

PACIFIC NORTHWEST NATIONAL LABORATORY
TECHNICAL LETTER REPORT

**EVALUATION OF ALTERNATIVE TO 10 CFR 50.55A(G)(6)(II)(F)(4) FOR LIMITATIONS TO
VOLUMETRIC EXAMINATIONS OF DISSIMILAR METAL WELDS**

**FLORIDA POWER & LIGHT
ST LUCIE NUCLEAR POWER PLANT Unit 1
DOCKET NUMBER: 50-335**

BACKGROUND

By letter dated, February 4, 2013 (ADAMS Accession Number ML13046A101), Florida Power and Light, Inc. (the licensee), submitted a request for relief from the examination requirements of Title 10 of the Code of Federal Regulations (10 CFR) 50.55a(g)(6)(ii)(F) which, in part, requires licensees implement American Society of Mechanical Engineer's Boiler and Pressure Vessel (ASME) Code Case N-770-1, "Alternative Examination Requirements and Acceptance Standards for Class 1 PWR Piping and Vessel Nozzle Butt Welds Fabricated With UNS N06082 or UNS W86182 Weld Filler Material With or Without Application of Listed Mitigation Activities," 10 CFR 50.55a(g)(6)(ii)(F)(3) requires a baseline examination of each butt weld in the reactor coolant pressure boundary that uses Alloy 82/182 weld materials. These inspections are to be performed in accordance with the requirements of Appendix VIII of ASME Code Section XI, for Class 1 components.

The licensee submitted an alternative to volumetric examination coverage requirements for several cold leg dissimilar metal welds (DMWs) at St. Lucie Nuclear Power Plant Unit 1 (St. Lucie). The alternative applies to limited coverage obtained on axial scans (for detection of circumferentially-oriented cracking), as well as for limited coverage on circumferential scans (for detection of axial cracking) on select DMWs. The NRC requested that Pacific Northwest National Laboratory (PNNL) evaluate the licensee's alternative with respect to claimed coverage and ultrasonic technique capabilities as applied to two reactor coolant pump (RCP)-to-primary loop piping welds identified as Weld RC-121-6-504 and Weld RC-124-7-504 as these two DMWs have the least examination coverage among all cold leg DMWs. PNNL's evaluation included theoretical modeling of the sound beams based on actual phased-array design parameters and component geometrical information provided by the licensee. Based on NRC request, PNNL performed limited "backscattered" acoustic energy response modeling from a simulated circumferential flaw. It should be noted that currently PNNL modeled sound field extents and densities, and reflected energy from the simulated flaw, represent only isotropic material, i.e., actual grain sizes, orientations and microstructures, acoustic velocity variations, and other material variables that affect sound beam attenuation, re-direction, specular reflections from flaws, and signal-to-noise values have not been applied, and in some cases, are presently unknown.

Another consideration is the potential for inconsistent transducer coupling and physical limitations. The transducer coupling variable is not addressed in the current modeling software, as CIVA¹ applies ideal coupling (contact) between the probe-wedge and the component being examined. However, the actual component outside diameter (OD) weld surfaces, from where

¹ CIVA is a trademarked acoustic modeling software package developed by Commissariat à l'Énergie Atomique (CEA).

the manual phased-array examinations were performed, exhibit variations in surface contour (waviness) around the circumference of the pipe, as the weld crowns would have been manually ground or blended smooth during the time of fabrication. Depending upon the extent of surface irregularities encountered during the examination, intermittent and unpredictable losses in signal response amplitudes and degradation of sound beam coherence are likely to occur, due to ultrasonic transducer coupling inefficiencies. This can be more pronounced with phased-array probes, as the array is generally required to be adequately coupled over the entire primary axis in order for wave-fronts emitted from individual elements to constructively interfere to produce proper beam steering and focusing. In addition, the licensee stated that probe wedges with flat contact surfaces were used for these examinations, which could also contribute to coupling inconsistencies in wavy regions, or if the probe were to rock during circumferential scans on the component.

Further, in a letter dated July 30, 2013, the licensee stated that the transmit-received (TR) phased array probe consisted of each array containing 2 rows of 16 elements where for operation of the probe the ‘row elements were tied together with the cable wiring’ (Response to RAI-5 B). As PNNL could not model this physical modification to the operation of the array, an electronic modification was simulated by PNNL where side-by-side row elements were delayed with matching time, to best represent the wiring modification for operation of the probe. PNNL used the licensee provided delay laws for all simulations in this document.

Based on the physical limitations described above, PNNL’s models should be viewed as a “best-case” representation only. As requested, PNNL performed individual assessments for each of the subject welds for all disclosed axial scan limitations due to resistance temperature detector (RTD) and spray nozzle obstructions. These are provided in the following sections of this report.

EVALUATION

Weld RC-121-6-504

Weld RC-121-6-504 is a full penetration DMW on a RCP outlet nozzle joining the carbon steel primary piping to a cast austenitic stainless steel (CASS) safe end. The carbon steel primary piping is clad with stainless steel on the inside diameter (ID), and the CF8M CASS safe end is welded directly to the RCP housing. An idealized cross-sectional illustration of Weld RC-121-6-504 is provided in Figure 1. Note that this scaled drawing shows the OD surface to have some degree of irregularity. Because OD surface features of a ground weld crown can vary circumferentially, and no information could be obtained from the licensee to depict actual field conditions, PNNL modeled Weld RC-121-6-504 with essentially flat surfaces and only accounted for OD dimensional changes such as the slight axial taper noted across the weld. Figure 1 also provides the ASME examination volume required as a cross-hatched shaded area.

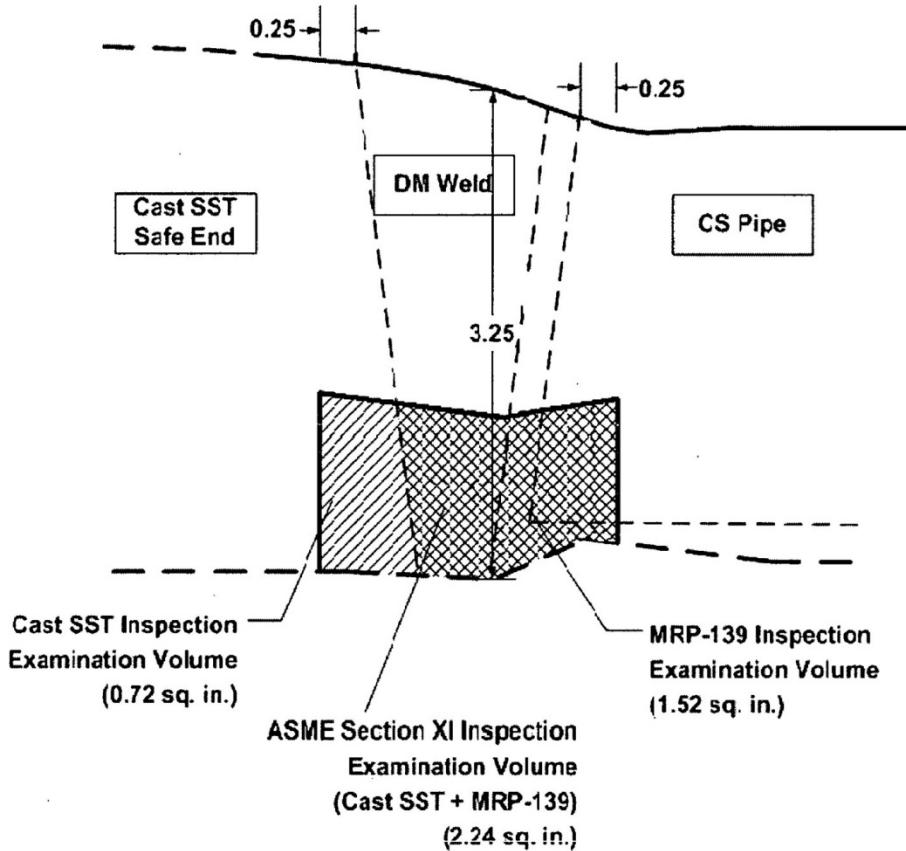


Figure 1. Idealized Cross Section of RCP Weld RC-121-6-504

The axial examination (for detecting circumferentially-oriented flaws) of this weld is physically limited by two nozzles that extend along a circumferential arc. As shown in Figure 2, the RTD nozzle obstruction introduces varying limitations for the axial scan path over an outside diameter (OD) circumferential length of 99.1 mm (3.9 in.). Figure 3 depicts the larger Spray Nozzle obstruction that also provides varying limitations that impact the axial scanning access over an OD circumferential length of 250.2 mm (9.85 in.). These physical limitations are illustrated in Figures 1-3. As a result of these limitations, the licensee has postulated the ray trace coverage for longitudinal angles between 40 and 50 degrees (EPRI-DMW-PA-1 Rev. 1) as well as the maximum circumferential PWSCC flaw size that could be detected at the B or H circumferential positions as depicted in Figure 3. The theoretical semi-elliptical flaw to be detected at the B or H position is to have an aspect ratio of 6:1 length-to-depth ratio with dimensions of 195 mm (7.7 in.) in length and a maximum of 32.5 mm (1.3 in.) in through-wall extent.

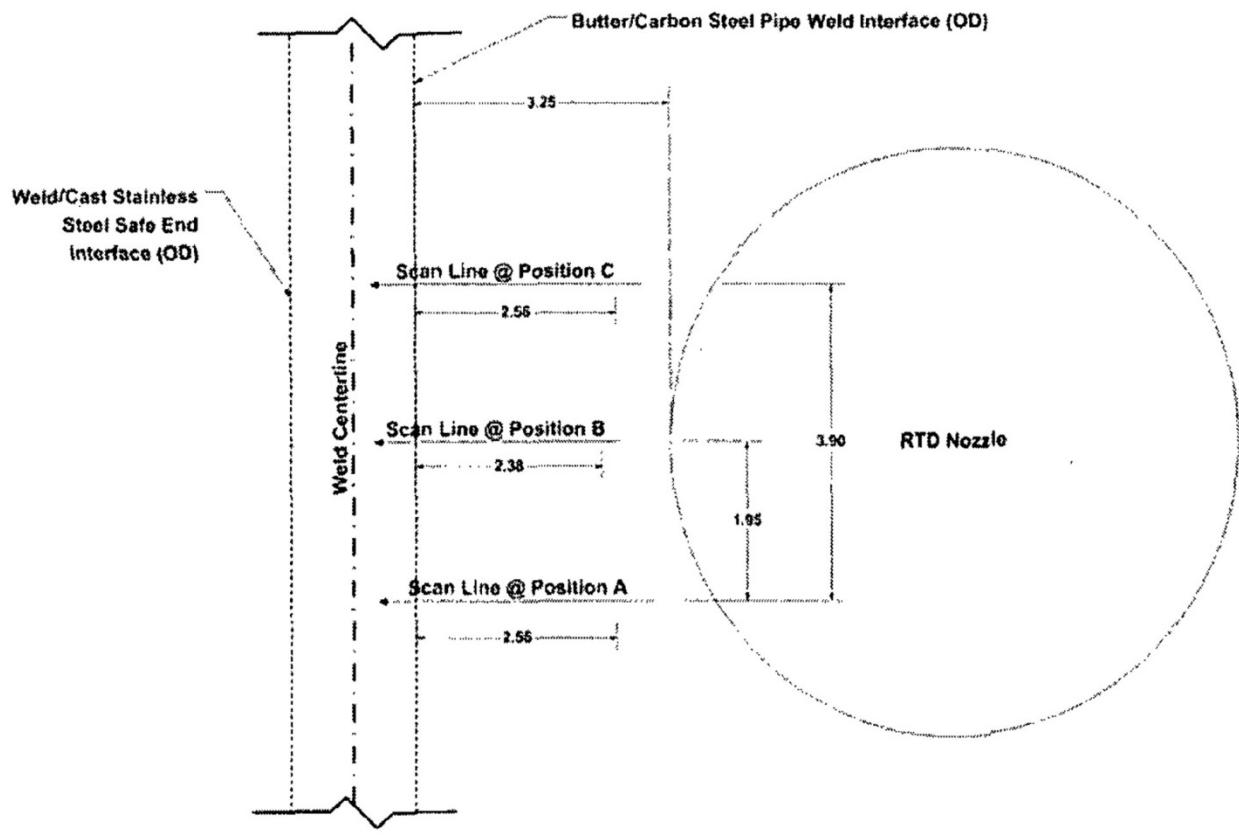


Figure 2. Top View of RCP Weld RC-121-6-504 Detailing Access Limitations as a Result of the RTD Nozzle Obstruction

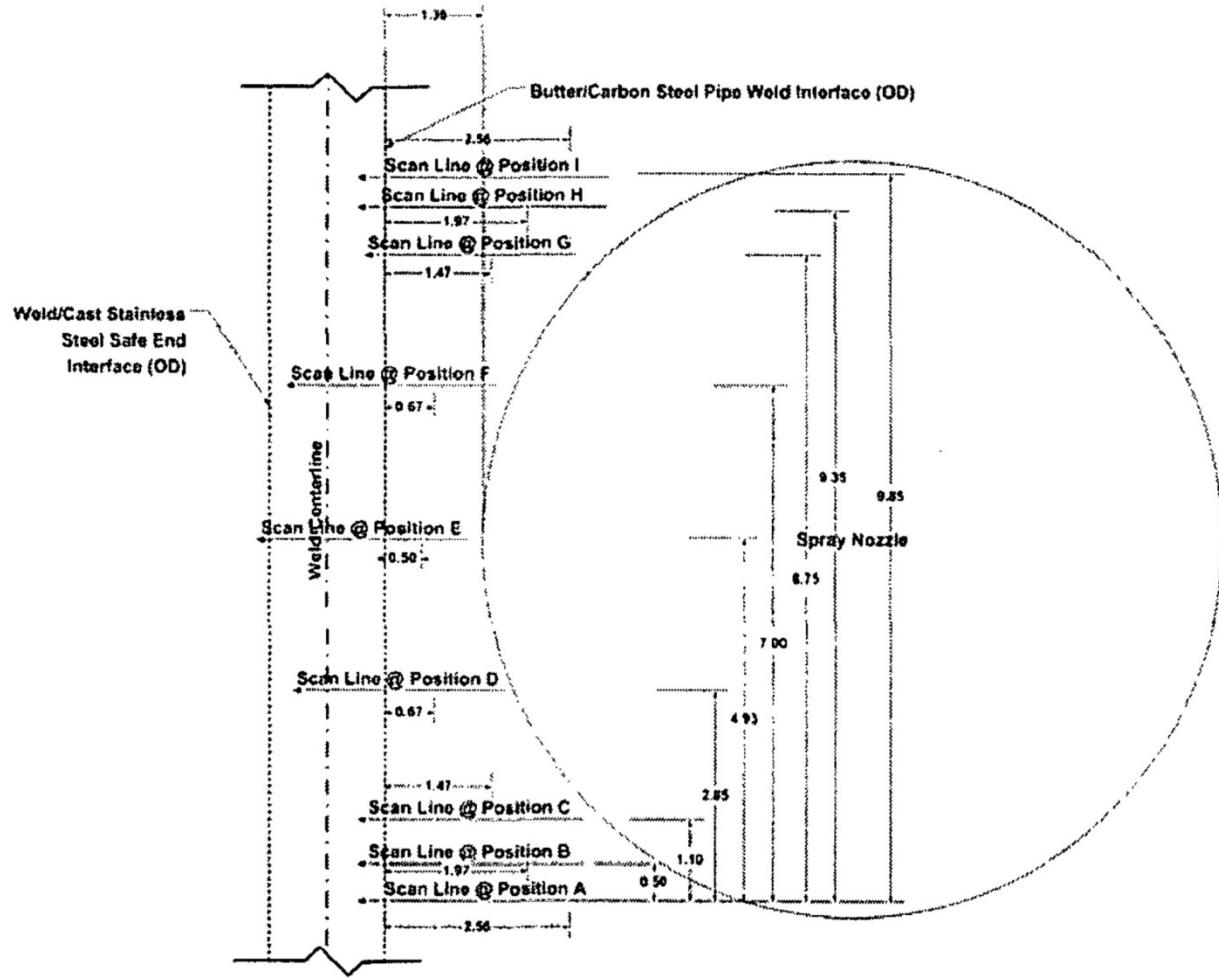


Figure 3. Top View of RCP Weld RC-121-6-504 Detailing Access Limitations as a Result of the Spray Nozzle Obstruction

The licensee also submitted volumetric examination sketches showing theoretical beam plots between angles of 40 to 50 degrees (EPRI-DMW-PA-1 Rev. 1) for axial scan coverage obtained across all the access limitations highlighted in Figures 2 and 3; e.g., RTD Nozzle limitation positions A, B, C. The licensee's sketches indicate that the credited coverage varies as a function of the axial scanning limitation. The licensee's theoretical coverage for the Spray Nozzle obstruction at positions B and H are shown in Figure 4. At the B and H positions the licensee postulated that a flaw developing in the susceptible material region could grow to a maximum through-wall extent of 40%, 32.5 mm (1.2 in.) before detection (via flaw corner or tip specular or diffracted responses) in the region containing the Spray Nozzle. Without these limitations, axial scans could be initiated at a sufficient distance away from the weld on the carbon steel primary piping to ensure 100% volumetric coverage of the susceptible material, as full volumetric scans were completed for the remaining circumferential sections of the weld. In addition, the licensee estimated volumetric coverage for axial scans at approximately 92.1% of

the required circumference of the weld (MRP-139 Volume Coverage), which includes the full inner one-third of the susceptible weld material, as examined from the ID-clad carbon steel piping. The licensee did not take credit for the examination coverage on the CASS safe end material because the ASME Code, Section XI, has no qualification procedures for the ultrasonic examination of the CASS material.

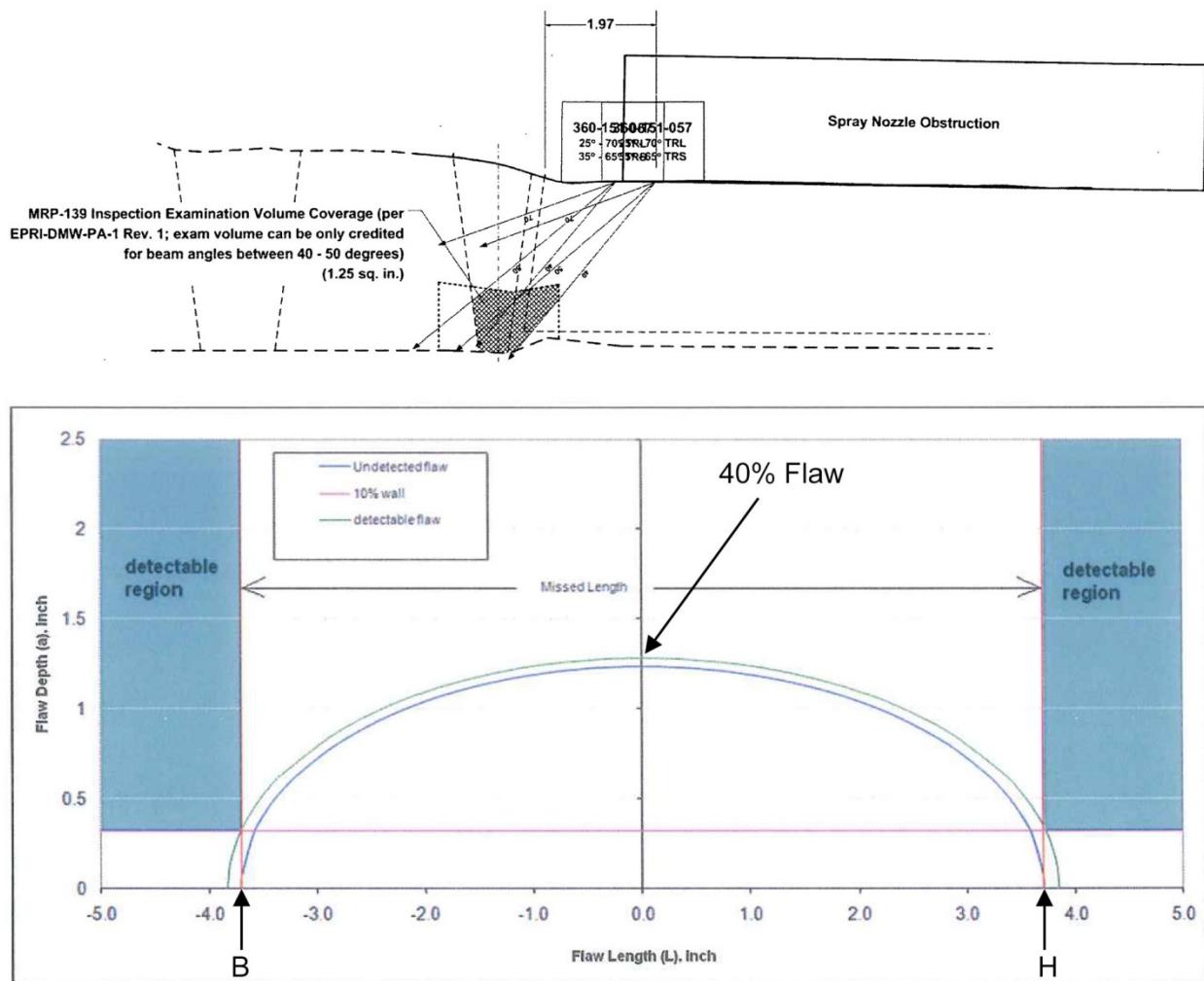


Figure 4. Licensee Ray Trace Volumetric Coverage and Largest Undetected Flaw for Weld RC-121-6-504 due to Spray Nozzle Limitation at Positions B and H

PNNL modeled theoretical ultrasonic beam intensities for the applied phased array examination using the licensee provided delay laws applied on this weld. Modeling included 5 degree increments from 25 to 70 degrees with a half path focus of 76.2 mm (3.0 in.). These focal law values, actual probe physical matrix parameters, and the idealized drawing submitted by the licensee were used as inputs to this model. Longitudinal sound field simulations were completed for all specified access limitations caused by the RTD and Spray Nozzle obstructions. Figure 5 shows examples of UT beams for 40 and 50 degrees at the B and H

positions on Weld RC-121-6-504, left to right, as simulated by CIVA. The models were generated using -6 dB (top) and -12 dB (bottom) filters applied to the sound beam. Although the licensee has not taken credit for angles below 40 degrees, PNNL simulated the beam coverage at lower angles demonstrating that ID coverage may be improved using lower refracted angles. PNNL found that as modeled, the 40 degree beam simulation (-12 dB filter) correlates well with the lower angle volumetric coverage provided by the licensee's description of beams from 40 to 50 degrees (as illustrated in Figure 4).

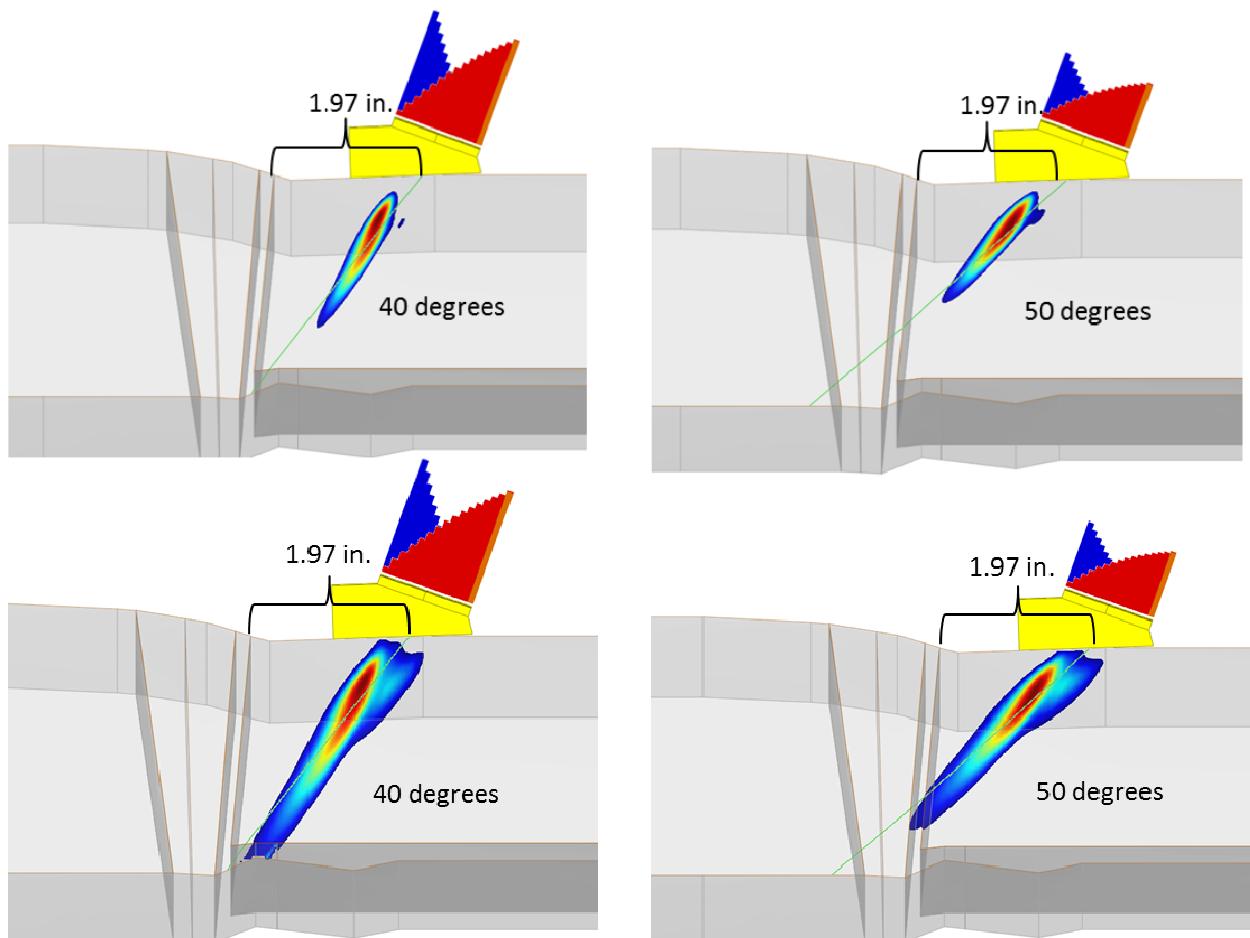


Figure 5. PNNL Modeled -6 dB (Top) and -12 dB (Bottom) Beams for 40 and 50 Degrees Respectively Located at the B and H Positions (Weld RC-121-6-504)

The licensee's phased array probe was operated with focal laws defined to produce steered beams from 25 to 70 degrees, at one-degree increments, each focused at approximately 76.2 mm (3.0 in.) of metal path after exiting the probe. This focal length is short of the ID surface for all steered beams used in the inspection—especially beam angles between 40 and 50 degrees. For reference, the theoretical metal path as calculated along a 40 degree refracted angle originating from the exit point of the wedge (component OD surface) and traveling to the

ID of the component, is nominally 96.2 mm (3.79 in.) where the actual thickness of the carbon piping component is 73.7 mm (2.9 in.).

Therefore, the licensee's model predicts that all sound beams in the accredited angle range (40-50 degrees) to have less than -6 dB beam intensities near the ID of the weld. The -6 dB value represents a point where field intensity is diminished by 50% of the initial maximum; every -6 dB is an additional 50% reduction. However, for a 40-degree beam, the PNNL model predicts -12 dB ID coverage of the weld for this particular inspection angle; this equates to a factor of 4 times lower initial sound energy at this angle. PNNL notes that angles greater than 40 degrees would also have less energy at the ID of the weld. The PNNL model represents a "best-case" scenario; that is, no material attenuation or backscattering from coarse grains in the weld is included. These factors as well as the potential for coupling inefficiencies will typically lower the amplitudes of signal responses from real flaws under field weld conditions, resulting in decreased signal-to-noise ratio (SNR), and making flaw detection significantly more challenging outside the -6 dB region.

Weld RC-124-7-504

Weld RC-124-7-504 is a full penetration DMW on a RCP outlet nozzle joining the carbon steel primary piping to a cast austenitic stainless steel (CASS) safe end. The carbon steel primary piping is clad with stainless steel on the inside diameter (ID), and the CF8M CASS safe end is welded directly to the RCP housing. An idealized cross-sectional depiction of Weld RC-124-7-504 is shown in Figure 6. Note that this scaled drawing from the licensee shows the OD surface to have some irregularity. Because OD surface features of a ground weld crown can vary circumferentially, and no information was available to depict actual field surface conditions, PNNL modeled Weld RC-124-7-504 with essentially flat surfaces and only accounted for OD dimensional changes such as the slight axial taper noted across the weld. Figure 6 also provides the ASME examination volume required as a cross-hatched shaded area.

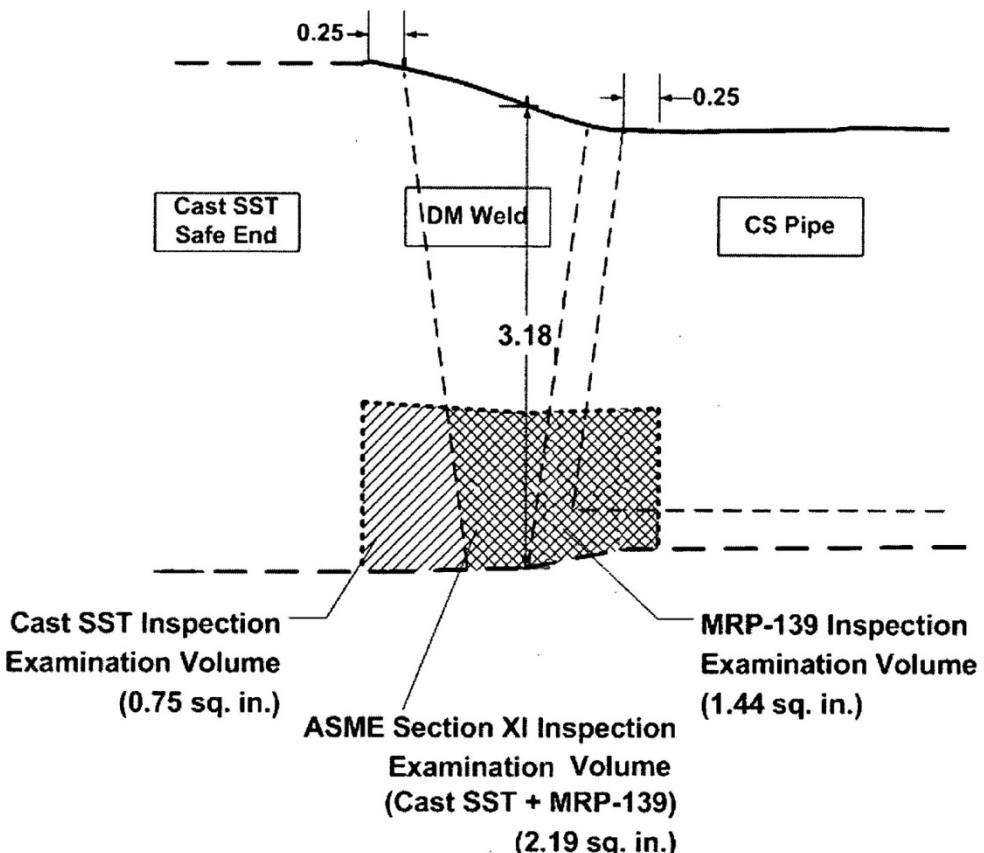


Figure 6. Idealized Cross Section of RCP Weld RC-124-7-504

The axial examination (for detecting circumferentially-oriented flaws) of this weld was physically limited by a single Spray Nozzle that extends along a circumferential arc. Figure 7 illustrates the Spray Nozzle obstruction that introduces varying limitations which inherently impact axial scanning access over an OD circumferential length of 197.6 mm (7.78 in.). Due to this limitation, the licensee has postulated the ray trace coverage for longitudinal angles between 40 and 50 degrees (EPRI-DMW-PA-1 Rev. 1).

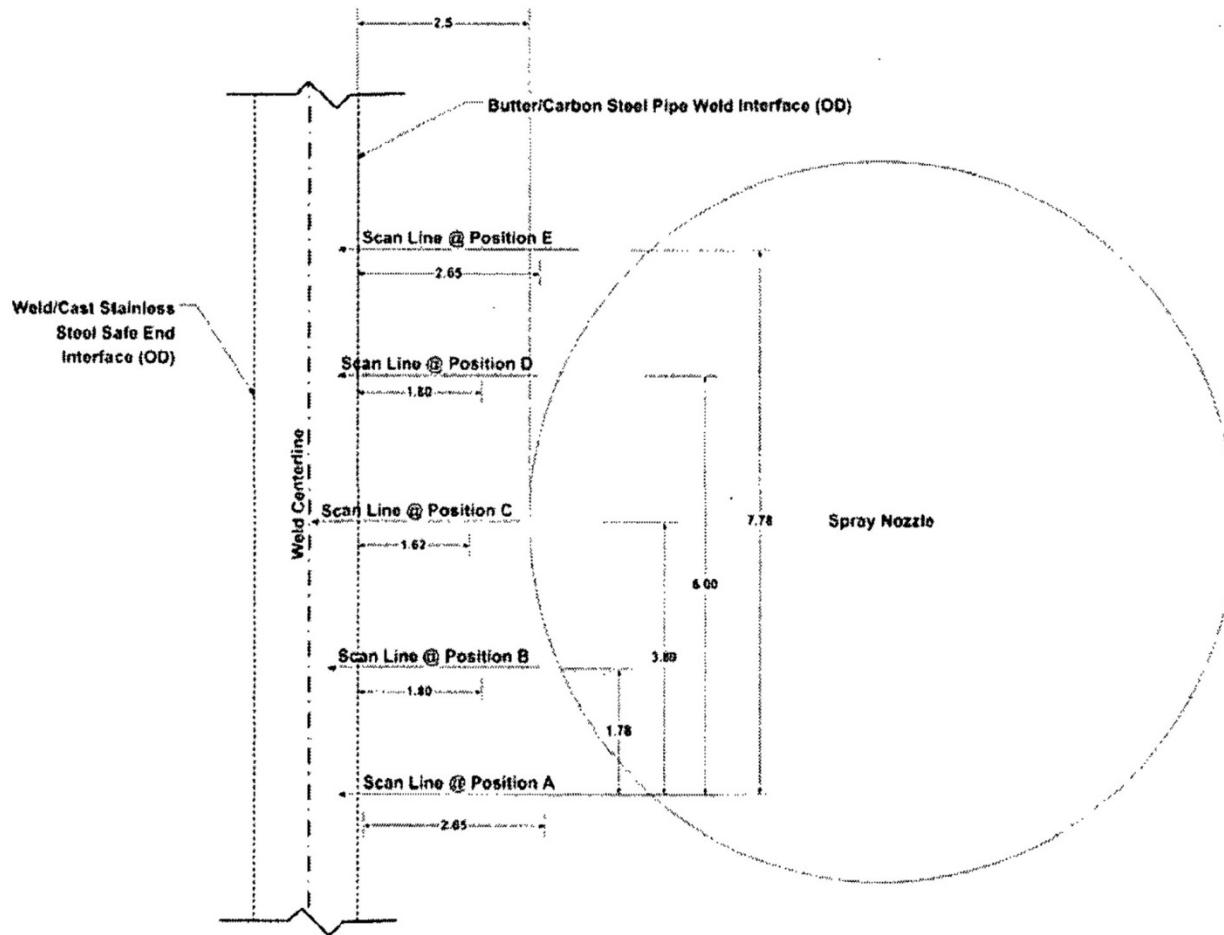


Figure 7. Top View of RCP Weld RC-124-7-504 Detailing Access Limitations as a Result of the Spray Nozzle Obstruction

The licensee also submitted volumetric examination sketches, showing theoretical beam plots between angles of 40 to 50 degrees (EPRI-DMW-PA-1 Rev. 1) for axial scan coverage obtained across all access limitations highlighted in Figure 7; e.g., Spray Nozzle limitation positions A, B, C, D, and E. The licensee's sketches indicate that the credited coverage varies as a function of the axial scanning limitation. The licensee's theoretical coverage for the Spray Nozzle obstruction at position C is shown in Figure 8. Without these limitations, axial scans can be initiated at a sufficient distance away from the weld on the carbon steel primary piping to ensure 100% volumetric coverage of the susceptible material, as full volumetric scans were completed for the remaining circumferential sections of the weld. Due to the scanning limitations described, the licensee estimated volumetric coverage for axial scans at approximately 97.7% of the required circumference of the weld (MRP-139 Volume Coverage), which includes the full inner one-third of the susceptible weld material, as examined from the ID-clad carbon steel piping. The licensee did not take credit for coverage on the CASS safe end material because

the ASME Code, Section XI, has no qualification procedures for the ultrasonic examination of the CASS material..

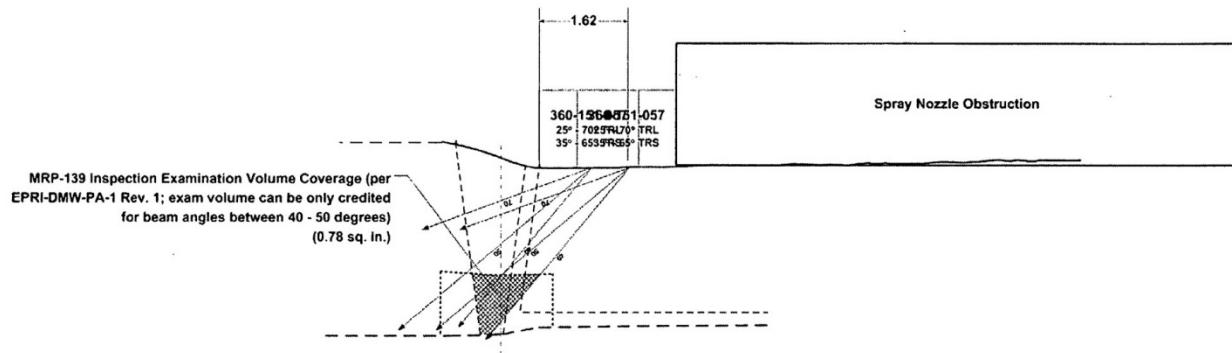


Figure 8. Licensee Ray Trace Volumetric Coverage for Weld RC-124-7-504 due to Spray Nozzle Limitation at Position C

PNNL modeled theoretical ultrasonic beam intensities for the applied phased array examination using the licensee provided delay laws applied on this weld. The model included 5 degree increments from 25 to 70 degrees with a half path focus of 76.2 mm (3.0 in.). Longitudinal sound field simulations were completed for all specified access limitations for the Spray Nozzle obstruction. Figure 9 provides examples of UT beams for 40 and 50 degrees at the B and H positions on Weld RC-124-7-504, left to right, as simulated by CIVA. PNNL generated the models using -6 dB (top) and -12 dB (bottom) filters applied to the sound beam. Again, although the licensee has not taken credit for angles below 40 degrees, PNNL simulated beam coverage at lower angles demonstrating that ID coverage may be improved using lower refracted angles. As modeled, PNNL's 40 degree beam simulation (-12 dB filter) mostly agrees with the lower angle volumetric coverage provided by the licensee's description of beams from 40 to 50 degrees (as illustrated in Figure 8).

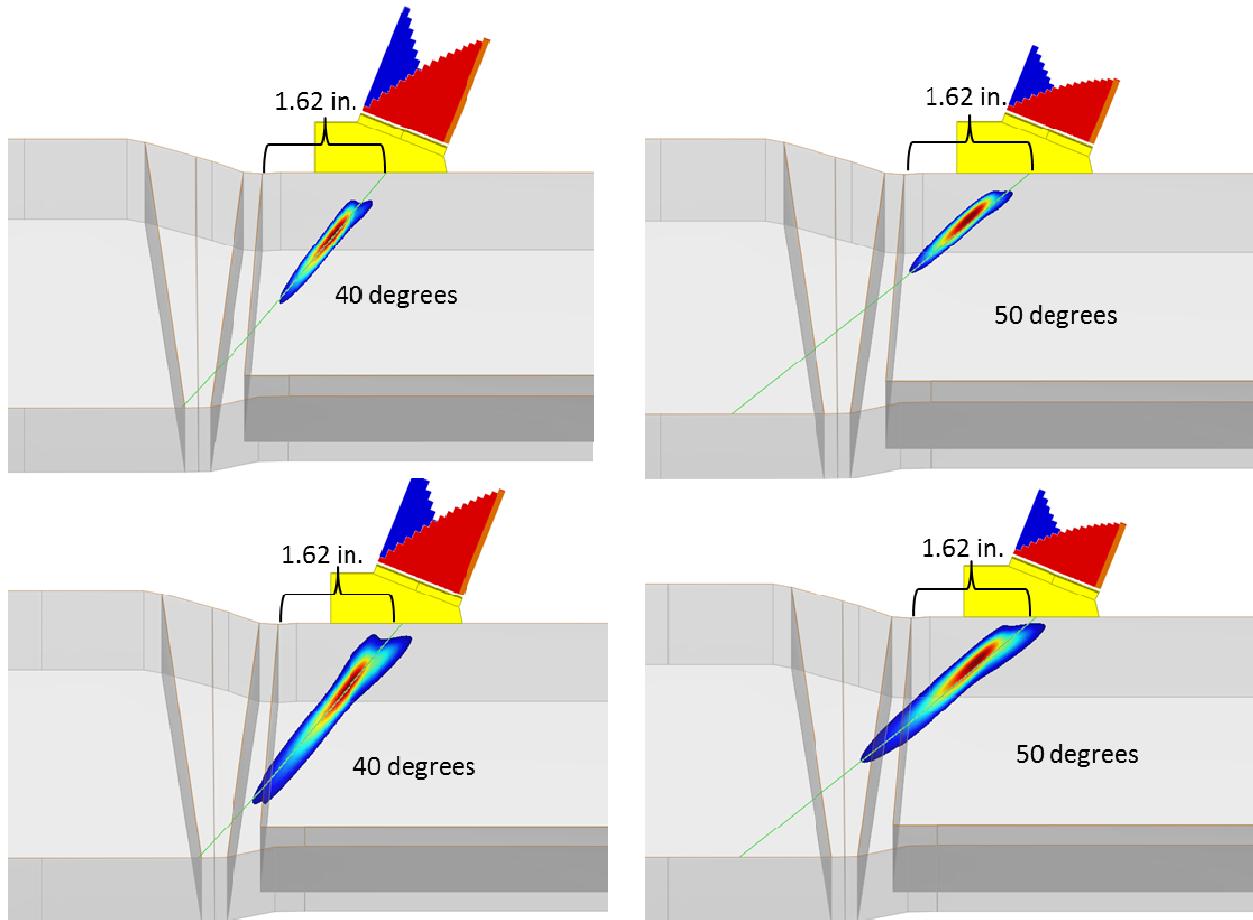


Figure 9. PNNL Modeled –6 dB (Top) and –12 dB (Bottom) Beams for 40 and 50 Degrees Respectively Located at the C Position (Weld RC-124-7-504)

Postulated Flaw Detection in Weld RC-121-6-504

PNNL evaluated theoretical detection of a licensee-postulated ID-connected circumferential flaw originating in the susceptible material region, by modeling backscattered ultrasonic responses from a semi-elliptical planar reflector. Initially, theoretical ultrasonic responses from a 40%, 32.5mm (1.2 in.) through-wall deep flaw with an aspect ratio (AR), or length-to-depth, of 6:1 were evaluated in the PNNL model. PNNL compared these responses against similar responses from a 10%, 8.1 mm (0.32 in.) deep circumferential ID-connected rectangular planar notch used to calibrate, or normalize, the modeled system amplitude. Both the semi-elliptical flaw and the notch were located in the butter/weld susceptible material region of the weld. The calibration notch was simulated without any OD obstruction limiting the scan path. As shown in Figure 10 the maximum (system normalized) response (response value of 0.0884) from the ID corner trap of the reference notch was set to 100% full screen height (FSH) in the A-scan view (top left) when evaluated at the 40 degree refracted angle. This was used as benchmark calibration reflector for all subsequent planar flaw simulations. The lowest credited angle

considered for detection was a refracted angle of 40 degrees for all simulations. The following series of simulations focused on assessing the detection of a planar, semi-elliptical flaw located in the weld with a scan region that was physically limited by the Spray Nozzle boss as previously depicted.

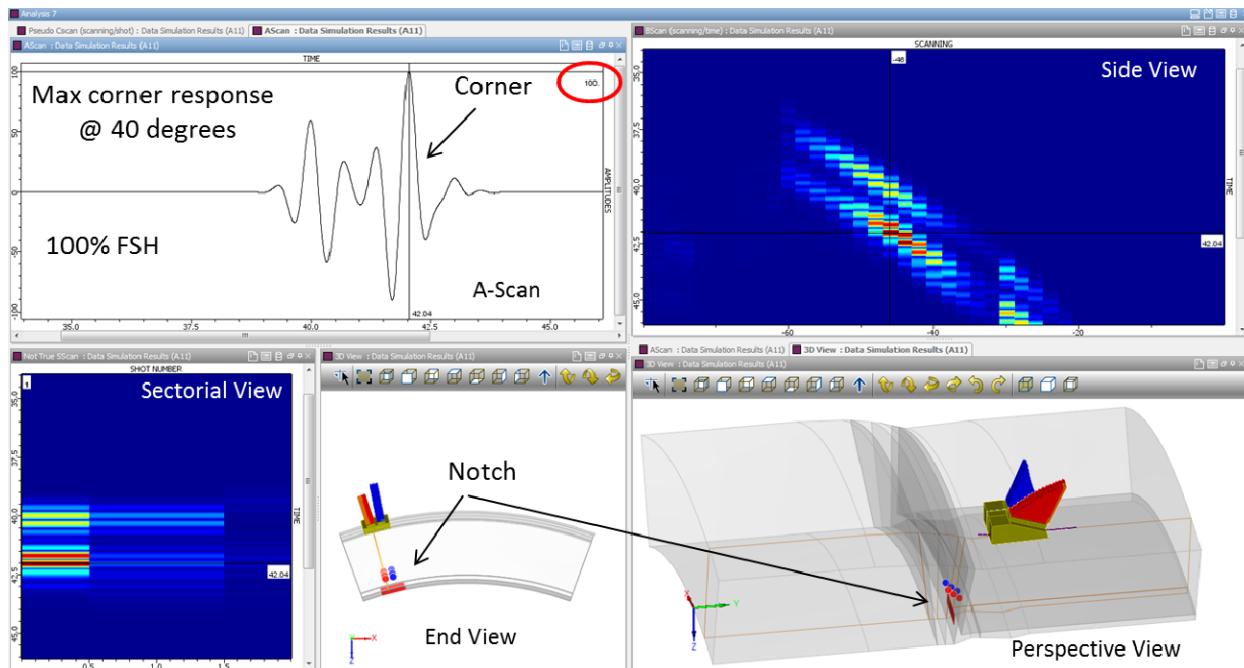


Figure 10. 10% Planar Reference Notch at 40 Degrees. Used as a calibration for subsequent simulations.

Based on the licensee's submittal, PNNL defined the 40% deep, AR 6:1, semi-elliptical planar flaw to have an arc length of 195 mm (7.68 in.) and a maximum through-wall extent of 32.5 mm (1.28 in.) at the crown of the flaw, as illustrated in Figure 11. The flaw was radial-circumferentially oriented and emanated from the ID in the butter/weld region of the component. The Spray Nozzle obstruction (not shown) limits the axial scan extent reducing ultrasonic coverage of the weld region. PNNL evaluated potential flaw detection as the axial scan path was restricted to the B and H positions previously described in Figure 4. The licensee proposed that the flaw would present a nominal 10% through-wall extent at the B and H positions, the smallest through-wall extent for which the licensee claims credit for detection.

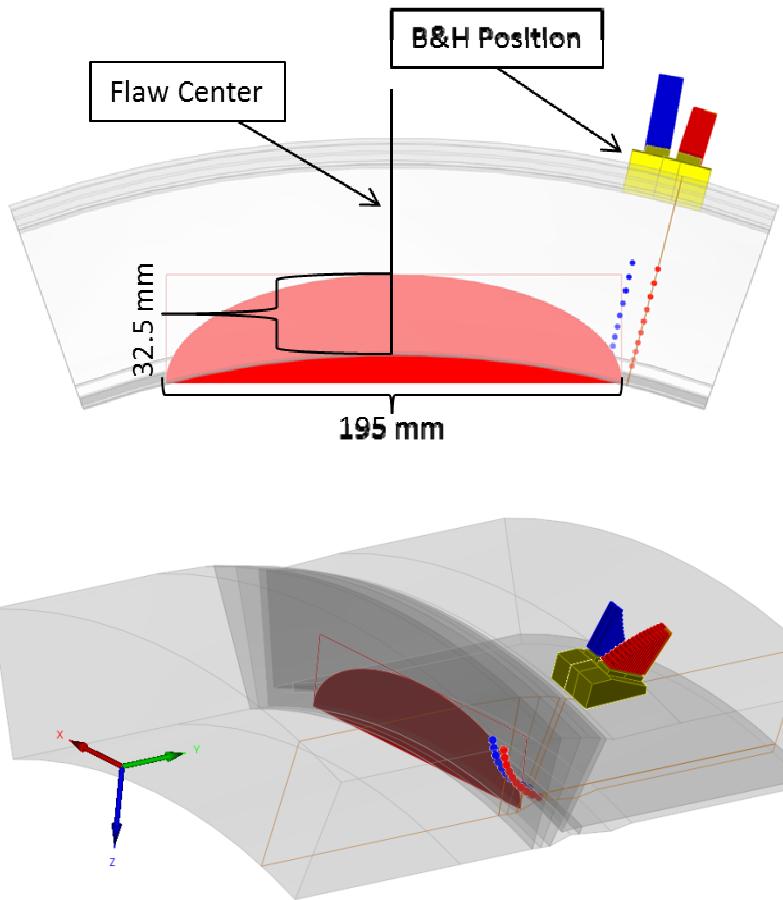


Figure 11. Top: End View of Semi-elliptical Planar Flaw; Bottom: Perspective View of Flaw

PNNL first assessed theoretical flaw detection by simulating a linear line axial pipe scan toward the weld, originating with the phased array probe positioned at the B and H position [50.0 mm (1.97 in.) from the wedge center to butter-to-carbon interface], as shown in Figure 12. PNNL selected insonification angles from 25 to 70 degrees in 5 degree increments for this simulation.

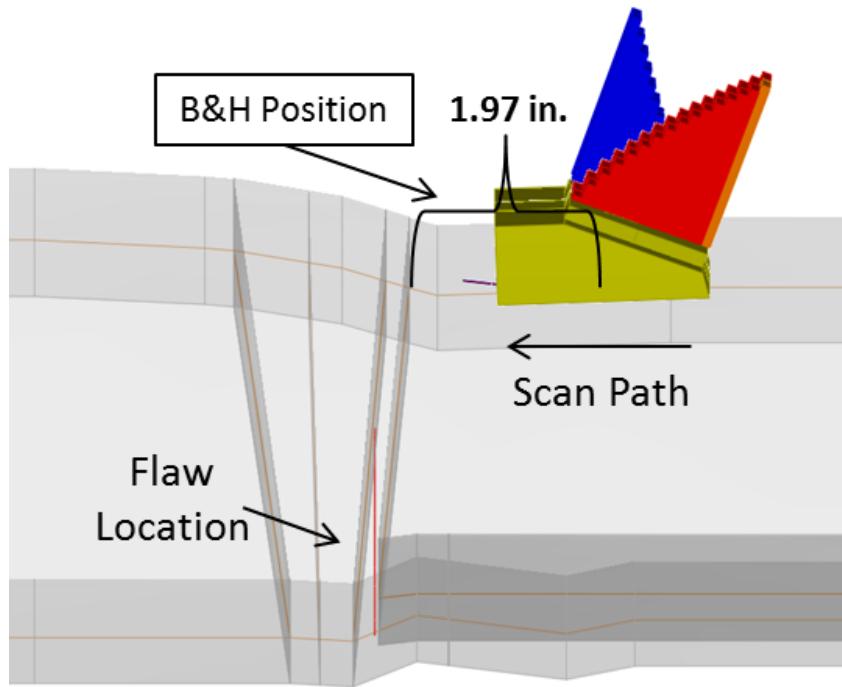


Figure 12. Side View of Flaw with Linear Scan Path

Figure 13 shows results of the backscattered response simulation with a 40 degree scan angle. The lower right two images show views of the probe on the component at the B and H position, with maximum distance to weld centerline as could be expected due to the Spray nozzle obstruction. The lower left image is an unprocessed non-volume corrected sectorial display showing all angles simulated versus time at a particular scan position. This view shows simulated flaw responses (if existent) for angles 25-70 degrees, at 5 degree increments (25 degrees on the left and 70 degrees on the right). The black cursors in this image are centered on the 'shot' number corresponding to 40 degrees. The upper right image shows a side view (scanning vs. time) that correlates with the selected refracted angle. The upper left quadrant shows the time-amplitude A-Scan view with the black cursor located at the maximum response detected from the 40% semi-elliptical planar flaw when detected with the probe located at the B-H position. The A-scan image with amplitude measured in decibels indicates that the specular (ID corner trapped) signal from the semi-elliptical flaw at this 40 degree angle is -10 dB below (circled in red) the calibrated 10% notch response. For reference, the normalized system response value is 0.0279 as compared to the calibration notch response value of 0.0884. As previously stated, a measure of comparison for a -12 dB reduction is 1/4 or 25% of the maximum response. When the simulated scan progressed away from the start position (toward the weld region), the postulated flaw disappeared from view in the simulation. Thus, it is imperative that the scan begin at the simulated starting point (as far back from weld centerline as possible) for the most reliable detection. The A-scan also displays the upper flaw reflection, or simulated tip signal, shown earlier in time than the ID-corner response.

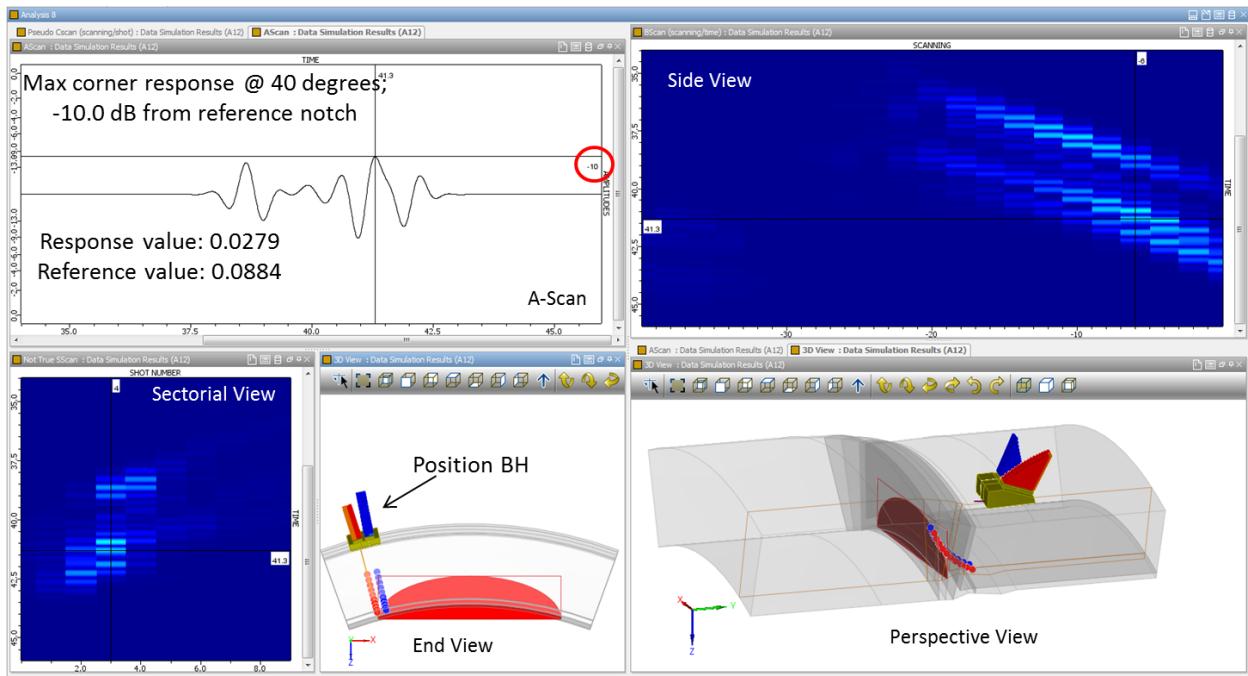


Figure 13. Defect Response at 40 Degrees with Probe Located at the B and H Position; 40% Through Wall Flaw

Based on discussions with NRC, PNNL conducted second and third evaluations at the B-H position using an AR 6:1 semi-elliptical planar flaw that has grown to a maximum through wall extent of 50%, or 40.6 mm (1.6 in.) and 60%, or 48.8 mm (1.9 in.), respectively. These simulations were performed to determine if increasing the flaw size raises the likelihood of theoretical detection as compared to the 10% reference notch. Similar to the presentation of the data shown in Figure 13, Figures 14 and 15 illustrate the computer-generated detection of the corner response from 50% and 60% through wall flaws, respectively, as examined from the B-H position with maximum distance from weld centerline. The 50% and 60% flaws indicate an amplitude reduction from the flaw corner of -9.5 dB (response value 0.0297) and -9.2 dB (response value 0.0307) from the reference notch response (circled in red in the figures).

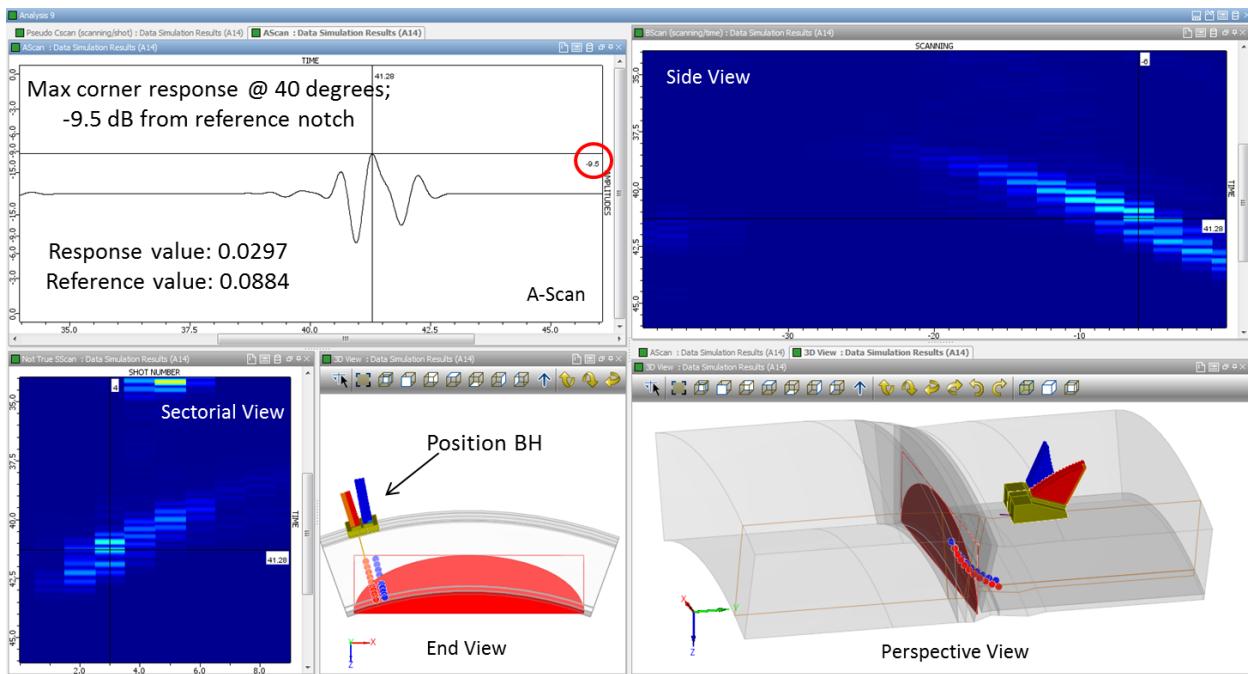


Figure 14 Defect Response at 40 Degrees with Probe Located at the B and H Position; 50% Through Wall Flaw

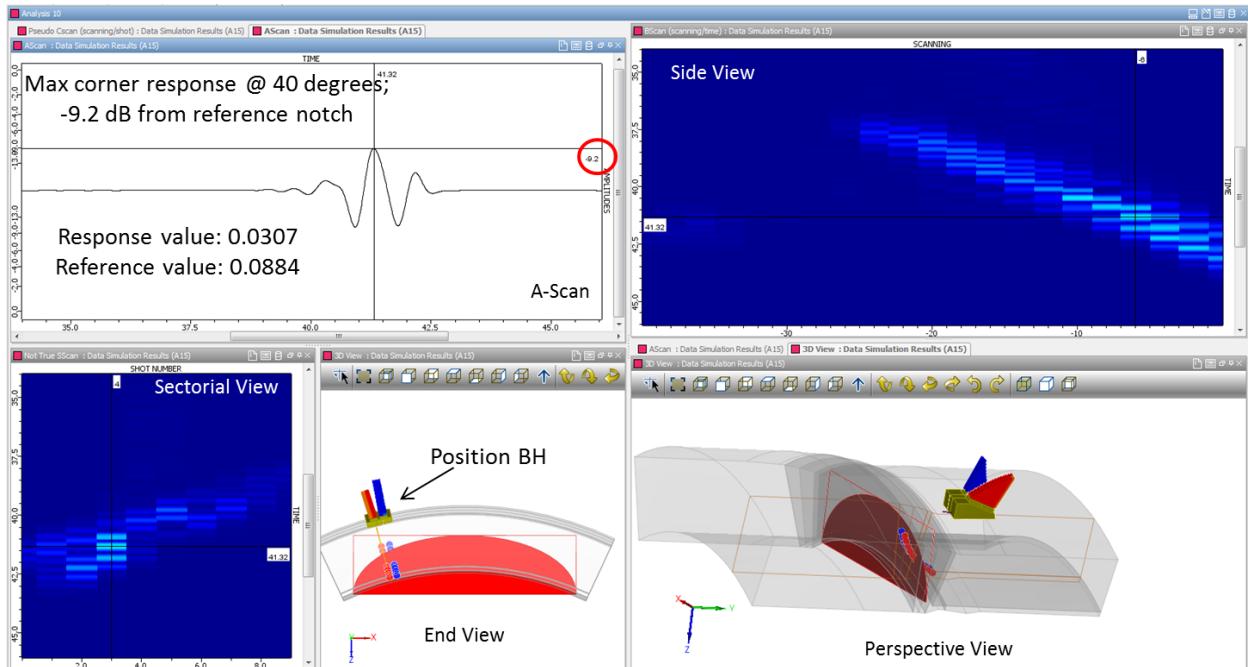


Figure 15 Defect Response at 40 Degrees with Probe Located at the B and H Position; 60% Through Wall Flaw

Thus, over the through wall extent range from 40% to 60%, the simulations show that only slight amplitude increases in ID corner-trap responses at 40 degrees occur as the through-wall extent of the flaw increases. Table 1 highlights the trend, albeit small, observed. This is expected and is likely the result of an increase in flaw surface area being presented to the focused inspection beam. One would also expect this trend to reach a peak, once the beam-to-flaw impact area has been exceeded, i.e., the flaw grows beyond the radial dimension of the sound beam.

Table 1 – 40 Degree Angle Corner of Flaw Response as a Function of Flaw Height

Flaw Height, mm (in.)	Corner of Flaw Response at 40 Degrees (dB)*
32.5 (1.3)	-10.0
40.6 (1.6)	-9.5
48.8 (1.9)	-9.2

*0 dB set to corner response of reference notch at 40 degrees.

A further analysis of top of flaw responses was also conducted using the semi-elliptical 50% through wall simulation as compared against the 10% reference notch. This revealed that the top response, or simulated tip signal, of the 50% flaw located at the B-H position exhibited only a -4.2 dB (response value 0.0542) amplitude reduction from the reference notch, when using a refracted angle of 50 degrees. The 50-degree angle was chosen because it represents the best impingement for top-of-flaw responses at the B-H position, and is the highest angle in the range of those having been qualified by the licensee. For purposes of comparison, the maximum response detected from the top of the 40% through wall flaw at the B-H position was -11.5 dB below the reference notch top-of-flaw response. Therefore, the less than -6 dB change between the 10% reference and the 50% through-wall planar flaw would indicate a favorable detection scenario.

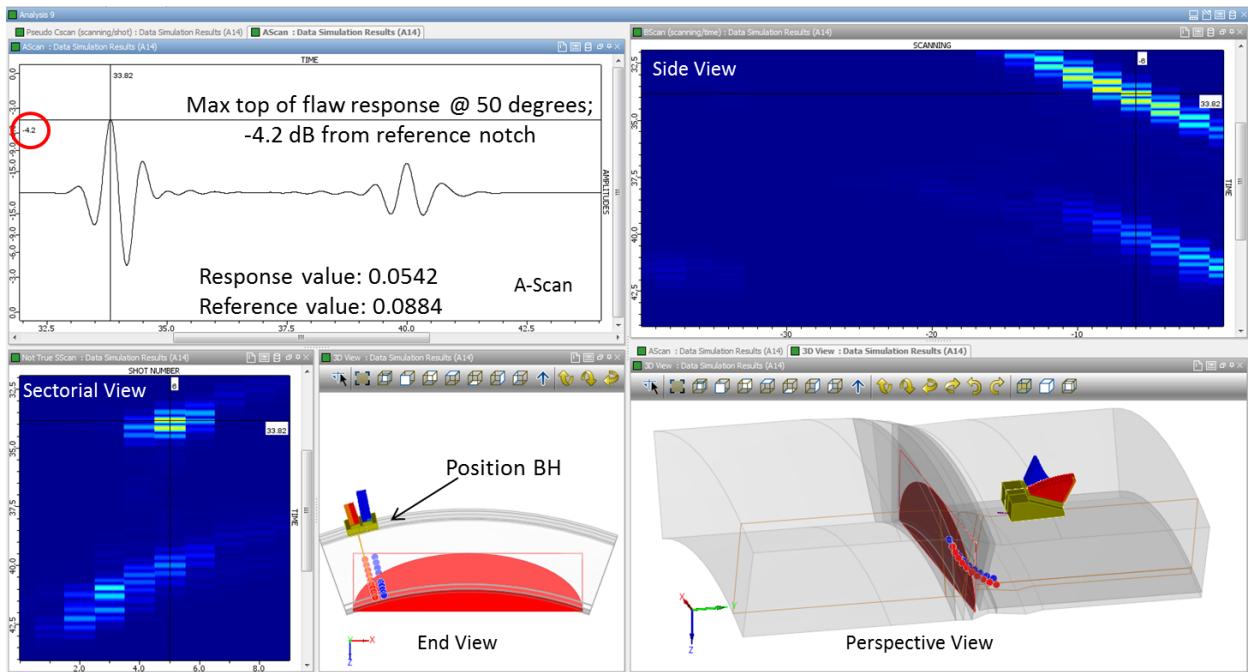


Figure 16 Top of Flaw Defect Response at 50 Degrees with Probe Located at the B and H Position; 50% Through Wall Flaw

CONCLUSIONS

PNNL finds that modeling of Welds RC-121-6-504 and RC-124-7-504 have shown approximate –12 dB beam sensitivity coverage at the ID region of the weld at a refracted angle of approximately 40 degrees, or less, using the licensee specified access limitations for each subject weld.

PNNL further finds that the CIVA simulations are in general agreement with the licensee's ray trace prediction of coverage, with –12 dB beam intensities, for the 40 to 50 degree angle range, as these are the only refracted angles claimed to have been qualified.

PNNL notes that the simulation models represent ideal conditions, and do not account for surface irregularities (waviness), coupling inefficiencies, material attenuation and/or noise factors (further reducing the sound field intensity) that may be present in the actual welds.

Due to the limited access caused by the Spray nozzle obstruction, reduced sound field intensities over the 40 to 50 degree steered beam range, and diminished ID-corner trap and flaw top responses shown by the simulations, PNNL would not expect that a 40% through-wall flaw with an aspect ratio of 6 to 1 would be detected from only the B-H position, as suggested by the licensee. Based on input from modeling, coupled with amplitudes of ultrasonic flaw responses observed both in the laboratory and in the field, PNNL determined that a semi-elliptical circumferential planar flaw must grow to a minimum of 40.6 mm (1.6 in.), or approximately 50%, in through-wall extent before it is reasonable to expect a top-of-flaw (tip signal) response to be reliably detected at the B-H position in Weld RC-12-6-504, given the

phased array examination technique parameters used by the licensee. Thus, PNNL concludes that a flaw would have to grow to the 50% through wall flaw with an aspect ratio of 6 to 1 in the subject DMW RC-12-6-504 in order for it to be positively detected by the current phased-array UT technique.

PNNL notes that the simulations were conducted without material noise or attenuation applied, which would reduce signal strength and quality for actual field examinations.

As a whole, the beam coverage plots and defect response simulations indicate that lower inspection angles may increase the overall coverage and likelihood of ID-connected flaw detection. Stronger ID sound fields and increased defect responses from flaw corners were noted from simulated examination angles of 25 to 40 degrees.