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Nondestructive Evaluation: Proposed Code Case Criteria for the Technical Basis of Weld Overlay Indication Evaluation and Disposition Based on Advanced Technology Assessments

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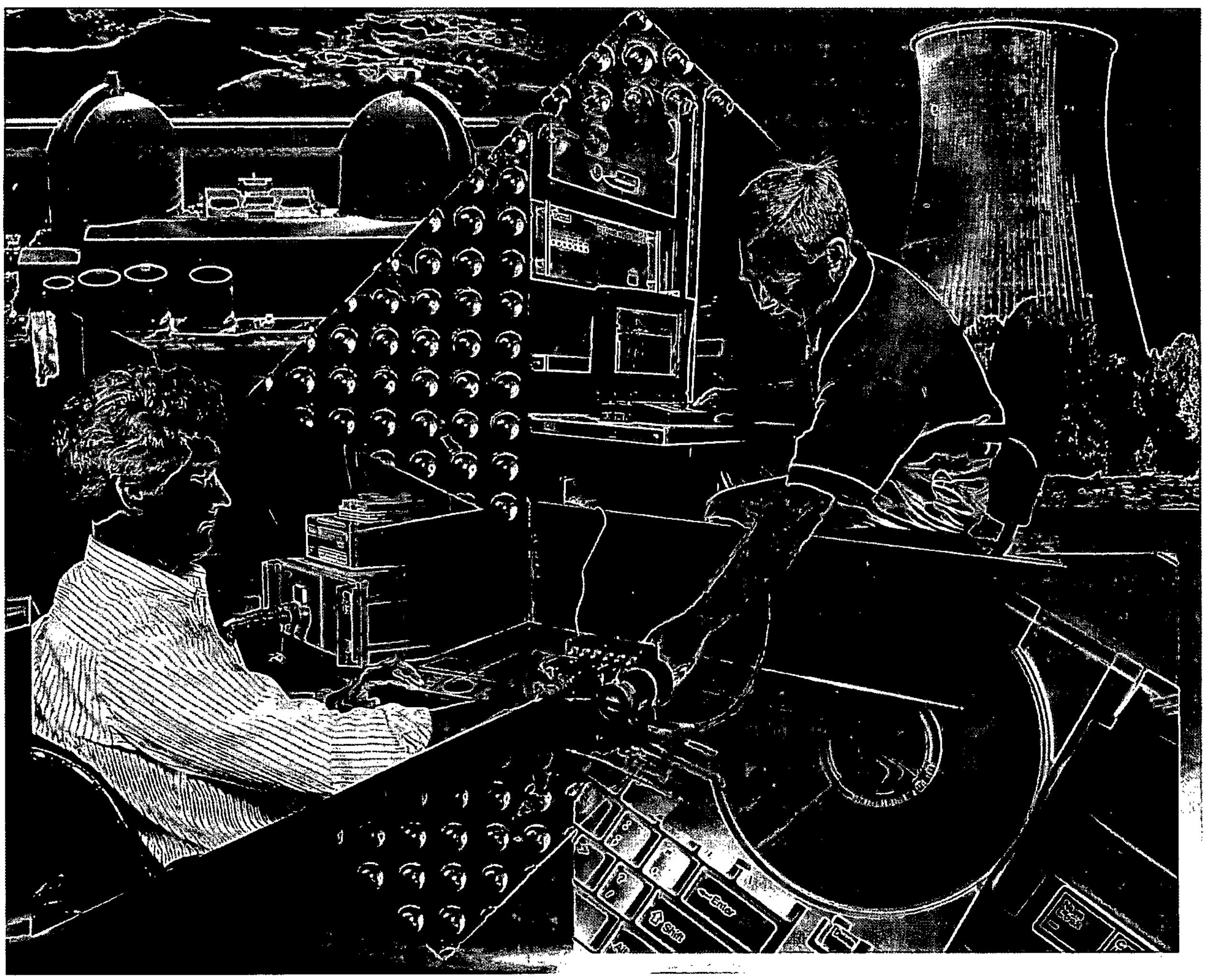

Nondestructive Evaluation: Proposed Code Case Criteria for the Technical Basis of Weld Overlay Indication Evaluation and Disposition Based on Advanced Technology Assessments

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Technical Update, December 2007

EPRI Project Manager

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PRODUCT DESCRIPTION

This document addresses new flaw evaluation requirements for the inspection of weld overlays imposed by the introduction of American Society of Mechanical Engineers (ASME) Code Case N-740. This Code Case references flaw acceptance criteria (IWB-3524-2 and 3) that require the accurate measurement of flaw width (laminar flaws) and the through-wall extension of embedded planar flaws. Measurement of these flaw dimensions is not currently provided by Performance Demonstration Initiative (PDI) overlay inspection procedures. This report describes laboratory studies using both conventional and phased array ultrasonic techniques that investigate the methodology and related accuracy of techniques used for measuring these flaw characteristics. Recommendations related to proposed changes to PDI overlay procedures are provided.

Results and Findings

Test results suggest that modifying the amount of signal amplitude drop used during width sizing based on the characteristics of the flaw's response can significantly improve the sizing accuracy of the flaw width when using conventional techniques. Data are also presented related to improved width sizing accuracy when focused phased array techniques are used. The ability of measuring the through-wall dimension of embedded flaws is also discussed and recommendations made. Measurements taken during this study confer with those provided by other industry studies. This report should provide a strong technical basis to support changes to the ASME Code qualification acceptance criteria, which may result in fewer repairs in weld overlays.

Challenges and Objectives

This report specifically addresses the measurement of embedded crack height using tip diffraction techniques and laminar width measurements using amplitude drop techniques.
The objectives of this project include the establishment of ultrasonic sizing techniques to more accurately size laminar and embedded weld overlay flaws, the submittal of the appropriate Code changes necessary to take advantage of these newly developed techniques, and proceduralization of the results. Additionally, these techniques will be qualified through the industry's PDI program and made available to all utilities and vendors. The use of these sizing techniques would allow for more accurate flaw sizing and disposition, resulting in fewer repairs of weld overlays. Total weld overlay fabrication times and personnel dose would thereby be reduced.

Applications, Value, and Use

In the short term, changes made to qualified procedures will allow more accurate sizing techniques to be used until formal qualification criteria are developed and placed in the ASME Code. This document will be used as the technical basis for these changes.

EPRI Perspective

Electric Power Research Institute (EPRI) is in the unique position of having the only approved ASME Section XI, Appendix VIII qualification program in the world and is the only organization positioned to implement these changes.

Approach

The primary goals of this report were to:

- Perform physical trials on available mockups in order to determine the achievable accuracy of the current techniques
- Evaluate advance techniques to determine if they could improve the accuracy of the examination
- Evaluate research and trials performed by other industry organizations in order to build on the technical basis of the technique
- Compile all available data into one report that can be used to support future ASME Code changes

Keywords

Overlay
Weld overlay

ABSTRACT

This document addresses new flaw evaluation requirements for the inspection of weld overlays imposed by the introduction of American Society of Mechanical Engineers (ASME) Code Case N-740. This Code Case references flaw acceptance criteria (IWB-3524-2 and 3) that require the accurate measurement of flaw width (laminar flaws) and the through-wall extension of embedded planar flaws. Measurement of these flaw dimensions is not currently provided by Performance Demonstration Initiative (PDI) overlay inspection procedures. This report describes laboratory studies using both conventional and phased array ultrasonic techniques that investigate the methodology and related accuracy of techniques used for measuring these flaw characteristics. Recommendations related to proposed changes to PDI overlay procedures are provided.

ACKNOWLEDGMENTS

EPRI would like to thank WesDyne International, LLC for their contribution to the development of this technical update.

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1 INTRODUCTION

The use of overlay welds for the repair of flawed piping (weld overlay repair [WOR]) or as a preemptive strategy (preemptive weld overlay [PWOL]) has become common in both BWR and PWR facilities. Full structural overlay welding involves the introduction of weld material on the outer diameter surface of the component, which effectively replaces the structural function of the original pipe material. Overlay repairs can serve as an alternative solution to weld replacement where intergranular stress corrosion cracking (IGSCC) or stress corrosion cracking (SCC) of Alloy 82/182 has occurred. The presence of an overlay also reduces the potential for future cracking through the introduction of compressive residual stresses at the inside surface, thus mitigating crack formation and/or growth. Additionally, overlays utilize crack-resistant material provide structural reinforcement to the original joint design. The use of an overlay can improve conditions for in-service inspection by removing geometrical inconsistencies of the inspection surface (for example, tapers) between adjoining pieces. The application of a weld overlay typically increases the inspection interval of the pipe joint. In addition, there have been no reported cases of existing flaws propagating into the overlay material [1].

The examination of an overlay requires the filing of a relief request referencing Code Case N-740. This Code Case references American Society of Mechanical Engineers (ASME) acceptance criteria IWB-3514-2 for detected planar flaws and for evaluating assumed planar flaws associated with areas of reduction in coverage (RIC). Also, N-740 references IWB-3514-3 for the acceptance of laminar flaws. In all cases, there is clear justification and need for improved ultrasonic methods in the characterization of embedded flaw dimensions. This report specifically addresses the measurement of embedded crack height using tip diffraction techniques and laminar width measurements using amplitude drop techniques. The objectives of this project include the establishment of ultrasonic sizing techniques to more accurately size laminar and embedded weld overlay flaws, the submittal of the appropriate Code changes necessary to take advantage of these newly developed techniques, and proceduralization of the results. Additionally, these techniques will be qualified through the industry's Performance Demonstration Initiative (PDI) program and made available to all utilities and vendors. The use of these sizing techniques would allow for more accurate flaw sizing and disposition, resulting in fewer repairs of weld overlays. Total weld overlay fabrication times and personnel dose would thereby be reduced.

2 BACKGROUND

2.1 Overlay Flaw Types

Overlay welding of dissimilar metal welds involves the application of nickel-based alloys in a field environment where the control of weld parameters can be challenging and where the geometrical conditions are less than ideal. As a result, the presence of weld defects in the overlay layers is common. The vast majority of such defects are relatively small (~1 mm) but can form in clusters, making them appear large or continuous when examined ultrasonically. As described in the following paragraphs, these defects can be in the form of cracks, lack of bond (LOB), lack of fusion (LOF), porosity, and slag/oxide deposits. Code Case N-740 requires that the characterization and subsequent assessment of a flaw be based on its classification as either planar or laminar.

2.1.1 Cracking

Cracks that are formed in overlays during fabrication are either ductility dip cracking (DDC) or hot cracking. DDC typically is characterized by small (0.25- to 2-mm) fissures of migrated dendrite boundaries. DDC normally occurs during reheating within a temperature range where the material experiences a significant reduction in ductility (ductility dip). The phenomenon requires a tensile stress applied across the susceptible boundary as well as the low-ductility composition. DDC tends to occur more commonly in welds having high restraint and/or multiple weld layers. In fact, the welding heat is the source of heat that cycles the material through the susceptible temperature range. Weld shrinkage is the source of the requisite stress. The phenomenon is similar to the reheat cracking seen in low-alloy steels. DDC can be minimized by controlling the welding process (reduction in thermal cycles and lower heat input) but usually must be mitigated by optimizing the weld metal compositions.

Micro-fissuring is another form of small, localized cracking that is typically found at the intersection of grain boundaries and the substrate fusion line. It is caused by a compositional imbalance of nickel-chrome-iron alloys at the grain boundaries when combined with thermal stresses [2].

Hot cracking is another type of defect found in austenitic filler materials that occurs at primary dendrite boundaries. Often called *solidification cracking*, the phenomenon is the product of weld shrinkage stresses from cooling and a grain boundary weakened by impurity content. Another form of hot cracking occurs in weld heat-affected zones of austenitic materials where impurity levels on the grain boundaries are high. In this case, it is known as *liquation cracking*, but the idea is the same. The grain boundary is weakened due to the thin layer on the boundary having a slightly lower melting composition, and as cooling stresses are applied, the boundary separates. The phenomenon occurs in both austenitic stainless steels and in austenitic nickel-based materials. Hot cracking is promoted by inappropriate welding parameters, including excessive heat input during welding and excessive dilution from the substrate. Hot cracking in nickel-based materials is often associated with excessive dilution with iron and is normally controlled by the welding process. Hot cracking is also caused by the presence of excessive amounts of low melting impurities such as sulfur. Such impurities may be introduced by contamination, base material composition (often segregation of impurities or compounds such as sulfides), or poor quality filler materials [2].

Cracks have a unique ultrasonic signature where the multi-faceted crack face produces a combined response of both reflected and diffracted energy. As a result, a crack produces a signal that varies in amplitude as impinging sound is directed up the crack face. Tip-diffracted signals are typically observed at the crack tips. In fact, embedded cracks can exhibit tips from both the upper and lower crack extremities, enabling direct measurement of the crack height. Overlay cracking can be associated with deposition of a specific layer of weld material, resulting in the formation of an embedded flaw. In such a case, techniques that are directed only at the measurement of the remaining ligament of the upper tip, with crack height calculated based on an assumed bottom tip position (overlay/pipe interface), will result in an oversized flaw. Therefore, the capability to detect and measure the remaining ligament of both the lower and upper crack tips produces a more accurate assessment of the through-wall extension of a flaw, resulting in fewer unnecessary repairs. Cracking should always be classified as a planar flaw, with its evaluation based upon its length and through-wall extension.

2.1.2 Lack of Bond/Lack of Fusion

Lack of bond (LOB) is a defect found at the interface between the pipe outer surface and the first overlay layer. An LOB defect can result from a variety of reasons, including surface contamination on the component being overlaid. However, the principal reason for lack of bonding is a lack of penetration in the welding process, caused by inappropriate welding parameters or technique (improper bead placement/electrode angle or tilt).

Lack of fusion (LOF) defects are essentially the same as the defects described as LOB, but by definition, these defects are located between the layers of overlay deposits. They are caused by the same mechanisms. It is noted that nickel-based filler materials develop a tenacious and transparent oxide that forms on the solidified beads and, if the penetration is insufficient, the oxide will not break down and bonding issues will result. Defects most likely occur during the downward progression of horizontally oriented pipe welds. The reason is that the molten deposit rolls ahead of the welding torch and interferes with the arc penetration into the substrate [2].

LOB and LOF defects appear as long and narrow circumferential indications along the direction of welding. Both flaw types are located at a constant depth across the flaw face and are considered laminar flaws when evaluated against acceptance criteria. The evaluation of a laminar flaw is based upon the accurate measurement of the flaw length and width. Accurate measurement of laminar width is of particular importance when using Code Case N-740 because this dimension will have a direct impact on the dimensions of the assumed planar flaw used for an RIC calculation.

2.1.3 Floaters/Oxide Inclusions

Oxide floaters are thin, flat oxides that are not removed by the welding process. The defect is found on the top sides of the weld beads and tends to form after the second layer has been deposited. The formulation of the original Alloy 52 produced a large number of these oxides that became trapped during downhill welding. The only way to minimize the issue was to restrict welding to the uphill progression. Once the oxides were incorporated, welding over the top of them only produced redistribution [2].

Oxide floaters yield ultrasonic responses that indicate length and width but no depth. They typically appear as long indications along the direction of welding and are classified as laminar flaws when evaluated against Code Case N-740 acceptance criteria. The evaluation of a laminar flaw is based upon the accurate measurement of the flaw length and width. Accurate measurement of laminar width is of particular importance when using Code Case N-740, because this dimension will have a direct impact on the dimensions of the assumed planar flaw used for RIC calculations.

2.1.4 Porosity

Porosity, or pockets of gas in the overlay material, is normally caused by inadequate inert gas coverage during welding. The component geometry, the gas cup size and configuration, the gas lens diffuser, and the gas purity and flow are key variables in dealing with porosity. Drafty work areas can also degrade the inert gas coverage. Another cause of porosity is carrying too large a volume of a molten weld puddle. If the volume of deposited weld metal is too great, the heat is too low, torch oscillations are too rapid, or the electrode tip is degraded, porosity will be generated. Porosity to some degree will likely be present in overlays, but normally the size of the porosity will be very small [2].

Porosity is typically not of sufficient size to produce a significant ultrasonic response and thus is not recordable. In the event that porosity is present and is either of sufficient size or closely clustered, it may appear as a planar flaw if it presents a significant through-wall dimension. If the porosity is present across a constant depth, it may appear to the operator as a laminar flaw. In either case, the ability to accurately measure dimensions of the flaw (height, width, and length) may be required. It should be noted that porosity is not normally an issue unless the welding process is out of control.

2.2 PDI Flaw Characterization Techniques

The inspection of overlays is currently required using a procedure qualified through the ASME Section XI Appendix VIII PDI process. Inspections are categorized as either a pre-service inspection (PSI) or an in-service inspection (ISI). In a PSI exam, the entire overlay volume is inspected, including the pipe-to-overlay interface boundary. The main focus of this examination is to detect LOB flaws at the interface boundary or between weld layers, welding defects in the overlay material, and cracks in the overlay and outer 25% of the original pipe wall. The ISI exam of the overlay is designed to detect and size cracks that have extended into the outer 25% of the original pipe wall or into the overlay material.

In both cases, flaw characterization using current PDI techniques involves the measurement of flaw length and remaining ligament to the uppermost tip. No other dimensions, such as flaw width or crack height, are recognized.

The length of laminar and planar flaws in the weld overlay is measured by noting probe positions where the flaw response diminishes into the background noise. For flaws in the original weld and base material, only the portion of the flaw that has propagated into the outer 25% of the original material is measured. PDI procedures do not designate separate techniques for measuring flaw length and width [3]. In fact, a technique used for determining the width of a laminar flaw is not part of the Appendix VIII qualification process, and no documented acceptance criteria for sizing are available to judge the accuracy of this technique. Electric Power Research Institute (EPRI) performed laboratory work during the development of the welding processes for application of Alloy 52 overlays that addressed possible sizing errors. During this exercise, the actual defects were measured with ultrasonic techniques similar to the techniques used by qualified overlay depth sizing procedures. This exercise demonstrated that the PDI length measurement techniques were conservative when applied to sizing the flaw width. Generally, PDI length measurement techniques tend to oversize dimensions that are less than the width of the sound beam [2]. The introduction of Code Case N-740 adds additional acceptance criteria for laminar flaws beyond those found in Table IWB-3514-3. As a result, the ability to accurately determine laminar width is much more critical.

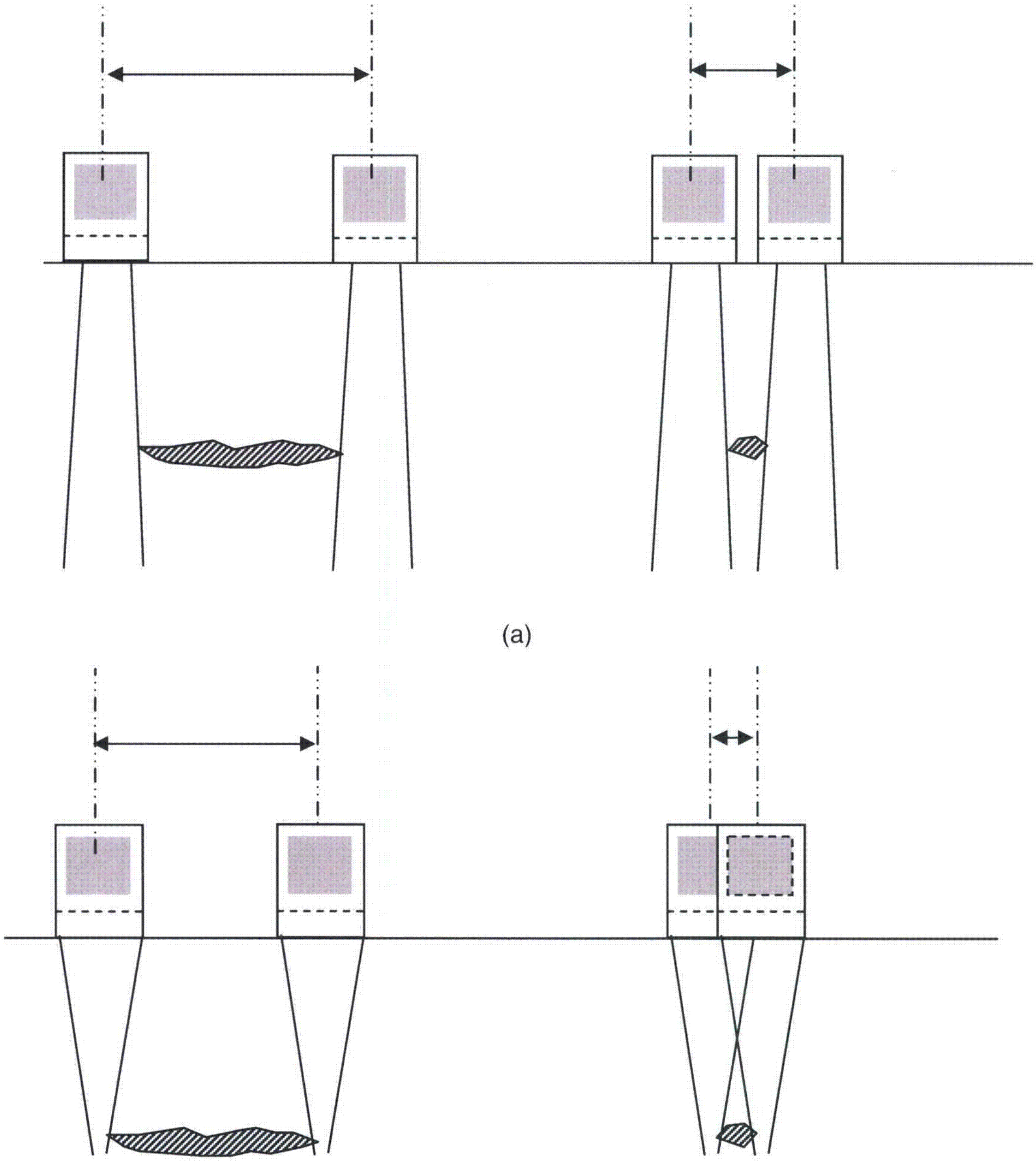
The flaw depth is determined by a direct measurement of the remaining ligament (distance between the scan surface and tip) using the absolute arrival time technique. However, current wording in PDI procedure PDI-UT-8, "PDI Generic Procedure for the Ultrasonic Examination of Weld Overlaid Similar and Dissimilar Metal Welds," states: "For contamination cracks or any other planar flaws located within the overlay material only the upper flaw tip response can be obtained." This wording implies that remaining ligament measurements can be made only from the upper tip or tip closest to the scan surface. For embedded cracks, flaw height is dependent upon the capability to measure the lower tip remaining ligament as well. However, techniques used for determining the through-wall dimension of embedded planar flaws are not part of the Appendix VIII qualification process, and there are no available documented acceptance criteria for sizing to judge the accuracy of this technique.

2.3 Non-PDI Flaw Characterization Techniques

The introduction of Code Case N-740 has emphasized the need for more accurate flaw sizing techniques specifically related to laminar width and embedded crack height measurements. The following is a description of techniques that could be used to improve these measurements.

2.3.1 Flaw Width Measurements (Laminar Flaws)

Typically, the width of a weld overlay laminar flaw will be significantly less than the width of the sound beam used during examination. In such a case, the flaw width will be significantly overestimated with its measured dimension heavily influenced by the sound beam width. In some cases where the flaw is significantly smaller than the sound beam, the flaw appears to have a width with dimensions that equate to those of the sound beam used. It is important to note that a common method for characterizing beam profiles associated with ultrasonic probes is to scan across a small spherical reflector while recording the response. This laboratory procedure used for measuring beam width is effectively simulated when a small welding flaw is evaluated. Figure 2-1 is provided to illustrate this effect. The error associated with amplitude drop method increases as the ratio of the beam width to flaw size increases.



(a)

(b)

Figure 2-1
Length/Width Sizing Using (a) Unfocused Beam and (b) Focused Beam (The unfocused beam oversized flaws especially when the flaw is significantly smaller than the beam width.)

There are two proposed approaches to increase the accuracy of laminar width measurement. The first approach is to minimize the width of the ultrasonic beam at the flaw location. Minimizing beam width requires focusing capability readily available using phased array technology. Phased array has already proven itself as an effective method for inspecting overlays with recent PDI demonstrations of an EPRI overlay procedure [5]. However, this procedure does not specifically address laminar width measurements or invoke related beam-forming requirements to maximize measurement accuracies. Procedural modifications where the focal depth of the instrument is modified to the depth of a detected flaw prior to its evaluation should significantly increase sizing accuracies for small flaw dimensions. The addition of this extra procedural step during flaw analysis should make the phased array approach a preferred method based on measurement accuracy when evaluating flaws per Code Case N-740.

A second approach for increased accuracy for small flaws is related specifically to the amount of signal drop used when locating the flaw end positions. The current technique for identifying flaw end positions in all EPRI PDI overlay procedures is to mark locations where the flaw signal diminishes into the background noise. This approach has proven adequate when measuring flaw length but overly conservative for flaw width measurements. The measured dimension can be modified by adjusting the amplitude-based criteria for determining end point location. For example, Figure 2-2 provides an illustration showing how a -6-dB measurement is less than a -24 dB measurement. Therefore, it is plausible to use varying degrees of amplitude drop (-3 dB, -6 dB, -12 dB, and so on) depending on flaw signal characteristics. Rules regarding the use of a specific technique for a particular flaw type involve the collection of data on known flaws. A relevant study has been performed by WesDyne International, LLC, and is described in this report.

2.3.2 Flaw Height Using Tip Diffraction

The current PDI technique for determining the remaining ligament of a detected flaw uses an absolute arrival time technique of the tip-diffracted signal associated with the uppermost tip. Tip-diffracted signals are low-amplitude omni-directional signals that originate from the crack tips when insonified by the transmitted sound wave. Although this approach provides an accurate measurement of the thickness of the ligament that exists between the top of the crack and the examination surface, flaw height is not measured for embedded flaws. In order to determine the height of an embedded crack, the tip-diffracted signal associated with the bottom tip must also be detected and its remaining ligament determined. Knowing the depth of both the upper and lower crack tips, the through-wall extension of the crack can be calculated as illustrated in Figure 2-3. It is this measurement that can then be used in IWB-3514-2 for determining the acceptance of an embedded flaw.

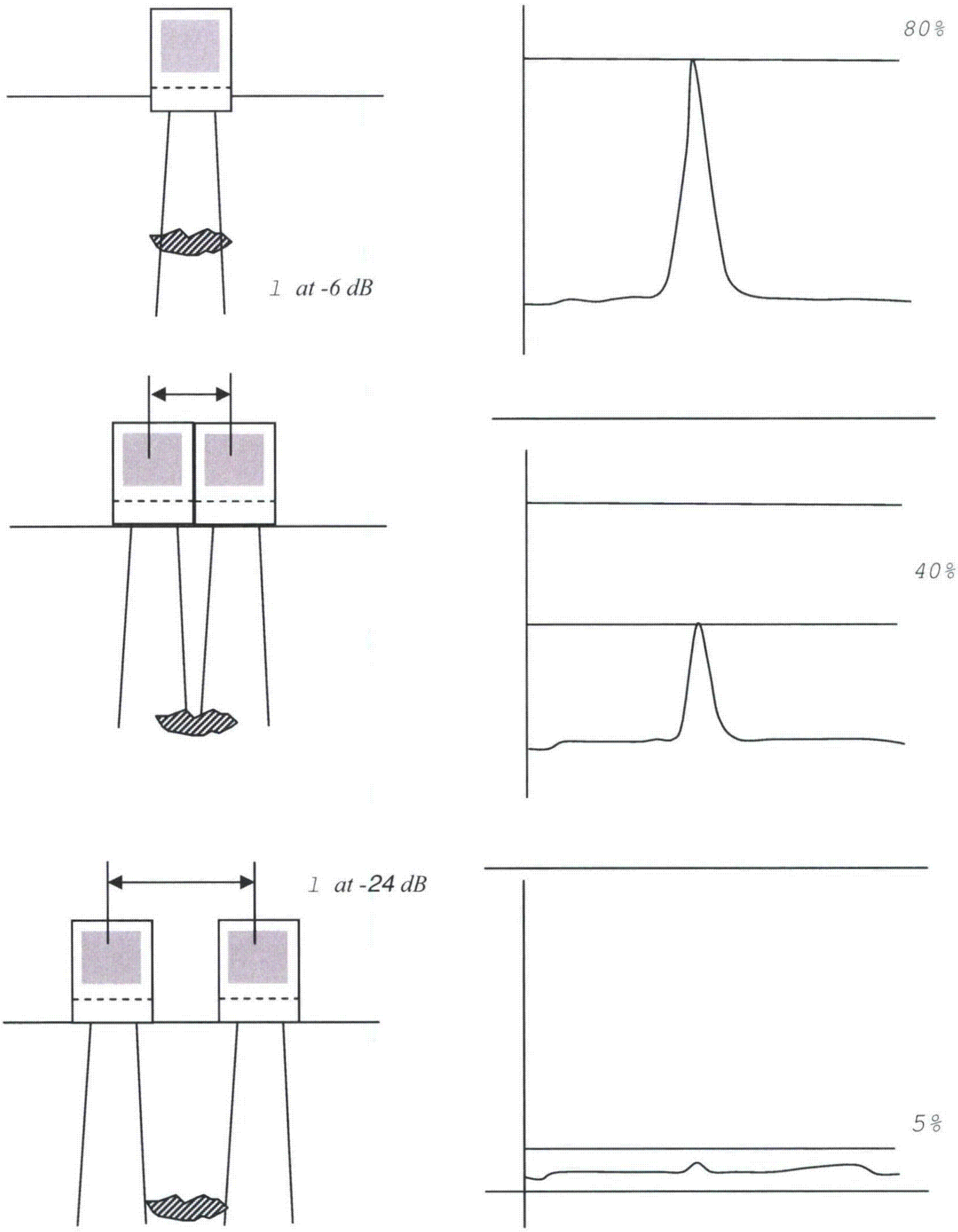


Figure 2-2
Measured Length Depends on the Amount of Signal Drop Used for Determining End Locations

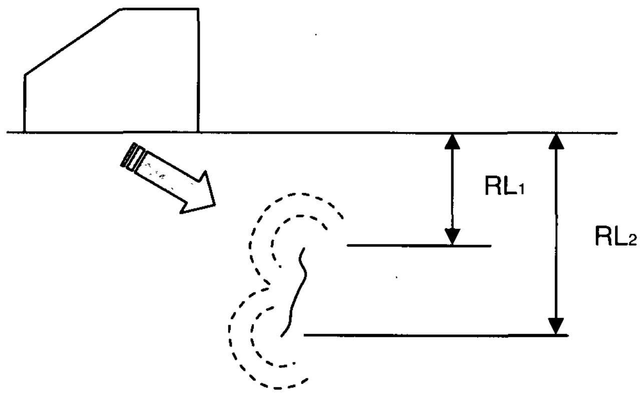


Figure 2-3
Example of Forward Backscatter Tip Diffraction Sizing

2.4 Code Case N-740 Evaluation Requirements

Currently ASME Section XI does not address the inspection of overlays directly. As a result, utilities have been forced to submit relief requests prior to utilizing overlays in their facilities. Historically, these relief requests have been in accordance with Code Case N-502, N-638-1 or Appendix Q. However, the latest Code Case, N-740, has been introduced and has combined aspects of these previous documents. It is now considered the controlling document for overlay inspection. In general, N-740 evaluation criteria are multi-tiered acceptance criteria that are more comprehensive than previous acceptance requirements. As a result, there is added incentive to refine ultrasonic flaw measurement techniques in order to minimize the occurrence of unnecessary overlay repairs. The following is a brief description of the acceptance criteria as they apply to planar and laminar flaw types.

2.4.1 Planar Flaw Evaluation per Code Case N-740

Acceptance criteria for planar defects are provided by the pre-service requirements of ASME IWB-3514-2. In applying the acceptance standards, wall thickness (TW) shall be the thickness of the weld overlay. Table IWB-3415-2 [7] provides separate acceptance criteria for surface flaws and subsurface flaws [2]. Current PDI overlay procedures do not specifically address the sizing of subsurface flaws (2a dimension for subsurface flaws), because the bottom tip-diffracted signal must be used. Flaw depth (S) and length (l) are PDI-qualified dimensions that can be used for flaw acceptance.

2.4.2 Laminar Flaw Evaluation per Code Case N-740

Acceptance criteria for laminar defects are provided by ASME IWB-3514-3, *Allowable Laminar Flaws*. These acceptance criteria are based on the ability to make accurate area measurements, length and width, for each laminar flaw. In addition, the totaled areas of all laminar flaws shall not exceed 10% of the weld surface area, and no individual laminar flaw shall have a dimension that exceeds 76.2 mm.

2.4.3 Reduction in Coverage

Code Case N-740 also requires an RIC calculation where the percentage of the overlay acceptance volume is obscured by the presence of laminar flaws in both the axial and circumferential directions. If this reduction in coverage is 10% or greater, then the overlay is unacceptable.

2.4.4 Assumed Planar Flaws

Code Case N-740 also takes into consideration the possibility that a planar flaw exists in any volume of material that is obscured by a laminar flaw. In this case, the largest planar flaw that would fit in the volume that cannot be inspected is assumed with consideration for both the axial and circumferential directions. The dimensions of this assumed planar flaw are then applied to ASME Table IWB-3514-2 with TW being the thickness of the overlay.

3 EXPERIMENTAL MEASUREMENTS OF SIZING ACCURACY

The following information is a summary of experimental data and conclusions related specifically to the accuracy of flaw sizing using amplitude drop methods, and through-wall sizing of embedded flaws using tip diffraction. This information was collected to support changes that are proposed to existing PDI procedures to allow compliance to Code Case N-740, where flaw width and height measurements are required.

3.1 WesDyne Investigation

The following information is based on work performed by WesDyne International, LLC, with experimental results and methodology documented in the related internal report [6]. The experimental work performed in this study dealt with both width sizing of laminar flaws and through-wall depth sizing of embedded planar flaws.

3.1.1 Width Sizing of Laminar Flaws

Five laminar-type reflectors (end mill notches) in a stainless steel plate sample, four laminar flaw regions in a surge nozzle weld overlay sample, and three indications in weld overlay samples (FFD-1 and FFD-53-1) were used in this laminar flaw indication width sizing investigation. Both 0° L-wave, dual-element probes and ultrasonic testing (UT) instrumentation qualified for laminar detection per EPRI Procedure PDI-UT-8 were used. Width measurements were collected using the amplitude (dB) drop methods of -3 dB, -6 dB, -12 dB, and full-amplitude where the signal was initially placed at 80% full screen height, and moved off the flaw until the appropriate amplitude drop occurred. Tests were performed with the probe parallel and perpendicular to the axis of the flaw.

Test results indicated that for flaw width measurements, where the flaw size is less than the beam width, the measured size approximates the beam width measured off a side-drilled hole. Probes with less beam spread (higher frequency) exhibit less error due to the smaller beam dimension. For example, the 2-MHz probe (MSEB2 model) produced errors ranging from 3.048 to 11.43 mm (mean error of +7.112 mm), and the 4-MHz probe (MSEB4 model) produced errors ranging from 0.508 to 6.35 mm (mean error of +3.048 mm). In comparison, errors associated with flaws larger than the beam width ranged from -2.54 to 0.508 mm, a much more accurate measurement.

Another observation related to measurement accuracy was the orientation of the probe. The probes used in EPRI Procedure PDI-UT-8 are dual-element 0° units where an acoustic insulation boundary separates the two elements. These probes are constructed with elements that are longer in one dimension than the other. As a result, the beam spread is more severe in one plane due to the smaller effective aperture. Tests performed in this study indicated that width measurement accuracies were better when the orientation of the acoustic boundary was perpendicular to the major axis of the lamination as illustrated in Figure 3-1.

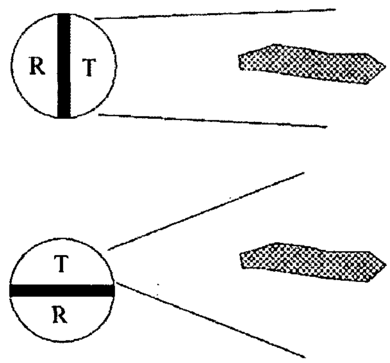


Figure 3-1
Laminar Width Measurement Accuracies Increase with Acoustic Barrier Perpendicular to the Laminar Major Axis Due to Reduced Beam Spread Associated with the Larger Effective Aperture

This investigation compared the accuracy of different amplitude reduction (dB drop) methods on flaws of differing types and noted signal response characteristics associated with each. Table 3-1 is a summary of these findings, showing the most accurate dB drop method for sizing a particular flaw type.

Table 3-1
Laminar Flaw Width Sizing Methodology

Flaw Type	Ultrasonic Signature	Signature Characteristics	Width Sizing Method
Round, Volumetric	Distinct, rather sharp response	• Relatively stable and repeatable peak amplitude • Smooth amplitude envelope as the probe is scanned across the width • Relatively low signal amplitude/bandwidth (BW) ratio • Very good signal-to-noise ratio with defined start and stop points in both the length and width directions	-3-dB drop
Small, Singular	Distinct, rather sharp response	• Relatively stable and repeatable peak amplitude • Smooth amplitude envelope as the probe is scanned across the width • Relatively low signal amplitude/BW ratio • Very good signal-to-noise ratio with defined start and stop points in both the length and width directions	-3-dB drop

Table 3-1 (continued)
Laminar Flaw Width Sizing Methodology

Flaw Type	Ultrasonic Signature	Signature Characteristics	Width Sizing Method
Large, Singular	Distinct, sharp response	• Stable and repeatable peak amplitude • Relatively smooth amplitude envelope as the probe is scanned across the width • Relatively high signal amplitude/BW ratio • Excellent signal-to-noise ratio with defined start and stop points in both the length and width directions	-6-dB drop
Cluster	Broad, multi-peaked response	• Difficult to peak amplitude • Variable amplitude envelope as the probe is scanned across the width • Relatively low signal amplitude/BW ratio • Good signal-to-noise ratio (>2:1) with less definitive start and stop points in both length and width directions	Full-amplitude

The WesDyne investigation had the following conclusions with regard to the sizing of laminar flaw widths:

- The full-amplitude dB drop sizing methodology is too conservative for the measurement of width for all laminar types.
- The orientation of the MSEB2 and MSEB4 probes is significant with respect to laminar flaw width sizing accuracy. If the acoustic barrier is perpendicular to the laminar flaw major axis, the width sizing accuracy is better.
- The -3-dB drop technique provides a better estimate for the width dimension of a round singular or a small singular flaw. Such flaws are typical of a weld inclusion or a small inter-bead lack of fusion.
- The -6-dB drop technique provides a better estimate for the width dimension of a large, singular laminar flaw. Such a flaw is an extensive LOB.
- The full-amplitude drop technique best encompasses the width dimension of a cluster laminar flaw. Such a flaw is typical of a high-density region of small, multi-directional cracks.

3.1.2 Through-Wall Sizing of Laminar Flaws

Five planar-type flaw reflectors in a stainless steel plate sample and seven planar in two EPRI samples (PSI 1-3 and PSI 1-4) were used in the through-wall sizing investigation. Numerous UT probes were used, along with a UT instrument qualified for crack detection/sizing per EPRI PDI-UT-8. Flaws were evaluated using a backscatter tip-diffraction technique similar to that qualified for determining the ligament of a planar indication from the weld overlay OD surface. For this investigation, the difference in remaining ligament measurement associated with the upper and lower tip signals was recorded as the crack height measurement.

The results of this investigation indicated that the backscatter technique had a root-mean-square (rms) accuracy of 0.813 mm on ideal flaws embedded in flat, smooth samples. However, with consideration of real world conditions and the fact that accurate measurements depend on the operator's ability to recognize tip signals, the ability to measure within an rms of 3.175 mm seemed reasonable. This investigation also documented the resolution of the probes used in distinguishing between the upper and lower tip signals. As a flaw's height decreases, the upper and lower tip signals move closer together on an ultrasonic A-scan presentation. As a result, there is a minimum height where these two signals are no longer distinguishable. This investigation found this minimum flaw height to be approximately 3.556 mm. The through-wall extent of flaws smaller than 3.556 mm typically is not measurable using the backscatter technique. When this dimension is applied to ASME IWB 3514-2 acceptance criteria, the use of tip-diffracted methods for the sizing of embedded planar flaws in overlay with thickness less than 12.7 mm is not practical.

The WesDyne investigation had the following conclusions with regard to the through-wall sizing of planar flaws using the backscatter technique:

- The backscattered tip diffraction technique is reasonable for use in establishing the through-wall extent of planar indications in a weld overlay. It is not new to the industry or the qualified UT examiners implementing PDI-UT-8, and this approach is already being applied to the dimensioning of the ligament between the uppermost extent of a planar flaw indication and the weld overlay OD surface.
- The backscattered tip diffraction technique, when applied using a manual inspection process as implemented by a qualified PDI-UT-8 UT examiner, should provide a result within an RMS error of less than or equal to 3.175-mm. This considers the influence of field conditions.
- The backscattered tip diffraction technique may be limited to sizing weld overlay planar flaw indications in weld overlays having through-wall extent of approximately 3.556 mm and greater.
- The use of tip-diffracted methods for sizing of embedded flaws in overlays less than 12.7 mm thick is not practical.

3.2 EPRI Investigation—Conventional Width Sizing

The following information is based on work performed by EPRI using laminar flaws selected randomly from the PDI overlay test inventory. The purpose of this investigation was to compare the differences in width measurements when applying the -3-dB drop, -6-dB drop, -12-dB drop, and full-amplitude drop methods to an actual PDI flaw. Because the flaws used for this demonstration were part of the PDI test inventory, the actual flaw widths could not be disclosed. However, PDI personnel assisted in determining at what dB drop the correct width would have been reported. Two additional flaws contained in open practice samples (Flaws 51 and 55) were also evaluated where a comparison to actual flaw width could be made. The flaw width for these two flaws was 6.35 mm. The data presented are designed to provide a relative comparison between the sizing differences associated with the different techniques described previously. All data were collected using a KBA 4.0-MHz MSEB probe (PDI-approved) and collected in an encoded format so that accurate measurements could be made subsequent to data collection using software analysis tools.

Tables 3-2 and 3-3 summarize the results of this test. Figures 3-2 through 3-9 show examples of the echo dynamics of the flaw responses for Flaws 51 and 55 and how each measurement was obtained. These results indicate the range of flaw width measurements for these PDI laminar flaws. The full-amplitude drop method is the technique required by Procedure PDI-UT-8 for measuring flaw length.

The data indicate significant difference between the different amplitude drop techniques for measuring flaw width. As expected, the -3-dB drop measurements produced the smallest flaw width estimate. The remaining methods produced errors that were progressively larger as the required amplitude drop increased. These differences in the measured flaw widths are dramatically different primarily due to the small size of the reflector and the effect of beam width. Such large differences between these methods would not be expected when applied to flaw length measurements where the measured dimension is greater than the size of the ultrasonic beam.

Table 3-3 provides the estimated dB drop required to achieve the as-built dimension of each flaw using the echo-dynamic data. These estimated amplitude drop values ranged from 1.7 to 6 dB with an average of 3.4 dB over the sample set. These data suggest that measurements collected with a full-amplitude drop when the flaw is smaller than the beam will result in significant oversizing.

The flaw widths of Flaws 51 and 55 were made available because they were part of an open sample used for practice. Data from these two flaws indicated that the -3-dB drop method actually undersized the flaw width an average of 1.168 mm. However, the -6-dB method oversized these flaws an average of 1.626 mm. Clearly, the -12-dB or full-amplitude drop methods would have significantly oversized these two flaws.

This investigation suggests that there are significant differences in the measured width of flaws when performed with the different dB drop methods. As a result, an approach where a specific dB drop method is used for a given flaw type or condition could potentially improve width sizing accuracy when using conventional techniques. These results are consistent with those presented in the WesDyne report [6] described in Section 3.1.

Table 3-2
Deviations in Width Measurements Using Different Techniques (in.)

	-3-dB Drop	-6-dB Drop	-12-dB Drop	Full-Amplitude Drop
Flaw 1	0.006	0.041	0.183	0.431
Flaw 2	0.020	0.018	0.339	0.419
Flaw 3	0.011	0.024	0.165	0.341
Flaw 4	0.021	0.014	0.127	0.232
Flaw 5	0.028	0.098	0.204	0.416
Flaw 6	0.028	0.135	0.240	0.417
Flaw 7	0.028	0.106	0.205	0.463
Flaw 8	0.028	0.178	0.250	0.321
Flaw 55[1]	0.064	0.047	0.195	0.269
Flaw 51	0.028	0.080	0.270	0.344

Notes:
[1] The width of Flaws 51 and 55 is 0.25 in. These flaws are contained in open practice samples.
1 in. = 25.4 mm

Table 3-3
Amplitude Drop Used to Achieve As-Built Width Measurements

Flaw Number	dB
1	3.5
2	1.7
3	4.6
4	6.0
5	2.9
6	2.5
7	2.4
8	3.3
Average dB	3.4

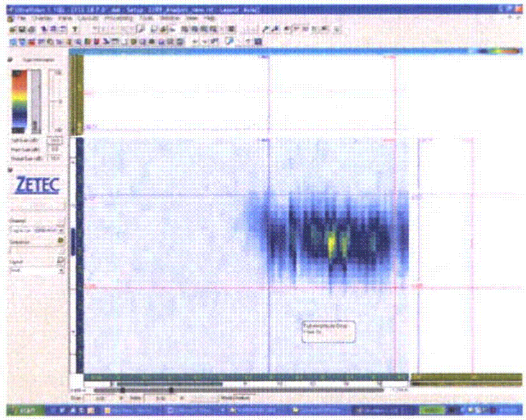


Figure 3-2
Flaw 55 Width of 13.183 mm Measured Using Full-Amplitude Drop

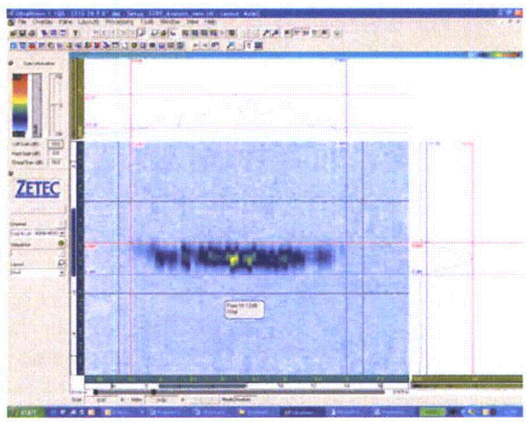


Figure 3-3
Flaw 55 Width of 11.303 mm Measured Using 12-dB Amplitude Drop

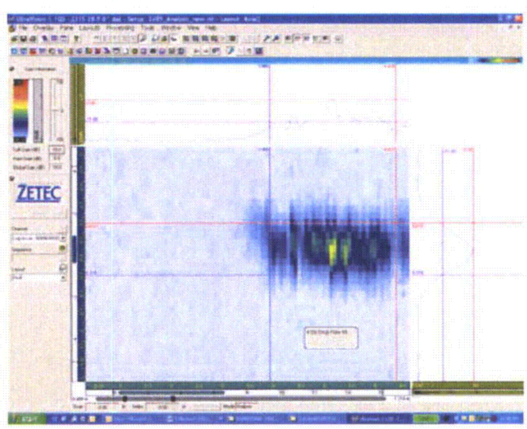


Figure 3-4
Flaw 55 Width of 7.544 mm Measured Using -6-dB Amplitude Drop

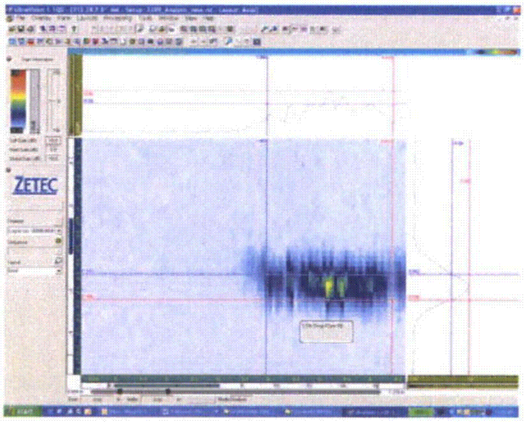


Figure 3-5
Flaw 55 Width of 4.724 mm Measured Using -3-dB Amplitude Drop

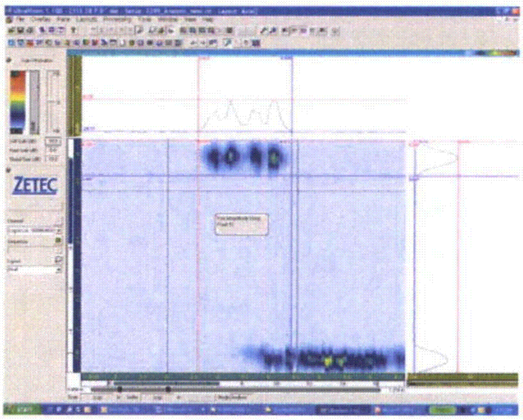


Figure 3-6
Flaw 51 Width of 15.088 mm Measured Using Full-Amplitude Drop

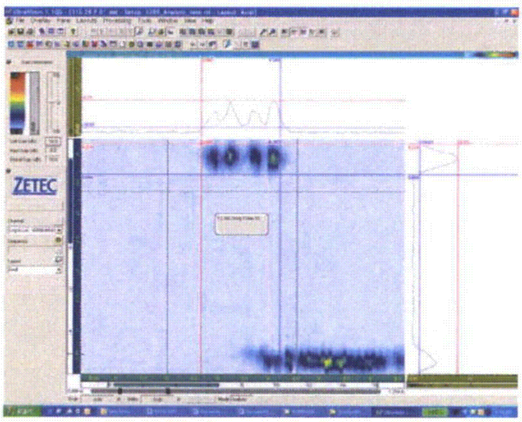


Figure 3-7
Flaw 51 Width of 13.208 mm Measured Using -12-dB Amplitude Drop

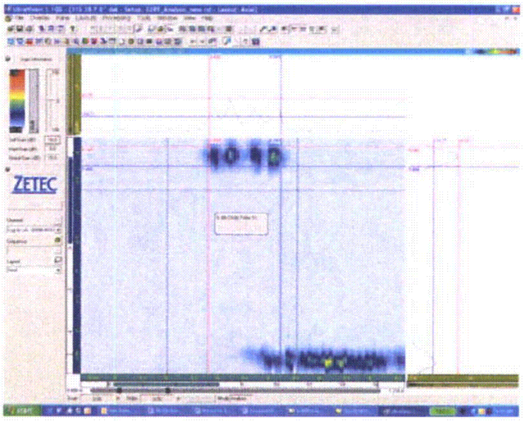


Figure 3-8
Flaw 51 Width of 8.382 mm Measured Using -6-dB Amplitude Drop

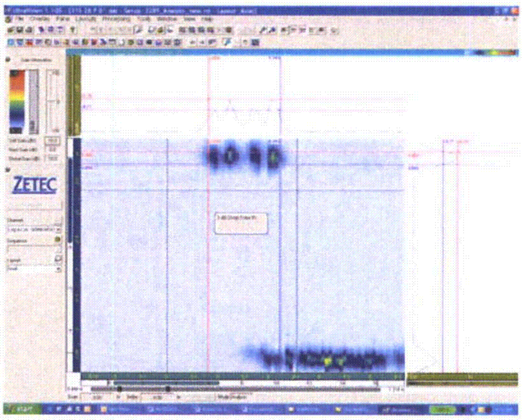


Figure 3-9
Flaw 51 Width of 5.639 mm Measured Using -3-dB Amplitude Drop

3.3 EPRI Investigation—Phased Array Width Sizing

The following information is based on work performed by EPRI to demonstrate the effectiveness of beam focusing in accurately measuring flaw width using a portable phased array instrument operated in a manual mode. All tests were performed using a Harfang X-32 portable phased array system. All tests were performed using the dual-array, 16-element linear array, 2-MHz probe specified in procedure EPRI-WOL-PA-1 like that shown in Figure 3-10. However, a different wedge configuration was used for each sample type tested.

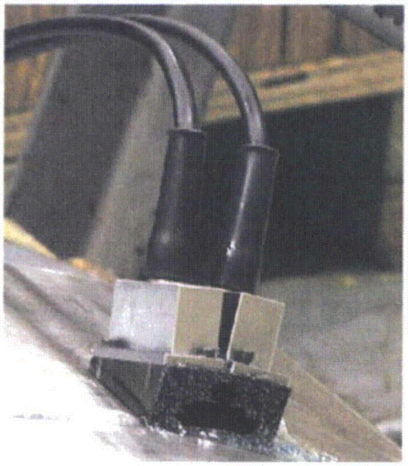


Figure 3-10
Probes Used for All Width Measurements (Shown on wedge used for inspecting Westinghouse Safety Relief Overlay Mockup sample)

The first sample inspected was a 711.2-mm diameter overlay pipe section containing two laminar flaws, Flaw 51 and Flaw 55. The wedge used for this inspection was a 0° wedge as shown in Figure 3-11. Numerous width measurements were collected with the focus depth at four different settings: unfocused, focused at 12.7 mm, focused at 28.448 mm, and focused at 38.1 mm. Table 3-4 summarizes the flaw width measurements. It should be noted that the width of both flaws was 6.35 mm.

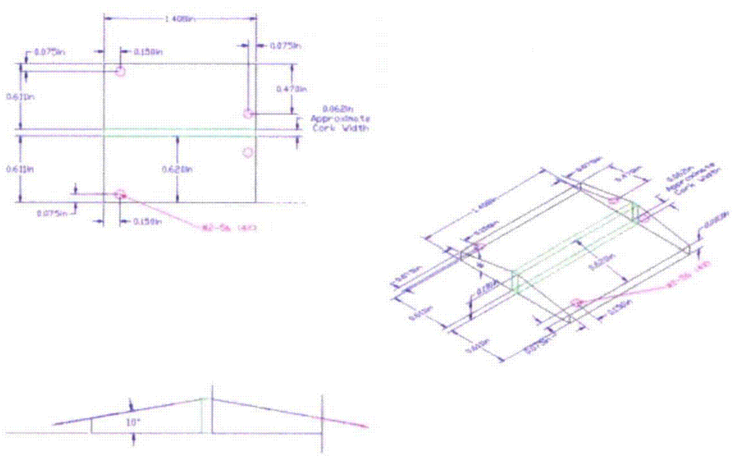


Figure 3-11
Wedge Used for Testing 711.2-mm Sample

Table 3-4
Flaw Width Measurements with Phased ArrayProbe Focused at Various Depths

		Flaw	Width (in.)
Unfocused	-1-dB drop	51	0.50
	-6-dB drop		0.95
	-12-dB drop		1.15
0.5-in. focus	-1-dB drop		
	-6-dB drop		0.24
	-12-dB drop		0.42
1.12-in. focus	-1-dB drop		
	-6-dB drop		0.31
	-12-dB drop		0.48
1.5-in. focus	-1-dB drop		
	-6-dB drop		0.40
	-12-dB drop		0.65
Unfocused	-1-dB drop	55	0.49
	-6-dB drop		0.80
	-12-dB drop		1.05
0.5-in. focus	-1-dB drop		
	-6-dB drop		0.20
	-12-dB drop		0.30
1.12-in. focus	-1-dB drop		
	-6-dB drop		0.30
	-12-dB drop		0.45
1.5-in. focus	-1-dB drop		
	-6-dB drop		0.30
	-12-dB drop		0.60

Note:
1 in. = 25.4 mm

In all cases, focusing the probe and using the -6-dB drop method produced the most accurate results. There was not a great deal of deviation in accuracy as long as focusing was used, although focusing at or near the flaw depth seemed to produce the best results. Also, when using a focused probe, the signal was in the process of either peaking or dropping in amplitude, making a width measurement based on the initiation of a signal drop (-1 dB) impractical. These results indicate that when using a focused phased array probe, accuracies on the order of ±1.27 mm are possible. Figures 3-13 through 3-24 are sectorial scans showing the flaw responses for each setting.

The second sample inspected was an overlaid Westinghouse safety relief nozzle, or Westinghouse Safety Relief Overlay Mockup, containing two laminar flaws, Flaw 4 and Flaw 5. The wedge used for this inspection was an 18.5° wedge also used for laminar detection per EPRI-WOL-PA-1. This wedge is shown in Figure 3-12. Tests performed on this sample were collected using only two focus settings, unfocused and focused at the flaw depth, with all measurements taken using a -6-dB drop method. Table 3-5 summarizes the flaw width measurements. It should be noted that the width of both flaws was 6.35 mm.

The results also indicate that focusing produces much better accuracy compared to an unfocused phased array probe. These results also suggest that when using a focused phased array probe, accuracies on the order of ±1.27 mm are possible.

It can be concluded that accurate measurements in the width of a flaw can be achieved when using a focused phased array technique.

Table 3-5
Width Measurements Taken on Westinghouse Safety Relief Nozzle

	Measured Width	
	Unfocused in. (mm)	Focused at Flaw in. (mm)
Flaw 4	0.400 (10.16)	0.250 (6.35)
Flaw 5	1.100 (27.94)	0.300 (7.62)

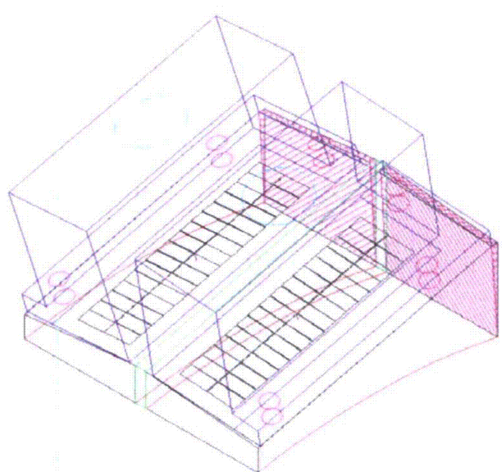


Figure 3-12
Wedge Used for Inspecting the Westinghouse Safety Relief Nozzle Sample

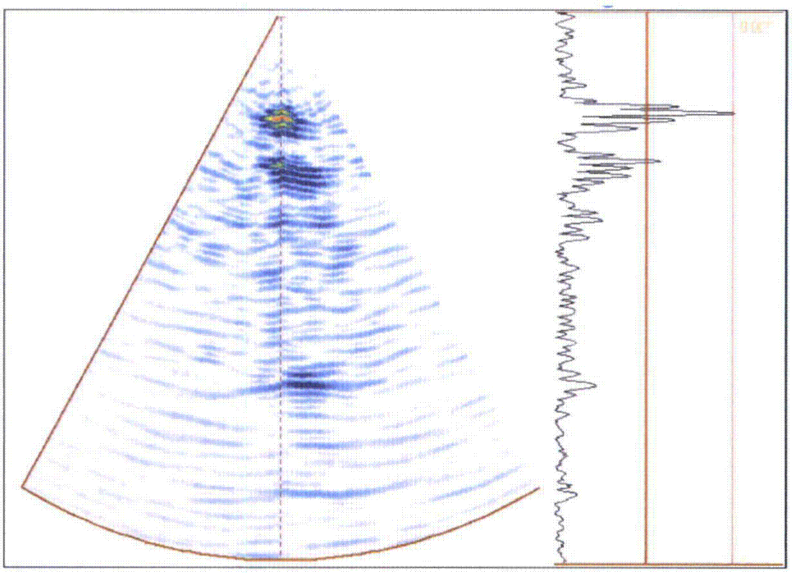


Figure 3-13
Flaw 51 Using Unfocused Phased Array Probe

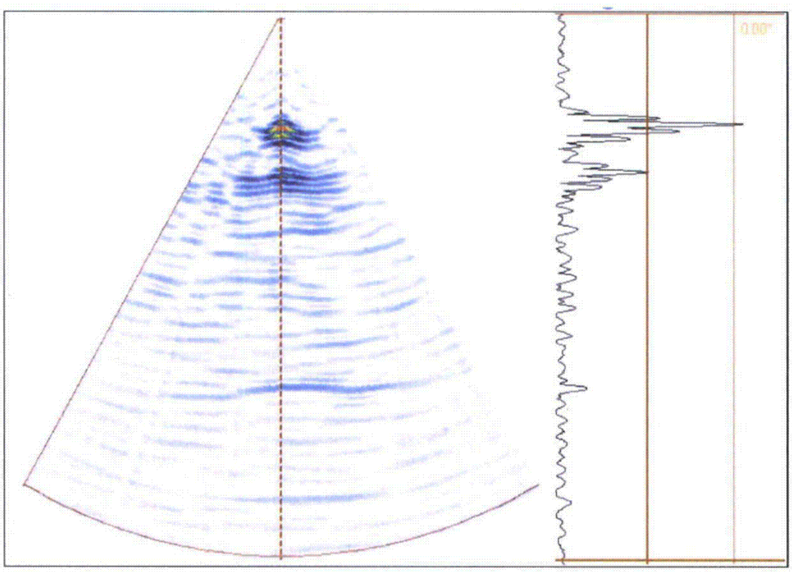


Figure 3-14
Flaw 51 Using Phased Array Probe Focused 2X Beyond Flaw

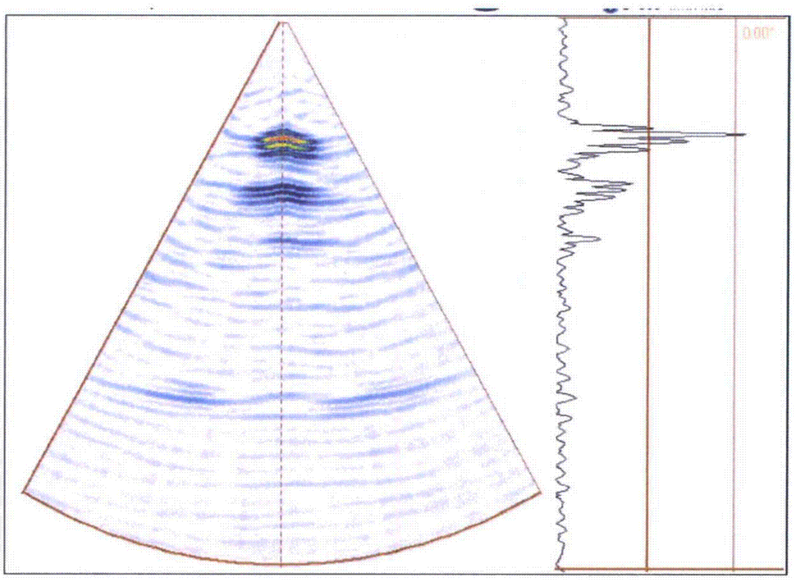


Figure 3-15
Flaw 51 Using Phased Array Probe Focused at Flaw

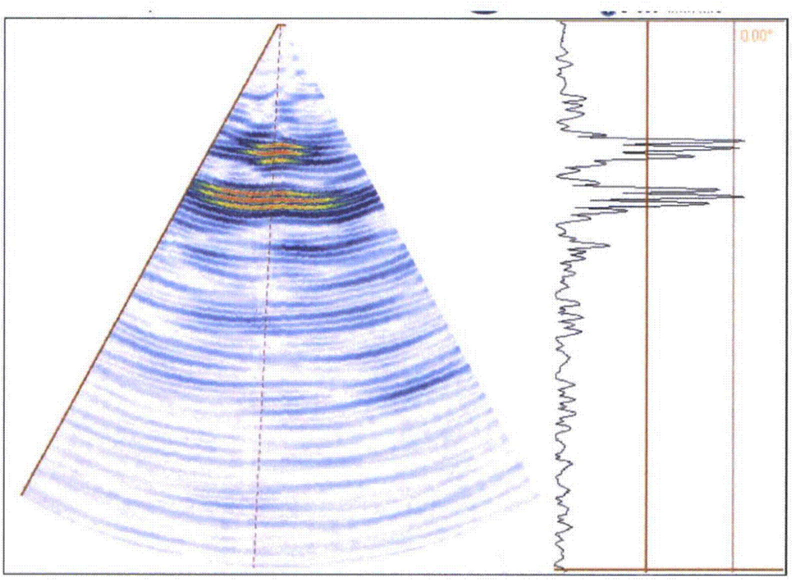


Figure 3-16
Flaw 51 Using Phased Array Probe Focused 1/2 Depth to Flaw

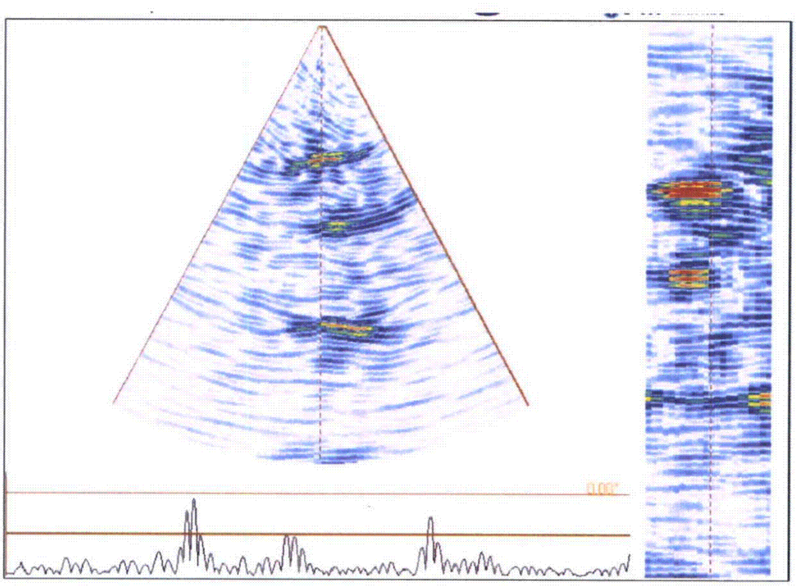


Figure 3-17
Flaw 55 Using Unfocused Phased Array Probe

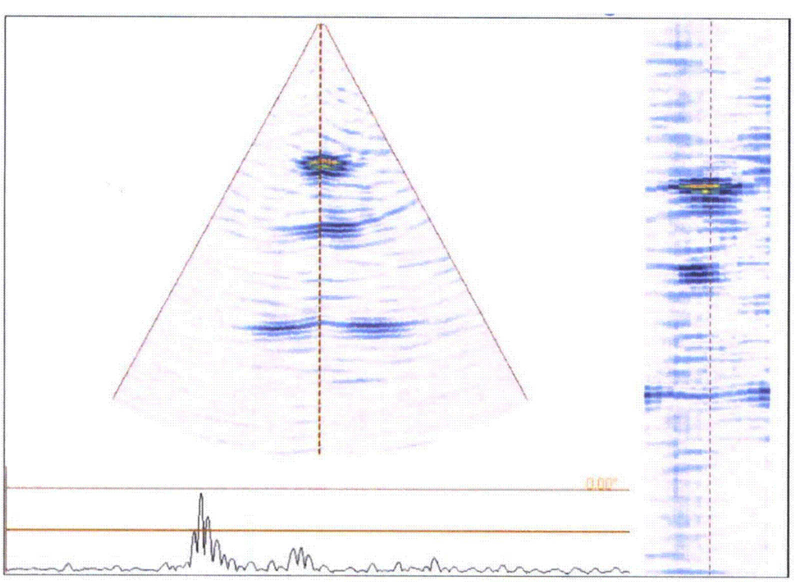


Figure 3-18
Flaw 55 Using Phased Array Probe Focused 2X Beyond Flaw

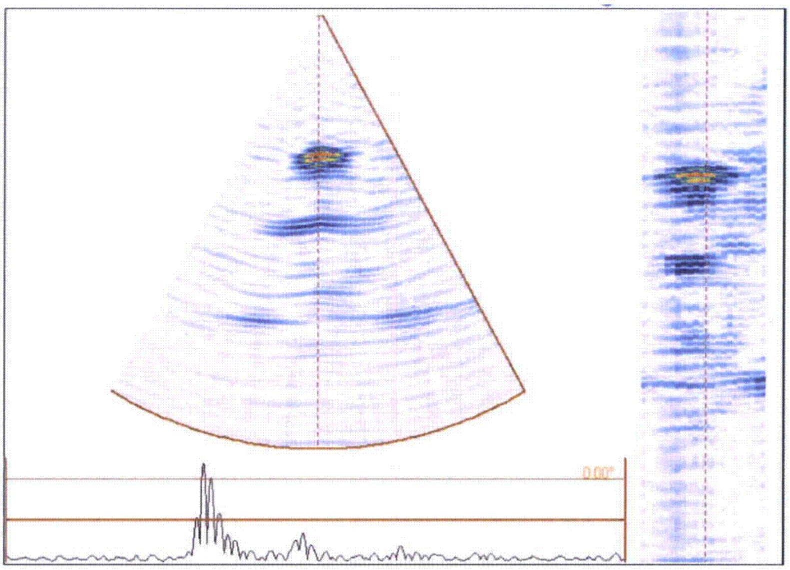


Figure 3-19
Flaw 51 Using Phased Array Probe Focused at Flaw

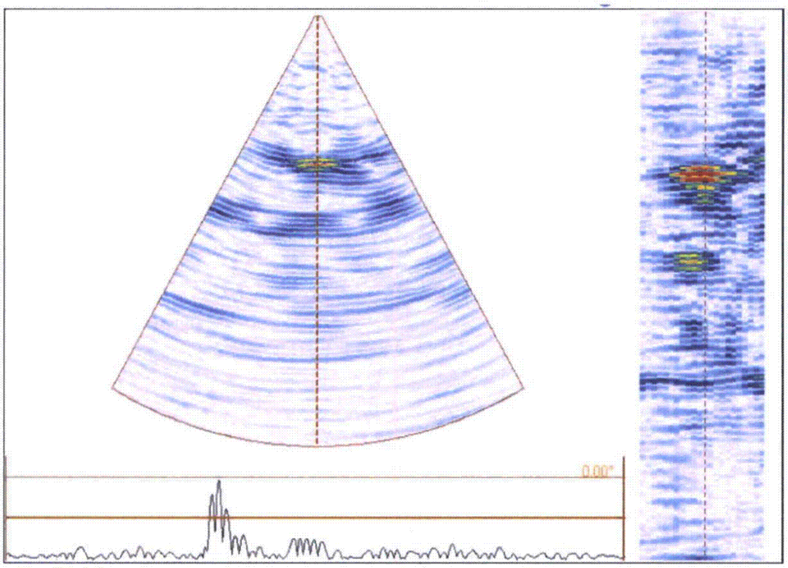


Figure 3-20
Flaw 51 Using Phased Array Probe Focused 1/2 Depth to Flaw

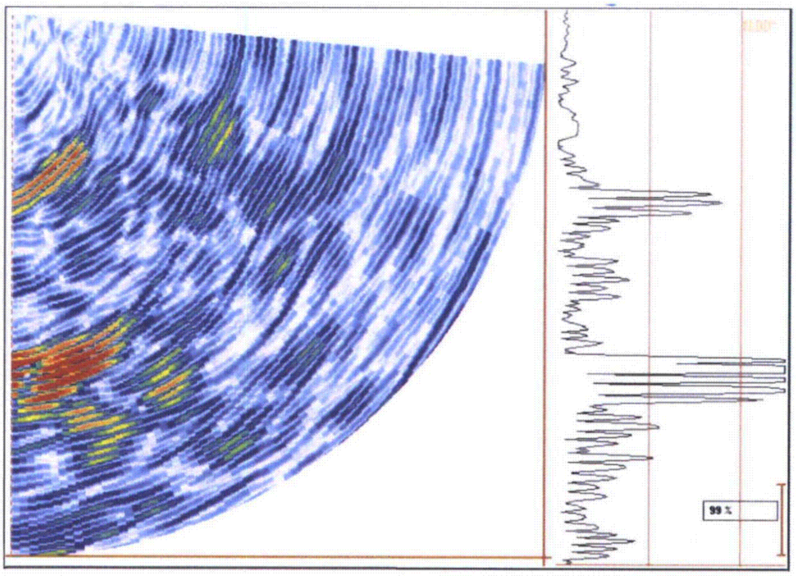


Figure 3-21
Flaw 4 on Westinghouse Safety Relief Overlay Mockup Sample Using Unfocused Phased Array Probe

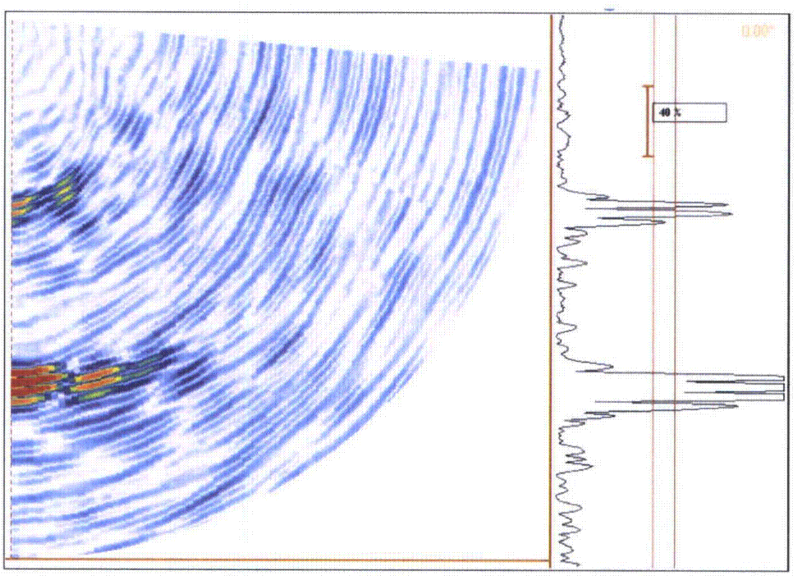


Figure 3-22
Flaw 4 on Westinghouse Safety Relief Overlay Mockup Sample Using Phased Array Probe Focused at Flaw Depth

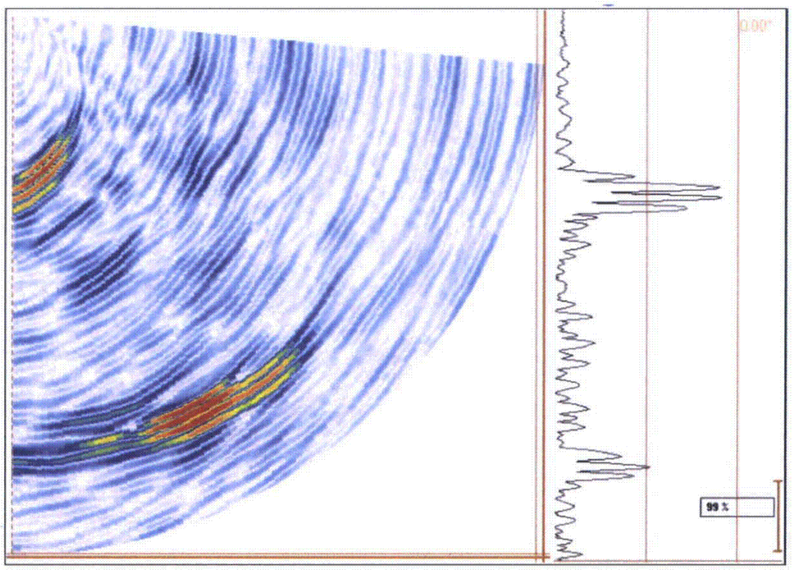


Figure 3-23
Flaw 5 on Westinghouse Safety Relief Overlay Mockup Sample Using Unfocused Phased Array Probe

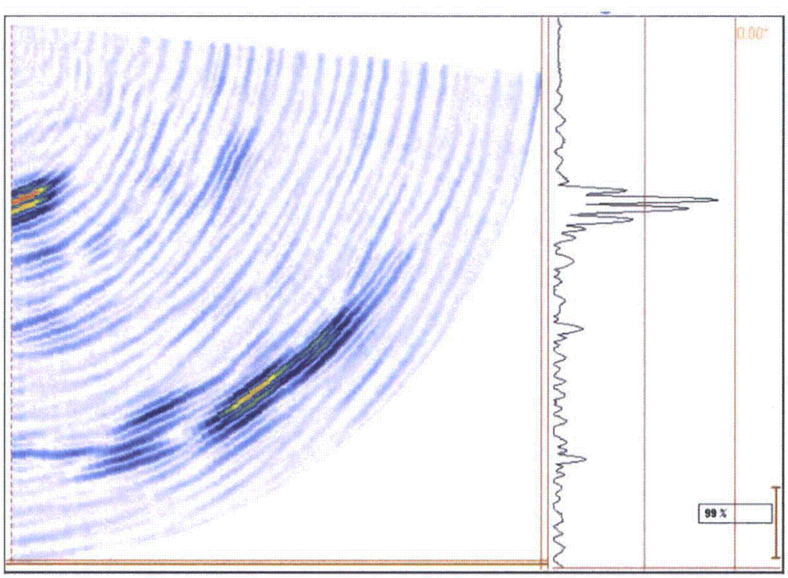


Figure 3-24
Flaw 5 on Westinghouse Safety Relief Overlay Mockup Sample Using Phased Array Probe Focused at Flaw Depth

4 ACTIONS

4.1 Procedure Revision

Two EPRI PDI procedures are currently available for the ultrasonic inspection of overlay welds: PDI-UT-8, "PDI Generic Procedure for the Ultrasonic Examination of Weld Overlaid Similar and Dissimilar Metal Welds," and EPRI-WOL-PA-1, "Procedure for Manual Phased Array Ultrasonic Examination of Weld Overlaid Similar and Dissimilar Metal Welds."

The following is an example of possible changes to PDI-UT-8 in order to add width sizing for laminar indications and height sizing for embedded indications. It should be noted that approved changes that successfully pass PDI requirements may differ slightly from those provided. Similar changes to EPRI-WOL-PA-1 are still under consideration.

1.6 This procedure is qualified for:

1. Detection, length, and width sizing of fabrication flaws located in the weld overlay material or at the base material/overlay material interface.
2. Height of embedded planar flaws in overlays with thickness greater than 12.7 mm.
3. Detection, length, and depth sizing of circumferentially oriented base metal flaws, and detection and depth sizing of axially oriented base metal flaws.

1.7 This procedure is <u>not</u> qualified for:

1. Length sizing axially oriented flaws regardless of location. However, the techniques described in this procedure may be used to estimate the length of a detected axial flaw as long as the effects of the component curvature are taken into account.
2. Depth sizing flaws detected in overlay material <12.7 mm in thickness.
3. Detection, length, or depth sizing of flaws contained within the base material of cast stainless steel components.

9.5 Width Sizing

9.5.1 Width Sizing Technique

Width sizing should be performed in a manner similar to the technique identified below. Responses from all search units shall be reviewed in order to properly discriminate flaw responses from surrounding metallurgical and geometric conditions.

a) Optimize the signal response from the flaw indication.

b) Scan the indication area with specific focus on the flaw signal responses (for example, signal shape, signal-to-noise orientation, dynamic response of peaking during scanning, amplitude of back wall signal, effect of skew, and so on). Adjust the system gain as needed to optimize flaw responses.

c) Scan adjacent unflawed areas in close proximity to the flaw area with specific focus on the surrounding geometric responses (weld material noise, edge of overlay, and so on).

d) Maximize the signal response from the flaw indication.

e) The width of flaws shall be determined by scanning along the width of the flaw in each direction until the signal response has diminished as specified in Table 4-1, depending on signal characteristics.

f) When examining non-standard overlays that have varying diameters, the location of the search unit with relation to the flaw location shall be accounted for during the measurement.

Table 4-1
Laminar Flaw Width Sizing Methodology

Flaw Type	Ultrasonic Signature	Signature Characteristics	Width Sizing Method
Round, volumetric	Distinct, rather sharp response	• Relatively stable and repeatable peak amplitude • Smooth amplitude envelope as the probe is scanned across the width • Relatively low signal amplitude/BW ratio • Very good signal-to-noise ratio with defined start and stop points in both the length and width directions	-3-dB drop
Small, singular	Distinct, rather sharp response	• Relatively stable and repeatable peak amplitude • Smooth amplitude envelope as the probe is scanned across the width • Relatively low signal amplitude/BW ratio • Very good signal-to-noise ratio with defined start and stop points in both the length and width directions	-3-dB drop
Large, singular	Distinct, sharp response	• Stable and repeatable peak amplitude • Relatively smooth amplitude envelope as the probe is scanned across the width • Relatively high signal amplitude/BW ratio • Excellent signal-to-noise ratio with defined start and stop points in both the length and width directions	-6-dB drop
Cluster	Broad, multi-peaked response	• Difficult to peak amplitude • Variable amplitude envelope as the probe is scanned across the width • Relatively low signal amplitude/BW ratio • Good signal-to-noise ratio (>2:1) with less definitive start and stop points in both length and width directions	Full-amplitude

9.6 Depth Sizing

9.6.1 Depth Sizing Technique

a) Flaw depth sizing shall be performed utilizing the absolute arrival time technique (see Figure 3). This technique relies upon obtaining direct signal responses (diffraction) from both the upper and lower (embedded flaws) flaw tips. The amount of unflawed material, or remaining ligament, is then read directly from the screen. Flaw depth for an ID-connected indication is then calculated by subtracting the remaining ligament from the actual material thickness. Flaw depth associated with an embedded flaw is determined by subtracting the remaining ligament associated with the top tip from the remaining ligament measured for the bottom tip.

b) When depth sizing axially oriented indications the flaw tip position(s) shall be plotted or calculated to compensate for the component curvature.

c) When depth sizing flaws in non-standard overlays that contain tapers or transitions, the flaw tip position(s) shall be plotted and the effect of the component geometry shall be compensated for in the final measurements.

4.2 Additional Test Sample Fabrication

Additional data are needed to evaluate the effectiveness of techniques used for laminar width and flaw height measurements of embedded flaws. EPRI is in the process of fabricating additional test samples containing such flaws with an emphasis on overlays with thicknesses ranging from 15.24–35.56 mm. These test samples will contain a wider range of laminar widths and embedded planar flaws with varying heights. These samples will also be used to confirm that embedded flaws with height less than 3.556 mm cannot be sized.

4.3 Code Case Revisions

An effort to write a Relief Request coupled with a Code Case that addresses qualification criteria needed to qualify these techniques is underway.

5 SUMMARY

This report provides background and supporting data related to ultrasonic techniques for the improvement in accuracy of width sizing of laminar-type flaws and the added ability for determining the through-wall extension of embedded planar flaws using conventional ultrasonic techniques. Test results suggest that modifying the amount of signal amplitude drop used during width sizing based on the characteristics of the flaw's response can significantly improve sizing accuracy of flaw width when using conventional techniques. Data are also presented related to improved width sizing accuracy when focused phased array techniques are used. The ability of measuring the through-wall dimension of embedded flaws is also discussed and recommendations made. Measurements taken during this study concur with those provided by WesDyne International, LLC.

Data collected on embedded flaws indicate that the limit on tip-diffracted signal resolution requires a flaw larger than 3.556 mm for flaw height measurements to be possible. When compared to ASME acceptance criteria, the through-wall sizing of embedded flaws in overlays thinner than 12.7 mm is not practical.

The ability to size embedded planar flaws to an accuracy of 3.175 mm rms is reasonable.

Modifications to the existing conventional PDI procedure are provided that are expected to improve width sizing accuracy and permit the through-wall sizing of embedded flaws.

New test samples are currently being fabricated that will provide more data on width sizing accuracy and the through-wall sizing capabilities on embedded planar flaws. These samples will represent thicker overlays with a wide range of flaw widths and through-wall dimensions.

An effort to write a Relief Request coupled with a Code Case that addresses qualification criteria needed to qualify these techniques is underway.

Phased array techniques were investigated and significant improvement in width sizing accuracy demonstrated. Continued evaluation of advanced phased array techniques will be evaluated to see if additional improvements can be made.

6 REFERENCES

1. *A Summary of Technical Information Related to the Application and Ultrasonic Examination of Weld-Overlaid Components.* EPRI, Palo Alto, CA and TEPCO, Tokyo, Japan: 2005. IR-2005-84.
2. EPRI Overlay Handbook, EPRI Report 1014554. 2007 (draft).
3. PDI-UT-8, "Generic Procedure for Ultrasonic Examination of Weld-Overlaid Austenitic Pipe Welds."
4. EPRI-WOL-PA-1, "Procedure for Manual Phased Array Ultrasonic Examination of Weld Overlaid Similar and Dissimilar Metal Welds."
5. *Nondestructive Evaluation: Procedure for Manual Phased Array UT of Weld Overlays.* EPRI, Palo Alto, CA: 2007. 1015134.
6. "Technical Justification for Width Sizing of Laminar Flaw Indications and Through-Wall Sizing of Planar Flaw Indications in Structural Weld Overlays," Report Number WDI-TJ-1024, WesDyne International, LLC, 2007.
7. ASME Boiler and Pressure Vessel Code, Section XI, 2001.

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