# Assessment of Ultrasonic Phased Array Inspection Method for Welds in Cast Austenitic Stainless Steel Pressurizer Surge Line Piping

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# Outline

- Issue Summary
- Background
- CASS Materials
- PA-UT Examinations
- PA-UT Examination Results
- Conclusion

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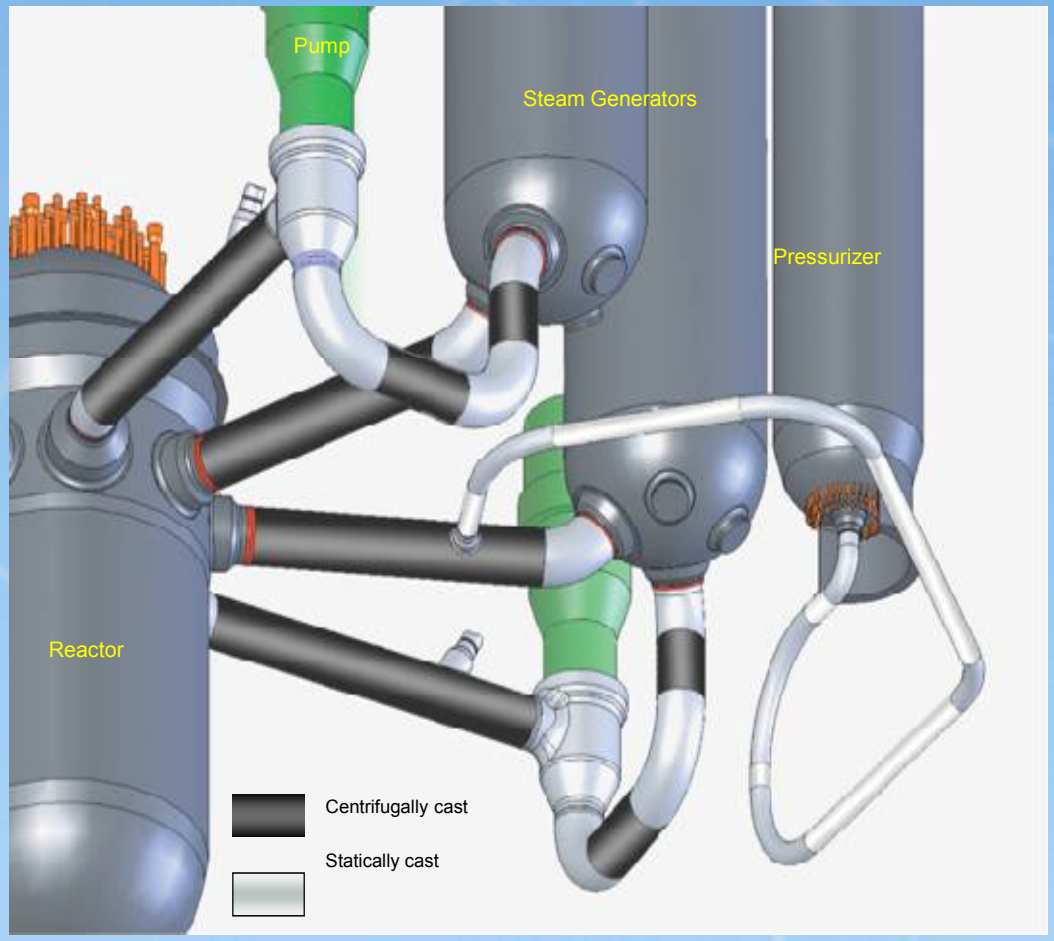
# Issue Summary

- CASS usage is prevalent in Class 1 reactor components, especially in Westinghouse reactors
- CASS has many advantageous properties
- CASS is susceptible to thermal aging
- Course-grained microstructure makes CASS difficult to inspect
- Concern is that low toughness material containing casting defects or service-induced flaws could fail during loading transients

# Background

- Previous work focused on heavy-walled primary loop piping with outer diameter measurements ranging from 71.12 to 91.44 cm (28 to 36 in.)

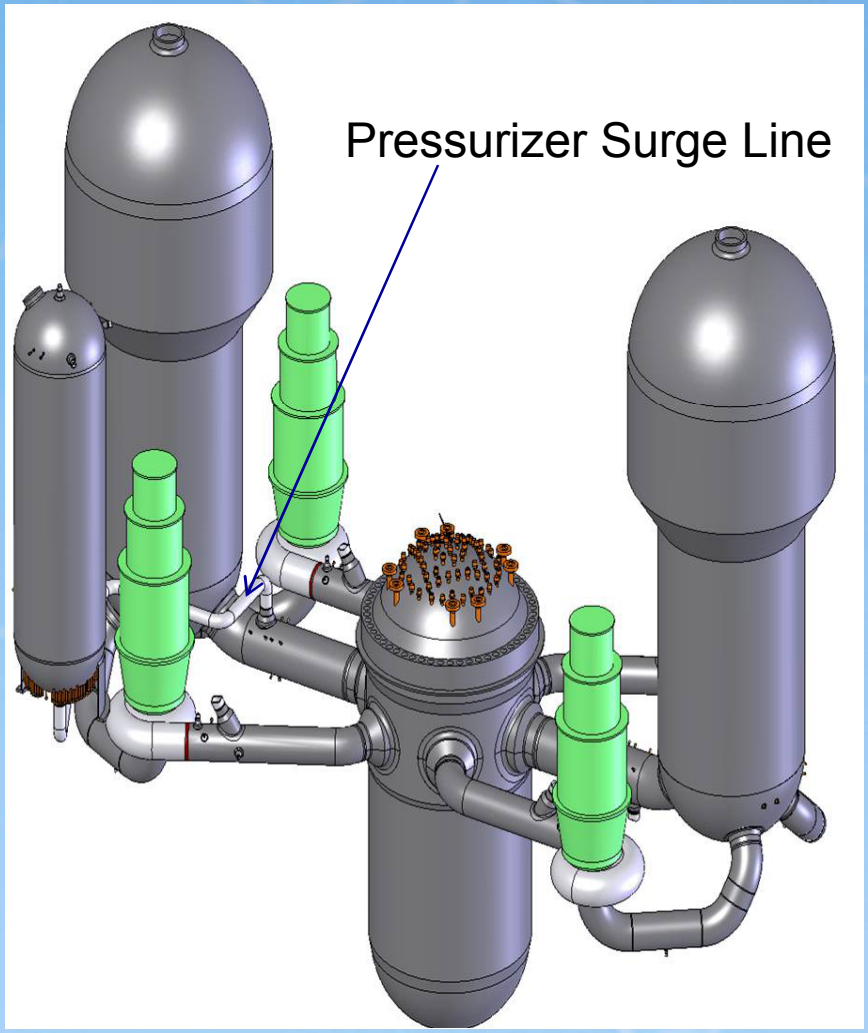
- CASS material in the Primary Coolant System in a Westinghouse Designed PWR 3-loop Plant shown at right *(courtesy of Chockie Group International)*



# Background (cont.)

- Thinner cast piping found pressurizer surge lines and safe ends with OD msmts ranging from 20.48 to 35.56 cm (12 to 14 in.) and wall thicknesses from 3.05 to 4.32 cm (1.2 to 1.7 in.)

- CASS material in the Primary Coolant System in a Combustion Engineering Designed PWR 2-loop Plant shown at right

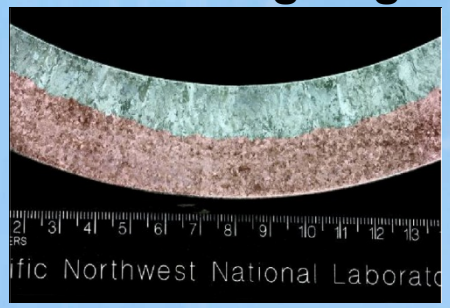


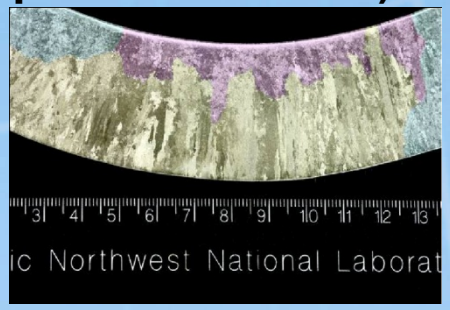
# Background (cont.)

- Set of thermal fatigue cracks implanted into three CASS pressurizer surge-line pipe-to-elbow welds
  - Vintage CASS materials formed in the 1970's used
  - Material salvaged from Combustion Engineering designed units that were never brought into full operation
- Specimens sliced, polished, and chemically etched for microstructural analysis
- Baseline CASS material noise analysis conducted
- Phased array ultrasonic examinations performed

# CASS Materials

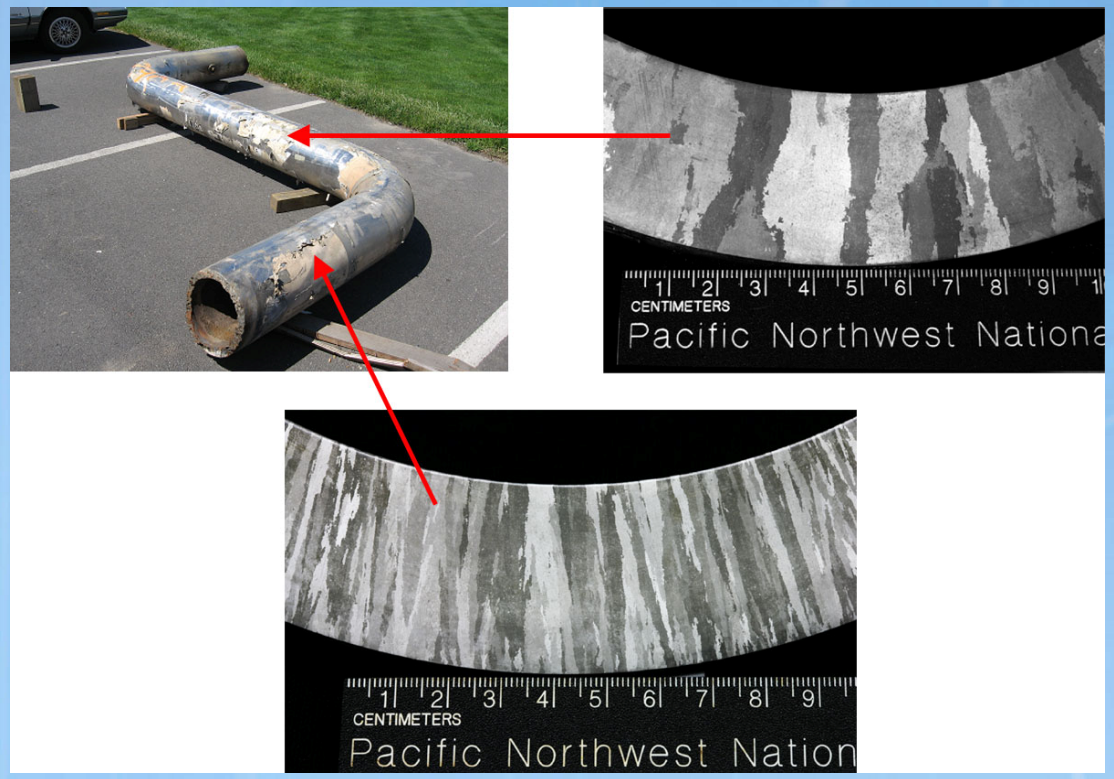
**Photographs of the Side-View (left) and End-View (right) of the CASS PZR Ring Segment (specimen 7C-059)**




**Photographs of Polished and Chemically Etched CASS PZR Ring Segment (specimen 7C-059) Showing the Pipe-Side (CCSS) Grain Microstructure (left) and the Elbow-Side (SCSS) Grain Microstructure (right)**

# CASS Materials




**WNP-3 Surge Line Section Showing the Locations of the Pipe and Elbow Cuts to Produce Two Pipe-to-Elbow Specimens, 9C-001 and 9C-002. The centrifugally cast pipe microstructures are displayed for both specimens.**

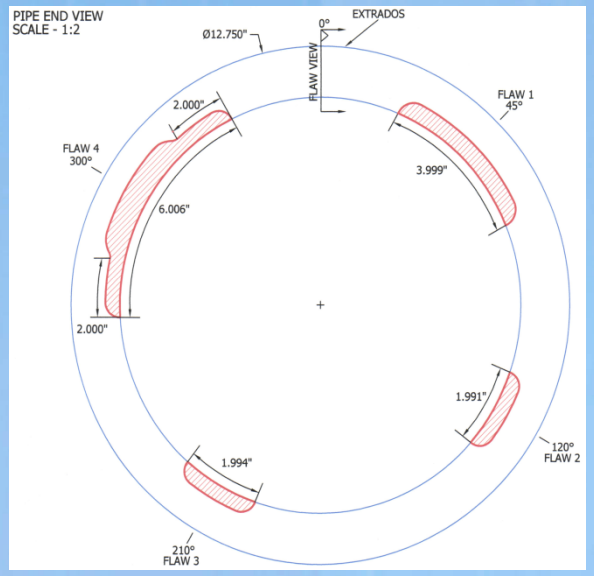
# CASS Materials

- Grain diameter measurements from three PZR surge-line specimens

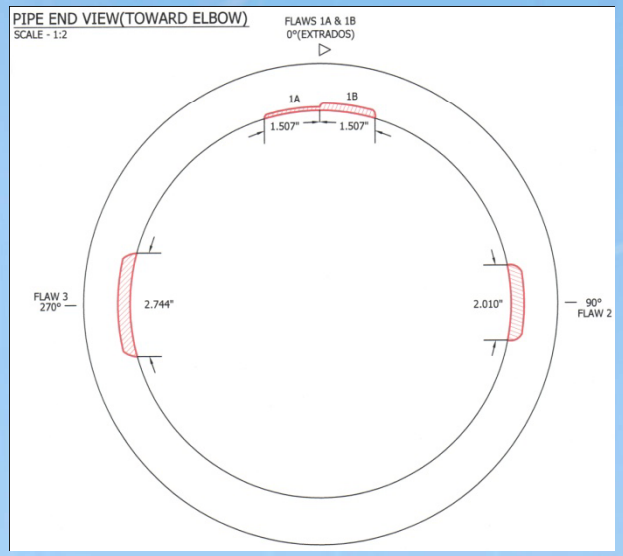
| | Surge Line 1 Grain Diameter (7C-059), mm (in.) | | WNP3 Surge Line Grain Diameter (9C-001 and 9C-002), mm (in.) | | |
|---|---|---|---|---|---|
| | Elbow | Pipe | Elbow | Pipe Center | Pipe Outside |
| Average | 2.6 (0.10) | 1.9 (0.07) | 10.3 (0.41) | 6.6 (0.26) | 3.5 (0.14) |
| Minimum | 0.5 (0.02) | 0.6 (0.02) | 2.6 (0.10) | 1.3 (0.05) | 0.8 (0.03) |
| Maximum | 6.3 (0.25) | 6.7 (0.26) | 41.0 (1.61) | 25.6 (1.01) | 13.9 (0.55) |

# CASS Materials

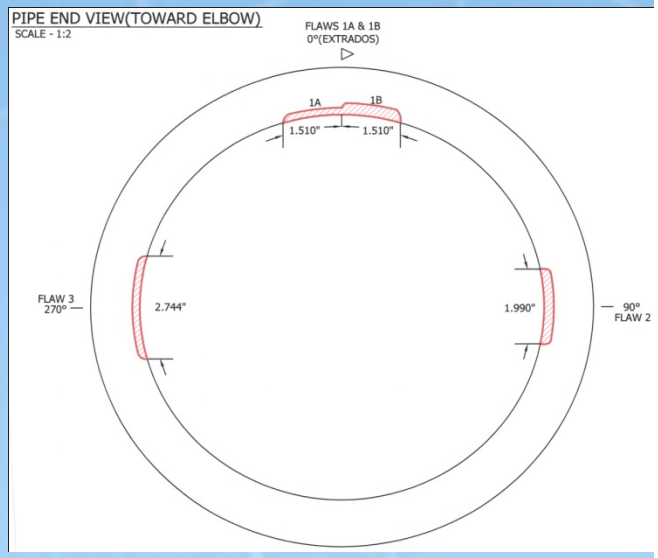
## End View Illustrations of Implanted Flaws




**Specimen 7C-059**




**Specimen 9C-001**




**Specimen 9C-002**

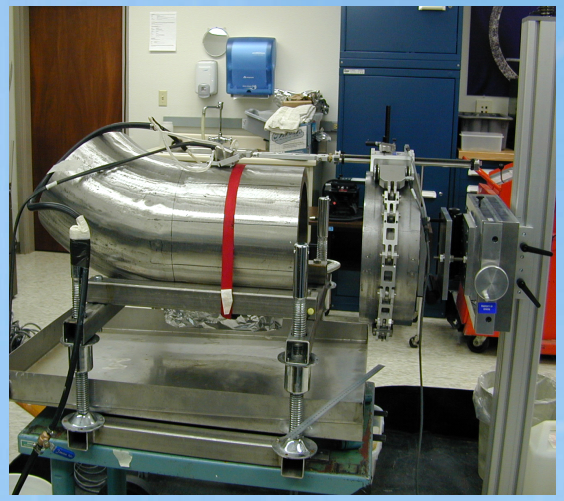
# CASS Materials

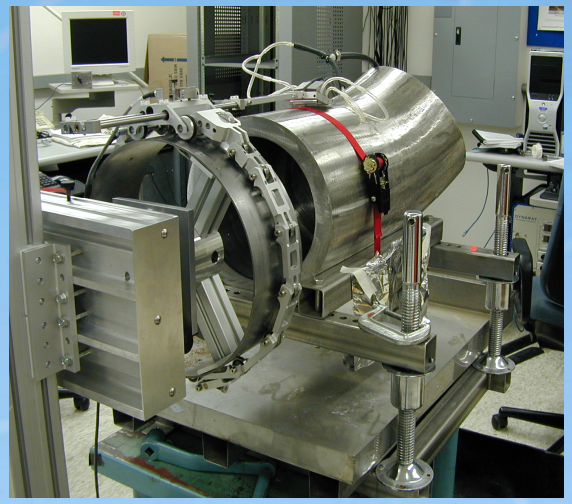
**True-state dimensions and locations of all implanted thermal fatigue flaws for three specimens. All flaws are oriented in circumferential direction.**

| Flaw | Flaw Location | Flaw Length, cm (in.) | Flaw Depth (Height) in % of thickness | Degree Location |
|---|---|---|---|---|
| 1-1 | Weld Centerline | 10.2 (4.0) | 35.2% T | 45° |
| 1-2 | Pipe Side Near Fusion Line | 5.1 (2.0) | 30.3% T | 120° |
| 1-3 | Weld Centerline | 5.1 (2.0) | 29.8% T | 210° |
| 1-4 | Weld Centerline | 15.2 (6.0) | 30.4/50.2% T | 300° |
| 2-1 | Weld Centerline | 7.6 (3.0) | 10/20% T | 0° |
| 2-2 | Weld Centerline | 5.1 (2.0) | 28.6% T | 90° |
| 2-3 | Weld Centerline | 6.4–7.6 (2.5–3.0) | 27.1% T | 270° |
| 3-1 | Weld Centerline | 7.6 (3.0) | 16/25.1% T | 0° |
| 3-2 | Weld Centerline | 5.1 (2.0) | 20.6% T | 90° |
| 3-3 | Weld Centerline | 6.4–7.6 (2.5-3.0) | 16% T | 270° |

# Set-up on Pressurizer Surge Line Specimen 7C-059

- Configured for standard PA-UT.
- Pipe-end on right side.
- Elbow-end on left side.





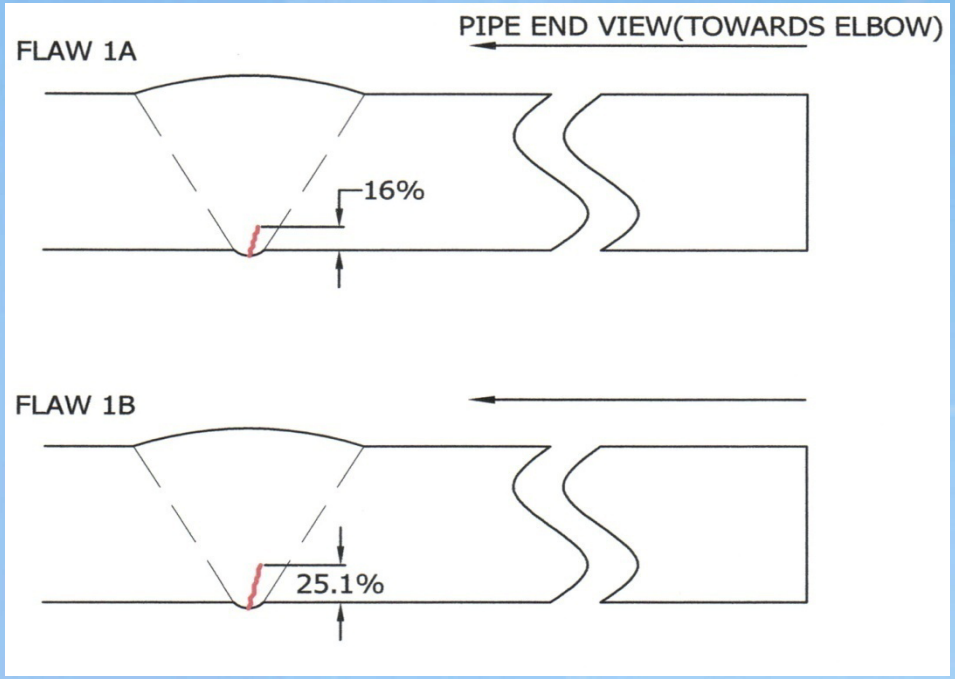
Guide ring, translation slide, and floor to ceiling brace shown to left.

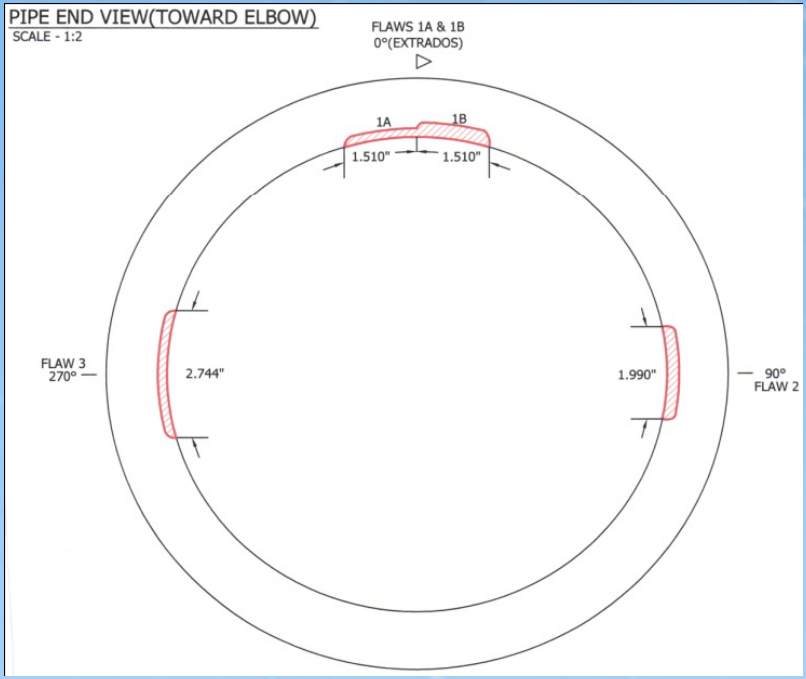
# PA UT Examinations

- Phased Array Ultrasonic (PA-UT) Examinations
  - To evaluate detection, localization, and sizing performance as function of frequency.
  - Four custom-designed PA-UT probes used:
    - 800 kHz, 1.0 MHz, 1.5 MHz, and 2 MHz
    - Inspection angles – $30^{o}$ to $70^{o}$ in $1^{o}$ increments
    - Data collected from both the CCSS pipe side and the SCSS elbow sides of the weld

# PA-UT Examination Results

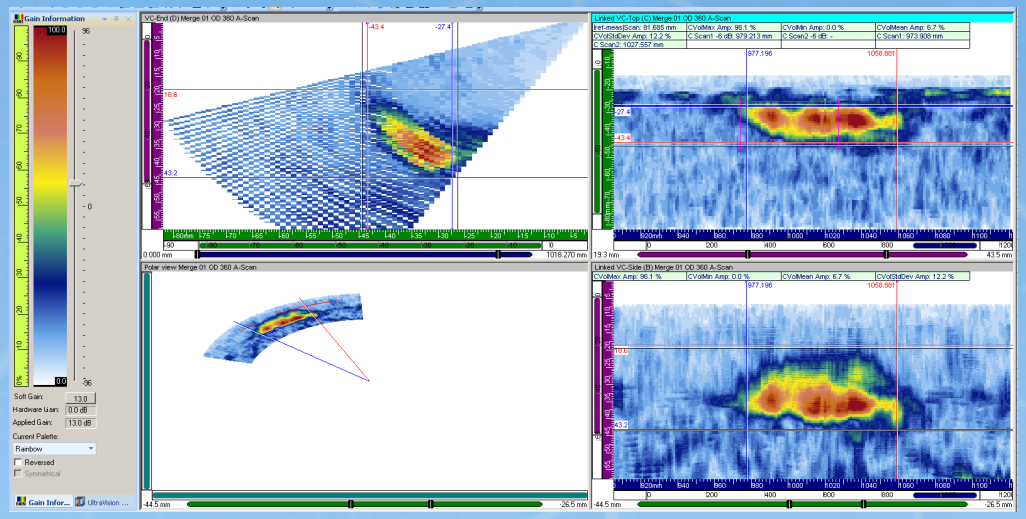
## Specimen 9C-002, Flaw 1



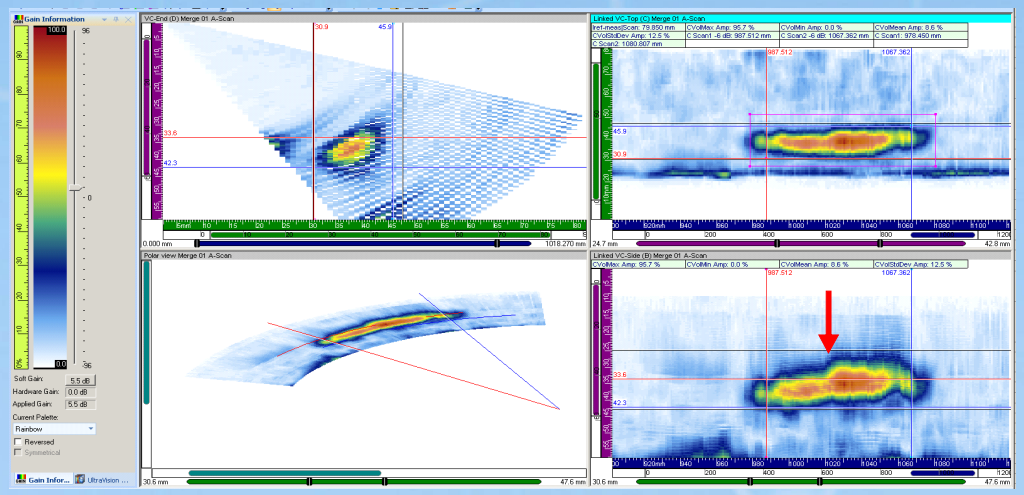



# PA-UT Examination Results

- **Flaw 1 of 9C-002**
- **800 kHz**
- **merged image for length sizing**



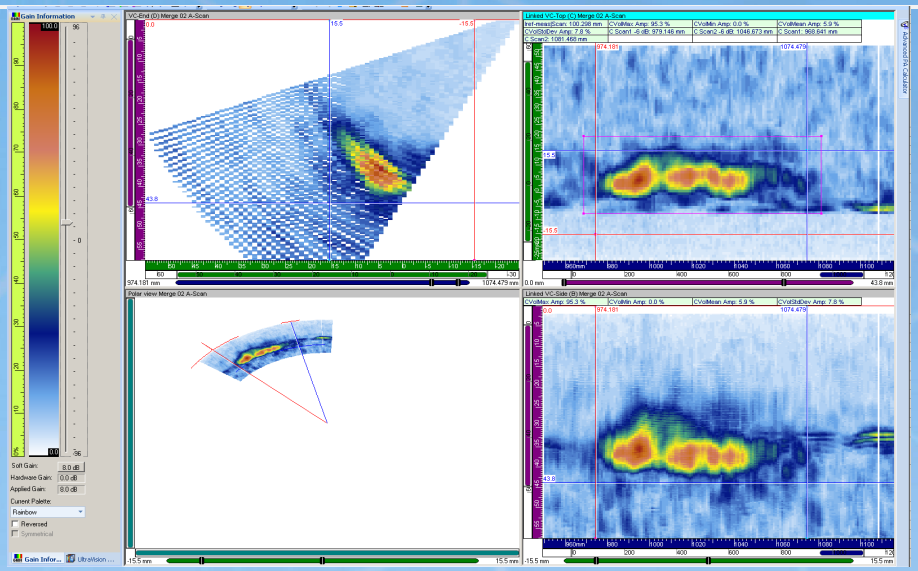
**from pipe side**



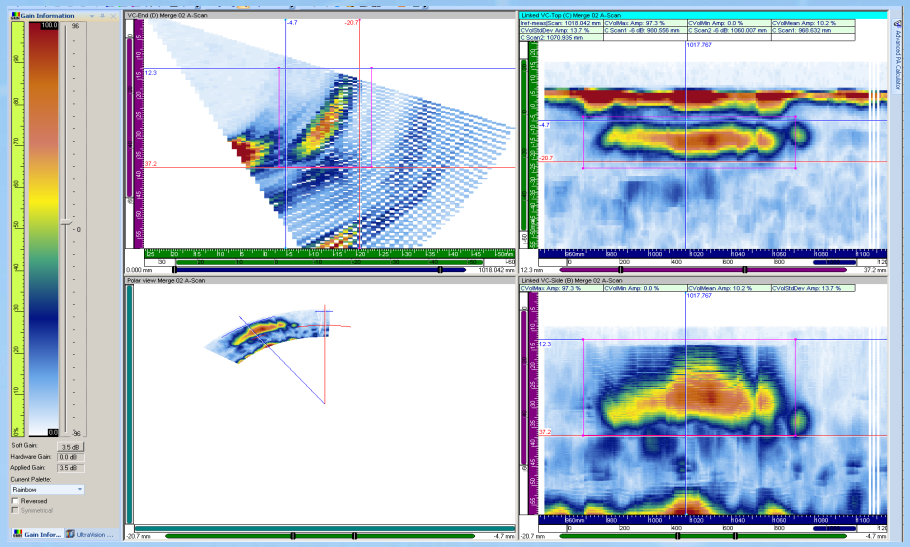
**from elbow side**

# PA-UT Examination Results

- **Flaw 1 of 9C-002**
- **1.0 MHz**
- **merged image for length sizing**



**from pipe side**

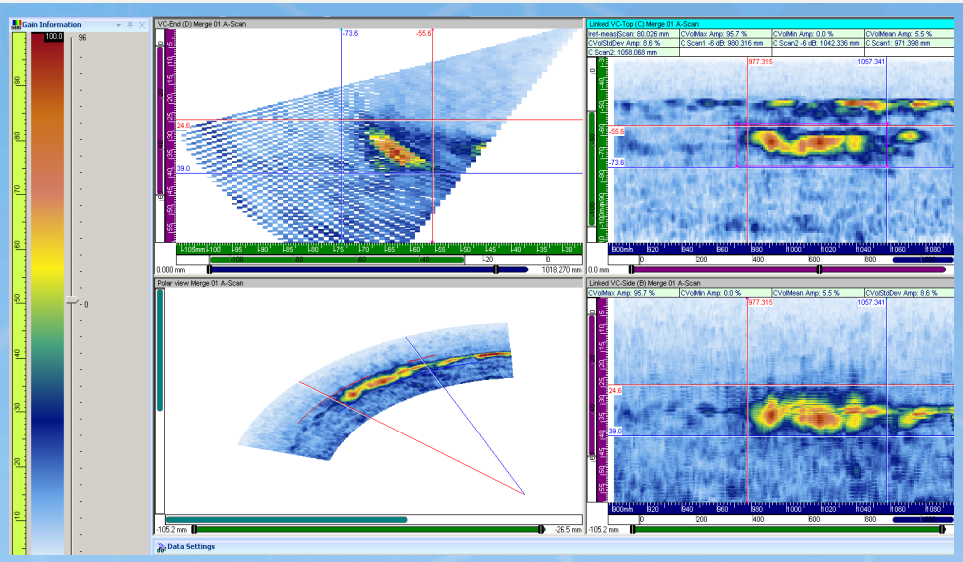


**from elbow side**

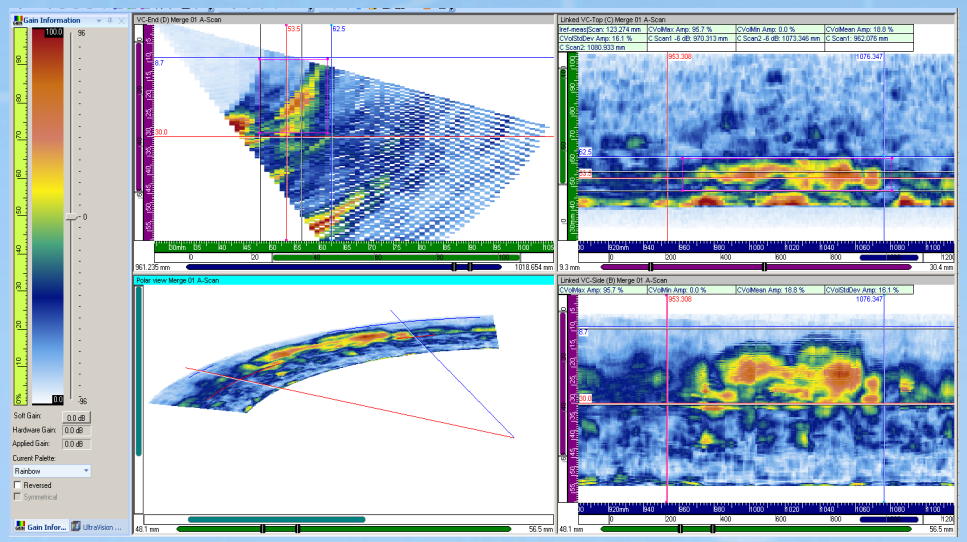
# PA-UT Examination Results

- **Flaw 1 of 9C-002**
- **1.5 MHz**
- **merged image for length sizing**

**from pipe side**

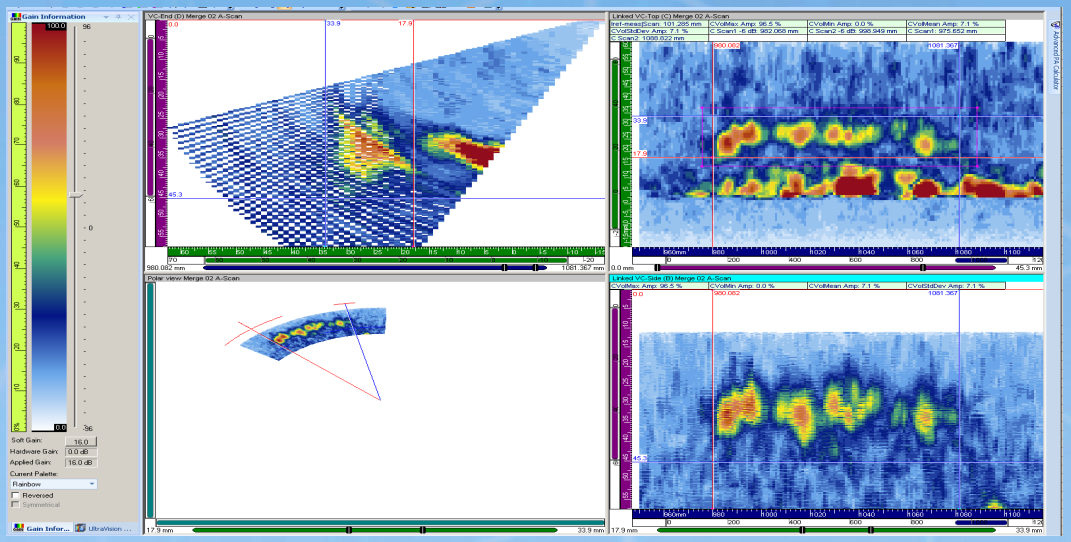


**from elbow side**

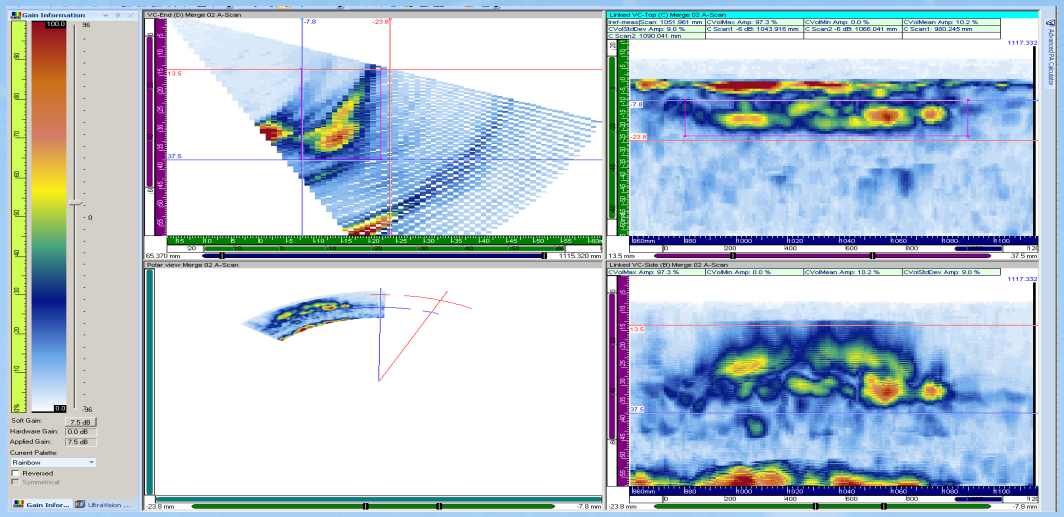


# PA-UT Examination Results

- **Flaw 1 of 9C-002**
- **2.0 MHz**
- **merged image for length sizing**



**from pipe side**



**from elbow side**

# PA-UT Examination Results

## Length Sizing Summary of Results

| | | 800 kHz | | 1.0 MHz | | 1.5 MHz | | | 2.0 MHz | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Specimen/ Flaw** | **True-State Length, mm** | **CCSS, mm** | **SCSS, mm** | **CCSS, mm** | **SCSS, mm** | **CCSS, mm** | **Raster CCSS, mm** | **SCSS, mm** | **CCSS, mm** | **SCSS, mm** |
| **7C-059** | | | | | | | | | | |
| 1 | 101.6 | 104.7 | 114.9 | 116.1 | 112.9 | 116.5 | | 102.4 | 119.3 | 96.6 |
| 2 | 50.6 | 63.0 | 19.1 | 69.2 | 61.4 | 34.8 | | 34.8 | 36.0 | 57.1 |
| 3 | 50.6 | 72.0 | -- | 49.3 | 39.3 | 49.7 | | 74.0 | 45.8 | 62.4 |
| 4 | 152.6 | 190.5 | 160.2 | 186.4 | 181.2 | 187.3 | | 181.3 | 181.4 | 143.3 |
| **9C-001** | | | | | | | | | | |
| 1 | 76.6 | 89.3 | 92.3 | 96.3 | 94.5 | 91.5 | 76.6 | 83.3 | 104.4 | 77.4 |
| 2 | 51.1 | 56.4 | 74.5 | 59.2 | 72.8 | 64.1 | 51.1 | 46.8 | 37.8 | 57.8 |
| 3 | 69.7 | 77.1 | 69.4 | 70.3 | 77.1 | 88.4 | 69.7 | 69.1 | 93.2 | 64.0 |
| **9C-002** | | | | | | | | | | |
| 1 | 76.7 | 68.6 | 79.9 | 100.3 | 96.5 | 62.0 | 88.2 | 79.0 | 101.3 | 90.5 |
| 2 | 50.5 | 53.2 | 67.2 | 57.4 | 73.9 | 53.3 | 50.3 | 63.3 | 54.1 | 66.9 |
| 3 | 69.7 | 60.8 | 70.2 | 68.0 | 91.0 | 55.3 | 54 | 55.3 | 53.8 | 71.9 |
| **RMSE** | | ***15.7*** | ***16.0*** | ***16.6*** | ***18.5*** | ***16.9*** | ***8.0*** | ***14.4*** | ***19.4*** | ***9.1*** |

# PA-UT Examination Results

## Depth Sizing Summary of Results

| | | 800 kHz | | 1.0 MHz | | 1.5 MHz | | | 2.0 MHz | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Specimen/ Flaw** | **True-State Length, mm** | **CCSS, mm** | **SCSS, mm** | **CCSS, mm** | **SCSS, mm** | **CCSS, mm** | **Raster CCSS, mm** | **SCSS, mm** | **CCSS, mm** | **SCSS, mm** |
| **7C-059** | | | | | | | | | | |
| 1 | 10.9 | 12.6 | 11.5 | 10.6 | 11.8 | 10.9 | | 11.5 | 11.4 | 10.6 |
| 2 | 9.3 | 11.6 | 9.6 | 11.3 | 9.1 | 9.2 | | 8.3 | 10.9 | 10.5 |
| 3 | 9.3 | 9.8 | -- | 10.4 | 10.0 | 10.6 | | 10.0 | 11.1 | 10.3 |
| 4 | 15.6 | 16.3 | 14.5 | 15.0 | 14.7 | 14.5 | | 14.9 | 15.0 | 15.3 |
| **9C-001** | | | | | | | | | | |
| 1a | 3.4 | 5.0 | 4.0 | 3.4 | 3.2 | 4.2 | 3.5 | 2.5 | 3.5 | 5.2 |
| 1b | 6.4 | 7.5 | 7.9 | 5.8 | 6.2 | 5.7 | 5.2 | 7.7 | 6.1 | 6.9 |
| 2 | 8.9 | 8.6 | 8.0 | 7.7 | 7.1 | 8.1 | 7.1 | 9.2 | 11.5 | 11.2 |
| 3 | 8.3 | 11.1 | 7.2 | 9.7 | 9.0 | 8.8 | 7.8 | 7.7 | 10.3 | 9.0 |
| **9C-002** | | | | | | | | | | |
| 1a | 4.8 | 4.3 | 6.9 | 4.8 | NA | 4.3 | 4.2 | 4.5 | 4.4 | 5.8 |
| 1b | 7.5 | 9.5 | 7.9 | 9.3 | 6.4 | 7.4 | 6.5 | 4.6 | 7.9 | 9.0 |
| 2 | 6.3 | 6.4 | 8.1 | 7.9 | 8.2 | 6.6 | 6.7 | 4.4 | 6.0 | 7.0 |
| 3 | 4.8 | 6.3 | NA | 6.5 | 3.6 | 5.3 | 8.3 | 5.1 | 6.0 | 6.9 |
| **RMSE** | | ***1.5*** | ***1.8*** | ***1.2*** | ***1.7*** | ***0.7*** | ***1.5*** | ***1.2*** | ***1.3*** | ***1.3*** |

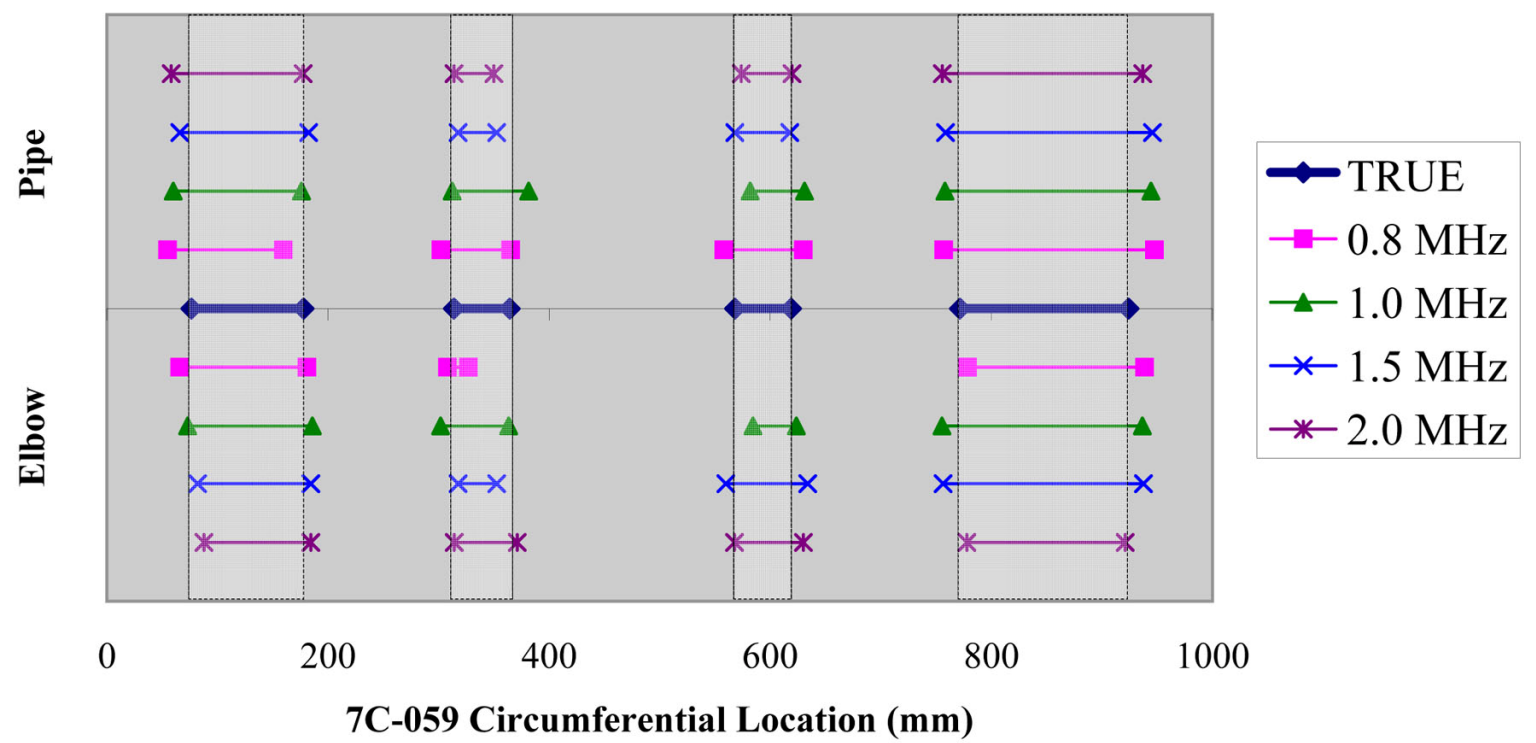
# PA-UT Examination Results

## Signal-to-Noise Ratio Summary of Results

| | 800 kHz | | 1.0 MHz | | 1.5 MHz | | | 2.0 MHz | |
|---|---|---|---|---|---|---|---|---|---|
| Specimen/ Flaw | CCSS, dB | SCSS, dB | CCSS, dB | SCSS, dB | CCSS, dB | Raster CCSS, dB | SCSS, dB | CCSS, dB | SCSS, dB |
| **7C-059** | | | | | | | | | |
| 1 | 17.0 | 15.7 | 16.6 | 18.3 | 14.7 | | 18.7 | 18.2 | 22.4 |
| 2 | 13.7 | 10.4 | 14.2 | 11.4 | 14.3 | | 11.6 | 16.9 | 11.1 |
| 3 | 14.5 | -- | 16.2 | 9.5 | 17.7 | | 17.5 | 19.9 | 18.1 |
| 4 | 15.1 | 17.4 | 16.3 | 15.8 | 17.3 | | 16.6 | 15.7 | 19.0 |
| **9C-001** | | | | | | | | | |
| 1 | 20.0 | 15.2 | 20.7 | 14.2 | 21.1 | 22.6 | 16.3 | 19.4 | 18.1 |
| 2 | 19.6 | 15.5 | 18.9 | 14.0 | 17.8 | 21.3 | 15.1 | 20.7 | 15.6 |
| 3 | 17.4 | 13.7 | 17.2 | 18.1 | 16.4 | 17.4 | 18.9 | 15.5 | 16.7 |
| **9C-002** | | | | | | | | | |
| 1 | 16.6 | 24.6 | 16.8 | 22.6 | 17.6 | 18.4 | 11.2 | 18.3 | 16.5 |
| 2 | 13.9 | 20.0 | 14.9 | 21.0 | 15.9 | 19.7 | 21.7 | 17.5 | 19.9 |
| 3 | 17.2 | 16.7 | 18.0 | 19.7 | 18.1 | 18.9 | 17.3 | 17.1 | 17.9 |

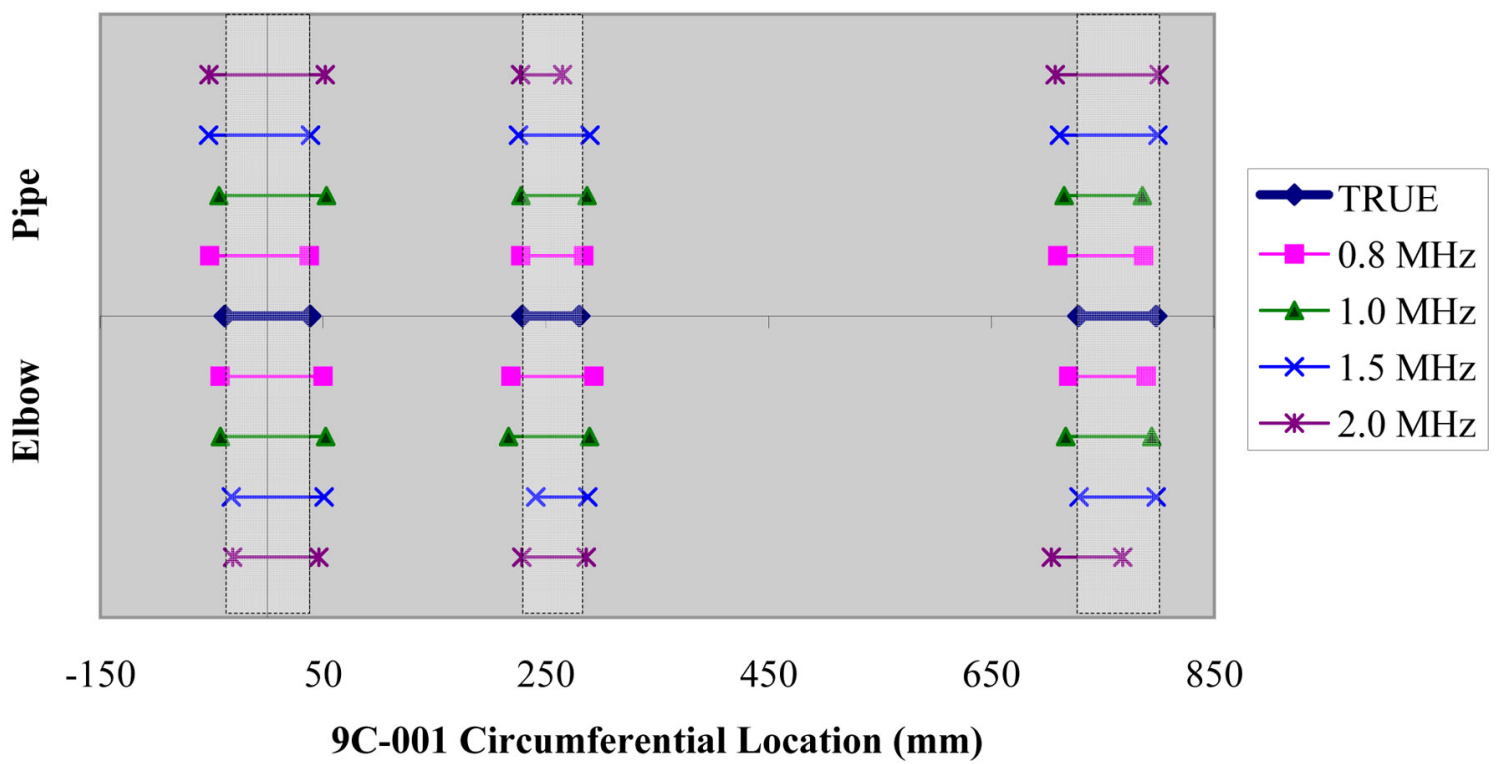
# PA-UT Examination Results

**Map of true-state and measured circumferential flaw localization data for specimen 7C-059**



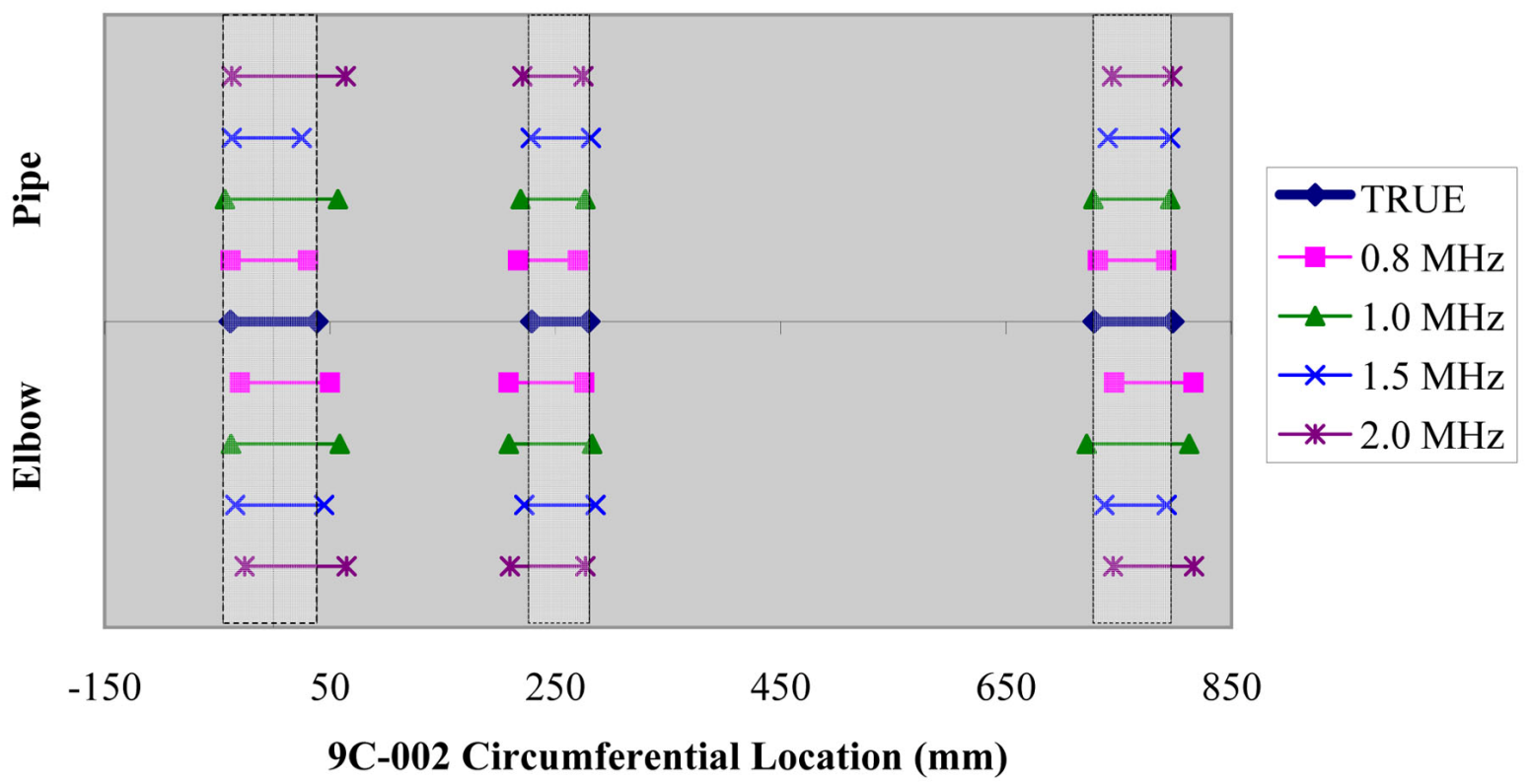
# PA-UT Examination Results

**Map of true-state and measured circumferential flaw localization data for specimen 9C-001**



# PA-UT Examination Results

**Map of true-state and measured circumferential flaw localization data for specimen 9C-002**



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# Conclusion

- State-of-the-art phased array inspection approaches are rapidly evolving and have enabled this demonstration of the capability to reliably detect and effectively characterize 10% - 50% through wall thermal fatigue cracks in cast austenitic stainless steel components where the wall thickness is less than 50 mm (2 in.).
- PA-UT data obtained using inspection frequencies ranging from 800 kHz to 2.0 MHz yielded strong signal-to-noise ratios and provided accurate length and depth sizing results.