INTRODUCTION

Piping welds in the pressure boundary of light water reactors (LWRs) are subject to a volumetric examination based on Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. Due to access limitations and high background radiation levels, the technique used is primarily ultrasonic rather than radiographic. Many of the austenitic welds in safety-related piping systems provide limited access to both sides of the weld, so a far-side examination is necessary. Historically, far-side inspections have performed poorly because of the coarse and elongated grains that make up the microstructures of austenitic weldments. The large grains cause the ultrasound to be scattered, attenuated, and redirected. Additionally, grain boundaries or weld geometry may reflect coherent ultrasonic echoes, making flaw detection and discrimination a more challenging endeavor.

Previous studies conducted at the Pacific Northwest National Laboratory (PNNL) on ultrasonic far-side examinations in austenitic piping welds involved the application of conventional transducers, use of low-frequency Synthetic Aperture Focusing Techniques (SAFT), and ultrasonic phased-array (PA) methods on specimens containing implanted thermal fatigue cracks and machined reflectors [1-2]. From these studies, PA inspection provided the best results, detecting nearly all of the flaws from the far side. These results were presented at the Fifth International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurised Components in 2006. These successful results led to an invitation to examine field-removed specimens containing service-induced intergranular stress corrosion cracks (IGSCC) at the Electric Power Research Institute’s (EPRI) Nondestructive Evaluation (NDE) Center, in Charlotte, North Carolina. Results from this activity are presented below.

IGSCC SPECIMENS

A number of specimens from the EPRI performance demonstration set were made available to PNNL for ultrasonic examination. These specimens were field-removed piping segments taken from several U.S. boiling water reactor (BWR) primary recirculation systems and contain service-induced IGSCC. Some of the specimens were part of a practice set and some were part of a secure set used for blind performance demonstration tests. These specimens varied in configuration with different weld crown geometries, counterbore, weld root conditions, etc. Figures 1 and 2 show some of the variations in practice specimens as viewed from the outside and inside surfaces of the pipe segments. Specimens had a nominal 28-in. (71-cm) diameter and 0.8–1.6-in. (2.0–4.1-cm) wall thickness. The secure specimens were similar in configuration to the practice specimens but access was limited to the outer surface only. A mapping of the flaws was provided, showing flaw location in the circumferential direction and axial position as upstream or downstream from a weld center line. However, a center line position was not marked on the specimen so the axial position for acquired data was referenced relative to the center of the weld crown. True-state location and length sizing information were provided but no true-state depth information was available. The examinations for this activity focused on detection of inner diameter (ID)-connected cracks, oriented circumferentially (parallel to the weld).

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PHASED ARRAY INSPECTION

The PNNL PA system used for data acquisition consisted of a Tomoscan III® 32-channel instrument, available off-the-shelf from ZETEC, Inc. The instrument can be programmed by the development of focal laws to control up to 32 channels for transmission and reception of ultrasonic signals. It acquires 12-bit data and operates through a local Ethernet connection to a standard desktop computer.

Three PA probes were used in this work and included two transmit-receive longitudinal (TRL) wave probes, one designed to operate at 1.5 MHz and one at 2 MHz, and a 2-MHz transmit-receive shear (TRS) wave probe. All three probes were specially designed for near- and far-side applications in wrought stainless steel material ranging from approximately 0.5 to 1.5 in. (13 to 38 mm) in thickness. The 2-MHz probes were used in an earlier PNNL far-side study [1-2] on thermal fatigue cracks and machined flaws. These two probes have integral wedges that were contoured to fit the appropriate pipe curvature for these specimens. The 1.5-MHz probe with removable wedges was designed later. It contains three elements in the secondary direction, which allows for improved lateral (side-to-side) beam skewing.

The 2-MHz TRL array was designed for near- and far-side applications in thinner pipe sections. It consists of two 2-element by 14-element matrix arrays. One array is used for transmitting, the other for receiving ultrasonic signals. The highly damped probe has a 70% bandwidth (BW) at −6 dB and an approximately 25-mm² footprint with an integral wedge for data collection in tight geometrical configurations. This smaller size generally allows insonification of the far side even with a weld crown present. The probe’s nominal wavelength in stainless steel is 3.0 mm at its average center frequency of 1.9 MHz. Skew angles of ±10 degrees were possible with this array.

The 1.5-MHz TRL array consists of two 3-element by 10-element matrix arrays with a 62% bandwidth at −6 dB. This array is designed with a non-integral wedge allowing change out of the wedge for inspecting pipes of varying diameters or flat plates. Its footprint is approximately 50 by 50 mm. The larger size and increased number of elements in the lateral direction provides improved beam forming and skewing but limits its application in tight geometrical conditions. This TRL array has a wavelength of 3.8 mm in stainless steel, at its average center frequency of 1.5 MHz. Skew angles of ±10° and ±20° were possible with the larger number of elements in the secondary axis of this probe.

Figure 1 - Examples of Specimens as Viewed from the Outer Surface
The 2-MHz TRS array consists of two 24-element linear arrays with an integral wedge. Its footprint is approximately 50 by 30 mm. The array has a −6 dB bandwidth of 65% and an average wavelength of 1.4 mm in stainless steel at its center frequency of 2.14 MHz. Skewing was not possible with this array.

Focal laws were developed for the TRL and TRS arrays and programmed into the Ultravision® acquisition software. The focal laws were developed to provide ultrasonic longitudinal beam angles from 30° to 70° at 1° increments for the 2.0-MHz TRL array in the piping specimens, and from 40° to 70° at 1° increments for the 1.5-MHz TRL. Shear wave focal laws were developed for the 2.0-MHz TRS array to provide beam angles from 40° to 70° at 1° increments. This resulted in the sound field being swept through many discrete beam angles in near real time at each position along the entire length of the linear scan. In other words, for each axially oriented cross section of material, data were acquired from 30° to 70° or from 40° to 70°, while the linear scans progressed circumferentially.

Sound field modeling results are summarized in Figs. 3–5 for the 1.5-MHz TRL, 2-MHz TRL, and 2-MHz TRS probes in stainless steel. The left portion of each figure shows an idealized sound field as a function of depth, in a side view (B-scan), for a 45° inspection angle. The designed focal depth is noted in the image by a black crossed circle. A top view of the sound field at the focal depth is shown in the right portion of each figure. Note that the top view color scheme has been normalized to show the full color range, white to red, in the view. Reference lines separated by 2 mm are displayed in the figures to show scale. Theoretical spot sizes as measured from these simulations at the red level, approximately 3 dB points, are 3.4 by 2.7 mm for the 1.5-MHz TRL probe, 5 by 4.3 mm for the 2-MHz TRL probe, and 2.9 by 1.7 mm for the 2-MHz TRS probe. The spot sizes at the yellow level, approximately 6 dB points, are 9 by 6.9 mm for the 1.5-MHz TRL probe, 11.2 by 9 mm for the 2-MHz TRL probe, and 7.2 by 2.6 mm for the 2-MHz TRS probe.

For the three probes and all specimens, data were acquired with a manual scanner. The scanner was mounted on a curved section or ring positioned adjacent to the specimen. The 1.5-MHz TRL probe and scanner are shown in Fig. 6. Data were acquired with the sound beam directed perpendicular to and pointing toward the weld, while the manual scanner was moved in the circumferential direction. The scanner
Figure 3 - TRL 1.5-MHz Beam Model at 45° with the Side View on the Left and Top View on the Right. The top view is at the focal depth of 30 mm. Vertical and horizontal lines with 2-mm separation are shown for reference.

Figure 4 - TRL 2-MHz Beam Model at 45° with the Side View on the Left and Top View on the Right. The top view is at the focal depth of 30 mm. Vertical and horizontal lines with 2-mm separation are shown for reference. The focal spot in Side View is in the green to blue transition zone, showing that this probe focuses closer to the near surface than at the desired depth.

Figure 5 - TRS 2-MHz Beam Model at 45° with the Side View on the Left and Top View on the Right. The top view is at the focal depth of 32 mm. Vertical and horizontal lines with 2-mm separation are shown for reference.
encoder was calibrated to the specimen to give circumferential positional information. A network of Tygon® tubing was connected to embedded ports on both sides of the probe yoke for delivery of a water stream to provide coupling. Several linear scans were acquired from both the near side and the far side when specimen configuration allowed. A line scan with the probe positioned as close as possible to the weld crown center was acquired first. Additional scans with added offsets from the first probe position were then acquired from both sides when possible, typically at offset distances of 0.25 in. (0.64 cm) and/or 0.5 in. (1.27 cm). The line scans proceeded clockwise with respect to the flow, and the flow direction was noted by an arrow on the specimens. Skewed data were also acquired to enhance flaw detection because the flaws were true IGSCCs and typically exhibited branching out of the plane of the flaw parallel or axial to the weld. Data obtained at skewed angles can be sensitive to the crack branching, and when combined with the normal data, may improve the flaw detection. Skew angles of ±10° and ±20° were used with the 1.5-MHz TRL probe. The linear TRS probe was not skewed and the 2.0-MHz TRL probe was skewed at ±10°. Data were acquired such that each file contained only a single skew angle. The default skew was 0°.

PHASED ARRAY RESULTS

Flaw data from the EPRI specimens were analyzed for detection with the three PA probes. The detection criteria are discussed here. Given the true state of a specimen, if a clear response that was distinct from geometry and possessing a good signal-to-noise ratio (SNR) was found at any of the skew angles in the region noted as flawed, a “Yes” result was recorded for the flaw. If a weak signal that was discernable but not clearly separate from geometry or close to the noise levels was found in the region noted as flawed, a “Marginal” result was recorded. If no signal was found in the region noted as flawed, then a “No” result was recorded.

Flaw detection generally involves two parts. One part of the detection process relates to signal amplitude. How high above the background noise level is the signal of interest? A measurement used for this process is the SNR. An SNR of at least two to one, or 6 dB, is commonly desired, but current analytical techniques allow lower values with most procedures requiring analyses of flaw responses down to the material noise level. The SNR for these data were calculated from the peak signal responses from “Yes” detected flaw responses and the average noise level obtained in the near proximity of the flaws. Noise values were taken at the same part path as the signal responses. SNR values from the different detected cracks were averaged with results shown in Fig. 7 for each probe and for near- and far-side access. Results indicate that the SNR values are good; all exceeding 10 dB (signal is 3.2 times the noise level). The higher near-side SNR for the TRS probe is possibly due to the lack of mode conversion taking place. From the far side, the SNRs are similar for each of the three probes for a detected flaw. With SNRs being adequate in these data sets, the challenge in flaw detection then becomes one of signal discrimination.

Another major step for flaw detection is in signal discrimination—is the ultrasonic response being generated from a geometrical condition, material noise, or a flaw? Ideally, one would determine
the weld area profile along the pipe axis using a contour gauge on the outer diameter (OD) surface and 0° incident ultrasonic thickness readings to exhibit the approximate ID contour. These contour measurements were not made during this exercise. In addition, the presence of weld crowns prohibits the collection of a normal beam ultrasonic measurement to map the ID weld region. If the weld area is diagrammed, indications from subsequent specimen evaluations can be mapped to the originating location in the specimen profile. Signals mapped to the counter bore, weld root, etc. can be classified as geometrical indications. Often geometrical signals have significant length and amplitude associated with them. A strong counterbore signal provides a reference point for all other signals, whether the weld area profile is known or not. As an example of a known configuration, an austenitic stainless steel piping specimen, typical of that found in a primary coolant BWR recirculation system, was fabricated with sawcuts and implanted thermal fatigue cracks. The weld cross section is shown in Fig. 8. PA data acquired from the far side of the flaw is shown in Fig. 9. The sector side view on the left of Fig. 9 shows, from left to right in the image, a geometrical signal from the inner diameter mismatch step, a geometrical signal from the weld root, and the flaw signal.

Data from the EPRI specimens were generally not as straight forward and were cluttered with many signals to consider. Figure 10 shows near-side data from a practice specimen. The geometrical signal from the far side of the weld is clearly seen and can be used as a reference. The side view shows three main reflectors between the red and blue horizontal lines. This region is gated and shown in the top view. The far-side geometrical signal is identified and all other signals referenced to it. Notice that the far-side geometry produces a strong signal, but with signal dropout evident. The flaw signal is sandwiched between two geometrical signals in the side and top views and the near-side geometry signal does not extend the full length of the image. The vertical red and blue lines in the side view are used to gate out the flaw signal with results shown in the end view. The flaw signal is at the bottom of the end view and is boxed with the magenta lines. Other signals are detected at that same axial position but are lower in amplitude.
For this reason, the flaw was considered “Yes” detected. In general, for data analyses, a narrow vertical gate such as that shown in the side view is moved across the image while looking at the end view for signals of interest. In the PNNL analyses, one considered if there was a signal in the area noted as flawed that was separable from other signals and of higher amplitude. All images in this report are from merged data but unmerged data were also reviewed during the flaw detection analyses.
Figure 11 shows data from a region that was categorized as “Marginal” in detection. There is a signal in the region of interest that is slightly higher than the background, but it does not have much length associated with it compared to surrounding area signals. Another signal in the data (end view) with similar amplitude stands out as a possible flaw but this region was not shown to be flawed. This could potentially lead to a false call in this area. False calls were not tracked in this analysis but contributed to the “Marginal” result as opposed to a “Yes” detected call.

Figure 12 shows data from a region that was classified as “No” in detection. There is no signal in the flaw region that stands out from the surrounding area. A lack of signal might be evident in the region of interest in the end view, but this was not used as one of the flaw detection criteria.
The secure and practice data results were combined to give a larger sample population and to protect the integrity of the secure set. A summary of the results are listed in Table 1 [3]. This combined data set represents a number of service-induced cracks in a variety of pipe and component configurations joined with an austenitic weld. The depths of the cracks were not known nor measured from the data as tip-diffracted signals were not sought out. The lengths of the cracks were variable, as reported by EPRI true-state information. This study focused on flaw detection only, so crack lengths were not measured. In general, cracks on the small end of the observed length range could be confused with material noise, and cracks on the long end of the range could be confused with part geometrical reflectors such as counterbore or weld root. Medium to long indications whether from a flaw or geometry could also exhibit signal drop out due to sound field redirection, scattering, or attenuation. These issues make signal discrimination more challenging.

The detection summary shows that a near-side inspection using methods similar to those described in this report will be superior with approximately 70% to 80% of the flaws being detected. On a far-side inspection using similar methods, the detection rate drops to approximately 50% for shear waves and is just under 70% for the longitudinal wave modality.

**BEAM FIELD MAPPING**

As part of ongoing efforts at PNNL in understanding sound field propagation through materials, a coupon was cut out of a wrought stainless steel piping specimen used in earlier far-side studies [1-2] and examined. The coupon shown in Fig. 13 has a wrought stainless steel base material end and an austenitic welded end, both machined at 30°. To map the longitudinal sound field, a probe was placed on the specimen OD facing the cut surface and a pin transducer was scanned normal to the 30° cut surface in an immersion tank. The experiment was performed at both ends of the coupon. In this way, a comparison of the sound field as measured through the base material and the weld material was made. Only the longitudinal mode has been measured to date. The results for the 1.5-TRL probe at a focal depth of 25 mm and angles of 30°, 40°, 50°, and 60° are shown in Figs. 14–17. Each image represents a 1 by 1 in. (2.54 cm) area.
In comparing the base material and weld material sound fields, the peak average SNRs are similar at 40° and 60° but approximately 4 dB less at 30° and 50° in the weld side. In all images, the SNR is very good at 18 dB or greater. The spot-size differences are perhaps greatest at 40° and 50° in the horizontal direction with the beam spreading more through the weld material than in the base material. At 70° both ends of the coupon

![Figure 13](image13.png)

Figure 13 - Side View of Wrought Stainless Steel Specimen Containing an Austenitic Weld Used in the Beam Mapping Experiments

![Figure 14](image14.png)

Figure 14 - 1.5 TRL Image at 30°, WSS Side on the Left and Weld Side on the Right. Each image represents a 1 by 1 inch (2.54 cm) area.

![Figure 15](image15.png)

Figure 15 - 1.5 TRL Image at 40°, WSS Side on the Left and Weld Side on the Right. Each image represents a 1 by 1 inch (2.54 cm) area.
show an expanded sound field. These images in general still show a coherent sound field passing through the weld material, which implies that a valid inspection is possible in the far-side region with this probe. This sound field mapping work is continuing with experiments being planned for shear-mode mapping.

**SUMMARY AND CONCLUSIONS**

In summary, practice and secure data set results from a PA inspection of components containing service-induced IGSCC were combined to maintain integrity of the secure set. The combined results showed that the TRL inspection and analysis produced a far-side detection rate of approximately 69% while the TRS results were lower at 52%. The data images obtained with the TRS probe showed much more scattering of the beam in passing through the austenitic weld material as well as the base material. This observation will be validated in the future with shear wave sound field mapping experiments. SNRs in both longitudinal and shear wave responses were good for detected flaw signals, suggesting that signal discrimination remains the most challenging aspect of flaw detection.

The 2-MHz TRL probe, while not producing as well defined a beam as the 1.5-MHz TRL probe, had a smaller footprint and therefore allowed better access to the far-side area of interest. This was an advantage in tight geometrical configurations. Lower frequency probes are less susceptible to beam steering, scattering, and attenuation, but require a larger probe footprint, provide reduced resolution due to an increase in the wavelength, and therefore, make weld crown removal necessary for a far-side inspection. Surface undulations when present also cause coupling problems with larger
probes. These trade offs suggest that an inspection should be performed with multiple probes to take advantage of the benefits of both higher frequency smaller element and lower frequency larger element designs.

Weld crown removal would also provide enhanced signal discrimination in two ways. The first and most important is that in the absence of weld crowns, the inner diameter profile of the specimen in the complex weld region can be better determined by employing more effective normal-beam ID profiling methods. With a known profile, the mapping of ultrasonic response signals to part geometry is greatly simplified allowing the examiner to more readily eliminate geometrical responses in the complex data image. Second, more effective peaking of the ultrasonic signals can occur. This would likely be accomplished with raster scanning to peak both the corner and tip signals when present. In summary, signal discrimination in this often complex inspection and more specifically complex data interpretation task can be improved with weld crown removal.

REFERENCES

