Simulation



Key Takeaways to Date from Modeling Studies

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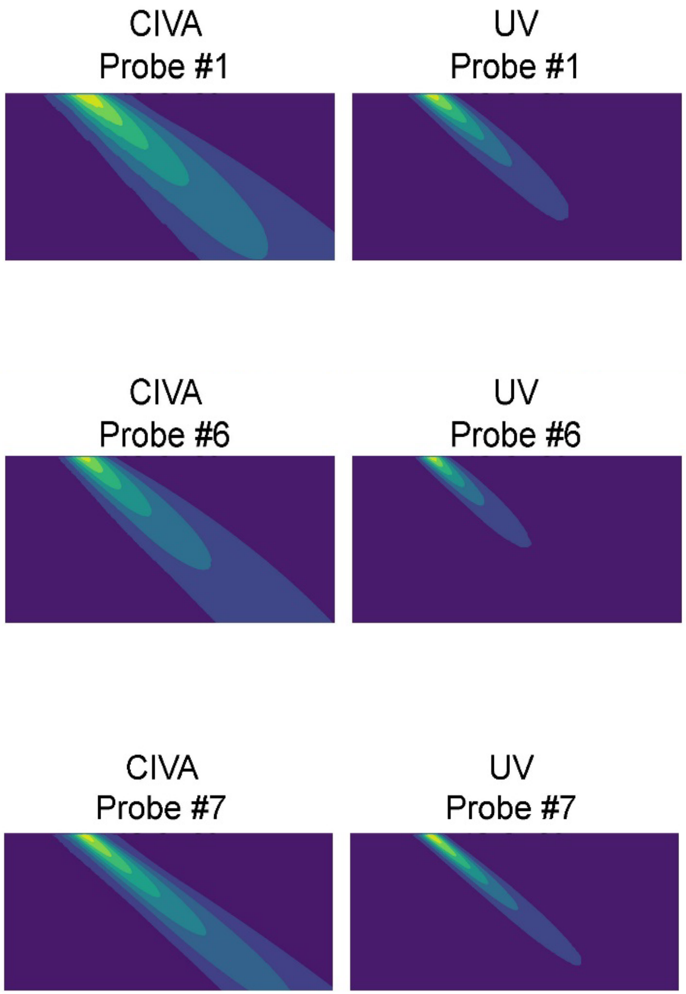
- Variability is expected across different modeling packages.
- Different models show some differences in beam coverage estimates in isotropic materials.
- Model capabilities/limitations should be well understood prior to estimating detection capability.
- Beam simulations have shown limited correlation of incident sound with simulated and measured amplitudes of flaw responses.
- Probe parameters, such as center frequency, bandwidth, and aperture, can vary from manufacturer specifications, and such variations affect model results.



UV = UltraVision

Key Takeaways to Date from Modeling Studies (continued)

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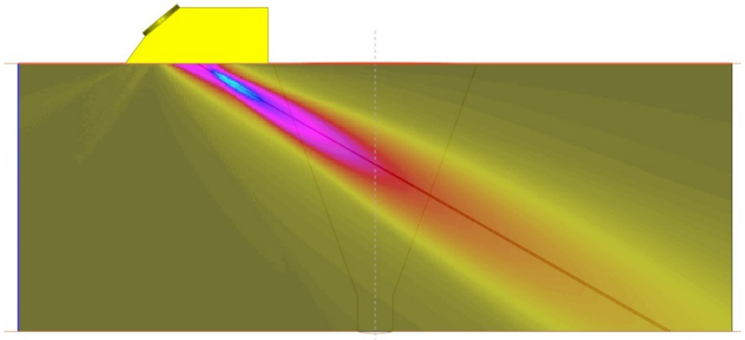
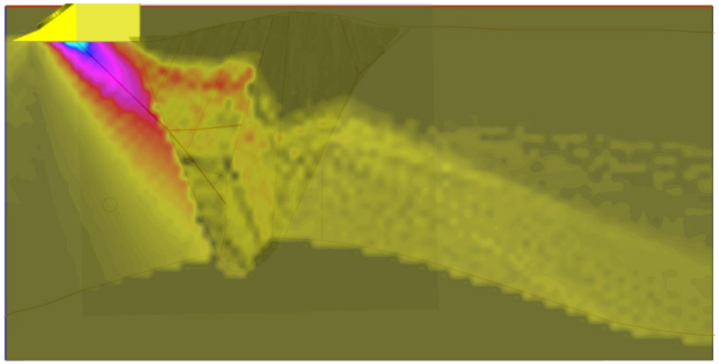
- Some models have limited ability to simulate beam propagation through complex materials (welds, coarse grained, or anisotropic base material).
- Beam and flaw response simulation accuracies are dependent on how accurately weld material properties are defined.
- Metrics to directly compare simulation results with experimental results need to be developed and validated.
- Including specimen geometries, such as weld root and counterbore, and frontwall/backwall bounces is computationally expensive but may be necessary.



Simulated Ultrasonic Beam in Isotropic Material



Simulated Ultrasonic Beam Through a Weld

Key Takeaways to Date from Modeling Studies (continued)

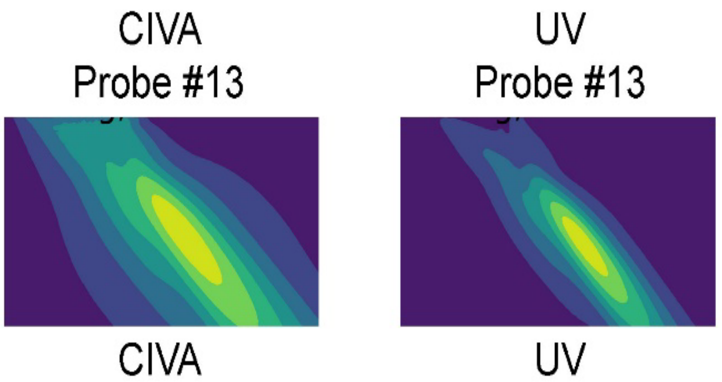
- Flaw response simulations are much more computationally intensive than beam simulations, especially when including specimen geometries and complex materials.

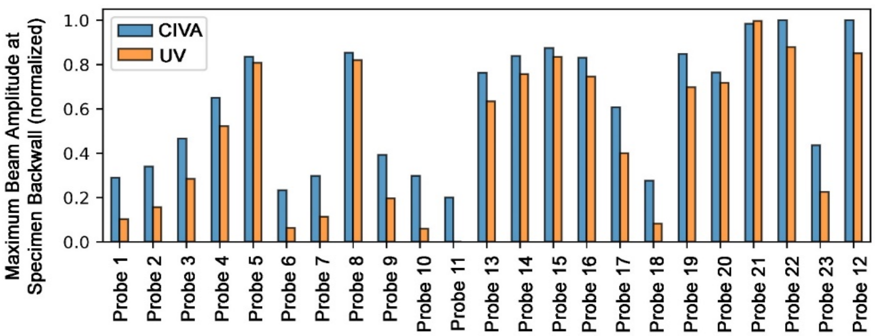
- It will be important to determine if simple beam simulations will suffice for assessing flaw detectability.

- If so, subsequent work can focus on beam simulations and use the correlations to infer insights into flaw detection.

Comparison of Modeling Platforms

- Beam modeling in wrought stainless steel
  - Different platforms use different models for computing beam simulations
  - Focus on qualitative comparison of multiple beam simulation software packages
  - Qualitative similarity in computed beam shapes, though peak amplitudes, beam angle, and spot sizes vary
  - Study did NOT attempt to rank-order tools based on comparison to experimental data





How Model Parameter Uncertainties Affect Simulation Results

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Ideal Scenario: Model results are not very sensitive to uncertainty or variations in input parameters.

Large Input Parameter Uncertainty

Small Simulation Uncertainty

Problematic Scenario: Model results are extremely sensitive to variations in input parameters.

Small Input Parameter Uncertainty

Large Simulation Uncertainty

There are Many Model Parameters

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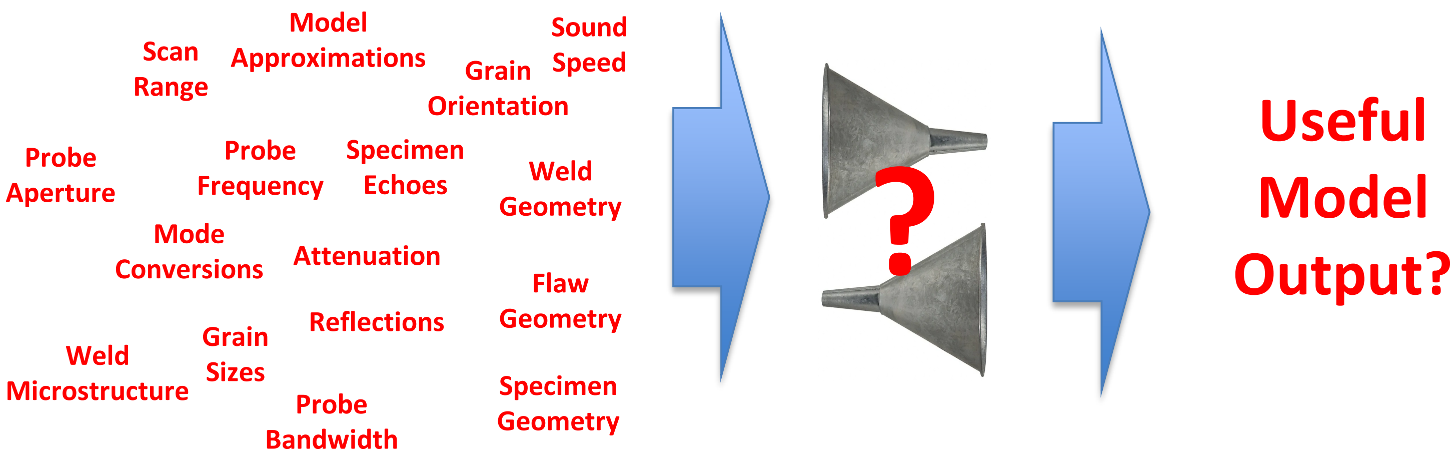
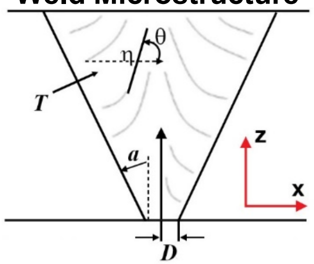
- As the number of free parameters increases, the amount of uncertainty in the models increases and confidence in results decreases.
- Some parameters are impossible to know, such as weld microstructure and specific material properties.
- **Which parameters need to be well understood? Which ones are less critical?**
- **What are the industry priorities for modeling?**

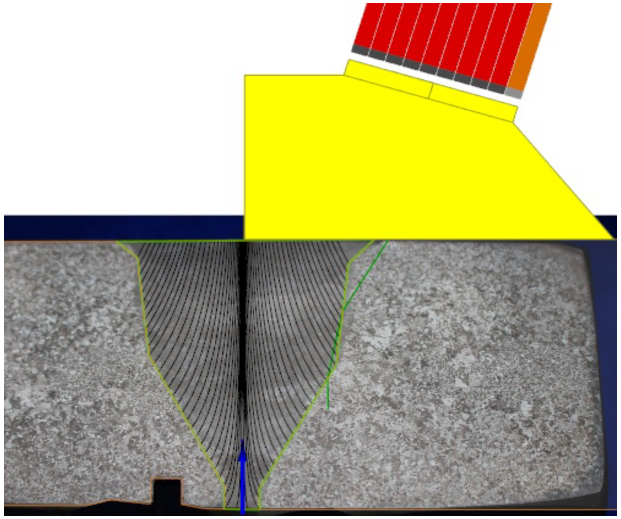


Effects of Weld Microstructure on Beam Simulations

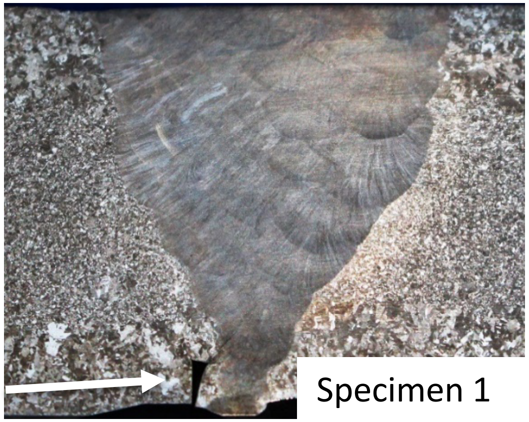
- Weld microstructure is an important parameter for simulations through weld material.
- Current work uses:
  - Weld structure defined by the Ogilvy model
  - Two different weld structures (so far)
  - Ultrasound propagation using dynamic ray tracing
  - Cubic material symmetry

Ogilvy Model of Weld Microstructure

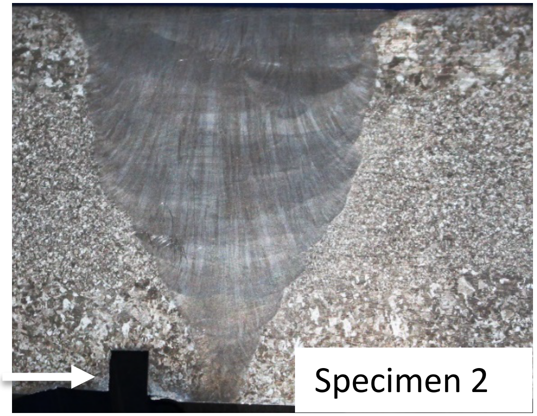




Phased Array Inspection (Flaw on Far Side of Weld)



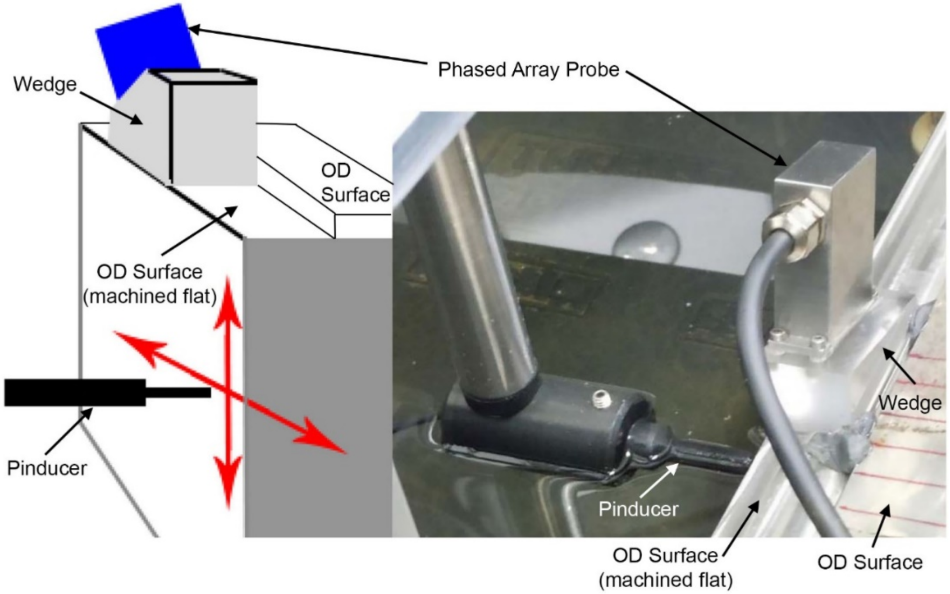
Saw cut

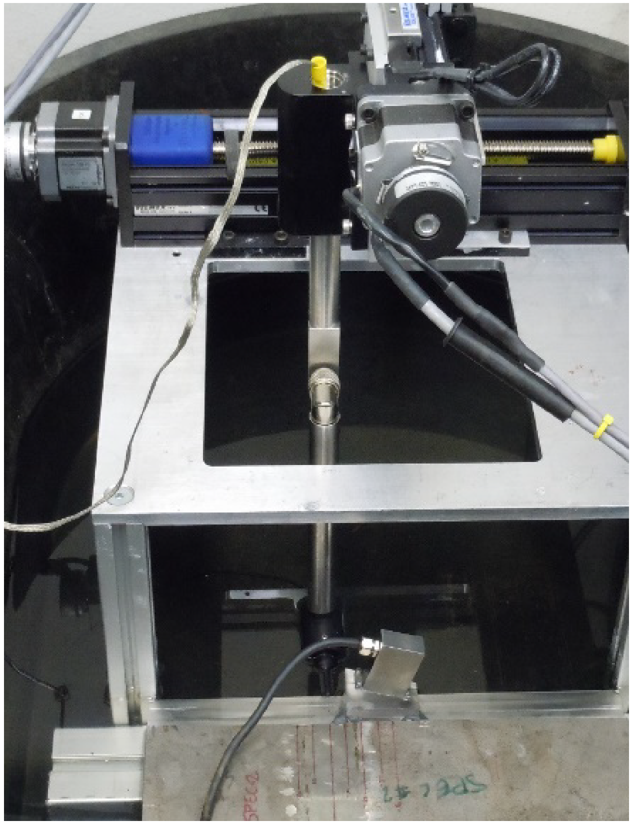


EDM Notch

Effects of Weld Microstructure on Beam Simulations: Experimental Validation

- Measurements on two specimens which were used to set model parameters
- Used a 2 MHz 10x5 matrix TRL phased array probe (transmit only) to measure the B-scan (side profile) sound fields in these specimens





Effects of Weld Microstructure on Beam Simulations: Results

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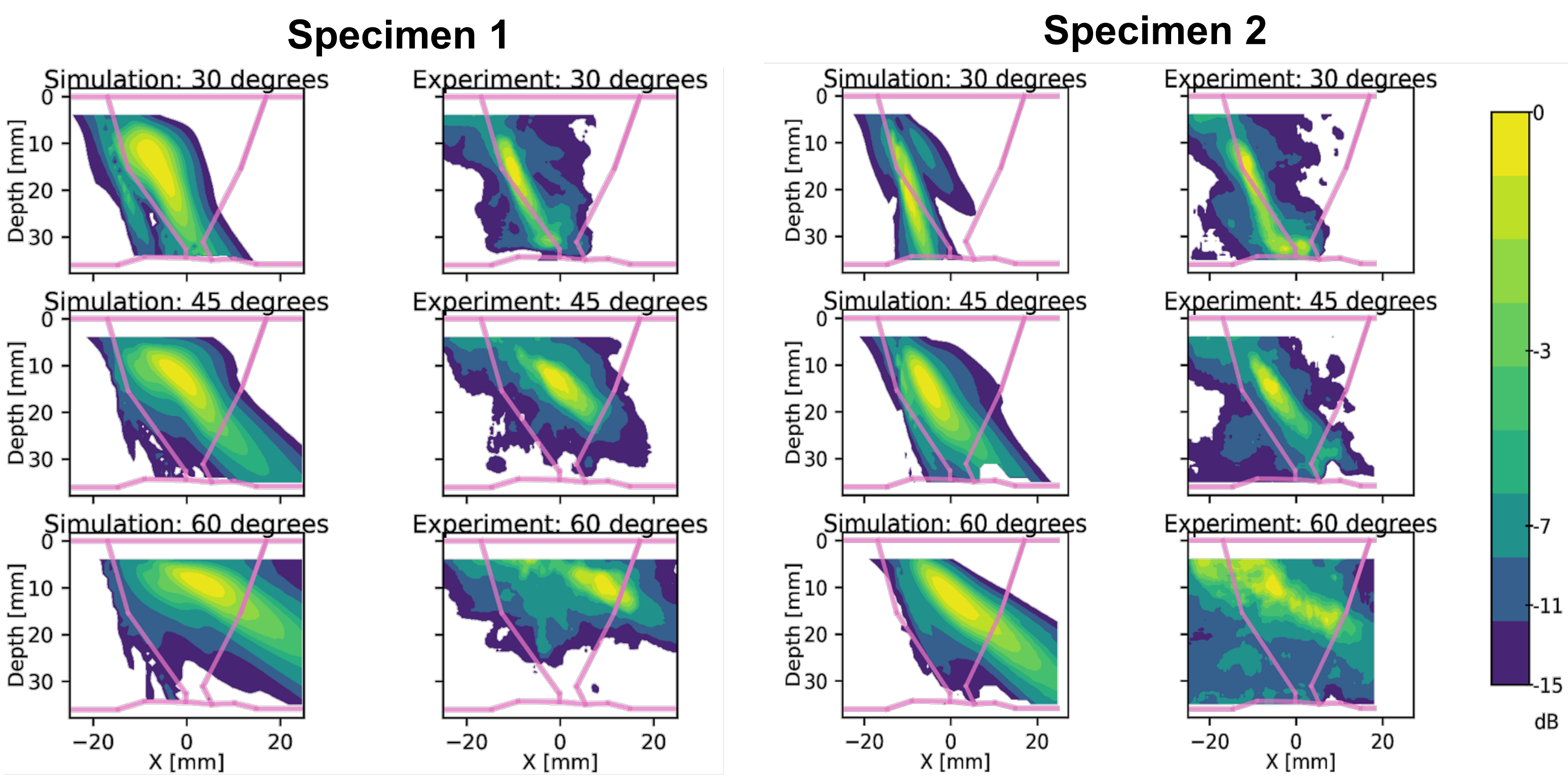
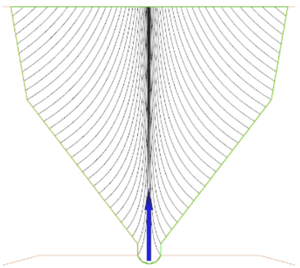
- Results show qualitative agreement between simulation and experiment, but the differences need to be better understood.
- Effects such as mode conversions, scattering, and attenuation are not represented in the simulation results.



Note: Flaws not shown in weld overlays.

Effects of Weld Microstructure on Flaw Response: Simulation Setup

- Initially, reflections from weld interfaces and specimen geometries/surfaces were ignored
- Model complexity and computation time increase rapidly when reflections and mode conversions are added.



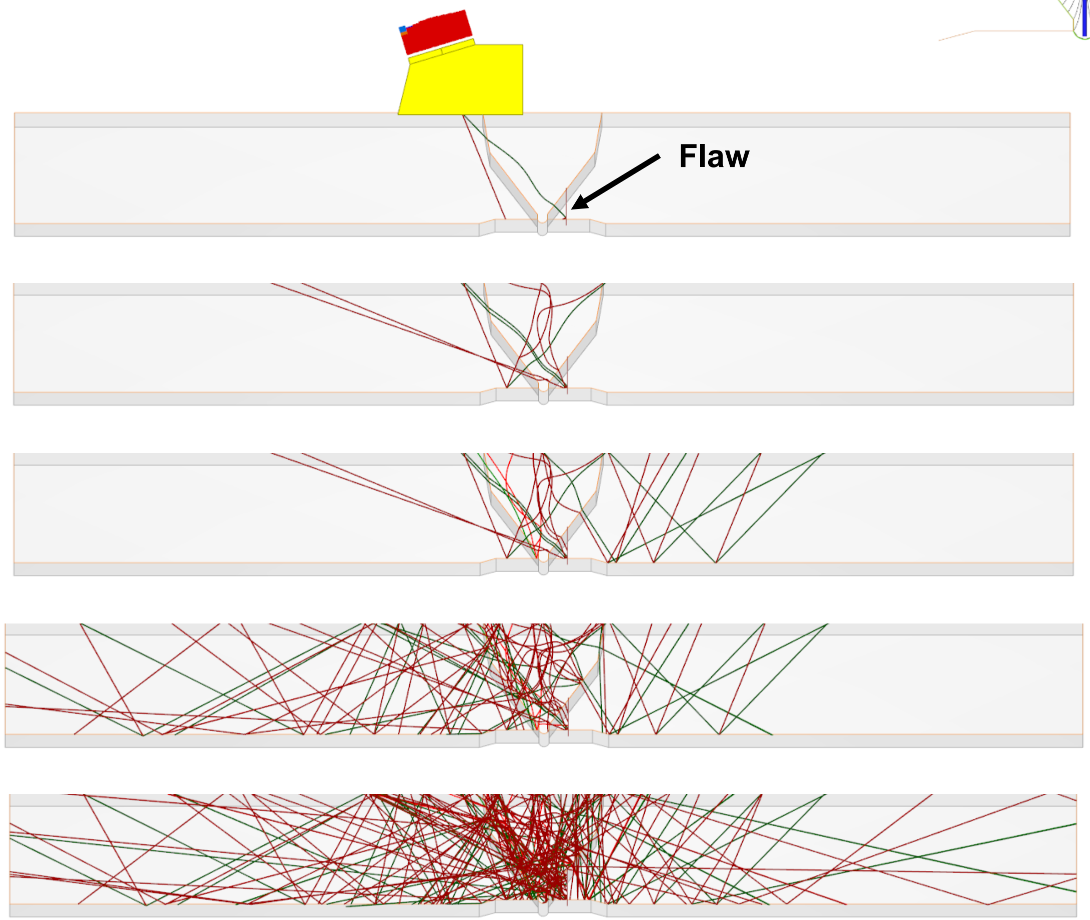
Primary L (green) and T (red) Ray Paths
Initial Setup

With Backwall Reflections

With Frontwall Reflections

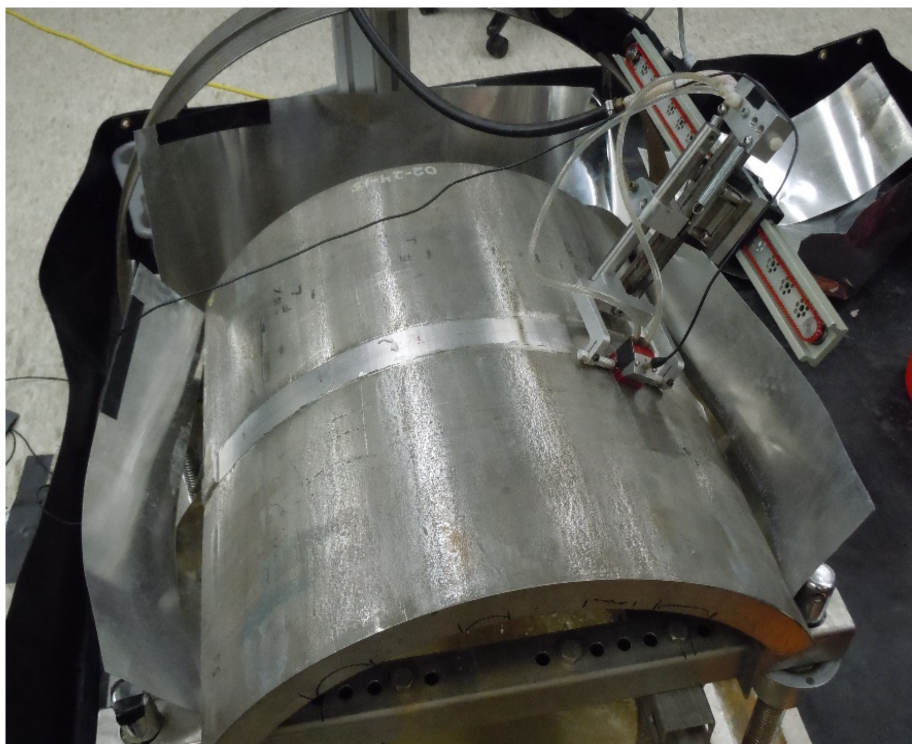
With Interface Reflections

With Internal Mode Conversions



Effects of Weld Microstructure on Flaw Response: Experimental Validation

- Wrought SS to wrought SS specimen with austenitic weld
- Three probes: shear, dual element TRL, and phased array probe (TRL)
- All probes were 2 MHz and 45° refracted angle
- A saw cut flaw with dimension 65 mm x 10 mm was scanned.



Effects of Weld Microstructure on Flaw Response: Results

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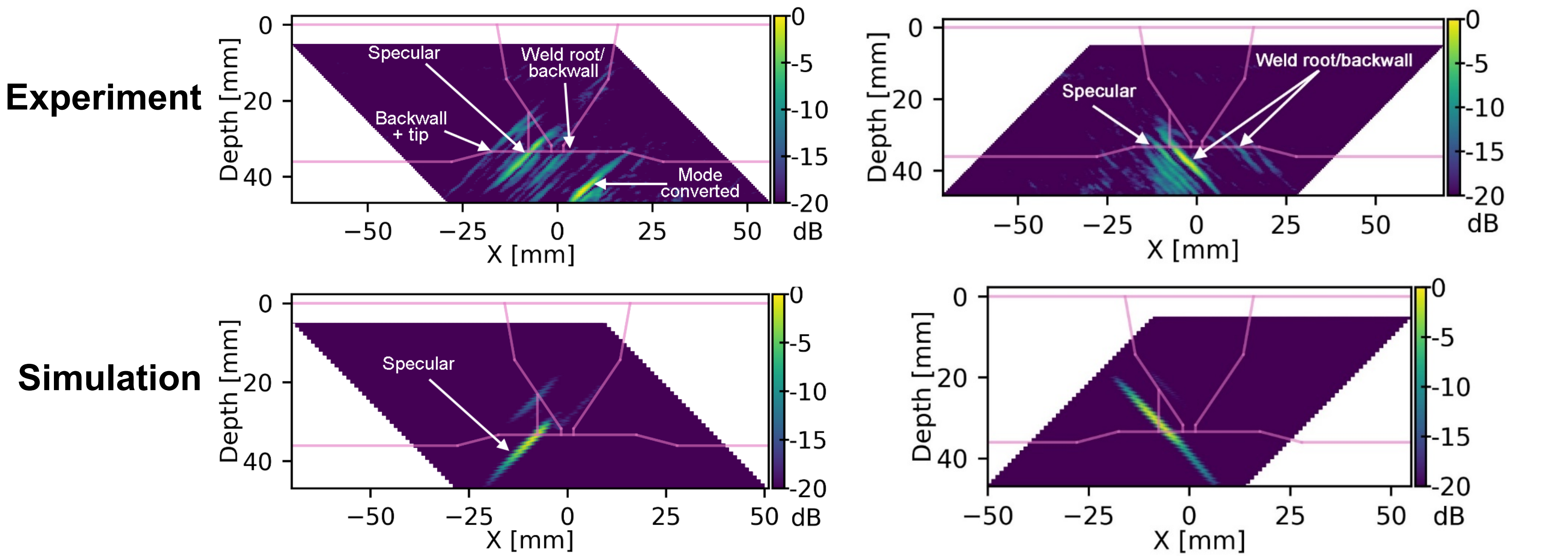
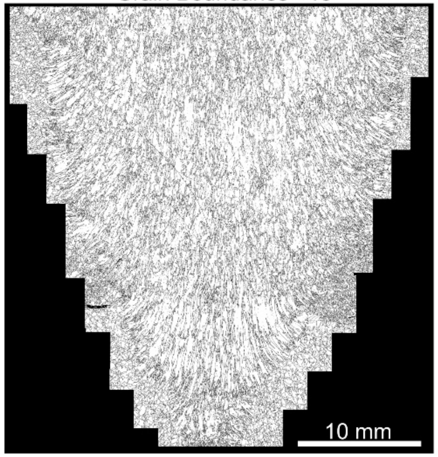
- TRL probe, flaw 10 mm deep in HAZ.
- Simulations show the specular echo from the flaw but not the “clutter”.
- Attenuation, mode conversions, and specimen reflections are needed to improve simulation results.
- What are sources of uncertainty? How much uncertainty is acceptable?



Ongoing Work: Weld Microstructure Characterization

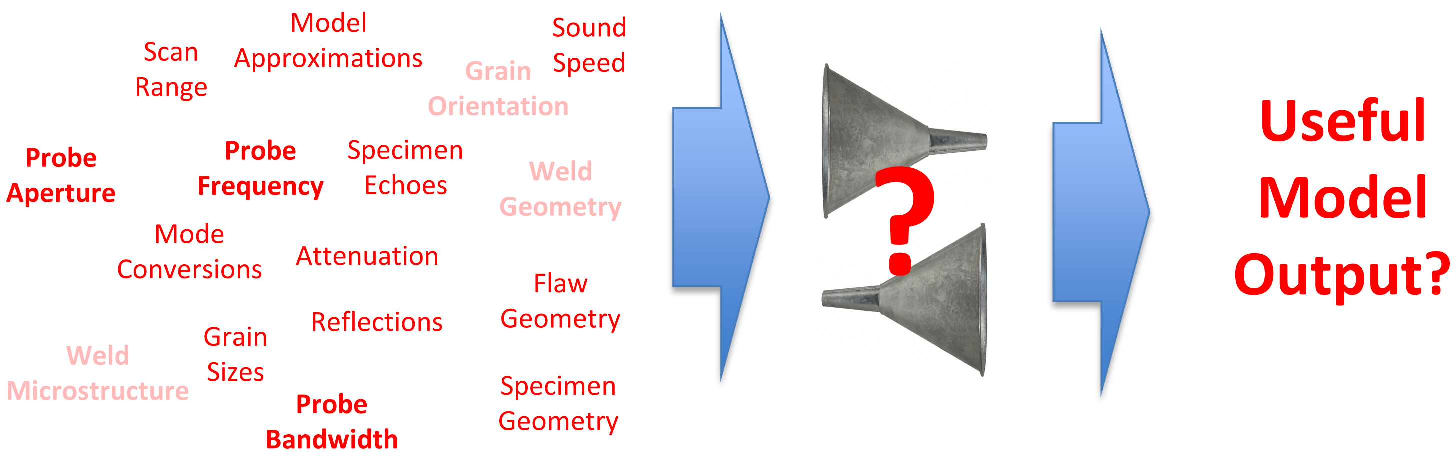
- A weld sample was polished and etched to characterize the microstructure.
- Electron microscopy measured the grain sizes and orientations to 4 µm resolution.
- This provides a basis, or true-state, for simulation input of weld microstructure.
- The true-state will be used to create a range of simulation inputs of varying resolution that can be used to test sensitivity to weld microstructure parameters.
- Direct comparisons to the Ogilvy model and other approximations can then be made.
  - Are weld microstructure approximations a significant source of simulation uncertainty?
  - How can such uncertainty be minimized without invasive or costly weld characterization?

Grain Boundaries >15°



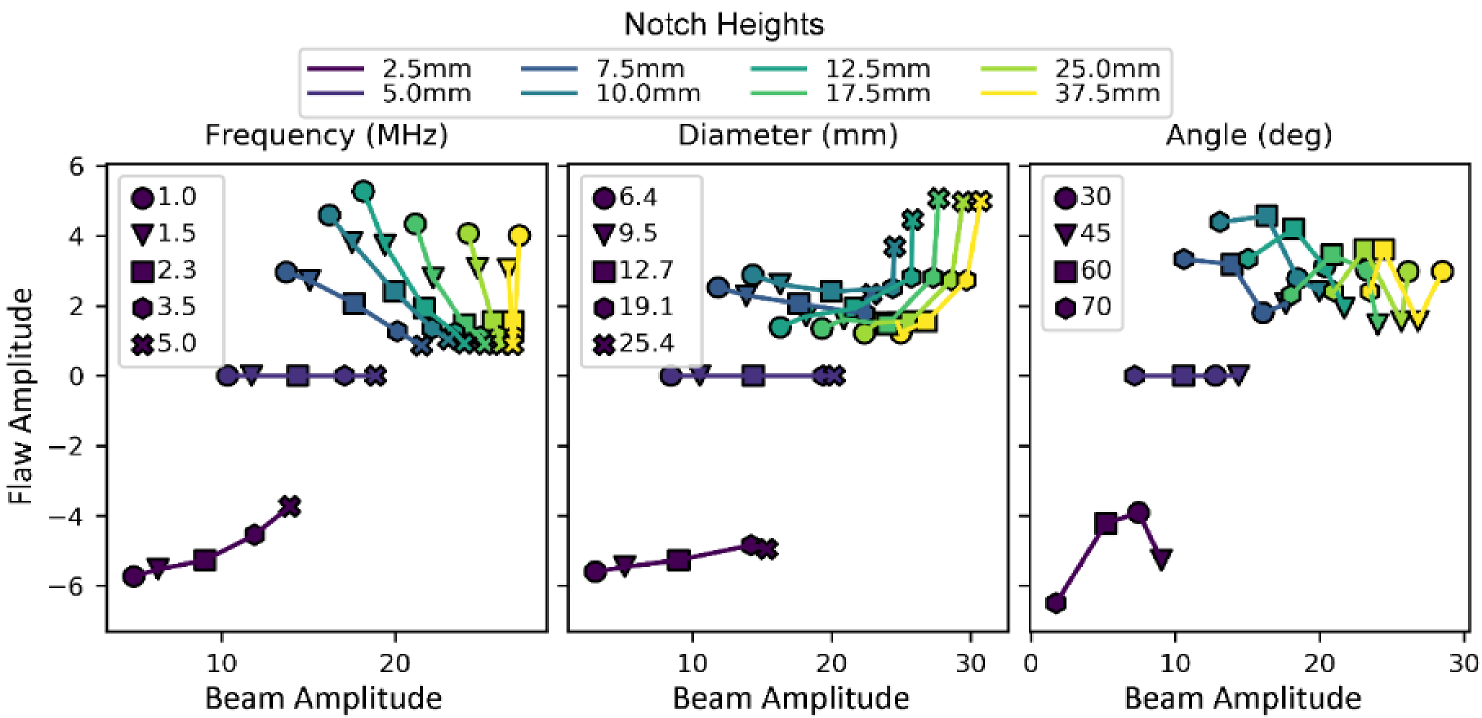
Effect of Probe Parameters on Simulations

- Models depend on many probe parameters as inputs.
  - Center frequency, bandwidth, aperture, angle, excitation pulse, etc.
- Probe parameters are relatively easy to measure.
- How much variation exists between probes of the same nominal specifications?
- Are such variations significant to simulation accuracy?



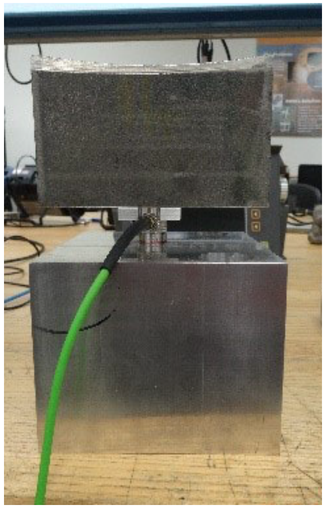
Flaw Response Modeling: Effect of Probe Parameters

- Vary probe frequency, diameter, and angle for different flaw heights.
  - No simple correlations found between beam amplitude and flaw response amplitude.
  - Flaw response is a complex function of several variables.

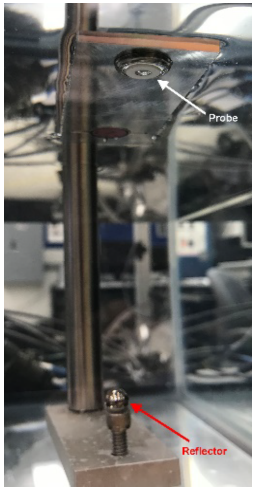


Transducer Characterization

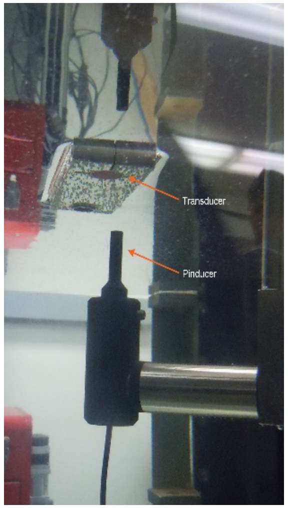
- Characterization of 10 *nominally identical* transducers using ASTM E-1065 procedures
  - 5 MHz, 0.5” (12.7 mm) diameter, single element
- Measure key transducer parameters
  - Center frequency, bandwidth, near-field distance, aperture, and beam divergence in the far-field
- Immersion and contact measurements



Contact Measurement (Probe frequency/bandwidth)



Immersion Measurement (Ball Target)



Immersion Measurement (Pencil Probe)

Transducer Characterization: Experimental Results

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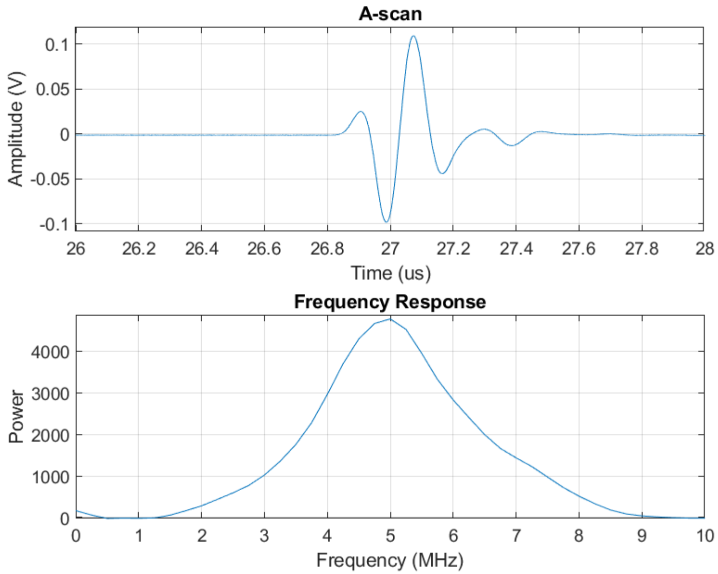
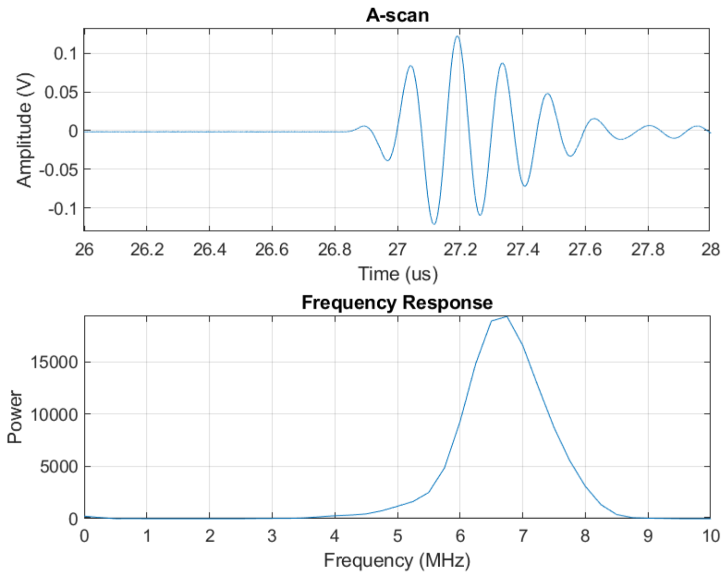
- Frequency and bandwidth varied somewhat from specified values.
- Average frequency = 4.9 ± 0.8 MHz
- Average bandwidth = 54 ± 11 %



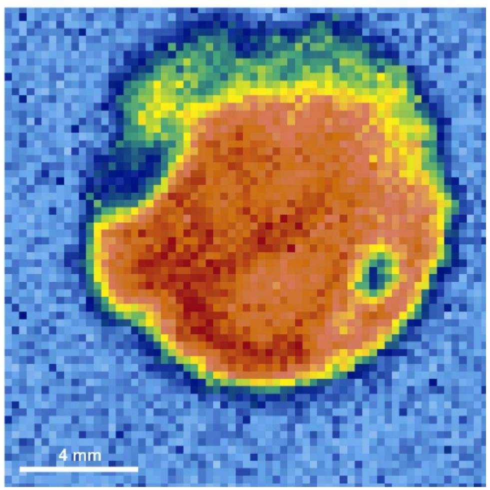


Time (top) and frequency (bottom) response for two different transducers with the same nominal specifications.

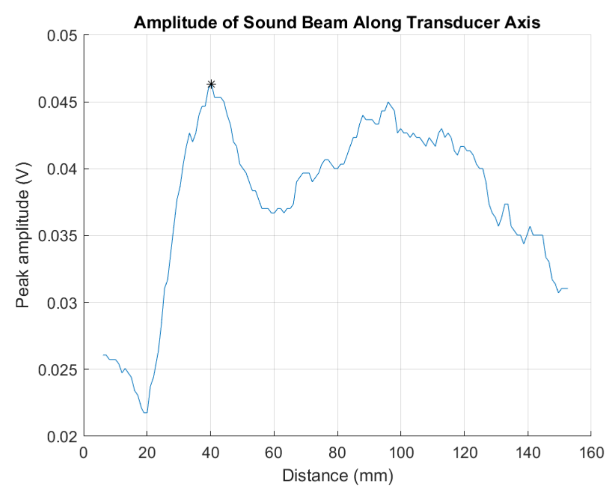
Transducer Characterization: Experimental Results

- Examples of results from one transducer from different experimental measurements to evaluate aperture and near-field/far-field transition.

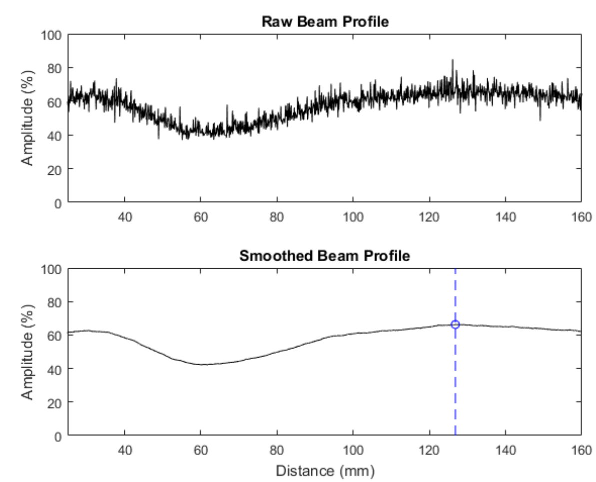
Beam Map (Pencil Probe)



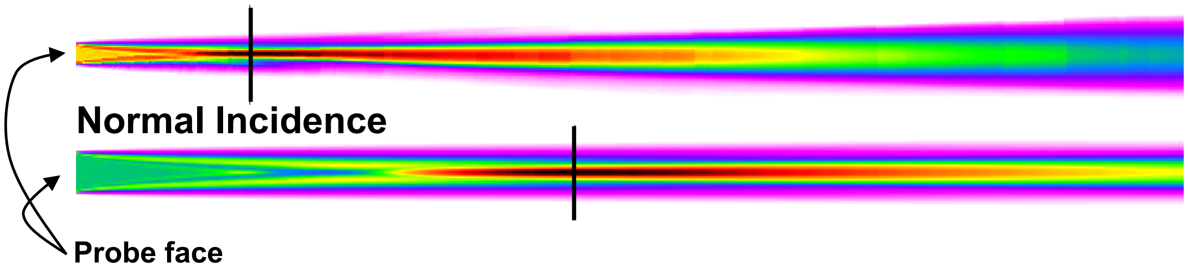
Ball Target



Pencil Probe

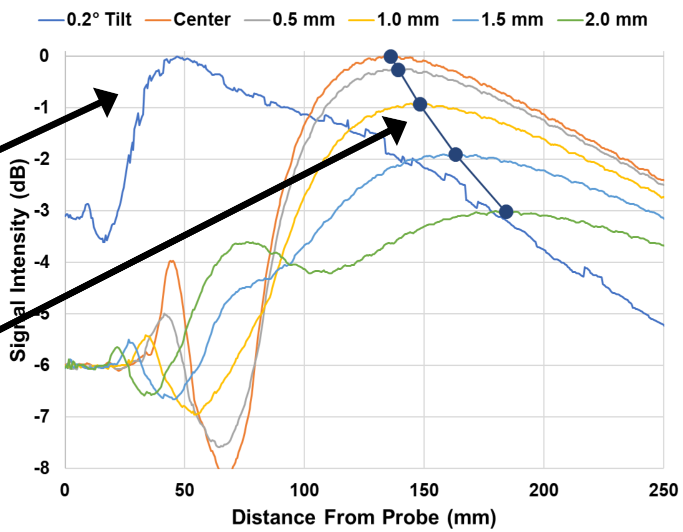


Transducer Characterization: Simulation Results



Simulated Ultrasound Beam

- Simulations indicate that probe alignment is critical
  - Angular misalignment moves the apparent near-field transition closer to the probe
  - Lateral misalignment moves the apparent near-field transition farther from the probe



Impact of Misalignment on Signal Intensity (Simulated)

Transducer Characterization Summary

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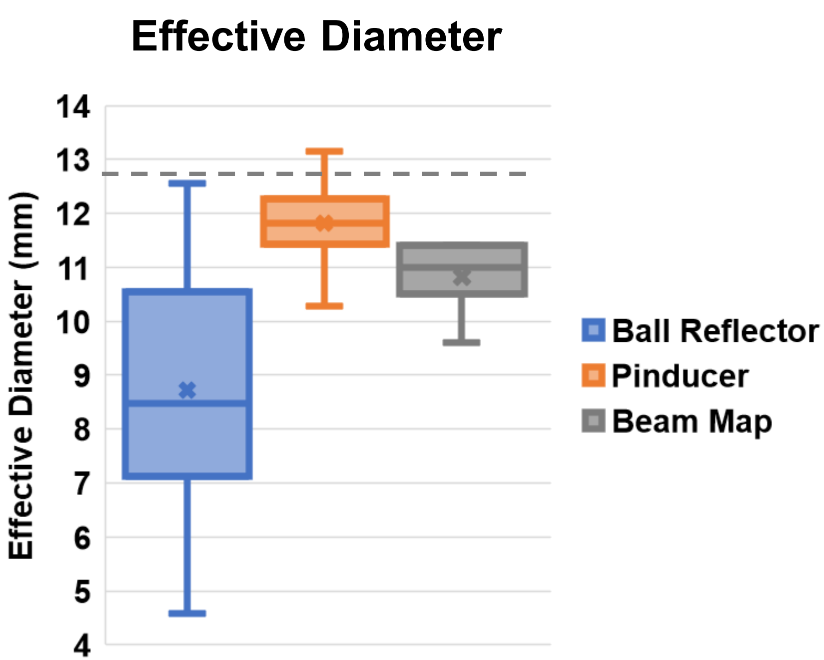
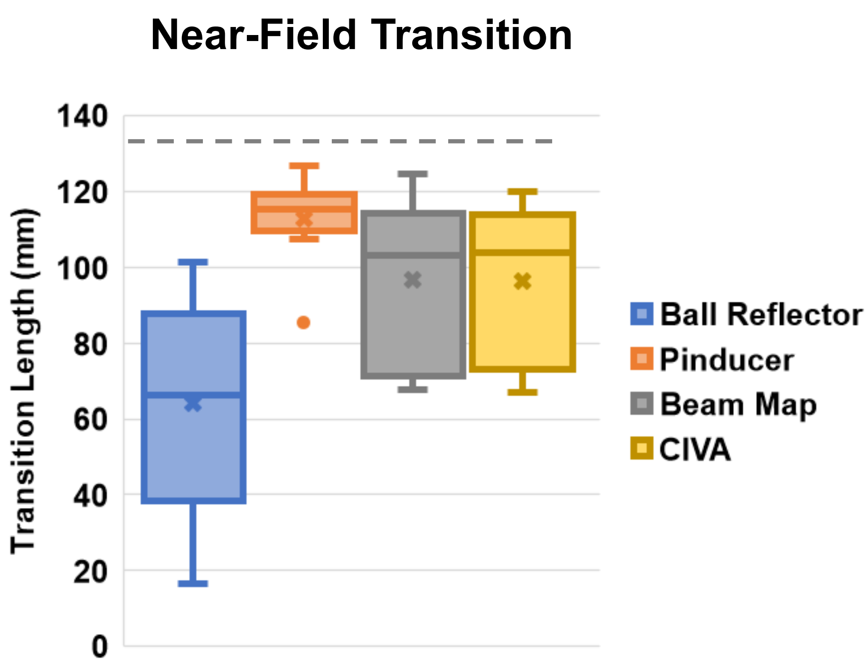
- Different measurement techniques resulted in different probe characterizations
- Precise probe alignment is critical for accurate results
- This exercise was an example of ideal synergy between modeling and experiment: test results informed the modeling approach and modeling informed the experimental approach



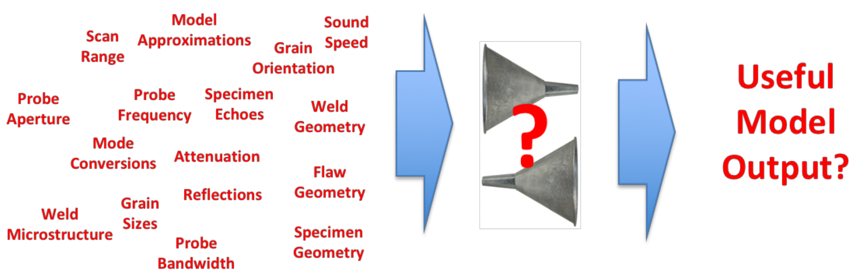


Transducer Characterization Summary

- Actual probe performance can vary significantly from expected performance.
  - Frequency, bandwidth, aperture size, near-field transition distance.
- Probe input parameters play a significant role in simulation output accuracy.
- Probe parameters should be carefully characterized prior to use in simulation studies.

Summary

- Model input parameters can have a profound impact on beam and flaw response simulation results
  - Probe parameters of center frequency, aperture, and bandwidth
  - Weld microstructure – but to what level of detail?
- Models should include as many attributes as possible to improve agreement with experiment
  - Attenuation, mode conversions, and specimen reflections
  - Is this worth the significant increases in computation time? How to find a balance?
- Beam simulations can be used to characterize probe performance, but it is important to have correct probe parameters as inputs
  - This may require measurement of center frequency, bandwidth, and aperture

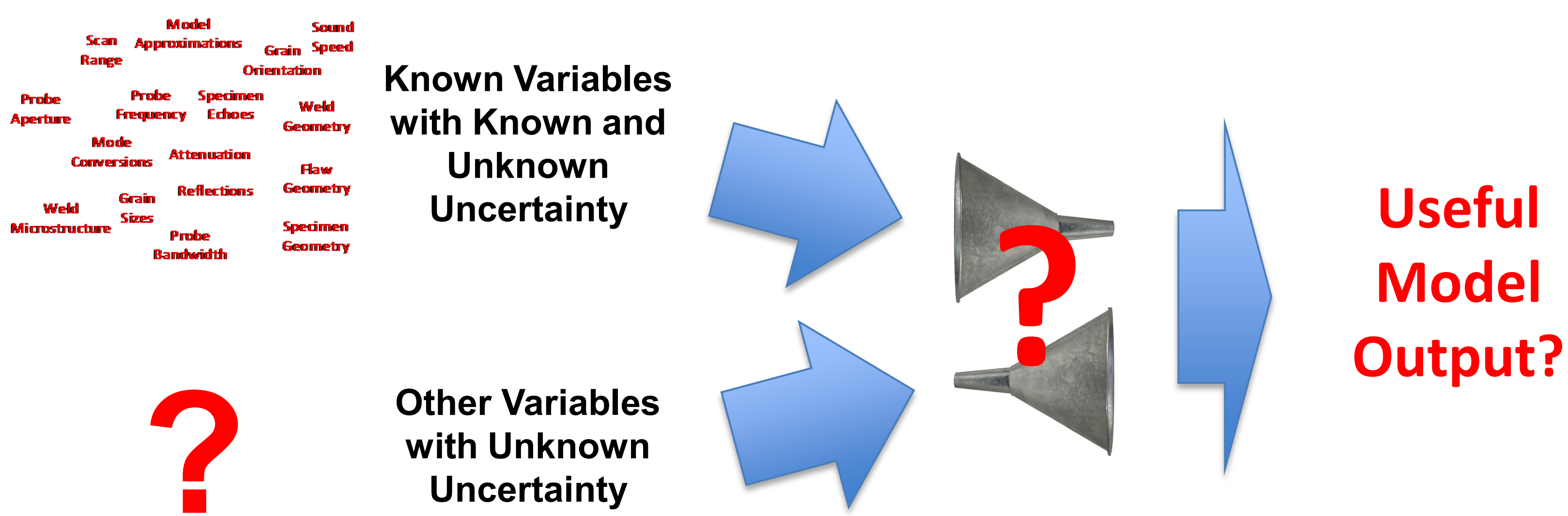


Conclusions

- While beam models in isotropic materials are reasonably accurate (regardless of the software tool used), their use in anisotropic or complex microstructures is more challenging.
- Simulated beam profiles through welds are qualitatively in agreement with experiments.
- Simulated flaw responses through welds are challenged by long computation times and uncertainties in weld properties.
- Simulations may be limited in their ability to estimate flaw detection capability in the vicinity of welds/geometry with low computational effort.
- It is unclear how accurately the weld properties need to be defined to minimize simulation uncertainty.

Conclusions (continued)

- To improve simulation accuracy, adequate care must be taken to address:
  - Unknowns in model implementation and normalization procedures
  - Uncertainties in material property specifications
  - Uncertainties in transducer parameters
- **Not all variabilities of interest are accounted for by models.** Hardware and human factors play an important role in inspections (e.g. instruments, inspection conditions, examiner skill levels, etc.).



Ongoing Research: Modeling & Simulation

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- Integrate weld microstructure information (grain size, orientation, elastic properties) into simulations at different levels of detail – where do results converge?
- Identify important input parameters that contribute to simulation uncertainty, determine what level of "ground truth" precision is needed.
- Increase simulation realism:
  - Include specimen frontwall, backwall, and interface reflections.
  - Add weld root and counterbore geometries.
  - Add mode conversions and attenuation.
  - Mimic realistic cracks by adding flaw morphology.
- Coordinated work with EPRI through MOU
  - OptiSon beam maps of the same probes characterized at PNNL.
  - Impact of noise in simulations, especially of large-grained materials.
    - What is the best way to model noise or incorporate empirical noise?
    - Is simulating noise worth the significant increase in computation time?
    - Alternative to simulating noise, can empirical noise be added to simulation results?

Ongoing Research: Empirical Measurements

- It is important to understand uncertainty in simulation results, but it is equally important to understand uncertainty in empirical results being used to compare with simulations.
- Perform a design of experiments (DoE) over the variables of interest to focus the empirical studies on key aspects of:
  - **Transducers:** Multiple transducers of the same specifications, characterization of sensitivity and other transducer parameters
  - **Specimens:** Different weld morphologies and coarse grained materials; characterization of elastic properties/velocity variation, crystal orientation
  - **Flaws:** Notches/saw cuts, thermal fatigue, and SCC. Characterization nondestructively if possible; if not, destructively characterize a subset
  - **Equipment:** Characterize equipment/cables used for data collection.
  - **Location:** Acquire data at various locations within the specimen, to understand the effects of spatial material variations on ultrasound propagation.
- Correlate empirical and modeling results and integrate into guidance document.

How You Can Help

- We need information on industry planned use cases for modeling and simulation.
  - Helps focus efforts, should result in better targeted guidance documents based on NRC and industry research in this area
- What are the relevant inspection geometries and materials?
- Provide feedback with your experiences with model development and running simulations.
  - Success stories
  - Frustrations or concerns

Contact:
Carol Nove - NRC COR
Sr. Materials Eng. RES/DE/CIB
Email: Carol.Nove@nrc.gov

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Status of Limited Coverage Assessments

RICHARD E. JACOB, MATTHEW S. PROWANT, PRADEEP RAMUHALLI, AARON A. DIAZ

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NRC-Industry NDE Technical Information Exchange Meetings
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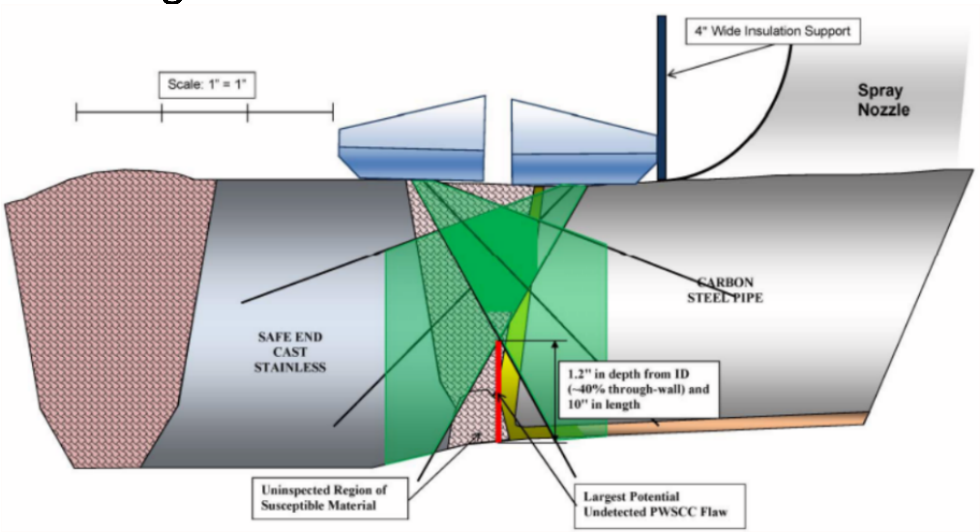
Limited Inspection Coverage

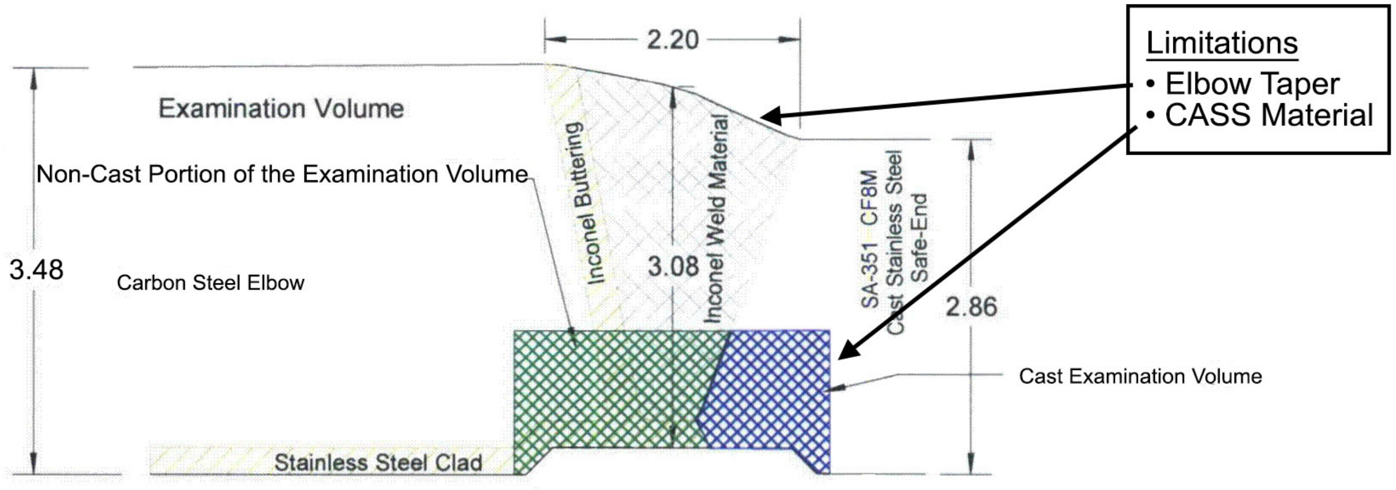
- Goal: Identify important factors that govern flaw detectability and sizing in limited coverage examinations, and quantify flaw detection rates as a function of these factors
- Approach
  - Develop a statistics-based design of experiments (DoE) to inform an optimized test matrix
  - Develop metrics for assessing flaw detection capability under limited coverage conditions
  - Use a combination of measurements and simulations to assess flaw detectability and factors influencing detection

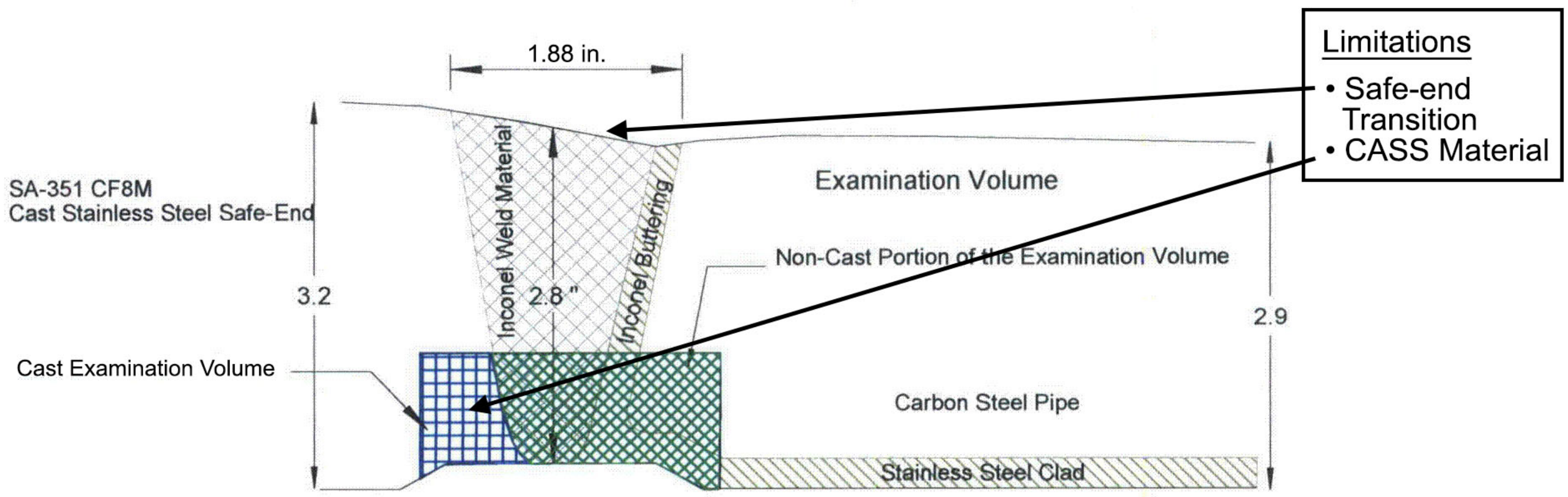


From Stanley 2012, ML12164A372

Limited Coverage Examples in PWRs

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

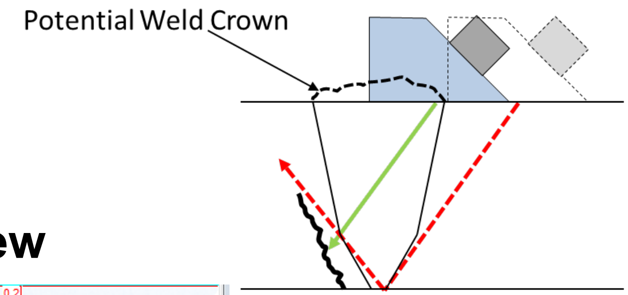




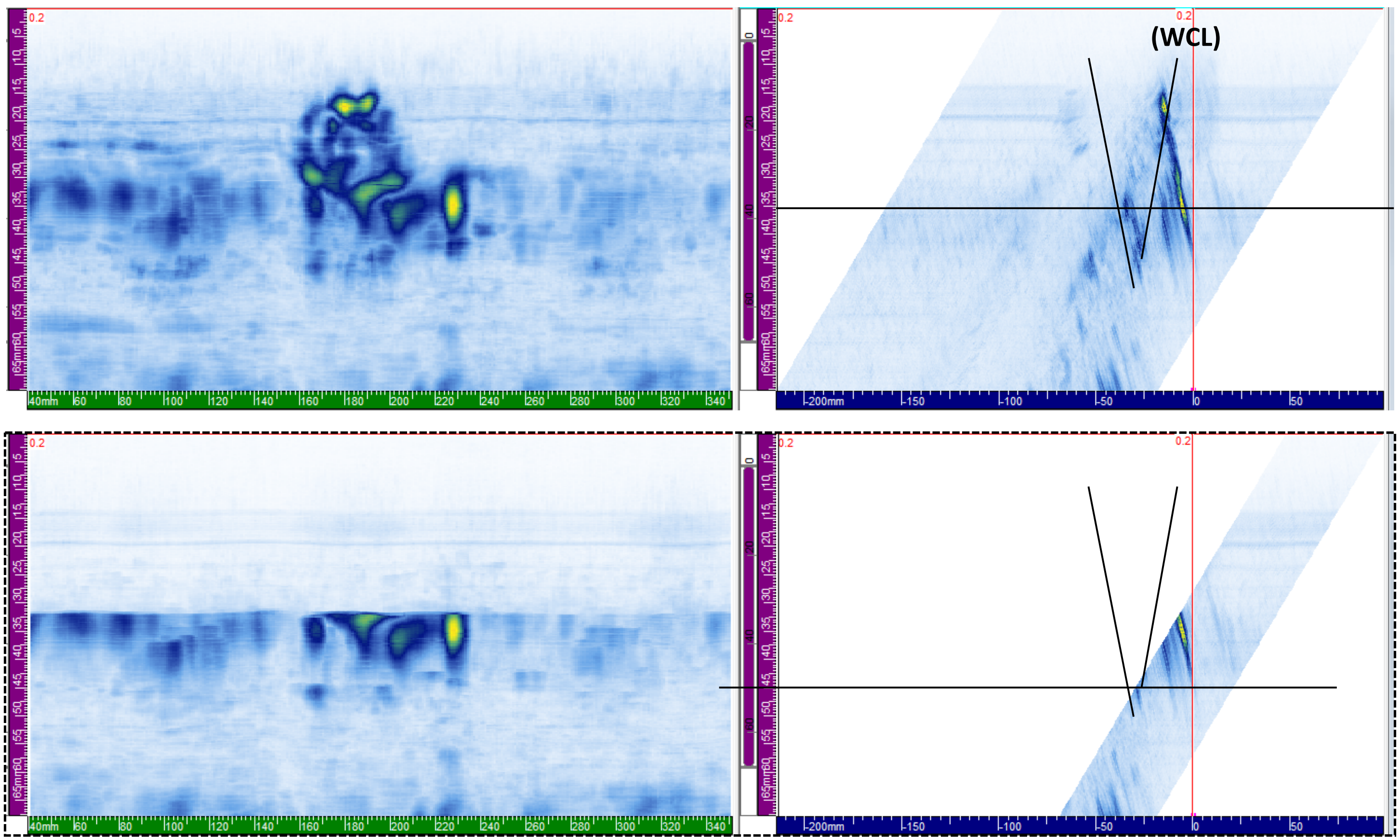
From Sartain 2014, ML14051A109

What Happens in a Limited Coverage Scenario?

- Partial flaw insonification: How much is sufficient for detection?



End View | **Side View**



Full coverage (Ground weld crown)

Limited coverage (Intact weld crown)

Design of Experiments: Factors and Levels

- 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	No scans to be performed from the CASS sides.
Wall Thickness	2	Thin, Thick	Thin ≤ 1.6 in.; Thick > 1.6 in.
Weld Root Condition	1	None	Using best case scenario of no weld root, although some specimens may have existing weld root.
Probe Aperture	2	Small, Large	
Probe Type	3	Single Element, Phased Array, TRL	
Refracted Angle	4	30° ,45° ,60° ,70°	PA to include intermediate angles as well; Conventional – 45° ,60° ,70°; TRL – 30° ,45° ,60° ,70°
Wave Mode	2	Shear, Longitudinal	Shear is only applicable for conventional probes and near-side exams.
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 Aspect Ratio	3	<4.5 4.5-9.0 >9.0	Ranges may need to be adjusted due to lack of specimens with aspect ratio >9.0
Flaw Parameters	Ongoing assessment with respect to size distributions, location, orientation, and tilt. Other factors may also be included as assessment progresses.		

Design of Experiments Matrix

- Matrix resulting from the Design of Experiments analysis

THICK-WALL (> 1.6")

DMW (CS/SS)	TW%	Aspect Ratio <4.5	Aspect Ratio 4.5-9	Aspect Ratio >9
	0-30%	✓	✓	
	30%-50%	✓		
	50-70%			

WSS/CASS	TW%	Aspect Ratio <4.5	Aspect Ratio 4.5-9	Aspect Ratio >9
	0-30%	✓		(x2)
	30%-50%	✓		
	50-70%			

WSS/WSS	TW%	Aspect Ratio <4.5	Aspect Ratio 4.5-9	Aspect Ratio >9
	0-30%			(x2)
	30%-50%			
	50-70%			

THIN-WALL (<= 1.6")

TW%	Aspect Ratio <4.5	Aspect Ratio 4.5-9	Aspect Ratio >9
0-30%	✓	✓	
30%-50%	✓	✓	
50-70%	✓		

TW%	Aspect Ratio <4.5	Aspect Ratio 4.5-9	Aspect Ratio >9
0-30%			(x2)
30%-50%			
50-70%			

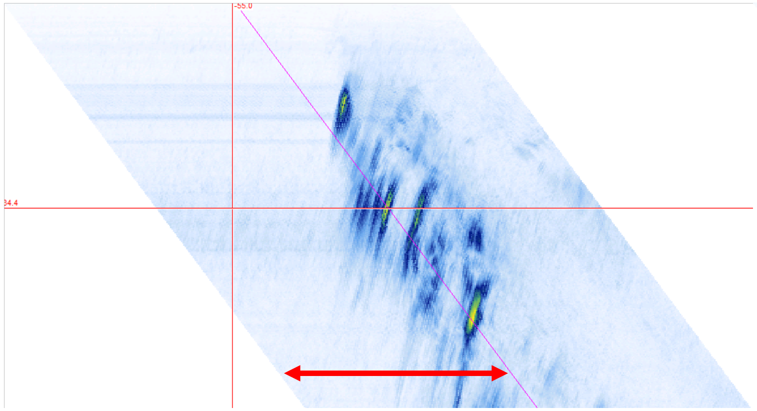
TW%	Aspect Ratio <4.5	Aspect Ratio 4.5-9	Aspect Ratio >9
0-30%	✓	✓	✓
30%-50%	✓		
50-70%	✓		

Blank entries = specimen gaps; Red highlighted = high priority
✓ = specimens currently available to PNNL

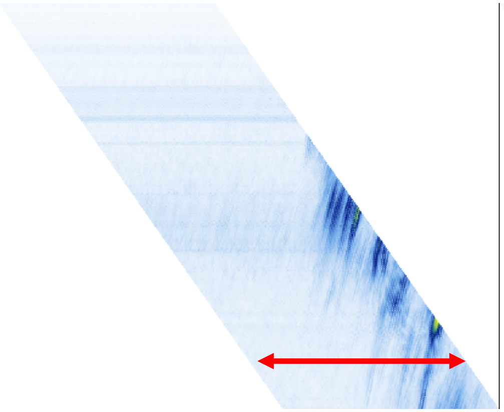
Experimental Approach

- Experimental data acquired using UltraVision.
- Left: a scan acquired with full probe access.
- Center: limited access; the probe was stopped at the weld boundary
- Right: full probe access and parsed in UltraVision.
- Results confirm that full coverage scans can be acquired and limited coverage scenarios implemented afterward.
  - Huge savings in acquisition time
  - Allows for decision making about specific coverage limitations to occur after data collection

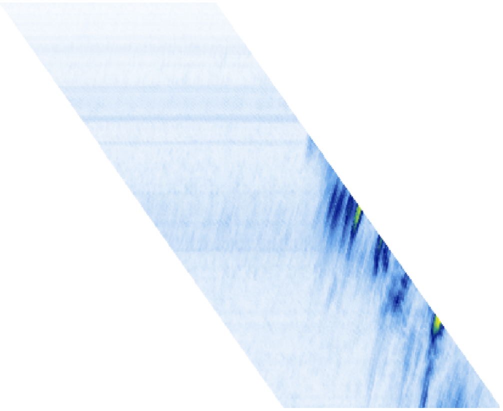
Full coverage scan



Limited Coverage Scan

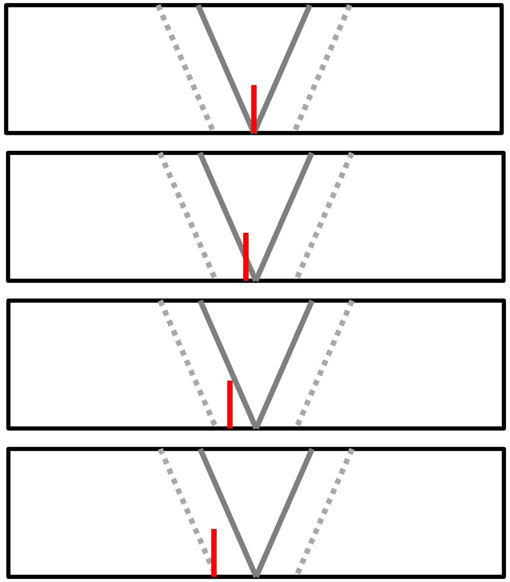


Parsed Full Coverage Scan



Control Specimen to be Fabricated

- Two flat WSS plates (thick and thin) with an austenitic weld
- 4 non-overlapping identical notches placed from WCL to HAZ, 30% TW
- Scans will be done from near side and far side to study the effects of coverage limitations in a range of scenarios
- Empirical results will be compared to simulations with different levels of flaw insonification



Flaw 1: Weld Center Line

Flaw 2: In the weld, off-center

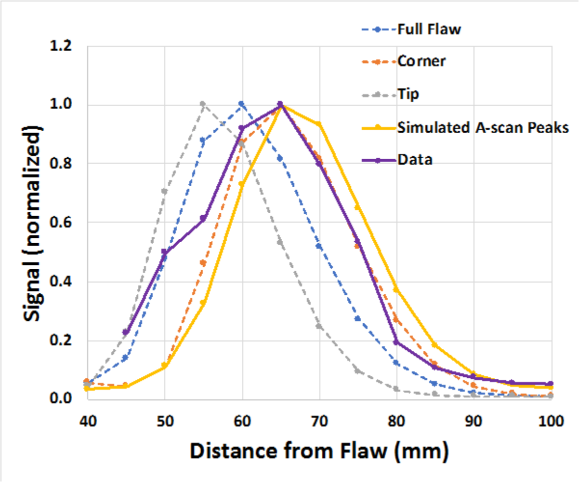
Flaw 3: In the HAZ

Flaw 4: Near the HAZ boundary

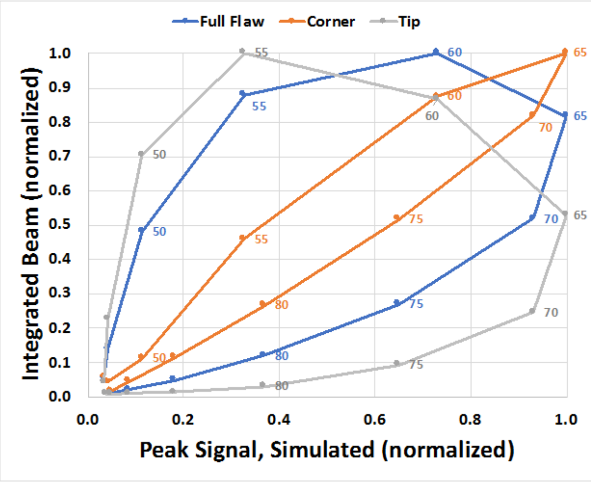
Experimental and Simulated Results

- WSS specimen, 63 mm thick, no weld, 20% EDM notch
- Beam simulations: integrate sound energy incident on the flaw tip, flaw corner, and full flaw for each probe position (5 mm increments)
- Flaw response simulations: measure peak flaw response for each probe position
- Experimental results: measure peak flaw response for each probe position

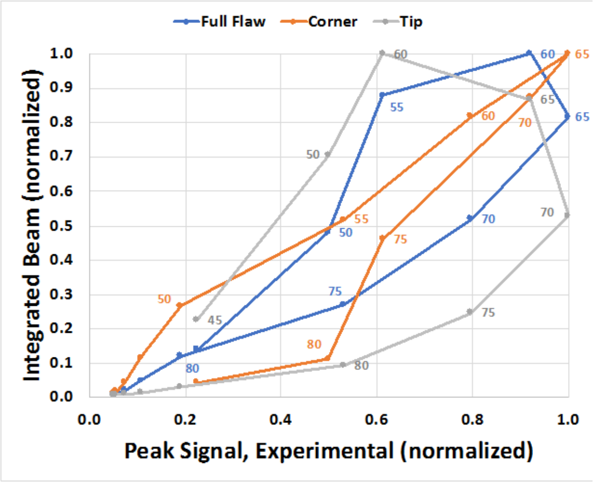
Beam Simulation and Experimental and Simulated Flaw Response



Beam Simulation vs Simulated Flaw Response



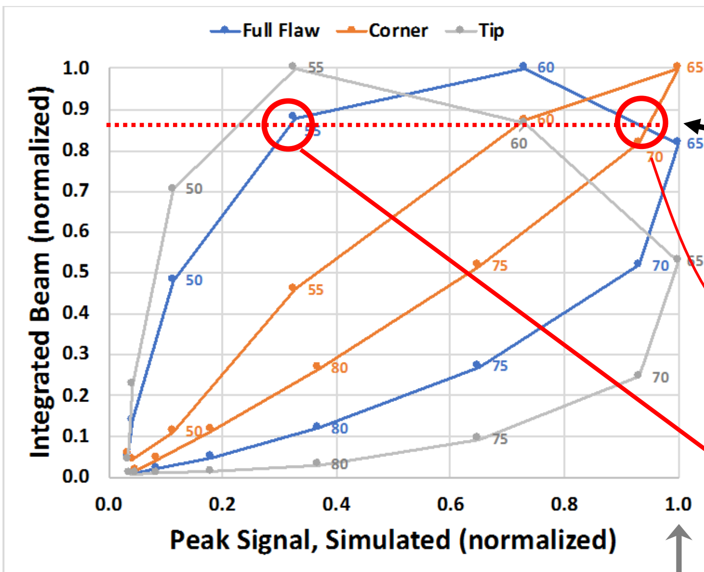
Beam Simulation vs Experimental Flaw Response



Dashed lines are beam simulation results
Full flaw = 12.7 mm
Corner = bottom 3 mm
Tip = top 5 mm

Experimental and Simulated Results

- Results show that the level of insonification is not predictive of the signal amplitude.
- Any beam model predictions of flaw detection based on flaw insonification must take into account probe position.

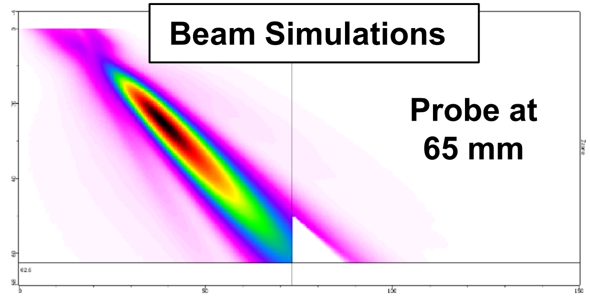


Maximum incident sound energy

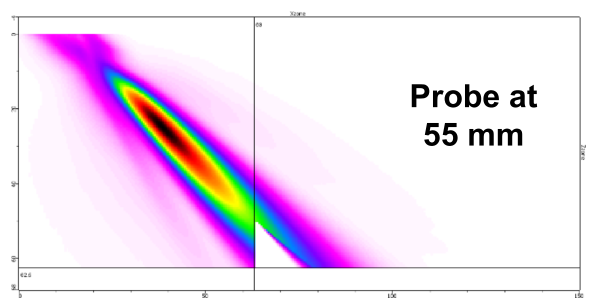
Example:
At 85% of incident sound energy on the full flaw, the peak signal response can be ~30% of max or ~95% of max, depending on the probe position.

Maximum flaw signal

Beam Simulations



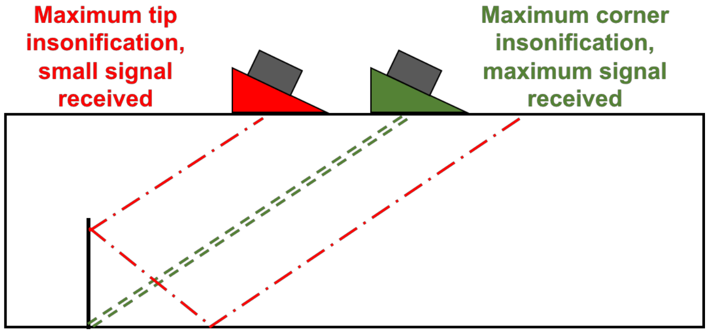
Probe at 65 mm



Probe at 55 mm

Evaluating the Effects of Coverage Limitations

- Need to develop metrics for evaluating whether limited coverage scenarios will be effective for flaw detection.
- Metrics being considered:
  - Volume of coverage at a particular sound beam dB level (from beam simulations or other calculations)
  - Flaw insonification – how much energy is incident on the face of a flaw (from beam simulations)
  - Corner response relative to tip signal (tip-corner signal ratio)
- As illustrated on the previous slide, flaw response estimations based on beam simulation results should be considered in light of probe position.



Key Takeaways to Date (Limited Coverage Research)

- The Design of Experiments significantly reduced the number of specimens and scans needed.
  - Recommended number of experiments reduced from 1836 (full factorial design) to 118.
  - The actual numbers will likely change based on allowable flaw parameters, allowable probe-frequency combinations, and available specimens.

- Specimens under consideration are welds between
  - CS – CASS
  - SS – CASS
  - SS – SS

Key Takeaways to Date (Limited Coverage Research)

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- 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.
- Scans to date have been collected assuming full coverage possible.
  - Coverage limitations will be imposed artificially for analysis.
- Simulation studies indicate potential metrics that include coverage volume and fraction of flaw insonified must also include probe position.

Next steps: Limited Coverage Assessments

- Truncate current full-coverage data in UltraVision to simulate limited coverage.
  - Limit forward coverage to simulate presence of weld crown – face and corner insonification.
  - Limit backward coverage to simulate obstruction or taper – face and tip insonification.
- Analyze truncated data, determine metrics.
- Correlate predicted flaw insonification based on beam models with actual signal intensity.
- Use flaw response modeling to simulate limited coverage and fractional flaw insonification for specimens that we do not have.
  - Benchmark models against actual results for a subset of specimens.
- Use statistical analysis to develop POD estimates for limited coverage scenarios.

Thank you

- Questions?