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Detection of Small-Sized Near-Surface Under-Clad Cracks For Reactor Pressure Vessels

Prepared by T.T. Taylor, S.L. Crawford, S.R. Doctor, G.J. Posakony

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ABSTRACT

The analysis of pressurized thermal shock (PTS) shows it is necessary for nondestructive evaluation to demonstrate high probability of detecting cracks 0.250 inches deep and deeper at the clad/base metal interface.

Ultrasonic techniques developed and used in Europe are evaluated in this paper for their applicability to U.S. reactor pressure vessels for detecting cracks of interest for PTS.

Flaw detectability experiments were carried out by testing the inspection technique's ability to detect artificial flaws under several types of clad, including some Manual Metal Arc (MMA) clad. Both ground and unground clad surfaces were evaluated. Crack sizing tests of the inspection technique were made using a crack tip diffraction technique.

The data reported here indicate that for sufficiently smooth clad surfaces, the dual 70° compressional wave technique is extremely effective for detecting under-clad cracks. In addition, results show that dramatic signal-to-noise improvements can be made by grinding the clad surface. Specifically, an improvement of 10 to 12 dB in signal-to-noise ratio was achieved by smoothing the clad surface roughness from 12.6×10^{-3} inches RMS to 5.6×10^{-3} inches RMS. The improvement in surface finish allowed sufficient ultrasound to penetrate the clad surface to improve crack detection confidence from low to very high.

EXECUTIVE SUMMARY

It has been postulated that small (0.25 inch deep) cracks beneath the clad of pressure vessel belt line welds could result in vessel failure during a reactor overcooling transient. Nondestructive evaluation must demonstrate a high probability of detecting these small cracks. The cracks of interest lie parallel or perpendicular to the clad lay and within the first one inch of the vessel surface.

European techniques (DeRaad, Engl and Bergh, 1981; Launay et al., 1981) using 70° compressional waves have been shown to be effective in detecting under-clad cracks 3 mm deep or shallower under ideal conditions (smooth clad and cracks predominantly perpendicular to the clad lay). Most circumferential welds in U.S. pressure vessels have been clad using the manual metal arc (MMA) process. This welding process creates rough surfaces that contribute to ultrasonic inspection noise and inhibit inspection effectiveness. This paper reports progress in a program in which the Pacific Northwest Laboratory is evaluating European and other inspection techniques that may be useful for inspecting U.S. pressure vessels.

Flaw detectability experiments were carried out by testing the inspection technique's ability to detect artificial flaws under several types of clad, including MMA clad. Both ground and unground clad surfaces were evaluated. Crack sizing tests of the inspection technique were made using a crack tip diffraction technique.

The data reported here indicate that for sufficiently smooth clad surfaces, the dual 70° compressional wave technique is extremely effective for detecting under-clad cracks. In addition, results show that dramatic signal-to-noise improvements can be made by grinding the clad surface. Specifically, an improvement of 10 to 12 dB in signal-to-noise ratio was achieved by smoothing the clad surface roughness from 12.6×10^{-3} inches RMS to 5.6×10^{-3} inches RMS. The improvement in surface finish allowed sufficient ultrasound to penetrate the clad surface to improve crack detection confidence from low to very high.

The results of flaw detectability experiments reported in this paper show that few U.S. reactor vessels have been effectively examined for Pressurized Thermal Shock (PTS) type flaws. The conclusions (on page 17) suggest changes to Codes and/or regulatory guides that would improve detection of PTS-type flaws.

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DETECTION OF SMALL-SIZED NEAR-SURFACE
UNDER-CLAD CRACKS IN U.S. PRESSURE VESSELS

INTRODUCTION

The belt line welds in the pressure vessels of several U.S. reactors have suffered serious radiation damage. This damage resulted from high copper content in the welds. It has been postulated (Gamble and Strosnider) that under-clad cracks as small as .250 inches in depth could result in vessel failure during an overcooling transient. A combination of conditions would be required for this type of failure to occur. These include: crack existance, high radiation damage, and high pressure (approaching operating pressure) at a low temperature. This generic safety issue is identified as Pressurized Thermal Shock (PTS).

The ability of nondestructive evaluation (NDE) to detect and characterize flaws provides an opportunity to assess the integrity of the inner surface of the vessel. Currently, a specialized technique developed in Germany and France is generally accepted as providing optimum detection resuls (DeRaad, Engl and Bergh; Launay et al.; Becker; Gruber). At the direction of the U.S. Nuclear Regulatory Commission (NRC), the Pacific Northwest Laboratory (PNL) is evaluating the effectiveness of this technique. The objective of this study is to provide NRC with information on how well the technique detects flaws in pressure vessels fabricated in the U.S.

The technique developed in Europe utilizes high-angle (generally greater than 50^{o}) compressional waves. This technique was developed to detect under-clad cracks in light water reactor vessels. Inspection is performed with the search unit in contact with the clad surface (i.e., near surface flaw detection). It has been shown to be effective in detecting under-clad cracks 3 millimeters deep under ideal conditions (smooth clad and cracks predominantly perpendicular to the clad lay). Figure 1a shows the directivity pattern in steel of a 70^{o} zone focused compressional wave emitted from a dual element transducer. The directivity pattern in Figure 1a shows that the peak energy of a 70^{o} zone focused transducer lies between 0.25 in. and 0.5 in. below the surface of the metal, which makes the high-angle compressional waves ideal for detecting defects near the clad/base metal interface. The compressional waves have better penetrating power through clad than shear waves, providing a better signal-to-noise ratio. Commercially available transducers specially designed for under-clad-crack detection incorporate a transmit/receive design that allows the high-angle zone focusing (see Figure 1b).

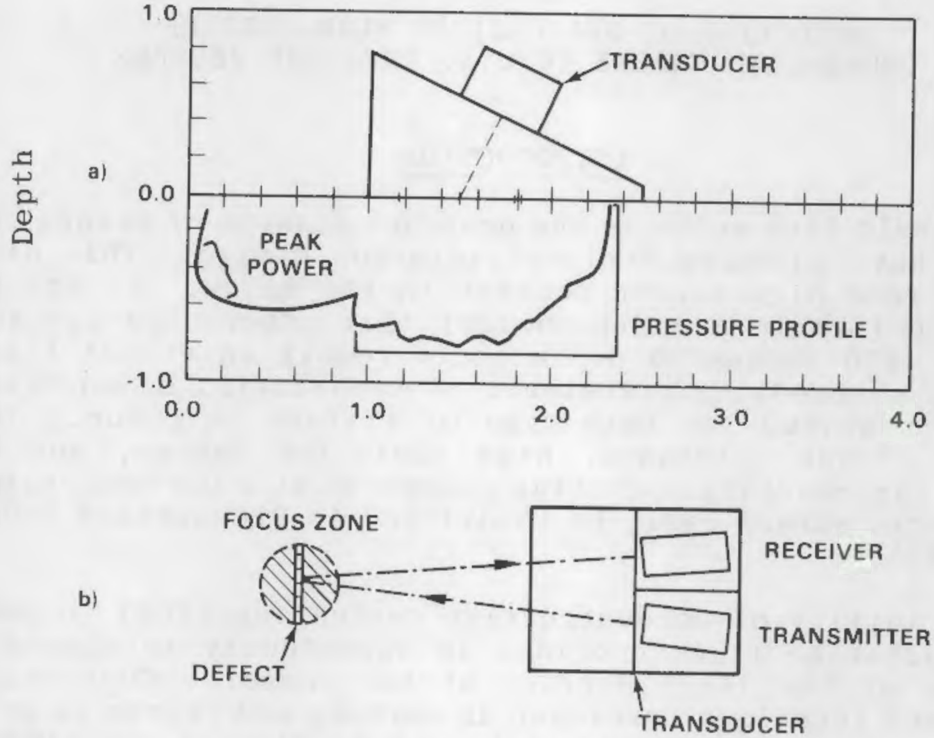


FIGURE 1. Probe for Under-clad Crack Detection: a) Directivity Pattern for 70° Compressional Wave; b) Send/Receive Design for Commercial Probes.

The PNL evaluation of this technique included an assessment of flaw detectability and initial crack characterization experiments. This evaluation is part of a long-term NRC program designed to identify ultrasonic inspection technology that can reliably detect and characterize cracks beneath the clad of a reactor pressure vessel. This report deals with study results to date. The following report section discusses flaw detectability experiments in which European technique were used to detect artificial flaws under several types of clad. The subsequent section describes crack characterization experiments. Conclusions are followed by a discussion of plans for the long-term program.

FLAW DETECTABILITY

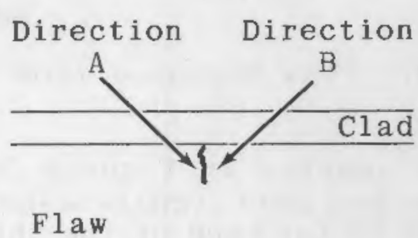
Flaw detectability experiments have been carried out on strip clad, single-wire subarc clad, and manual clad. Both ground and unground surfaces were evaluated. The test blocks used for this evaluation included: a 29.5 in. dia. clad dropout, two 23.6 in. square blocks with strip and single-wire clad with one side ground and the other as deposited,[a] and two small samples with ground and unground, manually clad surfaces. The pressurizer dropout contained through-clad notches as well as thermal fatigue cracks under the clad. The two EPRI blocks contained notches under the clad (under-clad notches). The two manually clad samples contained two reference reflectors each and were used to evaluate general noise level.

The measurements reported here were taken using a 2-MHz dual-beam longitudinal (SEL) 70° transducer with .39 x .59 in. elements and focal zone of .67 in. This unit was considered optimal for the clad conditions and thicknesses (.25 to .35 in. tested. All measurements were performed manually.

Measurements of flaw amplitude response from each of the under-clad thermal fatigue cracks (labeled A through I) in the pressurizer dropout sample were compared with the amplitude response from a 1/8 in. dia., flat-bottom reference reflector (Table 1). The flaw amplitude response was measured from two directions (180° apart) as would be done during actual field tests. The amplitude responses were higher than responses from the reference reflector; therefore, these cracks should be easily detectable with this technique even under field conditions.

TABLE 1. Flaw Amplitude Response from Nine Under-Clad Thermal Fatigue Cracks

Flaw	Flaw Depth Through Wall (in.)	Flaw Response[b] Direction A	Flaw Response[b] Direction B
A	0.50	+3 dB	+6 dB
B	0.50	+5 dB	+5 dB
C	0.25	+6 dB	+10 dB
D	0.50	+3 dB	+5 dB
E	0.25	+14 dB	+5 dB
F	0.15	+4 dB	+8 dB
G	0.50	+1 dB	+2 dB
H	0.75	+6 dB	+12 dB
I	0.75	+9 dB	+1 dB



(a)Access to these two samples was made possible through J.R. Quinn, Electric Power Research Institute (EPRI), Palo Alto, California.

(b)Sensitivity Standard: 1/8 in. dia., flat-bottom reference reflector.

Figures 2 through 6 show the relative signal amplitudes for: a 1/8 in. dia., flat-bottom hole (FBH) at the interface, an ASME-type through-clad notch, thermal fatigue under-clad cracks, under-clad notches, the base line noise, and indications from within the clad. The base line is the level which would yield a nearly continuous recording. Occasional clad indications arise from the clad itself and are particularly prevalent when signal propagation is perpendicular to unground clad. These clad signals have been measured and will be addressed later.

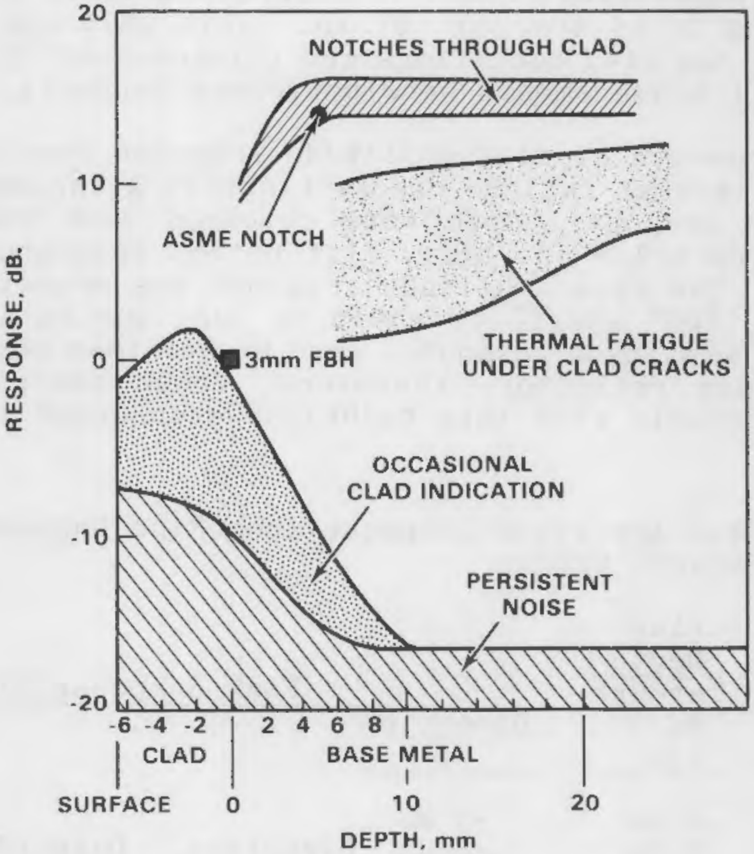


FIGURE 2. Flaw Response from Pressurizer Dropout.

The samples in Figures 2 through 4 each exhibit similar responses and good signal-to-noise ratios. Calibration gain was within ± 2 dB for each of the three samples. The signal-to-noise ratio for the ground single-wire clad of Figure 5 is slightly less, but satisfactory. An additional gain of 6 dB was required for calibration of the sample in Figure 5 over that used for the samples in Figures 2 through 4. An additional gain of 14 dB was required for calibration of the unground single-wire clad of Figure 6.

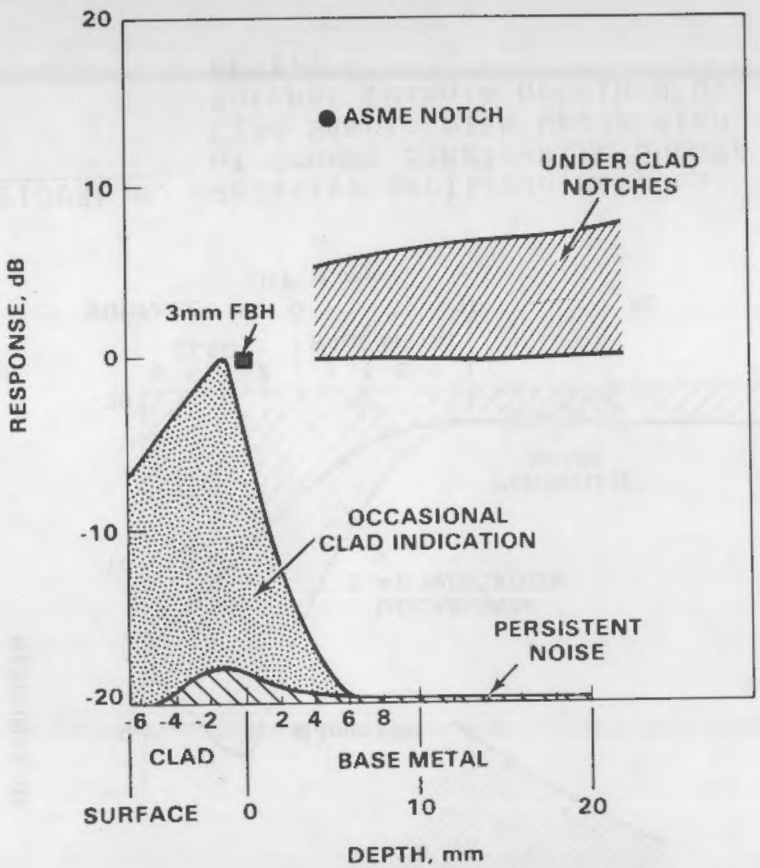


FIGURE 3. Relative Amplitude Response of Ground Strip Clad Sample with Under-clad Notches (sample provided by EPRI).

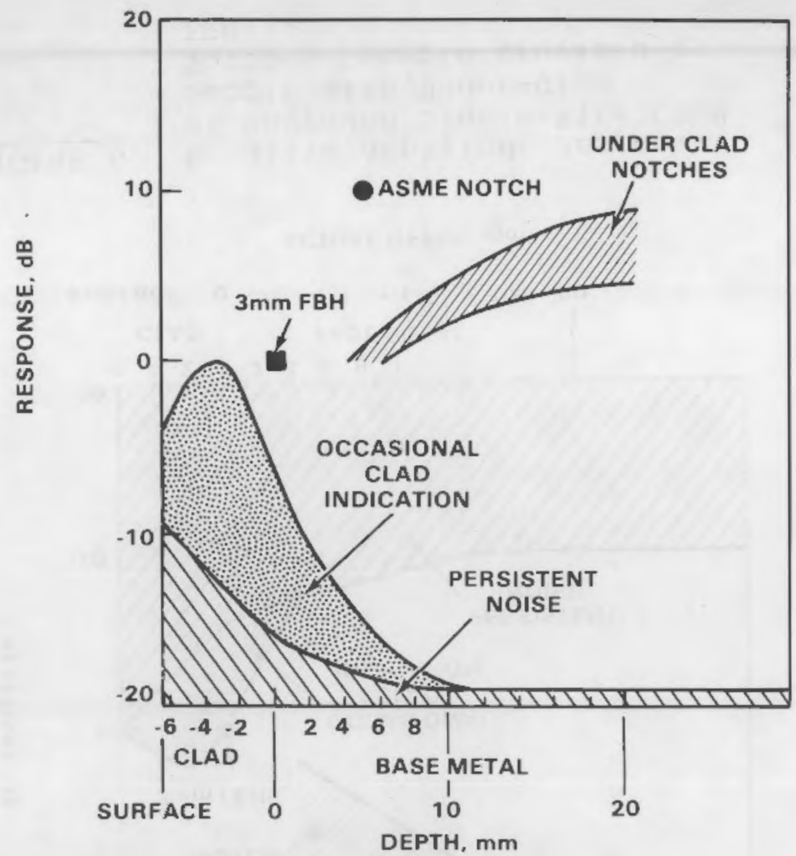


FIGURE 4. Relative Amplitude Response of Unground Strip Clad Sample with Under-clad Notches (sample provided by EPRI).

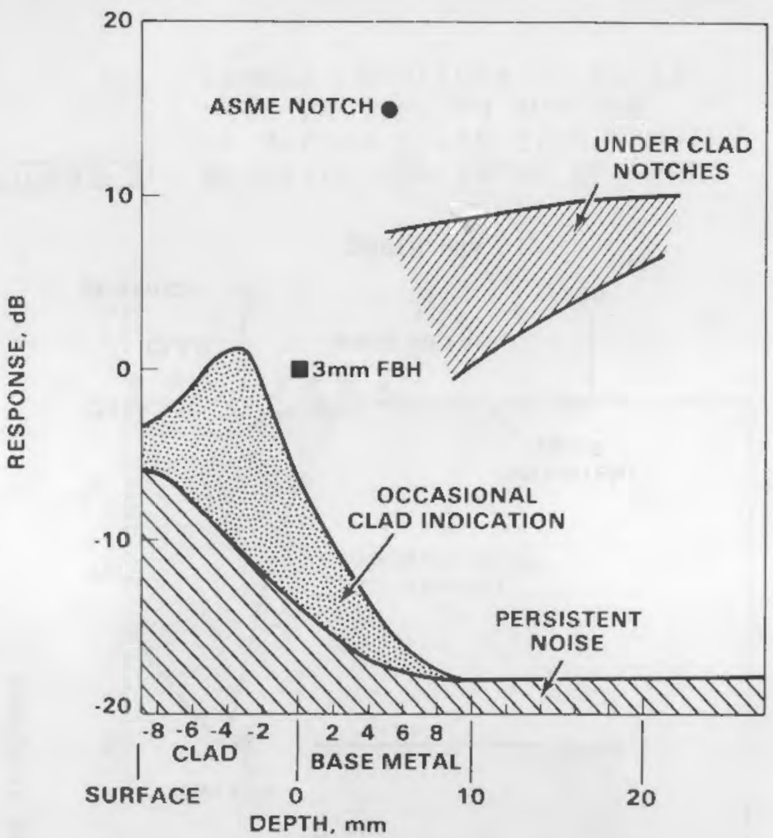


FIGURE 5. Relative Amplitude Response of Ground Single-Wire Subarc Clad Sample with Under-clad Notches (sample provided by EPRI).

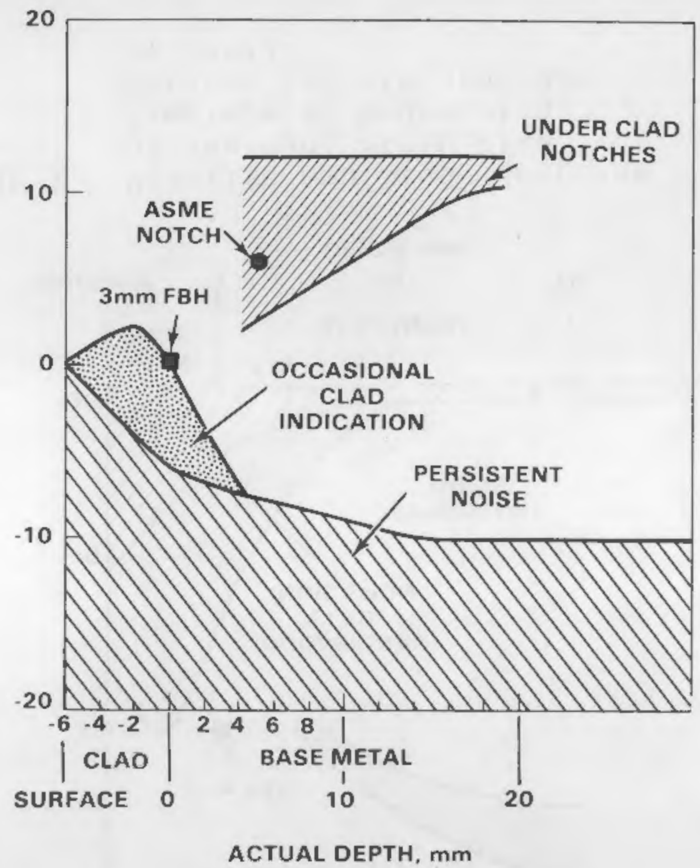


FIGURE 6. Relative Amplitude Response of Unground Single-Wire Clad Sample with Under-clad Notches (sample provided by EPRI).

The flaw detectability measurements just described show a marked dependance on surface condition (i.e., "as welded" versus ground). To provide an estimate of inspectability under noisy clad conditions, noise level measurements were made on manually clad test blocks.

The test blocks used for the noise level measurements are shown in Figure 7. Both blocks were clad using stainless steel, single-wire, manual metal arc welding and contain a 1/8 in. dia., flat-bottom hole. The block shown in Figure 7a was "as welded" and the block in Figure 7b was lightly hand ground.

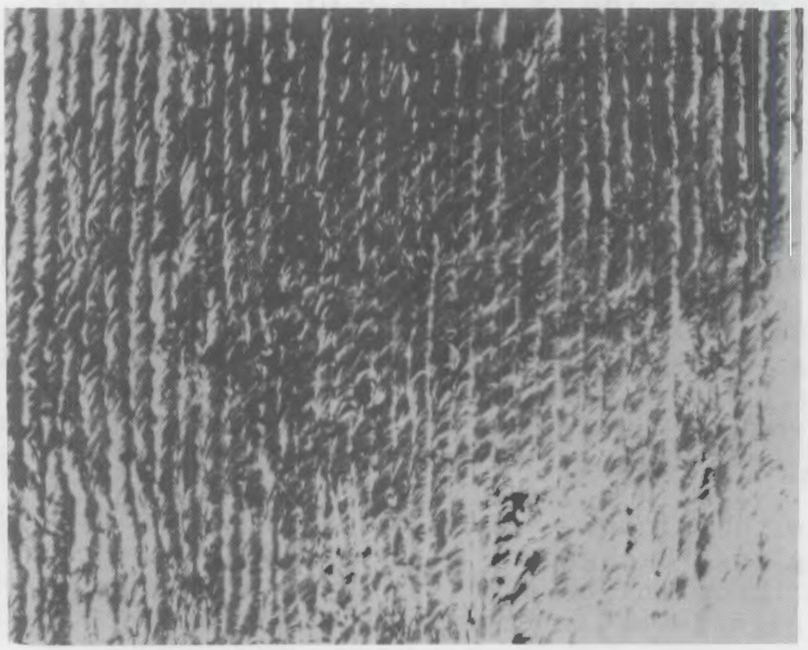
Noise level measurements were made on both samples by adjusting the response from a 1/8 in. dia., flat-bottom-hole to 80% of full screen height. A time exposure photograph was taken of background noise generated while scanning perpendicular to the clad in a defect-free area of the clad specimens.

This technique, while perhaps crude, provides a method for recording peak background noise. A measure of peak background noise is important because an operator must be able to differentiate signals of interest from inherent background noise.

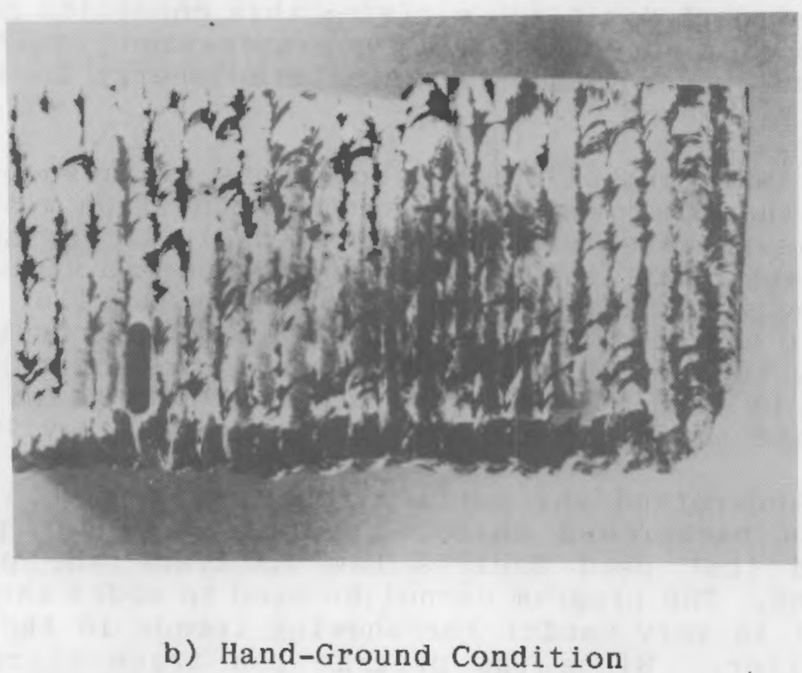
Figure 8 illustrates the results of ultrasound energy backscattered from two conditions of surface finish. Figure 8a shows large amounts of backscattered ultrasound energy resulting from a rough "as clad" surface; this condition makes signal interpretation very difficult for examination personnel. Light hand grinding can reduce backscattered energy 10 to 12 dB as shown in Figure 8b.

A measurement of surface roughness was also performed to quantify the "improvement" of surface condition with grinding. These measurements were taken using a linear variable differential transformer (LVDT) that was attached to a stylus and moved across the surface of the test block both parallel and perpendicular to the clad. Figures 9 and 10 show the results of these measurements. The change in surface roughness measurements from 0.012 in. RMS for the as-welded surface to 0.006 in. RMS for the hand-ground surface reduced backscattered energy 10 to 12 dB.

To understand why surface roughness has such a dramatic effect on background noise, a simple computer program was developed that used Snell's Law to trace the path of the ultrasound. The program cannot be used to model the ultrasound beam, but is very useful for showing trends in the ultrasonic beam scatter. Since the program can trace ultrasonic rays through an arbitrary surface condition, surface profile mea-

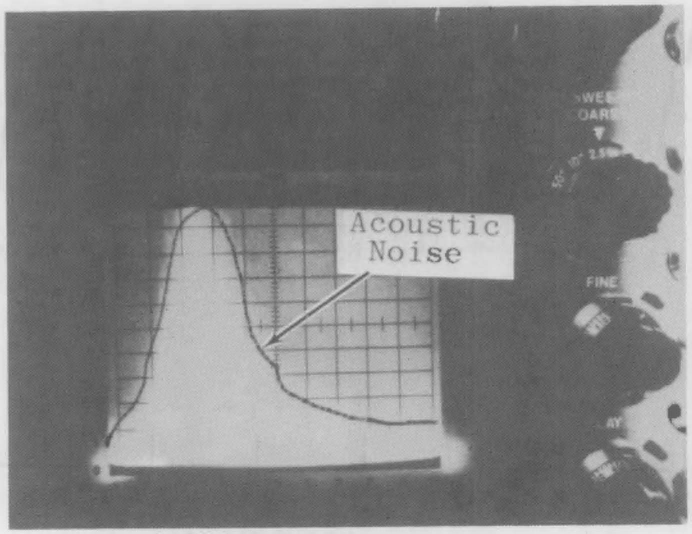


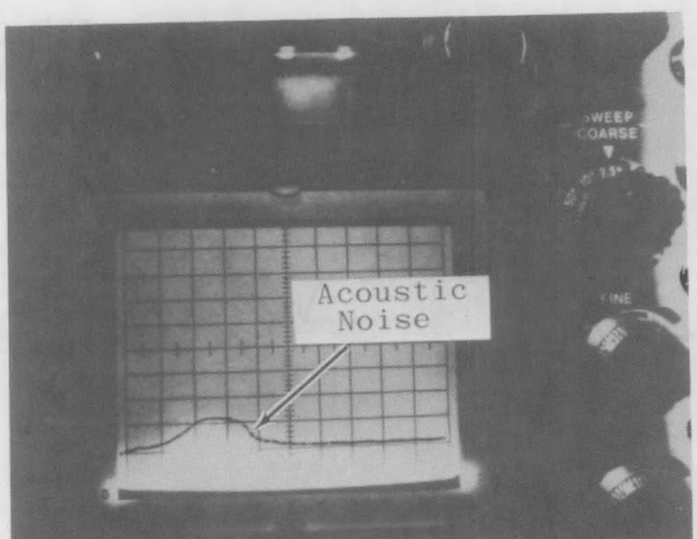
a) As-welded Condition



b) Hand-Ground Condition

FIGURE 7. Test Blocks for Background Noise.





Background Noise for Hand-Ground Condition

FIGURE 8. Background Noise Measurements.

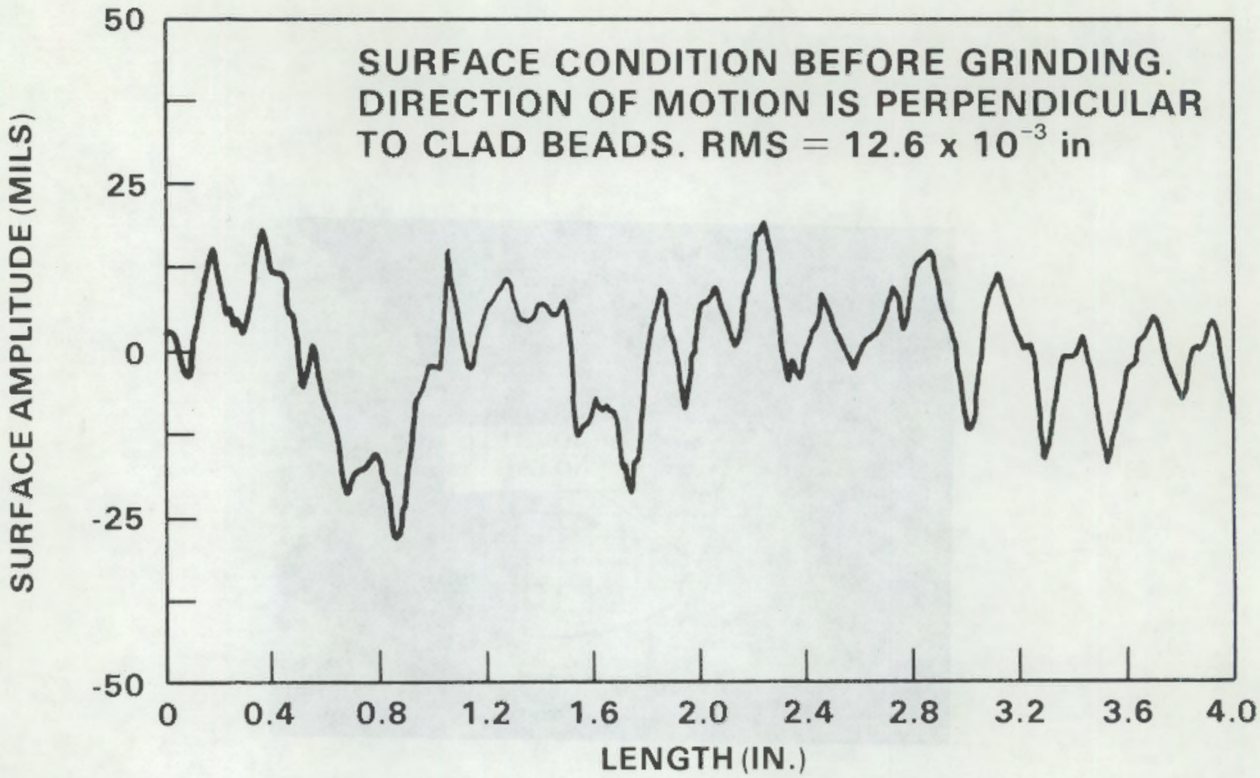


FIGURE 9. Surface Condition Before Grinding (Direction of motion is perpendicular to clad beads).

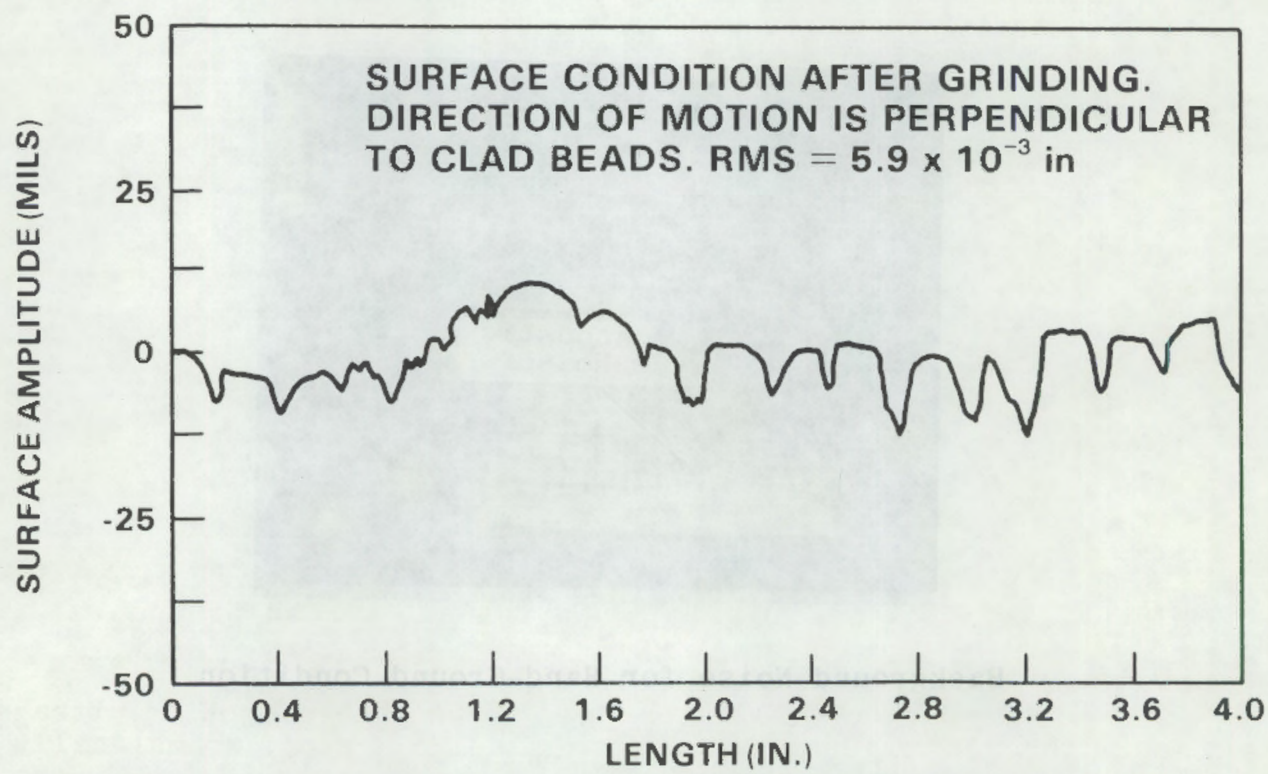


FIGURE 10. Surface Condition After Grinding (Direction of motion is perpendicular to clad beads).

surements of the "as-welded" condition and hand-ground surface were plotted to show the relative scatter of sound for each condition.

Figure 11 shows the scatter of ultrasound when penetrating an as-welded clad surface. Figure 12 shows the scatter of ultrasound when penetrating hand-ground surface.

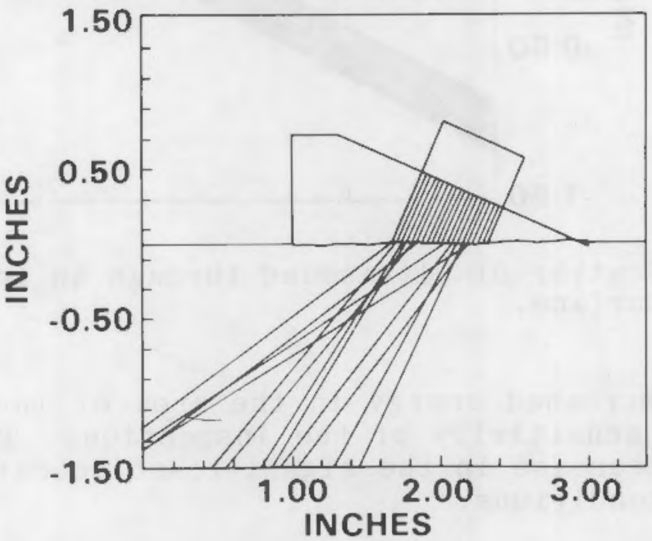


FIGURE 11. Scatter of Ultrasound through an Unground Clad Surface.

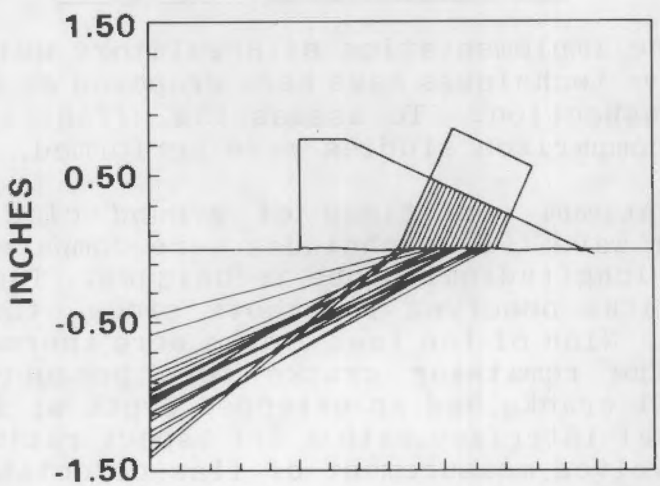


FIGURE 12. Scatter of Ultrasound through a Hand Ground Clad Surface.

For comparison, Figure 13 shows the penetration of ultrasound through an ideally smooth surface. The plots dramatically illustrate that the welded surface increases scatter of the ultrasound considerably. This scattering of the ultrasound

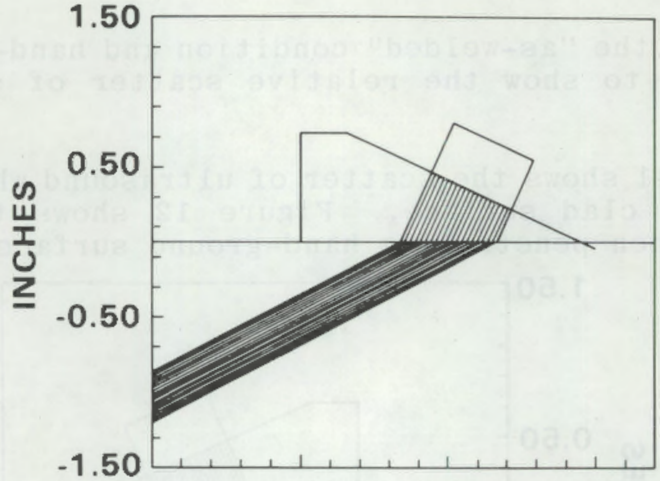


FIGURE 13. Scatter of Ultrasound through an Ideal (Smooth) Surface.

results in decreased energy in the area of interest, thereby reducing the sensitivity of the inspection. This would also explain the decrease in the signal-to-noise ratio for the as-welded clad conditions.

COMPARISON OF PULSE ECHO SHEAR WAVE AND DUAL ELEMENT TECHNIQUES

Since the implementation of Regulatory Guide 1.150, several shear wave techniques have been proposed or used for underclad crack inspection. To assess the effectiveness of these techniques, comparison studies were performed.

Under optimum conditions of ground clad, 60° and 70° contact shear wave (PE) techniques were compared with contact dual element longitudinal probe techniques. The test involved use of 12 cracks observed from both sides, thus allowing 24 observations. Nine of the test cracks were thermal fatigue type cracks and the remaining cracks were produced by hydrogen cracking. All cracks had an extended depth of 12 mm below the clad/base metal interface with a 3:1 aspect ratio. The comparison test involved measurement of flaw detectability and flaw amplitude response.

All techniques were calibrated using a 1/16 in. diameter side-drilled hole (SDH). The results of the comparison test are shown in Table 2 below.

TABLE 2. Crack Detection Performance

	70° Shear Single	60° Shear Single	45° Long. Dual	60° Long. Dual	70° Long. Dual
Number of Cracks Not Detected	7	6	0	0	0
Number of Cracks Detected	17	18	24	24	24
Average Amplitude of Detected Cracks (Relative to DAC)	-5.8 dB	-8.5 dB	-7.7 dB	+1.2 dB	+2.7 dB

Both shear wave pulse echo techniques not only failed to detect a quarter of the flaws, but provided very poor flaw amplitude response and signal-to-noise ratio. The dual element longitudinal wave techniques performed much better. The 45° dual element longitudinal techniques provided poor amplitude response; however, the improved signal-to-noise ratio allowed all flaws to be detected. The 70° dual element longitudinal technique proved to be the best performer. Using this technique, all flaws produced responses above the 1/16 in. SDH reference level.

UNDER-CLAD CRACK CHARACTERIZATION

Characterization of a crack after detection provides estimates of crack size (both length and depth) so appropriate engineering decisions can be made for crack disposition.

Crack sizing via the crack tip diffraction technique (see Figure 14) was investigated for underclad cracks. Ultrasound energy is reflected from both the face of the crack and diffracted from both the top and bottom tips. This sizing technique involves detecting ultrasound energy diffracted from the bottom of the crack tip. The 12 cracks used in the comparison test previously described were sized using crack tip diffraction with both 45° and 60° dual element probes. Crack depths (C_p) were calculated from sound path measurements using the formula

$$Cp = \cos(\theta) \times M_p.$$

where θ is the inspection angle and M_p is the sound metal path.

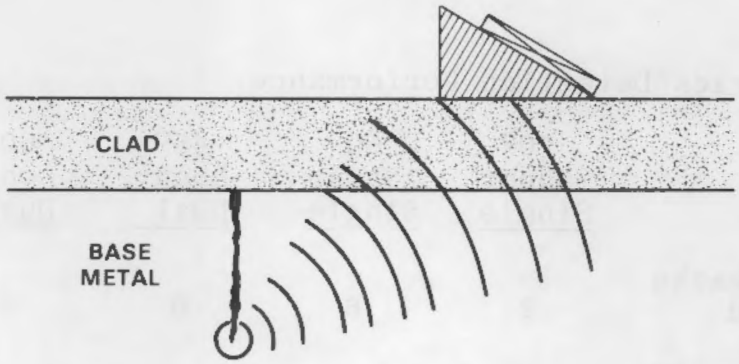


FIGURE 14. Crack Tip Diffraction Technique for Sizing Underclad Cracks.

In addition, under-clad nocthes of known depth were also sized. The results of the crack sizing experiments are shown in Table 3. The results of the notch sizing experiments.

TABLE 3. Crack Sizing Data for Matrix I Flaws.

Crack Description Type	Orientation	Depth Ave. (inches)	Sample Std Dev. S
45° Sizing			
Hydrogen cracking	∥	.673	.102
	⊥	.675	.035
Thermal fatigue through clad	∥	.768	.181
	⊥	.680	.073
Thermal fatigue	∥	.763	.060
	⊥	.765	.051
60° Sizing			
Hydrogen cracking	∥	.713	.180
	⊥	.723	.229
Thermal fatigue through clad	∥	.903	.167
	⊥	.690	.048
Thermal fatigue	∥	1.033	.311
	⊥	1.078	.139

The 60^{O} dual element probe provided very good correlation to theory for both cracks and notches when compared with actual defect size (Figure 15). The 45^{O} probe shows a good correlation between sound beam path measurements and defect size. However, the experimental results indicate the cladding is affecting the propagation path of the 45^{O} longitudinal wave for the notches resulting in consistently undersizing them as shown in Figure 16.

Wooldridge (1982) has shown that the grain structure of stainless steel cladding tends to act as a waveguide for 45^{O} shear. Since clad grains tend to be oriented normal to the ferritic base metal, this means that 45^{O} shear ultrasound propagates in the manner shown in Figure 17. If the propagation model that Wooldridge used for 45^{O} shear is applied to the 45^{O} longitudinal wave data, the mathematical model in Figure 17 can be applied. The results of this assumption are shown in Figure 18, which shows an excellent correlation.

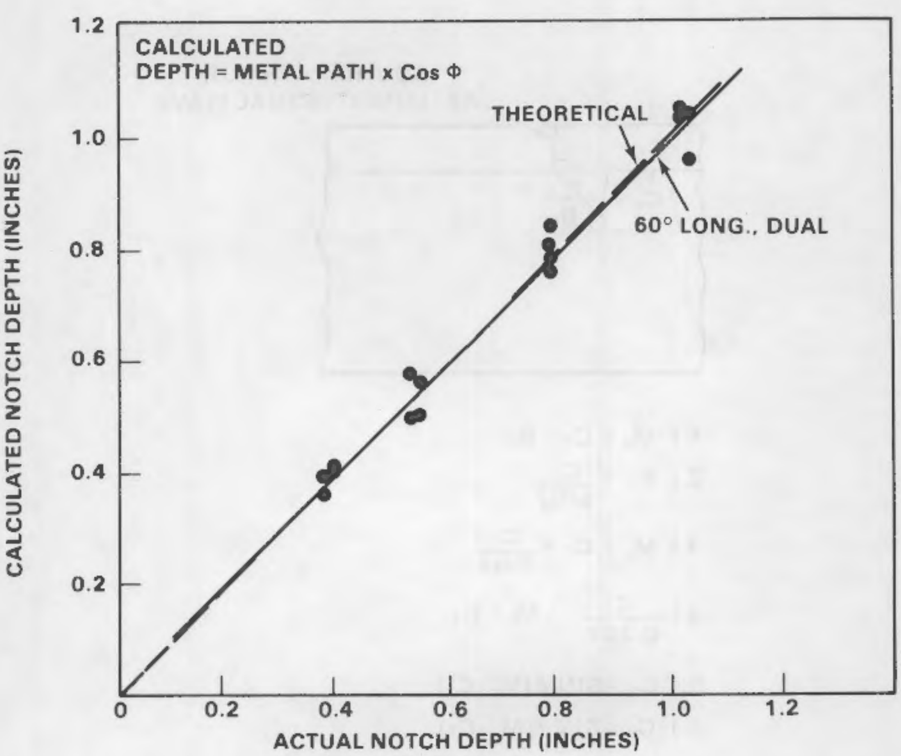


FIGURE 15. Experimental Sizing Data for 60^{O} Longitudinal Dual.

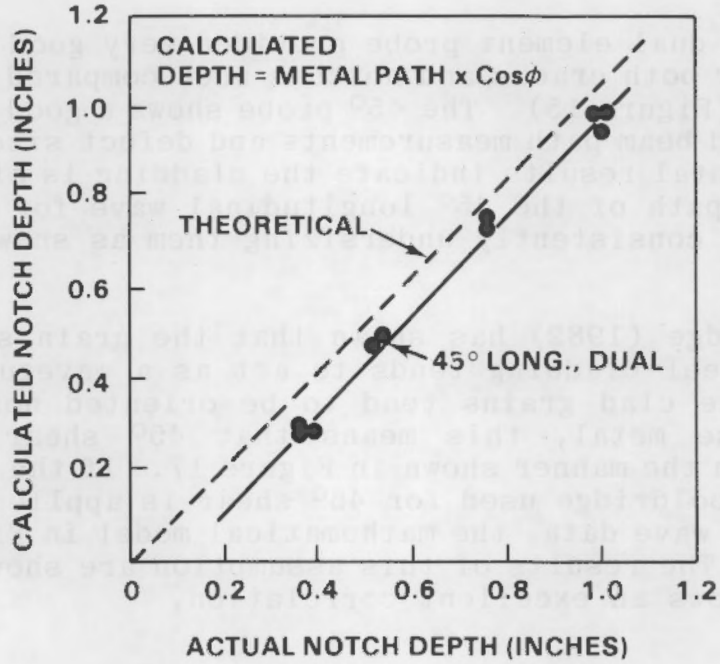
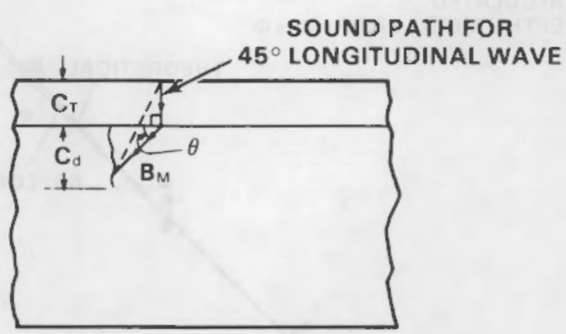


FIGURE 16. Experimental Sizing Data for 45^{O} Longitudinal Dual.



1.) $M_p = C_T + B_M$

2.) $B_M = \frac{C_d}{SIN\theta}$

3.) $M_p = C_T + \frac{C_d}{SIN\theta}$

4.) $\frac{C_d}{0.707} = M_p - C_T$

5.) $C_t = SIN\ \theta\ (M_p - C_T)$

6.) $C_d = SIN\ \theta(M_p - C_T)$

FIGURE 17. Sound Path through Clad Surface for Shear Waves.

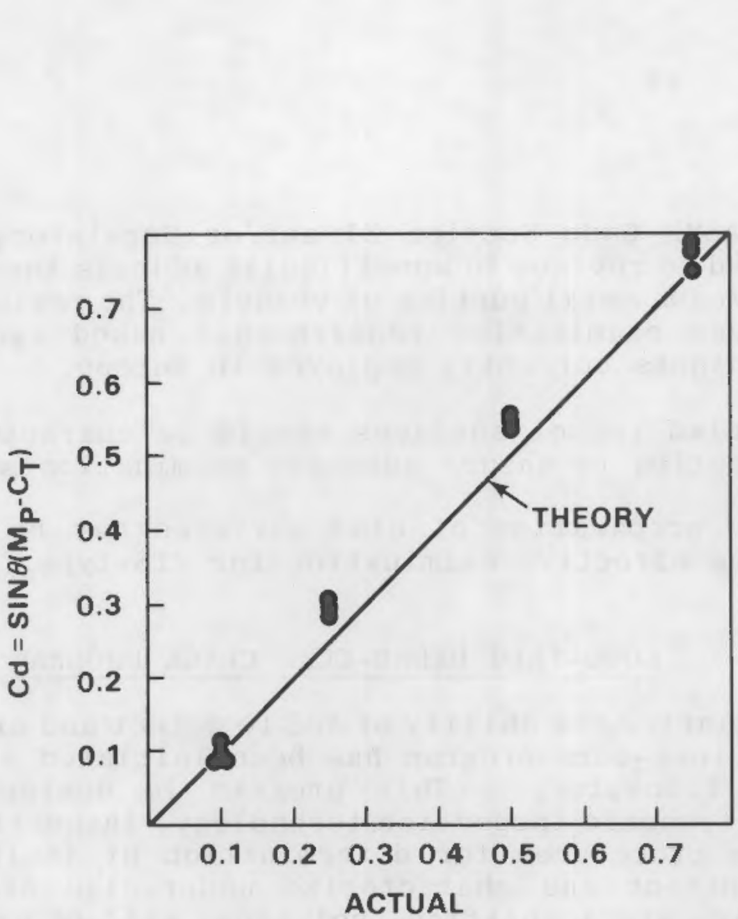


FIGURE 18. Correlation of Proposed Sound Path to Experimental Data (each axis has units in inches).

The experimentation performed is not intended to show that the modelling done for shear waves applies to longitudinal waves. Rather, it shows that stainless steel clad does affect the propagation path of longitudinal ultrasound in steel. Further work is planned to develop a model based on elastic constraints and grain orientation to explain our experimental data.

CONCLUSIONS

Based upon the work performed to date on the vessel application task, the following conclusions can be drawn:

- Few U.S. reactor vessels have been effectively examined for PTS-type flaws, based on comparison testing between U.S. standard practice and European techniques.

- For future inservice inspection of U.S. reactor pressure vessels, a 1/16 inch diameter side-drilled hole or 1/8 inch diameter flat bottom calibration reflector should be added to existing vessel calibration blocks for examination of the clad/base metal region.

- The ASME Code Section XI and/or Regulatory Guide 1.150 should be revised to specifically address inspection of the clad/base metal portion of vessels. The revision(s) should include examination requirements based upon inspection techniques currently employed in Europe.

- All clad vessel surfaces should be characterized before inspection to ensure adequate examination sensitivity.

- Minor preparation of clad surfaces may be necessary to ensure effective examination for PTS-type flaws.

LONG-TERM UNDER-CLAD CRACK PROGRAM

To quantify the ability of NDE to detect and size under-clad cracks, a long-term program has been initiated at the Pacific Northwest Laboratory. This program is designed to assess current ultrasonic inspection technology, inspection teams, and inspection procedures for determination of their adequacy to reliably detect and characterize under-clad cracks. Where inadequacies are identified, solutions will be evaluated. The solutions that resolve inadequacies will be recommended for inclusion into the appropriate pressure vessel inspection Codes.

The first task is to evaluate the under-clad crack fabrication techniques. Phase 1 contains the specimens with which six different cracking methods will be used to create the under-clad cracks. Ultrasonic measurements of Phase 1 will provide a comparison of the different cracking methods. Since no experience exists for under-clad cracks in American vessels, the most ultrasonically conservative cracking method will be used.

Phase 2 will be used to evaluate the effects of different clad types and roughness. This is extremely important so that the test sensitivity for a given inspection can be properly established. The clad roughness will be quantified in terms of a surface profile and backscattered noise. Inspection variables such as transducer frequency, size, and angle will be evaluated for the effects of clad conditions.

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To provide confidence in the integrity of a reactor during an over cooling transient, it is necessary for nondestructive evaluation to demonstrate high probabilities of detecting cracks located 6.0 mm deep and deeper at the pressure vessel clad surface. The cracks of interest may be parallel or perpendicular to the clad lay. Ultrasonic techniques developed and used in Europe are evaluated in this paper for their use on U.S. reactor pressure vessels. Flaw detectability experiments were carried out by testing the inspection technique's ability to detect artificial flaws under several types of clad, including some Manual Metal Arc (MMA) clad. Both ground and unground clad surfaces were evaluated.. Crack sizing tests of the inspection technique were made using a crack tip diffraction technique. The data reported here indicate that for sufficiently smooth clad surfaces, the 70° compressional wave technique is extremely effective for detecting under-clad cracks. In addition, results show that dramatic signal-to-noise improvements can be made by grinding the clad surface. Specifically, a reduction in noise level of 10 to 12 dB was achieved by improving the surface condition by a factor of two from 0.012 in. RMS to 0.006 in. RMS. This reduction in noise moves the crack detectability confidence level from low to very high.

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