Cast Austenitic Stainless Steel

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Outline

- Issue Summary
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- CASS Inspection Issues
- Evaluation of Phased Array Inspection Approach
  - Specimens, microstructures and flaws
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  - Data acquisition and analysis
- Additional Research
  - Investigation of Delta Technique
  - In-situ CASS Microstructural Characterization
- Summary of Results/Conclusions
- Future Work

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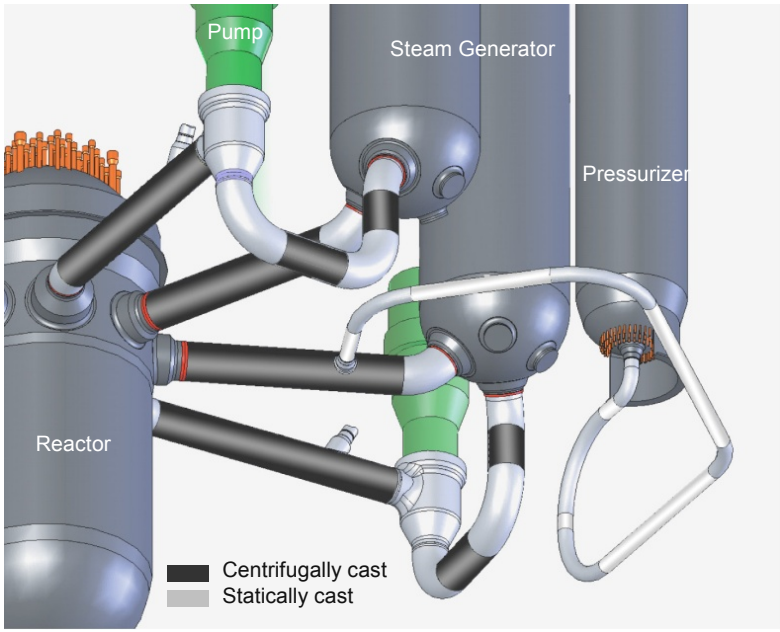
Issue Summary

- CASS usage is prevalent in class 1 reactor components, especially Westinghouse
- CASS has many advantageous properties
  - Good sensitization and SCC resistance
  - Material can have good strength and toughness
- CASS is susceptible to thermal aging
  - Susceptibility dependent on composition and processing history
  - Long-term toughness degradation of most susceptible materials is very low
- Coarse-grained microstructure makes CASS difficult to inspect
  - Decreased beam penetration
  - Decreased signal-to-noise ratio
- Concern is that low toughness material containing casting defects or service-induced flaws could fail during loading transients
  - Failure likelihood increases with time
  - Mitigation through inspection alone is challenging

CASS Use in NPP



- Westinghouse plants extensively used cast components
  - 27 Westinghouse plants use centrifugally-cast CASS for primary piping
  - All 48 Westinghouse plants use static castings for elbows, fittings, valve bodies, and pump casings
- Other BWR and PWR plants contain some CASS components
  - Elbows, fittings, valve bodies, pump casings

CASS Inspection Challenges

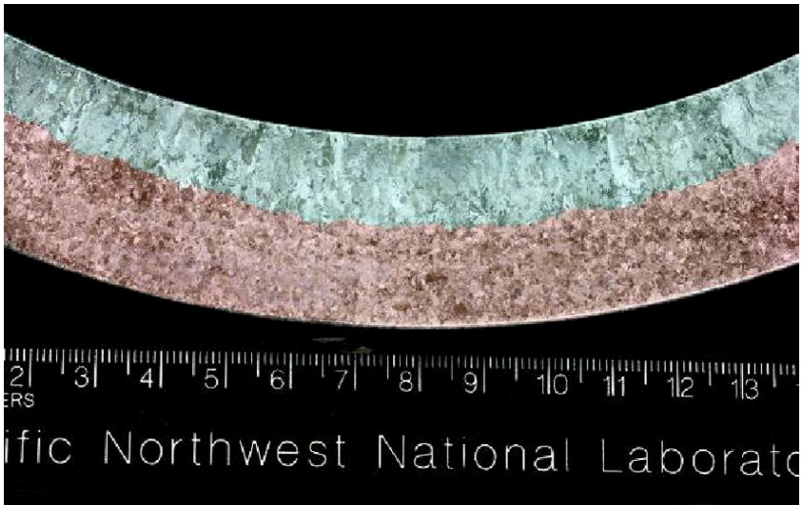
- Conventional UT inspections are challenging due to the anisotropy and inhomogeneity of the coarse microstructures in CASS components affecting sound field propagation
- CASS component inspections continue to yield poor results due to:
  - Large size/orientation of anisotropic grains (relative to the acoustic pulse wavelength)
    - Severe attenuation (primarily scattering)
    - Beam skewing
    - Changes in acoustic velocity as a function of position
    - Refraction/reflection of sound at grain boundaries, root conditions, counterbore, weld fusion lines
- This translates into lower SNR, difficulties in signal (echo) discrimination and the potential for incomplete insonification of the part

Evaluation of Phased Array Inspection Approach

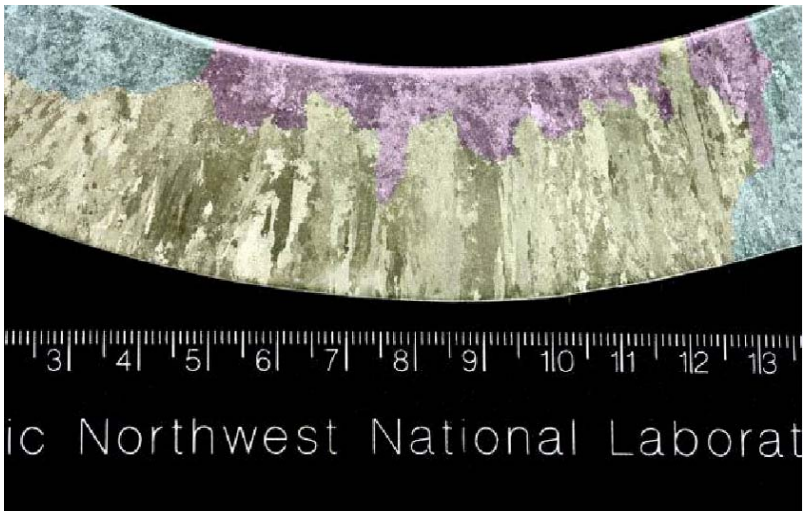
- Ultrasonic PA data were acquired and analyzed on
  - 3 pressurizer (PZR) surge-line (pipe-to-elbow) specimens
    - Centrifugally cast to statically cast component configuration
  - 3 PWROG traveling set specimens on loan from the EPRI NDE Center in Charlotte, NC., USA
- Data were analyzed for
  - Flaw detection capability
  - Both depth and length sizing in PZR surge line specimens
  - No depth sizing attempted for PWROG specimens (tips not detected); length sizing only
- Crack morphology and true state data were known for all specimens
- 500 kHz and 800 kHz used for PWROG samples
  - λ = 11.6 mm (0.45”) and 7.2 mm (0.29”) respectively
- 800 kHz and 1.5 MHz used for PZR surge-line samples
  - λ = 7.2 mm (0.29”) and 3.9 mm (0.15”) respectively

PZR Surge Line Specimens

Sample 7C-059

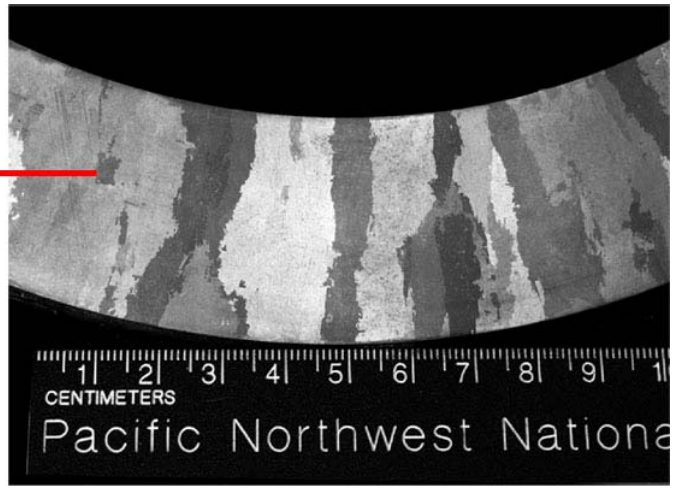


Pipe Side – CCSS
30 mm (1.2 in.) wall

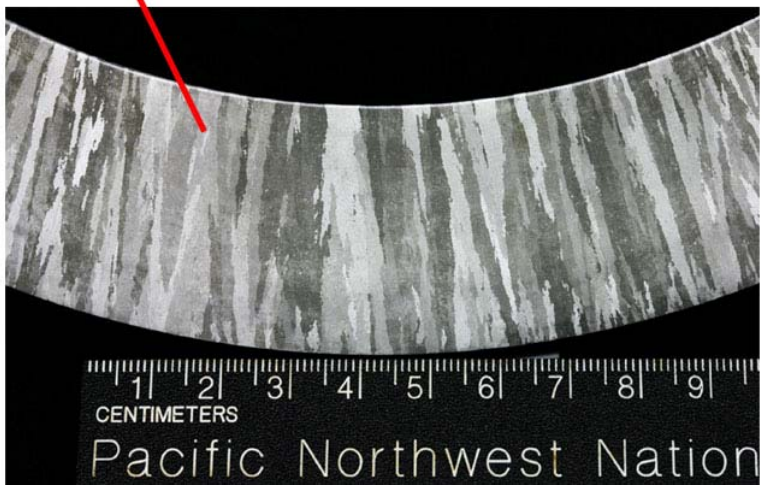


Elbow Side – SCSS
39 mm (1.5 in.) wall

PZR Surge Line Specimens (WNP-3)



9C-002
Pipe Side
33 mm
(1.3 in.) wall



9C-001
Pipe Side
33 mm
(1.3 in.) wall

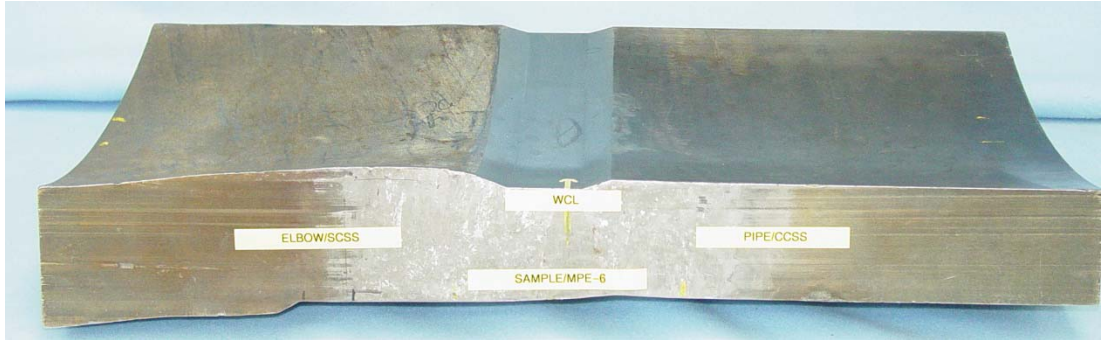
PZR Surge Line Specimens (WNP-3)

Microstructure of elbow segment from WNP-3 PZR surge line specimen
34 - 44 mm (1.3 - 1.7 in.) wall

PWROG Specimens

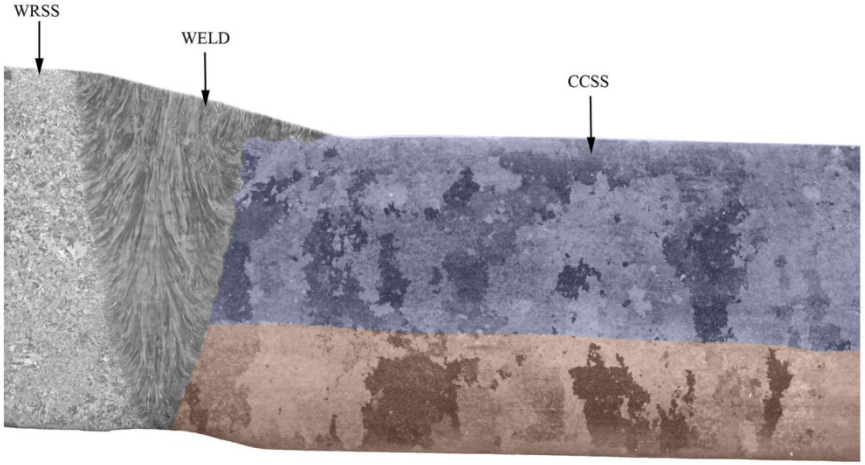
OPE-5, SCSS elbow 7.1 cm (2.8 in.) wall, CCSS pipe 5.8 cm (2.3 in.) wall

ONP-3-5, clad CS outlet nozzle to forged SS safe end to CCSS pipe 6.4 cm (2.5 in.) wall

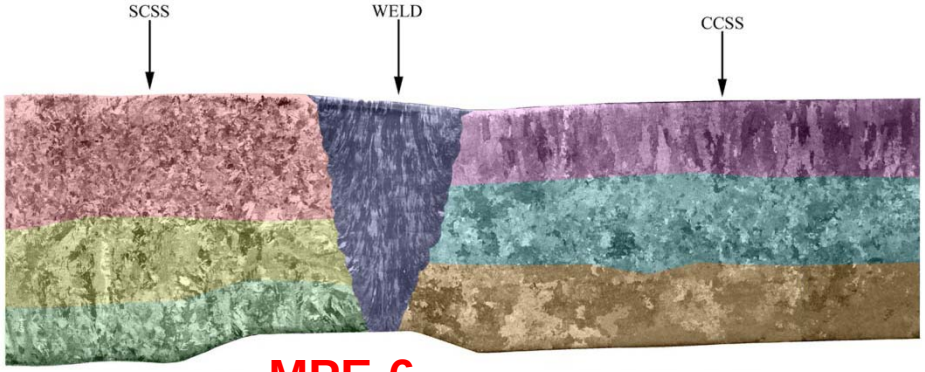


MPE-6, SCSS elbow 8.4 cm (3.3 in.) wall, CCSS pipe 6.6 cm (2.6 in.) wall

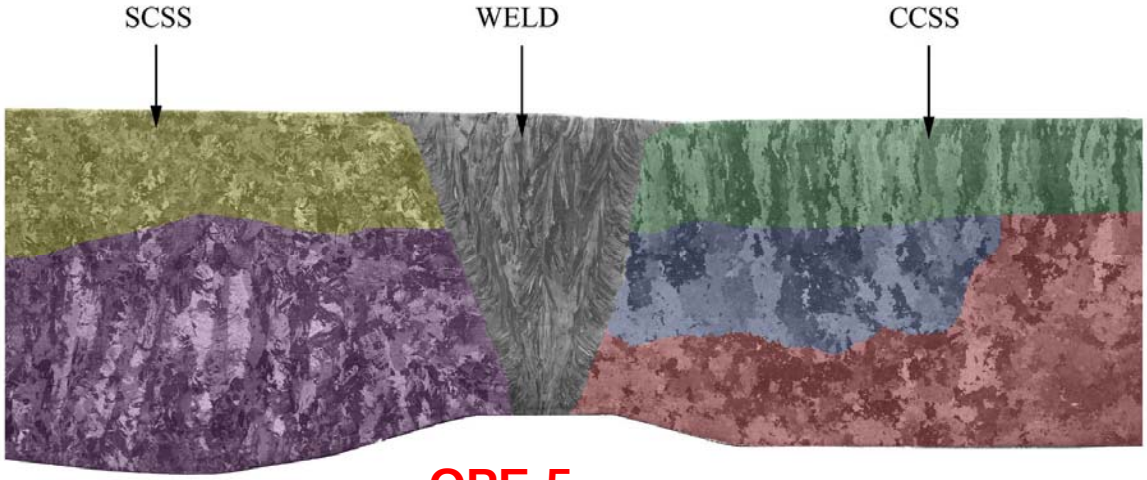
PWROG Specimen Microstructures



ONP-3-5



MPE-6



OPE-5

Grain Diameter Analysis

Specimen	CCSS (Pipe Side)		SCSS (Elbow Side)	
	Minimum mm (in.)	Maximum mm (in.)	Minimum mm (in.)	Maximum mm (in.)
PZR Surge Line 7C-059	0.6 mm (0.02 in.)	6.7 mm (0.26 in.)	0.5 mm (0.02 in.)	6.3 mm (0.25 in.)
PZR Surge Line 9C-001	0.8 mm (0.03 in.)	13.9 mm (0.55 in.)	2.6 mm (0.10 in.)	41.0 mm (1.61 in.)
PZR Surge Line 9C-002	1.3 mm (0.05 in.)	25.6 mm (1.01 in.)	2.6 mm (0.10 in.)	41.0 mm (1.61 in.)
MPE-6	0.56 mm (0.02 in.)	26.81 mm (1.06 in.)	0.28 mm (0.01 in.)	5.59 mm (0.22 in.)
ONP-3-5	0.33 mm (0.01 in.)	26.67 mm (1.05 in.)	n/a Carbon-Forged SS	n/a Carbon-Forged SS
OPE-5	0.21 mm (0.01 in.)	16.67 mm (0.66 in.)	0.21 mm (0.01 in.)	5.21 mm (0.21 in.)

PZR Surge Line Implanted Flaw Data (True State)

	Flaw	Flaw Type	Flaw Location	Flaw Orientation	Flaw Length	Flaw Depth (Height)	Degree Location
7C-059	1-1	Thermal Fatigue	Weld Center Line	Circumferential	4.0 in. (10.2 cm)	35% T	45°
	1-2	Thermal Fatigue	Pipe Side Near Fusion Line	Circumferential	2.0 in. (5.1 cm)	30% T	120°
	1-3	Thermal Fatigue	Weld Center Line	Circumferential	2.0 in. (5.1 cm)	30% T	210°
	1-4	Thermal Fatigue	Weld Center Line	Circumferential	6.0 in. (15.2 cm)	30%–50% T	300°
9C-001	2-1	Thermal Fatigue	Weld Center Line	Circumferential	3 in. (7.6 cm)	10 - 20% T	0°
	2-2	Thermal Fatigue	Weld Center Line	Circumferential	2 in. (5.1 cm)	25 – 30% T	90°
	2-3	Thermal Fatigue	Weld Center Line	Circumferential	2.5 – 3 in. (6.4–7.6 cm)	25%	270°
9C-002	3-1	Thermal Fatigue	Weld Center Line	Circumferential	3 in. (7.6 cm)	15 – 25% T	0°
	3-2	Thermal Fatigue	Weld Center Line	Circumferential	2 in. (5.1 cm)	20% T	90°
	3-3	Thermal Fatigue	Weld Center Line	Circumferential	2.5 – 3 in. (6.4–7.6 cm)	15% T	270°

PWROG Specimen Flaw Data (True State)

PWROG Specimen Flaw Data (True State)						
PWROG Sample ID	**Side UT Applied[1]**	**Crack Type[2]**	**Flaw Thru-wall Depth[3] %, cm., (in.)**	**Flaw Area[4] (cm^2)**	**Flaw Orientation**	**Flaw Length cm. (in.)**
ONP-3-5	CCSS	TF	28% 1.78 cm (0.7 in.)	11.7	Circumferential	6.6 cm (2.6 in.)
OPE-5	CCSS SCSS*	TF	23% 1.63 cm (0.64 in.)	10	Circumferential	6.15 cm (2.42 in.)
MPE-6	CCSS SCSS*	TF	18% 1.5 cm (0.59 in.)	8.8	Circumferential	5.9 cm (2.33 in.)

Notes and Definitions:

*) Denotes side of weld on which flaw is located

1) Denotes from which side of the weld the PA UT was applied; CCSS = centrifugally cast stainless steel, SCSS = statically cast stainless steel

2) TF = thermal fatigue

3) Flaw depth information as determined by Westinghouse

4) Assume rectangular aspect ratio using depth and length information to show potential area available for specular reflections

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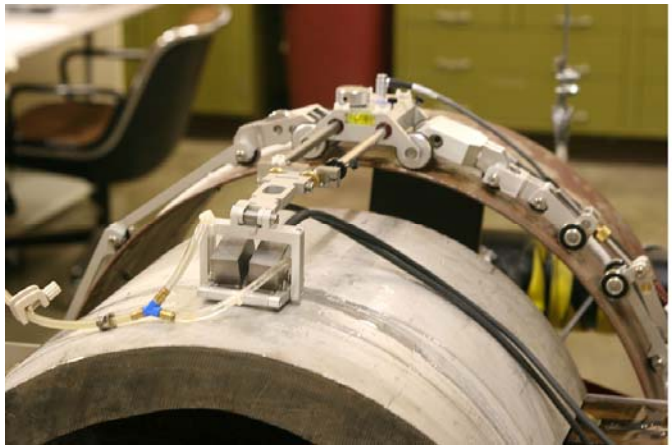
Phased Array Data Acquisition System

0.2 – 20 MHz

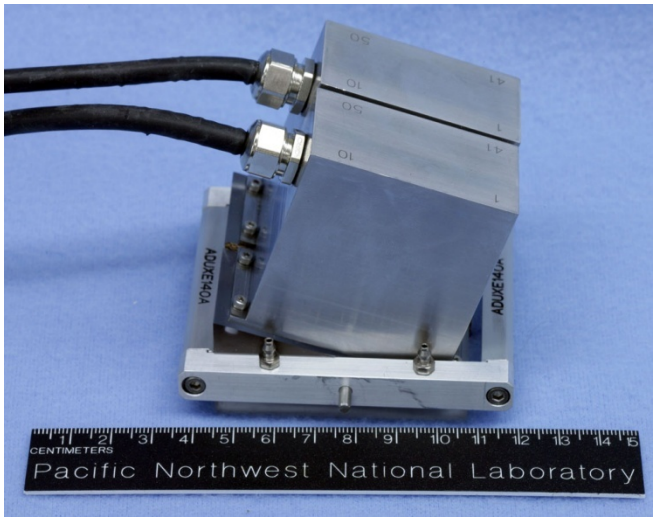
256 channels

Ultravision® software



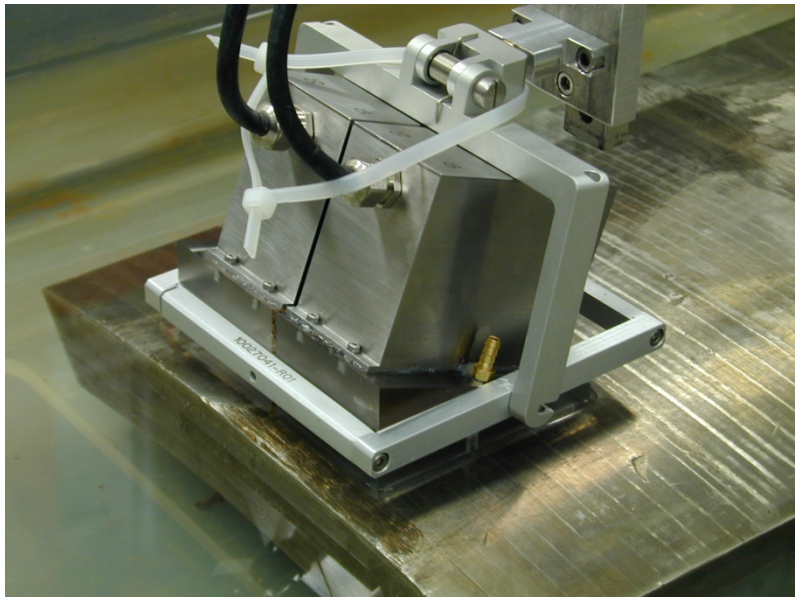
Scanner arm, probe and coupling configuration

Phased Array Probes



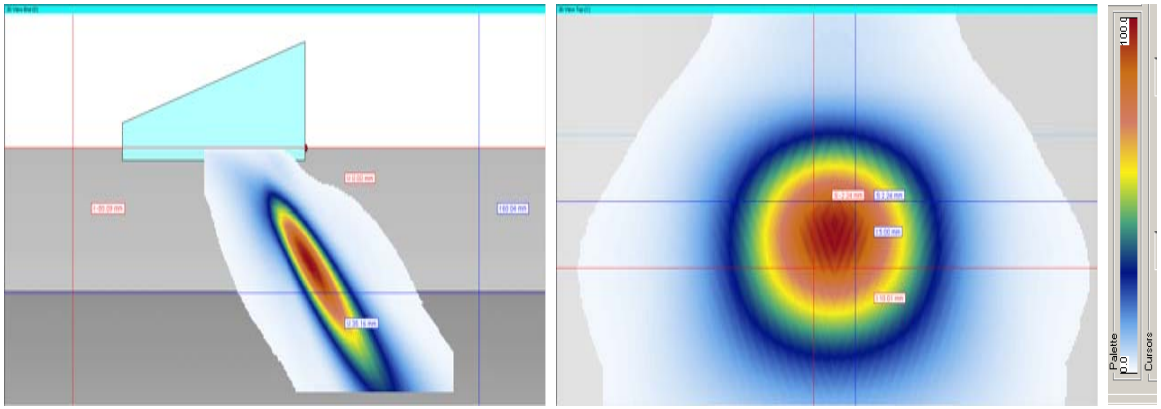
800 kHz, 10 x 5,
TRL

1.5 MHz, 10 x 3
Mini-TRL

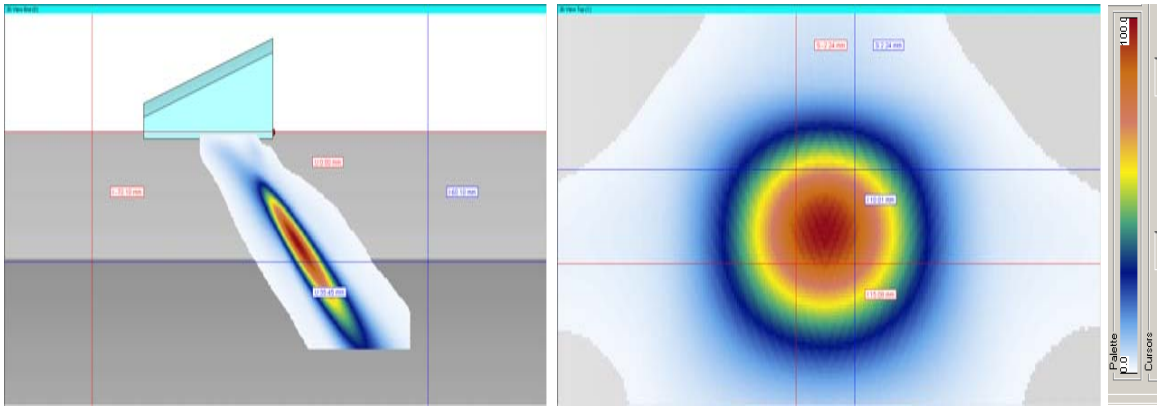


500 kHz, 10 x 5,
TRL

Modeled Sound Field Beam Profiles - PZR Surge Line



800 kHz TRL, 50 mm half path focus, 7.2 mm x 5.7 mm spot size:

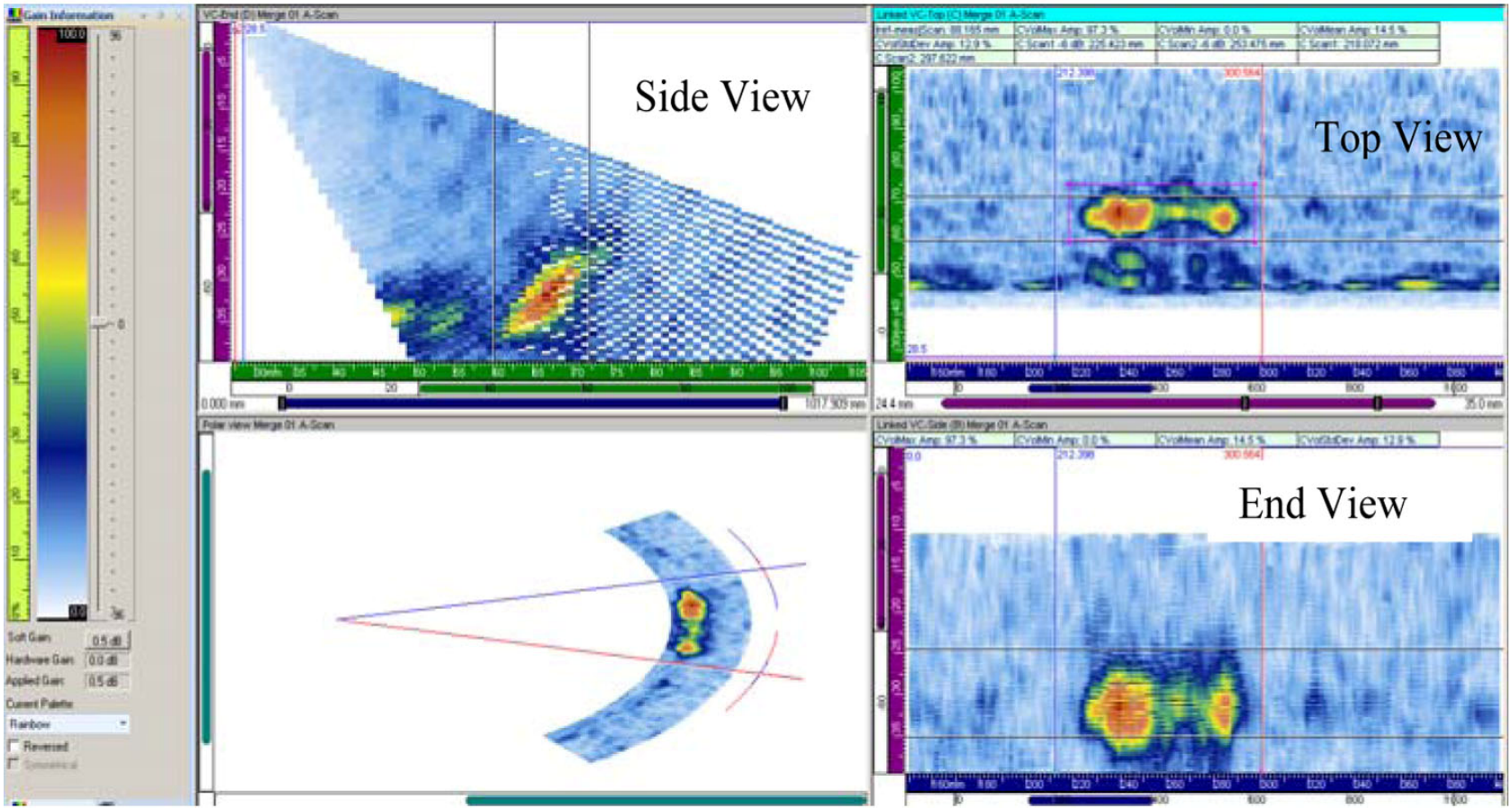


1.5 MHz TRL, 50 mm half path focus, 5.0 x 3.8 mm spot size:

= - 6dB point

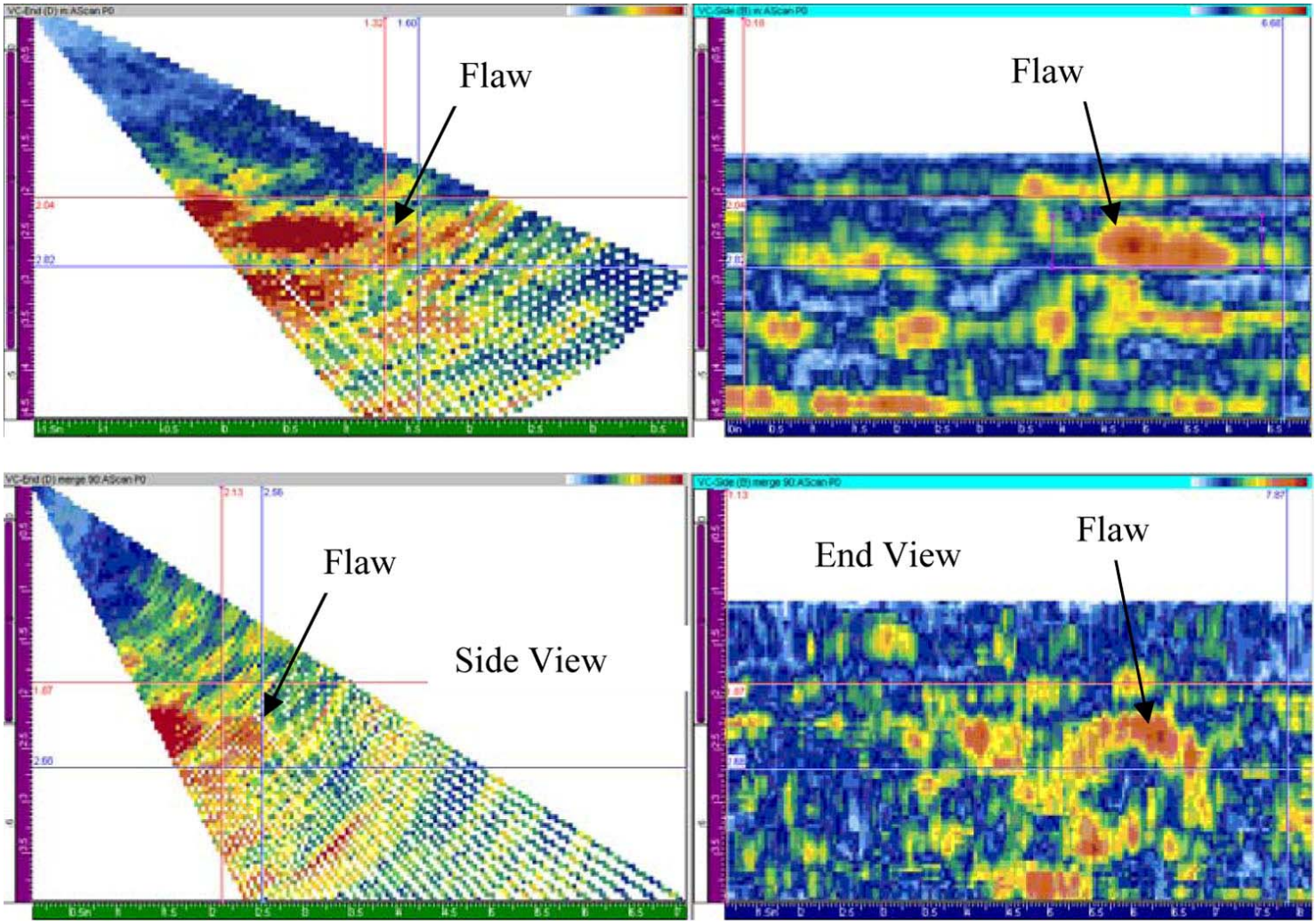
PZR Surge Line Data

Flaw 2-2, 1.5 MHz TRL, 9C-001, From the CCSS Pipe Side



PWROG Specimen Data

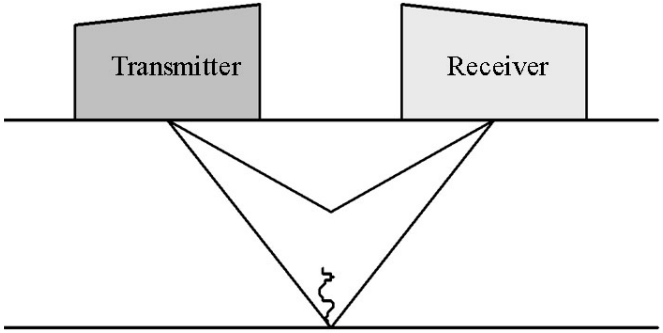
OPE-5 Pipe Side (Far Side) PA Data at 500 kHz (top) and 800 kHz (bottom)



500 kHz

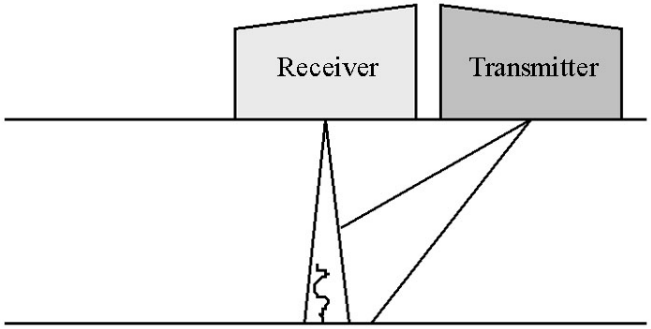
800 kHz

Additional Investigations – Delta Technique



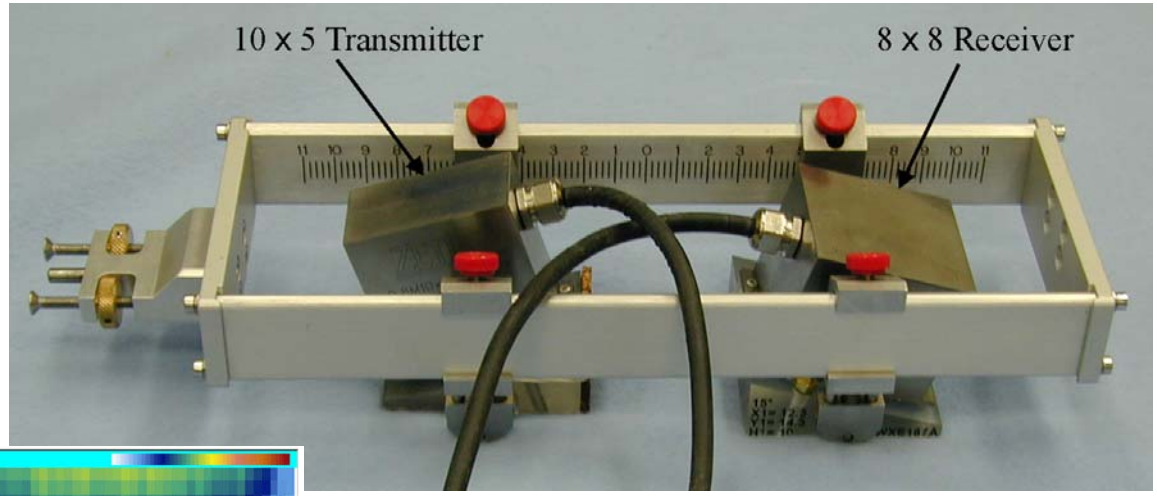
Probes positioned equidistant from center of flaw

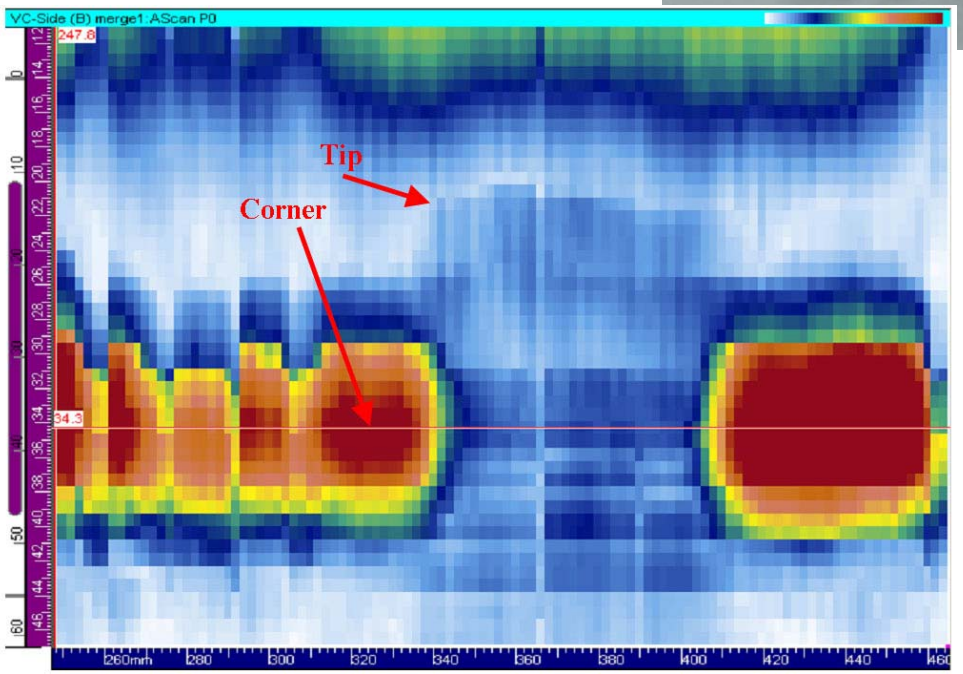
Receiver positioned directly over flaw

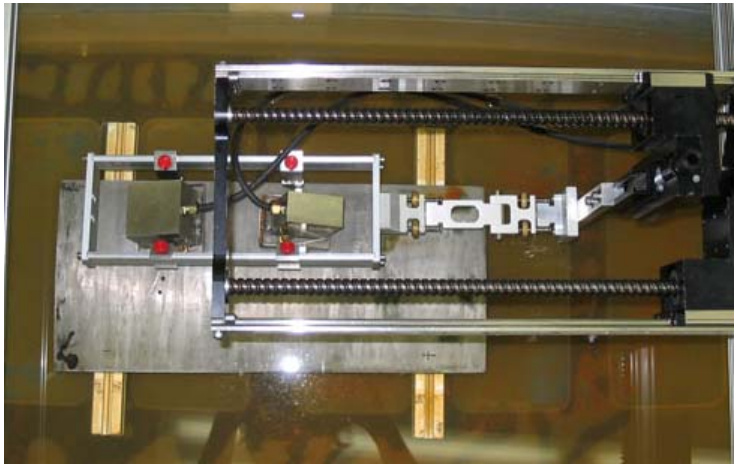


Additional Investigations – Delta Technique

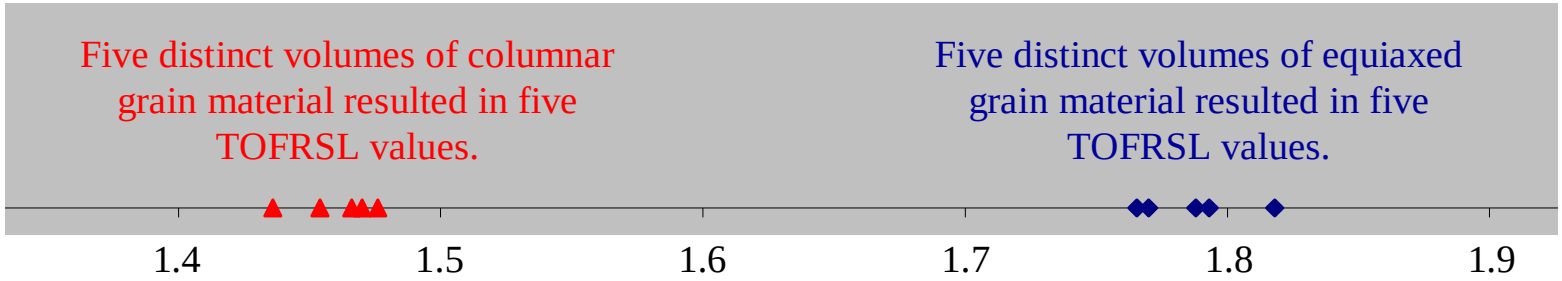
800 kHz Delta Approach:
Weak tips coupled with loss of back wall echo



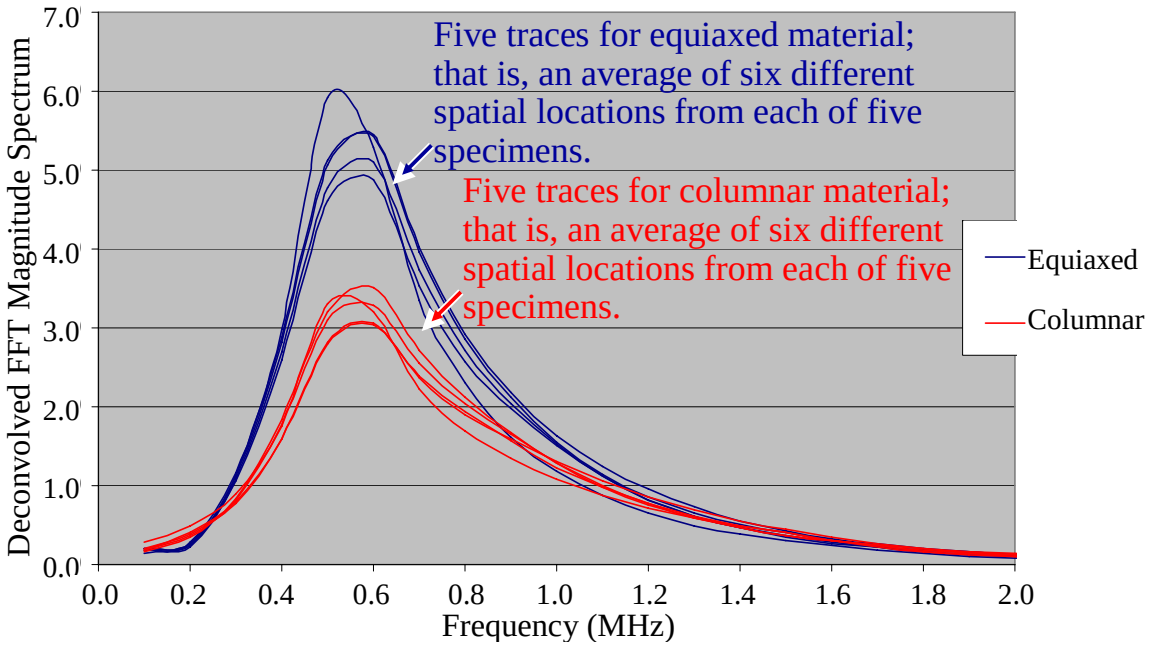


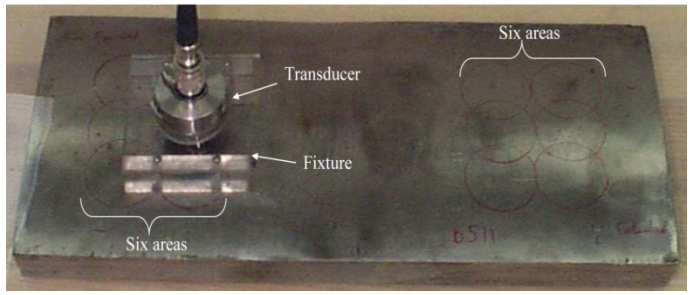


In-Situ, Microstructural Characterization of CASS



Time-of-Flight Ratio Shear Wave to Longitudinal Wave Measurements





10 Spatially Averaged, Deconvoluted FFT Magnitude Spectrums Illustrating Difference between Data Obtained from Equiaxed Grain and Columnar Grain Microstructures

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Future Work

- Continue sound field mapping of various CASS microstructures as a function of:
  - Incident angle, Inspection frequency, Focal depth, Modality, etc.
  - Provide validation data for theoretical modeling results
- Continue refinement of in-situ microstructural characterization methods
  - Investigate mixed and layered microstructures
  - Acoustic backscatter as a function of angle
- Complete assessment of casting fabrication processes and their impact on resultant microstructures
- Continue to conduct confirmatory research of advanced signal processing methods, enhanced transducer/probe design, and other alternatives for improved detection and sizing in CASS materials

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Backup

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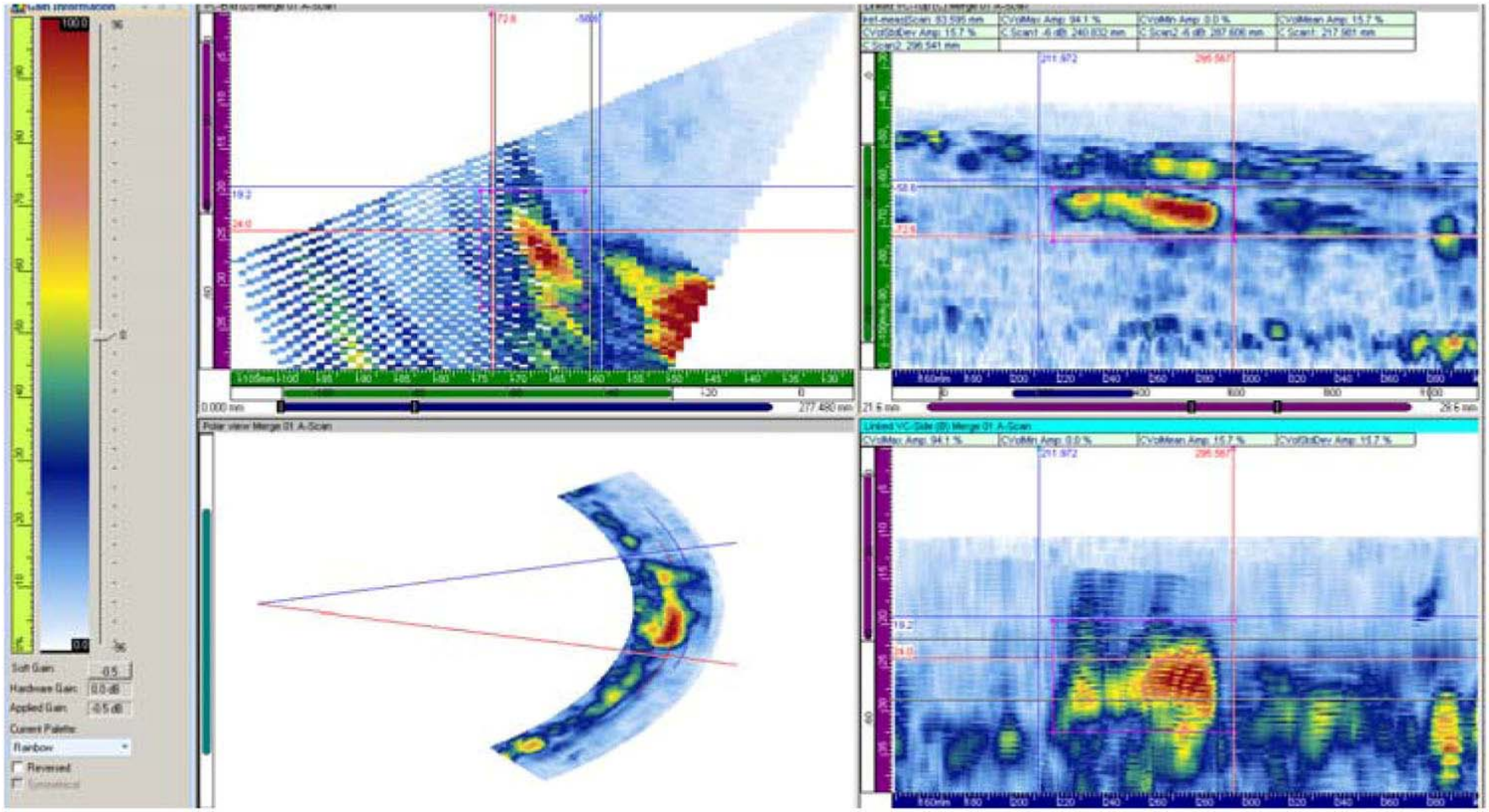
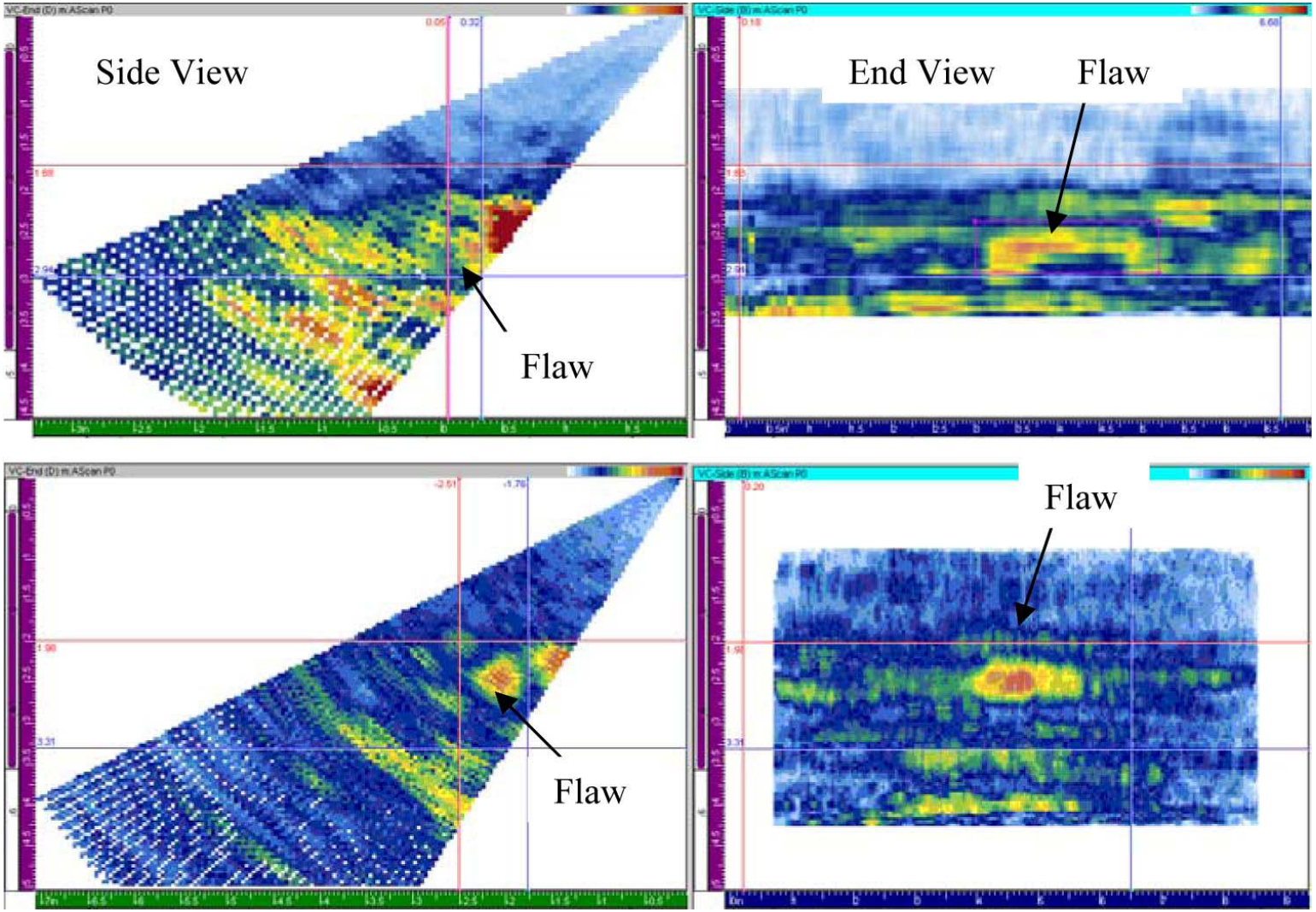
PZR Surge Line Data

Flaw 2-2, 1.5 MHz TRL, 9C-001, From the SCSS Elbow Side



PWROG Specimen Data

OPE-5 Elbow Side (Near Side), PA Data at 500 kHz (top) and 800 kHz (bottom)



500 kHz

800 kHz

PZR Surge Line Results: Length Sizing Units: mm (in.)

		800 kHz		1.5 MHz	
Flaw	**True**	**CCSS**	**SCSS**	**CCSS**	**SCSS**
7C-059_1	104 (4.09)	122 (4.80)	88 (3.47)	111 (4.37)	83 (3.27)
7C059_2	51 (2.01)	52 (2.04)	54 (2.13)	37 (1.46)	72 (2.84)
7C059_3	50 (1.97)	56 (2.21)	--	40 (1.56)	--
7C059_4	152 (5.98)	78 (3.07)	132 (5.20)	190 (7.48)	161 (6.34)
9C-001 _1	76.6 (3.02)	89.3 (3.52)	92.3 (3.63)	93.7 (3.69)	83.4 (3.28)
9C-001 _2	51.1 (2.01)	56.4 (2.22)	74.5 (2.93)	64.1 (2.52)	46.8 (1.84)
9C-001 _3	69.7 (2.74)	77.1 (3.04)	69.4 (2.73)	88.4 (3.48)	69.5 (2.74)
9C-002 _1	76.7 (3.02)	72.6 (2.86)	79.9 (3.15)	62.0 (2.44)	79.0 (3.11)
9C-002 _2	50.5 (1.99)	53.2 (2.09)	54.1 (2.13)	53.3 (2.10)	63.3 (2.49)
9C-002 _3	69.7(2.74)	60.8 (2.39)	70.2 (2.76)	55.3 (2.18)	55.3 (2.18)
RMSE	***ASME Code Section XI-acceptable criterion is Length RMSE less than 19.05 mm (0.75 in.)***				
Specimen					
7C-059		**38 (1.50)**	15 (0.59)	**21.1 (0.83)**	17.9 (0.71)
9C-001		9.0 (0.35)	16.3 (0.64)	16.5 (0.65)	4.6 (0.18)
9C-002		5.9 (0.23)	2.8 (0.11)	12.0 (0.47)	11.2 (0.44)

PZR Surge Line Results: Depth Sizing Units: mm (in.)

Flaw	True	CCSS Side	SCSS Side
7C-059_1	10.9 (0.43)	13.0 (0.51)	12.0 (0.47)
7C-059_2	9.3 (0.37)	12.0 (0.47)	10.0 (0.39)
7C-059_3	9.3 (0.37)	13.5 (0.53)	--
7C-059_4	15.6 (0.61)	16.0 (0.63)	11.0 (0.43)
9C-001_1	6.4 (0.25)	10.6 (0.42)	7.9 (0.31)
9C-001_2	8.9 (0.35)	15.4 (0.61)	8.0 (0.32)
9C-001_3	8.3 (0.33)	13.3 (0.52)	7.2 (0.28)
9C-002_1	7.5 (0.30)	7.4 (0.29)	10.5 (0.41)
9C-002_2	6.3 (0.25)	6.6 (0.26)	4.4 (0.17)
9C-002_3	4.8 (0.19)	5.3 (0.21)	5.1 (0.21)
RMSE	***ASME Code Section XI-acceptable criterion is Depth RMSE less than 3.81 mm (0.125 in.)***		
Specimen			
7C-059		2.7 (0.11)	2.8 (0.11)
9C-001		**5.3 (0.21)**	1.2 (0.047)
9C-002		0.35 (0.014)	2.1 (0.083)

PWROG Specimen Results: Length Sizing

PWROG Specimen	Side	Length, mm (inch) True State Length	500 kHz	800 kHz	Reported Depth (%)
ONP-3-5	CCSS	66 (2.60)	ND*	ND	25
OPE-5	CCSS	61 (2.40)	42 (1.66)	74 2.91()	23
	SCSS	61 (2.40)	60 (2.37)	43 (1.69)	23
MPE-6	CCSS	59 (2.32)	47 (1.85)	36 (1.42)	18
	SCSS	59 (2.32)	34 1.34()	62 (2.44)	18

*ND = Not Detected

ASME Code Section XI-acceptable criterion is Length RMSE less than 19.05 mm (0.75 in.)

Length RMSE: 500 kHz = 16.8 mm (0.66 in.)

Length RMSE: 800 kHz = 16.0 mm (0.63 in.)