Improved Ultrasonic Inspection Method for Stainless Steel Piping

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Research Project 892

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NOTICE

FOREWORD

The reliability of nuclear power plant ultrasonic inspection (UT) may be improved by many methods, including personnel training, automation, and equipment improvement. This document is a compendium of reports on EPRI-sponsored UT development to improve the equipment available for detecting intergranular stress corrosion cracking (IGSCC) in nuclear plant stainless steel piping. An advanced transducer optimized for detection of IGSCC near circumferential pipe butt welds was developed and has gained wide acceptance in nuclear plant inspection throughout the world.

This document, prepared for those concerned with such inspection, summarizes the history, development and evaluation testing of this UT equipment. Transducer specifications for normally expected plant pipe sizes and a theoretical analysis that should aid in adapting the transducer to alternate applications are included.

The document consists of a brief assessment of the IGSCC incidents followed by a summary of the overall EPRI UT reliability improvement program and abstracts of contractor-prepared design and evaluation reports. The complete reports are provided as appendixes.

The results of this work suggest that a substantial detection reliability increase can be expected from proper equipment design. This point is perhaps most dramatically illustrated by comparison testing on a flawed specimen removed from a foreign reactor. IGSCC not readily detected by conventional, high frequency transducers was readily observed using the optimized unit. The comparison is of particular significance in that the field experience with the reactor in question has been responsible for substantial concern over UT detection adequacy.

The works reported herein derive from EPRI Research Project 892. The contractual organizations responsible for major contributions include: Southwest Research Institute, General Electric Nuclear Energy Division, Battelle Columbus Laboratories, and Drexel University.

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ABSTRACT

This report, prepared for those concerned with in-service inspection on nuclear plant piping, presents a summary of work conducted under EPRI Research Project 892 to improve the reliability of IGSCC detection by ultrasonic techniques.

The document consists of a brief assessment of the IGSCC incidents followed by a summary of the overall EPRI UT reliability improvement program and abstracts of contractor-prepared design and evaluation reports. The complete reports are provided as appendixes.

The transducer which resulted from this work has gained wide acceptance in nuclear plant inspection throughout the world.

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IMPROVED ULTRASONIC INSPECTION METHODS FOR STAINLESS STEEL PIPING

1.0 BACKGROUND AND INTRODUCTION

An ultrasonic (UT) transducer developed under EPRI sponsorship is now widely used in nuclear plants for inspection of austenitic, stainless steel piping. This report provides a summary of the history, development and evaluation of this transducer for interested users.

1.1 OPERATING PLANT EXPERIENCE

The identification of intergranular stress corrosion cracking (IGSCC) in bypass and emergency core cooling subsystem piping of boiling water reactors (BWRs) prior to 1974 and in early 1975 resulted in considerable emphasis on understanding and eliminating the cause of this phenomena (1). The development of nondestructive in-service inspection procedures received particular attention as a material result of these observations and as a consequence of U.S. Nuclear Regulatory Commission (NRC) orders to carry out in-service inspection and report results on the pipes in question (2). Some twenty three operating units were affected.

The NRC-ordered inspection prescribed the ultrasonic method (UT) of nondestructive testing for IGSCC identification, basically by the techniques recommended in ASME Code Section XI specifications. The confidence that could be placed in such techniques became a substantial question when leakage, resulting from IGSCC, was observed in pipe locations which had not been characterized as flawed during previous inspections. One response to this situation was the acceleration of inspection programs to focus on this specific BWR incident class. The work described in this report is a part of these activities (3).

1.2 INSPECTION IMPROVEMENT CONSIDERATIONS

1.2.1 Piping Material and Implication

The inspected pipes are austenitic, type 304 stainless steel, either seamless or welded, in schedule sizes ranging from 60 to 100. Nominal diameters range from 1-30 inches. Ultrasonic inspection of fine grain austenitic materials is not usually a difficult undertaking. However, austenitic stainless steel weld areas, which are not normally fine grain, may pose inspection difficulties because of attenuation and grain noise. In addition, IGSCC are not usually as strong a sound reflector as are slots, holes or sharp cracks.

There are a number of possible methods of enhancing defect signals while suppressing grain noise for inspection in austenitic stainless steel weld zones. Those of generic interest include:

1. Selection of a low frequency at which grain scatter is much reduced (i.e. selection of a wave length much greater than grain size), trade-off being implied since sensitivity to small defects is also reduced.

2. Selection of a propagation direction along which grain scatter is minimal, trade-off being required since the emphasis on a preferred orientation may yield high sensitivity to grain misalignments which may occur.

3. Use of narrow beams to reduce the detectability of individual grains; a possible tradeoff being required between the desire to use small size probes (for purposes of contact and resolution) and the possible complexity of ancillary devices needed for such attainment (e.g. acoustic lenses).

4. Use of ultrasonic pulses of low coherence length thus reducing interference effects between different grain echoes (i.e. short pulse systems).

5. Use of microstructure insensitive ultrasonic detection techniques (i.e. those which emphasize frequency spectrum analysis).

Although all of the preceding approaches have merit, they are substantially differentiated from each other in terms of their probable implementation requirements. Specifically, Items 1-3 may be implemented by modifiying transducers; no other modification to most existing ultrasonic equipment would appear to be required. Conversely, the effective use of "short pulse" (Item 4) methods might require substantial modifications of inspection equipment whereas the use of frequency spectrum analysis methods (Item 5) virtually mandates the use of digital data acquistion and processing equipment, very little of which was available for field usage in 1975.

Because of the importance of supplying field usable equipment in the most expeditious fashion, the EPRI program was configured to provide initial emphasis on transducer improvements. The alternate approaches were included in subsequent program elements as illustrated in Figure 1 and further described in the subsequent section.

1.2.2 Weld Configuration and Implications

IGSCC results when a critical level of stress (stress intensity), a sensitized microstructure and an environment that will promote IGSCC all coexist for a substantial period of time. The heat affected zone (HAZ) of austenitic, type 304 stainless steel piping welds is considered to be a susceptible area for IGSCC in the operation of BWR nuclear units. The requirement to inspect the HAZ introduces several constraints on UT methods. One, related to geometry, is that the transducer be of sufficiently small size so as to permit inspection of the comparatively small HAZ without significant obstruction from the weld crown (this requirement will vary from plant to plant depending on what weld dressing, if any, was accomplished). A second consideration is that the weld interface and counterbore can introduce substantial reflections which can be easily mistaken for IGSCC reflections. Thus, to improve UT inspection, it would be desirable to discriminate these "geometric reflectors" from those of IGSCC.

In considering the discrimination techniques possible, it became apparent that a limited number could be accommodated in transducer implementations, whereas the majority of approaches would require advanced signal processing methods. Accordingly, the decision was made to emphasize discrimination techniques in the alternate phase of the EPRI program (Figure 1). The earliest phase, described in

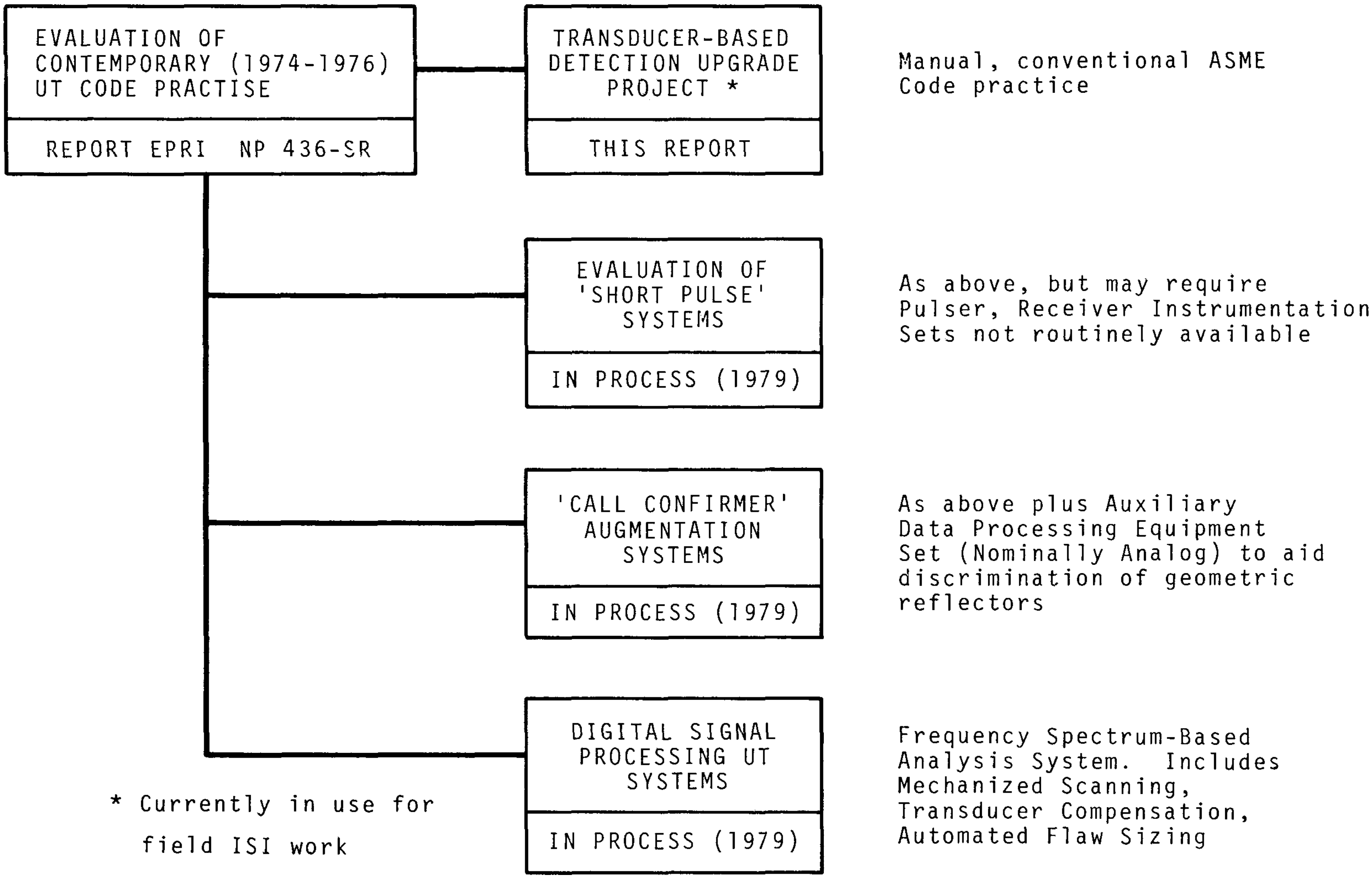

FIGURE 1 EPRI PIPE INTERGRANULAR STRESS CORROSION CRACKING (IGSCC) ULTRASONIC INSPECTION (UT) METHODS PROGRAM OUTLINE

necessary, erring on the conservative side by accepting the possibility of "calling" a geometric reflector a crack. Evaluation and "round-robin" tests were incorporated in the program to provide a quantitative basis for assessing the magnitude of the discrimination error.

1.2.3 Other Factors

Welding and fabrication specifications for piping, automation of UT inspection and the somewhat separable category of sizing a detected flaw all are important factors which can contribute to improved UT inspection reliability. Again, because of the importance of producing equipment for near-term field utilization (and secondarily because of the desire to develop UT methods which were Code-acceptable under contemporary standards) these improvement investigations were confined to later elements of the EPRI program (Figure 1). Parenthetically, it should be noted that in the early history of IGSCC incidents crack sizing did not appear to be an important consideration since all detected cracks were assumed to be capable of rapid propagation. Subsequent observations suggest that this assumed behavior is very much dependent on the stress intensity and residual stress pattern in the weld area. Hence rapid propagation need not be characteristic of all pipe sizes and welding techniques.

1.3 TRANSDUCER PROGRAM DEVELOPMENT

EPRI undertook the development and verification of a transducer-oriented program to improve confidence in ultrasonic inspection of austenitic 304 stainless steel pipe weld areas. Theory, transducer development, transducer evaluation and product refinement tasks were conducted both in series and parallel by the following organizations:

Southwest Research Institute (SwRI)
Development and Evaluation Tests
Amos Greer, Jerry McElroy

Drexel University
Theoretical Studies, Transducer Improvement
J.L. Rose, G.P. Singh

General Electric Nuclear Energy Group
Field Evaluation
J. Clark

2.0 PROGRAM BASIS AND SCOPE

Figure 2 illustrates the scope of the transducer improvement effort undertaken viewed in the context of an overall in-service inspection (ISI) program. As suggested by the shaded area of the illustration, the primary aim of the program was to increase the probability of IGSCC detection in the initial phases of an ISI program. Sizing and verification of the detected flaw size were not emphasized as would normally be expected in this type of work.

2.1 BASIS OF THE PROGRAM

During August and September of 1975 EPRI conducted a "round-robin" study to quantify the ability of code-required ultrasonic inspection methods to detect IGSCC and to provide a basis for defining developmental needs. The study, reported in EPRI NP-436-SR "A Study of In-service Ultrasonic Inspection Practice", provided the opportunity to:

a. Evaluate the performance of industrial inspection teams using UT methods of their own choice and

b. Define some of the basic characteristics of the signals reflected from IGSCC in samples removed from operating units.

The specimens utilized were radiation-contaminated samples removed from the 4-inch recirculation bypass of a BWR plant and from the 10-inch core spray lines of another.

As of present date, each examination service vendor is free to interpret the Code requirements as they desire from a technical standpoint within the approval authority of the utility, the authorized inspector and the NRC. Consequently, procedures, equipment, personnel qualifications and technique may vary from vendor to vendor. This characteristic was in evidence in the "round- robin" tests. However, most inspection teams chose inspection frequencies of 2.25 and 5.0 MHz, the nominal Code specification for investigation of ferritic materials.

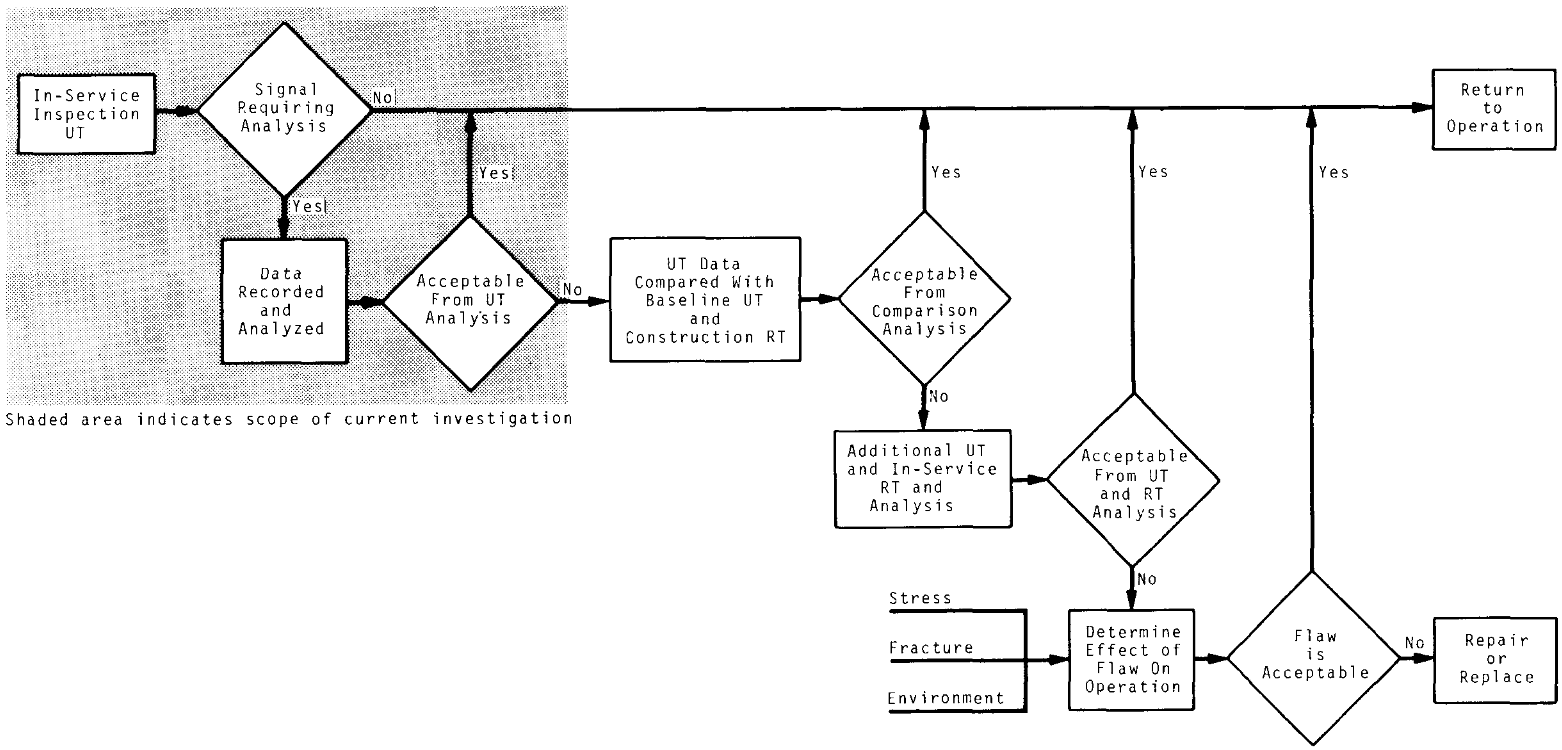

FIGURE 2 OVERALL IN-SERVICE INSPECTION PROCESS

This selection appeared to be at odds with the subsequent results of a basic measurements program performed by SwRI personnel on these samples. These results, reported in EPRI Report NP676-SR, "Detailed Analysis of the Fundamental Ultrasonic Response Data From Stainless Steel Corrosion Crack Specimens", examined the response of cracked pipe specimens with sets of specially developed search units (transducers). These search units (SU) varied in frequency from 1.0 to 10 MHz and in piezoelectric size from 1/4 to 1/2 inch in diameter. Shear beam angles used were 45 and 60 degrees. Use of this set of search units on the EPRI cracked pipe specimens showed that the 1.5 MHz search units provided ten times the amplitude obtained with a 2.25 MHz examination, that is, cracks which gave 20 to 40 per cent distance amplitude correction curve (DAC) amplitudes at 2.25 MHz gave 200 to 400 per cent DAC amplitudes at 1.5 MHz.

The difference in DAC amplitude values appeared consistent with concurrent frequency spectrum analysis of the RF wave form reflected from cracks. These analyses showed that, regardless of the operating frequency of the transducer, the combination of material microstructure and crack interface filtered and/or scattered the higher frequency components of the beam and returned only frequencies of 1.2 tol.8 MHz. It was also found that transducers displaying narrow bandwidths performed better than wide bandwidth transducers.

2.2 SCOPE OF THE PROGRAM

Based on observations reported in the preceding sections, the transducer improvement scope was specifically defined as the detailed evaluation and optimization of low frequency (1.5 MHz) transducers for detection of IGSCC in austenitic type 304 stainless steel pipes characteristic of BWR installations. This work, described in subsequent sections of this report included:

a. Transducer configuration analytical studies and laboratory evaluations

b. Independent evaluations of applications by organizations not concerned with development and

c. Field usage reports by various ISI groups.

At program initiation BWR incidents centered on 4-inch bypass lines. However, since many repairs and/or replacements to these lines have been made, the program emphasis gradually shifted to larger diameter (10-28 inch) pipes. IGSCC has been found in furnace-sensitized 10 inch pipes and in 24 inch piping of a foreign BWR.

Note: English units are used to describe pipe sizes since the nominal pipe size is not always equal to the actual diameter. (The O.D. exceeds the nominal size up to nominal diameters of 14 inches)

3.0 PROGRAM DETAIL AND REPORTS SUMMARY

Details of the results obtained with both the single and dual crystal unit are presented in this section. The application of these results and future work plans are also discussed.

3.1 PRELIMINARY DEVELOPMENT, SINGLE CRYSTAL UNITS

As a result of the preliminary studies identified in Section 2.0, a series of experimental, single crystal, low frequency transducers were fabricated by SwRI for use in ISI and pre-service inspection (PSI). The performance of these transducers was evaluated by SwRI during the conduct of these inspections and independently by Battle-Columbus Laboratories as summarized in Appendices A1 and A2. Overall the results indicated improved IGSCC detection capability (as determined by signal amplitude) which was confirmed by subsequent liquid penetrant evaluations. However, problems were encountered with the time span required for inspection since the composite of use of small diameter search units and low frequency beam spreading resulted in an increased number of geometric recordings. This observation lead to the postulate of a transducer designed for improved beam directivity to overcome the larger beam spread of the lower frequency. This directive system, consisting of a dual crystal, "pitch-catch" configuration underwent preliminary evaluation during this phase as described in Appendices A1-A2 and subsequently became the main developmental theme of the program.

3.2 THEORY AND BACKGROUND OF THE DUAL TRANSDUCER

Concurrent with the decision to pursue a dual, low frequency unit, Drexel University was assigned the task of examining the background of alternate experience with dual units and developing an ultrasonic field analysis program to aid in optimizing the size, shape and bandwidth characteristics of these units for particular pipe size applications. The results of this effort are summarized in Appendix A3.

A conventional concern with the use of directive transducers is that they can be misapplied if they are optimized for inspection of one metal thickness and used for another. Pipe wall thicknesses of concern to this program do not cover a wide range. However, some transducer performance variations with pipe size and with characteristics of the instrumentation utilized may be expected. The theoretical analysis provides a basis for understanding this behavior and also resulted in specifications for modified transducer construction which yielded further performance improvement.

The dual transducer for convential UT and that preferred for microstructural insensitive UT approaches (Section 1.2.1, Item 5) are fundamentally similiar, however, important differences may exist with respect to bandwidth. Typically the conventional approach favors a narrow bandwidth; the alternate techniques, which may depend on the use of "information" (i.e. waveform characteristics) significantly removed from the center frequency, favor an intermediate or broad band transducer. The development of a transducer for the latter application was also examined in this work.

3.3 APPLICATION EVALUATIONS

Because neither UT instrumentation nor transducer manufacture are rigorously specified in practice--and because techniques of inspection vary from group to group, it is usually insufficient to establish the adequacy of a particular technique based on a set of isolated results. This appears to be particularly true for nuclear plant applications where a variety of pipe conditions, weld configurations and accessibility problems may be encountered. It is also important to validate techniques on actual service-induce flaws rather than assumed geometeric equivalents. For these reasons, the formal evaluations of several organizations were sought. These included independent teams from General

Electric and SwRI as well as the Battle-Columbus work noted in Section 3.1. Samples examined were either pipes in service or service removals.

The opinion of all evaluation teams was that the dual, low frequency transducer (either as built by SwRI or as built to comparable specifications by independent manufacturers) offered substantial improvement in IGSCC detection as a result of increased amplitude and improved signal-to-noise ratio. This behavior was most particularly in evidence in the larger pipe sizes (greater than 14 inches) . On smaller pipe sizes (nominally 4 inches) several investigators noted that the dual unit performance was not substantially better than that of single crystal, 2.25 MHz transducers, largely because of access limitations imposed by the weld crown. This behavior, which is consistent with analytical expectations, could be modified by design. No such design effort was undertaken since the program emphasis has shifted to larger pipes.

One comparative evaluation of samples taken from a nuclear unit which had been responsible for much doubt over the adequacy of UT inspection appears to be of particular significance. The unit in question was discovered to have IGSCC in some 24 inch diameter 304 stainless steel safe ends and weldments. These flaws were stated to have escaped UT detection. The comparative evaluations, conducted on samples where great care was taken to preserve inside diameter surfaces in the acquired state, suggested that few, if any, indications would be expected with conventional, single crystal transducers. However, virtually all of the cracks, including those of extremely small depth, were identified using dual, low-frequency transducer units. This comparative evaluation was considered extremely significant because of the potential operational significance of flaws in larger pipes and the oppportunity to examine the only such flaws encountered in service to date.

The results of these efforts are summarized in Appendix A4.

3.4 SUPPLEMENTARY DATA

Appendix A5 contains information on BWR piping and welds as well as on inspection observations of those involved in this program which may prove useful to investigators concerned with the IGSCC detection effort.

3.5 FUTURE WORK

A limited amount of further work on the transducer-based IGSCC detection approach is currently underway. The bulk of applied effort relates to the alternate approaches noted in Figure 1.0. A primary approach, which involved detailed frequency spectrum analysis by digital data processing techniques (4), currently utilizes a single crystal, broad band transducer. A derivative using approach simpler data processing is based on the dual unit described in Appendix A3.

3.6 MISCELLANEOUS

One of the unique aspects of this UT development program was the early and sustained emphasis on the use of service or service equivalent flaws for evaluation efforts. The program was fortunate to have available to it a comparatively large number of flawed samples withdrawn from service. However, even this quantity would have proved insufficient without the concurrent availability of IGSCC samples of essential equivalence which could be manufactured as needed. These manufacturing methods are briefly described in Appendix A6 for the benefit of future investigators.

4.0 REFERENCES

1. H.H. Klepfer et al. Investigation of Cause of Cracking in Austenitic Stainless Steel Piping. San Jose, CA.: General Electric Company, July 1975. NEDO-21000-1,-2.

2. Office of Inspection and Enforcement (IE), Failures in 4-in. Bypass Piping at Dresden 2, January 24, 1975. Bulletin No. 74-10B

3. Planning Support Document for the EPRI Nondestructive Evaluation (NDE) Program. Palo Alto, CA: Electric Power Research Institute, December 1978. NP-900-SR.

4. R. Shankar et al. Development of Adaptive Learning Networks for Pipe Inspection. Palo Alto, CA: Electric Power Research Institute, January 1978. NP-688.

APPENDIX A1

DEVELOPMENTAL HISTORY OF DUAL ELEMENT TRANSDUCERS FOR DETECTION OF INTERGRANULAR STRESS CORROSION CRACKS IN STAINLESS STEEL WELDMENTS

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Section 1

INTRODUCTION

This report is a historical summary of research performed by Southwest Research Institute (SwRI) on intergranular stress corrosion cracking (IGSCC) of 4-inch, Schedule 80, stainless steel piping welds for the Electric Power Research Institute. It provides the developmental history of dual transducers.

As a result of efforts incorporated in: A Study of In-Service Ultrasonic Inspection Practise for BWR Piping Welds (EPRI NP436 SR), EPRI sponsored investigators determined that pulse-echo, shear wave ultrasonic testing is a viable, in-service volumetric inspection method for the detection of IGSCC, but that improvement is required because

- Detection of small IGSCC is not limited but identification is limited
- Separation of IGSCC and geometric reflectors is a fundamental problem
- Final result is heavily dependent on the decision-making process of the examiner.

These conclusions, based on ultrasonic testing techniques then in vogue, are consistent with the well recognized observation that there are acoustic problems encountered in examining austenitic materials. These problems are further complicated when the defect is caused by IGSCC. Instead of presenting the relatively straight and highly reflective surface of classic fatigue cracking, stress corrosion cracks present a very diffuse face which follows the grain-boundaries in the material. This diffusion can cause a rather poor ultrasonic response relative to typical machined calibration reflectors. Amplitudes, signal-to-noise ratios, and overall nature of the reflected signals result in difficulty in detecting and sizing the reflectors.

Consideration of these factors resulted in a jointly sponsored SwRI/EPRI project to study the character of the reflected signal from stress corrosion cracks.

The results of this study indicated that the microstructure in the weld heat-affected zone (where the majority of the cracks occurred) and the nature of the crack interface displayed preferential bandpass characteristics. Frequency spectrum analysis of the RF waveform reflected from these cracks showed that, regardless of the operating frequency of the transducer, the combination of the microstructure and crack interface filtered and/or scattered the higher frequency components of the beam and returned only frequencies of 1.2 to 1.8 MHz. It was also found that transducers displaying narrow bandwidths performed better than wide bandwidth transducers.

In response to this information, a series of prototype search units was designed and fabricated. The design parameters were as follows:

1. Piezoelectric element--lead metaniobate.
2. Frequency--1.5 MHz.
3. Element size--9.5 and 12 mm diameter.
4. Bandwidth--(6 dB points) 0.8 MHz (53 percent).
5. Beam angle--45 shear wave.

The performance of these prototype units was compared to search unit types typically used in stainless steel piping examinations (i.e., 2.25 and 5 MHz) with diameters of 6.3 mm and 12.7 mm. The comparison was made using the same IGSCC specimens used during the course of the EPRI round robin and SwRI/EPRI signal characteristic programs. For control, each search unit was calibrated on a Code-acceptable, basic calibration standard. A reference level distance amplitude correction (DAC) curve was established for each search unit. The prototype search unit produced a signal amplitude on a series of IGSCC specimens which were 7 to 11 dB greater than that from commonly used search units.

In subsequent field evaluations, the prototype units continued to demonstrate improved sensitivity in detecting stress corrosion cracks. However, it became apparent that the number of recordable geometrical indications had increased substantially.

Reflected signals from geometrical reflectors, such as weld crown and root, exceeding the 50 percent DAC reference level must be recorded and identified. This results in an increase in the number of hours required to conduct the examination.

It was postulated that a search unit, designed for improved beam directivity, could overcome the larger beam spread of the lower operating frequency of 1.5 MHz and assist in reducing the reflections from the root crown.

A dual element "pitch catch," 45-degree, shear wave configuration was designed with the transmitter and receiver elements set at a "pitched in" angle of 5 degrees, as shown in Figure A1-1. The 5-degree convergence angle assigns a maximum response zone or focusing effect at a given metal path distance. Piezoelectric element sizes also determine the metal path distance for maximum response. Two designs were optimized for pipe wall thickness of 9 and 19 mm, respectively. The respective working ranges are 5-30 mm and 12-50 mm. A prototype of this design is shown in Appendix A2, Figure A2-1.

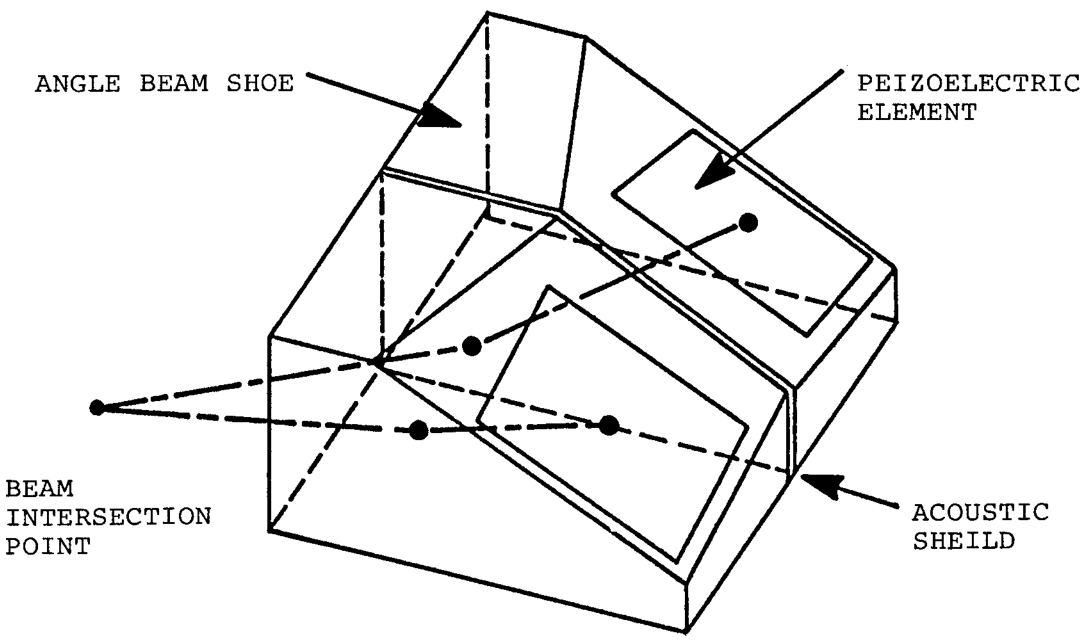
The design parameters were as follows:

1. Piezoelectric elements--lead metaniobate.
2. Element size--3.2 x 6.3 mm and 9.5 x 9.5 mm.
3. Frequency--1.5 MHz.
4. Damping factor--5 to 6.
5. Bandwidth at 6 dB down--53 percent. (Defines working range.)
6. Angle beam shoes--45 degrees refracted shear with a 5-degree "pitch angle;" Material--Rexolite[R].

These units were evaluated on stainless steel piping welds at an operating nuclear power plant on welds chosen for the evaluation which had a large number of geometrical reflectors.

The welds were examined in accordance with the examination procedure being used at the plant. Three search unit types were used; single element--9.5 mm, 2.25 MHz; single element--9.5, 1.5 mm, 1.5 MHz; and the prototype, dual element 1.5 MHz.

The results showed the single element 1.5 MHz units recorded 25 percent more geometrical indications than the 2.25 MHz unit. The dual element 1.5 MHz unit recorded 5 percent more geometrical indications than the 2.25 MHz unit. Improved beam directivity also resulted in an increased sensitivity. When a comparison was made on the IGSCC specimens, the dual element 1.5 MHz unit produced a signal amplitude



DUAL ELEMENT SEARCH DESIGN
FOR ZONE ISOLATION

Figure A1-1

12 dB greater than the 2.25 MHz and 4 dB greater than the single element 1.5 MHz unit.

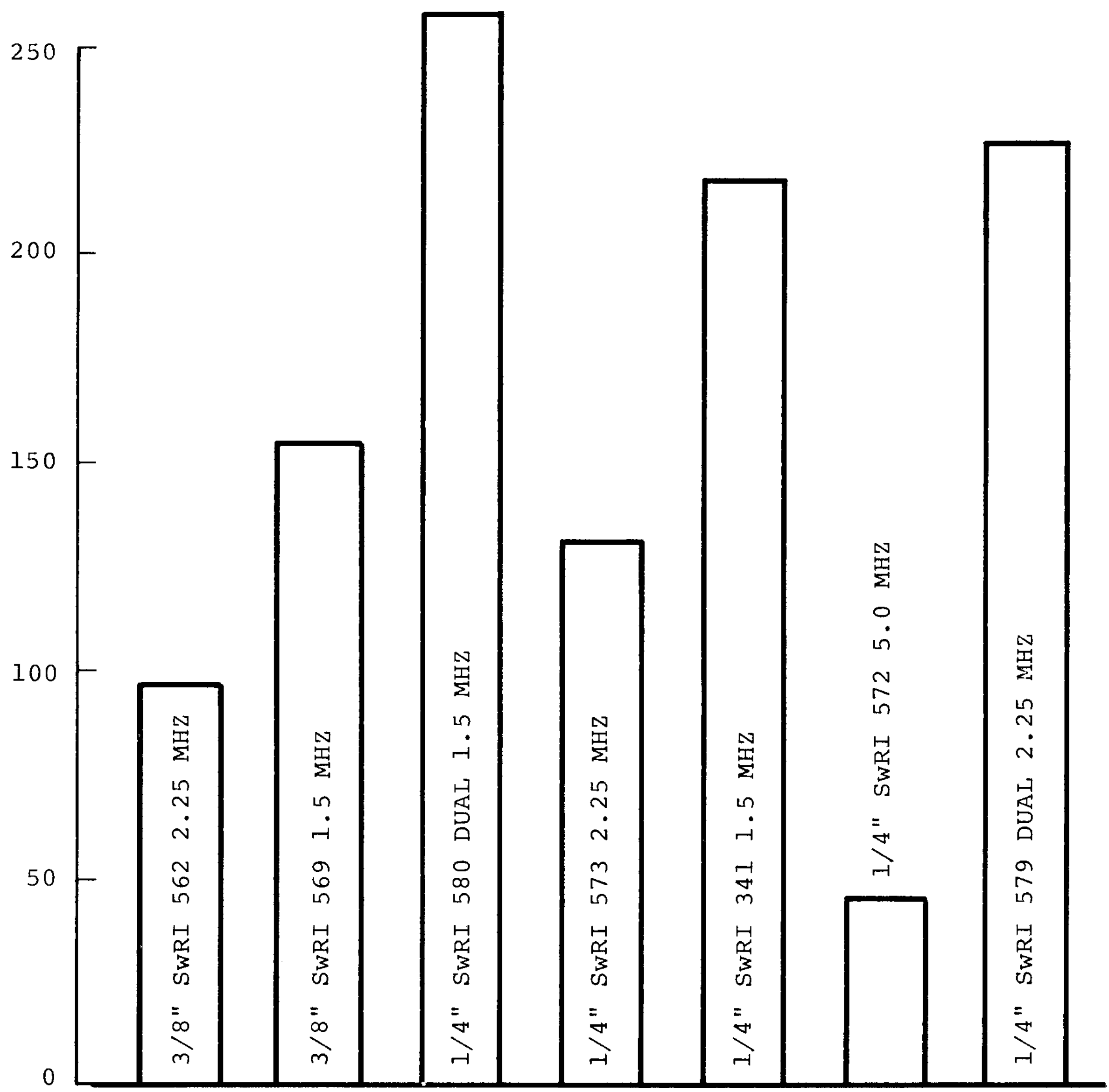
IGSCC specimens provided by the GE Pipe Test Laboratory under the RP 892-1 program, containing multiple cracks, were used to further compare the dual element 1.5 MHz transducer to other search unit types. These pipe specimens were 304 stainless steel, 101 mm diameter, Schedule 80, and contained nine circumferential welds. Some are half sections and access for dye penetrant examination provided confirmation of cracks ranging from 2.5 mm to 152 mm in length. Figure A1-2 shows the number of crack indications recorded with an amplitude exceeding the 50 percent DAC level detected by each search unit type. These data provided further evidence of the improved detection capability of the 1.5 MHz, dual element design.

A search unit was designed and constructed at 2.25 MHz, dual configuration, same design parameters as the 1.5 MHz dual element unit. It can be seen in the bar chart in Figure A1-2 that its detectability was also superior to other single element search units.

In some actual field work performed on reactor piping, examiners were able to detect IGSCC with the dual element search unit where no recordable signals were obtained with a standard 0.25-inch (6.4 mm) diameter single element, 45 degree angle beam, 2.25 MHz pulse echo search unit (3). This field test supports the results found previously in lab experiments (4). The dual element search unit possesses an additional advantage over conventional single-element search units in that the units can be made smaller (shorter from front to back). This is because control of internal wedge reflections is not a factor in the wedge design as it must be with a standard pulse echo design. Using a shorter search unit increases the chances of obtaining a 1/2 V-path examination without interference from weld crown geometry.

EPRI presented a workshop on ultrasonic testing detection of IGSCC at Battelle-Columbus on January 16-20, 1978. The purpose of this workshop was to enable industry examination personnel to learn and experience first-hand the latest ultrasonic testing approaches to examination for IGSCC. These approaches use a procedure developed by SwRI (5) using the 1.5 MHz dual element search unit.

Continued refinements and development of this search unit are planned during Phase 3 of the RP 892-1 program.



NUMBER OF INDICATIONS 50%
DAC OR GREATER

Figure A1-2

Section 2

PERFORMANCE SPECIFICATION FOR 1.5 MHz, 45 DEGREE DUAL ELEMENT SEARCH UNIT

In view of the fact that IGSCC occurs in the heat affected zone adjacent to the root of the weld, it was postulated that a well defined ultrasonic beam was needed to differentiate the reflection from small IGSCC and the reflection from the root of the weld.

The design of the 1.5 MHz dual element assists in overcoming beam dispersion and provides a maximum response zone or focusing effect at a given metal path distance. Thus, specifications governing the axial field distribution of the beam are necessary.

Based on the findings of the study conducted on IGSCC specimens removed from operating nuclear plants (2) frequency and bandwidth specifications for these search units are required.

2.1 AXIAL FIELD DISTRIBUTION CHARACTERISTICS

2.1.1 1/4 inch x 3/16 inch 1.5 MHz Dual Element Search Unit.

(Dimensions of the transmitting element are 1/4 inch x 3/16 inch and the dimensions of the receiver element are 1/4 inch x 3/16 inch.)

Axial filed distribution, i.e., distance vs. amplitude curve plotted in steel using 1/8 inch (3.4 mm) side drilled hole reflectors at 1/8 inch (3.4 mm) increments in depth shall exhibit a far field peak at 3/8 inch plus or minus 1.8 inch (3.4 mm), (Figure A1-3). The 6 dB down points in the near field and the far field shall extend between 1/4 inch to 1 inch, thus giving a zone of coverage of 3/4 inch.

2.1.2 3/8 inch x 3/8 inch 1.5 MHz Dual Element Search Unit.

(Dimensions of the transmitter element are 3/8 inch x 3/8 inch and the dimensions of the receiver are 3/8 inch x 3/8 inch.)

Axial field distribution, i.e., distance vs. amplitude curve plotted in steel using 1/8 inch (3.4 mm) side drilled hole reflectors at 1/8 inch (3.4 mm) increments in depth shall exhibit a far field peak at 7/8 inch plus or minus 1/8 inch (Figure A1-4).

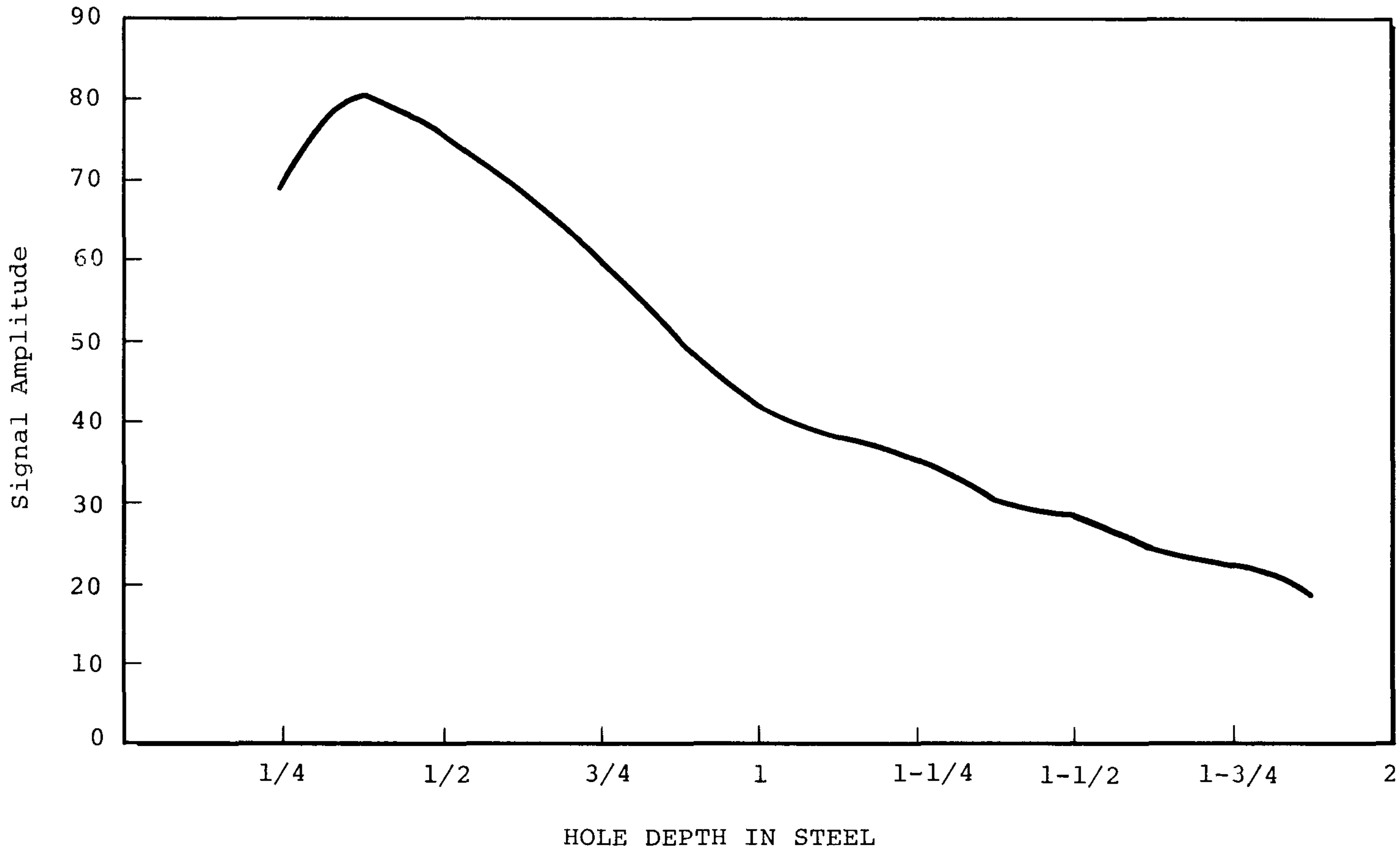


FIGURE A1-3 SEARCH UNIT BEAM PROFILE

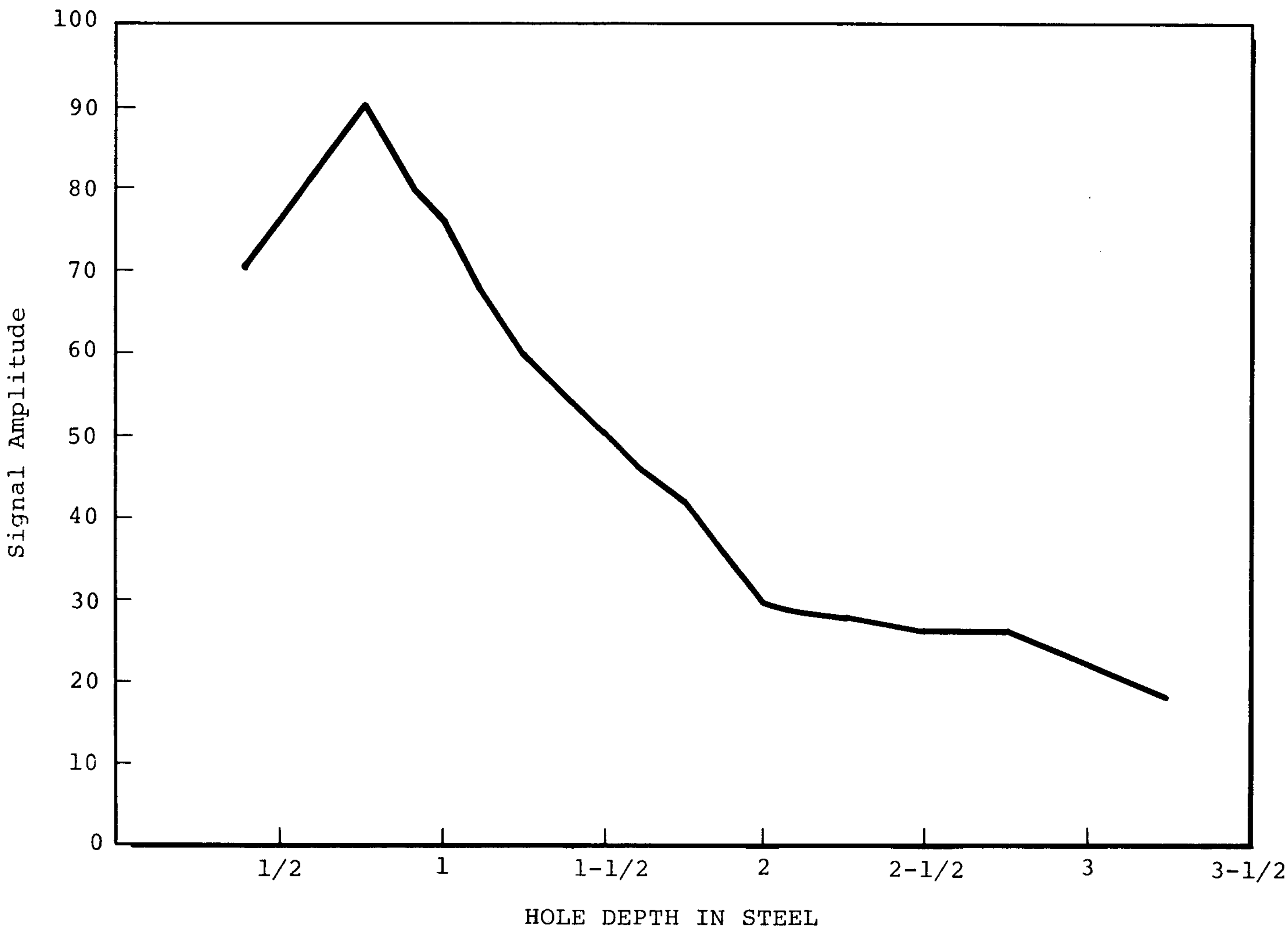


FIGURE A1-4 SEARCH UNIT BEAM PROFILE

The 6 dB down points in the near field and far field shall extend between 3/8 inch to 1-3/4 inch, thus giving a zone of coverage of 1-3/8 inch (Figure A1-4).

2.2 FREQUENCY AND BANDWIDTH SPECIFICATIONS

1/4 inch x 3/16 inch dual element and 3/8 inch x 3/8 inch dual element search units.

2.2.1 Center frequency shall be 1.5 MHz ± .2 MHz.

2.2.2 Bandwidth shall be 53 percent plus or minus 10 percent at the 6 dB down points as measured on an appropriate frequency spectrum analyzer from a signal reflected from a side drilled hole in steel at the maximum pressure distribution point.

2.2.3 The damping factor shall be 4 to 8 cycles, measured by counting the first half cycle and all other cycles in the composite signal equal to or greater than the first cycle, for a signal reflected from a side drilled hole in steel at the maximum pressure distribution point.

2.3 SHOE LENGTH AND DESIGN

2.3.1 General

The dual element search unit possesses an additional advantage over conventional single-element search units in that the units can be made smaller (shorter from front to back). This is because control of internal wedge reflections is not a factor in the wedge design as it must be with a standard pulse echo design. Use of a shorter search unit increases the changes of obtaining a 1/2 V-path examination without interference from weld crown geometry.

The shoe shall be designed so that the upper-most portion of the ultrasonic beam will exit at the front corner of the shoe, thus enabling the shoe to be of minimum length.

2.3.2 Physical Design Parameters

1. Active element piezoelectric ceramic.
2. Element size, 1/4" x 3/16" and 3/8" x 3/8" for both transmitter and receiver elements.
3. Angle beam shoes 45 degree refracted shear with a 5 degree convergence angle on both transmitter and receiver shoes.

4. Acoustic cross coupling shielding. An acoustic absorbing material with a maximum thickness of .060" and a minimum of .040" shall be placed between the shoes to prevent acoustic cross coupling ("cross talk").

5. Refracted Angle. The refracted angle shall be measured on a IIW block and shall be 45 degrees plus or minus 2 degrees. The incident point shall be determined by using an IWW block (conventional method). The search unit should be used in the transmitter and receiver mode when making these measurements (through transmission). Shoes must be flat and will not be radiused to fit the curvature of the pipe.

Section 3
PROCEDURE

3.1 GENERAL

This procedure defines modifications and recommended changes to present procedures written to be in accord with ASME Section XI, Appendix III, and would provide for:

A. The use of the dual element 1.5 MHz search unit design.

B. A calibration sensitivity and scan plan optimized for detection of IGSCC in stainless steel piping.

3.2 APPLICATION

3.2.1 The requirements are limited to base metal adjacent to full penetration welds in piping systems having a nominal wall thickness of 0.2" to 1" (5 mm to 25 mm).

The requirements are applicable only to similar metal welds in austenitic stainless steels.

Alternative examination techniques, calibration block designs, etc., may be used as provided by IWA-2240 of Appendix 3, Section 11.

3.3 SEARCH UNIT

3.3.1 Search units shall be 45 degrees, 1.5 MHz, 1/4" x 3/16" or 3/8" x 3/8" dual element type equivalent to those developed under EPRI RP-892 by Southwest Research Institute. 1/4" x 3/16" shall be used for pipe wall thickness of .2" to .5"; 3/8" x 3/8" shall be used for pipe wall thickness of .5" to 1".

3.3.2 Search Unit Shoes

The search unit shoes shall be flat to obtain adequate coupling when using swivel scanning motions on 4" to 12" piping.

Search unit shoes shall be short enough to permit 1/2 V-path examination of the weld root area.

3.4 PERSONNEL REQUIREMENTS

Personnel performing examinations shall be qualified in accordance with IWA 2300 of Appendix III, Section 11. In addition, they shall successfully complete a practical test specific to the IGSCC examination procedure used.

The test pieces upon which the performance test is conducted shall be sections of full-size welded austenitic stainless steel piping containing actual IGSCC.

In order to successfully complete the test, the examiner must demonstrate his ability to detect reflectors that are within the detectability limits specified in the IGSCC examination procedure and to locate them with the accuracy specified in the IGSCC examination procedure to the satisfaction of the Level III Examiner conducting the test.

3.5 IGSCC TEST SAMPLE REQUIREMENTS

The test shall be performed using full scale pipe samples which contain actual IGSCC. The samples shall be of sufficient length to permit a full 1" to 1/2" V-path examination of the parent metal adjacent to the weld over a volume a minimum of 1.0" (25 mm) from each edge of the weld bead and up from the bottom of the weld a minimum of 0.5 times the wall thickness.

The surface finish of the IGSCC test sample(s) shall be representative of the finish of the piping areas to be examined.

3.6 CALIBRATION

Calibration performed for procedure shall be in accordance with the requirements of Article III-3000.

Calibration shall be performed using the basic calibration blocks described in Article III-3400.

3.7 SCANNING SENSITIVITY

Manual scanning shall be performed at twice (+ 6 dB) the primary reference level as a minimum. Higher scanning gains may be used, but recording of ultrasonic reflectors shall be at the primary reference level gain [Article III-3230(c)].

3.8 RATE OF SEARCH UNIT MOVEMENT

The rate of search unit movement shall not exceed 2 in./sec. (50 mm/s) unless calibration and detection of actual IGSCC has been verified at the higher scanning speed.

3.9 SCANNING MOTIONS

The weld (if ground) and surrounding parent metal volume shall be scanned for at least 1.0 in. (25 mm) from each edge of the weld. Scanning shall be conducted in two directions parallel to the weld and at 90 degrees to the weld on each side of the weld. In addition, when scanning, the search unit shall be swiveled back and forth a minimum of 45 degrees from the nominal scan direction to search for "skewed" or off-angle IGSCC.

3.9.1 Examination Coverage

The volume shall be examined by moving the search unit over the examination surface so as to scan the entire examination volume out to 1-1/2 V-paths. As a minimum, each pass of the search unit shall overlap 50 percent of the transducer (piezoelectric element) dimension perpendicular to the direction of the scan. The transducer dimension is the width dimension of the transmitting element in the dual-element search unit.

REFERENCES

1. "A Study of Inservice Ultrasonic Inspection Practice for BWR Piping Welds," EPRI NP-436-SR, TPS-75-609, August 1977.

2. "Detailed Analysis of the Fundamental Ultrasonic Data from Stainless Steel Stress Corrosion Cracks", SwRI Report 17-4182, June 1976, and EPRI NP-676, 75-620, February 1978.

3. J. Fox, J.T. McElroy, and B. Rajala, "Summary of Laboratory and Field Results with Improved Transducer," presented to EPRI Project Review Meeting, Palo Alto, California (June 15, 1978).

4. M.J. Golis, "Investigation Into the Performance Characteristics of Three Experimental Ultrasonic Transducers," EPRI TPS 750620/04-2, Battelle-Columbus Laboratories (February 1978).

5. J. Fox, "Transfer of Technology, Round Robins and Workshops," Presented to EPRI Project Review Meeting, Palo Alto, California (June 15, 1978).

APPENDIX A2

INVESTIGATION INTO THE PERFORMANCE CHARACTERISTICS OF THREE EXPERIMENTAL ULTRASONIC TRANSDUCERS

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Section 1

INTRODUCTION

This report discusses the findings derived from an investigation into the performance characteristics of three experimental ultrasonic transducers. The transducers, both single and dual crystal, were designed for use in the detection of intergranular stress corrosion cracking (IGSCC) which may exist in the stainless steel piping systems found in boiling water reactors BWRs). The transducers were fabricated by J.T. McElroy of Southwest Research Institute. They were developed based partially on the finding that a minimum amount of frequency spectrum distortion is experienced by an acoustic wave passing through typical samples of stainless steel piping when excitation frequencies are below the commonly used frequency of 2.25 MHz. Details of similar transducer evaluations are reported in EPRI Special Report NP-676-SR, February, 1978.

This study was made to compare the ultrasonic responses exhibited by the three experimental transducers and a typical commercial transducer used for BWR pipe inspection. The test targets were IGSCC reflectors which had been detected near BWR piping welds. These pipe segments were removed from service, used in an ultrasonic testing capability study, and characterized nondestructively at Battelle-Columbus Laboratories. Detailed descriptions of the test reflectors are given in Appendix D, "Test Sample Characterization" of EPRI Special Report NP-436-SR, August, 1977, "A Study of In-Service Ultrasonic Inspection Practice for BWR Piping Welds".

The fundamental purpose of this study was to see if there would be an improvement in the apparent response from known cracked samples if the transducer comparison was made with respect to typical inspection transducers such as those used in routine in-service inspection (ISI). This study also represents an independent assessment of the performance of these transducers by personnel not involved in their development.

Section 2

CONCLUSIONS AND RECOMMENDATIONS

The three transducers evaluated during this study showed a marked improvement over the conventional unit used as a basis for comparison. The most outstanding difference has been the higher signal level observed on the ultrasonic instrument when these transducers are used on natural flaws even when the two transducers have been calibrated to the same standard and their response was made identical to a side drilled calibration hole. This suggests a unique sensitivity to flaws of a critical nature. It was noted that the same degree of sensitivity of less significant reflectors such as minor fabrication defects was not found.

The difference noted in response to natural flaws was predicated on a calibration reflector which was located in the center of the pipe wall while the reflectors of interest were located in the pipe's inside surface. Since the use of lower frequency transducers would capitalize on differential attenuation phenomena, the observed differences would probably be less dramatic if an inside diameter notch were used for calibration. The only differences observed in changing from a narrowband system to a broadband system was a decrease in signal to noise ratio, however, there were not enough comparisons made of this effect to come to any generalized conclusions.

Based on this study, it is quite evident that further work should be done in examination of the use of customized, low frequency transducers for their potential for being a more reliable source of detecting the presence of IGSCC in stainless steel piping systems.

Section 3
METHODOLOGY

A commercially available shear wave transducer assembly was used as a comparitor against which the experimental transducers were tested. The instruments used were also general purpose ultrasonic inspection units. One unit represented a narrowband class of circuitry (Sperry Reflectoscope - Model UM 721) and the other was typical of a broadband system (Branson Instruments - Model 301). The instrument/transducer combinations were calibrated on a 3.32-inch side drilled hole (SDH), located midway in the pipe wall and running transverse to the pipe axis. The transducer/instrument combinations were then used to record the general shape and degree of background noise observed when pulse echos reflecting from various natural discontinuities were observed on the screens. By noting carefully the relative gain changes needed to return the detected pulses to a near mid-screen level, the relative strength of the returned echos could be recorded. By using this normalized display scheme, the signal to noise ratios (S/Ns) for each combination can be read directly from the polaroid pictures. Table A2-1 lists the transducers used in the evaluation.

Transducers[1]	Frequency (MHz)	Size (Inches)
Reference (Aerotech)	2.25	1/2
SwRI #236	2.25	1/2
SwRI #230	1.50	3/8
SwRI #227	1.0	1/4 (pitch/catch)

[1]All transducers were shear wave configurations with a 45° refraction angle.

TABLE A2-1: TRANSDUCER COMPLEMENT

The test reflectors were principally natural discontinuities which had been found in BWR piping systems of commercial operating power plants. The pipe segments had been removed from service and were a part of the round robin study on BWR piping inspection as described in EPRI Special Report NP-436-SR. The reflectors represented (1) IGSCC samples (both through wall and approximately 50% of wall), (2) fabrication defects (such as lack of complete fusion of a root pass insert and a root pass overlap) as well as (3) a localized lap in the pipe base material. The specific test samples used are identified in Table A2-2. Their detailed appearance is shown in NP-436-SR.

Flaw Type	NP-436 SR Identification	Approximate Depth (% of wall)
IGSCC	19AL	100
	1024A (parallel to weld)	30 - 40
	1024A (skewed to weld)	40 - 50
	1028A (parallel to weld)	50 - 60
Weld Defects	10K18 (lack of insert fusion)	2 - 4
	1020A (weld overlap)	2 - 4
Pipe Defects	1021 (lap in pipe)	1 - 3

TABLE A2-2: EVALUATION TEST SAMPLES

Each sample was scanned several times using the Sperry UM 721 and each transducer. The Branson 301 was not available until late in the study, and was only used with the 10K18 sample as well as the calibration block. Once the operator was satisfied with his ability to reproduce the same signal levels with each repeat pass, the screen presentations were photographed. In each case, the change in instrument gain setting required to bring the test signal to near the center of the instrument screen was noted. Thus, a direct observation of S/N can be seen in the resulting set of photographs.

Figure A2-1 shows the two types of transducers used in this study. The unit on the left is a standard shear wave transducer with a refraction angle of 45°. The unit with the cable attached is one of the experimental transducers. The section of weld on which they are positioned is quite representative of the samples used in the study in that (1) the weld crown at the top limits traversal of the transducer across the weld region and does not allow for the ultrasonic beam to reach the root area and (2) the severe geometrical changes in the near-root region give rise to false indications which must be discriminated from reflections from IGSCC under normal ISI operations.

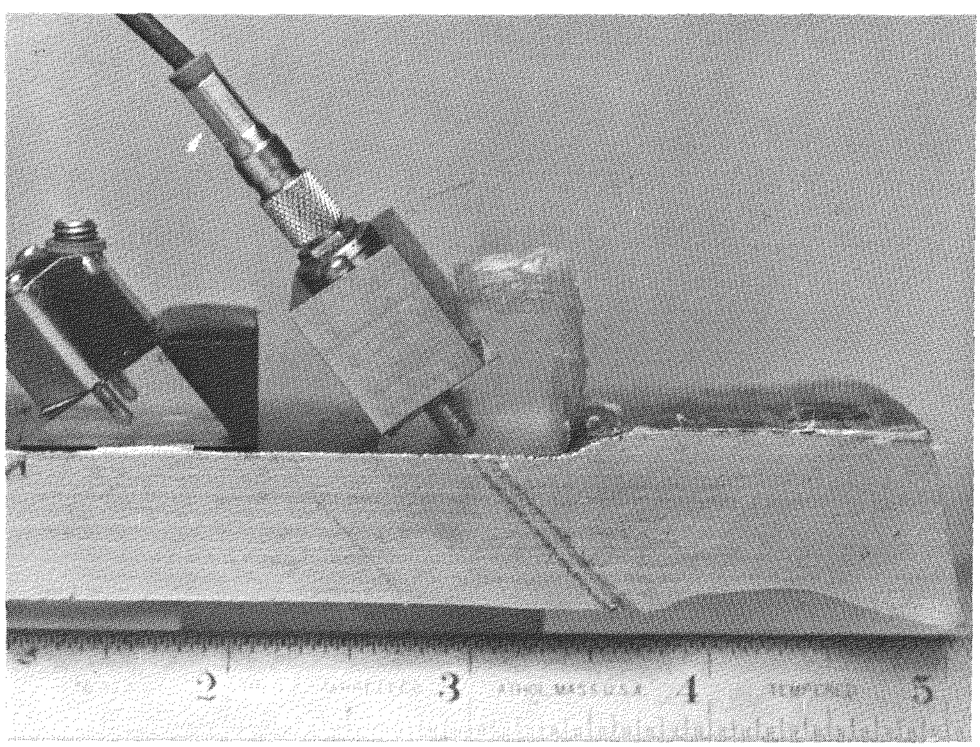


FIGURE A2-1: REFERENCE AND EXPERIMENTAL TRANSDUCERS POSITIONED ON ONE OF THE TYPICAL WELD SECTIONS USED IN THIS STUDY

Section 4
EXPERIMENTAL RESULTS

A summary of the experimental results is shown in Table A2-3. Each vertical column lists the signal levels received from each reflector as compared to the Distance Amplitude Curve (DAC). Each is expressed as a percentage of DAC. These columns also show the observed S/N ratios in each case. Note that in the case of the IGSCC samples, (the first three samples), the amplitude of the received signals is markedly higher for the lower frequency units (#230 and #227) accompanied with only a slight decrease in the observed S/N ratios. The lack of fusion reflector showed little difference between all of the units. The pitch/catch unit gave significantly improved signal levels in both the case of the weld root overlap and the pipe defects while the other units showed only slight differences.

The comparison between the narrowband and broadband system responses was inadequate to arrive at any conclusions, but from the small amount of data gathered, it appears that there is little difference in the relative amplitudes received. The S/N ratios observed for the wideband class of instruments were lower than those for the narrowband systems. Figures A2-2 through A2-7 show the actual signals received in each of the cases cited in Table A2-3.

It is evident from this cursory evaluation that the lower frequency units, particularly in the case of the pitch/catch unit, give higher amplitude signals from the natural crack reflectors. This holds true even though both the Aerotech and the experimental units were calibrated in an identical manner and to the same standard.

Sample		Reference (AeroTech) (2.25 MHz) 1/2 Sperry (1)	Reference (AeroTech) (2.25 MHz) 1/2 Branson (2)	SwRI #236 (2.25 MHz) 3/8 Sperry	SwRI #236 (2.25 MHz) 3/8 Branson	SwRI #230 (1.5 MHz) 3/8 Sperry	SwRI #230 (1.5 MHz) 3/8 Branson	SwRI #227 (1.0 MHz) P/C Sperry	SwRI #227 (1.0 MHz) P/C Branson
19AL		160[6] (18:1)[3]	--	130 (10:1)	--	360 (15:1)	--	560 (10:1)	--
1204A	(4)	55 (20:1)	--	40 (10:1)	--	120 (15:1)	--	130 (15:1)	--
	(6)	100 (20:1)	--	90 (20:1)	--	190 (20:1)	--	190 (10:1)	--
1028A		90 (15:1)	--	85 (15:1)	--	185 (15:1)	--	140 (7:1)	--
10K18 (LoF)		65 (15:1)	55 (15:1)	75 (15:1)	75 (6:1)	90 (20:1)	75 (5:1)	60 (8:1)	60 (9:1)
1020A overlap		80 (15:1)	--	45 (10:1)	--	45 (1o:1)	--	150 (5:1)	--
1021 (pipe)		10 (15:1)	--	10 (5:1)	--	15 (7:1)	--	60 (7:1)	--
Calibration Block (3/32 inch SDH)									
1/4 Vee Path		80 (20:1)	100 (20:1)	90 (20:1)	100 (20:1)	90 (20:1)	100 (5:1)	90 (2:1)	100 (1:1)
3/4 Vee Path		100 (20:1)	100 (8:1)	100 (20:1)	100 (4:1)	100 (10:1)	100 (3:1)	100 (3:1)	100 (2:1)

(1) Sperry Products - 721
(2) Branson Instruments - 301
(3) Ratios in ( ) are S/N ratios
(4) Portion of large crack parallel to circumferential weld
(5) Skewed crack indication
(6) Amplitudes expressed in % DAC, based on 3/32-inch SDH midway through pipe wall.

Table A2-3: Summary of Comparative Amplitudes and S/Ns

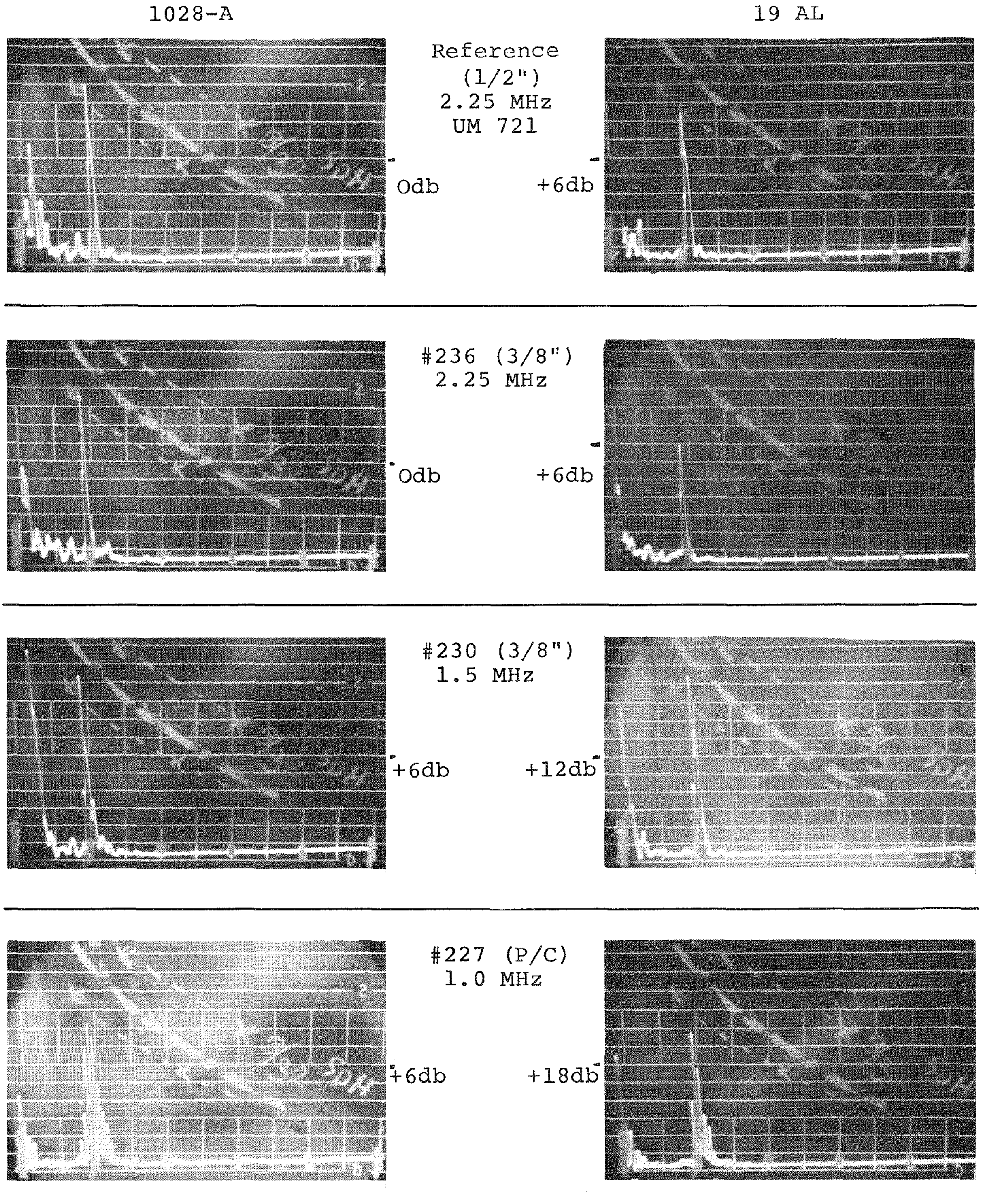
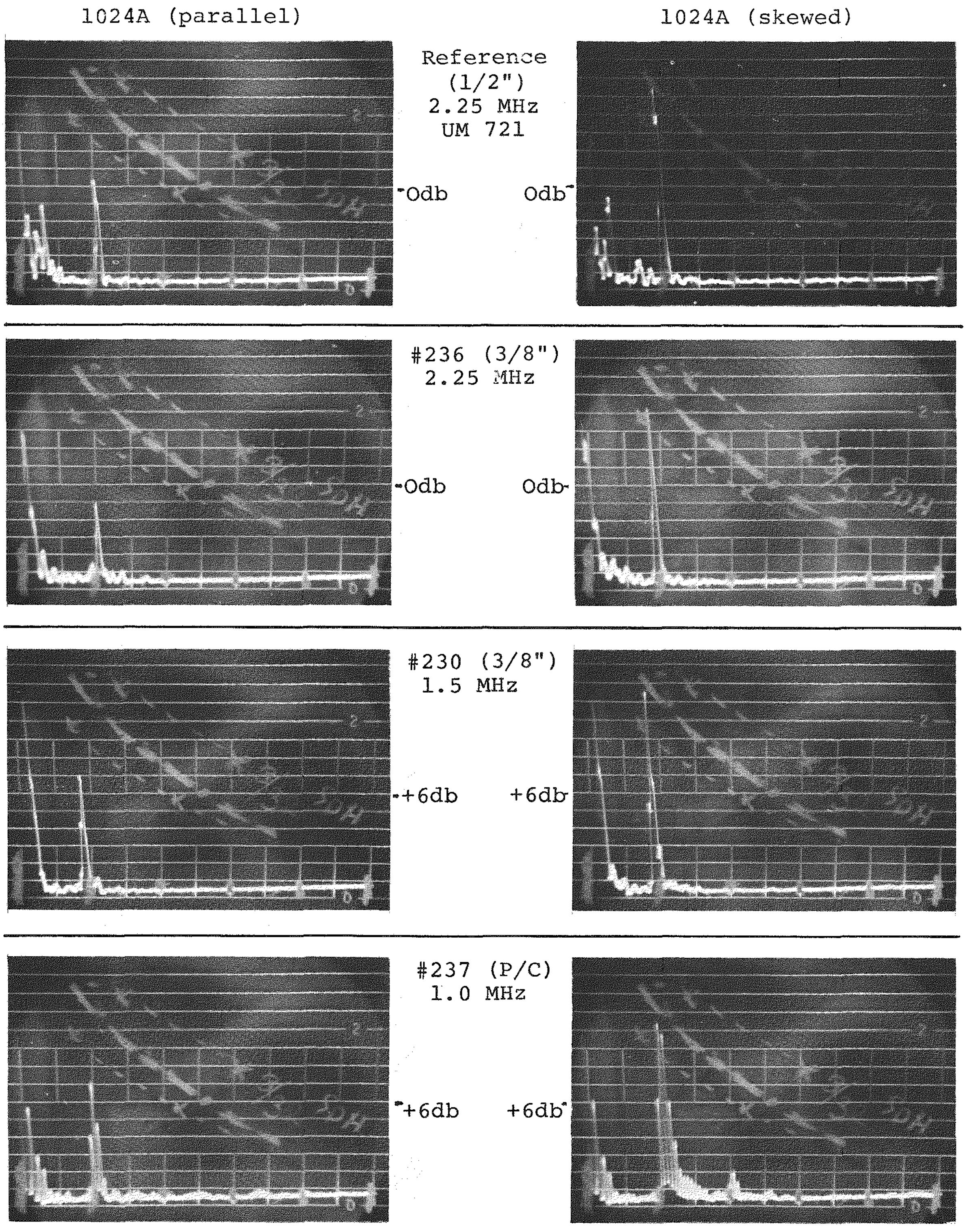


FIGURE A2-2: RESULTS WITH 1028A AND 19AL



RESULTS WITH 1024A PARALLEL AND SKEWED
Figure A2-3

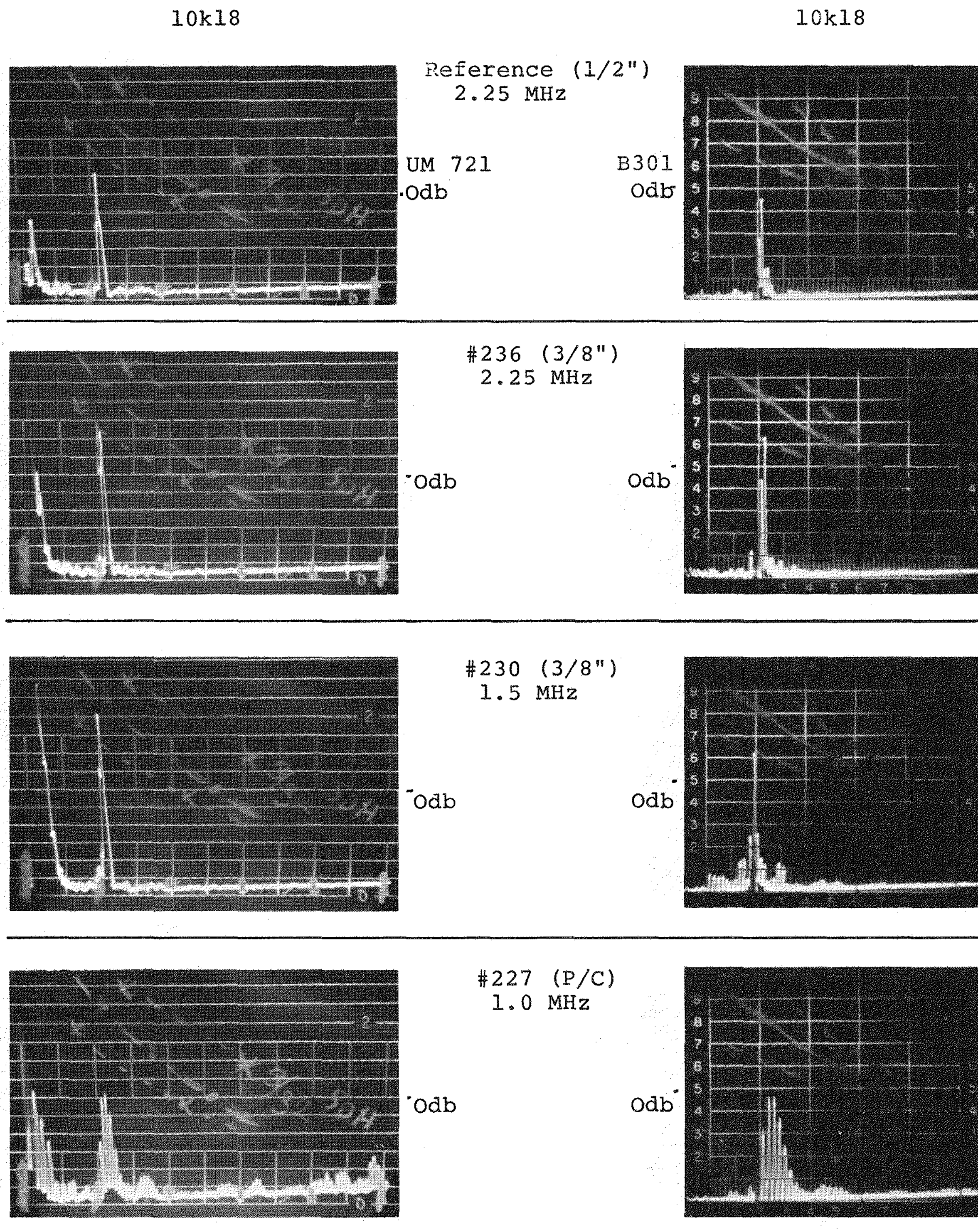


FIGURE A2-4: RESULTS WITH 10k18

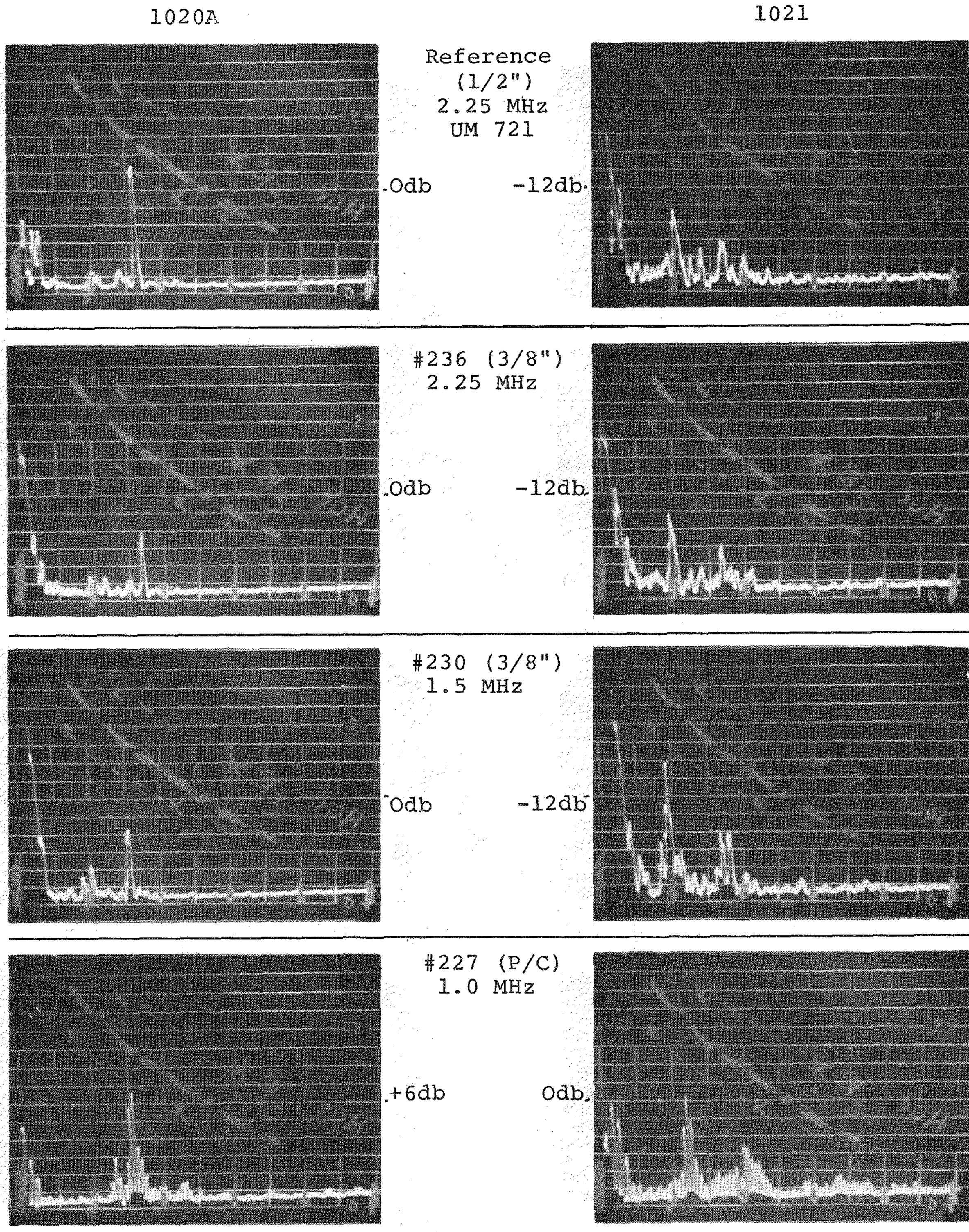
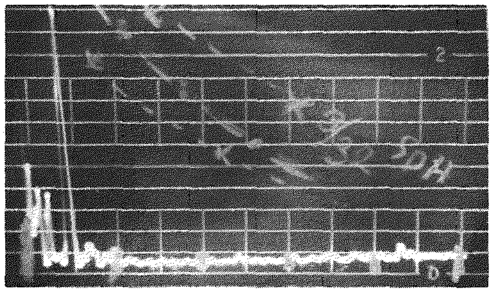
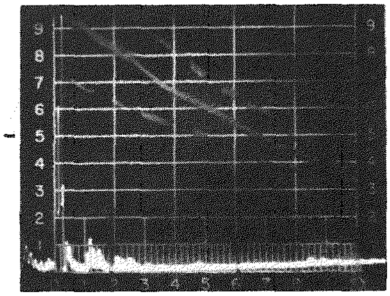


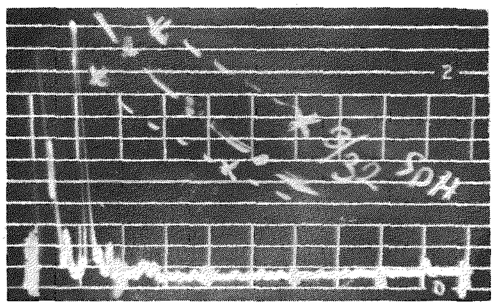
FIGURE A2-5: RESULTS WITH 1020A AND 1021



Reference (1/2")
2.25 MHz

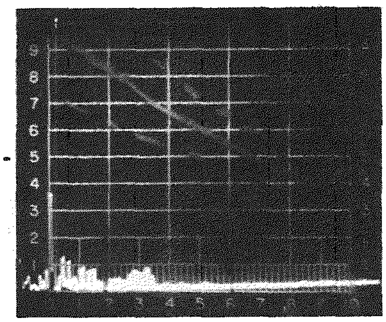
UM 721 B 301
Odb Odb

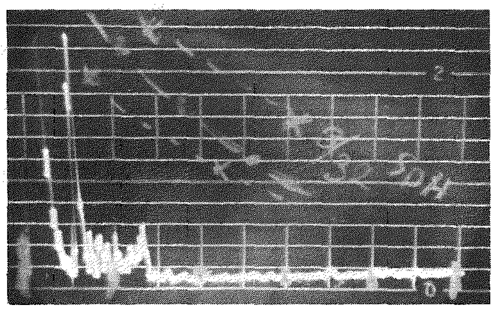




#236 (3/8")
2.25 MHz

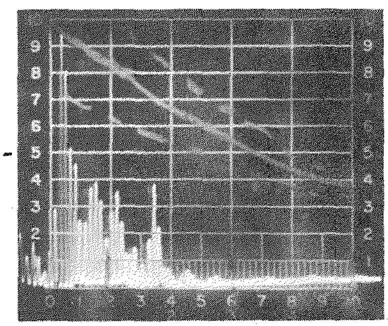
Odb Odb

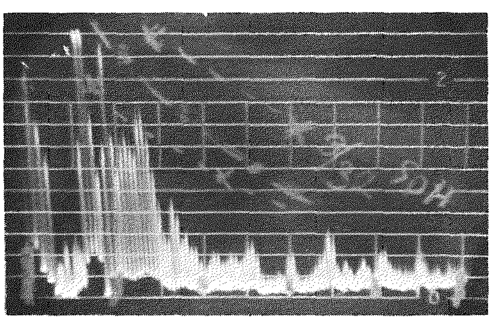




#230 (3/8")
1.5 MHz

Odb Odb





#227 (P/C)
1.0 MHz

Odb Odb

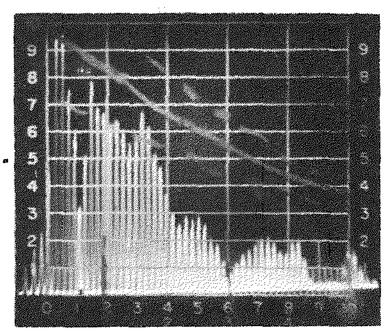


FIGURE A2-6: CALIBRATION STANDARD AT 1/4 VEE PATH

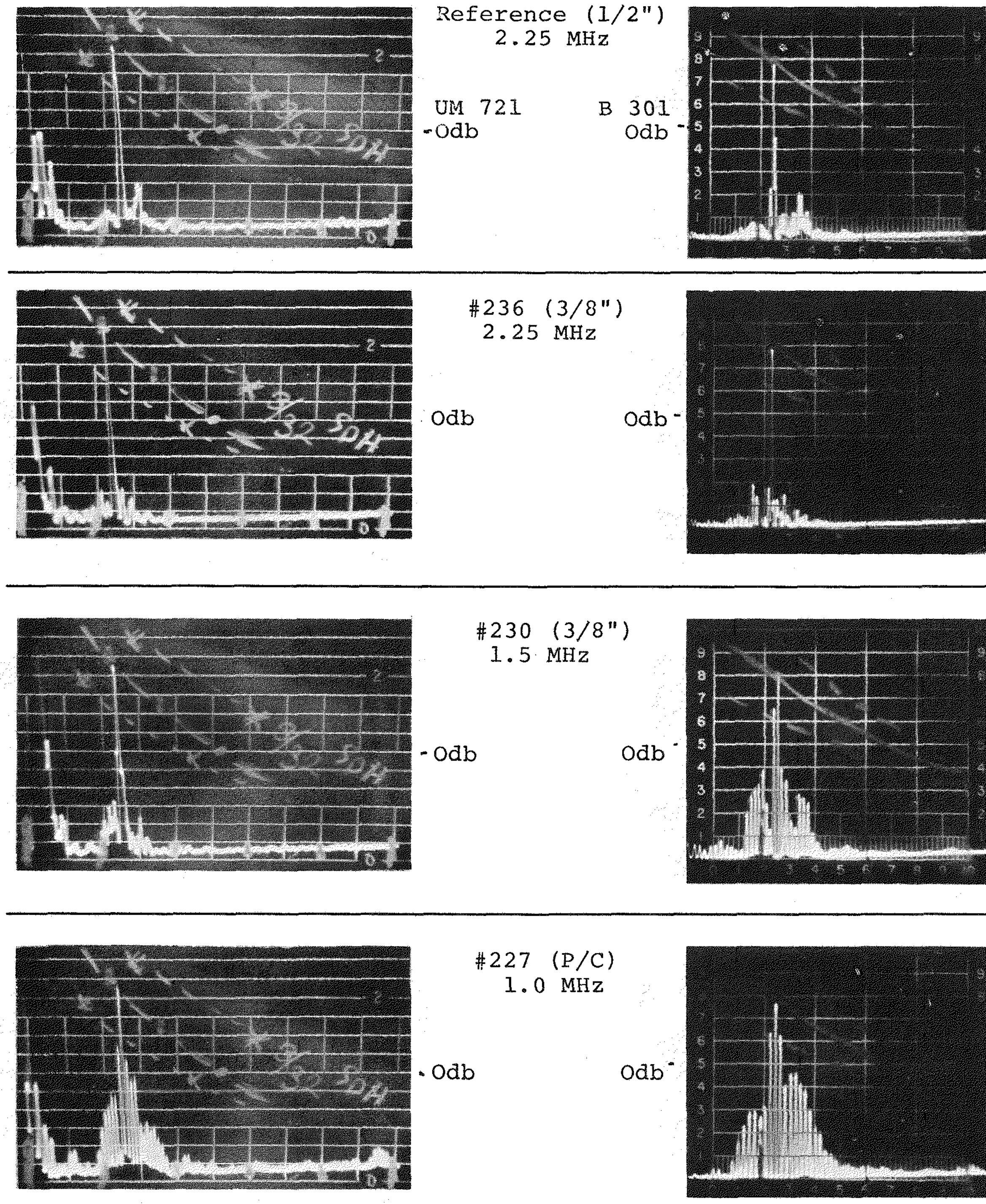


FIGURE A2-7: CALIBRATION STANDARD AT 3/4 VEE PATH

APPENDIX A3

THE DUAL ELEMENT ANGLE BEAM TRANSDUCER

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Section 1

INTRODUCTION AND SUMMARY

The dual element angle beam transducer has demonstrated its superiority in a number of inspection fields, particularly with respect to the evaluation of austenitic stainless steel. An explanation of the dual angle beam operation and suitability in severely attenuative environments is presented in this report. Experiments and a theoretical study are also included that present an optimization philosophy for improving dual angle beam performance.

Design parameters such as transducer shape, crystal separation distance, roof angle, and wedge angle are studied for their influence on performance parameters such as lateral resolution, focusing, and beam symmetry. A set of specifications for three transducers for ultrasonic inspection of austenitic stainless steel pipe having wall thicknesses in the range of 0.5 to 1.3 inches has been derived from this work and is as follows:

Dual Element Transducer Probe Specifications

• Nominal pipe diameter, Sch. 80 (inches)	4"	10"	24"
Wall thickness (cm)	.83	1.51	3.1
• Element shape	Square	Square	Square
• Element size (cm)	.6x.6	.9x.9	1.1x1.1
• Roof angle	9°	8°	7.5°
• Incident angle	(As required to yield 45° angle in steel)		
• Center frequency	1.5 MHz	1.5 MHz	1.5 MHz
• Frequency content	'Intermediate' (i.e., 6dB down bandwidth equals center frequency)		

- Other (common)
  - Height of transducer above interface 0.8 cm minimum.
  - 1/4 wave length reinforcing layer bonded crystal and wedge.
  - 0.08 cm (minimum) acoustical barrier between transmitter and receiver.
  - Wedge height such that near field occurs within wedge.
  - Careful construction and selection of backing and shoe material. Piezoelectric element. Lead Zirconate Titanate works well.

These specifications confirm those of the original developmental units used throughout the program. However, most developmental efforts accented two transducer sizes; one for 'small' pipes (4-10" diameter), a second for 'large' pipes (14-26" diameter). The use of these two transducers might suffice, but consideration of an intermediate range unit appears warranted. Note that the transducers are optimized for pipe wall thickness. Pipe diameter, used as a reference term, implies Schedule 80 construction. Optimization for other schedules can be derived by interpolation.

ATTENUATION PRINCIPLES

An important ultrasonic inspection consideration affecting transducer selection is attenuation of sound in the inspected material.

During ultrasonic examination of a material, it is noted that the amplitude of the back wall echo is less than the input signal even when the test piece is flawless. This decrease in amplitude may be due to dispersion and/or attenuation.

An ideal material (perfectly elastic) can be defined on the basis of decrease in sound pressure that is based only on the type and scattering or beam spreading of the ultrasonic waves. A plane wave does not show any increase in pressure along its direction of propagation, whereas the magnitude of spherical wave decreases inversely with the distance from the source. However, in real materials, there are other effects that further decrease signal amplitude. These effects are primarily grain scattering and/or absorption. These two phenomena are combined together in an attenuation coefficient concept as

$$p = p_o e^{-\alpha l}$$

where p and p_o represent acoustic amplitude value at distances l and o, respectively, and α is the attenuation coefficient.

There are many factors responsible for scattering, and, hence, partial attenuation of an ultrasonic wave. For a macroscopic point of view, the assumption of homogeneity holds for (infinitesimal deformation) elasticity; but from a microscopic point of view, the material is not homogeneous. There are gaps or voids between crystals. Assuming that the sound wave strikes at an oblique angle at the grain boundary, one can visualize how scattering takes place. In such a case, the wave is mode converted into various reflected and transmitted wave types. This process is repetitive for each wave along every grain boundary. Even when only a single type of crystal is present, the material may still be inhomogeneous for ultrasonic waves if the grains are randomly oriented. This is due to the fact that the crystal has different elastic properties and, therefore, different sound velocities in different directions (anisotropic materials). Because of nonhomogeneity, there exists boundaries between crystals at which the acoustic impedances are different. Due to this acoustic impedance mismatch, some of the sound energy is transmitted while other sound energy is reflected back from irregular boundaries in the medium causing scattering.

Another factor is known as "absorption". Absorption occurs in real materials (not perfectly elastic) due to the fact that the elastic potential energy changes into kinetic energy of the vibrating particles and vice versa. During this process, some of the energy is lost owing to factors such as internal friction and heat conduction. The result is that sound pressure decreases with the distance and attenuation takes place. It is evident that there will be more losses or a higher degree of absorption for rapid oscillation of the particles which is associated with the higher frequency sound waves. In the frequency range of ultrasonic testing, the wave length is often larger than the grain size. Scatter for all practical purposes is negligible when grain size is 1/1000th to 1/100th of the wave length. However, scatter increases very rapidly (as the third power of grain size) when the grain size is of the order of 1/16th to a full wave length. Scatter is also proportional to the fourth power of the frequency (1)(2). These exponential scattering losses dependencies sometimes mean that a specimen cannot be tested ultrasonically.

ATTENUATION CONSIDERATIONS FOR AUSTENITIC STAINLESS STEEL

A. Material

Austenitic stainless steels, with 18% Cr and 8% Ni are employed extensively in the fabrication of nuclear power plant components because they have excellent welding characteristics and good corrosion resistance features. The ultrasonic inspection of these steels is more difficult than for conventional ferrities, because of the very large attenuation which ultrasonic waves undergo during propagation through austenitic materials. The metallurgical conditions which have been identified as contributing factors to this very high attenuation include: grain size, grain orientation, ferrite content, microfissure content, precipitate content and heat treatment. Variations in any or all of these factors can cause variations in the attenuation and scattering characteristics of the material. One result is that variable attenuation may be encountered from location to location within the same material. The large absorption and scattering is responsible for the very low signal to noise ratio affecting both detectability and classification probability for flaws in austenitics.

B. Pipe Welds

A weld preparation procedure is carried out before actually welding the pipes together. Figure A3-1 shows the weld joint configuration before welding. Two different procedures, namely removable ring and open joint manual back up methods along with manual metal arc welding and submerged metal arc welding are employed. The process of welding involves raising the temperature of the joint to the melting point of the base material by the application of an intense local heat source. Austenitic filler material is then used, generally of matching composition to the base material, to form the molten weld pool. Various weld passes are laid one at a time according to prescribed specifications. Figure A3-2 shows typical weld pass configuration for 4 and 26 inch diameter, schedule 80 pipe.

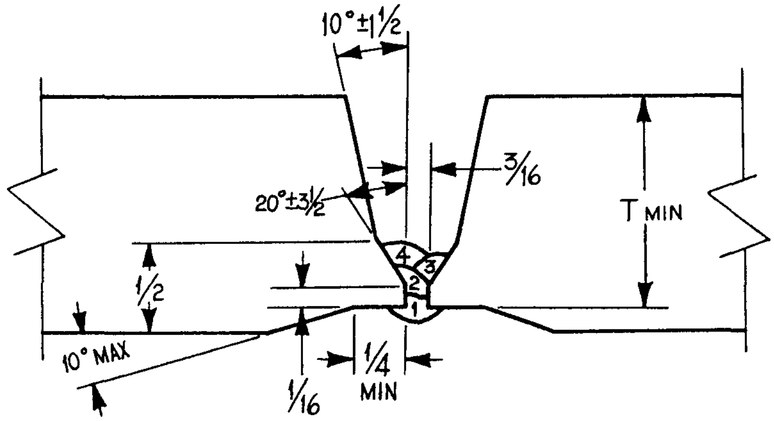
The welding operation has a number of consequences from an ultrasonic inspection point of view, in particular

(i) Molten weld metal solidifies as a cast structure resulting in dendritic grain growth perpendicularly to the isotherms of the solidifying weld metal and are directed perpendicularly to the side walls of the weld. The dendrites, therefore, run from side walls to the center of the weld and have a curvaceous structure. The dendritic fiber structure has 100 to 500 μm diameter and reach up to 10 mm length. These dendrites offer tremendous attenuation to the ultrasonic waves. They may also act as wave guides causing false indications (3)(4).

(ii) Formation of a heat affected zone (HAZ) defined as a zone where chromium depletion adjacent to, and chromium carbide precipitation in the grain occurs. This zone is anisotropic in nature; the kind, location, and direction of the crystals in HAZ influence the attenuation characteristics of the ultrasound (5)(6).

A micrograph of the base and weld metal including heat affected zone is shown in Figure A3-3. The micrograph is obtained from a 26 inch pipe specimen at 200 x using $10CH_3$:$10CH_3COOH$:15HCl + glycerol etchant.

The study of attenuation characteristics of the pipe weld materials is useful to understand the large attenuation of the ultrasonic waves. The dendritic grain growth in the weld metal and the presence of HAZ near the root weld explains the anisotropic nature of the material and variable attenuation. The presence of dendrites in the weld metal makes the total volumetric ultrasonic inspection very difficult.



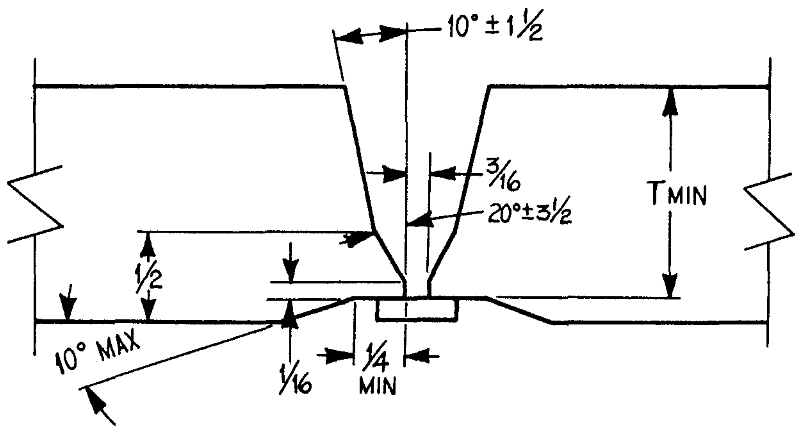
Manual metal arc data

Passes	Electrode	Average volts	Amps
1-4	1/8 Dia.	25	90-110

Submerged arc data

Passes	Electrode	Volts	Amps	Speed("/min)
1-10	1/8 Dia.	30-32	400-420	26-28
11-Balance	3/16Dia.	33-34	680-700	32
Cover	3/16Dia.	33-34	620	32

FIGURE A3-1A: WELDING CONFIGURATION:
OPEN JOINT - MANUAL BACKUP METHOD



Manual metal arc data

Passes	Electrode	Average volts	Amps
1&2	3/32dia	23	60-80

Submerged arc data

Passes	Electrode	Volts	Amps	Speed("/min)
1-10	1/8Dia.	30-32	400-420	26-28
11-Balance	3/16Dia.	33-34	680-700	32
Cover	3/16Dia.	33-34	630	32

FIGURE A3-1B: WELDING CONFIGURATION:
REMOVABLE RING METHOD

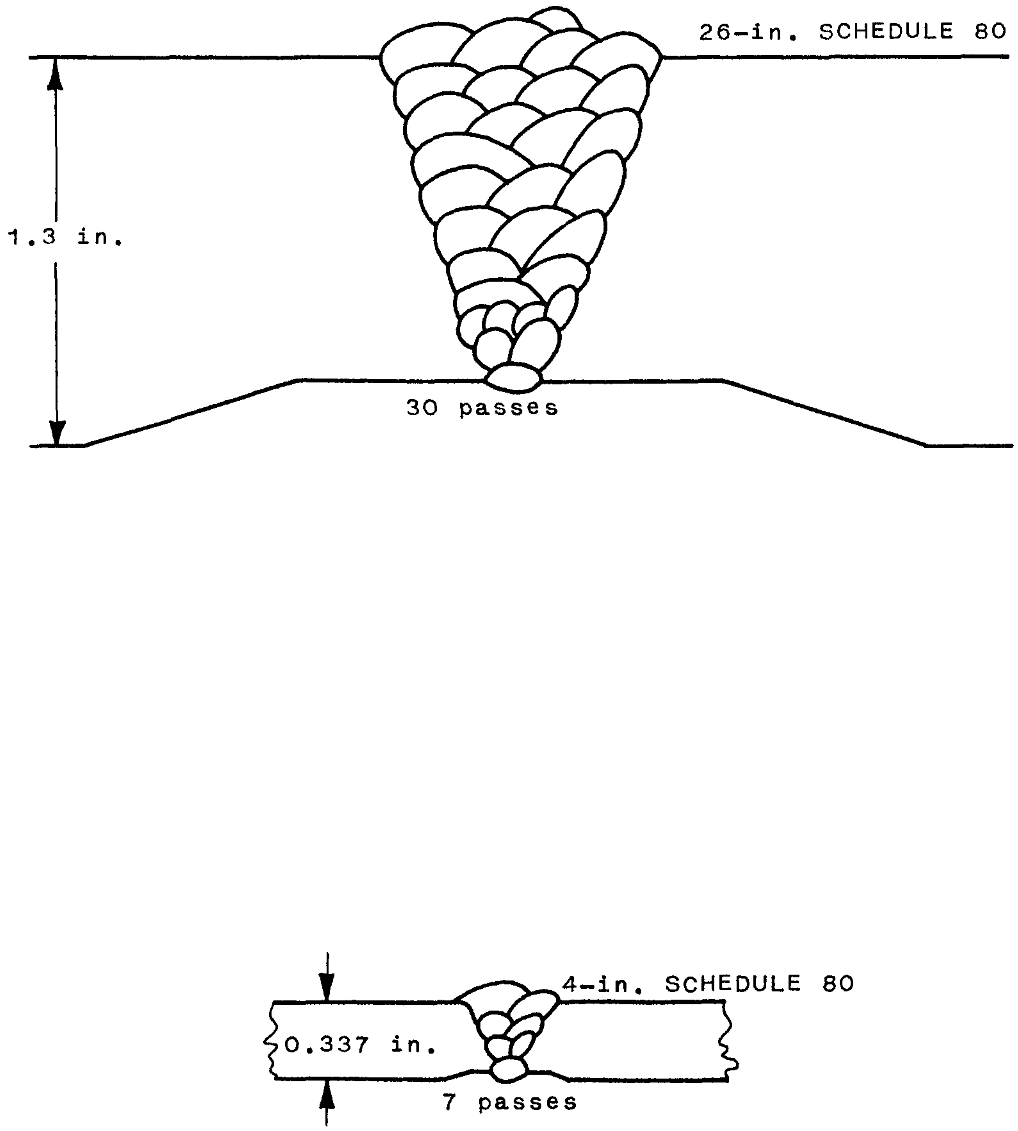


FIGURE A3-2: TYPICAL WELD PASS CONFIGURATION

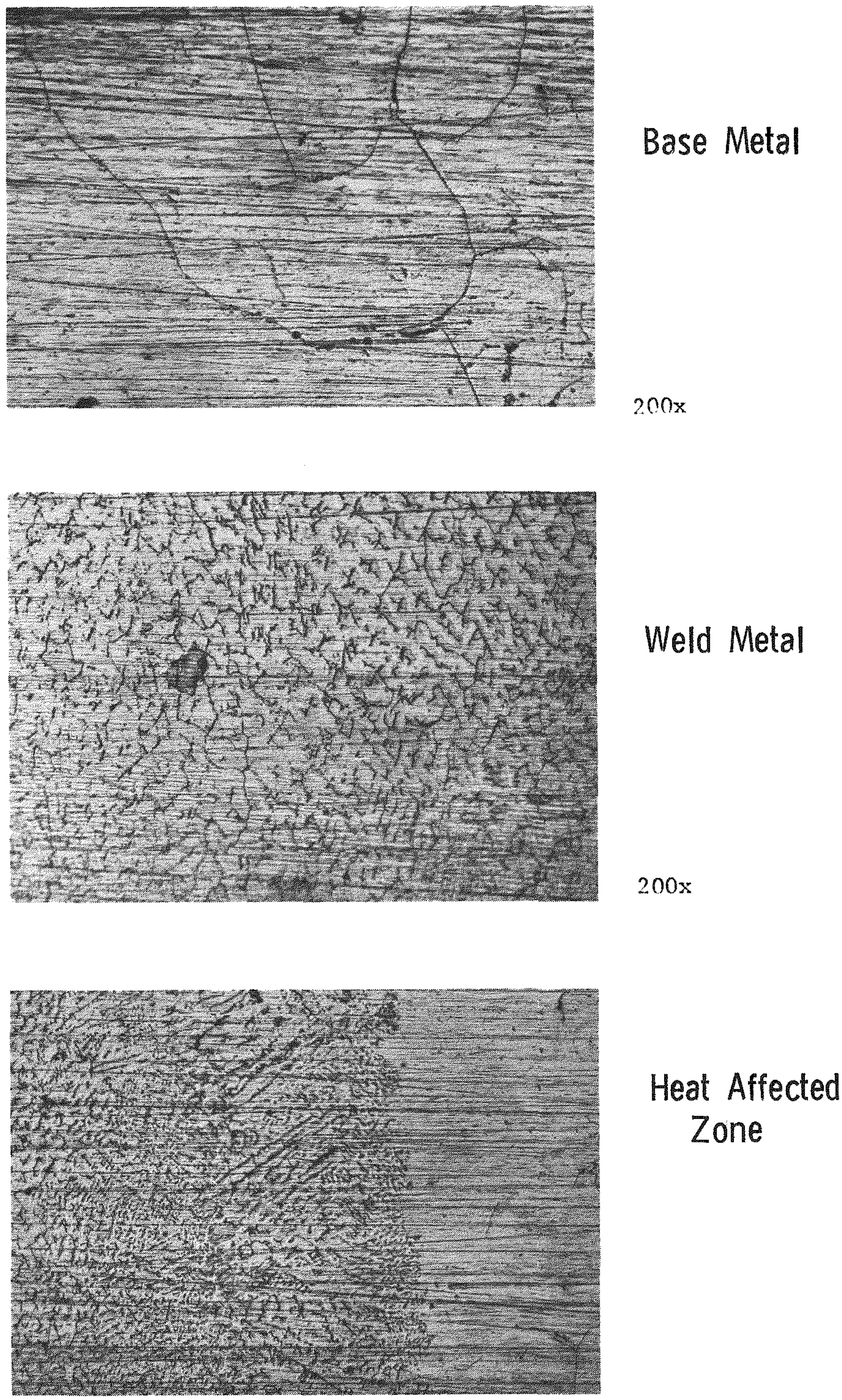


FIGURE A3-3: MICROGRAPH OF 26 INCH PIPE MATERIAL

Section 2

POTENTIAL VALUES OF A DUAL ELEMENT ANGLE BEAM TRANSDUCER

Several researchers (6)(7)(8)(9) recommend the use of dual element angle beam transducers for the detection of intergranular stress corrosion cracking in austenitic stainless steels. Their results indicate that the use of dual element angle beam probes yield much higher SNR and, therefore, higher reflector detection probability. An experimental study has been conducted for transducer selection based on SNR from reflector detectability and classification potential points of view. A brief discussion on the dual element angle beam transducers and their superiority in terms of high SNR is also presented.

The dual element transducers consist of acoustically and electronically separated transmitting and receiving elements. The transmitting and receiving elements are positioned at an angle to each other, as illustrated in Figure A3-4. The dual element angle beam transducer design is shown in Figure A3-5. The physical explanation of SNR superiority of the dual element probe in stainless steel inspection can be postulated in conjunction with Figure A3-6 as follows:

1. Directivity of the sending transducer is towards a crack surface with many grain scattering centers in its way.
2. Directivity of scattering centers is much more concentrated towards the sending transducer compared to the receiving transducer, especially when considering the cumulative effect of all grain scattering that occurs along the path from the sending transducer to the crack surface in question.
3. Grain scattering as the wave travels from the crack surface to the receiver will not impinge on the receiving transducer since sound is back scattered in the direction of the crack surface.

The reasoning for superiority also stems from the fact that the reflected energy received is returned from a rather small zone where the ultrasonic beams related to each crystal overlap. A dual element transducer is designed for a fixed thickness range. Its application beyond the design range results in poor SNR and the drop-off is very fast. In order to inspect large thicknesses, a number of probes would be required. It is due to this reason they are not commonly employed for

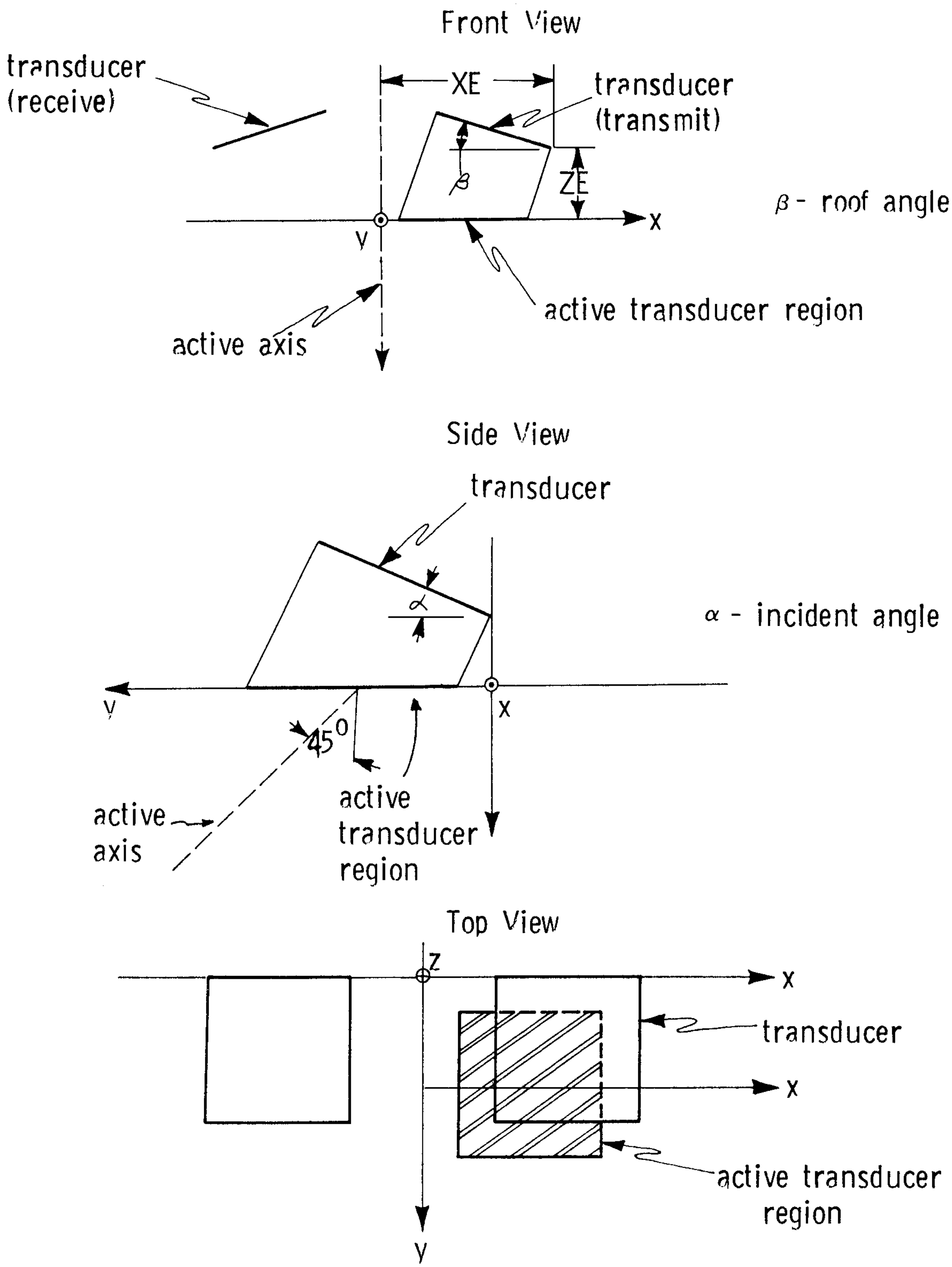


FIGURE A3-4: DUAL ELEMENT ACTIVE AXIS COMPUTATION CONCEPT

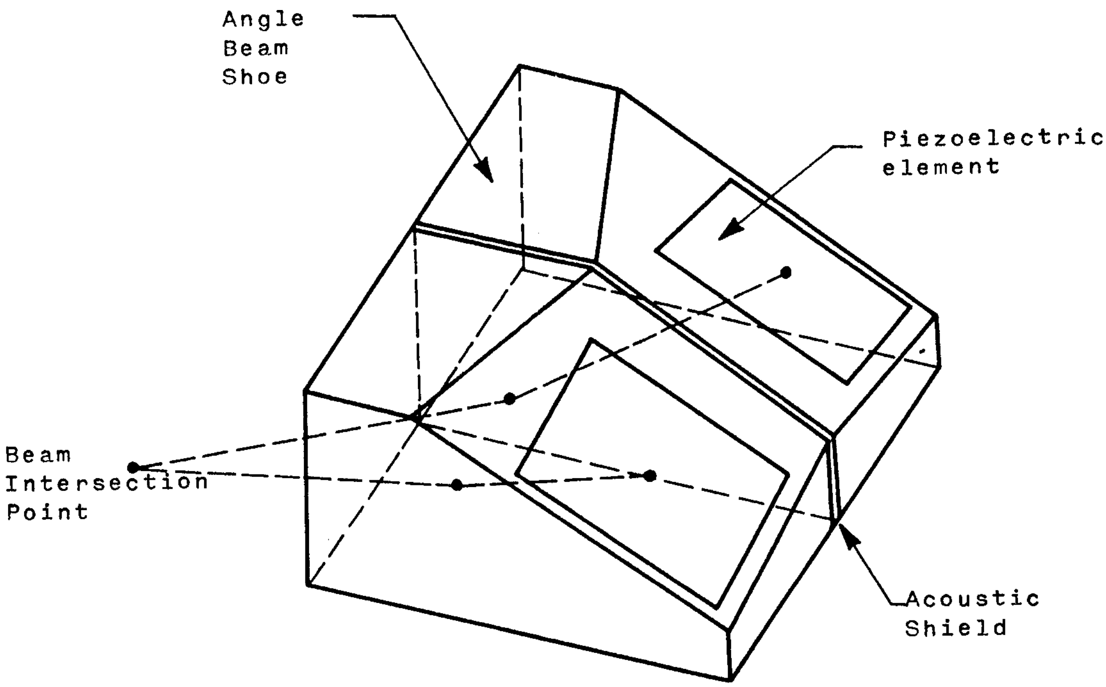
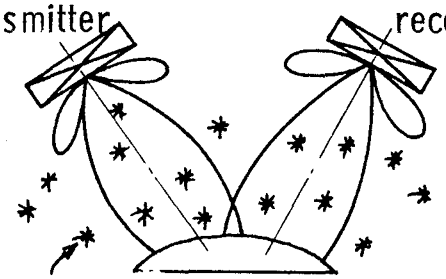


FIGURE A3-5: DUAL ELEMENT ANGLE BEAM TRANSDUCER DESIGN



1. directivity of the sending transducer is towards a crack surface with many grain scattering centers in its way.
2. directivity of scattering centers are much more concentrated towards the sending transducer compared to the receiving transducer, especially when considering the cumulative effect of all grain scattering that occurs along the path from the sending transducer to the crack surface in question.
3. Grain scattering as the wave travels from the crack surface to the receiver will not impinge on the receiving transducer since sound is back scattered in the direction of the crack surface.

FIGURE A3-6: PHYSICAL EXPLANATION OF DUAL PROBE VALUES IN STAINLESS STEEL PIPE INSPECTION every day inspection problems. From the postulated physical explanation it can further be argued that the dual element probes, for a fixed range of testing, are at least as good as a single element transducer, if not better.

SNR DETERMINATION ON A 26" PIPE SPECIMEN

Before proceeding with the test description and analysis, a discussion on SNR computation method is in order. SNR can basically be defined as a ratio of signal amplitude to noise amplitude. These amplitudes can be calculated by a variety of techniques, e.g., variance, root mean square, peak methods, etc. The standard SNR definition from an electrical engineering point of view is based on peak signal amplitude and variance of noise. This particular method from an ultrasonic detectability point of view is not suitable. The SNR from detectability considerations is defined as the ratio of peak signal amplitude to the peak noise value in the signal. This definition is deemed suitable since an ultrasonic operator makes his decision based on the video presentation of the amplitude values of various echoes in the flaw detector screen, the flaw echo amplitude being much larger than the "grass" noise amplitude value. However, for signal processing and pattern recognition analysis, the standard definition of SNR based on variance is acceptable. The SNR based on both these concepts are examplified in Figure A3-7. SNR based on noise variance is smaller for the case when an ultrasonic echo experiences large scattered and electrical noise. The SNR based on peak to peak value of noise, for the same case, is higher, On the other hand, however, when the returning echo has large amplitude noise but less oscillations in the noise segments, the SNR based on noise variance is higher and that based on the peak to peak value is lower. Both values of SNR are useful, one from a detectability point of view, and the other from a pattern recognition viewpoint.

The experiments were conducted on a 26 inch pipe specimen using six different transducers. These included three single element 1.5, 2.25, and 3.5 MHz transducers and three dual element transducers, all 1.5 MHz nominal frequency. The 26 inch pipe specimen corner was used as the reflector target. A typical test sequence included: Adjusting instruments to the proper predetermined settings, obtaining a maximum amplitude echo from the corner of the pipe, clamping the transducer, acquiring the signal several times into the computer memory through the A/D converter and calculating the signal to noise ratio based on the variance and peak to peak value techniques. A signal of 10.24 μsec was digitized at a sampling interval of .02 μsec. First, 256 points were searched for the peak of the signal, and the last 256 points provided the variance or peak to peak noise value.

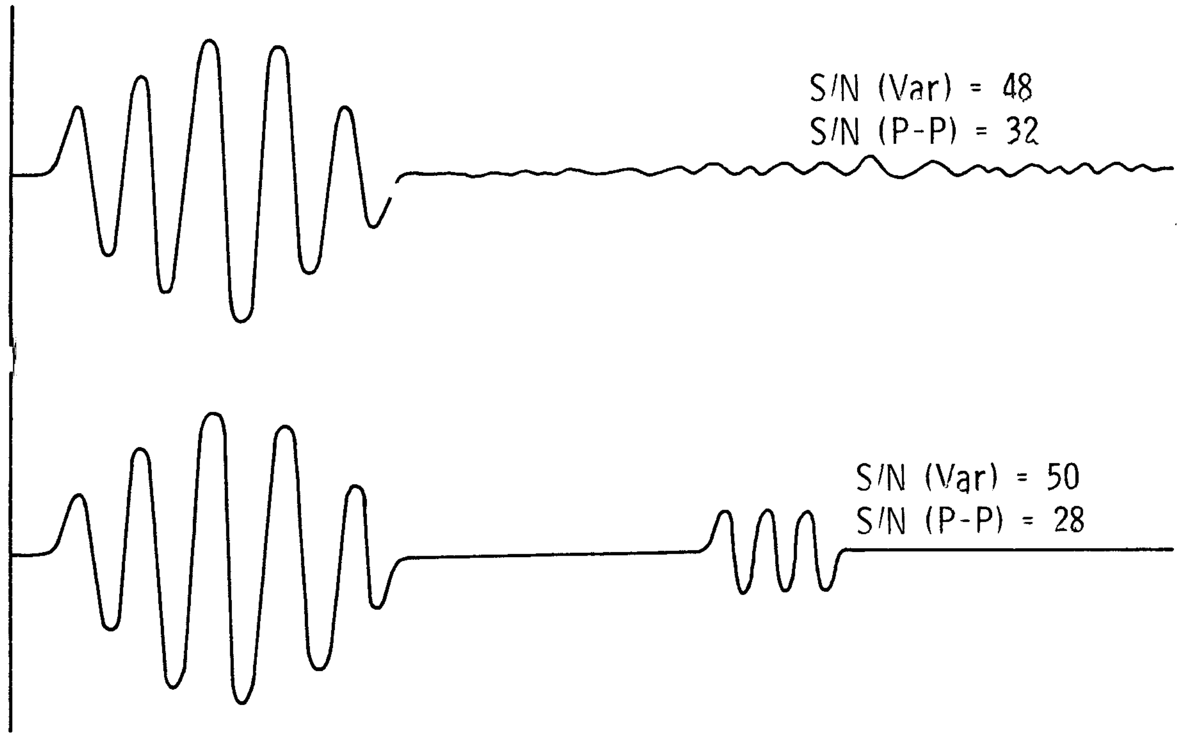


FIGURE A3-7: SNR CONCEPT: CURVES ILLUSTRATING DIFFERENCE BETWEEN NOISE VARIANCE AND NOISE PEAK TO PEAK TECHNIQUES

Figure A3-8 shows the SNR versus number of times averaged for six different transducers. Averaging in time is obviously beneficial for removing random electronic noise effects. Figure A3-8A shows results based on the peak to peak noise value. The curves can clearly be divided into two groups. The dual element transducers have 9-12 dB higher SNR compared to the single element transducers. The dual element KB-Aerotech, which was specifically optimized for 26 inch pipe, showed the highest SNR. Figure A3-8B shows the results for the SNR based on the noise variance. The 3.5 MHz transducer has a minimum SNR which can be explained by the fact that higher frequencies scatter more ultrasonic energy thereby creating larger noise oscillations and hence lower SNR based on the variance of noise.

Experimental analyses have also been conducted to determine the best transducer based on the gain criteria. The gain study considered the same six transducers used for SNR study. The experiment consisted of noting the attenuator setting for the same amplitude echo level for all the transducers and is presented in Table A3-1. The data were obtained from four different target reflectors, namely, corner of a 26 inch diameter pipe specimen, IGSC crack block, and a 1.6 mm diameter hole in carbon steel block. The 1.5 MHz dual element KB-Aerotech transducer, No. J28813, showed remarkably higher dB values for the same amplitude echoes. A consistent difference of approximately 28 dB was observed. This dual element transducer (or its equivalent) is therefore of specific interest for reflector detection as well as for signal acquisition and processing using advanced test data processing techniques.

DUAL ELEMENT ANGLE BEAM TRANSDUCERS: THEORETICAL ANALYSIS

Dual element transducers utilize separate transmitting and receiving elements to provide higher signal to noise ratio, thereby increasing the probability of the flaw detection. A lack of theoretical knowledge of the mechanism providing the higher signal to noise ratio contributes to the design complexity of these probes. A large number of variables must be considered for an optimum probe. An existing ultrasonic analysis computer program has been modified to model and optimize a dual element angle beam transducer (11). This program is used to evaluate the sound pressure field variations due to a number of dual element angle beam transducers in order to obtain an optimally shaped and designed transducer.

The theoretical dual element angle beam transducer pressure field computation concept was presented in Figure A3-4. The front view of the transducer shows both

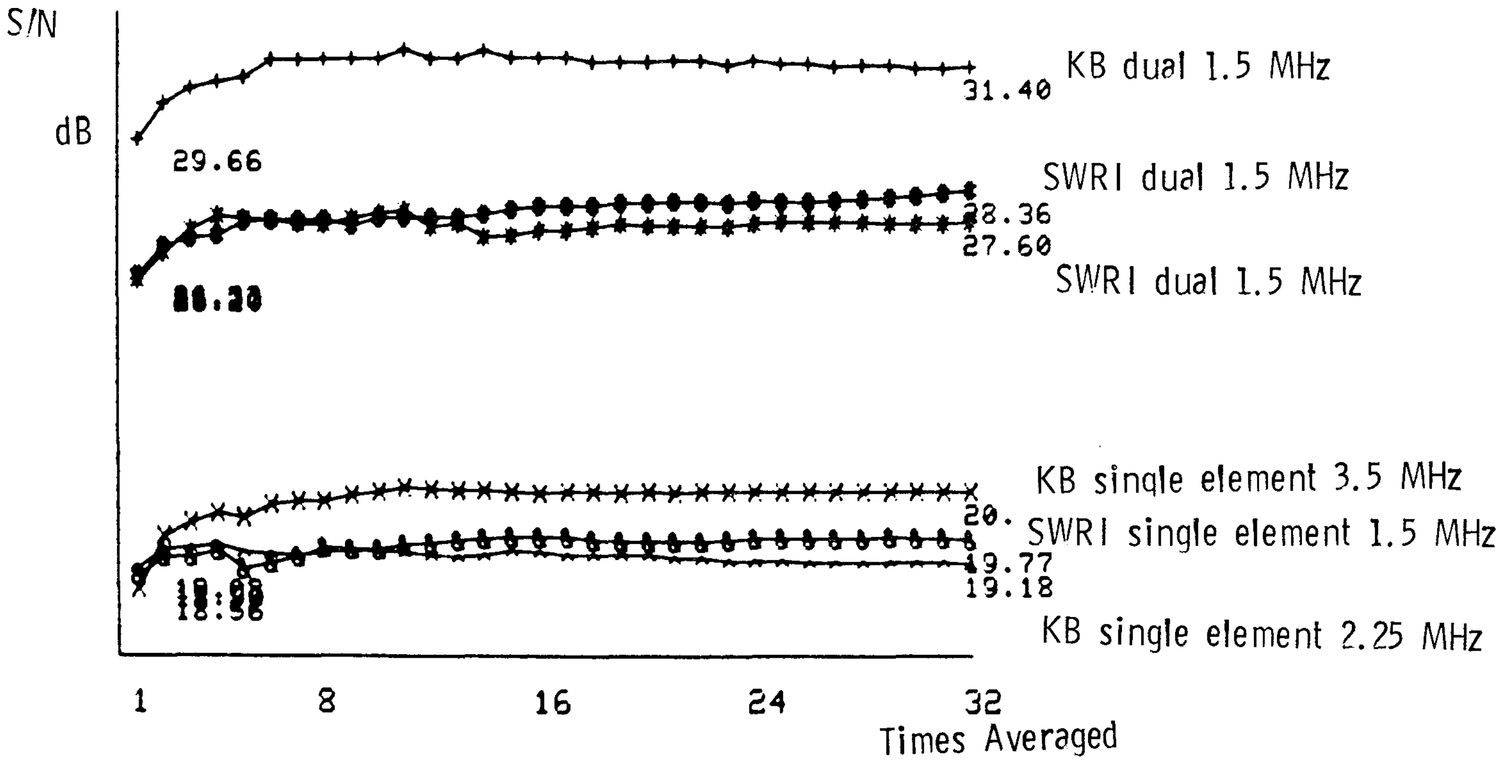


FIGURE A3-8A; SNR BASED ON NOISE PEAK TO PEAK VALUE FOR SEVERAL ULTRASONIC TRANSDUCERS

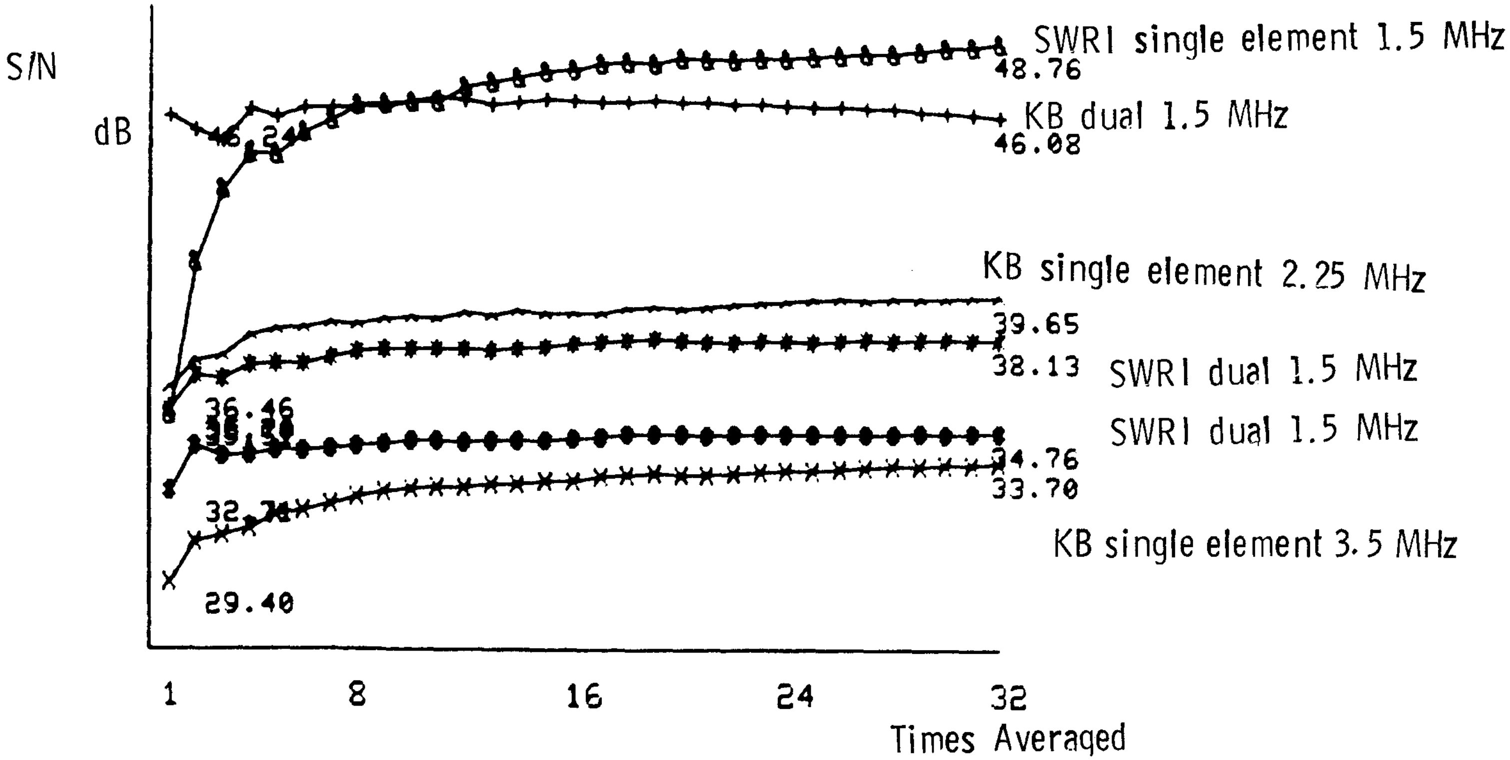


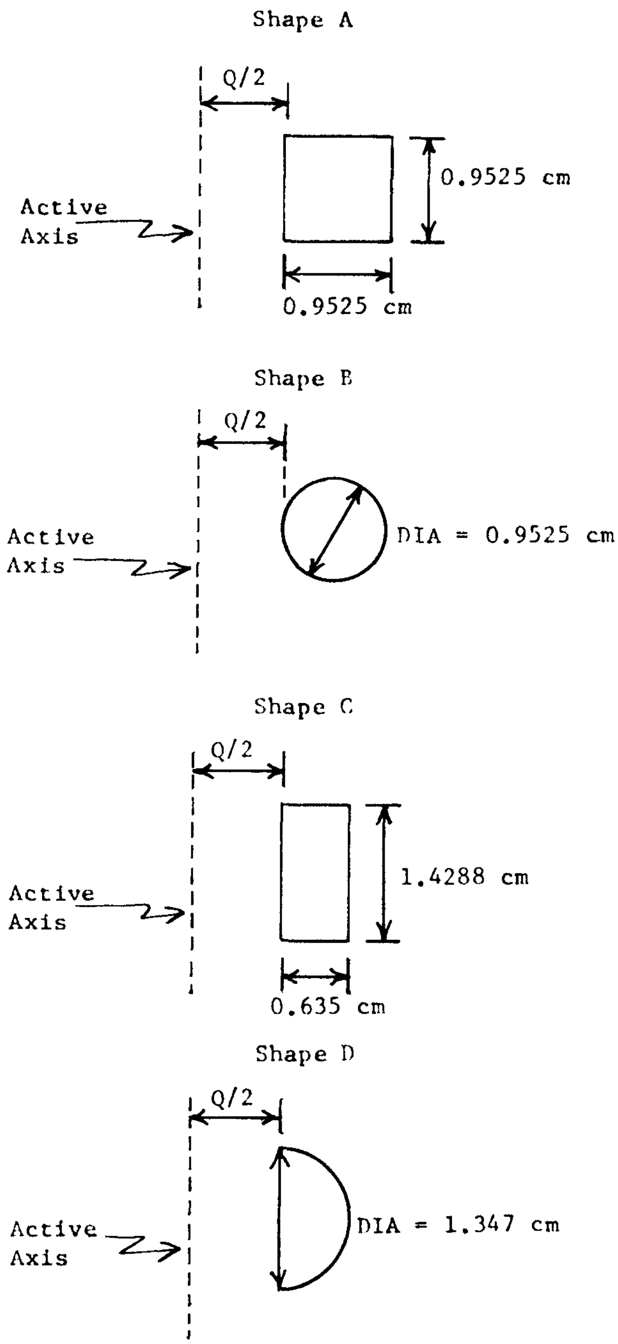
FIGURE A3-8B; SNR BASED ON NOISE VARIANCE FOR SEVERAL ULTRASONIC TRANSDUCERS

	Single Element Transducers			Dual Element Transducers 1.5 MHz Specified C.F.		
	1.5 MHz 3/8" dia SwRI #577	2.25 MHz 1/4" dia Aerotech C24601	3.5 MHz 1/4" dia Aerotech J06877	SwRI #877	SwRI #880	Aerotech J28813
		Attenuator Reading in dB				
Corner of Pipe Specimen	4	17	8	10	10	42
4" Radius of 11W Block	1	28	35	13	15	39
1.6 mm (62 mil) SDH in Carbon Steel Block 1-1/8" deep	0	6	16	0	0	39
IGSCC in 26" dia pipe specimen	0	13	0	3	4	31

TABLE A3-1: Gain Study for Transducer Selection Based on Detectability

transmitting and receiving transducers angulated towards each other at an angle β, known as the roof angle. The side view shows the incident shoe angle α. The ultrasonic transducer is represented by an active transducer region at the interface between the transducer shoe and the material. The active transducer region is shown in the top view. The pressure field calculations are made along and across the active axis as shown in Figure A3-4. These profiles can be used to study changes in the focal distances and lateral resolution of the transducers.

A theoretical study aimed at the determination of the optimal transducer shape for 26" pipe which minimizes the lateral resolution has been performed. The various transducer shapes used in this study are shown in Figure A3-9. Table A3-2 presents the results of this parametric study. One should note the effect that transducer shape has on the shape of the ultrasonic beam. Table A3-2 shows that a square transducer shape (shape A in Figure A.3-9) is clearly the best choice for minimizing the 3 and 6 dB down beam widths of the lateral resolution as obtained from a transverse pressure profile.



Square Transducer
Q = .8 cm TH = .8 cm
roof angle β = 5°

Circular Transducer
Q = .8 cm TH = .8 cm
roof angle β = 5°

Rectangular Transducer
Q = .8 cm TH = .8 cm
roof angle β = 5°

Semicircular Transducer
Q = .8 cm TH = .8 cm
roof angle β = 5°

FIGURE A3-9: TRANSDUCER CONFIGURATIONS USED IN THE SHAPE OPTIMIZATION STUDY

Computer Run	Transducer Parameters			Transverse Pressure			Active Axis Profile		
	Q (cm)	β (degree)	shape see Fig.10	Active Axis Distance (cm)	3 dB down width (Displacement from center) (cm)/(cm)	6 dB down width (Displacement from center) (cm)/(cm)	Focal Distance (cm)	Pressure Variation 1/2 F.D. (dB) 2 F.D. (dB)	3 dB down focal length (cm)
1	.8	5	A	3.302	0.5815 0.4179	0.9922 0.3604			
2	.8	5	A				5.0	-5.603 -5.150	5.017
3	.8	5	B	3.302	0.6663 0.3958	1.0539 0.3641			
4	.8	5	B				4.5	-6.484 -4.452	4.753
5	.8	5	C	3.302	0.9789 0.2477	1.3415 0.2343			
6	.8	5	C				3.5	-5.314 -2.799	5.105
7	.8	5	D	3.302	0.8749 0.4486	1.3169 0.4527			
8	.8	5	D				4.0	-8.503 -3.334	5.027

Table A3-2: Transducer Shape Optimization Study for Improved Lateral Resolution

Figure A3-10 shows how the 3 and 6 dB down widths and displacement from the centerline is calculated from the transverse pressure profile.

Figure A3-11 shows the focal distance, pressure at half and twice the focal distance and the 3 dB down focal length calculations from the active axis profile.

Figure A3-12 is a graph of the active axis profiles for the four transducer shapes shown in Figure A3-9 and Table A3-2.

Now that the optimally shaped transducer configuration has been found, a study was performed to find the optimal transducer parameters for the best transverse pressure resolution at a focal distance of 4.0 cm along the active axis.

Table A3-3 shows the results of the active axis profile and transverse pressure profile for this transducer configuration.

Listed below are the dual element angle beam transducer configuration which satisfies the above-mentioned criterion.

Transducer Shape - Square

Length - 1.1 cm
Width - 1.1 cm

Separation Distance of the crystal elements Q - 0.7 cm

Roof Angle β - 7.5°

Incident Angle α - 36.6°

Height of the transducer above the interface TH - 0.8 cm

Figure A3-13A is the active axis profile of the optimally shaped transducer. Figure A3-13B is the transverse pressure point profile for this transducer at the active axis focal distance of 4.0 cm.

To illustrate the lateral resolution variation with distance for this transducer configuration, a plot of the 3 and 6 dB down widths versus active axis distance is shown in Figure A3-14A. Figure A3-14B is a plot of 3 and 6 dB down width centerlines from the active axis (the zero coordinate on the transverse pressure profile). Figures A3-14A and A3-14B clearly demonstrate how the transverse pressure profile width and the centerline displacement from the active axis varies along the active axis.

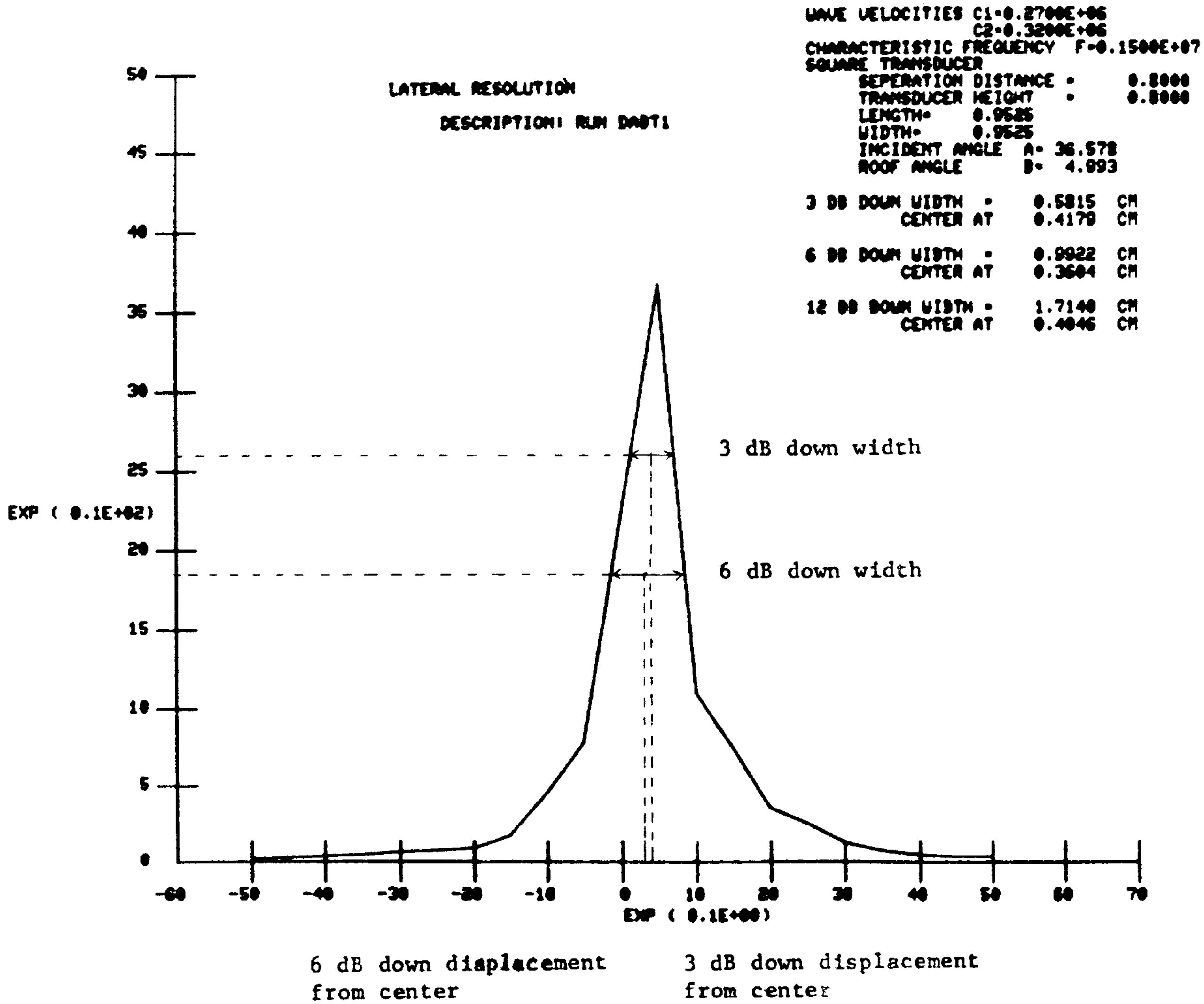


FIGURE A3-10: TRANSVERSE PRESSURE PROFILE CALCULATIONS

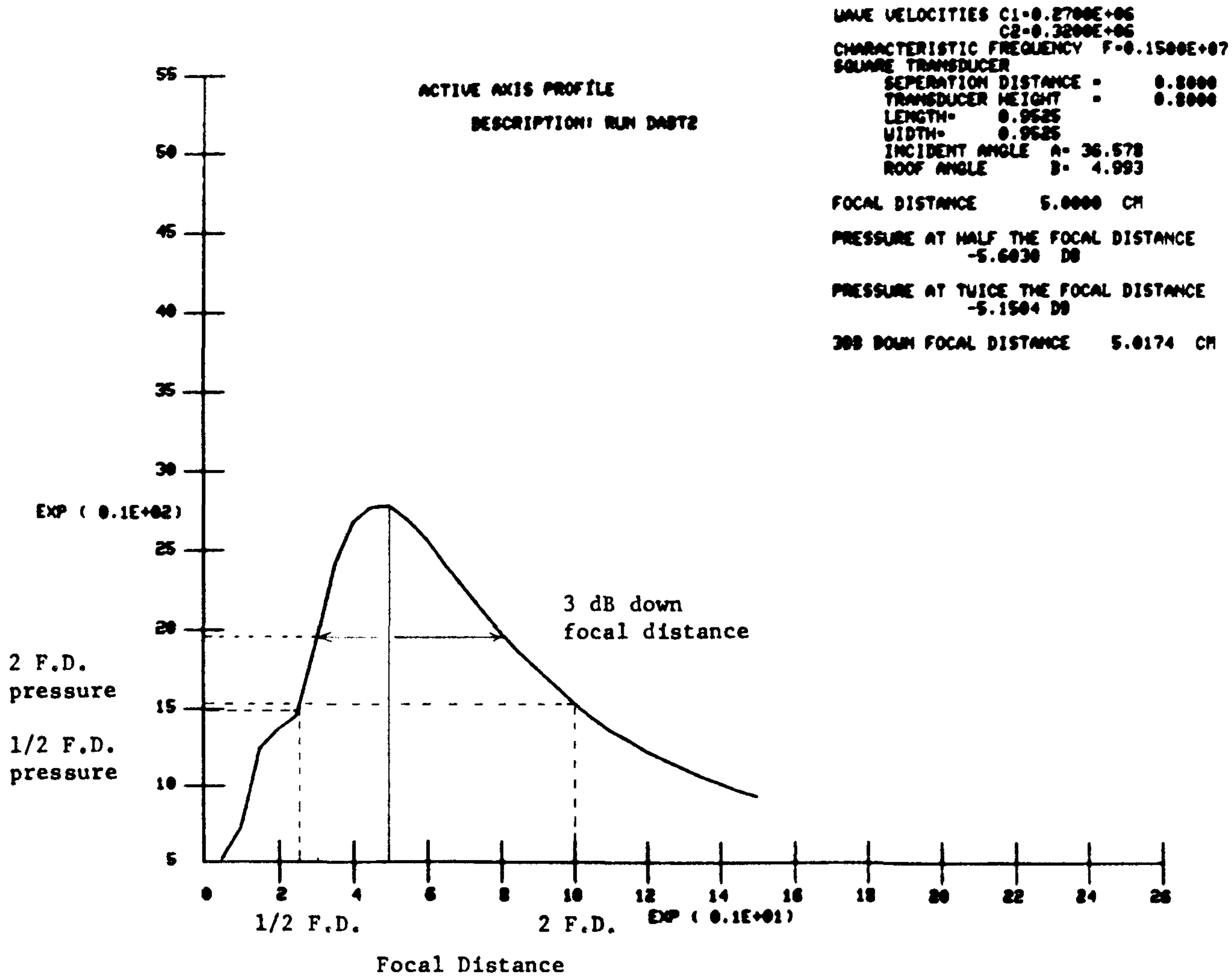


FIGURE A3-11: ACTIVE AXIS PROFILE CALCULATIONS

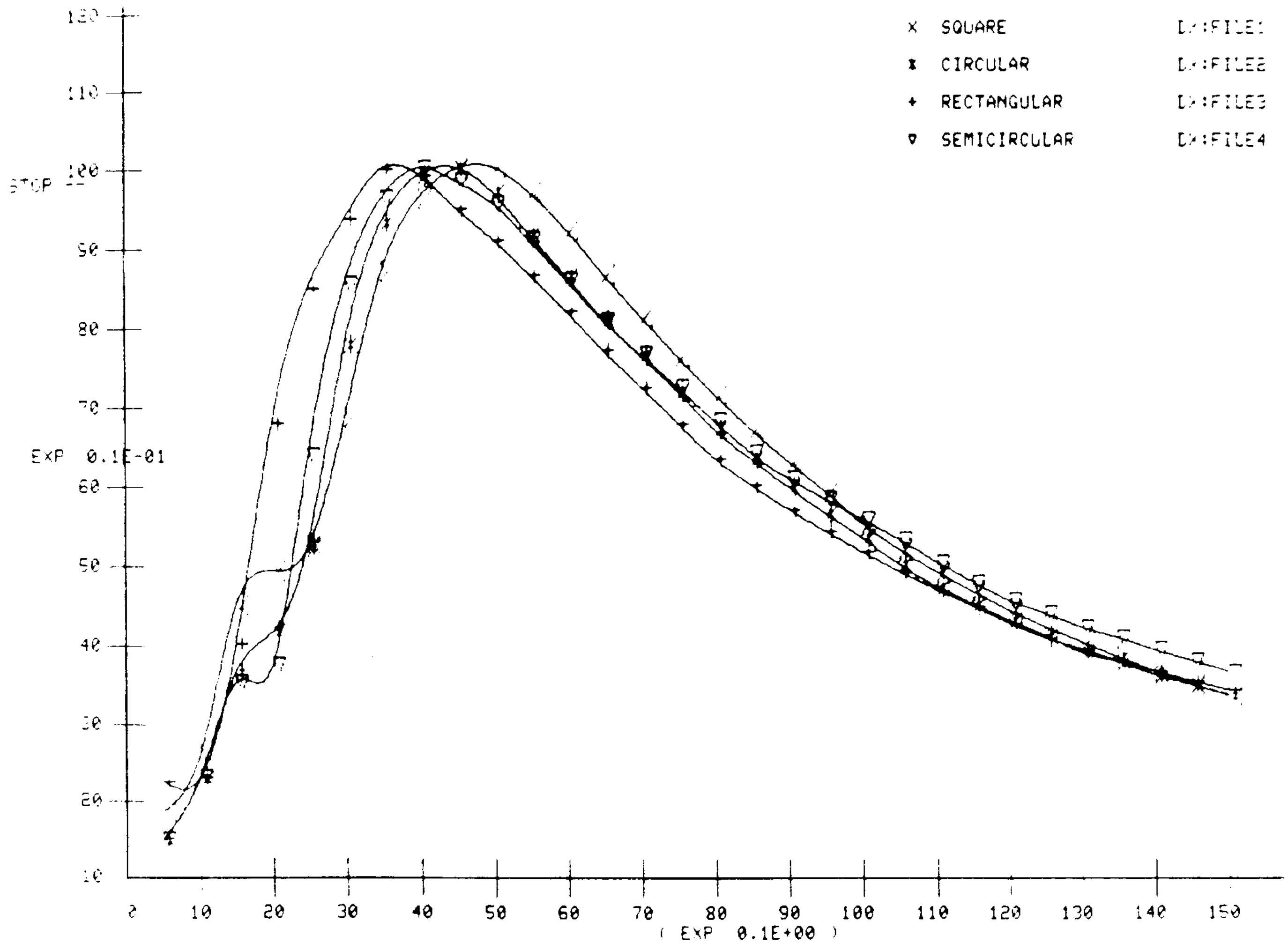


FIGURE A3-12: ACTIVE AXIS PROFILE FOR THE FOUR TRANSDUCER SHAPES IN FIGURE A3-9

	Transducer Parameters					Transverse Pressure			Active Axis Profile		
	Q (cm)	β (degrees)	Shape	Length (cm)	Width (cm)	Active Axis Distance (cm)	3 dB down width (Displacement from center) (cm)/(cm)	6 dB down width (Displacement from center) (cm)/(cm)	Focal Distance (cm)	Pressure Variation 1/2 F.D. (dB) 2 F.D. (dB)	3 dB down focal length (cm)
9	.7	7.5	square	1.1	1.1				4.0	-5.743 -7.758	3.268
10	.7	7.5	square	1.1	1.1	2.0	0.5425 0.4881	0.9266 0.4797			
11	.7	7.5	square	1.1	1.1	2.5	0.7904 0.3658	1.2022 0.3447			
12	.7	7.5	square	1.1	1.1	3.0	0.9152 0.2430	1.2849 0.2760			
13	.7	7.5	square	1.1	1.1	3.5	0.6560 0.1053	1.2280 0.1810			
14	.7	7.5	square	1.1	1.1	4.0	0.5858 0.0224	1.0333 0.0547			
15	.7	7.5	square	1.1	1.1	4.5	0.6668 -0.0913	1.1191 -0.0913			

Table A3-3: Beam Profiling of the Optimally Shaped Transducer Configuration for Best Transverse Pressure Resolution at 4.0

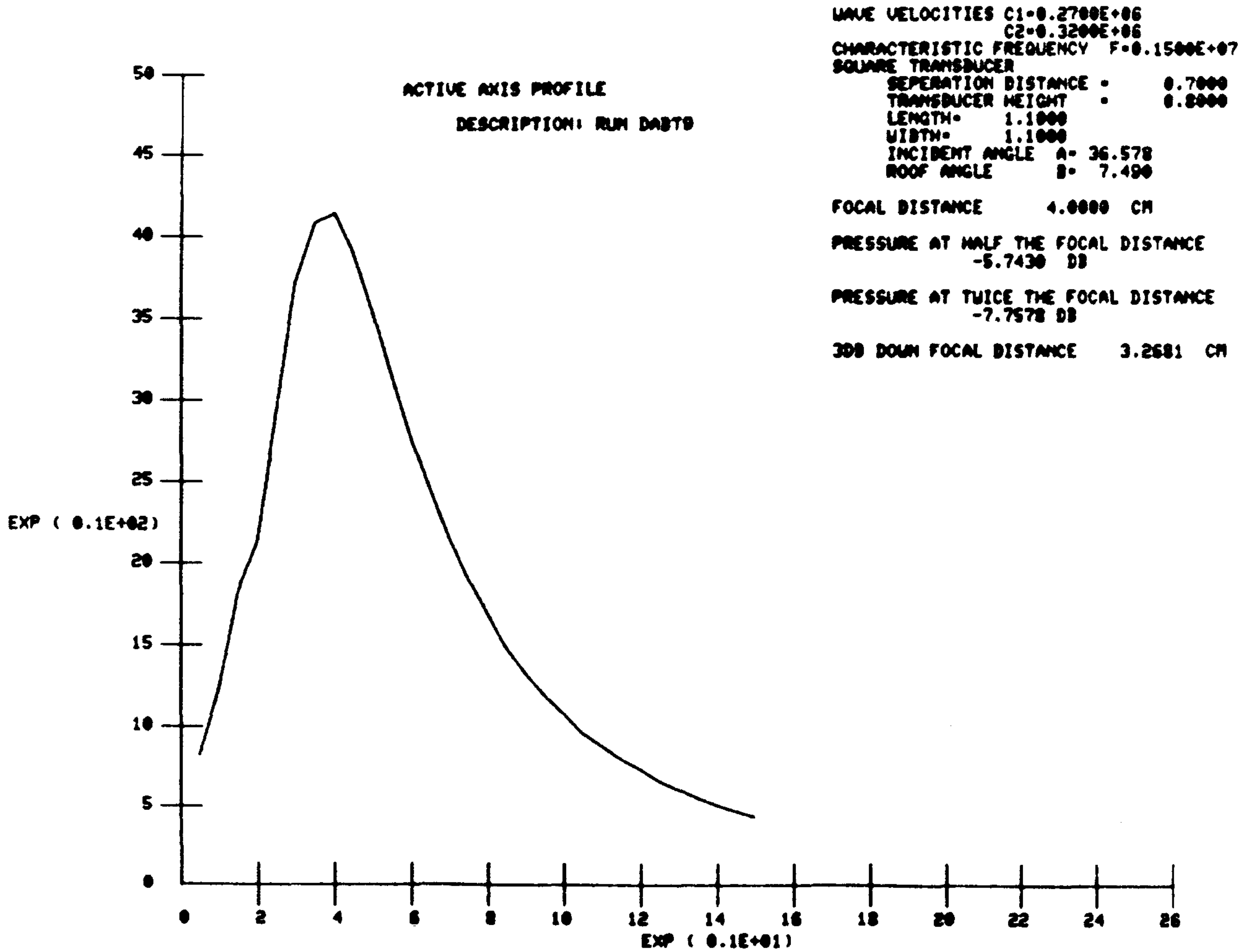


FIGURE A3-13A: ACTIVE AXIS PROFILE OF THE OPTIMALLY SHAPED TRANSDUCER CONFIGURATION

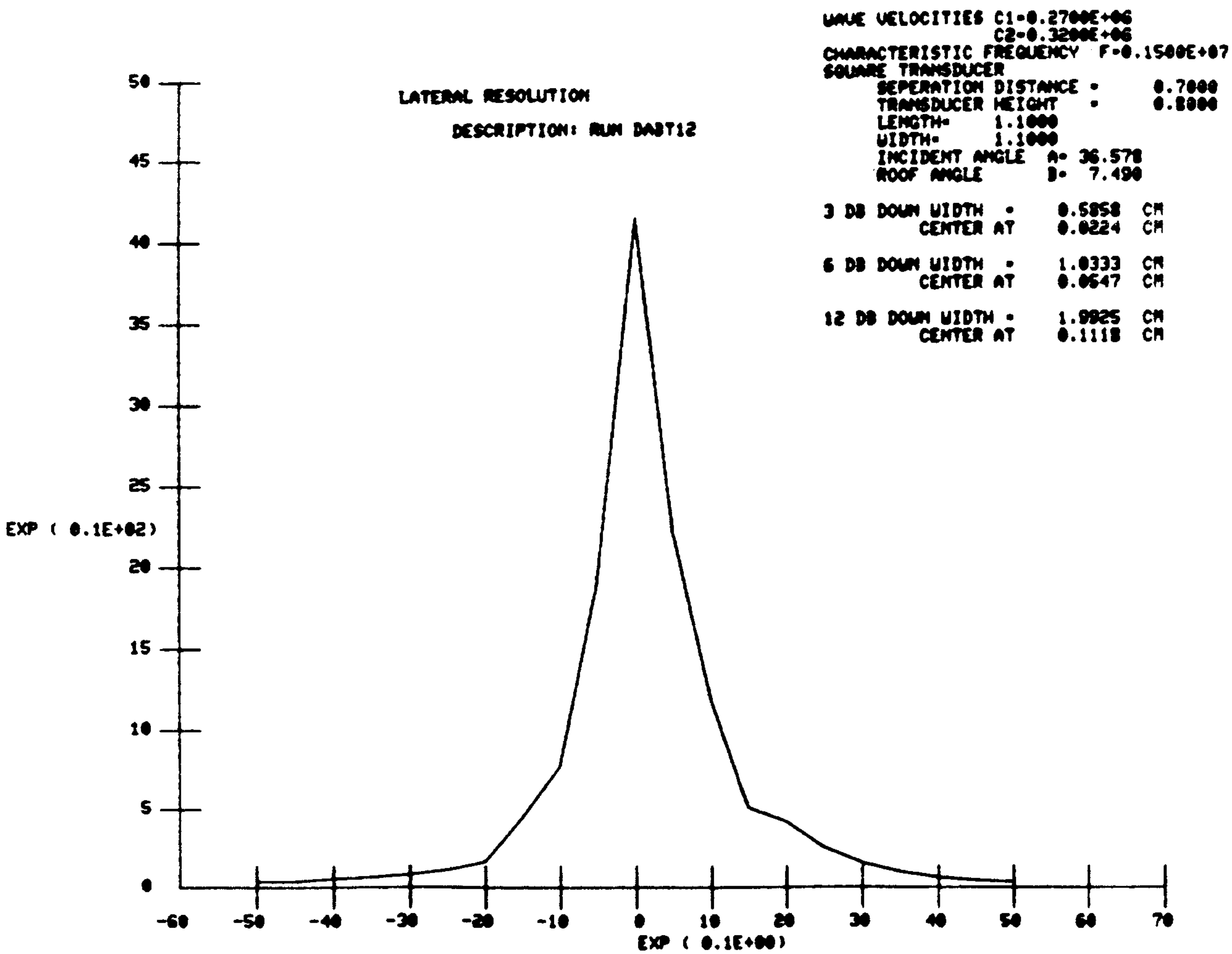


FIGURE A3-13B: TRANSVERSE PRESSURE PROFILE OF THE OPTIMALLY SHAPES TRANSDUCER CONFIGURATION

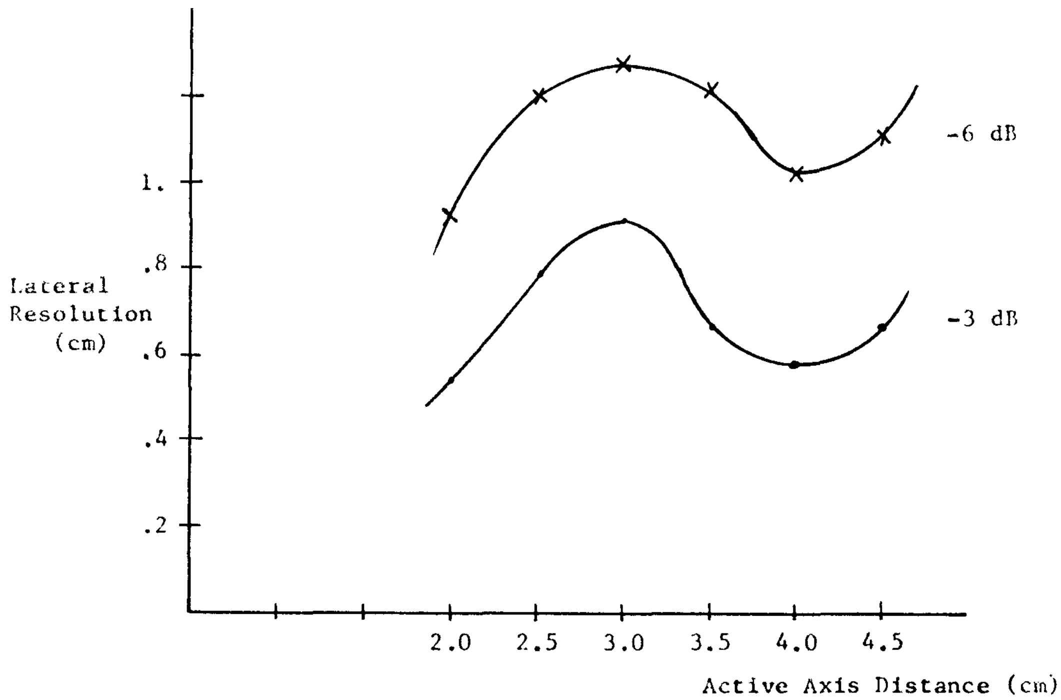


FIGURE A3-14A: LATERAL RESOLUTION VS. ACTIVE AXIS DISTANCE

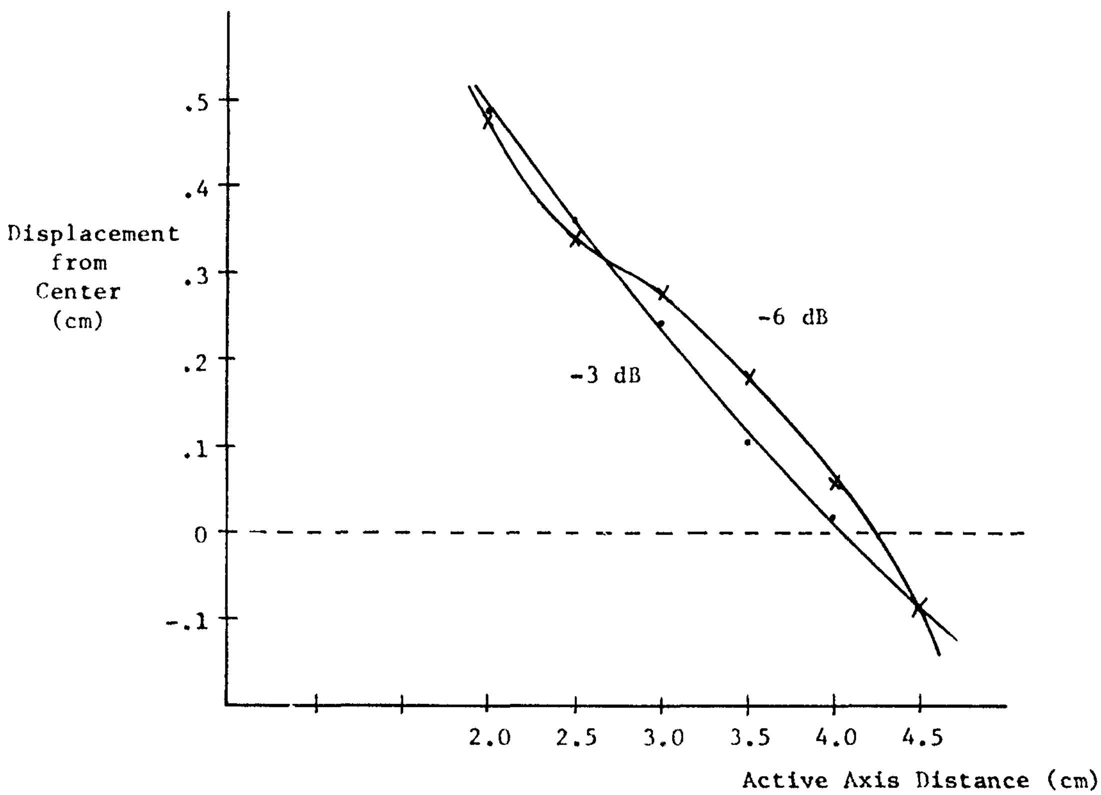


FIGURE A3-14B: CENTERLINE DISPLACEMENT FROM THE ACTIVE AXIS VS. ACTIVE AXIS DISTANCE

To complete the theoretical study for the optimally shaped transducer a study of beam profiling for perturbations of the transducer size, distance between the element crystals, Q, and the roof angle, β , were studied. The results of this study are presented in Table A3-4.

This section presents the results obtained from a theoretical angle beam transducer with a short focal distance such as would be required for 4", Schedule 80 pipe. The effects of variations such as roof angle, transducer size, and the separation distance between the transducers on focal distance and lateral resolution of the dual element angle beam transducer are examined. It should be noted that the objective of this report is to study the lateral resolution and beam symmetry for a dual element angle beam transducer configuration and not to study the gain or signal to noise ratio of this transducer configuration, this topic best being supported by experimental investigations.

The "UFA" computer program modified for studying the dual element angle beam transducer configuration was used to find the optimal transducer parameters for the best lateral resolution in the transverse pressure profile at a focal distance of 1.5 cm along the 45° active axis.

The dual element angle beam transducer configuration which satisfies the criterion mentioned above is listed below.

Transducer shape - square

length - .6 cm

width - .6 cm

Separation Distance of the
crystal elements Q - .4 cm

Roof Angle β - 9°

Incident Angle α - 36.6°

Height of the transducer
above the interface TH - .8 cm

Table A3-5 shows the results of the active axis profile and transverse pressure profile for the short focal distance transducer configuration.

Figure A3-15A is the active axis profile of the optimally shaped transducer. Figure A3-15B is the transverse pressure profile for the transducer at the focal distance of 1.5 cm.

Computer Run	Transducer Parameters					Lateral Resolution			Active Axis Distance		
	Q (cm)	β (degrees)	Shape	Length (cm)	Width (cm)	Active Axis Distance	3 db down width (cm) Δdisplacement from center (cm)	6 db down width (cm) Δdisplacement from center (cm)	Focal Distance	Pressure variation 1/2 F.D. (db) 2 F.D. (db)	3 db down focal length (cm)
14	.7	7.5	square	1.1	1.1	4.0	0.5858 0.0224	1.0333 0.0547			
9	.7	7.5	square	1.1	1.1				4.0	-5.743 -7.758	3.268
16	.7	7.5	square	1.0	1.0	4.0	0.6289 -0.0126	1.0998 -0.0203			
17	.7	7.5	square	1.0	1.0				3.5	-5.933 -5.287	3.11
18	.7	7.5	square	1.2	1.2	4.0	0.5955 0.0526	1.0811 0.1218			
19	.7	7.5	square	1.2	1.2				4.0	-5718 -7.270	3.381
20	.6	7.5	square	1.1	1.1	4.0	0.5693 -0.015	.9784 -0.0286			
21	.6	7.5	square	1.1	1.1				3.5	-5.786 -6.473	3.134
22	.8	7.5	square	1.1	1.1	4.0	0.6352 0.0721	1.1094 0.1355			
23	.8	7.5	square	1.1	1.1				4.0	-6.641 -7.036	3.343
24	.7	6	square	1.1	1.1	4.0	0.8899 0.2298	1.2169 0.2409			
25	.7	6	square	1.1	1.1				4.5	-5.639 -5.653	4.159
26	.7	7	square	1.1	1.1	4.0	0.6437 0.0787	1.1126 0.1410			
27	.7	7	square	1.1	1.1				4.0	-6.145 -6.438	3.482
28	.7	8	square	1.1	1.1	4.0	0.5773 -0.0209	0.9975 -0.0414			
29	.7	8	square	1.1	1.1				3.5	-5.990 -6.905	3.018

Table A3-4: Beam Profiling for Perturbation of Length x Width, Q and β of the Optimally Shaped Transducer Configuration for Best Transverse Pressure Profile Resolution at 4.0 cm

Com-puter Run	Transducer Parameters					Transverse Profile			Active Axis Profile		
	Q (cm)	β (de-grees)	Shape	Length (cm)	Width (cm)	Active Axis Dis-tance	3 db down width (cm) (displacement from center)	6 db down width (cm) (displacement from center)	Focal Dis-tance (cm)	Pressure Variation 1/2 F.D. (db) 2 F.D. (db)	3 db down focal length (cm)
30	.4	9	square	.6	.6				1.5	-4.5425 -4.1367	1.787
31	.4	9	square	.6	.6	.5	.2724 .2742	.4735 .2955			
32	.4	9	square	.6	.6	1	.3696 .1812	.5634 .1665			
33	.4	9	square	.6	.6	1.25	.4765 .1256	.6510 .1190			
34	.4	9	square	.6	.6	1.5	.4938 .0784	.7142 .0549			
35	.4	9	square	.6	.6	1.75	.5392 .0207	.7786 .0049			
36	.4	9	square	.6	.6	2	.5980 -.0367	.8592 -.0521			

Table A3-5: Beam Profiling of the Optimally Shaped Transducer Configuration for Best Transverse Pressure Resolution at 1.5 cm.

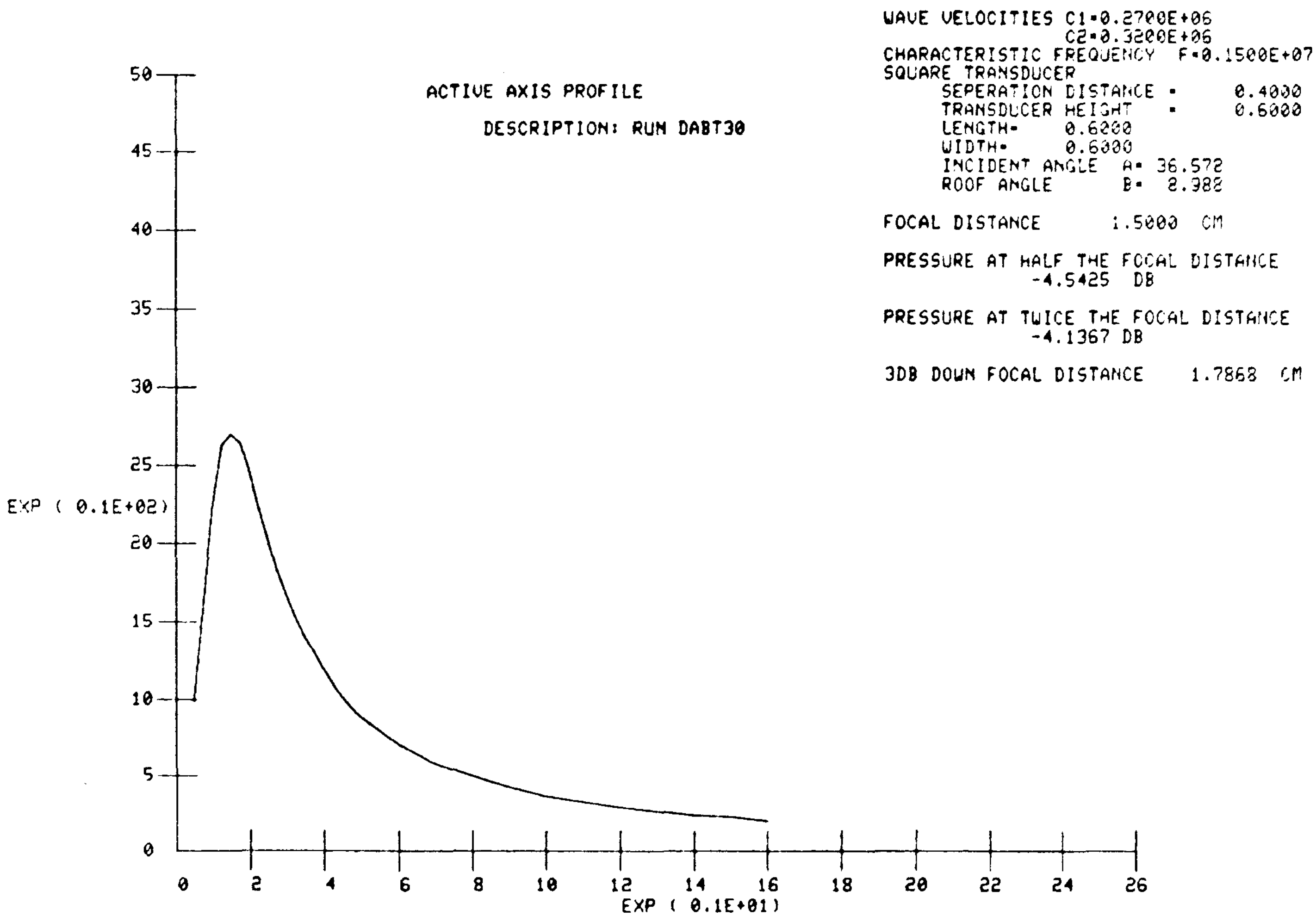


FIGURE A3-15A: ACTIVE AXIS PROFILE OF THE OPTIMALLY SHAPED TRANSDUCER CONFIGURATION

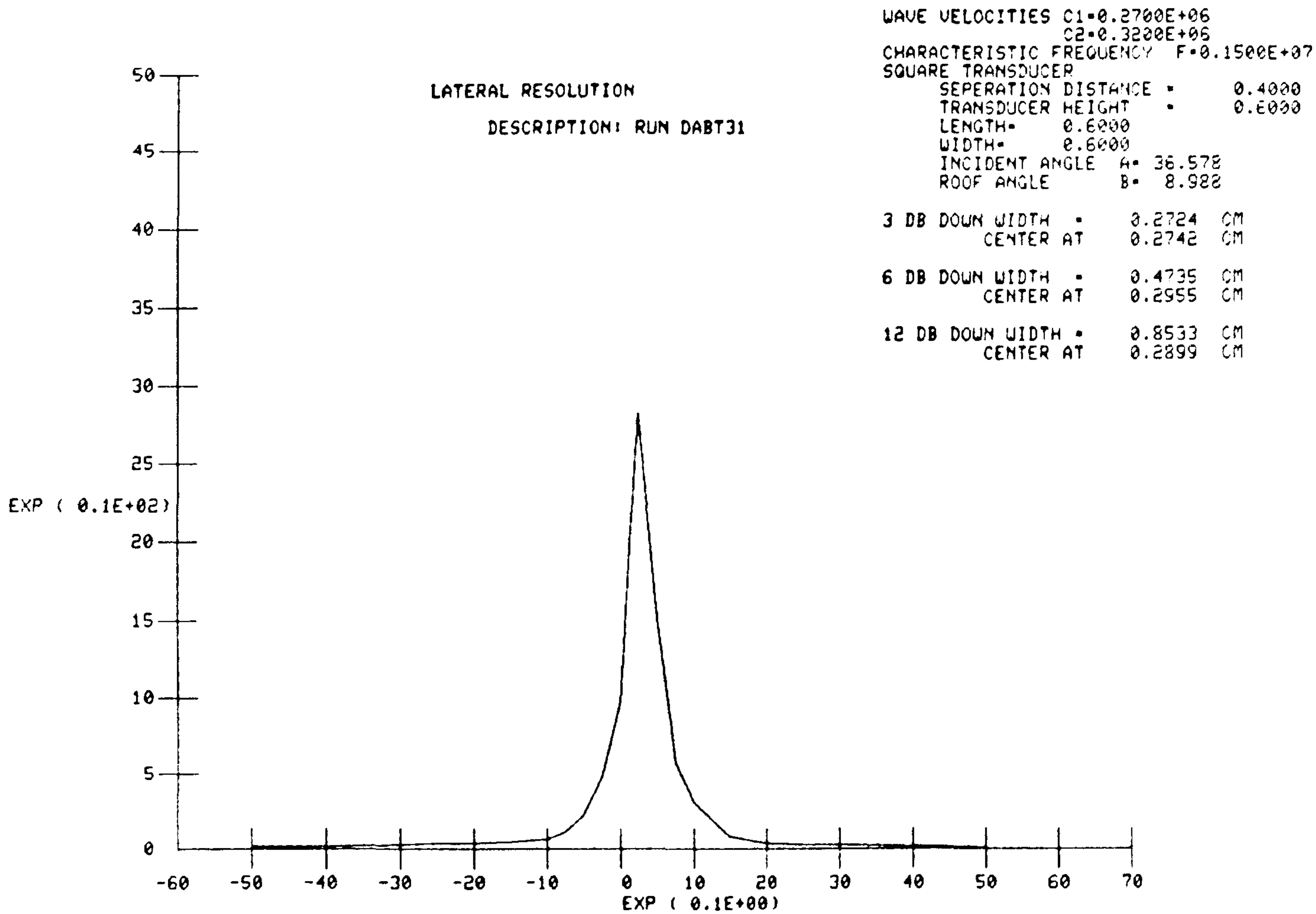


FIGURE A3-15B: TRANSVERSE PRESSURE PROFILE OF THE OPTIMALLY SHAPED TRANSDUCER CONFIGURATION

Perturbations of the transducer size, distance between the element crystals, Q, and the roof angle, β, were also studied for the short focal distance configuration. The results of perturbation study are presented in Table A3-6.

The data presented in Table A3-4 and Table A3-6 of this report show the following trends in the lateral resolution centerline displacement and active axis focal distance for the transducer parameter perturbation studied.

I. <u>Transducer Element Size</u>

A. For Smaller Transducer Element

1. 3 dB down width is increased
2. centerline displacement of the transverse pressure profile is improved
3. active axis focal distance is reduced

B. Larger Transducer Element

1. 3 dB width is increased slightly
2. centerline displacement is worse
3. active axis focal distance is increased slightly

II. <u>Transducer Roof Angle</u>

A. Smaller Roof Angle

1. 3 dB width is increased
2. centerline displacement is worse
3. active axis focal distance is increased

B. Larger Roof Angle

1. 3dB down width is reduced
2. centerline displacement is improved
3. active axis focal distance is reduced

III. <u>Transducer Element Separation Distance</u>

A. Smaller Separation Distance

1. 3 dB down width is reduced
2. centerline displacement is improved
3. active axis focal distance is reduced

B. Larger Separation Distance

1. 3 dB down width is increased
2. centerline displacement is worse
3. active axis focal distance is increased

The beam profiling data measured from the transverse pressure profiles calculated along the active axis in Tables A3-3 and A3-5 indicate the region over which the dual element angle beam transducer configuration focused at 4.0 cm shows good

Computer Run	Transducer Parameters: Q (cm)	β (degrees)	Shape	Length (cm)	Width (cm)	Transverse Profile: Active Axis Distance (cm)	3 db down width (Displacement center) (cm)	6 db down width (Displacement center) (cm)	Active Axis Profile: Focal Distance (cm)	Pressure Variation 1/2 F.D. (db) 2 F.D. (db)	3 db down focal length (cm)
34	.4	9	Square	.6	.6	1.5	.4938 .0784	.7142 .0594			
31	.4	9	Square	.6	.6				1.5	-.5425 -4.1367	1.787
37	.4	9	Square	.6	.6	1.5	.5535 .0241	.7941 .0064			
38	.4	9	Square	.5	.5				1.25	-4.4387 -3.5569	1.628
39	.4	9	Square	.7	.7	1.5	.5014 .1201	.6858 .1135			
40	.4	9	Square	.7	.7				1.75	-5.0623 -4.8674	1.865
41	.4	8	Square	.6	.6	1.5	.5139 .1156	.7066 .1060			
42	.4	8	Square	.6	.6				1.5	-5.5261 -3.0935	1.681
43	.4	10	Square	.6	.6	1.5	.4851 .0344	.7294 -0181			
44	.4	10	Square	.6	.6				1.25	-5.7634 -3.3796	1.585
45	.3	9	Square	.6	.6	1.5	.4729 .0293	.7166 .0149			
46	.3	9	Square	.6	.6				1.25	-5.0006 -3.4116	1.6246
47	.5	9	Square	.6	.6	1.5	.5162 .1177	.7131 .1082			
48	.5	9	Square	.6	.6				1.75	-4.4251 -4.8741	1.8861

Table A3-6: Beam Profiling for Perturbation of Length x Width Q and β of the Optimally Shaped Transducer Configuration for Best Transverse Pressure Profile Resolution at 1.5 cm.

lateral resolution over an active axis region from 3.5 to 4.0 cm. Table A3-5 for the transducer configuration focused at 1.5 cm shows good lateral resolution from 1.25 to 2.0 cm.

To provide inspection of pipes with wall thicknesses from .8 cm to 3.3 cm, two transducers might suffice, but a three transducer set warrants consideration. The third transducer (intermediate) would focus over an active axis region from 2.0 to 3.5 cm. This third transducer along with the two previously designed transducers would allow inspection over an active axis region from 1.25 to 4.5 cm. The design parameters for the third transducer can probably be found by interpolating between the parameters obtained for the transducer configurations focused at 1.5 cm and 4.0 cm, specifications of which would therefore be as follows:

Transducer shape - square
length - .9 cm
width - .9 cm

Separation Distance of the crystal elements Q - .55 cm

Roof Angle β - 8°

Incident Angle α - 36.6°

Height of the transducer above the interface TH - 0.8 cm

This should perhaps be confirmed theoretically, and confirmed experimentally.

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APPENDIX A4-1

AN EVALUATION OF SPECIAL ULTRASONIC TRANSDUCERS DEVELOPED FOR THE DETECTION OF INTERGRANULAR STRESS CORROSION CRACKING IN STAINLESS STEEL PIPING

November 1978

Prepared by
Plant Material Engineering
Nuclear Energy Business Group
General Electric

SUMMARY

Special ultrasonic transducers were developed by the Southwest Research Institute, under contract to the Electric Power Research Institute, for the specific purposes of detecting intergranular stress corrosion cracking in 304 stainless steel piping. These dual element, pitch and catch transducers have a narrow banded frequency of 1.5 MHz, an angle in steel of 45° and are aimed or focused for particular ranges of pipe wall thicknesses.

General Electric has made independent comparisons of these transducers with conventional transducers used in the field by most inservice inspection agencies for examining 304 stainless steel piping. The comparisons were made on real cracks some of which were as found in the field, as developed by chemical means, and as produced in General Electric's Pipe Test Laboratory.

The conclusions are that the special transducers provide a definite increase in the signal to noise ratio in the case of thick wall pipe (> 0.75" wall thickness) and with piping with unusual geometries. In the case of thinner wall pipes (wall thicknesses from 0.3" to 0.75") there may be a trade-off between resolution and response using higher frequency search units (2.25 MHz). In some cases, the dual search unit wedge intersects the outside weld crown before the leading edge of the sound beam has traversed the complete heat affected area of the weld. A redesign of the search unit wedge, which could overcome that problem, was undertaken during the period of this report.

INTRODUCTION

Southwest Research Institute (SwRI) performed studies for the Electric Power Research Institute (EPRI) on the Ultrasonic (UT) response data from intergranular stress corrosion cracking (IGSCC) in 304 stainless steel (S.S.) piping (1). Based on these studies SwRI has shown that the higher frequency components of a reflected ultrasonic beam are scattered or attenuated in the material and that the peak frequency received is around 1.5 MHz. Special narrow banded search units were then fabricated which employ the optimum conditions found during these studies. These conditions include the optimum angle of attack (45° in steel) and a dual element, pitch and catch arrangement which aims or focuses the sound on the inside surface of the pipe. Naturally, this included angle between the transmitting and receiving elements in the search unit must be changed for different ranges of pipe wall thicknesses. To accomplish this a series of search units are used.

Four search units, two optimized for 4" schedule 80 pipe, and two for 10" schedule 80 pipe, were furnished to the General Electric (GE) Company by EPRI for evaluation. (See Appendix A1 for specifications). The work was conducted under the GE contract, RP892 with EPRI.

This report documents the results of GE's evaluation of the transducers.

FIELD USE

GE had a unique opportunity to compare these search units with several conventional ones under field conditions. This occurred when IGSCC was discovered in some 24" diameter, furnace sensitized, 304 S.S. safe ends and in the heat affected zone (HAZ) of some of the adjacent pipe welds at an operating site.

The first safe end that was examined had a piece of pipe attached, which had a base metal weld repair made just adjacent to the pipe to safe end weld. In addition there had been grinding and possibly some shrinkage on the safe end side of the weld resulting in a concave surface condition. This condition is shown in Figure A4-1. These geometrical surface conditions made scanning very difficult.

The first examination was conducted using a 1/4" diameter x 2.25 MHz angle beam transducer plus a Krautkramer USIP-11 UT instrument. No indications were detected in the pipe or the safe end using this combination.

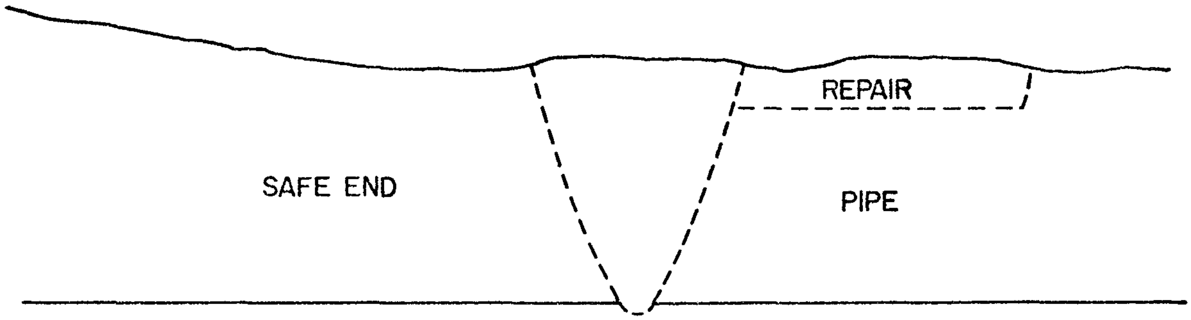
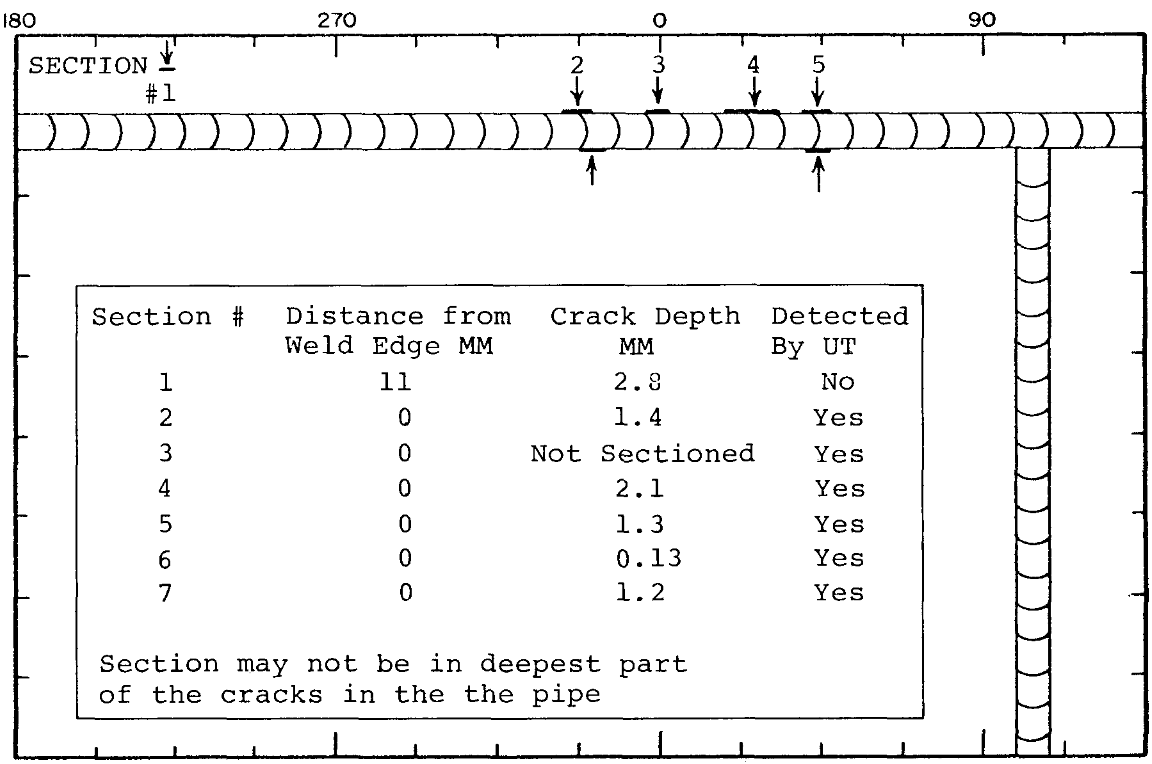


FIGURE A4-1 SAFE END A SHOWING SURFACE CONDITION LIMITING ULTRASONIC EXAMINATION



Section #	Distance from Weld Edge MM	Crack Depth MM	Detected By UT
1	11	2.8	No
2	0	1.4	Yes
3	0	Not Sectioned	Yes
4	0	2.1	Yes
5	0	1.3	Yes
6	0	0.13	Yes
7	0	1.2	Yes

Section may not be in deepest part of the cracks in the the pipe

FIGURE A4-2 CRACKS FOUND BY PENETRANTS ON SAFE END A

A change was then made to a 1/4" dual, transmit/receive or pitch and catch 1.5 MHz x 45° angle beam transducer. With this transducer four indications on the safe end side of the weld and two indications on the pipe side of the weld were detected. Liquid penetrants showed these indications to be cracks located very close to the weld root. (See Figure A4-2). Liquid penetrants showed an additional indication farther back from the weld root on the safe end which was not detected by UT. It is believed that the taper on the safe end restricted scanning in that area. Subsequent sectioning showed the cracks on the safe end side which were detected by UT to have depths of 1.3, 1.4 and 2.1 mm (~3 to 5% of wall thickness based on a 40 mm wall). One of the cracks was not sectioned. The crack that was not detected had a depth of 2.8 mm. The cracks on the pipe side of the weld had depths of 1.2 and 0.13 mm. However, it is important to note that these are probably not the deepest area of these cracks. The pipe cracks were directly on the other side of the weld from the safe end cracks and were removed in the same section as the safe end crack, with the cut being made at the center of the crack in the safe end. The section which showed the pipe crack depth of 0.13 mm was a cut through the very outer edge of the UT indication. However, the metallography on this indication shows that at this circumferential location the indication is a welding defect.

Another safe end was then examined. Both transducers plus several more were used and all the cracks were detected with all transducers. This safe end contains a series of short cracks located very close together and in some cases overlapping. (See Figure A4-3). With all transducers these cracks appear as a continuous indication and it is impossible to separate them as individual reflectors due to resolution limitations. The depths of the cracks in this safe end are not known.

Photographs taken of the UT scope showing the indications from 5 selected areas along the cracks with 5 different transducers, clearly show that a better response is obtained from the cracks with the 1.5 MHz x 45° dual element, transmit/receive or pitch-catch transducers.

LABORATORY USE

Similar studies were conducted in the laboratory on a sample of 26" pipe which had been cracked by chemical means (Strauss-Test). UT scope amplitude measurements again showed the superiority of the 1.5 MHz pitch and catch search units.

However, when similar experiments were conducted on 4" schedule 80 pipes, which contained cracks generated in the pipe test laboratory, problems were encountered.

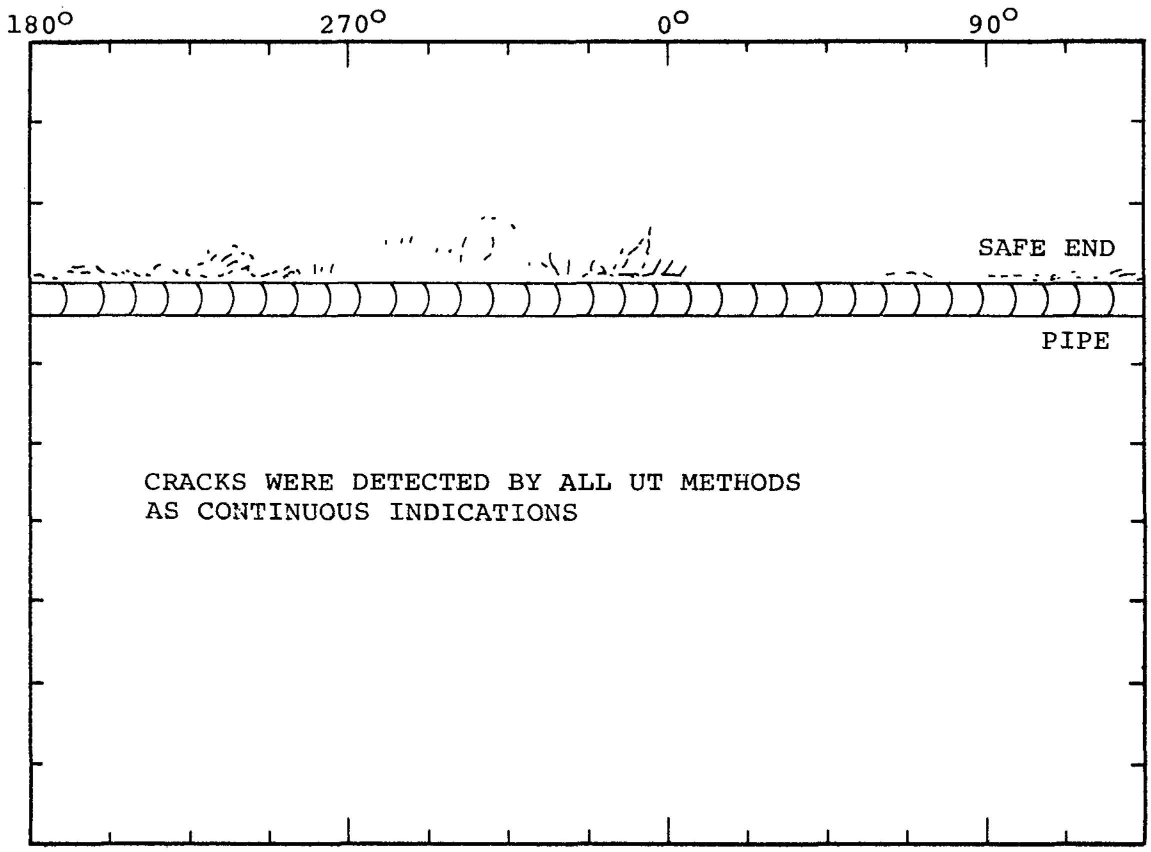


FIGURE A4-3 CRACKING PATTERN FOUND BY PENETRANTS ON SAFE END B

The transducer wedge (on the 1.5 MHz pitch and catch transducer) encountered the outside weld crown preventing the sound beam from being peaked on the cracks. Thus a much lower signal to noise ratio was achieved than with the conventional 1/4" diameter, 2.25 MHz pulse echo transducer.

A comparison of index points (the distance from the front edge of the transducer wedge to the central or maximum amplitude exit point from the wedge) clearly shows the reason. A tabulation of this data follows:

		INDEX
a.	Aerotech 0.25" diameter 2.25 MHz 45 minature	.25"
b.	Aerotech 0.5" diameter 2.25 MHz 45°	.375"
c.	Aerotech 0.5" diameter 1.0 MHz 45°	.375"
d.	SwRI 0.375" dual element 1.5 MHz	.400
e.	SwRI 0.375" dual element 1.5 MHz	.400
f.	SwRI 0.25 dual element 1.5 MHz	.430
g.	SwRI 0.25 dual element 1.5 MHz	.430

Based on these index points and current weld preparation designs the centerline of the sound beam on the SwRI search units would only reach the weld root (on a 1.2 V path) on 14" and larger schedule 80 pipes. The leading edge of the sound beam however would reach the weld root on 10" and larger pipes.

CONCLUSIONS

It can be concluded that the SwRI pitch and catch, 1.5 MHz search units offer distinct advantages over conventional search units on large diameter, heavy wall piping and on piping with unusual outside geometries. Based on this data, General Electric has revised the UT test procedure (2) to require the use of these transducers on piping 14" in diameter (0.75" wall thickness) and to permit their use for evaluation on all sizes of pipes. Studies are still being conducted on transducers with shorter index points (both pitch and catch plus pulse echo) at 1.5 MHz. If it can be shown in the laboratory that there are advantages in using these on the smaller diameter pipes, then the procedure will be further revised.

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APPENDIX A4-2
ON-SITE IGSCC STUDIES

Prepared by
Southwest Research Institute

SwRI has had three opportunities to perform onsite studies on suspected IGSCC indications in stainless steel piping. This section will discuss those studies and the results with respect to the development of the 1.5 MHz, dual-crystal search unit (SU).

SwRI implemented the use of single-crystal, 1.5 MHz, SUs in field inservice (ISI) and preservice (PSI) examinations prior to the development of the dual-crystal unit. An immediate result was a marked increase in the number of geometric indications recorded, a time consuming, expensive process which is particularly undesirable during ISI operations. A study was performed during a PSI to evaluate a new design, the dual-crystal SU, with respect to geometrical reflector sensitivity.

All three studies were conducted in effectively the same manner. At each of the three sites, crack-like indications had been located in stainless steel piping. Two sites were BWRs, both with indications in 10-inch core spray lines. On the other hand, the third study was conducted on an 8-inch, Schedule 10S safety injection line in a PWR plant.

In each study, several SUs were applied to the lines at preselected points designed to immediately locate the indications which were then maximized. Photographs of the echo RF waveform and frequency spectra were taken. An Ultrasonic Transducer Analyzer (UTA-2) was used as a pulser, amplifier, and gate. This unit delivers a wideband, half-cycle, spike pulse to the trnasducer.

In the three studies, 110 data points were recorded using 21 SUs. Unfortunately, most of these SUs were narrow band, a factor which may have influenced the results subsequently discussed.

Objectives of each study were met in the data acquisition process. That is, crack-like indications were interrogated by an assortment of SUs; RF and spectral data were recorded, and frequency shifts were determined. Results of these studies differed from those reported in NP676-SR in that significant frequency shifts were not observed, probably as a result of the barrow band nature of the SUs. All of the indications were later confirmed during repair to be cracks.

Description of the Geometrical Indication Study

To evaluate the sensitivity of search units (SU) to geometric indications with respect to two parameters, frequency and number of crystals, a study was performed on a portion of a stainless steel weld containing several hundred geometrical indications. Four SUs were involved:

Unit	Frequency	No. of Crystals
A	2.25	Single
B	2.25	Dual
C	1.5	Single
D	1.5	Dual

Each of these was mounted on 45-degree, shear wave shoes and was calibrated on the same standard. Gain settings at the primary reference level (DAC) differed by 4 dB or less, an insignificant amount. The weld was examined with each SU over the same 10-inch segment, and all indications over 50 percent of the primary reference level were recorded.

Indications recorded by each SU were counted and tabulated:

			No. of Indications	
Unit	Frequency	No. of Crystals	50% DAC	100% DAC
A	2.25	Single	24	2
B	2.25	Dual	25	4
C	1.5	Single	32	15
D	1.5	Dual	25	6

It is apparent that:

(1) The single, 1.5 MHz unit recorded significantly more indications than the other three units.

(2) There is no significant difference in the number of indications recorded with the other three units.

Based on these results, it is concluded that the use of a 1.5 MHz, dual SU does not significantly increase the number of geometric indications recorded.

Additional evaluation of the dual transducers was conducted by SwRI on EPRI Research Project (RP) 892-1. The performance of eight different transducers was established on IGSCC specimens provided by the GE Pipe Test Laboratory under the RP-892-1 program. The transducers used covered the frequency range of 1.5 MHz to 5.0 MHz, included single-crystal as well as dual-crystal types, and bracketed a crystal element diameter range of 1/4" to 3/8".

The pipe specimen was 304 stainless steel, 101 mm (4 inch) diameter, Schedule 80, and contained nine-circumferential welds. The pipe specimen was a half section thereby allowing dye penetrant examination of the inside surface (ID). Subsequent dye penetrant examination provided confirmation of cracks ranging from 1.16" (1.6 mm) to 6-1/2" (167 mm) in length. Data from the dye penetrant examination are presented in Tables A4-2 through A4-12, "Dye Penetrant Examination Data." The data are summarized for each of the nine welds.

A Sonic Mark I Pulser-Receiver was used in all of the experiments on the pipe specimen. Additionally, the same code acceptable calibration block containing 10% t notched (OD and ID) was used for each transducer experiment.

For uniformity of results 1/2 V data obtained are summarized in Table 4-1, "Transducer Performance Data Summary." All data points presented were recorded at 50% DAC or greater. Figure A4-4 enables one to visualize the results of the transducer comparison study.

The data clearly show that the dual-crystal transducers in the 1.5 to 2.25 MHz range are superior to single-crystal element transducers in detecting IGSCC.

Summaries of the transducer performance data for each weld in GE-1 are presented in Tables A4-13 through A4-15.

It should be noted that the 5.0 MHz transducer (single- and dual-crystal element) was essentially insensitive to IGSCC.

Transducer	No. of IGSCC Detected	No. of Geometric Reflectors Detected
#579-Dual 2.25-1/4"	71	2
#580-Dual 1.5-1/4"	61	20
#573-Single-2.25-1/4"	48	1
#341-Single-1.5-1/4"	43	33
#569-Single-1.5-3/8"	31	10
#562-Single-2.25-3/8"	22	0
#586-Dual-5.0-1/4"	6	0
#572-Single-5.0-1/4"	5	0

TABLE A4-1: TRANSDUCER PERFORMANCE DATA SUMMARY

CONCLUSIONS

Following a review of all data, several conclusions may be drawn:

(1) The use of a dual-crystal search unit significantly enhances the detectability of IGSCC.

(2) Weld and heat-affected zone microstructure in stainless steel welds exhibits preferential frequency characteristics.

(3) Continued development work on the dual-crystal SU is desirable to establish the following:

- (a) Optimum SU frequency for each material thickness
- (b) Optimum SU bandwidth
- (c) Instrument damping and filtering control settings for best results
- (d) Pulse shape, amplitude, and duration for the best combination of sensitivity and resolution
- (e) Type of pulser and receiver, i.e., tuned or broadband, for optimum results.

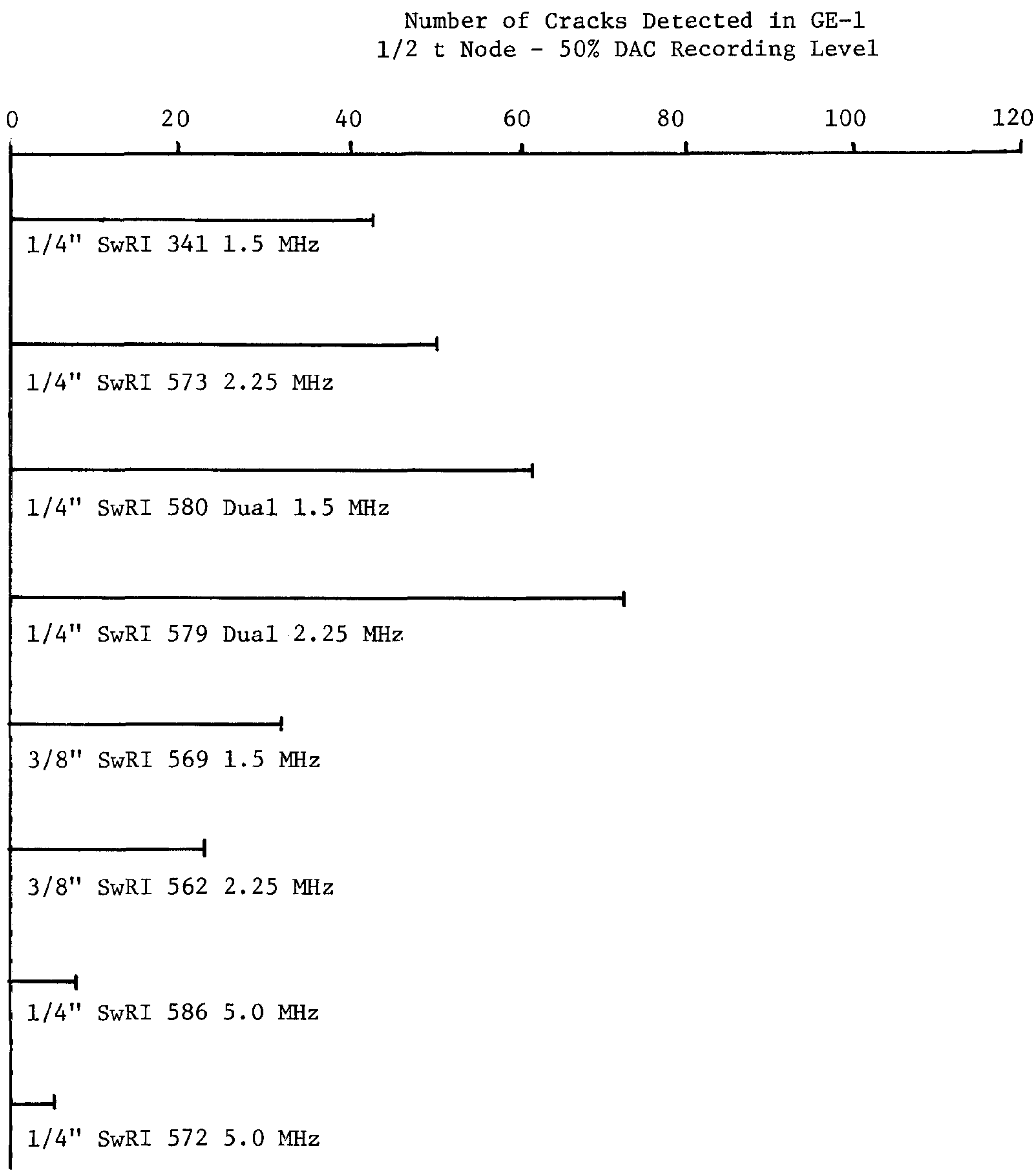

FIGURE A4-4: RESULTS OF THE TRANSDUCER COMPARISON STUDY

A1 A2
Pipe Specimen GE-1 Weld - A1&A2;B1&B2 B1 - Upstream B2 - Downstream
L_o = 0.0 inches 0.0 degrees L limit O.D. = 7-1/4 in. L limit I.D. = 6-1/2 in.

Indication No.	L (in.)	W (in.)	Location	Type	Size (in.)	Remarks
1 - O.D.	1-1/2 - 7-1/4	3/8	A2	Linear	5-3/4	Through Wall Crack
1 - I.D.	1-1/2 - 6-1/2	3/8	A2	Linear	5	Through Wall Crack
1 - O.D.	1-1/8	1/4	B1	Linear	1/4	
2 - O.D.	1-3/4	1/4	B1	Linear	1/4	
3 - O.D.	2-1/4	℄	B1	Linear	1/4	
4 - O.D.	4-1/2	1/4	B1	Linear	1/8 to 1/4	Grinding Marks
5 - O.D.	2-1/4	1/4	B2	Linear	1/4	
1 - I.D.	1/2	1/4	B1	Linear	1/2	Crack
2 - I.D.	1-1/4	1/4	B1	Linear	3/8	Crack
3 - I.D.	1-1/2	3/8	B1	Linear	1/4	Crack
4 - I.D.	0 to 6-1/2	3/8	B2	Linear	6-1/2	Crack
5 - I.D.	5-1/4	1/4	B2	Linear	1-3/4	Crack

TABLE A4-2: LIQUID PENETRANT EXAMINATION DATA SUMMARY

* * * *

Pipe Specimen GE-1 Weld- C1&C2 C1 - Upstream C2 - Downstream
L_o = 0.0 inches 0.0. degrees L limit O.D. = 7-1/4 in. L limit I.D. = 6-1/2 in.

Indication No.	L (in.)	W (in.)	Location	Type	Size (in.)	Remarks
1 - O.D.	5-3/4	1/4	C1	Round	1/8	Pit
2 - O.D.	3/8	1/4	C1	Round	1/8	Pit
3 - O.D.	6-1/4	3/8	C1	Linear	1/4	Grinding Marks
4 - O.D.	2-1/4	3/8	C2	Linear	3/8	Grinding Marks
5 - O.D.	6	3/8	C2	Linear	3/16	
1 - I.D.	0 to 6-1/2	3/8	C1	Linear	6-1/2	Multiple Cracks 180°
2 - I.D.	0 to 4	3/8	C2	Linear	4	Crack
3 - I.D.	4-1/8 to 5-1/4	1/4	C2	Linear	1-1/8	Crack

TABLE A4-3: LIQUID PENETRANT EXAMINATION DATA SUMMARY

Pipe Specimen GE-1 Weld D1&D2 D1 - Upstream D2 - Downstream
L_o = 0.0 Inches 0.0 degrees L limit O.D. = 7-1/4 in. L limit I.D. = 6-1/2 in.

Indication No.	L (in.)	W (in.)	Location	Type	Size (in.)	Remarks
1 - O.D.	3/4	1/4	D1	Round	1/8	Pit
2 - O.D.	1-7/8	1/4	D1	Round	1/8	Pit
3 - O.D.	4-1/2	1/4	D1	Linear	1/8	
4 - O.D.	6-3/8	3/8	D1	Linear	1/4	Grinding Marks
0 - O.D.	--	--	D2	---	--	No recordable indications
1 - I.D.	1-7/8	3/8	D1	Linear	3/16	Crack
2 - I.D.	2-3/8	3/8	D1	Linear	1/4	Crack
3 - I.D.	2-1/2 - 3-1/2	3/8	D1	Linear	1	Crack
4 - I.D.	4	3/8	D1	Linear	3/16	Crack
5 - I.D.	3-3/8	1/4	D2	Linear	1/4	Crack
6 - I.D.	3-1/2 to 6	1/4	D2	Linear	2-1/2	Crack
7 - I.D.	3	1/4	D2	Linear	1/8	Crack

TABLE A4-4: LIQUID PENETRANT EXAMINATION DATA SUMMARY

* * * *

Pipe Specimen GE-1 Weld E1&E2 E1 - Upstream E2 - Downstream
L_o = 0.0 inches 0.0. degrees L limit O.D.=7-1/4 in. L limit I.D. = 6-1/2 in.

Indication No.						
1 - O.D.	7/8	1/4	E1	Linear	1/4	
2 - O.D.	3-1/4	0 - C_L	E1	Linear	1/2	Grinding Marks
3 - O.D.	3-7/8	1/4	E1	Round	1/16	Pit
4 - O.D.	6-1/4	3/8	E1	Linear	1/4	Grinding Marks
5 - O.D.	1-1/4	1/4	E2	Linear	1/4	Grinding Marks
6 - O.D.	6	1/4	E2	Linear	1/8	
1 - I.D.	1/4	1/4	E1	Linear	5/16	Crack
2 - I.D.	1	3/8	E1	Linear	5/16	Crack
3 - I.D.	1-1/2 to 5-1/4	3/8	E1	Linear	3-3/4	Crack
4 - I.D.	2-1/2	7/16	E1	Linear	3/8	Crack
0 - I.D.	--	--	E2	---	--	No Recordable Indications

TABLE A4-5: LIQUID PENETRANT EXAMINATION DATA SUMMARY

Pipe Specimen GE-1 Weld F1&F2 F1 - Upstream F2 - Downstream
L_o = 0.0 inches & 0.0 degrees L limit O.D. = 7-1/4 in. L limit I.D. = 6-1/2 in.

Indication No.	L (in.)	W (in.)	Location	Type	Size (in.)	Remarks
1 - O.D.	1-5/8	0 - ℄	F1	Linear	3/16	Grinding Marks
2 - O.D.	3-3/8	0 - ℄	F1	Linear	3/16	Grinding Marks
3 - O.D.	4-1/2	0 - ℄	F1	Linear	3/8	Grinding Marks
4 - O.D.	6-3/4	1/4	F1	Round	1/8	Pit
5 - O.D.	3	1/2	F2	Linear	1/2	Grinding Marks
6 - O.D.	4-3/8	3/8	F2	Linear	3/8	Grinding Marks
7 - O.D.	5-1/4	1/4	F2	Linear	3/8	None
1 - I.D.	2-3/4	1/4	F1	Linear	1/4	Crack
2 - I.D.	3-1/8	1/4	F1	Linear	5/16	Crack
3 - I.D.	4-3/4 to 6	5/16	F1	Linear	1-1/4	Multiple Cracks
4 - I.D.	2	1/4	F2	Linear	5/16	Crack
5 - I.D.	4-3/4	1/4	F2	Linear	1/8	Crack

TABLE A4-6: LIQUID PENETRANT EXAMINATION DATA SUMMARY

* * * *

Pipe Specimen GE-1 Weld G1&G2 G1 - Upstream G2 - Downstream
L_o = 0.0 inches 0.0 degrees L limit O.D. = 7-1/4 in. L limit I.D. = 6-1/2 in.

Indication No.	L (in.)	W (in.)	Location	Type	Size (in.)	Remarks
1 - O.D.	3	1/4	G1	Linear	1/4	
2 - O.D.	3-3/8	0 - ℄	G1	Linear	1/4	Grinding Marks
3 - O.D.	5-1/4	1/4	G1	Linear	1/8	
4 - O.D.	1	1/4	G2	Linear	3/8	
5 - O.D.	2	1/4	G2	Linear	1/4	
6 - O.D.	3-3/8	1/4	G2	Linear	1/8	
7 - O.D.	6	1/4	G2	Linear	5/16	
0 - I.D.	--	--	G1&G2	--	--	No Recordable Indications

TABLE A4-7: LIQUID PENETRANT EXAMINATION DATA SUMMARY

Pipe Specimen GE-1 Weld H1&H2 H1 - Upstream H2 - Downstream

L_o = 0.0 inches 0.0 degrees L limit O.D. = 7-1/4 in. L limit I.D. = 6-1/2 in.

Indication No.	L (in.)	W (in.)	Location	Type	Size (in.)	Remarks
1 - O.D.	3	1/4	H1	Linear	3/8	Grinding Marks
2 - O.D.	5-1/2	1/4	H1	Round	1/16	Pit
0 - O.D.	--	--	H2	--	--	No Recordable Indications
0 - I.D.	--	--	H1&H2	--	--	No Recordable Indications

TABLE A4-8: LIQUID PENETRANT EXAMINATION DATA SUMMARY

* * * *

Pipe Specimen GE-1 Weld I1&I2 I1 - Upstream I2 - Downstream

L_o = 0.0 inches 0.0 degrees L limit O.D. = 7-1/4 in. L limit I.D. - 6-1/2 in.

Indication No.	L (in.)	W (in.)	Location	Type	Size (in.)	Remarks
1 - O.D.	3-1/2	0 - ℄	I1	Linear	1/4	Grinding Marks
2 - O.D.	4-1/2	1/4	I1	Linear	1/8	
3 - O.D.	4-1/2	1/4	I2	Round	1/16	
o - I.D.	--	--	I1&I2	--	--	No Recordable Indications

TABLE A4-9: LIQUID PENETRANT EXAMINATION DATA SUMMARY

* * * *

Pipe Specimen GE-1 Weld J1&J2 J1 Upstream J2-Downstream

L_o = 0.0 inches 0.0 degrees L limit O.D. = 7-1/4 in. L limit I.D. = 6-1/2 in.

Indication No.	L (in.)	W (in.)	Location	Type	Size (in.)	Remarks
1 - O.D.	4-5/8	1/4	J1	Linear	1/8	Grinding Marks
2 - O.D.	5-7/8	1/4	J1	Round	1/16	
3 - O.D.	1/2	3/8	J2	Linear	3/8	Grinding Marks
4 - O.D.	5-7/8	1/4	J2	Round	1/16	Pit
0 - I.D.	--	--	J1&J2	--	--	No Recordable Indications

TABLE A4-10: LIQUID PENETRANT EXAMINATION DATA SUMMARY

Pipe Specimen GE-1 Weld K1&K2 K1 - Upstream K2 - Downstream
L_o = 0.0 inches 0.0 degrees L limit O.D. = 7-1/4 in. L limit I.D. = 6-1/2 in.

Indication No.	L (in.)	W (in.)	Location	Type	Size (in.)	Remarks
0 - I.D.	--	--	K1&K2	--	--	No Recordable Indications
1 - O.D.	1-3/4	3/8	K1	Linear	1/2	Grinding Marks
2 - O.D.	3-3/8	1/4	K1	Linear	1/8	
3 - O.D.	3-1/4	1/4	K2	Linear	1/8	
4 - O.D.	5-1/2 to 7	0 - ℄	K2	Linear	5-1/2 to 7	Grinding Marks

TABLE A4-11: LIQUID PENETRANT EXAMINATION DATA SUMMARY

* * * *

Pipe Specimen GE-1 Weld L1&L2 L1 - Upstream L2 - Downstream
L_o = 0.0 inches 0.0 degrees L limit O.D. = 7-1/4 in. L limit I.D. = 6-1/2 in.

Indication No.	L (in.)	W (in.)	Location	Type	Size (in.)	Remarks
1 - O.D.	2-1/4	1/4	L1	Round	3/16	Pit
2 - O.D.	3-1/4	℄	L1	Linear	1/4	Grinding Marks
3 - O.D.	5-1/4	1/4	L1	Linear	1/4	
4 - O.D.	2-1/2	1/4	L2	Linear	1/4	
5 - O.D.	4-1/2	1/2	L2	Linear	1/8	
6 - O.D.	5-3/4	1/4	L2	Linear	1/8	
0 I.D.	--	--	L1&L2	--	--	No Recordable Indications

TABLE A4-12: LIQUID PENETRANT EXAMINATION DATA SUMMARY

Weld No.	#573-2.25 MHz 1/4"rd-Single Crack Indi-cations	Crown Reflec-tors	#341-1.5 MHz 1/4"rd-Single Crack Indi-cations	Crown Reflec-tors	#579-2.25 Single Crack Indi-cations	Crown Reflec-tors	#579-2.25 MHz 1/4" Dual Crack Indi-cations	Crown Reflec-tors	#580-1.5 MHz 1/4" Dual Crack Indi-cations	Crown Reflec-tors
A1	0	0	0	0	0	0	0	0	0	0
A2	-	-	-	-	-	-	-	-	-	-
B1	0	0	0	3	1	3	1	1	1	1
B2	7	0	8	0	8	0	8	0	8	0
C1	11	1	10	0	16	0	16	0	14	0
C2	11	0	5	1	13	1	13	1	14	2
D1	2	0	1	1	4	1	4	0	2	0
D2	3	0	7	0	7	0	7	0	6	1
E1	9	0	10	0	12	0	12	0	11	0
E2	0	0	0	1	0	1	0	0	0	2
F1	3	0	1	0	3	0	3	0	3	1
F2	0	0	0	1	1	1	1	0	0	1
G1	0	0	0	1	0	1	0	0	0	3
G2	0	0	0	3	0	3	0	0	0	0
H1	0	0	0	1	1	1	1	0	0	1
H2	0	0	0	2	1	2	1	0	0	0
I1	1	0	1	1	2	1	2	0	1	1
I2	1	0	0	6	2	6	2	0	1	2
J1	0	0	0	3	0	3	0	0	0	0
J2	0	0	0	2	0	2	0	0	0	3
K1	0	0	0	4	0	4	0	0	0	0
K2	0	0	0	2	0	2	0	0	0	0
L1	0	0	0	1	0	1	0	0	0	2
L2	0	0	0	0	0	0	0	0	0	0
Totals	48	1	43	33	71	33	71	2	61	20

TABLE A4-13: TRANSDUCER PERFORMANCE DATA

Weld No.	#562-2.25 MHz 3/8"-Single		#569-1.5 MHz 3/8"-Single		#586-5.0 MHz Single		#586-5.0 MHz 1/4" Dual		#572-5.0 MHz 1/4" Dual	
	Crack Indi-cations	Crown Reflec-tors	Crack Indi-cations	Crown Reflec-tors	Crack Indi-cations	Crown Reflec-tors	Crack Indi-cations	Crown Reflec-tors	Crack Indi-cations	Crown Reflec-tors
A1	0	0	0	0	0	0	0	0		
A2	0	0	0	0	-	0	-	-	-	-
B1	0	0	0	0	0	0	0	0	0	0
B2	5	0	4	0	4	0	4	0	3	0
C1	7	0	4	0	0	0	0	0	0	0
C2	4	0	5	1	0	1	0	0	0	0
D1	0	0	2	0	0	0	0	0	0	0
D2	3	0	7	1	1	1	1	0	1	0
E1	3	0	8	0	0	0	0	0	1	0
E2	0	0	0	2	0	2	0	0	0	0
F1	0	0	1	0	0	0	0	0	0	0
F2	0	0	0	1	0	1	0	0	0	0
G1	0	0	0	0	0	0	0	0	0	0
G2	0	0	0	1	0	1	0	0	0	0
H1	0	0	0	1	1	1	1	0	0	0
H2	0	0	0	0	0	0	0	0	0	0
I1	0	0	0	0	0	0	0	0	0	0
I2	0	0	0	1	0	1	0	0	0	0
J1	0	0	0	0	0	0	0	0	0	0
J2	0	0	0	1	0	1	0	0	0	0
K1	0	0	0	0	0	0	0	0	0	0
K2	0	0	0	1	0	1	0	0	0	0
L1	0	0	0	0	0	0	0	0	0	0
L2	0	0	0	0	0	0	0	0	0	0
Totals	22	0	31	10	6	10	6	0	5	0

TABLE A4-14: TRANSDUCER PERFORMANCE DATA

Computer Run	Transducer Parameters					Lateral Resolution			Active Axis Distance		
	Q (cm)	β (degrees)	Shape	Length (cm)	Width (cm)	Active Axis	3 db down width (cm) Δdisplacement from center	6 db down width (cm) Δdisplacement from center	Focal Distance	Pressure variation 1/2 F.D. (db) 2 F.D. (db)	3 db down focal length (cm)
14	.7	7.5	Square	1.1	1.1	4.0	0.5858 0.0224	1.0333 0.0547			
9	.7	7.5	Square	1.1	1.1				4.0	-5.743 -7.758	3.268
16	.7	7.5	Square	1.0	1.0	4.0	0.6289 -0.0126	1.0998 -0.0203			
17	.7	7.5	Square	1.0	1.0				3.5	-5.933 -5.287	3.11
18	.7	7.5	Square	1.2	1.2	4.0	0.5955 0.0526	1.0811 0.1218			
19	.7	7.5	Square	1.2	1.2				4.0	-5.718 -7.270	3.381
20	.6	7.5	Square	1.1	1.1	4.0	0.5693 -0.015	.9784 -0.0286			
21	.6	7.5	Square	1.1	1.1				3.5	-5.786 -6.473	3.134
22	.8	7.5	Square	1.1	1.1	4.0	0.6352 0.0721	1.1094 0.1355			
23	.8	7.5	Square	1.1	1.1				4.0	-6.641 -7.036	3.343
24	.7	6	Square	1.1	1.1	4.0	0.8899 0.2298	1.2169 0.2409			
25	.7	6	Square	1.1	1.1				4.5	-5.639 -5.653	4.159
26	.7	7	Square	1.1	1.1	4.0	0.6437 0.0787	1.1126 0.1410			
27	.7	7	Square	1.1	1.1				4.0	-6.145 -6.438	3.482
28	.7	8	Square	1.1	1.1	4.0	0.5773 -0.0209	0.9975 -0.0414			
29	.7	8	Square	1.1	1.1				3.5	-5.990 -6.905	3.018

TABLE A4-15: Beam Profiling for Perturbation of Length x Width, Q and β of the Optimally Shapes Transducer Configuration for Best Transverse Pressure Profile Resolution at 4.0 cm

APPENDIX A4-3

ULTRASONIC EXAMINATION OF GERMAN REMOVAL SAMPLES

Electric Power Research Institute
Contract RP892-1

Southwest Research Institute
Project 17-4912

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ULTRASONIC EXAMINATION OF GERMAN REMOVAL SAMPLES

1.0 INTRODUCTION

In the latter part of 1978 a utility in the Republic of Germany determined that intergranular stress corrosion cracking (IGSCC) had occurred in several of the piping systems in their boiling water reactor power plant. This problem was deemed significant in that very large diameter pipe (i.e., 24-inch to 26-inch diameter pipes) exhibited the IGSCC condition. Previous problems of this nature in both Europe and the United States had involved smaller diameter pipe. After extensive NDE examination and evaluation, a decision was reached by the German authorities to remove the affected piping.

The Electric Power Research Institute (EPRI) was informed of the above conditions and subsequently contacted German officials with the utility in an effort to secure as many samples as possible representative of the field conditions for independent evaluation and studies. Subsequent to pipe removal, nine (9) samples were shipped to Southwest Research Institute (SwRI) for execution of the above NDE studies and evaluations. The nine samples received represent portions of various sections of pipe and were received in a variety of sizes and configurations.

Extensive NDE analysis was performed by SwRI at the direction of EPRI program management and pursuant to the guidelines of the RP892-1 program. The primary objective of these studies was (1) to obtain correlative data between the 1.5 MHz dual transducer developed for the 892 program and other conventional transducers for the detection and classification of IGSCC, and (2) to secure independent NDE analyses for subsequent correlation with German NDE evaluations and post-removal destructive assay. These activities were conducted at SwRI and the following report summarizes the results of these examinations.

2.0 DISCUSSION OF EXAMINATION

2.1 Test Specimen Characteristics

Nine of the German removal samples were received by SwRI. These samples were all radioactive with fixed contamination fields on surface contact ranging from 20 to 190 MR. It should be noted that the fixed contamination surface fields were measured on the OD surface only. Photographs and descriptions of independent samples are contained herein. One sample consisted entirely of weld material while the remainder of the samples contained from one to three welds or portions of welds. Access for examination from at least one side of the weld was available on all welded samples.

For performance of the ultrasonic examinations conducted at SwRI, it was determined critical to maintain the as-received integrity of the ID of all specimens. This was considered advisable such that the examinations performed would represent as nearly as possible the precise specimen conditions as experienced during the German evaluation studies. As a consequence no cleaning, liquid penetrant examination, or other related operations were performed on the ID of the specimens to exclude the possibility of impairing the conditions and characteristics of the IGSCC. The samples were taped and radioactively bagged to permit cleaning and removal of loose contamination from the OD surface only. All examinations were performed with the specimens in this bagged condition and in a radiation-controlled environment. Specimen conditions such as surface irregularities and specimen size which were deemed to be limiting factors in performance of examinations are summarized herein.

2.2 Examination Procedure

In order to establish a basis for comparison between the 2.25 MHz single crystal transducer and the 1.5 MHz dual element transducer, each specimen was examined in the same manner as a weld of this type would be examined in the field during normal inservice examinations. Ultrasonic examination procedures previously developed under the RP892-1 program were applied during examination of the specimens. Initial examinations were conducted using the 2.25 MHz single crystal transducer and applying conventional field techniques and procedures. Subsequent to this conventional examination, each specimen was then reexamined utilizing the 1.5 MHz dual element transducer. In both instances, examinations were performed both parallel and transversely to the specimen welds.

It should be pointed out that indications were recorded during the conventional 2.25 MHz examination at much lower amplitudes than would normally have been recorded in a conventional application of the examination procedure. This was done to obtain direct amplitude correlation between indications detected with the 2.25 MHz and 1.5 MHz transducer. No attempts were made to correlate ultrasonic indications with liquid penetrant indications since no liquid penetrant examination was performed for the reasons stated above.

2.3 Examination Calibration

The calibration standard used during the ultrasonic examinations performed herein was SwRI calibration block EP-CAL-1. This block was chosen to insure a Code-legal examination. The block is representative of the material (P-groupings) of the German samples, contains calibration reflectors in accordance with ASME Section XI, and is of the appropriate size as indicated by Section XI. The block has dimensions of 1-3/4 inches long, 5-1/4 inches wide, and 10-1/2 inches thick. The block contains four side-drilled holes and one milled notch in accordance with ASME Section XI. Figure A4-5 provides a schematic of the calibration block.

To establish distance amplitude correction (DAC) curve, one side-drilled 1/8-inch diameter hole was used. This reflector located at a 3/4T position was used as the primary reference response. The instrument gain control was adjusted in order to position the peak response of this reflector at an amplitude of eight lines or 80 percent full screen height.

The response appeared at the 3/8 nodal position, as shown in Figure A4-6.

By manipulating the search unit in a backward manner from the previously attained 3/8 nodal position, a second response will appear. This response is that of the 3/4T reflector, as seen at the 5/8 nodal position (Figure A4-7). This is accomplished when the sound beam is reflected from the lower surface of the calibration block, prior to contact with the 3/4T hole (see Figure A4-7). At this point, without increasing instrument gain, peak response from both reflectors is marked directly upon the instrument screen.

Once the 3/8 and 5/8 DAC points had been attained and marked on the instrument screen, the calibration standard was then turned over. (Figure A4-8). This was done in order to attain additional response from the 3/4T reflectors at the 7/8 and 9/8 nodal position. (See Figure A4-9).

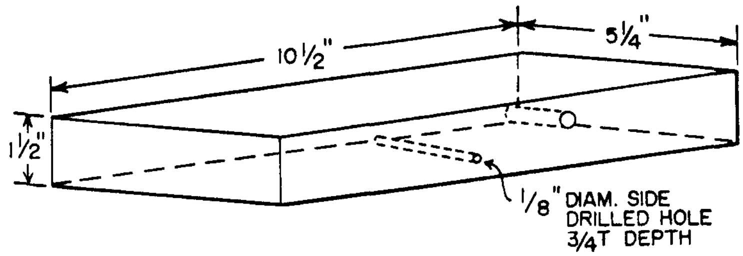


FIGURE A4-5

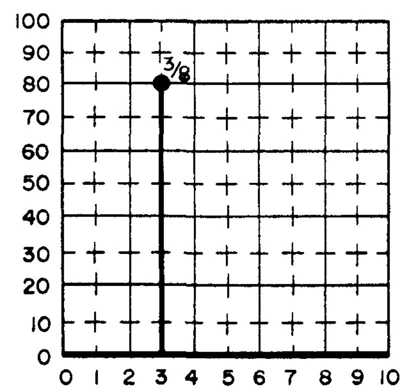


FIGURE A4-6

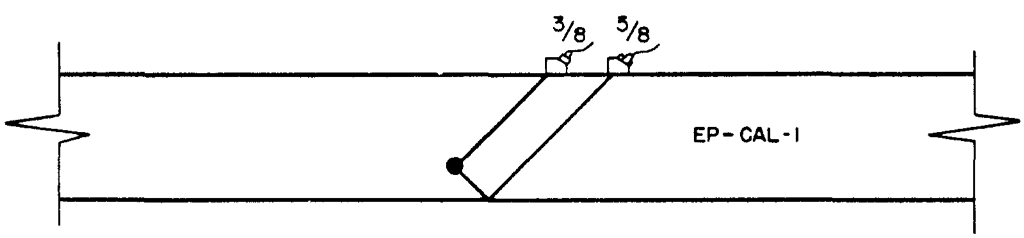


FIGURE A4-7

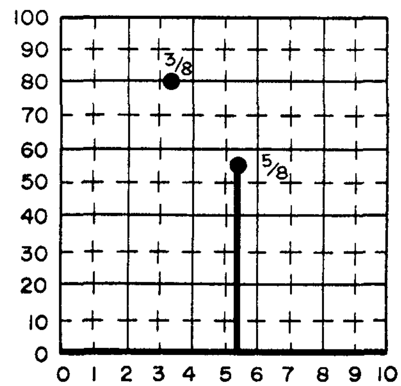


FIGURE A4-8

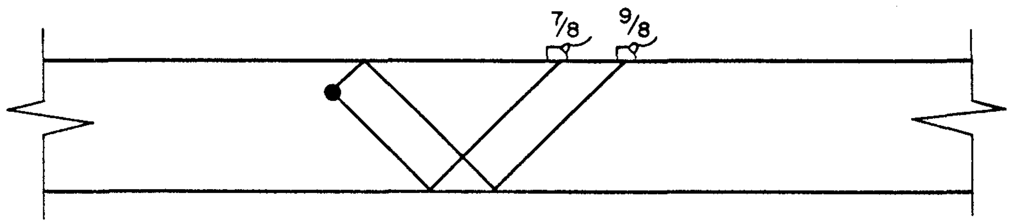


FIGURE A4-9

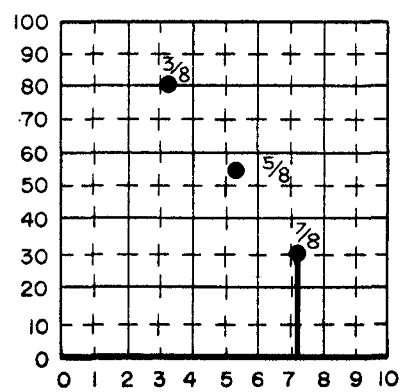


FIGURE A4-10

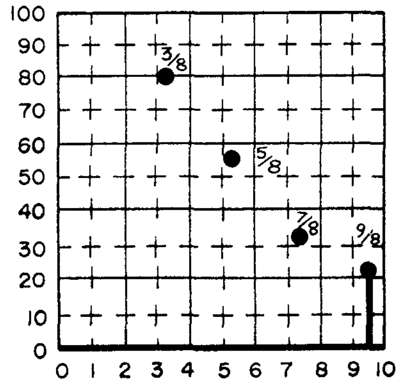


FIGURE A4-11

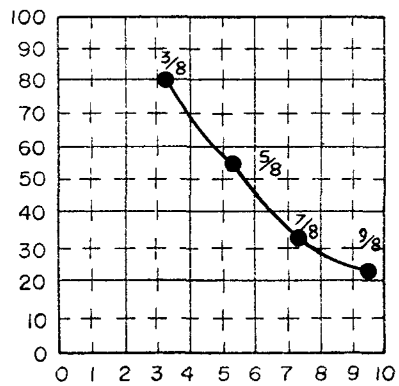


FIGURE A4-12

Again without an increase in instrument gain, the transducer was manipulated to points where peak response from both 7/8 and 9/8 nodal positions could be recorded on the instrument screen. (Figures A4-10, A4-11).

By joining these reference response peaks with a smooth line on the instrument screen, examination calibration was now complete. (Figure A4-12).

3.0 EXAMINATION RESULTS

The nine test specimens exhibited the following identifying, stamped numbers on receipt by SwRI:

L3HS/VI-4
L1 HS
L3HS/VI-3
1-19-2
1-19-1
1-19-3
1-19-212
LsHS/VI-1
L3HS/VI-2

These identifying numbers were retained throughout SwRI examinations and data recording.

A discussion of the results obtained follow. Note that data and calibration sheets have been retained by EPRI pending further comparative evaluations with advanced detector techniques and permission to perform destructive assay. It is anticipated that a full EPRI report will be issued when this work is complete.

3.1 Specimen No. L3HS/VI-4 (See Figure A4-13)

a) Examination Area

There is possible weld material at each end of the specimen.

b) Limitations

The sample welds are located at opposite edges of this specimen. The removal cuts were made through these welds and only portions of weld material remains. Both welds were examined from the remaining side. In addition to this examination each weld received a transverse scan in each direction.

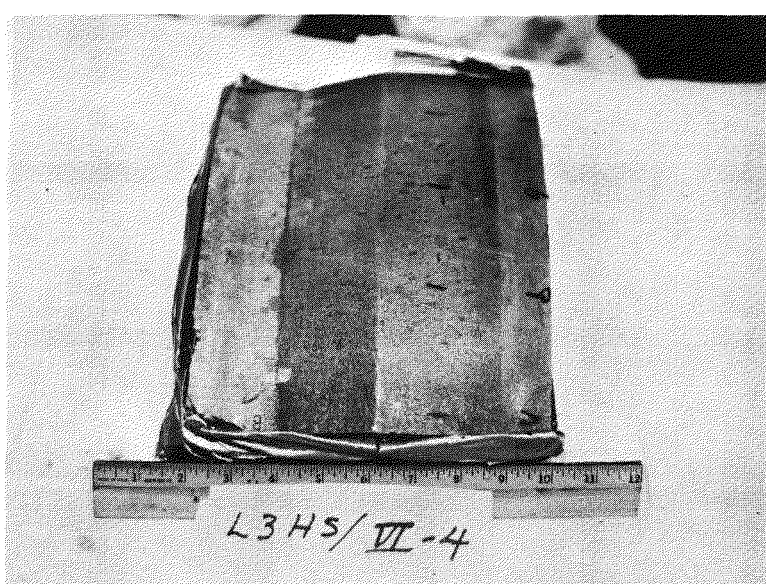
c) L3HS/VI-4 Examination Results

42° 1.5 MHz Dual				45° 2.25 MHz Single			
No.	"W" Max	MP	"L" Max	Ind. No.	"W" Max	MP	"L" Max
(1) 80%	2-3/8"	3.2"	10-13/16" A	(1) Evidently could not be seen with 2.25			
(2) 80%	1-11/16"	1.9"	9-1/2"-B	(2) Evodently could not be seen with 2.25			
				(1) 25%	2-1/2"	2.7"	6-1/4"-A
				(2) 28%	2-1/2"	2.7"	8"-A

d) Comparison Summarization

Indication Nos. (1) and (2) as recorded with the 1.5 MHz dual unit were not seen with the 2.25 MHz unit.

Side B



Side A

FIGURE A4-13

3.2 Specimen No. L1HS (See Figure A4-14)

a) Examination Area

There is apparently weld material on each end of the sample.

b) Limitations

This weld contains portions of two welds. Each weld is located at opposite ends and can be examined from only one side. A section of weld material and base metal has been removed from Side B. Each portion of weld material was examined from one side only due to configuration. Both welds received a transverse examination in clockwise and counterclockwise directions.

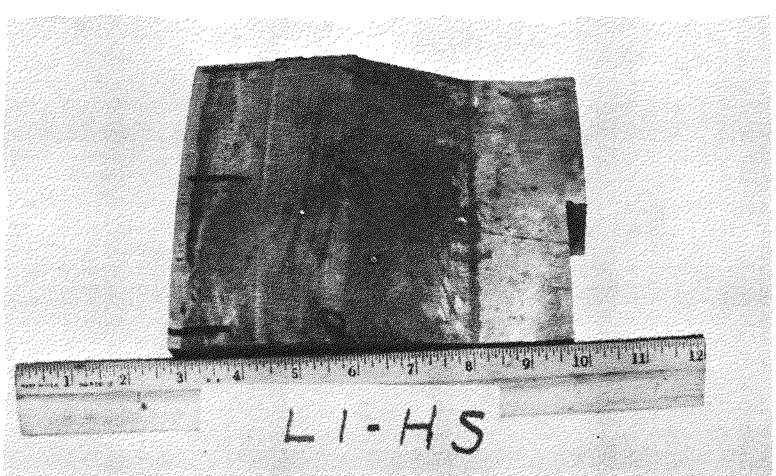
c) L1HS Examination Results

42° 1.5 MHz Dual				45° 2.25 MHz Single			
No.	"W" Max	MP	"L" Max	Ind. No.	"W" Max	MP	"L" Max
(1) 70%	1-5/16"	1.8"	5-9/16"		NO INDICATIONS		
(2) 50%	1-1/4"	1.9"	5-9/16"		NO INDICATIONS		

d) Comparison Summarization

No recordable indications were found with the 2.25 MHz search unit; therefore, a comparison of indications was impossible. The indications are believed to be geometric reflectors (weld interface).

Side A



Side B

FIGURE A4-14

3.3 Specimen No. L3HS/VI-3 (Figure A4-15)

a) Examination Area

This sample contains portions of weld material on both sides A and B.

b) Limitations

The weld area on each end of this sample was examined conventionally. Again the two sample welds are located too near the edges of the sample to allow examination from more than one side. Although both welds received a transverse examination in both directions, the transverse scanning on Side B was quite limited due to its contact surface configuration.

c) L3HS/VI-3 Examination Results

42° 1.5 MHz Dual				45° 2.25 MHz Single			
Ind. No.	MP	"W" Max	"L" Max	Ind. No.	MP	"W" Max	"L" Max
(1) 50%	2.65"	2"	A 1"	(1) 22%	2.7"	2"	1"
(2) 56%	2.6"	2-1/16"	A 2"	(2) 32%	2.65"	2-1/16"	2"
(3) 50%	2.7"	2-3/16"	A 3"	(3) 18%	2.7"	2-3/16"	3"
(4) 70%	2.7"	2-1/8"	A4-13/16"	(6) 20%	2.65"	2-1/8"	4-13/16"
(5) 80%	2.7"	2-1/8"	A5-3/16"	(5) 20%	2.77"	2"	5-3/16"
(6) 90%	2.6"	2-1/16"	A5-3/4"	(7) 40%	2.7"	2-1/16"	5-7/8"
(7) 100%	2.6"	1-7/8"	A8-3/8"	(8) 40%	2.65"	2"	8-1/2"
(8) 56%	2.6"	2"	A12-3/8"	(10) 18%	2.7"	2-1/4"	12-1/2"
(9) 32%	2.6"	2-1/16"	A10"	(9) 28%	2.7"	2"	10"
(10) 50% (45°)	2.6"	6-9/16"	A7/8"	COULD NOT BE FOUND			
(11) 63%	1.9"	1-3/4"	B4-11/16"	(13) 28%	2"	1-11/16"	4-5/8"
(12) 36%	1.9"	1-3/4"	B5-9/16"	(11) 36%	2"	1-3/4"	5-3/4"
(13) 56%	1.9"	1-3/4"	B4-13/16"				
				Indication Nos. (4) and (12) with 45°, 2.25 MHz evidently not seen with 45°/1.5 MHz.			
				(4) 28%	2.75"	2"	3-9/16"
				(12) 32%	2.0"	1-3/4"	5-5/16"

d) Comparison Summarization

Nine of the 13 indications found with the 1.5 MHz dual unit were also recorded with the 2.25 MHz unit.

Side B

Side A

SPECIMEN NO. L3HS/VI-3

FIGURE A4-15

3.4 Specimen No. 1-19-2 (Figure A4-16)

a) Examination Area

Sample 1-19-2 contains one centrally located weld.

b) Limitations

There were no limiting factors to this sample weld examination. The sample weld was examined from both sides and transversely examined in both directions.

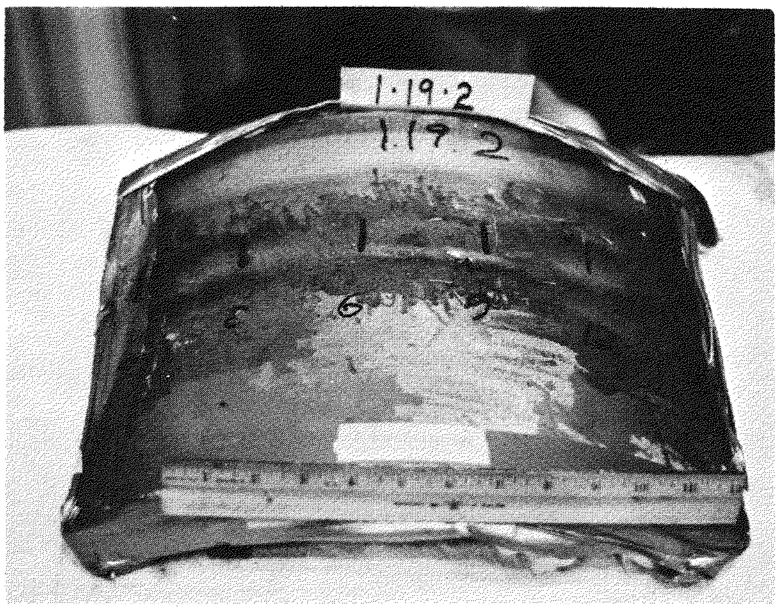
c) 1-19-2 Examination Results

42° 1.5 MHz Dual				45° 2.25 MHz Single			
Ind. No.	"W" Max	MP	"L" Max	Ind. No.	"W" Max	MP	"L" Max
(1) 36%	1-7/16"	2.0"	B 6-1/2"	(1) 20%	1-1/2"	2.1"	B 6-1/2"
(2) 32%	1-5/16"	2.1"	A 5-7/8"				
(3) 32%	1-5/16"	2.0"	A 3-9/16"				

d) Comparison Summarization

A correlation could only be made with Indication No. 1.

Side A



Side B

FIGURE A4-16

3.5 Specimen No. 1-19-1 (Figure A4-17)

a) Examination Area

This sample contains two welds, a circumferential weld and a longitudinal seam weld. The longitudinal seam weld is designated 1-19-1LS.

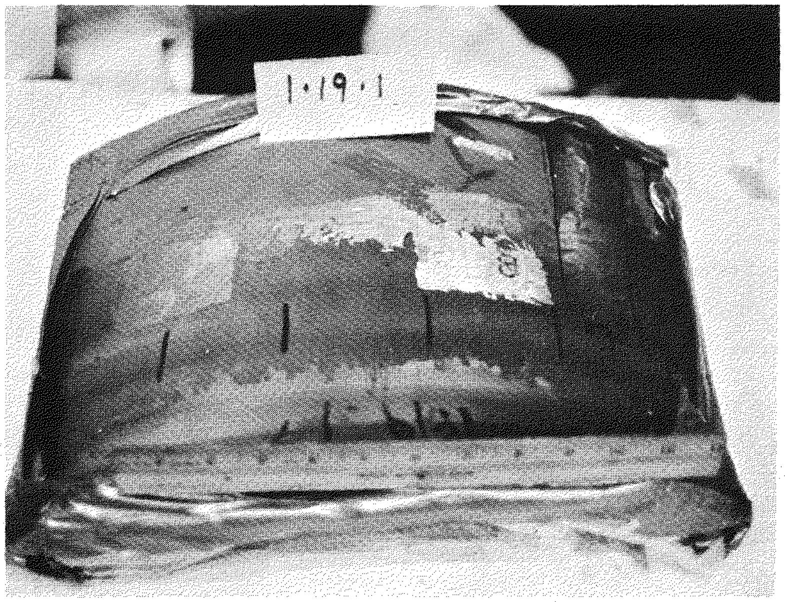
b) Limitations

The removal of this sample left ample area to allow proper examination of each weld from both sides. Each weld received circumferential and transverse scans from each side.

c) 1-19-1 Examination Results

No recordable indications were found during examinations of either weld.

Side B



Side A

FIGURE A4-17

3.6 Specimen No. 1-19-3 (Figure A4-18)

a) Examination Area

Sample 1-19-3 contains one weld which is centrally located.

b) Limitations

Due to the central location of this weld, conventional examinations from both sides were done. In addition to this examination, the sample weld received a transverse scan in both clockwise and counterclockwise directions.

c) 1-19-3 Examination Results

No recordable indications were found during examinations of either weld.

Side A

Side B

FIGURE A4-18

3.7 Specimen No. 1-19-212 (Figure A4-19)

a) Examination Area

This sample contains one weld which is centrally located. This sample is approximately 12 inches long and 10-3/4 inches wide.

b) Limitations

No apparent limitations exist on this sample. This weld was examined from both sides and transversely scanned in a clockwise and counterclockwise direction.

c) 1-19-212 Examination Results

42° 1.5 MHz Dual				45° 2.25 MHz Single			
Ind. No.	"W" Max	MP	"L" Max	Ind. No.	"W" Max	MP	"L" Max
(1) 32%	1-5/8"	2.1"	B 1-3/8"		NO INDICATIONS		
(2) 36%	1-9/16"	2.1"	B 2-1/2"				
(3) 28%	1-3/8"	2.1"	A 10-3/16"				

d) Comparison Summarization

No recordable indications were found with the 2.25 MHz search unit.

Side B

Side A

FIGURE A4-19

3.8 Specimen No. L3HS/VI-1 (Figure A4-20)

a) Examination Area

This sample contains essentially one weld. This weld is located at the end of the sample marked Side B. The removal cut was apparently made through the centerline of this weld, and only a portion of the weld root remains.

b) Limitations

Sample L3HS/VI-1 received a shear examination on Side B only. This weld received a transverse examination in both directions, and a standard weld scan from the one available side. The standard weld scan was limited to an area of 2-3/16 inches due to the surface configuration.

c) L3HS/VI-1 Examination Results

42° 1.5 MHz Dual				45° 2.25 MHz Single			
Ind. No.	"W" Max	MP	"L" Max	Ind. No.	"W" Max	MP	"L" Max
(1) 63%	1-3/4"	1.9"	B 13/16"	(3) 56%	1-3/4"	2"	B 1-1/2"
(2) 50%	1-11/16"	1.85"	B 1-7/16"	(1) 28%	1-3/4"	2"	B 1-15/16"
				(2) 28%	1-3/4"	2"	B 1-7/8"

d) Comparison Summarization

Indication No. (2) which was located with the 1.5 MHz corresponds with Indication No. (3) as found with the 2.25 MHz search unit.

Side B

Side A

FIGURE A4-20

3.9 Specimen No. L3HS/VI-2 (Figure A4-21)

a) Examination Area

This sample is composed of essentially all weld material. The size of this sample is a deterrent to a meaningful shear examination with available equipment.

b) Limitations

No shear examination was performed on this sample due to its size.

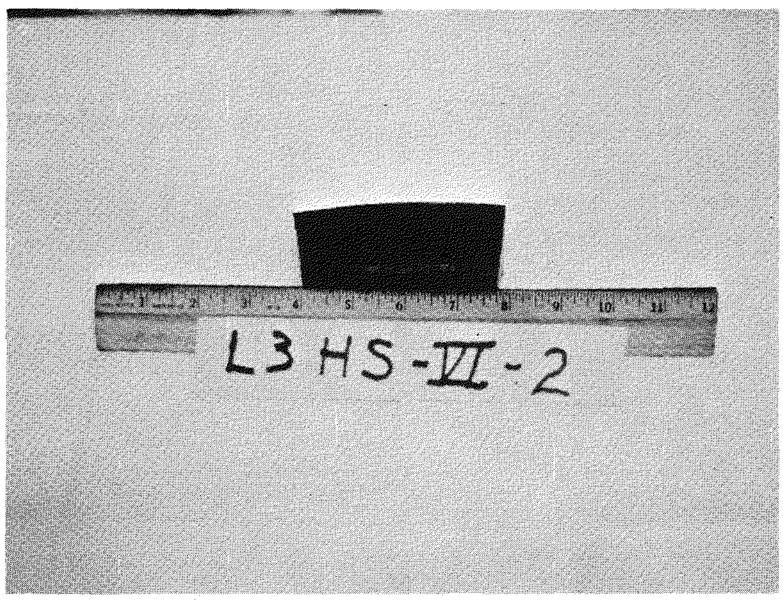


FIGURE A4-2

4.0 SUMMARY

EVALUATION OF 1.5 MHz DUAL ELEMENT TRANSDUCER ON SERVICE GENERATED IGSCC

The identification of intergranular stress corrosion cracking (IGSCC) in large (~26" diameter) pipes of the RWE Gundremmingen BWR has resulted in criticism of the adequacy of ultrasonic testing (UT) for such flaw detection. The most negative opinion advanced is that UT is not sufficiently reliable for meaningful IGSCC detection; this opinion apparently arising from adverse experience prior to pipe removal. Since UT reliability derives from a composite of technique, instrumentation and human factors, there is no method immediately available to adjudicate the RWE experience. However, through the kind offices of RWE, some results of current EPRI-sponsored research can be utilized to provide some basis for interpretation.

EPRI-sponsored UT improvement programs range from short-term transducer improvement studies through to UT automation augmented by advanced data processing techniques (1), (2). The transducer efforts have resulted in the recommendation that a 1.5 MHz dual transducer be utilized for austenitic piping inspection rather than the more conventional 2.25 MHz (or higher) single crystal transducer commonly recommended. This transducer is now in widespread industrial use in the United States. Via RWE nine pipe samples removed from the Gundremmingen plant were obtained and subject to comparative evaluation using the two transducer types. The results of this comparison cannot yet be considered complete (for reasons stated later), but there appears to be clear evidence that the actual reliability of contemporary UT techniques is substantially better than might be judged solely from examining conventional transducer utilization experience.

All samples received from RWE were radioactive with fixed surface contamination fields ranging from 20 to 190 MR. Each was a sector of a large pipe containing one to three welds or portions thereof. In the testing conducted it was deemed significant to maintain as-received I.D. integrity. So, no cleaning, liquid penetrant or related operations were performed. In this state comparative investigations were performed using standard project techniques (3) yielding the following results:

1. 17 indications of possible flaws at 50% DAC or greater were observed with the 1.5 MHz transducer whereas only one indication at this level was observed with the 2.25 MHz unit.

2. At the 20% DAC level 25 indications occurred at 1.5 MHz and 19 at 2.25 MHz.

3. 12 indications at 1.5 MHz were obtained where no detection or recordable indication was evidenced at 2.25 MHz.

4. Some ambiguities of correlation exist in the two signal sets because of transducer size and specimen geometry effects (no special transducers were made to provide a "best fit" to available specimens). However it appears that the conventional 2.25 MHz unit: a) missed 25% of the 1.5 MHz indications and, b) provided less than half the signal amplitude of the 1.5 MHz indications in virtually all correlatable cases. Whether or not the low signals from the 2.25 MHz would have resulted in "calls" is a matter of conjecture dependent on procedure used by specific operators.

5. The comparative tests conducted, thus far, suggest that many more "calls" would be made with the preferred transducer than with the conventional approach. Hence, many indications would have been subject to more detailed evaluation, whereas, in the extreme, only 20% or less of these indications might have been subject to further scrutiny from a 2.25 MHz base. This indicates a desired conservative trend, however, the absolute value of this comparison must await destructive assay which is recommended.

6. Note also that RF waveforms have been obtained from these samples for application to advanced data processing techniques.

The above work was performed by Southwest Research Institute for EPRI under contract RP892.

REFERENCES

1. Dau, G., Planning Support Document for the EPRI Nondestructive Evaluation (NDE) Program, EPRI Report NP-900-SR (December 1978).

2. Lapides, M., Notes on EPRI Ultrasonic Program for NRC IGSCC Workshop (December 1978).

3. Workshop on In-service Inspection of Stainless Steel Piping in Nuclear Systems, EPRI Project 892 Report (January 1979).

APPENDIX A5

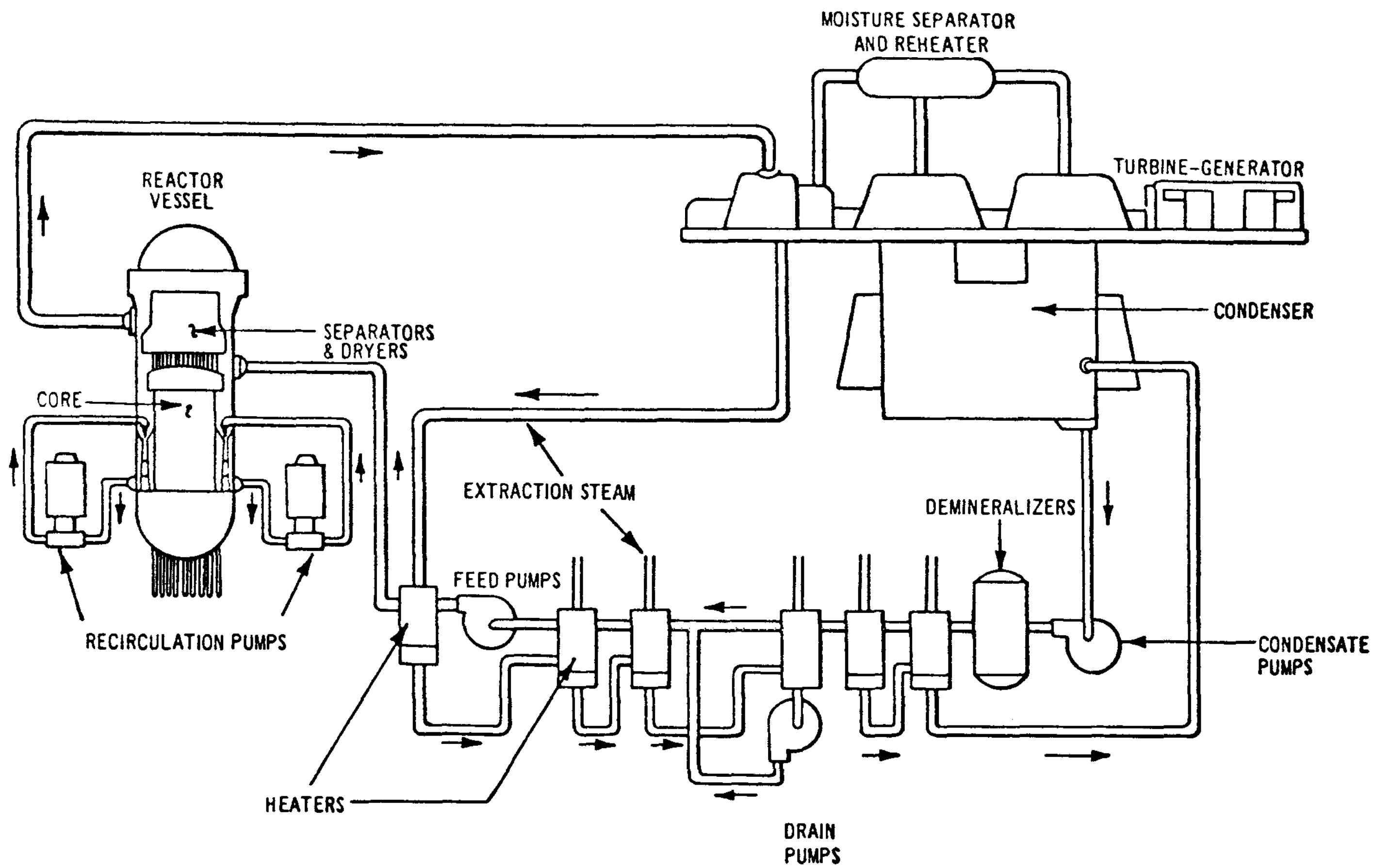
BOILING WATER REACTOR PIPING DATA

Abstract from
EPRI RP 892 Report: Workshop on In-Service
Inspection of Stainless Steel
Piping in Nuclear Systems
(January, 1978)
by
B. Rajala
General Electric Co.

The Boiling Water Reactor (BWR) nuclear system is a direct cycle system consisting of a steam generation system, control system, radiation monitoring system, core cooling and containment system, servicing and handling equipment, cleanup and filtering system, control panels, fuel and auxiliary systems (Figure A5-1). In the nuclear system feedwater enters the reactor vessel and mixes with water in the vessel. The water is pumped through the core forming steam which is transferred directly to the turbine through 4 main steam lines. The turbine employs a conventional regenerative cycle with condenser aeration and condensate demineralization. After demineralization, the condensate then passes through feedwater heaters and returns to the vessel through 4 or 6 (depending on size) feedwater lines.

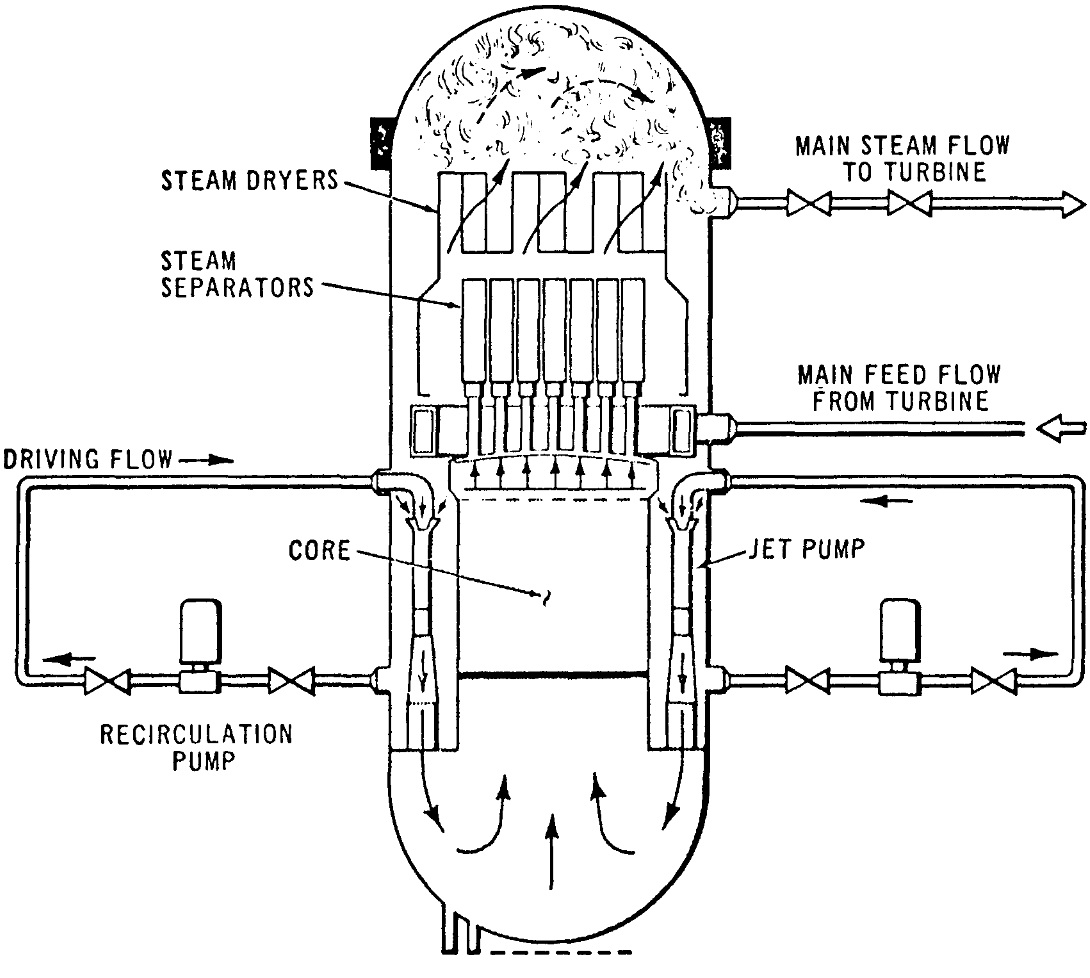
Recirculation water is forced through the core and steam separators by jet pumps located in the peripheral area around the inside of the vessel. Motive power for these jet pumps is provided by two recirculation pumps which draw a fraction of the water from the vessel and return it with increased pressure, Figure A5-2. The more descriptive schematic of one loop of the recirculation system is shown in Figure A5-3.

The control rod drives and piping form the balance of the primary system. Water is taken from the condensate storage tank, is pumped to a pressure of about 1600 psig and passed through filters. Pressure control for normal operation is obtained by maintaining constant flow through a series of pressure reducing valves and discharging the flow to the reactor. The first regulator maintains a pressure 250 psi above reactor pressure for control rod positioning and the second approximately



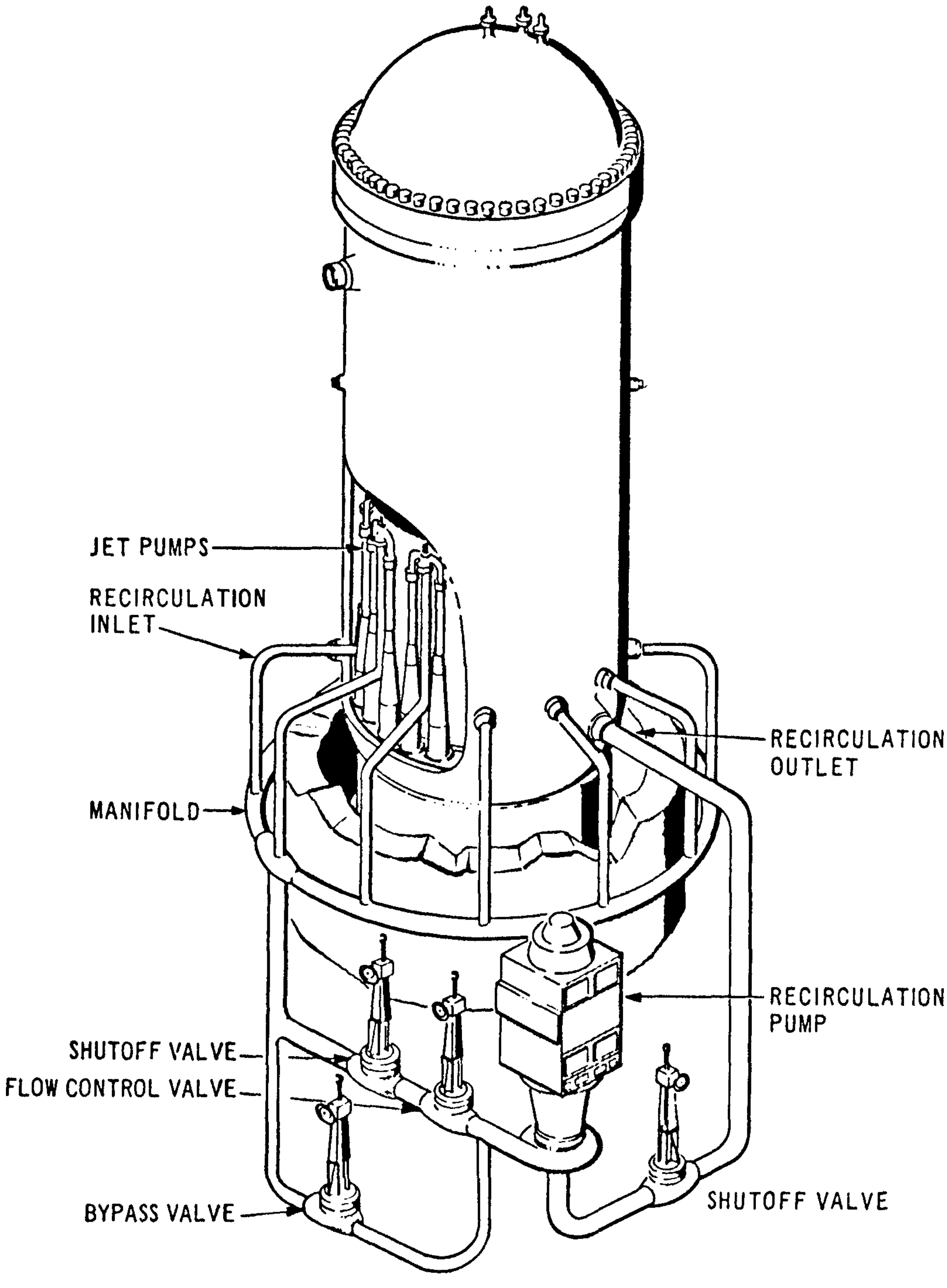
DIRECT CYCLE REACTOR SYSTEM

Figure A5-1



STEAM AND RECIRCULATION WATER FLOW PATHS

Figure A5-2



BWR VESSEL ARRANGEMENT FOR JET PUMP
RECIRCULATION SYSTEM

Figure A5-3

20 psi above reactor pressure for drive cooling. Excess water from each drive is discharged into the vessel.

The auxiliary systems for BWR operation may be broken down into two general categories: systems necessary for normal operation, and systems which provide backup or are designed to accommodate emergency or abnormal conditions.

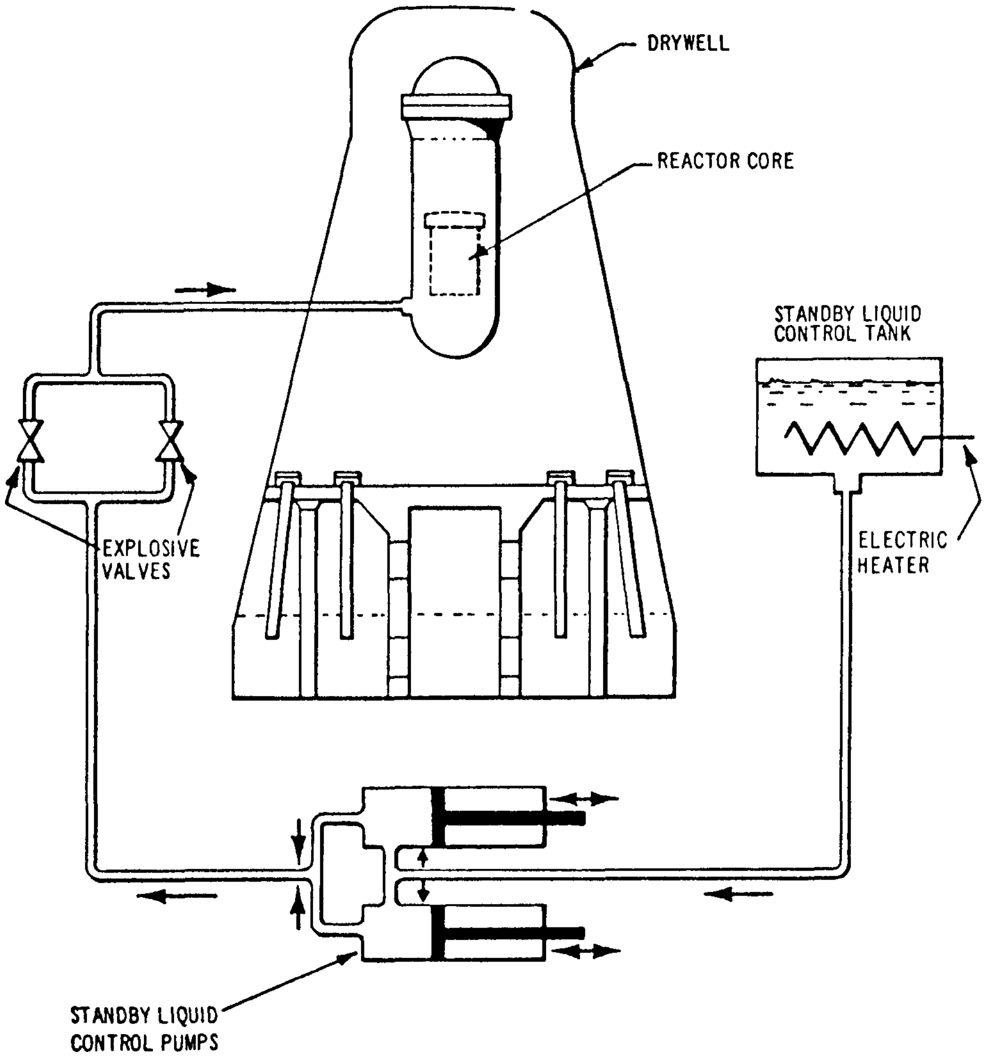
Systems which are used for backup or standby cooling are:

- Standby liquid control
- Reactor Core Isolation Cooling (RCIC)
- Residual heat removal system (hot standby mode, containment cooling mode and low pressure injection mode)
- Low pressure core spray system
- High pressure core system

In the reactor water cleaning system, recirculation system water is passed through heat exchangers, filter demineralizers, into regenerative heat exchangers and finally back into the feedwater system. The portion of this system subject to examination is that within containment and to a valve outside containment, Beyond that, the system is classified Class 3 and not subject to examination by other than visual methods.

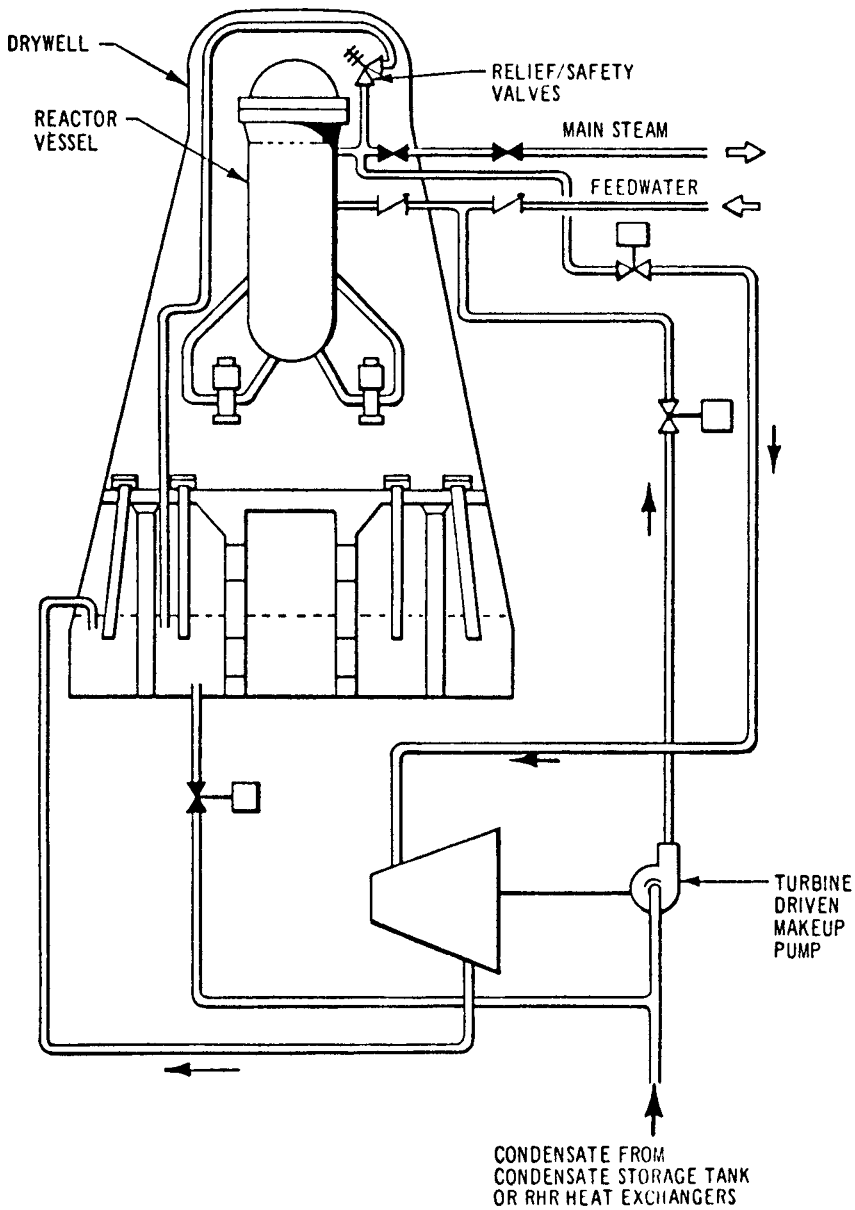
There are two isolation valves in the systems. These valves are to isolate the systems inside containment from the portions outside containment. Up to the first valve outside containment the systems are classified ASME Code Class 1 and are subject to the examination required by ASME Code Section XI, Subsection IW1B. Beyond the second valve the systems change classification and are subject to examinations specified in Section XI, Subsections IWC (for Class 2) and IWD for Class 3.

Figure A5-4 is the schematic of the standby liquid control. The primary function is to shut down the reactor even with control rods withdrawn. The Class 1 portion of this line is normally 1-1/2 inch diameter pipe. The fluid used is sodium pentaborate. Figure A5-5 shows a schematic of the reactor core isolation cooling (RCIC) system. This system is required to operate in the event the reactor becomes isolated from the main condensors by a closure of the main steam isolation line valves. Cooling is necessary since steam production will continue at a reduced rate even though the reactor is shut down.



STANDBY LIQUID CONTROL SYSTEM

Figure A5-4



REACTOR CORE ISOLATION COOLING SYSTEM

Figure A5-5

The function of the RCIC system is to maintain reactor water level when excess steam is being vented to the suppression pool. Part of the steam is directed to the RCIC turbine which drives a pump. The primary source of makeup water is from condensate storage, secondarily from the suppression pool. Water from these sources is pumped to feedwater lines and in the vessel.

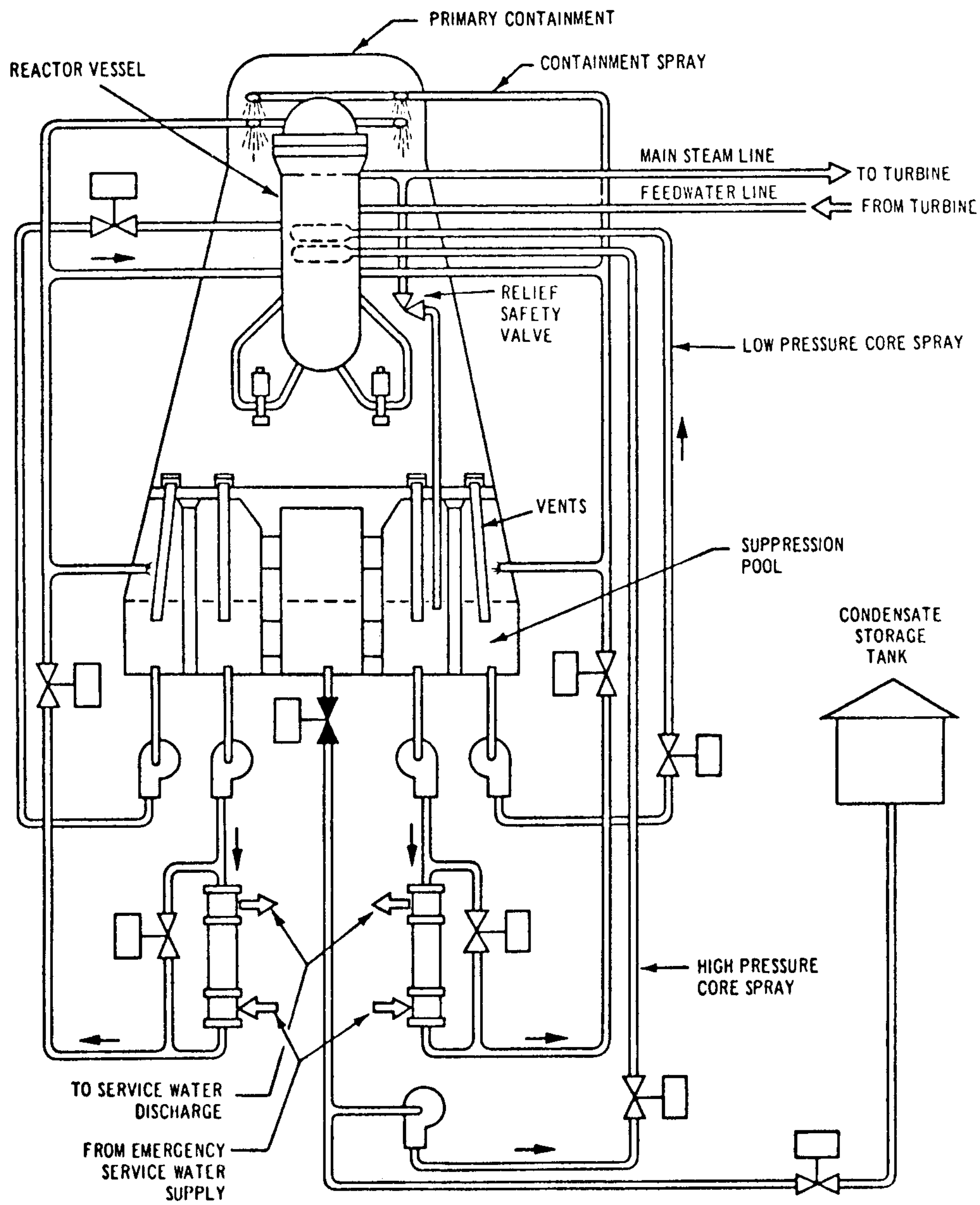
Except for the portion connected to the reactor pressure vessel and up to the second isolation valve outside containment, the emergency core cooling systems are Class 2 systems (Figure A5-6). The portions inside the containment are Class 1 and subject to Class 1 examination. All these systems are required to function during a design accident. The source of water is from the suppression pool or from the condensate storage. This water is directed into the reactor pressure vessel and into containment for containment cooling.

The final system subject to examination (volumetric and surface) is the residual heat removal system (RHR). Figure A5-7 is a schematic. There are two isolation valves in each line. The water is removed from the recirculation line by suction pumps which direct the water through heat exchangers and then back into the vessel. The system begins operation when the vessel has cooled to about 345°F (100 psig). The primary purpose is to bring the reactor to ambient temperature at a specified rate. Not shown on these preceding schematics are drains, instrument lines, hydraulic lines, test lines, or other operational small lines.

Table A5-1 lists the component pipes, which are all stainless steel in the aforementioned functional systems. The approximate number of circumferential welds are given with the range of pipe sizes. As the designs advanced from BWR 3's to 6's, less stainless steel systems were used and subsequently less stainless steel welds need to be examined.

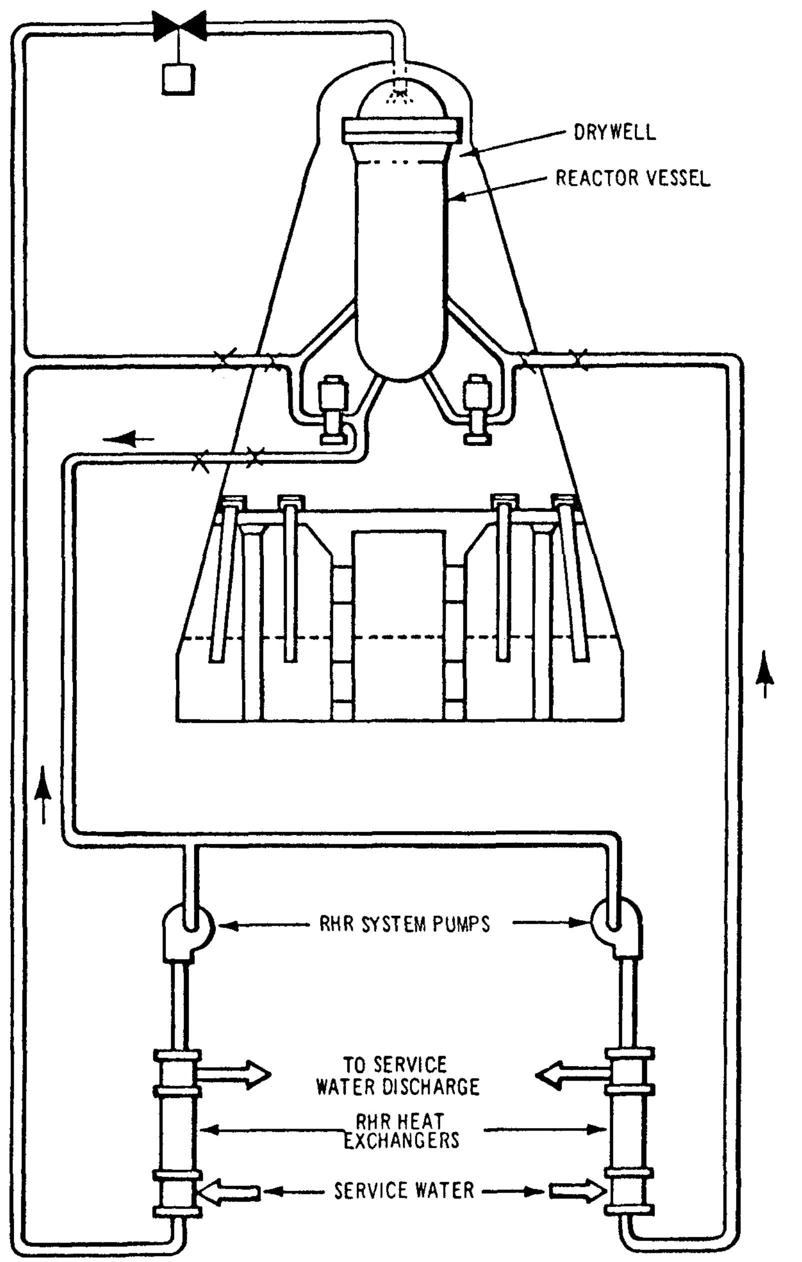
In Table A5-1 the designation "Target Lines" signifies those lines that are believed most susceptible to intergranular stress corrosion cracking. The NRC recommendation is the lines must either be removed or replaced by materials less sensitive to IGSCC. If neither is done, then an augmented ISI is required, every weld in these lines must be examined in 3-1/3 years and then again before 10 years has elapsed.

The service sensitive lines are those lines which have low velocity flow of water through them and/or portions of the lines have had thermal fatigue cracking



STANDBY CORE COOLING SYSTEM

Figure A5-6



RESIDUAL HEAT REMOVAL SYSTEM SHUTDOWN COOLING MODE

Figure A5-7

initiation with subsequent IGSCC. The nonservice sensitive lines are those containing reactor water at reactor pressure with high flow rates.

System and Size	Approx. No. of Welds	Target Lines	Service-Sensitive Lines	Non-service Sensitive Lines
	BWR-3			
Recirculation 12" to 28"	110			X
Recirculation Bypass 4"	20	X		
Core Spray 10"	32	X		
RHR Shutdown Cooling 14"	16 to 40			X
LPCI 10 to 14	40			X
CRD Hydraulic Ret. 3" & 4"	25		X	
Reactor Water Cleanup 3" to 8"	36		X	
Isolation Condensor	34			X
	BWR-4			
Recirculation 12" to 28"	110			X
Recirculation Bypass 4"	20	X		
LPCI-HPCI 10" to 14"	40	X		
CRD Hydraulic Return 3" , 6"	25		X	
Reactor Water Cleanup 3" , 8"	36		X	
RHR Shutdown Cooling	2 to 12"			X
Core Spray 10"	up to 32	X		
	BWR-5 & BWR-6			
Recirculation 12 to 28	110			X
RHR Shutdown Cooling 14"	4 to 8			X
Reactor Water Cleanup 3" to 8"	4 to 8		X	

TABLE A5-1

BWR STAINLESS STEEL PIPING SYSTEMS

APPENDIX A6
DEVELOPMENT OF INTERGRANULAR STRESS CORROSION CRACK PIPE SPECIMENS FOR NDE

INTRODUCTION

Because of the desirability of performing ultrasonic test development on actual IGSCC samples, considerable attention has been directed to the development of methods for introducing such flaws into full-size welded pipes of type 304 stainless steel. This appendix briefly summarizes techniques currently in use for production of such NDE standards.

GENERAL ELECTRIC PIPE TEST LABORATORY (PTL)

The PTL consists of two, controlled chemistry water circulation loops, each of which is capable of accommodating 36 pipe test stands. An individual stand permits a 44 inch length of 4 inch pipe to be tested under cyclic axial loading. A single larger stand capable of testing up to 16 inch diameter pipe was also available. Up to 12 butt welds can be included in the 4-inch stand.

The test conditions normally utilized to develop test standards were:

Temperature	550 degrees Fahrenheit (288 Celsius)
Stress	136% of 288 Celsius yield strength
Environment	High purity water - 8PPM dissolved oxygen
Cycles	0.67 cycles/hr, trapezoidal waveform

Depending on metal chemistry (nominally carbon content) and pre-test heat treatment, IGSCC would be obtained in weld HAZ areas after test times in the range of 100-500 hours. Sectioning of the multiweld stand provided the NDE specimens. Four-inch PTL specimens generally yielded multiple wide gap cracks in the HAZ rather than the very "tight" IGSCC often encountered. This behavior may have been due to:

a. the high stress level

b. rapid propagation typical of small pipes following initiation or

c. the absence of instrumentation or information signalling crack initiation.

The latter item has been at least partially rectified by current inclusion of acoustic emission monitoring equipment in the PTL.

The large (16-inch) pipe test stand has also been used for specimen generation. In this case, comparatively "tight" cracks were achieved by a composite of reducing operating stress level (to 110% of yield) and using acoustic emission signals to estimate crack initiation events.

CHEMICAL CORROSION

Various chemical corrodants offer the prospect of introducing IGSCC into pipes. Of those possible, the most effective found to date is the use of the Straus Reagent on pipe which has previously been subjected to a low temperature sensitization (LTS) process (furnace heat at 500 degree Celsius for 24 hours). The chemical treatment consisted of heating the region where cracks are desired in a boiling Straus solutuion (10 weight % $CuSO_4.5H_2O$,10 volume % reagent grade concentrated H_2SO_4, remainder water).

The LTS heat treatment maximizes sensitization in the HAZ but appears to have little effect on the weld or on pipe material outside the HAZ. The Straus reagent attacks only the more highly sensitized HAZ area, typically after 24-72 hours.

Masking of pipe areas to achieve selective location of IGSCC appears to be quite difficult because few adhesives retain their integrity during the required exposure period. However, some selectivity in circumferential location of cracks is achievable by the manner in which the pipe segment is configured as a reagent container. This procedure permits "tight" IGSCC to be introduced into large diameter pipes without mechanical stress.

ARTIFICIAL CREVICE METHODS

An inert fiberous mat or felt material such as teflon or graphite wools can be used to accelerate the introduction of IGSCC into piping materials. In application the felt is clamped against the pipe I.D. and the unit is immersed in high pressure, high temperture oxygenated water typical of reactor operating conditions. IGSCC will typically result after several hundred hours of exposure in weld sensitized areas without any addtional load. This technique, which offers the prospect of true simulation of crack propagation under reactor service conditions, is currently under intensive investigation as a means of controlling size and location of IGSCC introductions and for alternate diagnostic purposes.