ULTRASONIC TESTING FOR DETECTION OF IGSCC

by

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ABSTRACT

Beginning in the fall of 1974, numerous intergranular stress-corrosion cracks (IGSCC) have been found in the heat-affected zone (HAZ) of welded Type 304 stainless steel reactor piping. As a result of these findings, a 2-year program sponsored by EPRI was initiated at Argonne National Laboratory (ANL) in 1975 to help establish the adequacy of conventional ultrasonic-testing techniques for the detection of IGSCC. This paper discusses the quantitative data describing the effect of transducer parameter variations on ultrasonic echo amplitude from a variety of artificial and natural reflectors and gives suggestions for improvements in ultrasonic in-service testing methods, including the use of focussed probes. The effect of variation in ultrasonic attenuation between HAZ and base metal, the importance of adequate reference standards, and geometric effects are also discussed, and recent efforts at ANL and other institutions to improve ultrasonic detection of cracks are reviewed.

*Work supported by the Electric Power Research Institute and the U.S. Department of Energy.

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CONTENTS

Section 1

INTRODUCTION

The numerous problems associated with the in-service ultrasonic detection of intergranular stress-corrosion cracks (IGSCC) in nuclear reactor piping are well known: (a) Many geometrical reflectors are present; (b) the contour of the weld on the ID surface is unknown; (c) ultrasonic signals from the cracks are weak; (d) the weld crown interferes with transducer movement; (e) the working environment is poor (high temperature, humidity, and radiation levels); (f) pipe access is limited; (g) ultrasonic attenuation varies from one pipe region to another; (h) the weld metal produces ultrasonic "noise"; and (i) reference standards are unsatisfactory.

This paper describes an Argonne National Laboratory (ANL) program carried out in 1975 and 1976 under EPRI sponsorship to optimize the parameters associated with conventional ultrasonic in-service inspection techniques (1), discusses more recent ANL work on ultrasonic testing which may have possible applications to detection of IGSCC, and briefly reviews some work by others relating to ultrasonic detection of cracks in stainless steel.

Section 2

OPTIMIZATION OF CONVENTIONAL ULTRASONIC TESTING

In the EPRI-sponsored ANL program, conventional ultrasonic pulse-echo techniques for detecting IGSCC in 102-, 254-, and 660-mm Type 304 stainless steel Schedule 80 piping were evaluated. Ultrasonic transducers with varying frequency, size, and beam angle were tested; these included focussed, nonfocussed, and single- and dual-angle-beam transducers. In addition, curved and flat transducer wedges were compared. Artificial reflectors of varying size and orientation, in both welded and unwelded pipes, were examined to establish flaw-detection reliability and sensitivity of the transducers. Data were obtained from welded pipe sections with laboratory-grown and field-induced intergranular cracks. The probability of detection of small artificial reflectors in 102-mm pipes and small stress-corrosion cracks in 254-mm pipes was estimated for various transducers. Problems associated with spurious ultrasonic signals resulting from weld geometry were considered. The influence of attenuation by both the weld itself and the adjacent heat-affected zones (HAZ) was evaluated.

The results of the study indicated that no single conventional ultrasonic probe would optimally detect all the crack types (longitudinal, transverse, slanted, skewed) that might be expected in nuclear reactor piping. If a flaw of a specific size and orientation is sought, then some improvement can be made in detection capability. Some details of the program are discussed below.

WELD GEOMETRY

Machine preparation and grinding can result in spurious ultrasonic reflections at the pipe ID, severely limiting inspectability of the HAZ. Figure 2-1 shows coupons obtained from three azimuthal positions of a pipe-to-elbow section of 102-mm (4-in.) bypass piping. This pipe section was removed from service because of numerous ultrasonic indications. Sectioning of the pipe revealed no cracks; the signals, which varied in amplitude, were all from geometrical reflectors. This problem is not confined to bypass lines. Figure 2-2 shows a section of 660-mm (26-in.) piping, and signals obtained simultaneously from the root bead and land (step). A crack signal originating between the root and land would probably be obscured by the echoes from the geometrical reflectors. Inspectability could be improved by having the land in machine-prepared pipes at

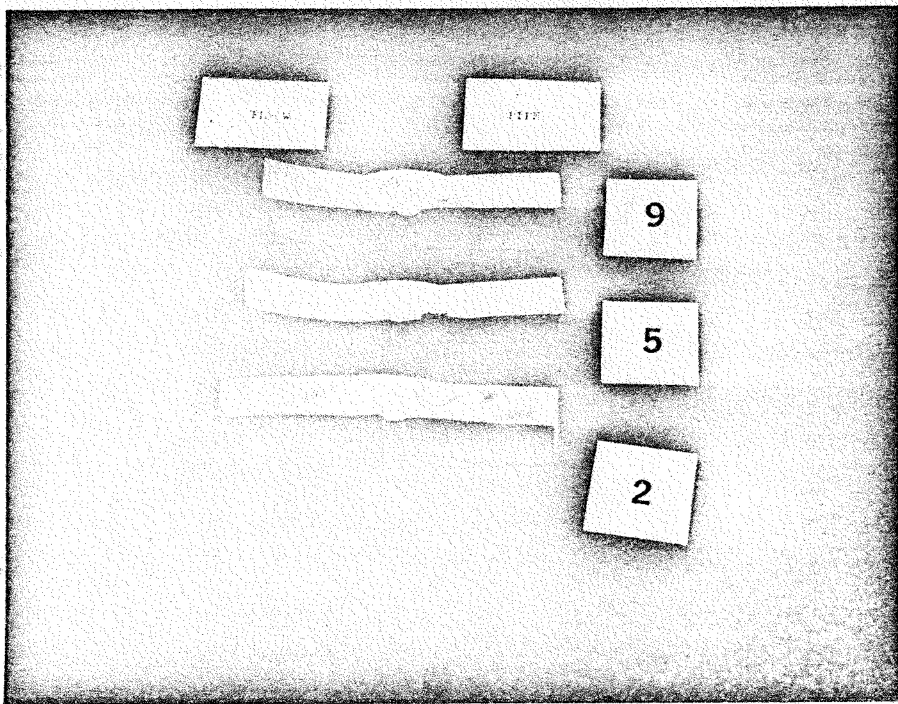

Figure 2-1. Photograph of Coupons Obtained from Sections of 102-mm Reactor Piping. As a result of polishing and etching, the weld metal is visible.

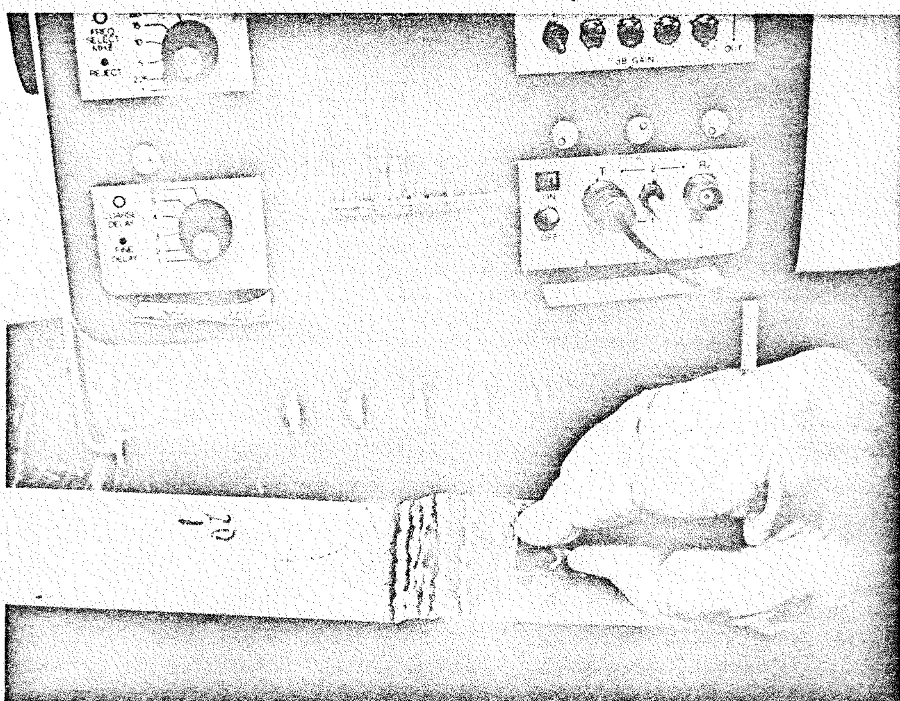

Figure 2-2. Ultrasonic Echoes from Both Root Bead and Land of 660-mm Pipe Section, Observed Simultaneously with a 13-mm 2.25-MHz Shear-wave Transducer and 45° Wedge.

least two wall thicknesses beyond the root bead. In addition, the weld crown can interfere with the motion of the transducer (particularly 13-mm probes), limiting detection of ultrasonic echoes from the region of the weld fusion line. Smoothed weld crowns would alleviate this problem.

ATTENUATION OF ULTRASONIC SIGNALS

Another inspection problem is the variability in ultrasonic attenuation among base metal, HAZ and weld metal. The magnitude of this variation is shown in Fig. 2-3 for a piece of 102-mm (4-in.) piping. A 2.25-MHz, 13-mm-dia transducer was used to detect identical 13 x 1.3-mm EDM notches in the HAZ and base metal. A variation of almost 10 dB between base metal and HAZ was noted, with a further loss of ∿ 10 dB as the signal passed through the weld metal. Careful calibration procedures employing actual field piping or very good mock-up samples will be required to compensate for this attenuation variation. Notches in a reference welded pipe section were found to be advantageous for setting the sweep position. EDM notches (0.5 to 1.0 mm deep) in the HAZ of mock-up pipes would be useful for setting up an in-service test. EDM notches at the weld fusion line can indicate potential difficulties in detection of cracks near that location.

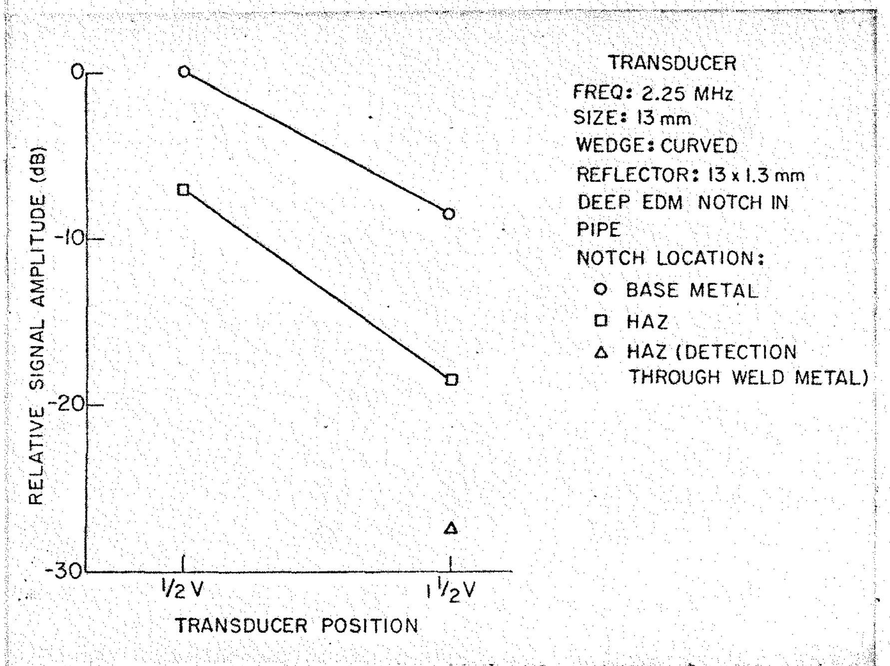

Figure 2-3. Signal Amplitudes from Identical Notches in HAZ and Base Metal.

USE OF FOCUSSED PROBES

The application of focussed probes to in-service ultrasonic testing could in principle improve the detection probability of IGSCC because of the narrower ultrasonic beam. This was found to be the case for small reflectors. Figure 2-4 shows plots of amplitude versus EDM notch depth for two transducers (one focussed, one not). The signal-to-noise ratio for an ultrasonic echo from a small notch using the focussed probe was more than double that with the unfocussed probe.

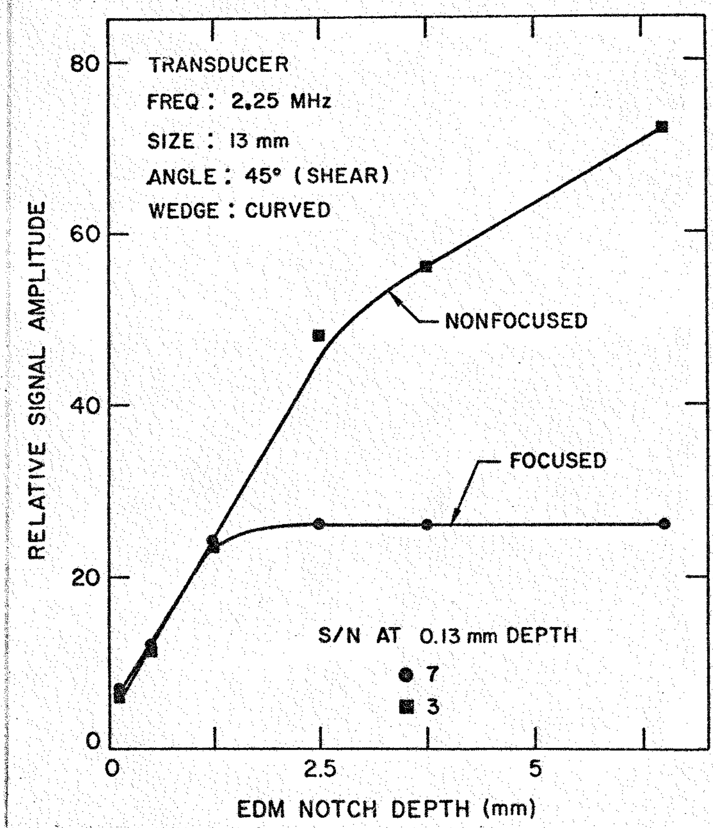

Figure 2-4. Relative Signal Amplitude vs EDM Notch Depth for Two Transducers.

The importance of a high signal-to-noise ratio is illustrated by results obtained on Dresden II pipe 10-24A. This pipe contained six short (< 25-mm-long) field-induced cracks which, on the basis of available data, were estimated to be 2.8-4.8 mm deep. The cracks were partially skewed relative to the pipe longitudinal axis. Because such cracks are difficult to detect, a comparison could be made of defect-detection probabilities with various ultrasonic probes. Four transducers were evaluated. The cracked area was scanned 10 times with each transducer, giving a maximum of 60 possible "detections" per transducer. The total time for each set of 10 scans varied from 30 to 35 min. Binomial distribution statistics were used to estimate the upper 95% confidence limit on the probability of missing one of the flaws in one scan of the pipe. The results are shown in Table 2-1. The data clearly show that the focussed transducer was superior for detecting these small flaws. These results are consistent with those obtained for 102-mm pipes with small artificial reflectors.

Table 2-1

PROBABILITIES THAT NONTHROUGHWALL STRESS-CORROSION CRACKS IN PIPE 10-24A WILL ESCAPE DETECTION ON A SINGLE PASS BY VARIOUS TRANSDUCERS[a]

Transducer Serial Number	Transducer Frequency, MHz	Size, mm	Type	Miss Probability	Upper 95% Confidence Limit
015957	2.25	6	unfocused	0.63	0.75
016443	2.25	13	unfocused	0.52	0.65
016506	2.25	13	focused	0.42	0.55
015956	1.0	13	unfocused	0.72	0.83

[a]All transducers are Aerotech miniature shear-wave probes with replaceable wedges. A Branson 303B pulser-receiver was used (serial number 507070). The beam angle was 45°, and flat wedges were employed. The probabilities are those obtained with a single transducer under a specific set of conditions and are not to be interpreted as absolute values for the cracks examined; only the relative effectiveness of the four probes is evaluated.

FREQUENCY SELECTION

The two major factors which determine the optimum frequency for inspecting stainless steel piping are diffraction (spreading) of the ultrasonic beam and scattering from the grain boundaries. In the present case, the apparent attention α can be expressed as

$$\alpha = \alpha_D + \alpha_S ,$$

where α_D is the loss due to diffraction and α_S is the loss due to grain-boundary (Rayleigh) scattering. For this scattering, $\lambda >> D$ where λ is ultrasonic wavelength and D is grain size. For a transducer of radius a generating longitudinal waves, α_D is about 1 dB for each a^2/λ (2). The Rayleigh scattering term for this case is

$$\alpha_S \propto f^4$$

where f = frequency. Figure 2-5 shows conceptually how these factors combine to form a minimum in the log-log plot of apparent attenuation versus frequency. The result is that the system behaves as if it were a "band-pass filter". Although this effect is observed primarily for longitudinal waves, a phenomenon that is at least qualitatively similar (that is, a minimum in apparent attenuation versus frequency) should occur for shear waves. In the ANL study, tests on stainless steel with 1-, 2.25- and 5-MHz, 13-mm-dia transducers showed empirically that a frequency of ∿ 2.25 MHz gave minimum attenuation. In another study with 13-mm-dia transducers, in which more frequencies were tested, the best frequency was found to be 1.8 MHz (3). Note, however, that a smaller transducer would shift the minimum attenuation to a higher frequency, and a larger one would shift it to a lower frequency.

USE OF DUAL- VERSUS SINGLE-ELEMENT PROBES

In the ANL study, a dual-element 2.25-MHz Panametrics transducer was compared with several single-element probes. The only advantage noted for the dual-element probe was in detection of skewed reflectors. Recently, a more compact dual-element transducer (made by Search Unit Systems) has been made available commercially. Preliminary results indicate that for small artificial reflectors, the single-element focussed probe has a greater signal-to-noise ratio than the Search Unit Systems dual-element probe. In Ref. 4, single-element probes are found to be superior to dual-element ones whereas in Ref. 5, the opposite was found. A more controlled study is necessary to resolve these discrepancies.

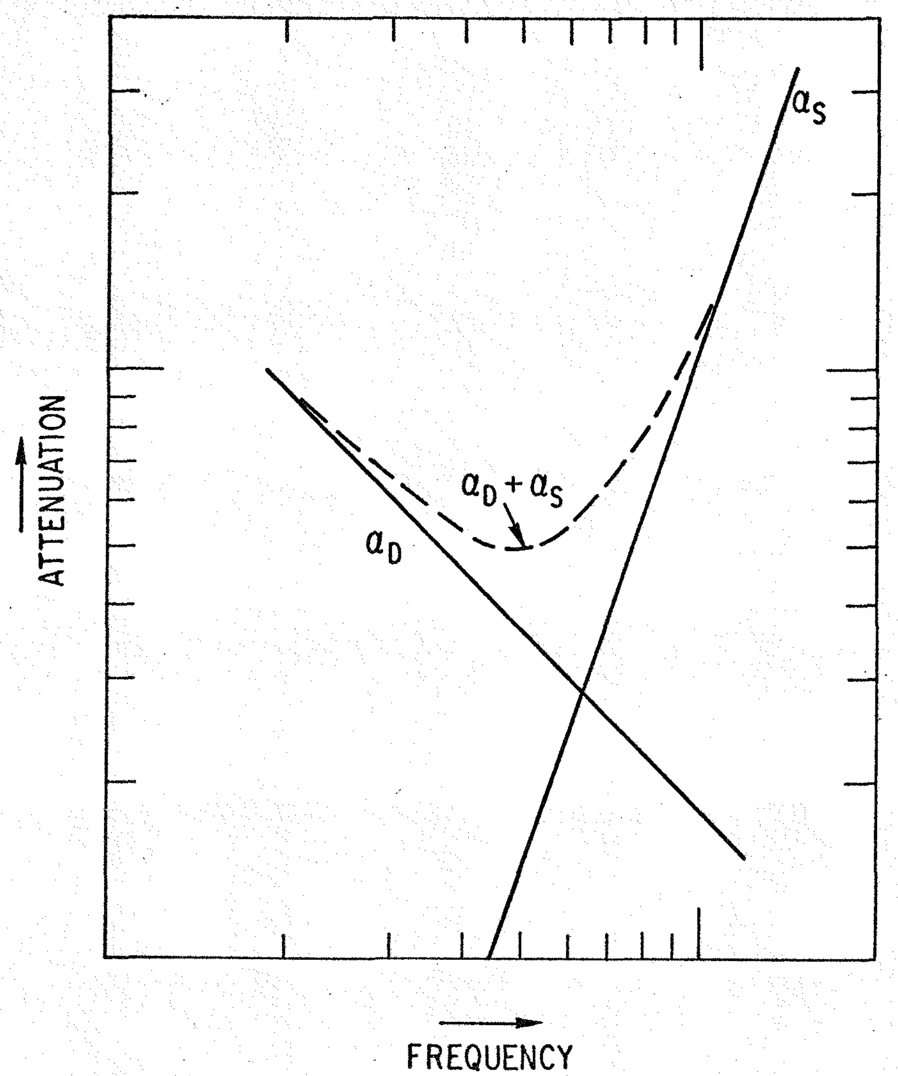

Figure 2-5. Attenuation vs. Frequency Resulting from Beam Spreading and Rayleigh Scattering.

Section 3

HORIZONTALLY POLARIZED SHEAR-WAVE TESTING

Conventional shear-wave testing, in which longitudinal waves are mode converted to shear, generates vertically polarized (SV) shear waves, with particle motion in the plane formed by the incident and reflected beams. Horizontally polarized (SH) shear waves, with particle motion perpendicular to the plane formed by the incident and reflected beams, would be preferable for ultrasonic inspection of piping.for these two reasons:

1. Spurious signals are reduced, since SH waves cannot be mode converted to longitudinal waves at the pipe inner wall, whereas SV waves can.

2. 45° SH waves can penetrate stainless steel weld metal better than 45° SV waves, because of the anisotropic nature of the weld. Thus, defects in the HAZ could be detected from the opposite side of the weld with SH waves.

Generating SH waves, however, is difficult because normal-incidence shear waves must be employed (requiring a very viscous couplant). The use of electromagnetic acoustic transducers (EMATs), which are noncontacting, may eventually alleviate this problem. Although the practical application of EMATs for routine reactor inspection is years away, they are currently being tested in Germany for stainless steel inspection (6).

Even without the use of EMATs, the practical advantages of SH waves can be seen for detecting a crack in a welded tensile specimen. A 1-cm-thick x 7.5-cm-wide specimen with a laboratory-grown crack (∿ 25%-throughwall, ∿ 2-cm-long) in the weld metal was provided by Hanford Engineering Development Laboratory. SH waves were produced with Panametrics normal-incidence 13-mm-dia shear-wave probes, placed on stainless steel wedges to generate 45° beams in the sample. The weld was scanned in a pitch-catch mode at 2.25 MHz. Both probes were on the same side of the weld with an ∿ 90° included angle. The rf signals obtained by passing the pitch-catch pair across the weld are more clearly evident with horizontally than with vertically polarized shear waves.

The ability of SH waves to penetrate stainless steel weld metal at 45° better than SV waves is demonstrated in Fig. 3-1. The transducers and sample are shown in Fig. 3-2. As the transducer pair was moved away from the hole in the weld metal, the signals diminished (Fig. 3-1b, bottom trace). No spurious signals from metallurgical reflectors, comparable in magnitude to that obtained from the side-drilled hole, were evident at any signal strength. The advantage of the SH shear waves is clearly evident when the above results are compared with those obtained from conventional shear-wave transducers. Two 45°, 2.25 MHz, 13-mm-dia Aerotech shear-wave transducers were used in the pitch-catch mode to detect the side-drilled hole at the center of the weld. No signal from the hole was detected.

(a)

(b)

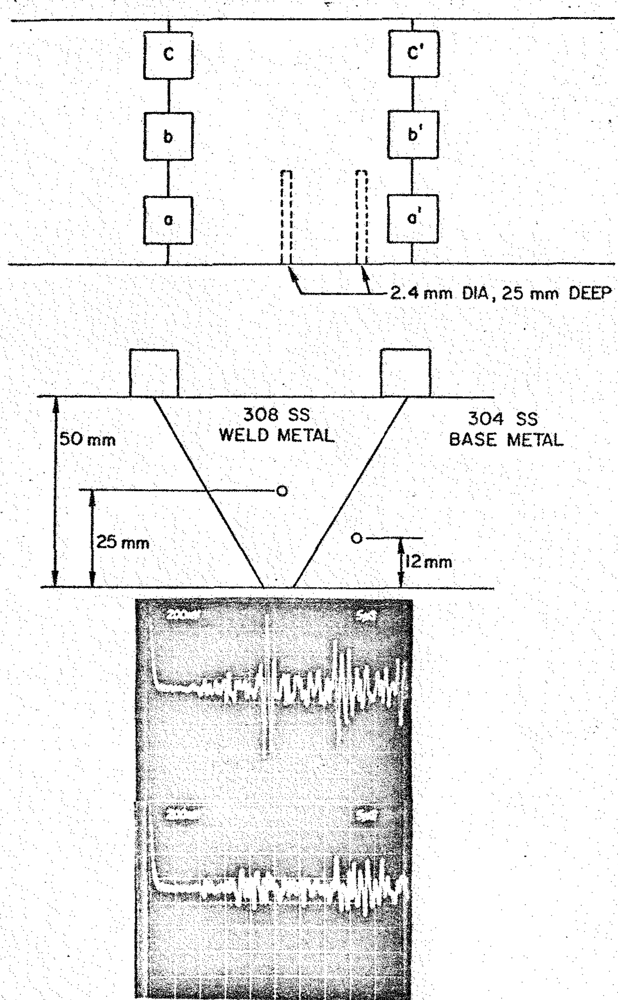

Figure 3-1. (a) Schematic Drawing of Experimental Setup for Detection of Side-drilled Holes in Stainless Steel Weld Metal. Ultrasonic data (shear waves, pitch-catch mode) were taken with the transducer pair at a/a', b/b' and c/c'. (b) RF Signals Generated with Transducers at a/a' (Upper Trace) and c/c' (Lower Trace).

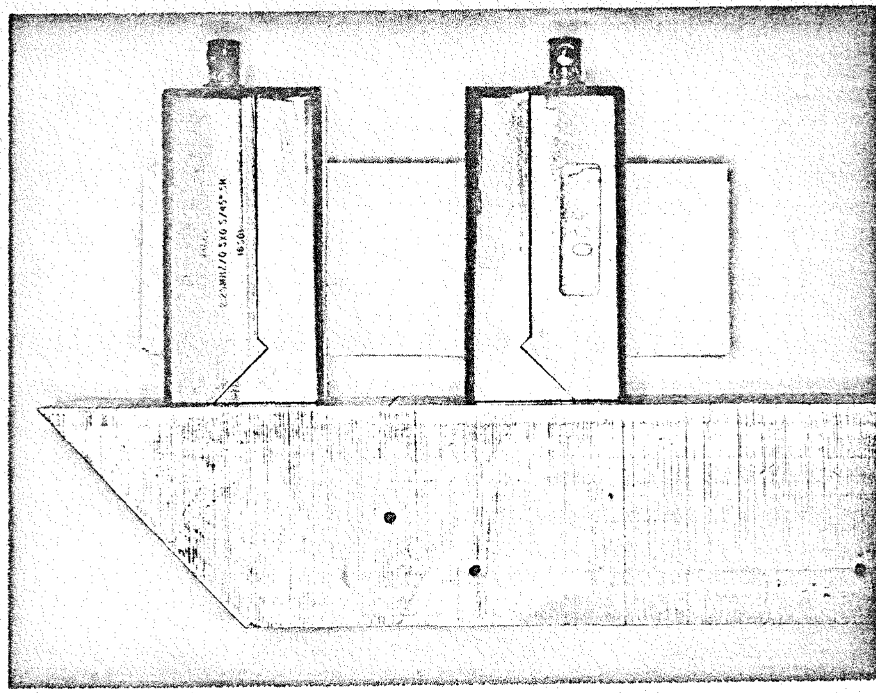

Figure 3-2. Photograph of Setup Shown in Fig. 3-1a.

Section 4

SPATIAL AVERAGING

Another technique that has potential application to the improved detection of IGSCC is spatial averaging. The problem in inspecting stainless steel, particularly around welds, often reduces to one of extracting the flaw signal from the noise signals. This problem is often related less to electronic noise than to coherent noise; that is, scattering from grain boundaries, rough surfaces or weld-metal interfaces. A signal-averaging method is demonstrated here for flat surfaces where the defect (crack or notch) is in the weld metal. The technique can also be applied to curved surfaces, and is expected to improve detection of cracks in the HAZ and increase the effectiveness of through-the-weld inspections by averaging out weld-metal noise.

A weld scanner, shown schematically in Figure 4-1, has been designed and built at ANL to demonstrate the advantages of spatial averaging. Water is used as a couplant. Two transducers (T and R in Fig. 4-1) are operated in a pitch-catch mode to generate 45° ultrasonic waves in stainless steel samples. The projection of the pitch-catch included angle θ to a horizontal plane is varied between 60 and 90° steps of $\sim$ 3°, and the receiving signal is averaged over several transducer positions. Each step incorporates a pause, during which the ultrasonic trace or "A-scan" is digitized by a transient recorder and stored in the memory of a Data General Corporation 2/10 minicomputer. The average of digitized traces from up to ten angular positions of the beams is printed out after the scan for a particular point in the sample is completed. As a result, one obtains a series of averaged A-scans and their overall average as the weld scanner moves across the specimen.

Several specimens have been inspected with this device. In the example presented here (shown schematically in Figure 4-2), the weld scanner was used to examine a flat weld by means of refracted longitudinal waves (45° beam). Figure 4-3 shows three individual traces and the computer average of ten such traces (corresponding to ten values of θ). The transducer was positioned so that $\sim$ 45° longitudinal waves were propagated in the weld metal. The averaged trace unambiguously shows the reflected longitudinal and shear wave and the shear wave mode converted from a longitudinal wave in the EDM-notch plane. These signals are not as evident in the individual traces. The water-metal interface is seen as the first large peak.

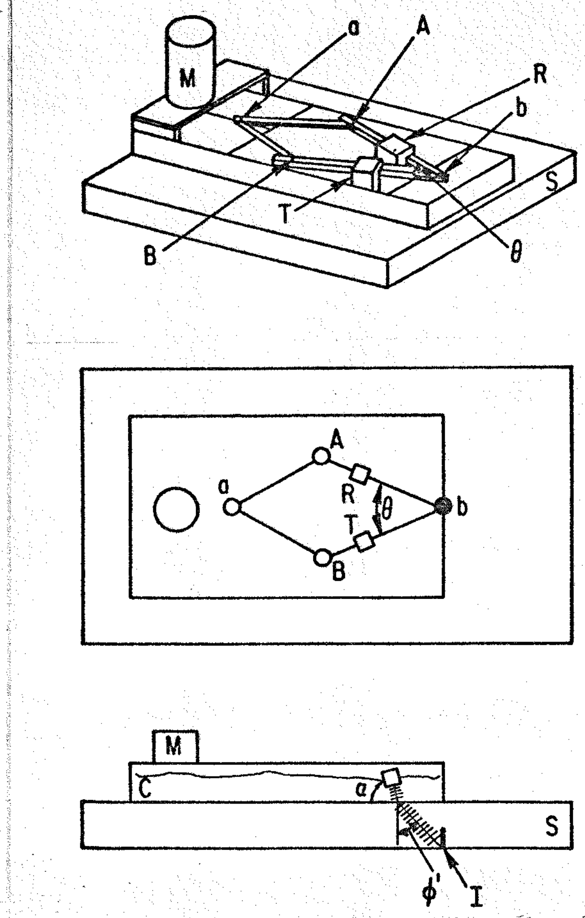

Figure 4-1. Schematic Representation of Weld Scanner. M = motor, C = couplant, S = sample, I = point of intersection of ultrasonic beams, α = incident angle in water, θ = scan angle, b = fixed pivot point, R = receiving transducer, T = transmitting transducer, and ϕ' = angle of refraction in the sample.

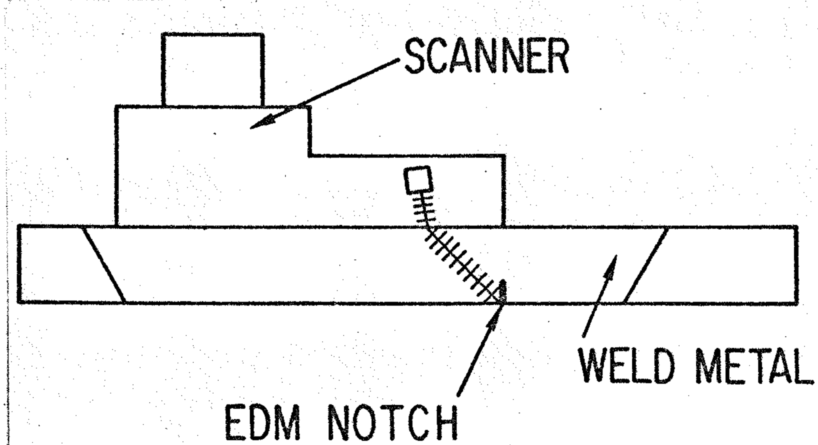

Figure 4-2. Arrangement of Scanner and Specimen for Detection of Weld-metal Notch. The scanner generated 45° longitudinal waves in the weld metal.

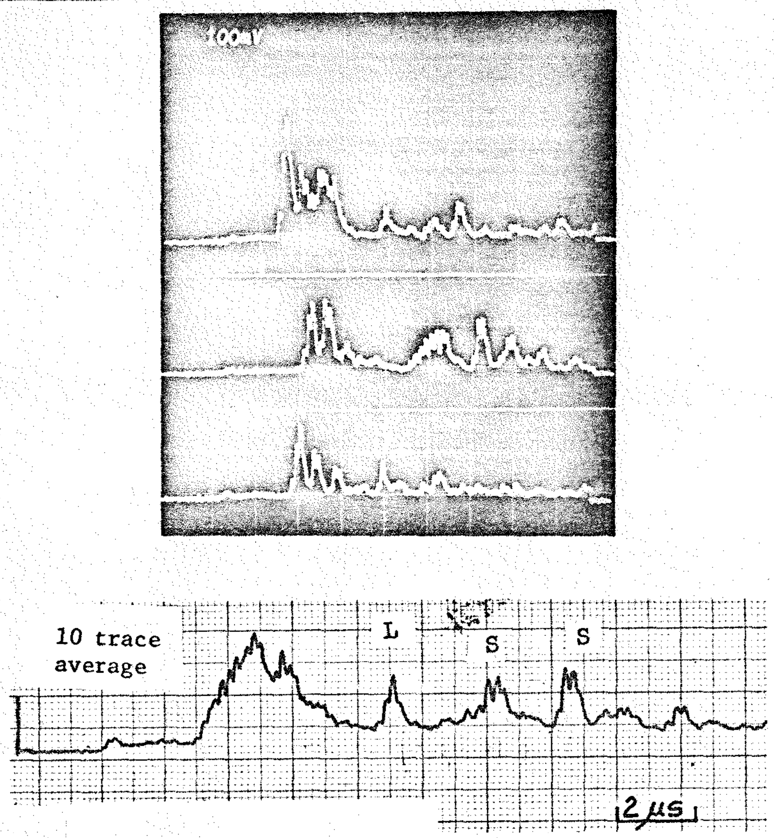

Figure 4-3. Three Individual Traces and Computer Average of 10 Traces from Improved Notch-detection System Shown in Figure 4-2. Refracted longitudinal (L) and two shear (S) waves can be seen.

With the scanner away from the notch but still over the weld metal, the averaged trace does not show the presence of a reflector. The present study demonstrates that coherent ultrasonic noise can be averaged so as to significantly enhance the signal-to-noise ratio for flaws in stainless steel weld metal. Increases of up to 20 dB over the ratios obtained with conventional ultrasonic techniques have been observed.

Another demonstration of the enhancement of signal-to-noise ratios is provided by the simplified system shown in Figure 4-4. Here, an Aerotech miniature shear-wave transducer (6 mm, 2.25-MHz, 45° beam) was moved parallel to the plane of a crack (2 cm long and up to 2 mm deep) in a stainless steel tensile specimen. A Sonic Mark I pulser-receiver with video output was used. The smoothing of the rf traces can often enhance the ability to detect flaws with the signal-averaging process. In this example, the transducer was displaced parallel to the crack plane in 3-mm steps. During this motion, 10 video traces, covering a total transducer displacement of 27 mm, were averaged to obtain the final A-scan.

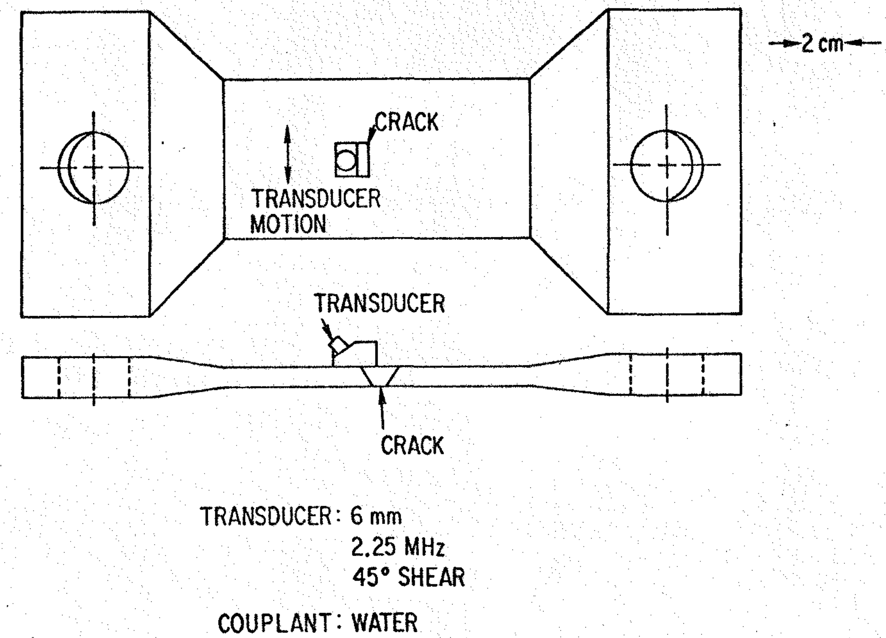

Figure 4-4. Sample and Transducer (2.25-MHz, 45° Shear Beam) Arrangement for Signal Averaging to Enhance Signal to Spatial Noise Ratio for Crack Detection.

Figure 4-5 shows a typical averaged trace and five of the data sets in that average. The peak is the crack signal. If the transducer is moved to a position ahead of the crack so that the beam still passes partially through the weld metal but does not impinge on the crack, the signal average should show a reduced noise level. Figure 4-6 shows an average of 10 traces with less background noise than in the individual traces.

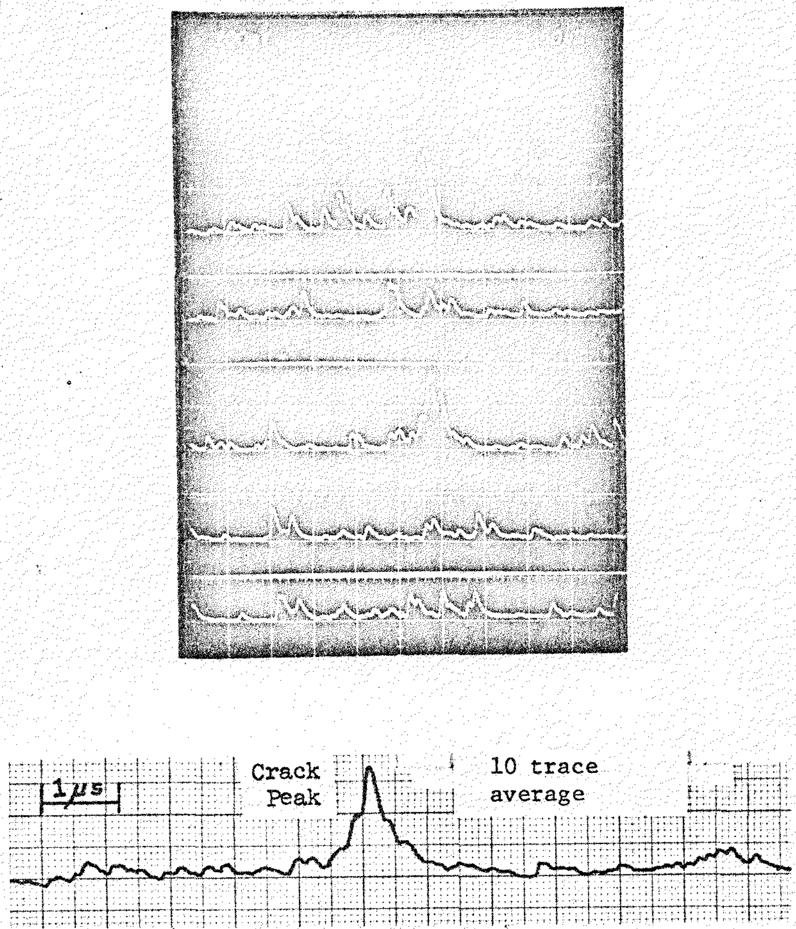

Figure 4-5. Five Oscilloscope Traces and Computer Average of Ten Traces from System Shown in Figure 4-1, with Beam Reflecting off Crack Plane.

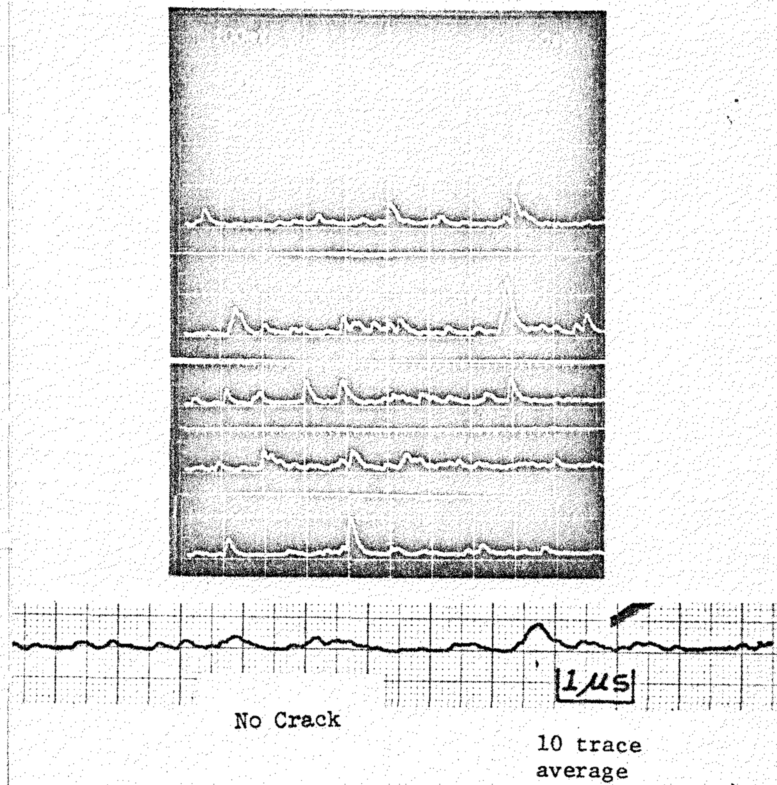

Figure 4-6. Five Oscilloscope Traces and Computer Average for System Shown in Figure 4-1, with Beam Not Reflecting off Crack Plane.

Section 5

OTHER WORK

Other ultrasonic techniques under development for inspection of stainless steel reactor components include synthetic aperture focussing (7) (SAFT), adaptive learning networks (ALN) (8), and phased arrays (9).

SAFT is based on the nonlinear phase shift response of a target as it is scanned. The use of this phase shift allows the lateral position of the target to be determined accurately, and thus results in a finer lateral resolution than can be obtained by using the physical beam width alone. SAFT may improve spatial resolution and thus flaw characterization. It does not necessarily provide a means for separating geometrical and metallurgical reflectors from crack signals. In addition, a means for obtaining the information rapidly will have to be fully developed before this technique is ready for field testing.

In the ALN method, an attempt is made to discriminate between IGSCC signals and spurious ones without relying on the skill of the operator. In this computer-assisted technique, a set of signal characteristics that can be calculated from the ultrasonic data is used to separate geometrical reflectors from cracks. The main advantage of the technique is that it does not rely on signal-amplitude information to carry out the analysis. Use of the ALN technique under actual field conditions will ultimately establish its viability.

With phase arrays, ultrasonic beams can be directed electronically at different angles in the material to be inspected. This arises from the sequential triggering of a large number of transducer elements. This type of probe configuration could lead to increased versatility in pipe inspections.

A reference set of pipe sections with field-induced IGSCC is clearly needed so that new techniques can be tested and procedures established for routine in-service inspection. Better characterization of the microstructure of reactor components and its effect on ultrasonic inspection results is also needed. In addition, improved calibration methods and setup procedures may be necessary.

Section 6

SUMMARY

This paper has discussed work carried out at Argonne National Laboratory on the optimization of parameters for detection of IGSCC by conventional ultrasonic means, possible advantages and difficulties of employing horizontally rather than vertically polarized shear waves for ultrasonic testing, and the potential use of spatial-averaging techniques for improving signal to coherent noise ratios in ultrasonic testing. The results of the parameter optimization study suggest that (a) no single probe is adequate to detect all the types of cracks that are found in reactor piping, (b) the use of single-element focussed probes may improve the probability of detecting very small IGSCC, (c) dual-element probes are not necessarily better than single-element probes, at least for detecting artificial reflectors (except possibly for skewed ones), and (d) the variation in attenuation due to microstructural differences between HAZ and base metal necessitates the use of special reference pipes (including pipes with welds and possibly IGSCC) for effective interpretation of ultrasonic signals. The studies on horizontally polarized shear waves indicate that research and development work with electromagnetic acoustic transducers for application to stainless steel components should be significantly increased, as it may ultimately allow reactor components to be inspected conveniently with 45° SH waves. These waves have been shown to be more effective for inspecting stainless steel welds than the conventionally used 45° SH waves.

Spatial averaging has been shown to be potentially useful in reducing spurious ultrasonic signals during testing of stainless steel welds by averaging out coherent ultrasonic noise.

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