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Status of Activities for Inspecting Weld Overlaid Pipe Joints

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Pacific Northwest Laboratory
Operated by
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FOREWORD

This interim report documents work performed by the Pacific Northwest Laboratory for the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research, Division of Engineering Technology. The work was performed as part of an NRC program, Integration of Nondestructive Examination Reliability and Fracture Mechanics, NRC FIN B2289. The NRC technical monitor is Dr. Joseph Muscara.

ABSTRACT

Pacific Northwest Laboratory (PNL) evaluated the ultrasonic inspectability of weld overlaid pipe joints. As part of this task, PNL is providing NRC staff with conclusions and recommendations concerning the effectiveness of ultrasonic inspections performed on weld overlaid pipe joints.

PNL evaluated data from available technical literature, conducted experiments to determine the distortional effects of weld overlay on ultrasound, and reviewed data from the weld overlay inspection development efforts of the Electric Power Research Institute NDE Center.

Based on these reviews and experiments, PNL concluded that ultrasonic inspection of weld overlaid pipe joints has not been demonstrated to be reliable, for two reasons. First, insufficient data exists to demonstrate the reliable detection and sizing of intergranular stress corrosion cracks. Second, the detection of unacceptable fabrication flaws contained within the weld overlay material has a low reliability due to poor signal-to-noise ratios. However, as current research and development programs lead to a more comprehensive engineering database, these conclusions may change.

EXECUTIVE SUMMARY

Weld overlay is used as a short-term repair for boiling water reactor (BWR) pipe joints that contain intergranular stress corrosion cracking. This measure was devised to provide a time period in which long-term solutions could be developed. One proposed solution being investigated by several organizations is to use weld overlay as a long-term repair for pipe joints. Of special interest was the joint effort of the BWR Owners' Group and the Electric Power Research Institute which is conducting a program to provide an engineering database to demonstrate the long-term adequacy of a weld overlay repair. Evidence of effective nondestructive examination is part of the information necessary to justify the long-term usage of weld overlay repaired pipe joints.

In support of the U.S. Nuclear Regulatory Commission (NRC), the Pacific Northwest Laboratory (PNL) is evaluating the ultrasonic inspectability of weld overlaid pipe joints. As part of this evaluation task, PNL was requested to provide an interim report to NRC staff with conclusions and recommendations concerning the effectiveness of ultrasonic inspections performed on weld overlaid joints.

Accordingly, PNL evaluated data from available technical literature, conducted experiments to determine the distortional effects of weld overlay on ultrasound, and reviewed data from the weld overlay inspection development efforts of the Electric Power Research Institute NDE Center.

As a result of these activities, PNL arrived at the conclusions and related recommendations listed below:

1. **Conclusion:** Shear wave examination of a weld overlaid pipe joint is neither effective nor reliable.

2. **Conclusion:** Longitudinal wave probes with an angle ranging between 40° and 70° provide the best results for detecting deep intergranular stress corrosion cracks, sizing the length of the detected crack, and sizing the remaining ligament of the pipe joint. The probes used most successfully had peak frequency responses ranging between 1.0 and 4.0 MHz.

   Recommendation: Examination of weld overlaid joints should be performed with longitudinal waves using at least two different angles ranging between 40° and 70° and separated by a difference of 15° (e.g., 45° and 60°).

Recommendation: Inspectors should demonstrate their capability to detect flaws in weld overlaid joints, because longitudinal inspection differs significantly from commonly employed shear-wave techniques.

3. **Conclusion:** A limited database indicated a strong <u>trend</u> whereby the detection and the sizing of an intergranular stress corrosion crack of depth greater than 50% through-wall of the original pipe wall thickness may be reliably determined. However, until sufficient data is available to demonstrate technique reliability, the technique shall be classified as having a low reliability.

   Recommendation: Perform additional experiments that add to the database of correlating ultrasonic measurements with destructive measurements.

4. **Conclusion:** The detection and the sizing of an intergranular stress corrosion crack of depth less than 50% through-wall of the original pipe wall thickness is not reliable.

5. **Conclusion:** The detection or sizing of an intergranular stress corrosion crack of depth less than 20% through-wall of the original pipe wall thickness is generally not possible.

6. **Conclusion:** High-angle L-wave (including creeping-wave) probes were more accurate than L-wave probes ranging between 40° and 60° in determining the remaining ligament associated with intergranular stress corrosion cracks that extended into the weld overlay material.

   Recommendation: High-angle L-wave (including creeping-wave) probes should be used to estimate the remaining ligament of intergranular stress corrosion cracks suspected of entering the weld overlay material.

7. **Conclusion:** The detection of unacceptable fabrication flaws contained within the weld overlay has not been demonstrated to be reliable. The Boiler and Pressure Vessel Code of the American Society of Mechanical Engineers was used as the acceptable/unacceptable criterion. However, the applicability of the Code is not clearly understood, given the extremely large stress contained within the weld overlay material.

8. **Conclusion:** Surface preparation of the weld overlay is required to perform meaningful ultrasonic inspections regarding intergranular stress corrosion cracks and weld overlay fabrication flaws.

The condition of the overlay surface should meet the following requirements:

- The rms surface roughness must be equal to or less than 250 microinches.
- The surface waviness must be equal to or less than a 0.060-inch radial deviation from peak to valley points within a 1.0- by 1.0-square inch surface area.
- All surface variations should not produce a depth variation having a radius of curvature less than 1 inch.

9. **Conclusion:** Additional research is needed to resolve the remaining questions concerning the reliable inspection of weld overlay repaired pipe joints.

As current research and development programs develop a more comprehensive engineering database, the conclusions and recommendations listed above may change.

CONTENTS

FIGURES

FIGURES

TABLES

ACKNOWLEDGMENTS

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STATUS OF ACTIVITIES FOR INSPECTING WELD OVERLAID PIPE JOINTS

1.0 INTRODUCTION

Since 1982, intergranular stress corrosion cracking (IGSCC) has been detected in the primary recirculation piping of most boiling water reactors (BWRs) in the United States (Bush et al. 1984). Weld overlay was initially developed as a long-term remedy (Newell 1984) for repairing BWR piping. However, the inability to reliably inspect the overlaid joint permitted it to be used as only a short-term repair (Bush et al. 1984). One proposed long-term solution is to develop a reliable inspection technique. Of the several resulting programs, the joint effort of the BWR Owners' Group and the Electric Power Research Institute is to provide an engineering database to demonstrate the long-term adequacy of weld overlay repairs. Evidence of effective nondestructive examination is part of the information necessary to justify the long-term use of weld overlay repair.

At the request of the U.S. Nuclear Regulatory Commission (NRC), the Pacific Northwest Laboratory (PNL)[a] evaluated the ultrasonic inspectability of weld overlaid pipe joints. The scope of PNL's evaluation encompassed a literature survey, laboratory experiments, and a review of data from related inspection development efforts under way at the Electric Power Research Institute (EPRI) NDE Center.

This interim report documents PNL's evaluation. Section 2.0 summarizes the literature survey related to the inspection of weld overlaid pipe joints. Section 3.0 documents the work performed at PNL to determine the distortional effects of the weld overlay on ultrasound. Section 4.0 summarizes and analyzes data resulting from the joint effort of the Electric Power Research Institute and the BWR Owners' Group to demonstrate detection and sizing of flaws contained within the weld overlaid pipe joint. In Section 5.0, conclusions and recommendations based on analyses of these information sources are provided. Section 6.0 presents PNL's suggestions for additional work in this area.

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[a] Operated for the U.S. Department of Energy by Battelle Memorial Institute.

2.0 LITERATURE SURVEY

Prior to beginning the experimental phase of weld overlaid pipe joint inspection, PNL researchers performed a literature search. The volume of published material on weld overlay inspection was found to be relatively small. However, reports related to weld overlay inspection problems have offered good insight into the inspection of weld overlaid pipe joints. The more important conclusions from these works are summarized and discussed in this section.

Beverly and Baker (1984) reported that the vertically polarized shear wave techniques commonly employed for inspecting non-overlaid pipe joints were inadequate for inspecting weld overlay repaired pipe joints. However, the weld overlay material used in their study was applied manually and certainly contained greater inhomogeneity and anisotropy than do the automated welding techniques typical of most field overlays. For this reason, shear waves were re-evaluated at PNL on specimens overlaid by an automated welding procedure.

A blind ultrasonic examination of two weld overlaid pipe joints was conducted during a weld overlay workshop at Argonne National Laboratory (ANL) in May 1984. The two 12-inch-diameter schedule 100 pipe-to-elbow joints that originated from a commercial BWR plant underwent decontamination, penetrant testing, ultrasonic testing, and destructive examination. Regarding the correlation of ultrasonic calls to destructive analysis, "Very few correct calls were made and when cracks were correctly called, the success was degraded by considerable overcalling" (Kupperman, Clayton, and Prince 1985). A conclusion from the workshop was that the ultrasonic techniques used were generally ineffective in detecting IGSCC contained within weld overlaid pipe joints. The detection techniques included shear waves and longitudinal waves. Three significant circumferential cracks were contained within the pipe joints. The crack depths were 57%, 22%, and 17% through-wall, which included the weld overlay material. The corresponding crack lengths were 8, 16, and 8 mm (Shack et al. 1985).

The literature survey also included material from research related, but not specific to, weld overlay examination. This reported research pertained to the far-side inspection of austenitic welds and the inspection of cladded components such as reactor vessels and pipe. These structures contain columnar grain austenitic material adjoining an isotropic material. A similar configuration exists for weld overlay (Figure 2.1). Shear waves were commonly used when attempting to inspect columnar grain structures. However, the use of longitudinal waves and/or creeping waves has become popular and has, in most cases, yielded better results than shear waves when inspecting such structures (Becker 1982; Edelmann 1981; Gruber 1982; Rogerson et al. 1982; Saglio et al. 1982; Saitoh and Takahashi 1981; Taylor et al. 1983; Trumpfheller 1981).

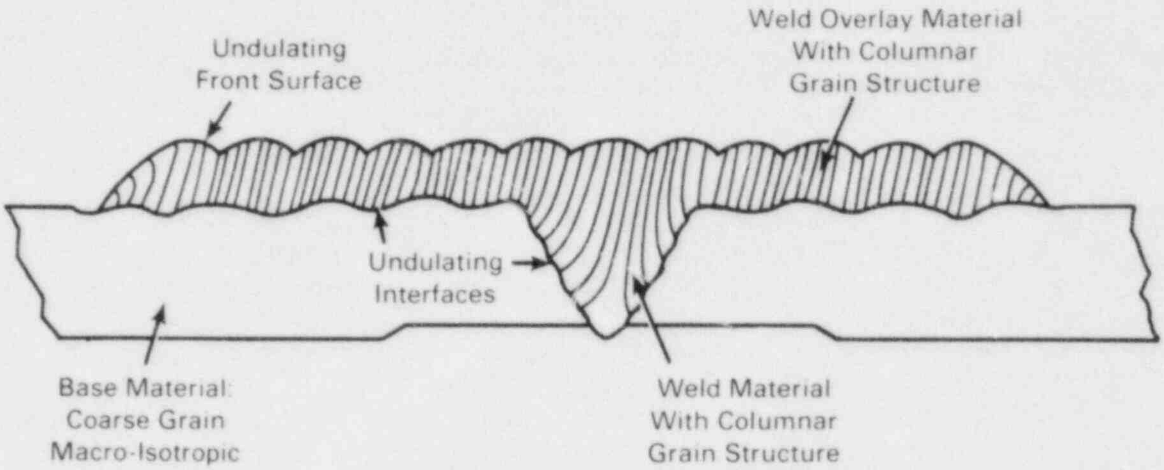

FIGURE 2.1. Typical Physical Features of a Weld Overlaid Pipe Joint (Columnar Grain Axis Orientation is Indicated for Both the Weld Overlay and the Weld).

An article by Ogilvy (1985a) proved valuable in understanding wave propagation when passing waves[a] through weld material for inspecting the heat-affected zone (HAZ) on the far side of the weld (see Figure 2.2). A second paper by Ogilvy (1985b) outlined propagational paths of the ultrasonic wavefront as it passed through the weld. This is important because similar wave behavior for far-side inspection of a HAZ contained within a weld overlaid pipe joint is expected.

Predicted propagational paths for the three principal propagation modes at 45° and 60° are illustrated in Figure 2.3. (Each block within Figure 2.3 has a 4.7-inch length and a 2.0-inch height. The weld-to-base material interfaces are inclined 30° from vertical.)

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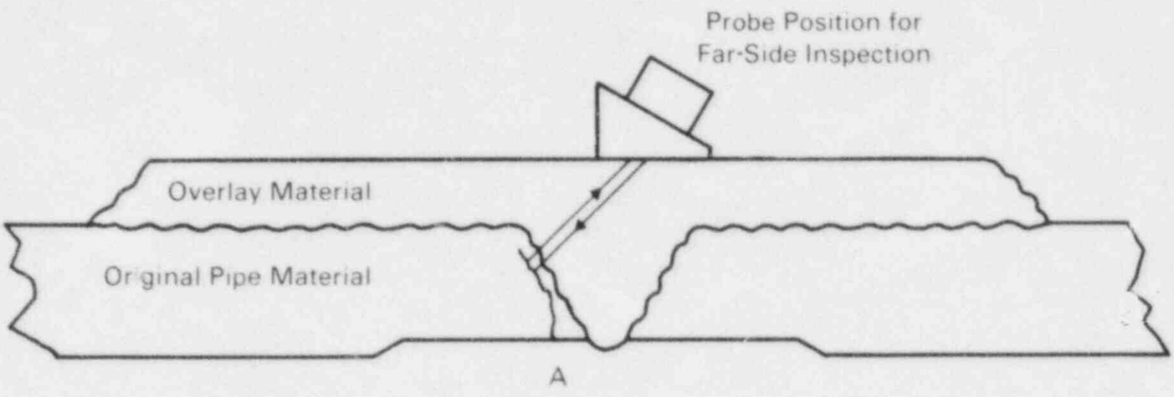
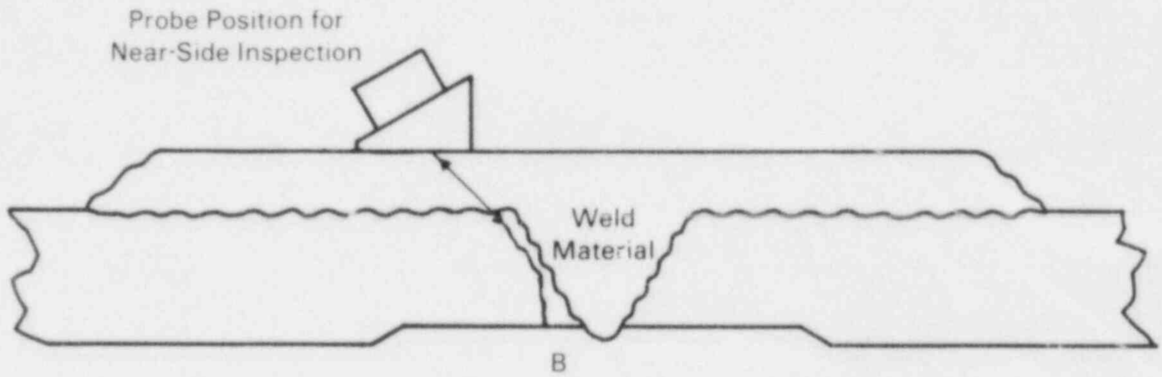
[a] The three principal wave modes in isotropic material are commonly denoted as vertically polarized shear (SV) waves, horizontally polarized shear (SH) waves, and longitudinal (L) waves. When dealing with anisotropic material, the terms quasi-shear or quasi-longitudinal should be used because the particle motion is generally not perpendicular or parallel to the propagational direction. In either case the waves in this report are respectively denoted by SV, SH, and L.



a. Far-Side Inspection



b. Near-Side Inspection

FIGURE 2.2. Near- and Far-Side Inspection of a Heat-Affected Zone on a Weld Overlay Repaired Pipe Joint

In Figure 2.3 [an illustration based on Oglivy's work (1985b)], the ultrasonic wavefront entered the base material adjacent to the weld. The wavefront, upon entering the weld, was incrementally redirected as determined by the columnar grain orientation and anisotropic wave behavior. The directional flow of ultrasonic energy or propagational wave path is indicated by a ray in each of the six diagrams. Two significant phenomena were the range of change in the propagational direction predicted upon crossing the base-to-weld material interface and the curved propagational paths associated with the weld material. Certainly, if a far-side inspection were implemented for weld overlaid pipe joints, and if the theory were correct, then the SV waves commonly associated with the inspection of non-overlaid pipe joints would be much more distorted than either the L waves or SH waves.

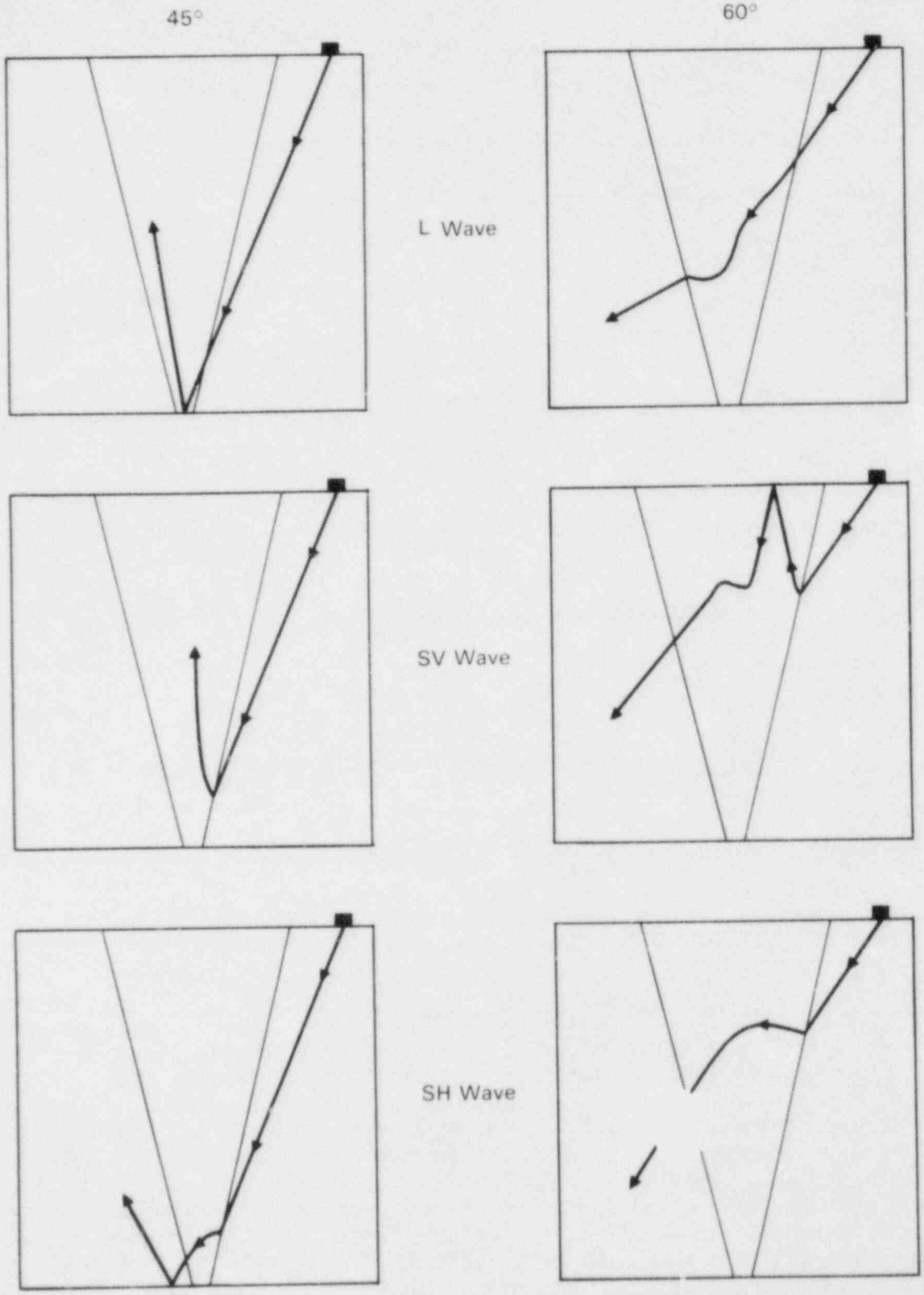


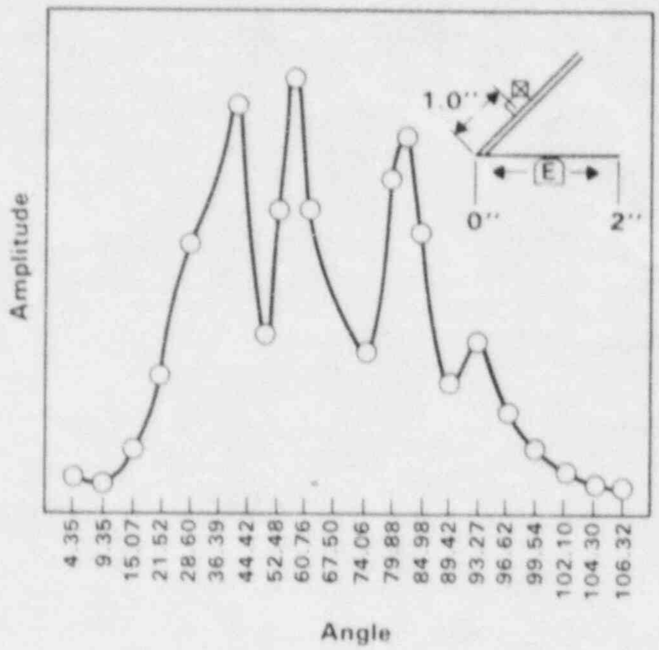
FIGURE 2.3. Predicted Propagational Paths of L, SV, and SH Waves from 45° and 60° Probes. Source: Ogilvy (1985b, pp. 75-76)

Work by Doctor et al. (1983) documented beam partitioning of ultrasonic waves that propagated through austenitic cladding layers. The partitioning effect was demonstrated by acquiring one-dimensional beam profiles resulting from attaching a transmitting probe on a smooth cladding layer and using an electromagnetic acoustic transducer as a receiver. Selecting data from this report permitted L waves to be compared to SV waves at a common wave length within the traversed medium (see Figure 2.4). Although only a limited amount of data was available, L waves were clearly less distorted than were SV waves when propagating through a columnar grained structure.

Kupperman, Reimann, and Kim (1980) described the determination of the velocity surfaces and energy-ray deviations for weld material, and experimentally confirmed the theoretical-based estimates. This was important because, first, the distortional processes were dependent on the magnitude and rate of change of these interrelated parameters and, second, only a limited amount of experimental data has been generated concerning these parameters. Clearly, both L and SH waves should exhibit less distortion than do the commonly used SV waves, because the magnitude and gradient of change are significantly less than those for SV waves (see Figures 2.5 and 2.6). Three graphs were illustrated in both Figures 2.5 and 2.6, one for each of the three propagational wave modes. Each velocity surface (Figure 2.5) is a polar plot of wave velocity versus the angle between the columnar grain axis and the wave propagational direction predicted for isotropic material. The theoretically determined velocity surfaces were determined for type 304 stainless steel weld metal. Experimentally measured data points were acquired from type 308 stainless steel. Each of the three graphs illustrated in Figure 2.6 is a plot of the predicted deviation of true energy flow from that predicted for isotropic material. Additional theoretical analysis and/or experimental data is reported by Hudgell and Seed (1980); Silk (1981); Thomson and Farley (1984); Tomlinson, Wagg, and Whittle (1978); and Yoneyama et al. (1984).

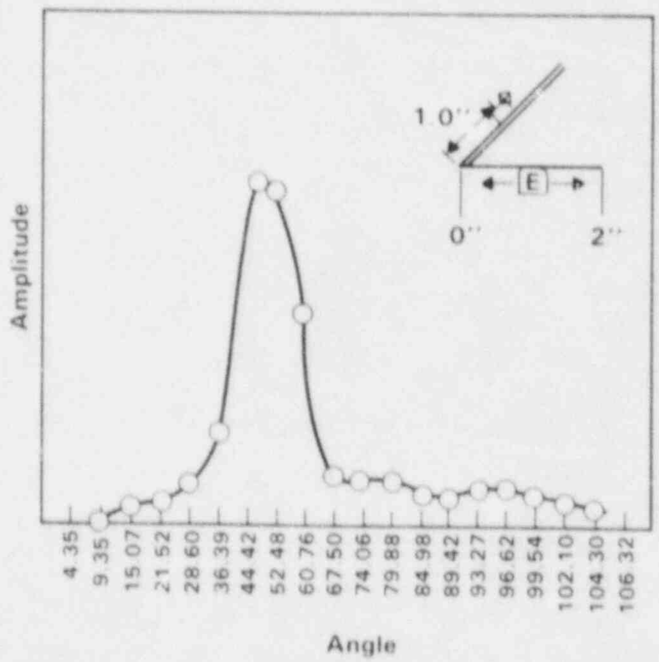
Kupperman, Reimann, and Yuhas (1982) described a LASER interferometer system that permitted the acquisition of two-dimensional ultrasonic beam profiles. The technique measured the particle displacement component parallel to the surface normal. SV and L waves incident at an angle generally produced particle motion that can be measured using through-transmission techniques. Using scans acquired from the LASER interferometer system as a reference, PNL researchers developed a system for acquiring ultrasonic beam profiles in weld overlay material.

F. L. Becker and colleagues at the EPRI NDE Center recently reported the progress of their effort to demonstrate the effectiveness of nondestructive evaluation techniques and equipment



A

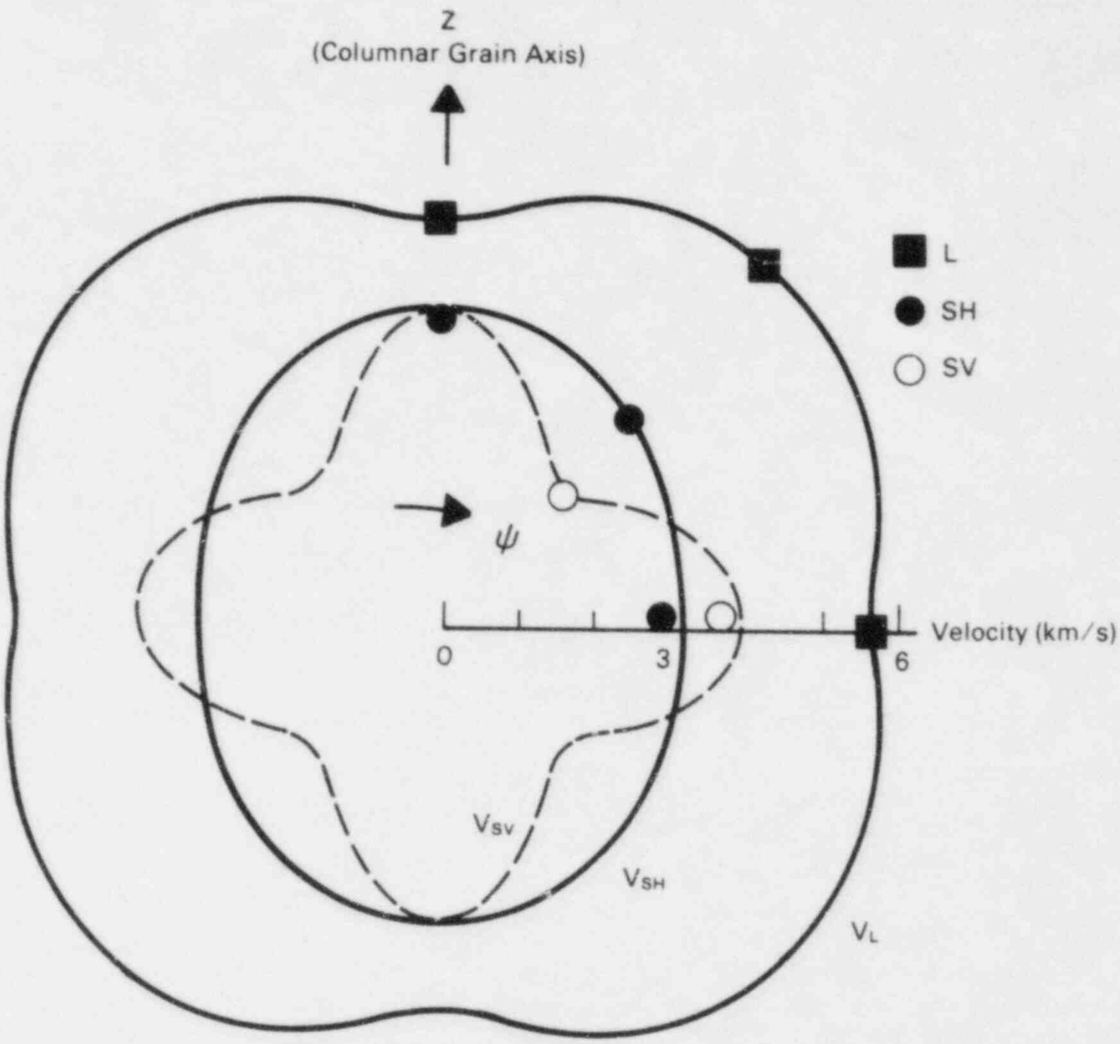
a. SV wave beam profile through clad at 2.25 MHz and 45°



B

b. L wave beam profile through clad at 5.0 MHz and 45°

FIGURE 2.4. Beam Profiles of a SV and a L Wave Propagating Through a Cladding Layer with Frequency Selected Such That λ = 0.05 Inch. Source: Doctor et al. (1983, p. 16)



Ψ is the propagation angle relative to the columnar grain axis

FIGURE 2.5. Polar Plot of Wave Velocity of the Three Principal Wave Modes as a Function of Angle Relative to the Columnar Grain Axis in the (110 Plane). Source: Kupperman et al. (1980, p. 203)

required for acceptance and long-term monitoring of the weld overlay repair. According to their unpublished report,[a] the EPRI NDE Center has developed a database describing the detection and sizing of flaws contained within weld overlaid pipe joints.

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[a] The EPRI NDE Center is tentatively scheduled to submit a report to EPRI in January 1986. A publication of this data is expected shortly thereafter.

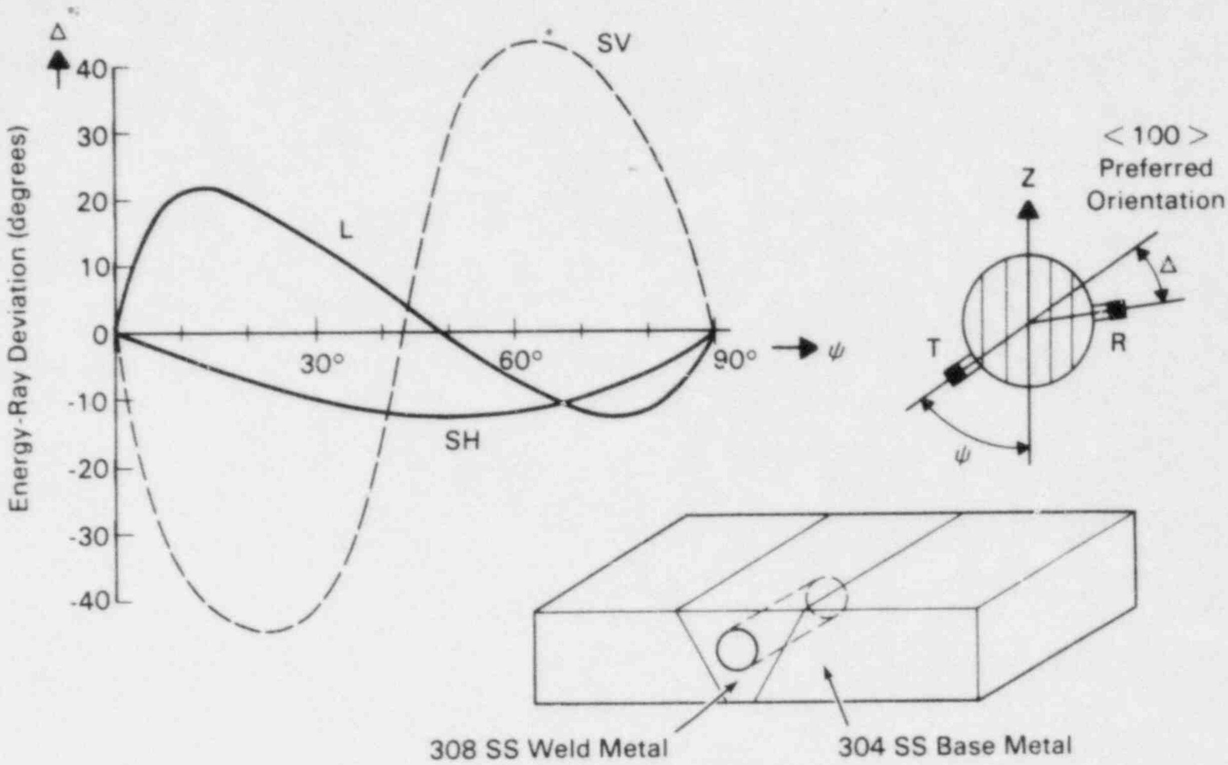

FIGURE 2.6. Energy-Ray Deviation of the Three Principal Wave Modes as a Function of Angle Relative to the Columnar Grain Axis in the (110) Plane. Source: Kupperman et al. (1980, p. 203)

Many inspection techniques were investigated; some performed very well. A high-angle L-wave probe used in a far-side inspection performed well for detecting deep IGSCC, determining the circumferential extent of the detected crack, and determining the remaining ligament of uncracked material. The significant conclusions presented in the Center's draft report are discussed in Section 4.0 of this report.

3.0 PNL EXPERIMENTAL STUDIES

For reliable ultrasonic inspections to be performed, passage of a coherent ultrasonic beam to the area of interest is necessary. This condition ensures a controlled energy flow to the area of interest. This section documents the studies conducted by PNL researchers to qualitatively examine the distortional effects of weld overlay on ultrasonic energy.

To determine whether a distorted or a coherent ultrasonic beam is passed through weld overlay material, ultrasonic beam profiles were acquired. These profiles were then used to study the distortional effects of different surface conditions and different thicknesses of weld overlay. The ultrasonic beam distortional effects were then analyzed by comparing ultrasonic beam profiles from base material (e.g., non-overlaid pipe) to profiles from weld overlaid pipe with differing surface conditions.

3.1 BEAM PROFILE SYSTEM

The PNL beam profile system (Figure 3.1) provided a two-dimensional mapping of the ultrasonic beam (Figure 3.2). A

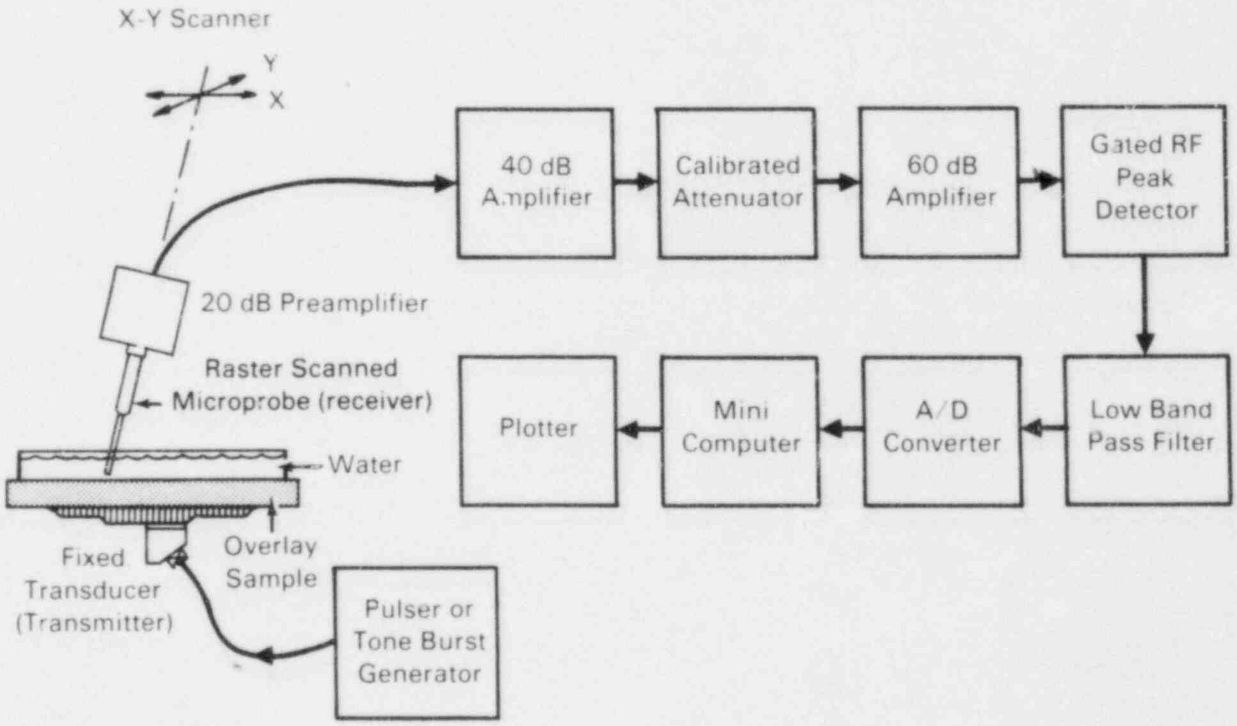

FIGURE 3.1. Ultrasonic Beam Profile System Used in PNL Experiments

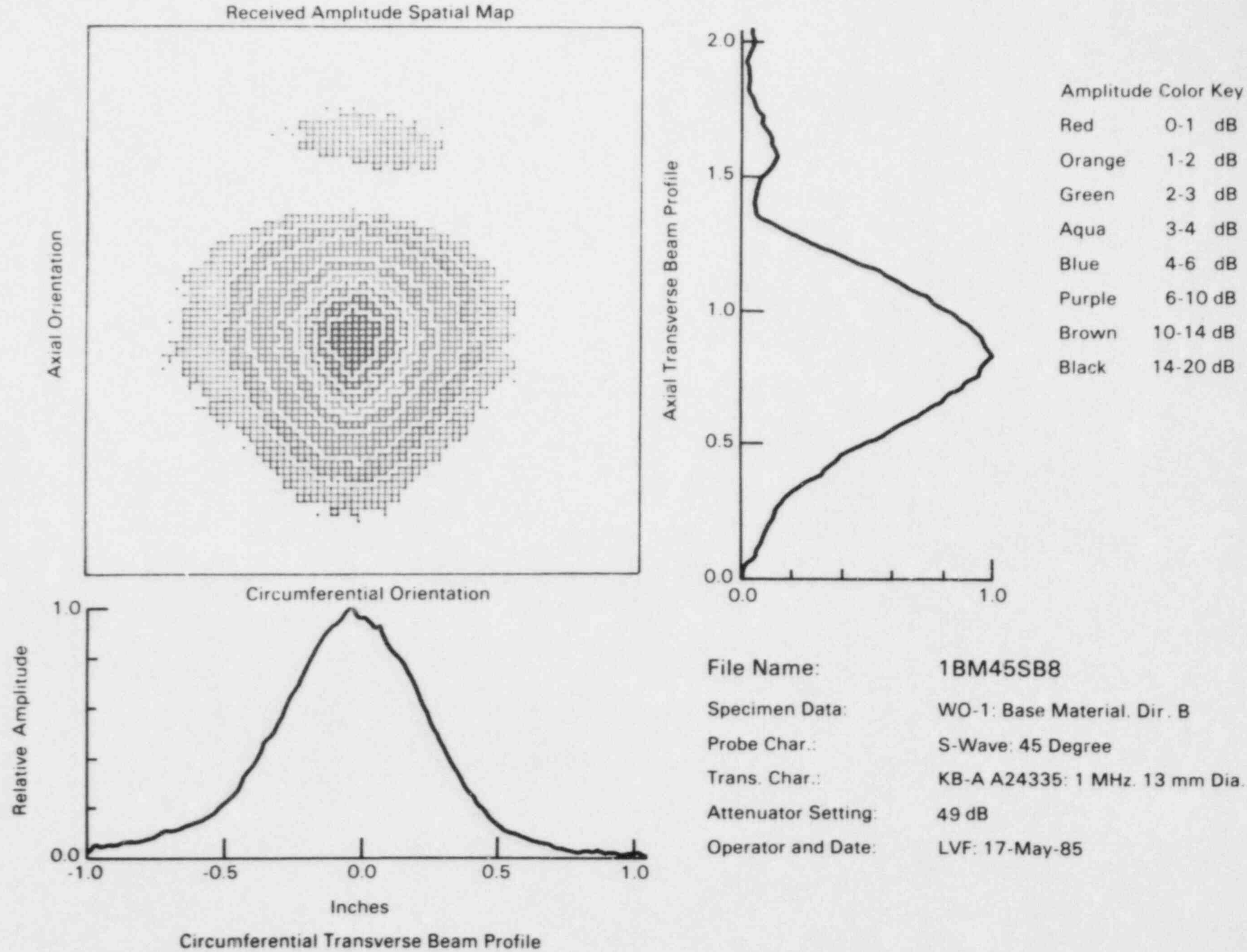

FIGURE 3.2. Typical Output of Beam Profile System

transmitting probe[a] was fixed on the outer diameter surface of a weld overlaid pipe section, denoted as Specimen WO-1. The inner diameter surface was machined flat to facilitate scanning with an x-y scanner (Figure 3.3). Specimen WO-1 was prepared from a 12-inch-diameter Schedule 120 pipe that did not contain a weld. The specimen consisted of six regions: base material, a 0.2-inch-thick weld overlay with a smooth surface, a 0.4-inch-thick overlay with a smooth surface, a 0.4-inch-thick weld overlay with an as-welded surface, a 0.2-inch-thick weld overlay with an as-welded surface, and base material.

The beam profile system acquired voltage values corresponding to the received signal amplitude or particle displacement. Because the system used a water couplant, only the signal component corresponding to particle motion perpendicular to the specimen-to-water interface was measured. Consequently, the system sensitivity was a function of propagational wave mode and the incident angle with respect to the surface norm of the specimen-to-water interface. However, changes in the beam profile were easily detected when referenced to scans of similar geometry of the pipe base material. Changes in the beam from distortional processes caused by the weld overlay were referenced to the corresponding base material scans.

3.2 BEAM PROFILE DATA ANALYSIS

Ultrasonic distortion was evaluated by comparing beam profiles of a matrix of scans, which included parameter changes of both the weld overlay and the transmitting ultrasonic probe as shown in Table 3.1. The trends in the distortional process incurred from both a smooth ground surface and an as-welded surface were then evaluated.

3.2.1 Distortion Evaluation of Both SV and L Waves

Data collected from an SV wave propagating through a 0.4-inch-thick weld overlay with a smooth surface illustrated severe beam distortion. Data collected from a 45°, 1-MHz probe showed less distortion[b] than that of the 2- and 3-MHz probes, as shown in Figure 3.4. Significant beam distortion occurred for the 60° probes at 1, 2, and 3 MHz (Figure 3.5).

The data suggested that a 1-MHz, 45° probe might be used for weld overlay inspection. However, the transition between

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[a] The transmitting probe for all cases consisted of a 0.5-inch-diameter transducer mounted on an acrylic angle beam wedge.

[b] All illustrations of beam profile data include base material profiles as a reference for comparison.

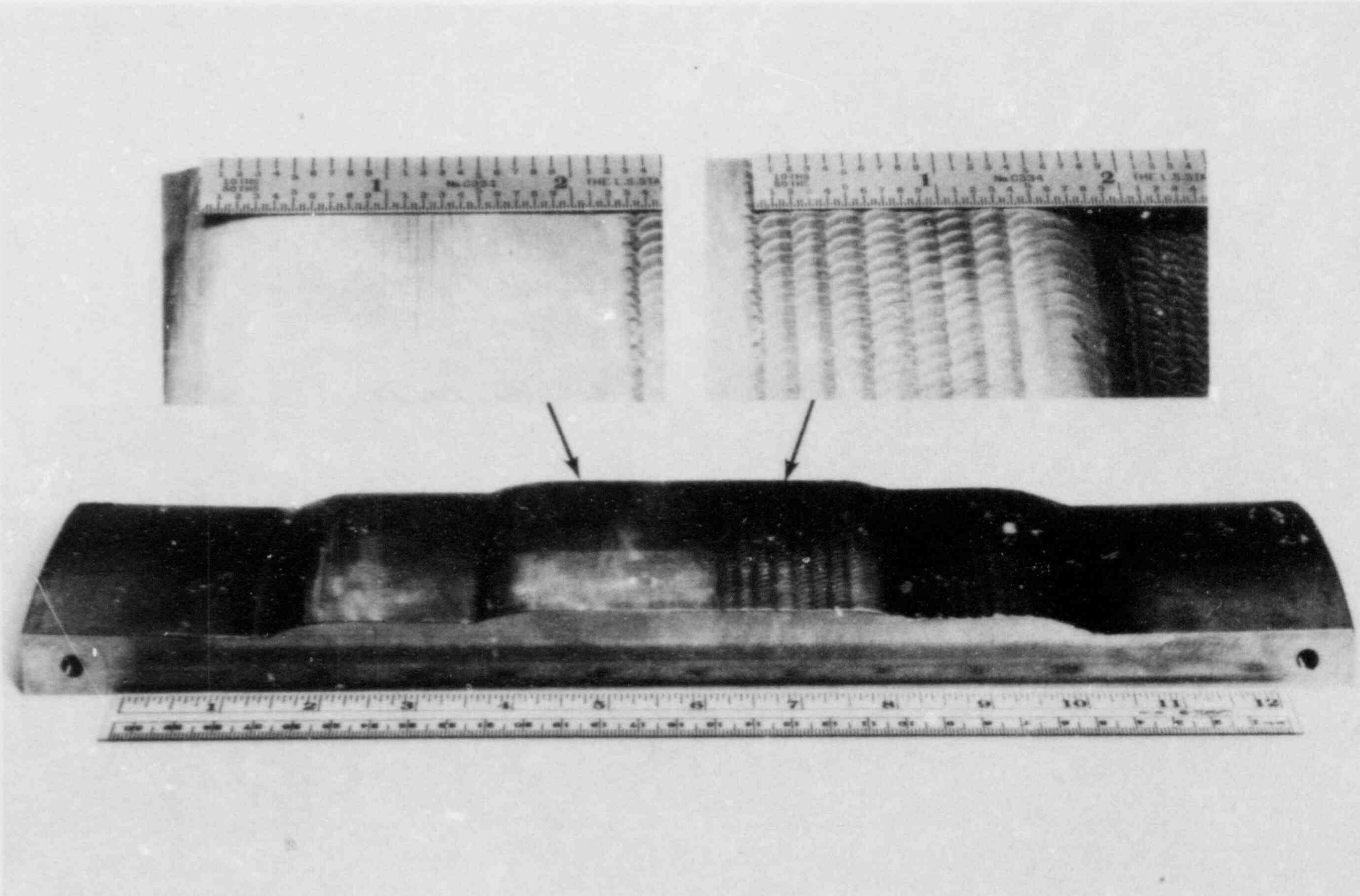
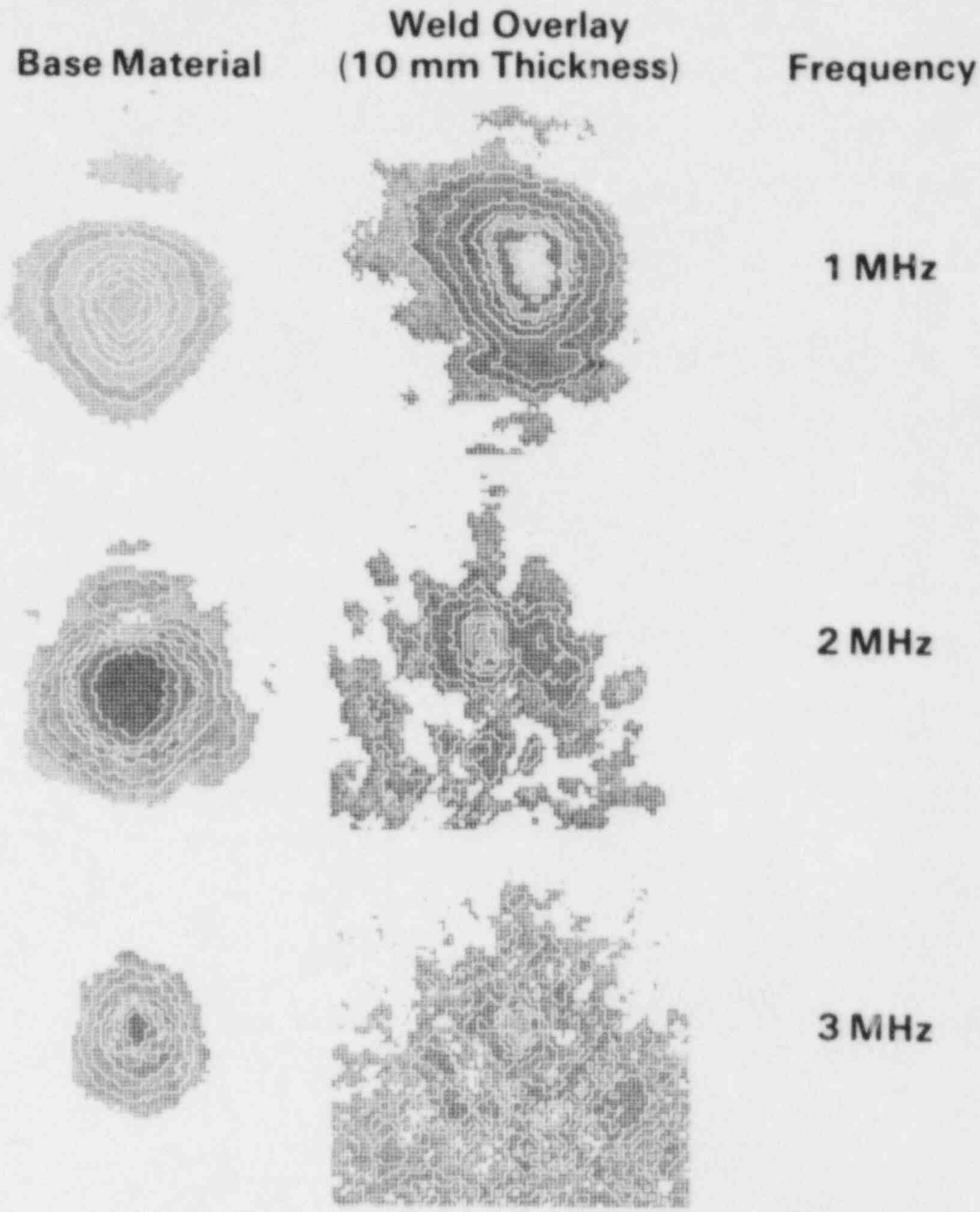


FIGURE 3.3. Weld Overlay Specimen WO-1 (Enlargements Display Surface Detail for Both a Smooth and an As-Welded Surface)

TABLE 3.1. Scanning Matrix for Evaluating Beam Distortion

Material	Surface Condition	Wave Mode	Angle, Degrees	Frequency, MHZ
Base Material[a]	---	SV	35	1, 2, 3
			45	1, 2, 3
			60	1, 2, 3
		L	35	1, 2, 3, 5
			45	1, 2, 3, 5
			60	1, 2, 3
0.2-inch-thick weld overlay[a]	As-welded	SV	35	1, 2, 3
			45	1, 2, 3
			60	1, 2, 3
		L	35	1, 2, 3, 5
			45	1, 2, 3, 5
			60	1, 2, 3
	Smooth	SV	35	1, 2, 3
			45	1, 2, 3
			60	1, 2, 3
		L	35	1, 2, 3, 5
			45	1, 2, 3, 5
			60	1, 2, 3
0.4-inch-thick weld overlay[a]	As-welded	SV	35	1, 2, 3
			45	1, 2, 3
			60	1, 2, 3
		L	35	1, 2, 3, 5
			45	1, 2, 3, 5
			60	1, 2, 3
	Smooth	SV	35	1, 2, 3
			45	1, 2, 3
			60	1, 2, 3
		L	35	1, 2, 3, 5
			45	1, 2, 3, 5
			60	1, 2, 3

[a] Two or more scans of each matrix entry were acquired.

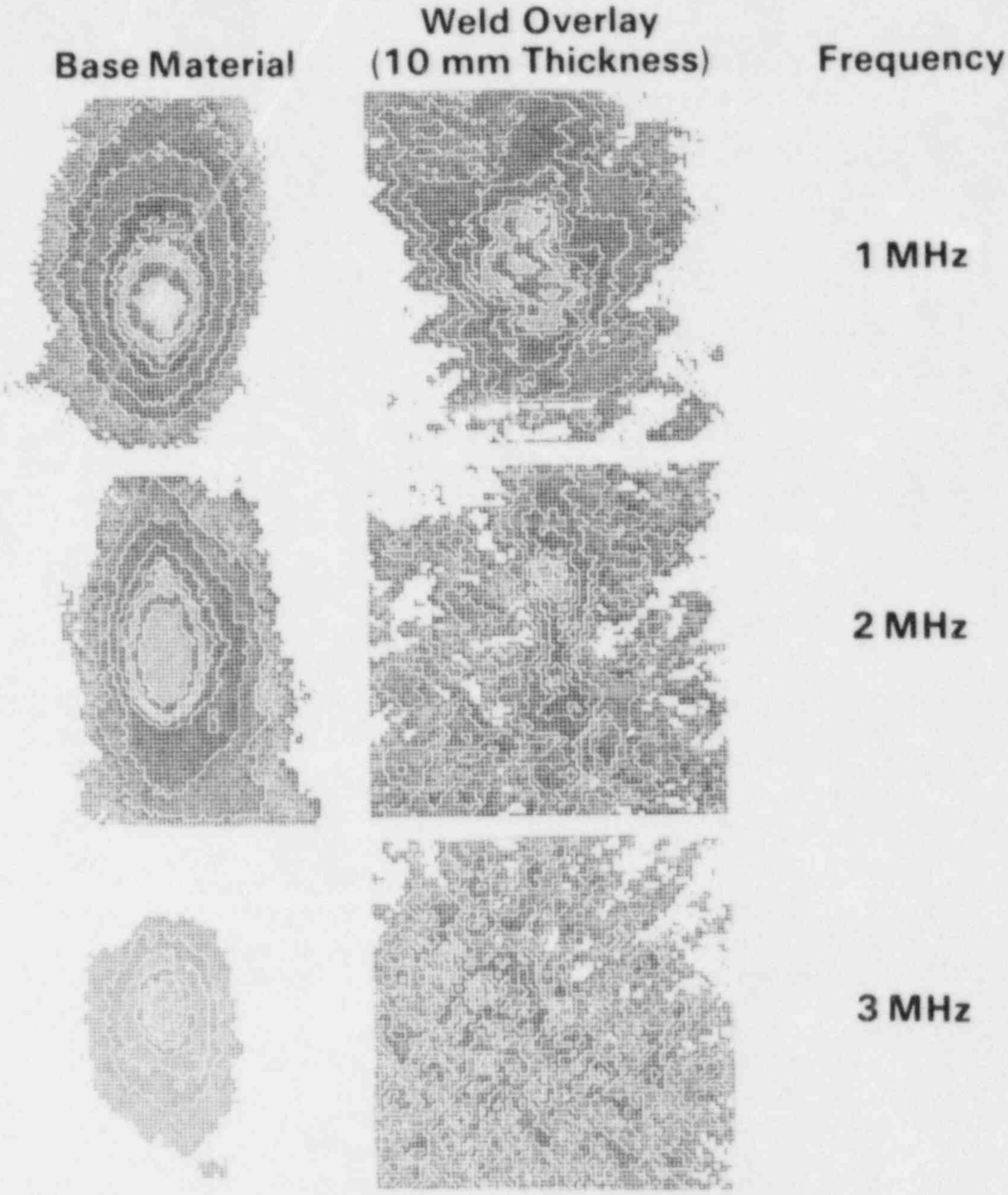


Amplitude Color Key

Red	0-1 dB	Blue	4-6 dB
Orange	1-2 dB	Purple	6-10 dB
Green	2-3 dB	Brown	10-14 dB
Aqua	3-4 dB	Black	14-20 dB

Scan Aperture: 50-x 50-mm

FIGURE 3.4. Beam Profiles of 45° SV Wave Traversing 0.4-Inch Weld Overlay with Smooth Surface



Amplitude Color Key

Red	0-1 dB	Blue	4-6 dB
Orange	1-2 dB	Purple	6-10 dB
Green	2-3 dB	Brown	10-14 dB
Aqua	3-4 dB	Black	14-20 dB

Scan Aperture: 50-x 50-mm

FIGURE 3.5. Beam Profiles of 60° SV Wave Traversing 0.4-Inch Weld Overlay with Smooth Surface

the amount of beam distortion for 1 and 2 MHz was dramatic and was certainly affected by grain size of the overlay material. Due to expected grain size variations in weld overlays, the severity of beam distortion for 2 MHz, and the distortion incurred by the 60° probe, PNL concluded that SV waves should not be used for inspecting weld overlay until further study can verify the effectiveness of 1-MHz SV-wave examination.

Data collected from L waves propagating through a 0.4-inch-thick weld overlay with a smooth surface illustrated little beam distortion. Coherent beam profiles were obtained for 1-, 2-, and 3-MHz frequency values at both 45° and 60° waves (Figures 3.6 and 3.7). A decrease in the signal-to-noise (S/N) ratio was observed for the 3-MHz, 60° probe. This was due to electrical noise and decreased signal strength, not acoustic noise. Based on the above data, PNL concluded that L waves appear to be the preferred[a] mode for ultrasonic inspection of weld overlaid pipe joints.

The selection of L waves as the preferred mode of inspection is further substantiated by two other phenomena. First, ultrasonic noise associated with grain boundary backscatter is less for L waves than for SV waves as determined by Goebbels, Romer, and Crostach (1981). This results in a S/N ratio increase so long as accompanying SV waves do not cause interfering signals from geometrical reflectors. Second, the electromagnetic acoustic transducer (EMAT) that generates SH waves is not currently pragmatic, for several reasons. The EMAT has insufficient power while operating in a pulse mode, inadequate depth resolution due to excessive ringing, and low S/N ratios due to its inefficient transmit and receive operation. In addition, austenitic steels have generally high ultrasonic attenuation values.

The distortion incurred by passing ultrasound through a 0.2-inch-thick weld overlay with a smooth surface was essentially identical to that of passing ultrasound through a 0.4-inch-thick weld overlay with a smooth surface. The only notable difference was that of signal strength. As expected when propagating through different thicknesses of strongly attenuative material, the thinner weld overlay yielded a stronger signal than did the thicker overlay.

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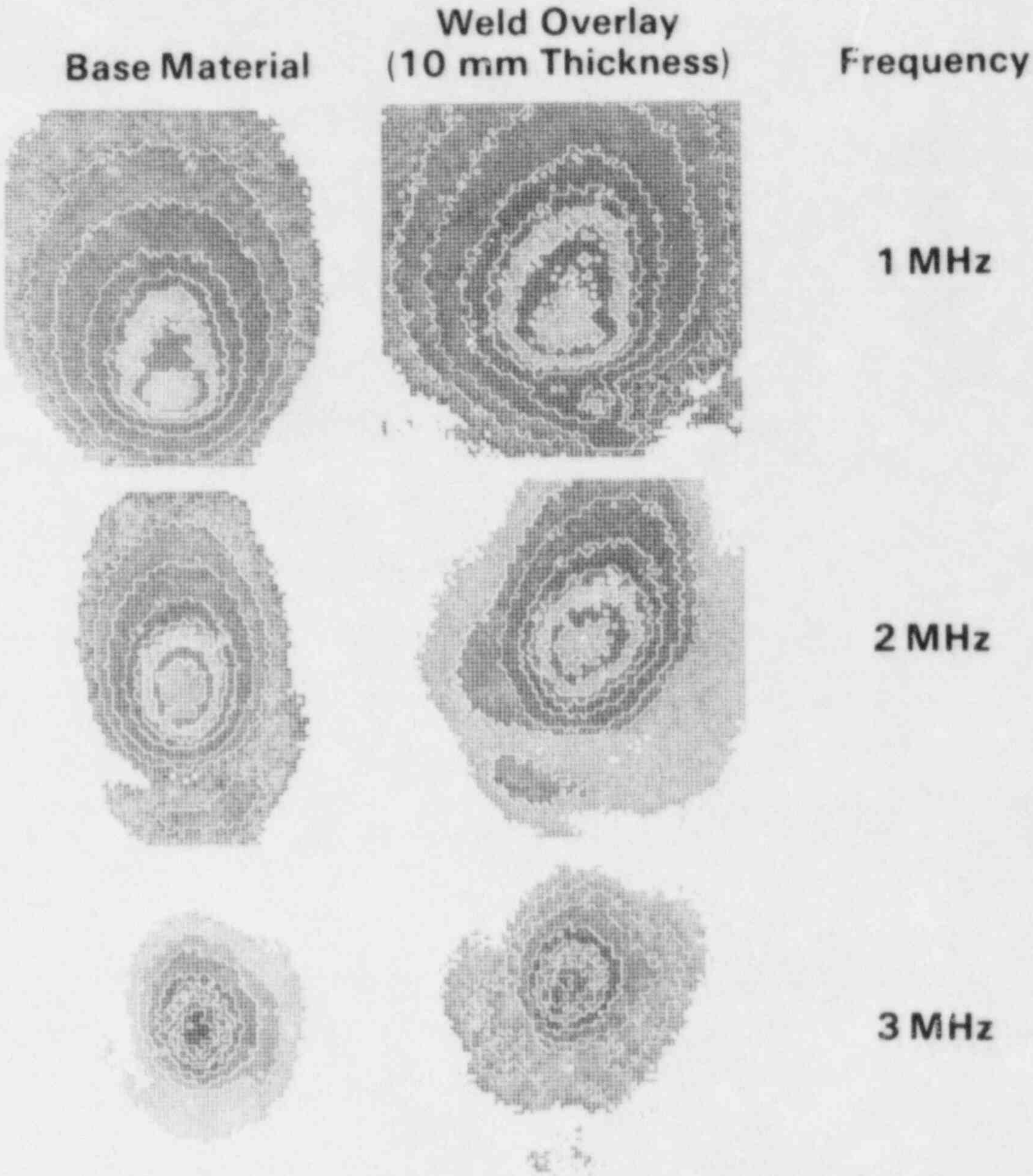
[a] For completeness the analysis should also include measurements on ultrasonic background noise levels. This action would aid in determining an optimal ultrasonic frequency for crack detection and/or related sizing measurements.



Amplitude Color Key

Red	0-1 dB	Blue	4-6 dB
Orange	1-2 dB	Purple	6-10 dB
Green	2-3 dB	Brown	10-14 dB
Aqua	3-4 dB	Black	14-20 dB

Scan Aperture: 50-x 50-mm

FIGURE 3.6. Beam Profiles of 45° L Wave Traversing 0.4-Inch Weld Overlay with Smooth Surface

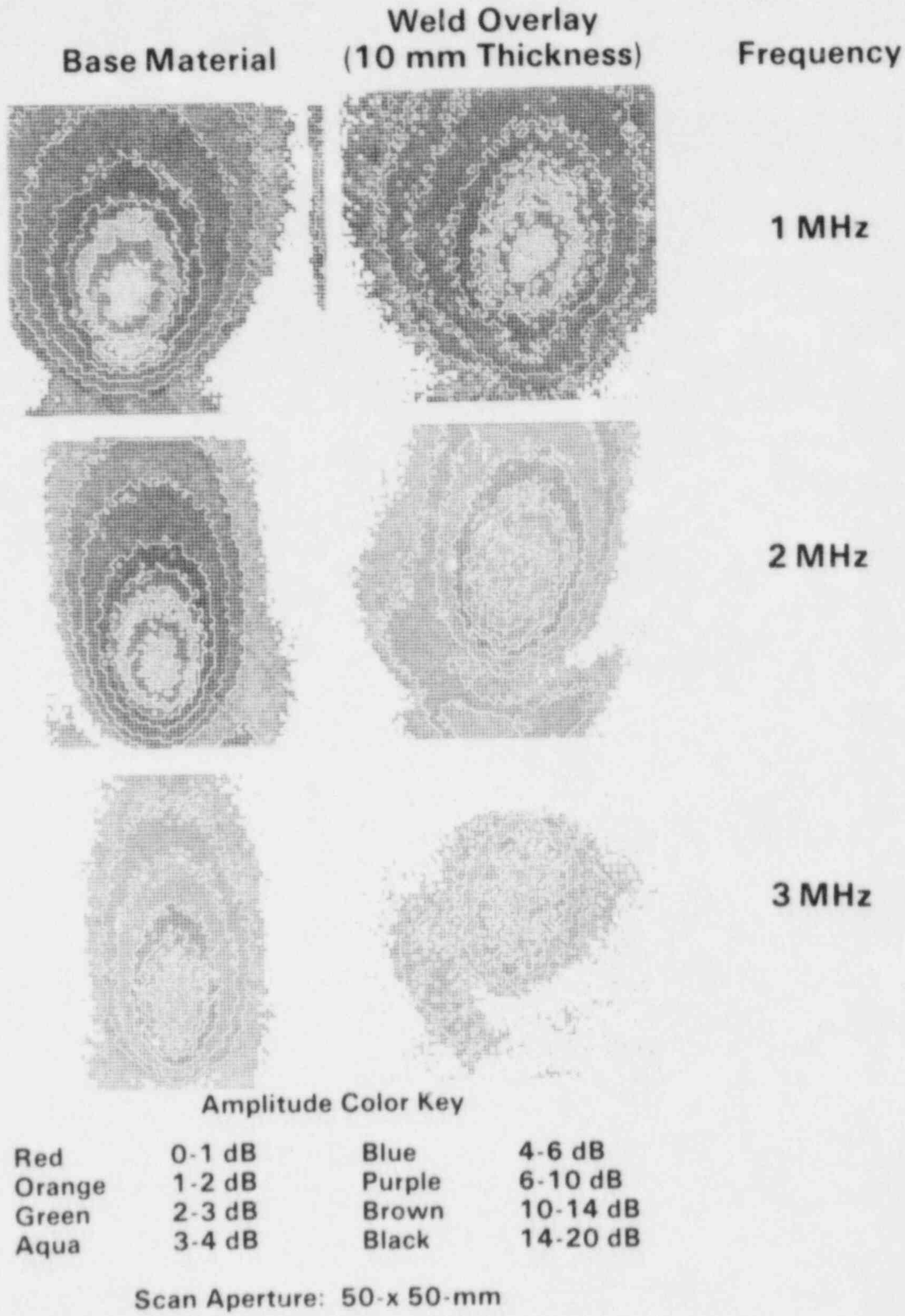


FIGURE 3.7. Beam Profiles of 60° L Wave Traversing 0.4-Inch Weld Overlay with Smooth Surface

3.2.2 Distortion from an As-Welded Surface

Data collected from ultrasonic probes mounted on a 0.4-inch-thick weld overlay on both the ground smooth and as-welded surfaces indicated significant beam distortion due to the increased roughness of the as-welded surface. The as-welded surface was characterized by both a weld ripple caused by side-to-side oscillation of the tungsten electrode and a weld overlap texture (noticeable in Figure 3.3). The weld ripple had a peak-to-valley radial displacement of 0.005 inch and a circumferential orientation. The weld overlap had a peak-to-valley radial displacement of 0.015 inch and an axial orientation. Data was collected solely with a 2-MHz, 45°, L-wave probe. Beam distortion was assumed to be greater for the 60° probe and/or higher frequency probes.

Both the scanning procedure and weld overlay specimen were changed for the as-welded surface study. To acquire proper probe-to-pipe surface interaction, Specimen WO-1 was turned over to permit the receiving microprobe to be fixed on the inner diameter surface while the transmitting probe performed a raster scan over the as-welded surface. However, Specimen WO-1 did not provide sufficiently large smooth or as-welded surface areas for the study. To provide the needed areas, the 0.4-inch-thick weld overlay region was smoothed while another specimen labeled WO-2 was prepared identical to WO-1 except that all weld overlay surfaces were left in their as-welded state.[a] This procedure yielded significant changes in the ultrasonic beam profile as a function of receiver position (Figure 3.8). This result agrees with the work performed by Rawsthorn, Murgatroyd, and Bann (1984) who used SV waves instead of L waves. PNL then calculated standard deviations from refracted angle measurements on both the smooth and as-welded surface conditions. Five measurements were used in each calculation. For the smooth surface a 2° standard deviation was calculated, while for the as-welded surface a 6° standard deviation was calculated.

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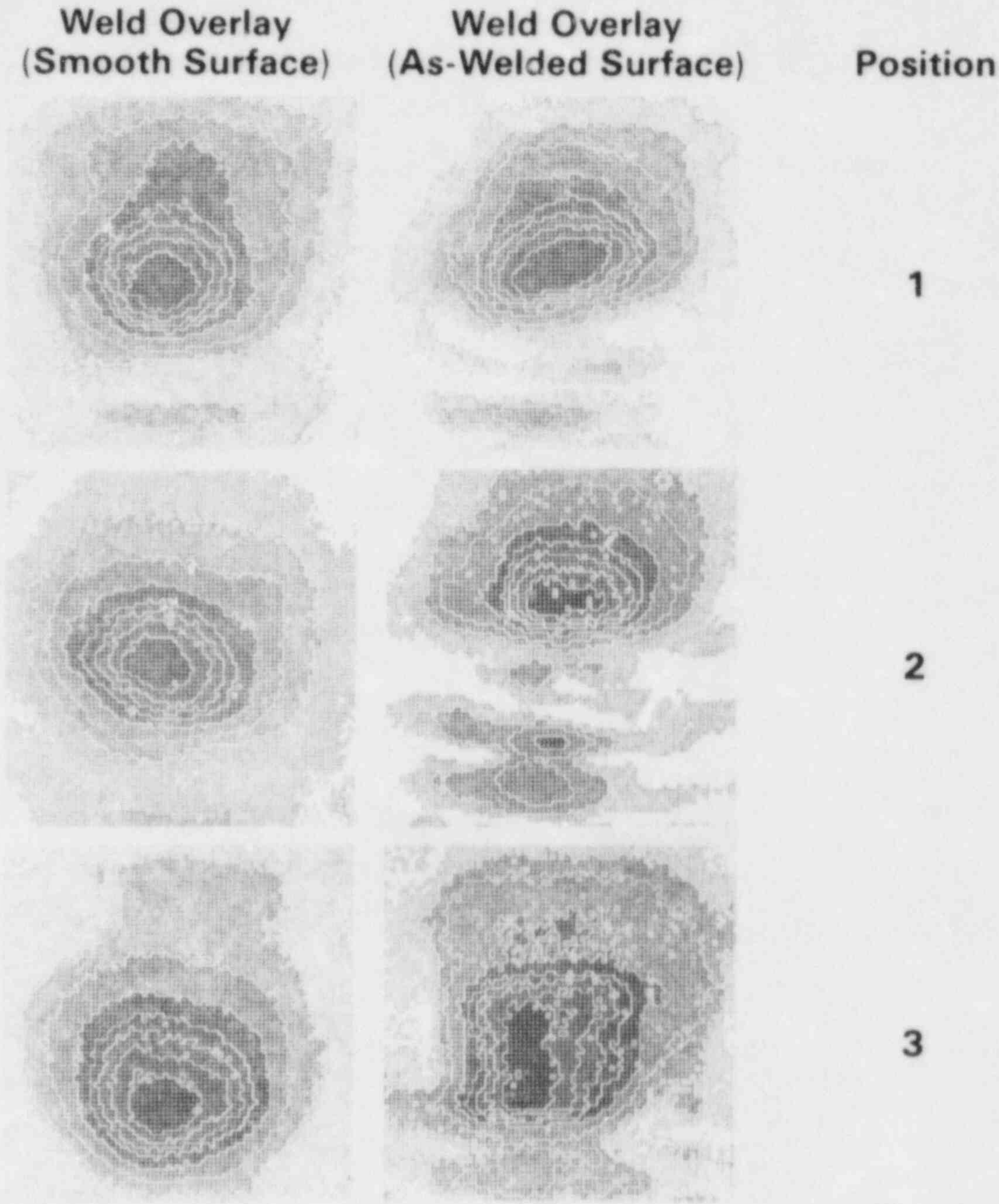
[a] All illustrations of beam profile data include smooth weld overlay profiles as a reference for comparison.



Amplitude Color Key

Red	0-1 dB	Blue	4-6 dB
Orange	1-2 dB	Purple	6-10 dB
Green	2-3 dB	Brown	10-14 dB
Aqua	3-4 dB	Black	14-20 dB

Scan Aperture = 50- X 50-mm

FIGURE 3.8. Beam Profiles of 2-MHz, 45° L Wave Traversing 0.4-Inch Weld Overlay with As-Welded Surface

4.0 EVALUATION OF EPRI NDE CENTER DATA

The third element of PNL's evaluation was a review of an experimental research program under way at the EPRI NDE Center in Charlotte, North Carolina. The program is being conducted jointly by EPRI and the BWR Owners' Group, to provide evidence that weld overlaid pipe joints can be examined effectively. The program encompasses two main efforts: the detection and sizing of IGSCC and the detection and sizing of unacceptable weld overlay flaws introduced during application of a weld overlay. Both efforts employed pipe joint specimens containing an assortment of reference reflectors such as notches, laboratory- or field-induced IGSCC, and weld overlay fabrication flaws.

This section documents PNL's review of data from the EPRI NDE Center program. The test specimens are described first, followed by detailed discussions of the Center's work in IGSCC and fabrication flaw detection and sizing.

The primary source of information for PNL's review was a draft interim report produced by the EPRI NDE Center. This report, documenting the program data and conclusions, was distributed at a weld overlay workshop held in April 1985 and again at a presentation to NRC staff in June 1985. Supplementary information was provided through written and oral communications between PNL and EPRI NDE Center personnel.

4.1 TEST SPECIMENS

The EPRI NDE Center used laboratory specimens identified as A5-A6, NC5-C6, EPRI-1, and four field specimens for investigating the detection of IGSCC, sizing the length or extent of IGSCC, and sizing the remaining ligament[a] of weld overlay repaired pipe joints.

Specimens A5-A6 and NC5-C6 were overlaid butt-welded joints where each section was a 12-inch-diameter Schedule 100 pipe. Both of the pipe joints were obtained from Ishikawajima-Harima Heavy Industries Company, Ltd. (IHI), and contained laboratory-induced IGSCC. Pre-overlay examination of Specimen NC5-C6 indicated that cracks were deep along the entire length except at the ends, where crack depth decreased sharply.

Liquid penetrant examination prior to each IHI pipe being overlaid showed extensive cracking along the HAZs. Ultrasonic measurements taken before the overlay was deposited indicated that crack depths ranged from 10% to 15% through-wall in speci-

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[a] Remaining ligament was defined as the remaining uncracked pipe wall thickness and included the overlay material.

men A5-A6, while crack depths ranged from 30% to 96% through-wall in specimen NC5-C6.

The same welding procedure was employed for applying a weld overlay on both IHI pipe joints and resulted in an overlay width of 6.8 inches. Surface profiles of the specimens indicated an overlay thickness of about 0.3 inch.

Specimen EPRI-1 was a 12-inch-diameter Schedule 80 weld overlaid pipe section containing notches from which through-overlay cracks were grown. The EPRI-1 specimen was not discussed in the interim report, as fabrication was not completed until after April 1985. However, ultrasonic analysis of the piece was presented at the EPRI/NRC meeting in June 1985.

The field specimens were four weld overlay repaired 12-inch-diameter Schedule 80 pipe joints in an operating BWR plant. The plant was known to contain deep cracking. Three of the pipe joints leaked before they were weld overlaid, while the fourth pipe joint had cracks estimated at 75% through-wall. The overlay thickness ranged from 0.6 to 0.7 inch. The as-welded surface in two of the field specimens contained a significant central rise due to a preexisting butt weld crown. Ultrasonic data from the field specimens were presented at the EPRI/NRC meeting in June 1985.

Both specimens BLC-1 and BLC-3 were used for investigating the detection of weld overlay fabrication flaws. Both specimens were weld overlaid butt-welded pipe joints where each section was a 12-inch-diameter Schedule 80 pipe. Specimen BLC-1 was fabricated to investigate the detectability of clustered flaws. The flaws induced during application of the weld overlay were lack of bond, lack of fusion, copper-induced cracking, tungsten inclusions, and porosity. Specimen BLC-3 was fabricated to investigate the detectability of isolated flaws. The flaws induced during application of the weld overlay were lack of fusion, lack of bond, and Inconel-induced cracking. Approximately 70% of the weld overlay surface was ground to a smooth finish. Each weld overlay was 0.4 inch thick.

4.2 INTERGRANULAR STRESS CORROSION CRACK DETECTION AND SIZING

Algorithms for IGSCC detection and sizing were developed on machined reflectors and tested on laboratory- and field-induced IGSC cracks. Due to the limited availability of field samples, most of the data was acquired on machined reflectors and laboratory-induced cracking. A 3-inch-long section of pipe containing laboratory-induced IGSCC was removed and destructively analyzed to provide a basis for error analysis on the acquired ultrasonic measurements.

4.2.1 Technique for Detecting and Sizing IGSCC

Reliable detection and sizing of cracks contained within the inner 50% of the original pipe wall is very difficult. This is due to both false indications and the high probability that a crack contained within the lower 50% of the original pipe wall will be a weak ultrasonic scatterer. The false indications are thought to be aberrations of SV and/or L waves distorted by the weld overlay. The weak ultrasonic scattering from IGSCC is a result of the extreme compressive stresses causing crack closure and increased ultrasonic transmission through the crack.

According to the Center, "The extent of this closure zone is not known; however, it is not expected to be more than 50 percent of the original pipe wall thickness...." Due to both false indications and crack closure, PNL analyzed data from only the outer 50% of the original pipe material. This was done because inspection of the outer 50% of the original pipe material was initially considered to be the only material for which a reliable inspection was feasible. Extension of reliable inspection to the inner pipe material must be preceded by an analysis concluding that crack closure and false indications would not significantly affect the inspection reliability. The term "reliable" is emphasized because cracks less than 50% through-wall have been detected and sized in depth.

The Center concentrated on detecting cracks deeper than 75% through-wall of the original pipe wall. Based on this action, the Center formed two examination objectives:

1. "Monitor at least the upper 25 percent of pipe wall."

2. "Characterize remaining sound portion of pipe wall in detail sufficient to support re-analysis for longer-term service of the joint."

These objectives created two zones for which different sizing techniques were developed. The first zone consisted of the outer 25% of the original pipe material. A crack detection scheme was developed to detect the planar response from these cracks using high-angle L-wave probes. The second zone consisted of the overlay material.

The remaining ligament was estimated by peaking the planar response, acquiring an echo dynamic pattern, using a selected dB-amplitude threshold, and determining remaining ligament by comparing arrival time with a calibrated display. The Center used 0-, 3- and 6-dB thresholds when manually acquiring data. However, both a 6-dB threshold and a subjective threshold determined by an operator were used when acquiring data with an automated scanning system. The subjective threshold was required because the ultrasonic instrument was saturated, and, therefore, an amplitude reference was not available from which selected dB values could be determined.

High-angle L-wave (including creeping-wave) probes were used to detect and size cracks suspected of propagating into the second zone. Data from through-overlay cracks contained within Specimen EPRI-1 indicated that these probes had a high sensitivity for short metal path distances. The use of these probes ensured a more accurate estimate of remaining ligament than did 40° to 60° angle L-wave probes in cases where IGSCC extended into the overlay.

Crack length was determined by monitoring the crack response as the probe was circumferentially moved, and was calculated as the difference between the points at which the crack response became obscured by background noise. Because of their penetrating capability, 40° to 60° angle L-wave probes were used.

4.2.2 EPRI NDE Center Conclusions Regarding ISCCC Detection and Sizing

The EPRI NDE Center arrived at three conclusions regarding the detection of IGSCC, the determination of IGSC crack length, and the determination of the remaining ligament within weld overlay repaired pipe joints.

First, the Center stated that "Surface preparation is required for effective angle-beam examination for most flaws of concern." The Center presented extensive data supporting the position that the surface finish on most weld overlay structures must be altered to permit meaningful ultrasonic examinations. However, the Center did not determine a complete set of specifications to ensure that an adequate surface finish was obtained. The Center indicated that work was proceeding to determine a full set of specifications, according to a letter provided by the EPRI NDE Center. The Center stated that "... variations on the order of 0.005 inch to 0.010 inch in the thickness and uniformity of the couplant layer have significant effect on coupling efficiency." This is further substantiated by work performed by Doctor et al. (1982).

At the EPRI/NRC meeting, a consensus seemed to exist that a rms surface roughness of 250 microinches or less was sufficient. PNL concurred that a rms surface roughness of 250 microinches or less was required for a meaningful weld overlay inspection. This action ensured that the weld overlay surface was ultrasonically smooth for the wave lengths of interest.

PNL determined the 250-microinch rms surface roughness as a maximum tolerable value from data presented in Clark and Wellman (1976). Their test provided a vast amount of data on signal amplitude lost at specific frequency values due to numerous surface roughness conditions. The 250-microinch rms value was derived from determining a 750-microinch rms to be acceptable and using a factor of safety of 3 as a conservative estimate. This value was derived independent of the EPRI NDE Center data.

The Center also stated that surface undulations are more critical than the rms surface roughness. PNL concurred that surface waviness (American National Standards Institute 1978) was critical; research by Rawsthorn, Murgatroyd, and Barn (1984) and Taylor et al. (1983) supported this conclusion.

Excessive surface waviness was known to prevent the probe face from resting locally against the cladding surface at the probe's beam exit point and to cause significant changes in the local effective incident angle at the couplant-to-metal interface. This resulted in a signal amplitude decrease, an inconsistently refracted beam angle, a change of beam focal characteristics, and beam partitioning. PNL concluded that the surface waviness period be the probe's diagonal length or typically a 1.0-square-inch surface. This ensures that the weld overlay surface would not significantly alter the ultrasonic beam characteristics. A maximum 0.060-inch radial deviation from peak-to-valley points within a 1.0- by 1.0-inch-square surface area was set by PNL. PNL also determined that surface curvature should be restricted by a minimum radius of curvature of 1.0 inch. These conditions still permit significant beam distortion as demonstrated by calculations using Snell's law and a three-layer geometry: angle beam wedge, couplant, and weld overlay. However, because the weld overlay material is transverse isotropic and the effects of surface waviness were not clearly understood, PNL did not wish to recommend an overly restrictive specification. PNL also concluded that future research should determine acceptable levels of surface waviness.

Second, the EPRI NDE Center stated that "Detection of shallow, tight cracks is presently very difficult." Specimen A5-A6 contained "... extensive IGSCC with a maximum estimated depth of approximately 17 percent of the original pipe wall thickness." Few crack indications have been obtained from this specimen, apparently because the cracks are extremely tight and, as a result, a poor ultrasonic reflector. PNL concurred that this data indicates that IGSC cracks less than 20% through-wall of the original pipe material are not generally detectable through weld overlay. This conclusion should be qualified, because reported data (Kurtz 1985) indicates that axial stresses in large-diameter pipes such as 24- to 28-inch-diameter may be significantly less than those of 12-inch-diameter pipe. Specimen A5-A6 was a 12-inch-diameter Schedule 100 pipe.

Third, the EPRI NDE Center stated that "Cracks reaching to within the upper 25 percent of the original pipe wall, and possibly shallower cracks also, can be effectively detected and sized." Deep cracks extending to at least the outer 50% of the original pipe wall were detected using L-wave probes ranging from 45° to 70°.

To examine the Center's statement, PNL reviewed data on both Specimen NC5-C6 and the field specimen set. The analysis of Specimen NC5-C6 focused on correlation between ultrasonic measurements, penetrant measurements, and destructive measurements. An evaluation of S/N ratios was used to evaluate detection of deep IGSCC. Penetrant data was used to evaluate length sizing of deep IGSCC. Destructive data was used to evaluate sizing of the remaining ligament. Destructive data was also used in correlating S/N ratios with different crack characteristics.

The destructive measurements on Specimen NC5-C6 were acquired by four axial cross sections across a weld known to have deep IGSCC in both HAZs. Of these eight cross-sectional views, one for each HAZ, two crack depth measurements were less than 30% of the original pipe wall thickness, while the remaining six ranged from 96% to 61% through-wall (Figures 4.1 through 4.8). Of the six IGSC crack depth measurements greater than or equal to 50% through-wall, two visually appeared[a] to be tight, while two other views showed cracks in a near vertical or radial orientation. The visually apparent tight cracks had a reported 61% and 82% through-wall depth, as shown in Figures 4.7 and 4.8, respectively. Cracks in the most vertical orientation appear in Figures 4.2 and 4.6. However, the upper major branch of each crack has, respectively, a 20° and a 10° inclination from vertical (Figure 4.9).

Excellent S/N ratios were reported for the majority of cracks; however, data was needed on crack characteristics that have previously been associated with a lower signal level. The cracks were examined and grouped into classifications according to characteristics thought to affect signal amplitude. These classifications were:

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[a] A necessary condition for a tight crack was a crack which visually appeared tight. However, a visually apparent tight crack may have been ultrasonically open or tight depending on the stress distribution. A crack that appeared open was assumed to be ultrasonically open. This logic did not account for the case where plastic deformation occuring at the time of coupon removal would make a tight crack appear as if it were open.

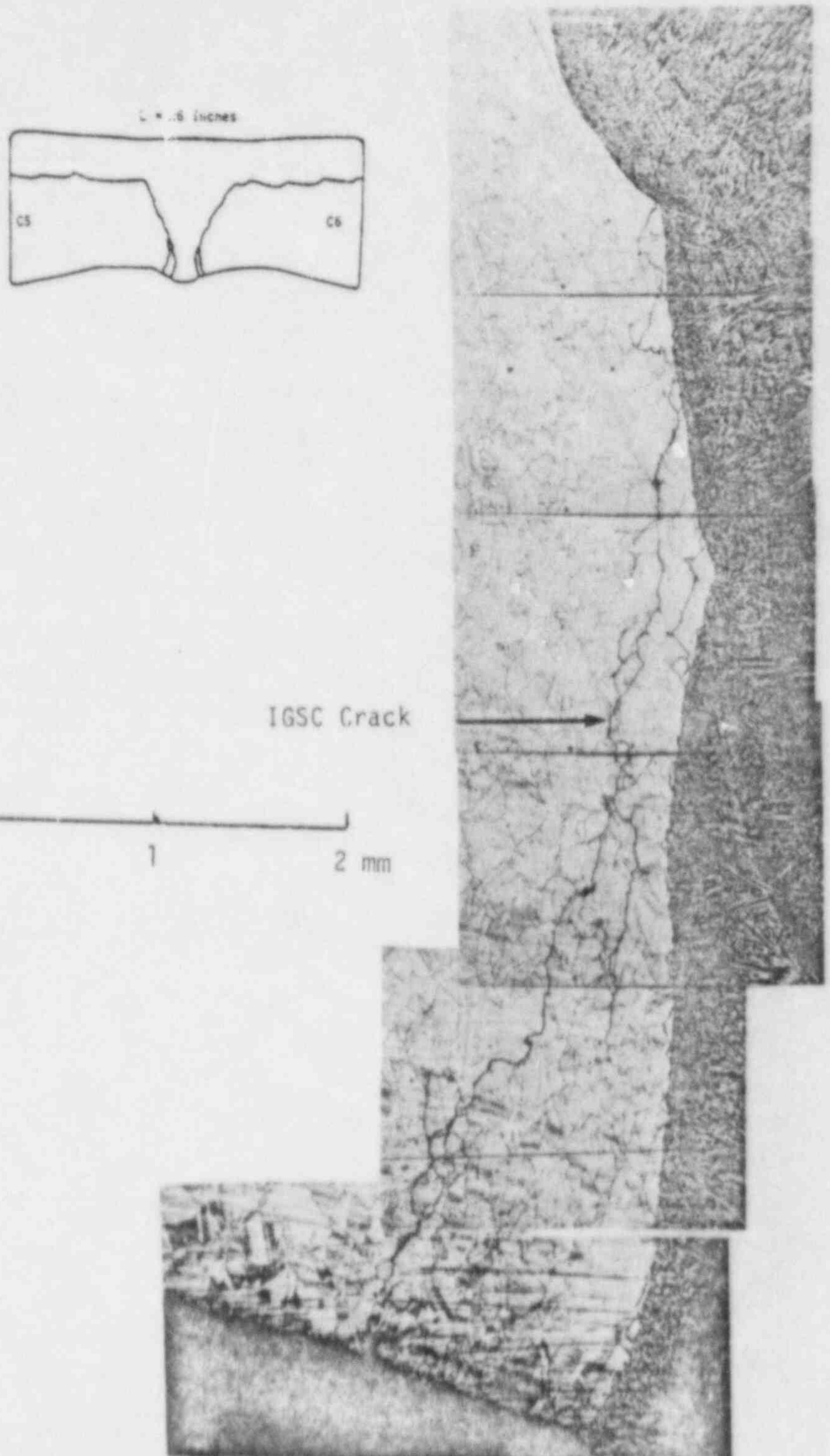

FIGURE 4.1. Cross Section of C5 Side of NC5-C6 at 26 Inches, Indicating a Through-Wall Depth of 30% of the Original Pipe Wall. (Crack Depth = 0.238 Inch; Total Remaining Wall = 0.928 Inch.) Source: Becker et al., EPRI NDE Center, April 1985.

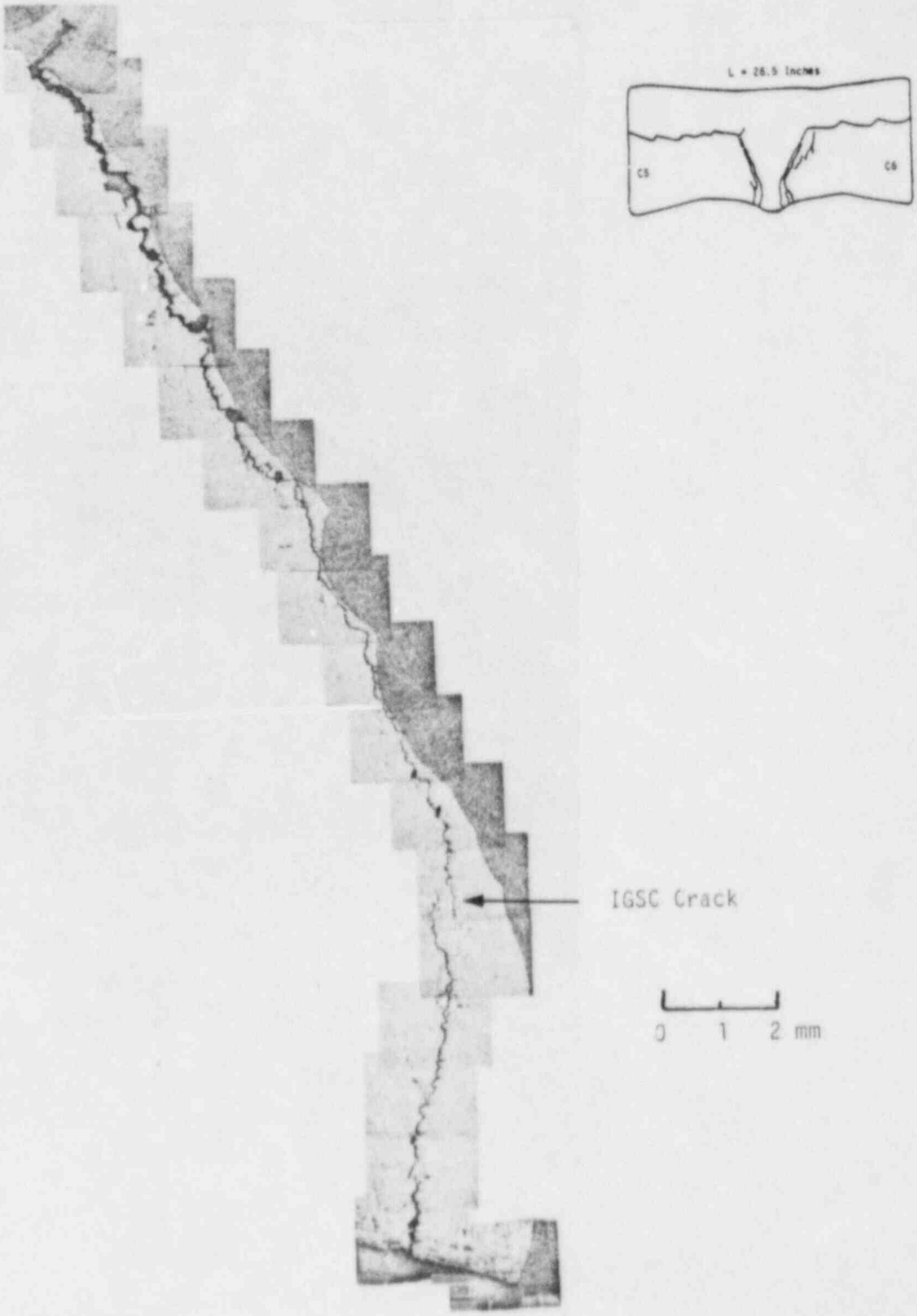

FIGURE 4.2. Cross Section of C5 Side of NC5-C6 at 26.5 Inches, Indicating a Through-Wall Depth of 96% of the Original Pipe Wall. (Crack Depth = 0.757 Inch; Total Remaining Wall = 0.365 Inch.) Source: Becker et al., EPRI NDE Center, April 1985.

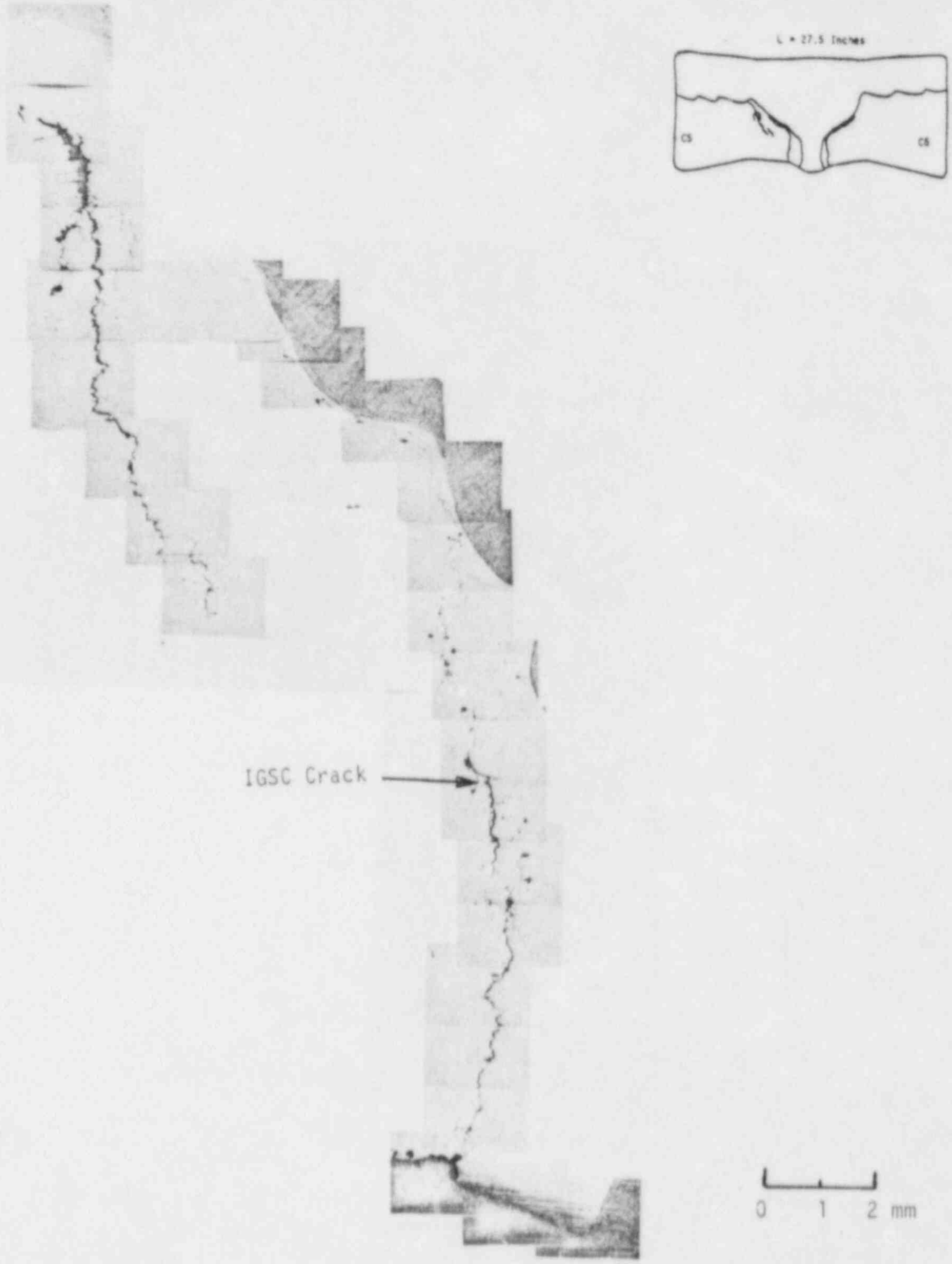

FIGURE 4.3. Cross Section of C5 Side of NC5-C6 at 27.5 Inches, Indicating a Through-Wall Depth of 86% of the Original Pipe Wall. (Crack Depth = 0.682 Inch; Total Remaining Wall = 0.396 Inch.) Source: Becker et al., EPRI NDE Center, April 1985.

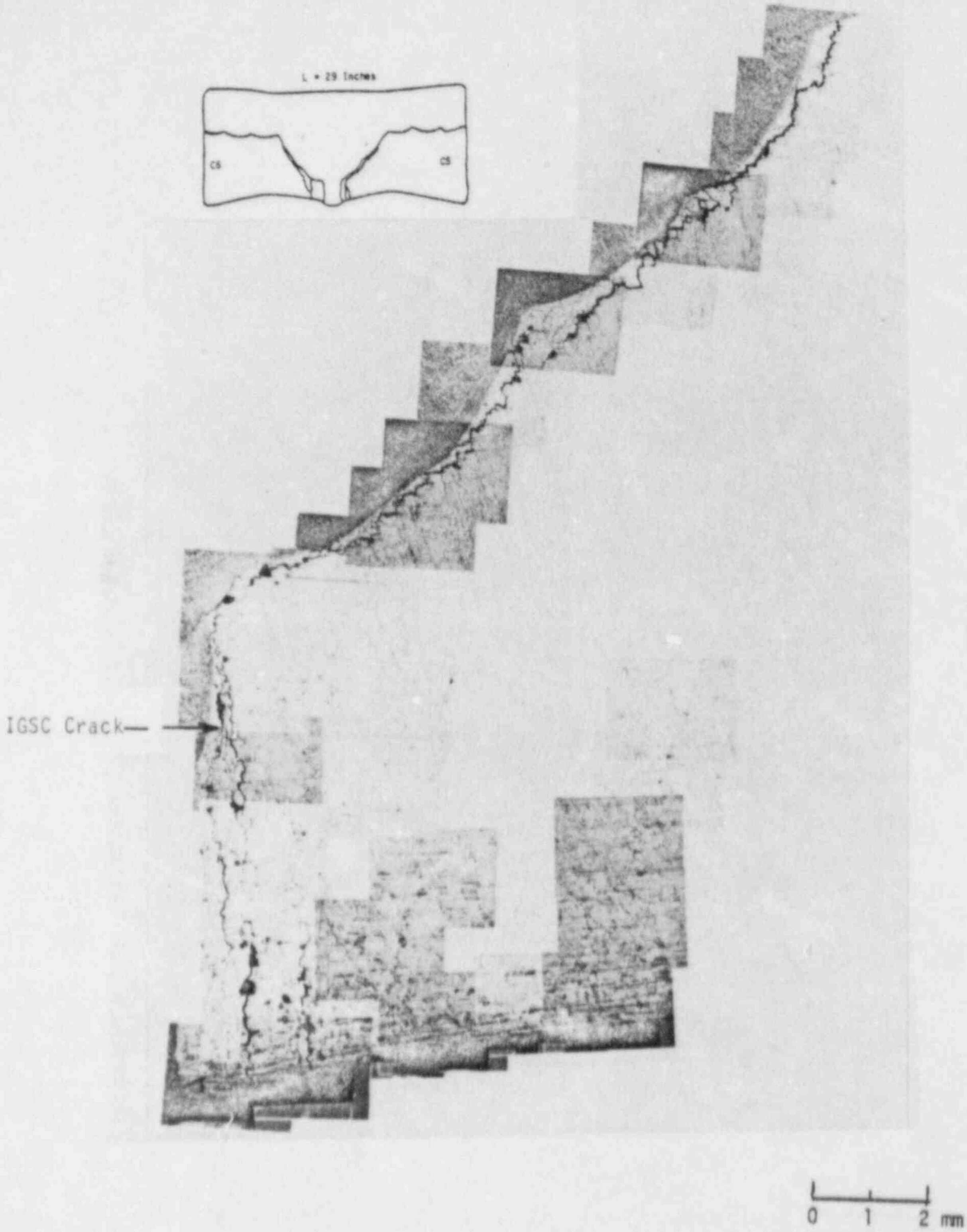

FIGURE 4.4. Cross Section of C5 Side of NC5-C6 at 29 Inches, Indicating a Through-Wall Depth of 72% of the Original Pipe Wall. (Crack Depth = 0.572 Inch; Total Remaining Wall = 0.515 Inch.) Source: Becker et al., EPRI NDE Center, April 1985.

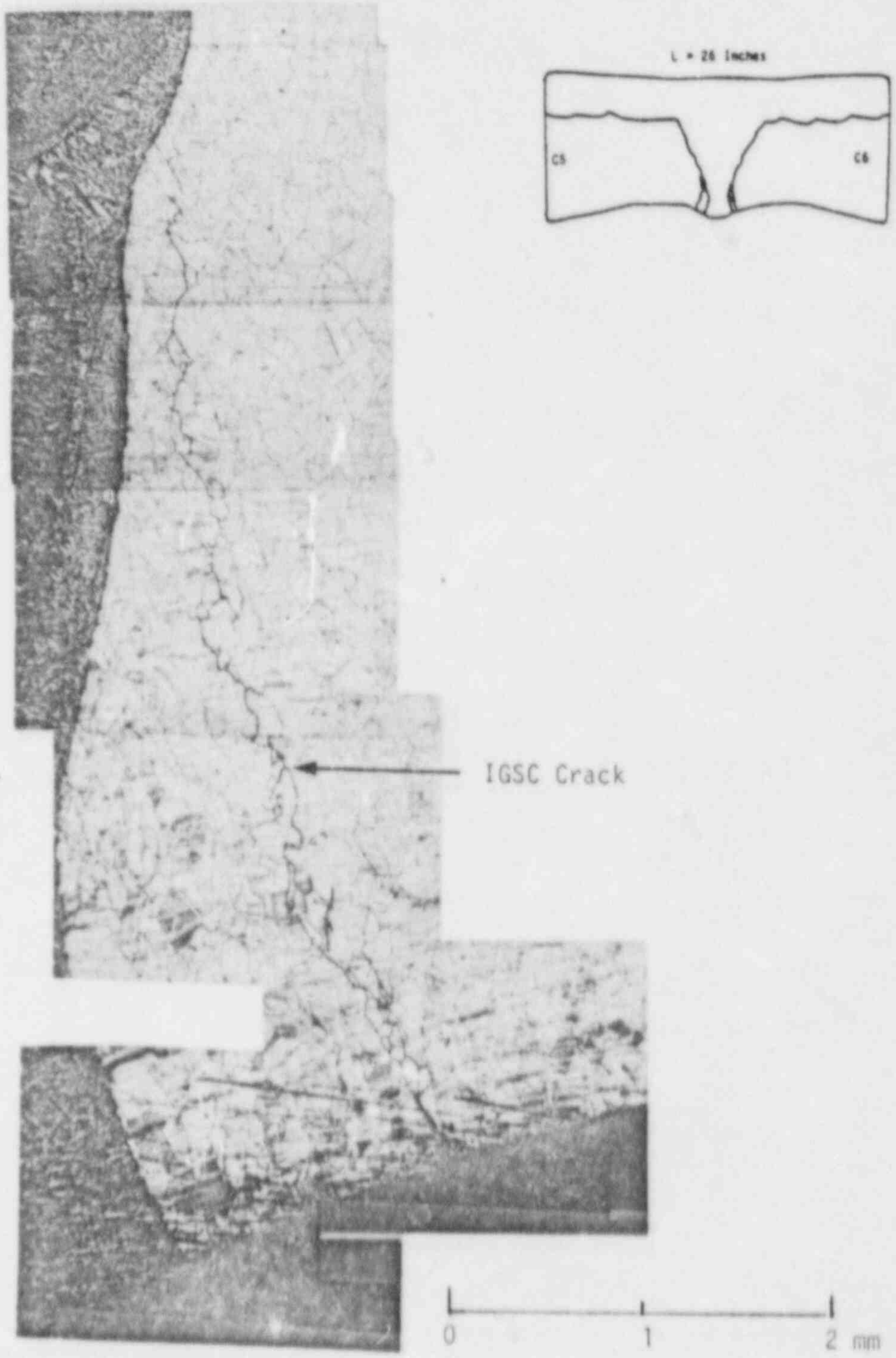

FIGURE 4.5. Cross Section of C6 Side of NC5-C6 at 26 Inches, Indicating a Through-Wall Depth of 25% of the Original Pipe Wall. (Crack Depth = 0.198 Inch; Total Remaining Wall = 0.968 Inch.) Source: Becker et al., EPRI NDE Center, April 1985.

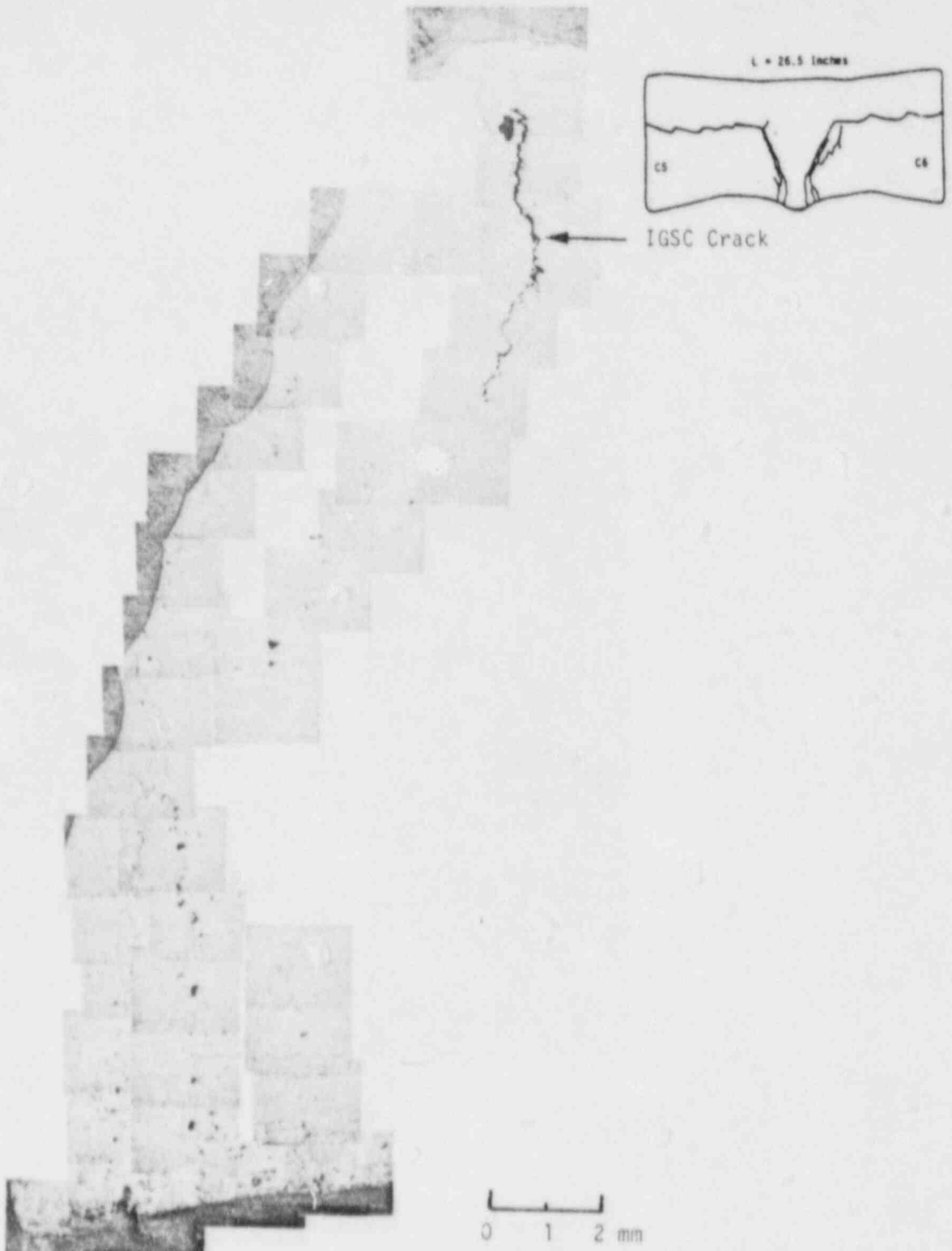

FIGURE 4.6. Cross Section of C6 Side of NC5-C6 at 26.5 Inches, Indicating a Through-Wall Depth of 95% of the Original Pipe Wall. (Crack Depth = 0.748 Inch; Total Remaining Wall = 0.374 Inch.) Source: Becker et al., EPRI NDE Center, April 1985.

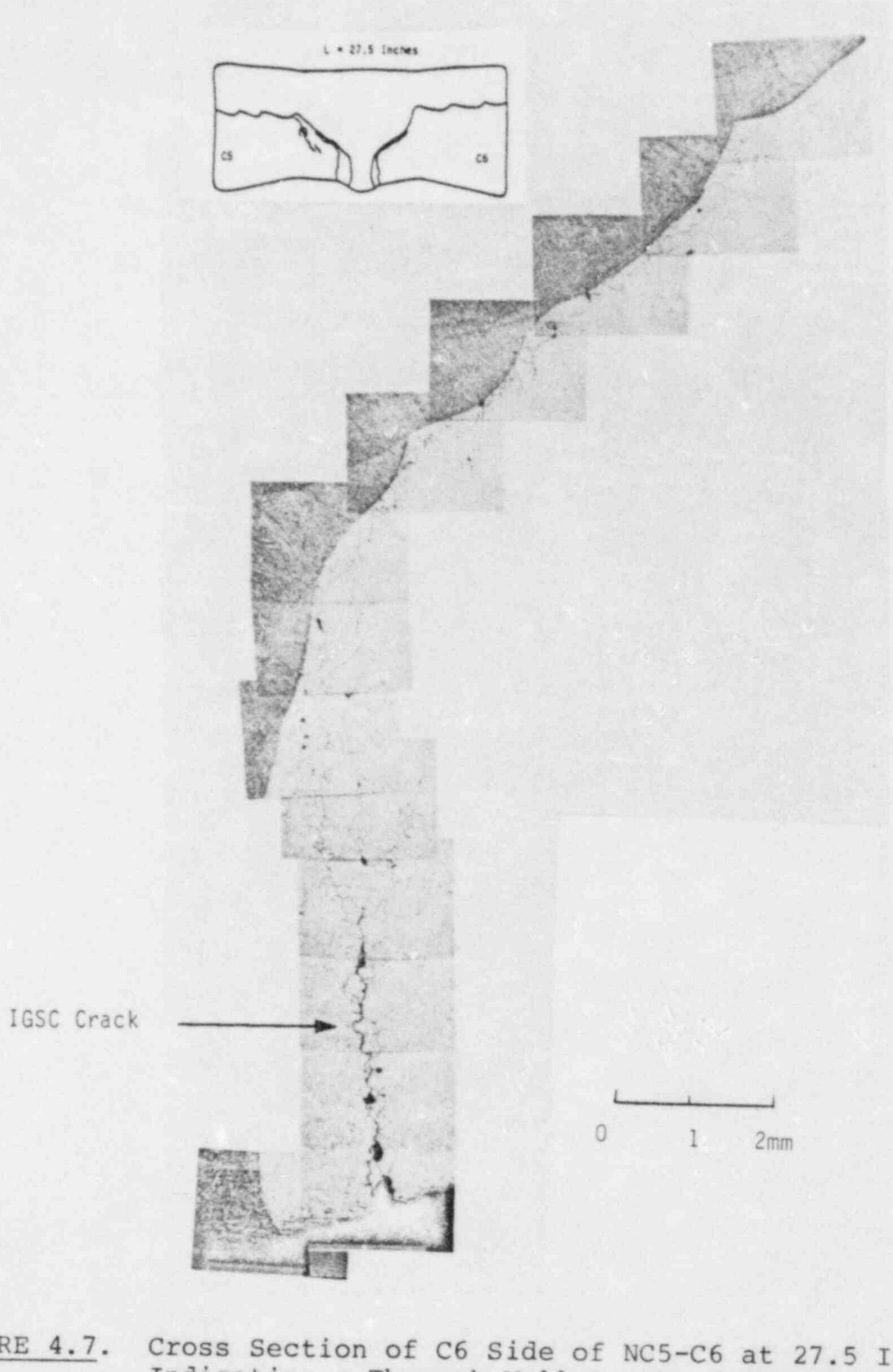

FIGURE 4.7. Cross Section of C6 Side of NC5-C6 at 27.5 Inches, Indicating a Through-Wall Depth of 82% of the Original Pipe Wall. (Crack Depth = 0.647 Inch; Total Remaining Wall = 0.462 Inch.) Source: Becker et al., EPRI NDE Center, April 1985.

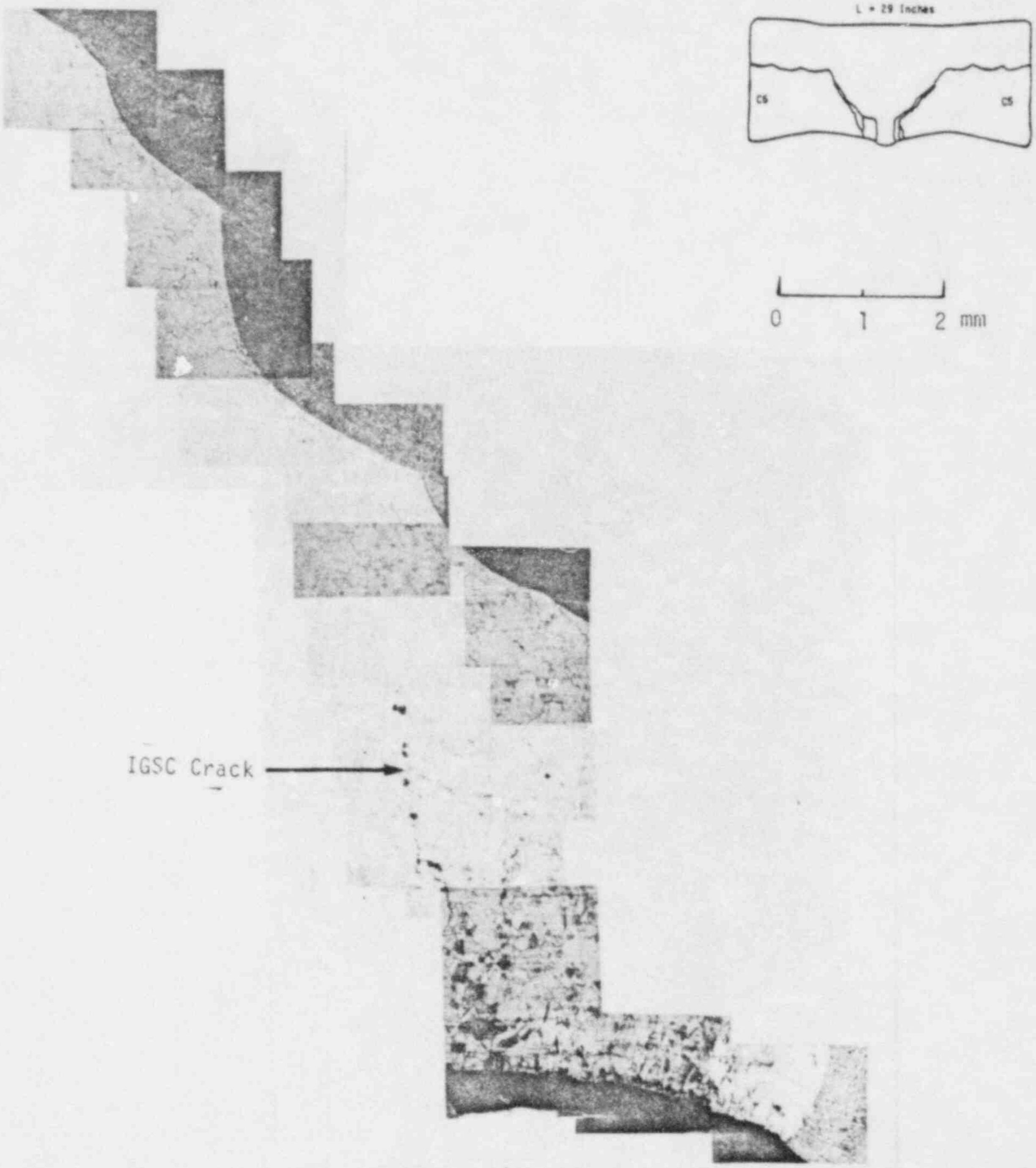

FIGURE 4.8. Cross Section of C6 Side of NC5-C6 at 29 Inches, Indicating a Through-Wall Depth of 61% of the Original Pipe Wall. (Crack Depth = 0.484 Inch; Total Remaining Wall = 0.603 Inch.) Source: Becker et al., EPRI NDE Center, April 1985.

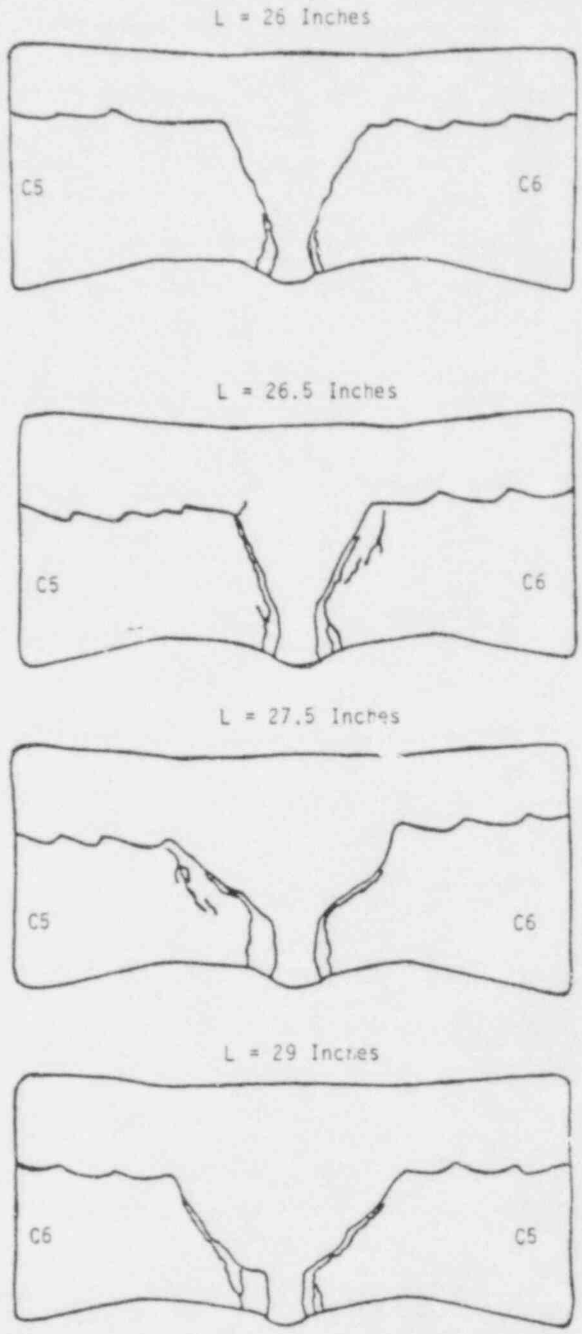

FIGURE 4.9. Sketch of the Cross Sections Through the Cracks in NC5-C6. Source: Becker et al., EPRI NDE Center, April 1985.

- open and preferentially oriented
- open and vertically oriented
- open and change of orientation
- apparently tight and preferentially oriented.

Although much data were presented in the EPRI NDE Center draft document, little information was included from which to determine a quantitative measurement of the S/N ratios. A S/N ratio of 20 dB was reported for most signals. However, an 8-dB loss was observed in signal gain for an apparently tight and preferentially oriented crack when using a 45° dual-element L-wave probe (Figure 4.10). The EPRI NDE Center stated that adequate S/N ratios existed for each of the six deep IGSCC

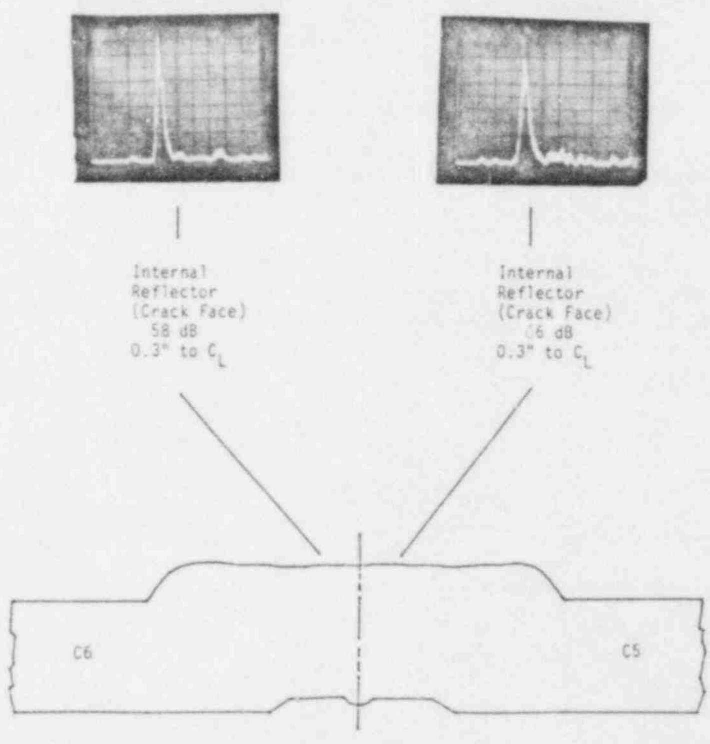

FIGURE 4.10. Ultrasonic Indications from NC5-C6 at 29 Inches Showing an 8-dB Difference Between an Open Preferentially Oriented Crack and an Apparently Tight Preferentially Oriented Crack. Source: Becker et al., NDE Center, April 1985.

indications. The Center also stated that the signal level of the C6 HAZ was generally less than that observed from the C5 HAZ. All cracks that were visually determined to be tight from the destructive analysis were contained within the C6 HAZ. PNL concluded that more information on S/N ratios was needed. An example where the S/N ratio was expected to be low was a tight vertical crack. This type of crack was not represented in the data obtained by the EPRI NDE Center.

A possible source of data is the recorded automated scans performed during the Center's program. If the ultrasonic instrument was not saturated and the data have not been lost, then recorded signal levels could be compared with the crack characteristics previously listed.

Information supplementing data concerning S/N ratios was provided by the field specimen set that contained four weld overlaid pipe joints with deep IGSCC. This was important because the IGSCC was truly representative of ultrasonic measurements performed in the field. Isolated cases of crack detection were provided where excellent S/N ratios were obtained with both a dual-element 60° L-wave probe and a tandem L-wave probe.

Destructive analysis of Specimen NC5-C6 was used to evaluate sizing of the remaining ligament of a weld overlaid pipe joint containing deep IGSCC. Of the eight cross-sectional views of the two IGSC cracks, visual inspection revealed six having a depth exceeding 50% of the original pipe wall thickness. The remaining ligament measurements and destructive results are given in Table 4.1. Table 4.1 indicates that the remaining ligament resultant from cracks characterized as other than open and preferentially oriented were, in general, measured less conservatively.[a] Analysis of data that was acquired by an automated system using a 60° L-wave probe and a threshold determined by the operator indicated a 0.13-inch[b,c] difference in measured values between the two flaw sets.

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[a] A nonconservative measurement was associated with a remaining ligament value greater than that given by the destructive test. A conservative measurement, therefore, ensured that the pipe joint strength or integrity was not overestimated.

[b] A subjective threshold was determined by the operator because the data was saturated and, thus, no reference amplitude level existed from which dB levels could be objectively determined. The EPRI NDE Center stated that the anterior rise of the echo dynamic pattern was fairly sharp and that significant changes in measurements were not expected due to the subjective edge detection of the crack.

[c] This data was the same as that used by the EPRI NDE Center when determining a mean error of 0.038 inch and a standard deviation of 0.079 inch for remaining ligament measurements. All eight cracks were used in the Center's calculation.

TABLE 4.1. Analysis of EPRI NDE Center Ultrasonic Measurements of Remaining Ligament (Only cracks larger than 50% through-wall are considered.)

Crack Characteristic	HAZ/Position	Destructive Measurement of Remaining Ligament[a]	Ultrasonic Measurement Error[a,b] (Automated Data Acquisition): 60°L/Operator Threshold	60°L/-6dB Threshold	45°L/Operator Threshold
Open and preferentially oriented	C5/27.5	0.396	-0.094	-0.087	-0.027
	C5/29.0	0.515	-0.133	-0.117	-0.056
Open and vertically oriented	C6/26.5	0.374	0.000	-0.052	---
Open and change of orientation	C5/26.5	0.365	0.031	0.008	0.013
Apparently tight and preferentially oriented	C6/27.5	0.462	0.092	-0.140	---
	C6/29.0	0.603	-0.027	-0.066	---
	Mean Error		-0.022	-0.076	-0.023
	RMS Error		0.078	0.089	0.037

	Ultrasonic Measurement Error (Manual Data Acquisition): -6dB Threshold	0dB Threshold
Mean Error	-0.088	0.037
RMS Error	0.128	0.104

[a] All measurements and associated errors are given in terms of inches.

[b] A positive error infers an oversized measurement of remaining ligament, which leads to a nonconservative estimate of structural integrity.

The mean error and rms error reported in Table 4.1 were determined with an extremely small database. This data, nonetheless, indicated a strong <u>trend</u> suggesting that the remaining ligament can be determined accurately.

Crack lengths were determined along selected regions of Specimen NC5-C6. As previously indicated, cracks contained within this specimen were deep along their entire length except at their ends. Penetrant indications and ultrasonic measurements are reported in Table 4.2.

TABLE 4.2. Ultrasonic Estimate of Crack Length from Data Acquired from Specimen NC5-C6

HAZ	Range Defined by PT, Inches	Length Defined by PT, Inches	Probe	Range Given by UT, Inches	Absolute Length Error,[a] Inches	Percent Error[a]
C6	6.0-12.0	6.0	60°L wave	6.4-11.8	-0.6	-10
C6	26.7-29.6	2.9	60°L wave	26.9-29.7	-0.1	-3
C5	8.5-13.2	4.7	60°L wave	7.9-13.8	1.2	26
C5	26.7-33.5	6.8	60°L wave	26.4-33.5	0.3	4
C5	8.5-13.2	4.7	45°L wave	9.4-13.3	-0.8	-17
C5	26.7-33.5	6.8	45°L wave	26.4-32.9	-0.3	-4
C6	6.0-12.0	6.0	40°L wave	6.4-11.5	-0.9	-15
C5	8.5-13.2	4.7	40°L wave	10.7-13.1	-2.3	-49

[a] A negative error infers both an undersized measurement of crack length and nonconservative estimate of structural integrity.

PNL concluded that a limited database indicated that a strong <u>trend</u> exists whereby deep IGSCC may be detected, sized in length, and the remaining ligament resultant from the crack determined. However, until sufficient data is available to demonstrate technique reliability, PNL will continue to classify the technique as unreliable.

A field condition in which the high-angle, L-wave, far-side inspection technique may suffer performance degradation is illustrated in Figure 4.11. The reference weld overlaid pipe joint was prepared to simulate a 12-inch-diameter pipe joint that was removed from Georgia Power Company's Hatch reactor (Kupperman et al. 1985). Of particular interest is the case where the ultrasonic beam must traverse a columnar-to-base metal interface at both the weld overlay metal-to-base metal interface and the weld metal-to-base metal interface. Note that the 45° probe is not affected by the geometric restraint determined for the 60° and 70° probes.

4.3 WELD OVERLAY MATERIAL INSPECTION

Detection and sizing of weld overlay fabrication flaws entailed fabricating the flaws, nondestructively examining the weld overlay to locate induced flaws, ultrasonically examining the weld overlay material, destructively testing eight coupons from the two specimens, and correlating ultrasonic measurement results with destructive measurement results.[a]

The EPRI NDE Center stated that "Code-unacceptable overlay flaws are generally detectable." A major objective of inspecting the overlay material, either immediately following overlay fabrication or in subsequent inservice inspection (ISI), is to justify the structural strength of the weld overlay material. To determine whether "code-acceptable flaws" could be detected, a specimen with an assortment of acceptable and unacceptable reflectors was fabricated. The flaws included in the specimen were both isolated and clustered. The flaws included cracking, lack of bond, lack of fusion, tungsten inclusions, and porosity. The Center stated that they did not expect any other flaw types to exist when applying an overlay with gas tungsten arc welding (GTAW), which is regarded as a high-quality welding process.

PNL concluded that the correlation of results of destructive tests with those from ultrasonic examination showed that unacceptable fabrication flaws contained within the weld overlay material were detected with low reliability. Good detection sensitivity was demonstrated for both acceptable and unacceptable lack of bonds. Clustered cracking and isolated cracking were detected in isolated cases. However, S/N ratios were generally too small to ensure reliable detection. Furthermore, the surface preparation and scanning techniques used by the EPRI NDE Center were designed for an optimal S/N ratio. Porosity and tungsten

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[a] Possible acceptance criteria for overlay material inspection may be defined by the Boiler and Pressure Vessel Code of the American Society of Mechanical Engineers. However, the applicability of the Code is not clearly understood, given the extremely large stress contained within the weld overlay material.

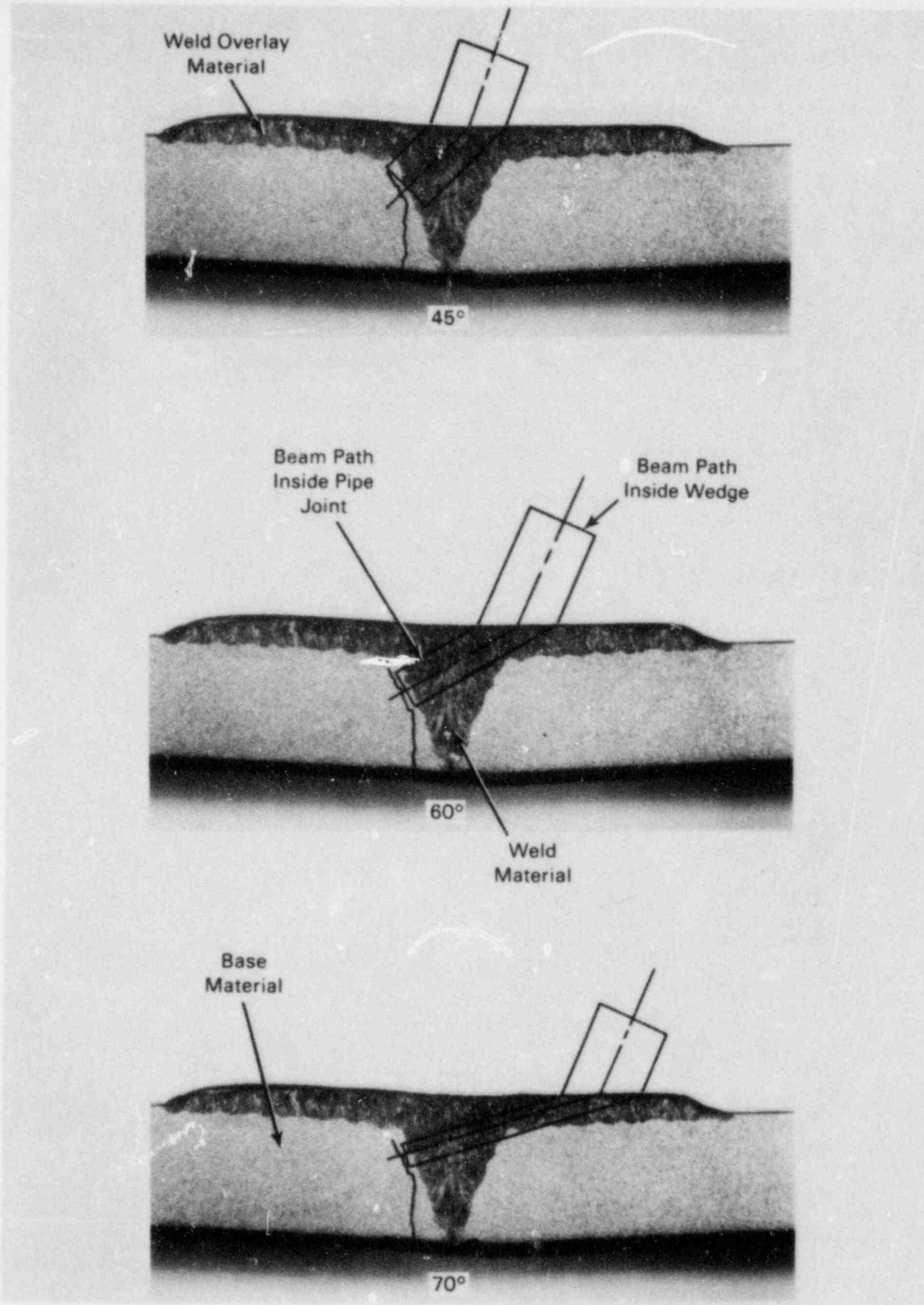

FIGURE 4.11. Ray Diagrams of Propagational Paths to a Deep Crack with a 45°, 60°, and a 70° L-Wave Probe (Transducer Diameter is 0.5 Inch)

inclusions were not detected by an ultrasonic method. The Center stated that they may be detectable by a radiographic method.

Based on review of the data describing the detectability of unacceptable flaws, PNL concluded that:

- A limited database shows a strong trend that lack of bond can be detected reliably.
- Unacceptable flaws such as a crack and lack of fusion were detected with low reliability, whether isolated or clustered.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Based on review of available technical literature, results of the PNL experiments conducted to determine the distortional effects of weld overlay on ultrasound, and review of data from the weld overlay inspection development program at the EPRI NDE Center, PNL arrived at nine major conclusions. The PNL conclusions and related recommendations are:

1. **Conclusion:** Shear wave examination of a weld overlaid pipe joint is neither effective nor reliable.

2. **Conclusion:** Longitudinal wave probes with an angle ranging between 40° and 70° provide the best results for detecting deep intergranular stress corrosion cracks, sizing the length of the detected crack, and sizing the remaining ligament of the pipe joint. The probes used most successfully had peak frequency responses ranging between 1.0 and 4.0 MHz.

   Recommendation: Examination of weld overlaid joints should be performed with longitudinal waves using at least two different angles ranging between 40° and 70° and separated by a difference of 15° (e.g., 45° and 60°).

   Recommendation: Inspectors should demonstrate their capability to detect flaws in weld overlaid joints, because longitudinal inspection differs significantly from commonly employed shear-wave techniques.

3. **Conclusion:** A limited database indicated a strong trend whereby the detection and the sizing of an intergranular stress corrosion crack of depth greater than 50% through-wall of the original pipe wall thickness may be reliably determined. However, until sufficient data is available to demonstrate technique reliability, the technique will be classified as having a low reliability.

   Recommendation: Perform additional experiments that add to the database of correlating ultrasonic measurements with destructive measurements.

4. **Conclusion:** The detection and the sizing of an intergranular stress corrosion crack of depth less than 50% through-wall of the original pipe wall thickness is not reliable.

5. **Conclusion:** The detection or sizing of an intergranular stress corrosion crack of depth less than 20% through-wall of the original pipe wall thickness is generally not possible.

6. **Conclusion:** High-angle L-wave (including creeping-wave) probes were more accurate than dual-element L-wave probes ranging between 40° and 60° in determining the remaining ligament associated with intergranular stress corrosion cracks that extended into the weld overlay material.

   Recommendation: High-angle L-wave (including creeping-wave) probes should be used to estimate the remaining ligament of intergranular stress corrosion cracks suspected of entering the weld overlay material.

7. **Conclusion:** The detection of unacceptable fabrication flaws contained within the weld overlay has not been demonstrated to be reliable. The Boiler and Pressure Vessel Code of the American Society of Mechanical Engineers was used as the acceptable/unacceptable criterion. However, the applicability of the Code is not clearly understood, given the extremely large stress contained within the weld overlay material.

8. **Conclusion:** Surface preparation of the weld overlay is required to perform meaningful ultrasonic inspections regarding intergranular stress corrosion cracks and weld overlay fabrication flaws.

   The condition of the overlay surface should meet the following requirements:

   - The rms surface roughness must be equal to or less than 250 microinches.

   - The surface waviness must be equal to or less than a 0.060-inch radial deviation from peak to valley points within a 1.0- by 1.0-square-inch surface area.

   - All surface variations should not produce a depth variation having a radius of curvature less than 1 inch.

9. **Conclusion:** Additional research is needed to resolve the remaining questions concerning the reliable inspection of weld overlay repaired pipe joints.

As current research and development programs develop a more comprehensive engineering database, the conclusions and recommendations listed above may change.

6.0 FUTURE WORK

Evidence of effective nondestructive inspection is necessary if weld overlay is to be used as a long-term repair for pipe joints weakened by intergranular stress corrosion cracking. To provide such evidence, additional research is required to develop reliable inspection procedures. The main areas of concern are inspecting the weld overlay for unacceptable fabrication flaws and measuring the remaining ligament. Both must be performed reliably in order to justify the structural integrity of the repaired pipe joint.

Areas in which work is needed to provide evidence of effective nondestructive inspection are:

1. An enlarged database must be acquired consisting of the correlation of blind nondestructive measurements with destructive test measurements. Because high-angle longitudinal waves and creeping waves have shown a strong tendency for providing the needed nondestructive measurements, a database of additional weld overlay repaired pipe joints of different pipe diameters and thicknesses with a variety of crack depths is needed.

2. The distortional effects of the weld overlay on an ultrasonic wave must be examined for inspecting through both the weld overlay and the weld material. To date, experimental data has been obtained on the distortion resulting from only the weld overlay layer.

3. A criterion for acceptable/unacceptable weld overlay fabrication flaws must be established.

4. Based on the acceptance criterion selected for weld overlay fabrication flaws, nondestructive methods must be shown to be sensitive in detecting unacceptable flaws in both the regime of unacceptable/acceptable and slightly into the acceptable category.

5. A complete set of specifications regarding surface roughness and waviness must be determined that will ensure meaningful ultrasonic examinations. A particular need exists to quantify the adverse affects of surface waviness on the ultrasonic examination.

6. A qualification program must be developed whereby individuals demonstrate their competence in performing a reliable nondestructive examination.

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Pacific Northwest Laboratory (PNL) evaluated the ultrasonic inspectability of weld overlaid pipe joints. As part of this task, PNL is providing NRC staff with conclusions and recommendations concerning the effectiveness of ultrasonic inspections performed on weld overlaid pipe joints.

PNL evaluated data from available technical literature, conducted experiments to determine the distortional effects of weld overlay on ultrasound, and reviewed data from the weld overlay inspection development efforts of the Electric Power Research Institute NDE Center.

Based on these reviews and experiments, PNL concluded that ultrasonic inspection of weld overlaid pipe joints has not been demonstrated to be reliable, for two reasons. First, insufficient data exists to demonstrate the reliable detection and sizing of intergranular stress corrosion cracks. Second, the detection of unacceptable fabrication flaws contained within the weld overlay material has a low reliability due to poor signal-to-noise ratios. However, as current research and development programs lead to a more comprehensive engineering database, these conclusions may change.

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