HPI Nozzle Enhanced UT Development

B&W NUCLEAR SERVICE COMPANY

HPI NOZZLE

ENHANCED UT DEVELOPMENT

Performed by:

B&W Nuclear Service Company

for

Toledo Edison Company

DOCUMENT NUMBER: 47-1178263-01

ABSTRACT

BWNS has, under contract to Toledo Edison, developed ultrasonic inspection techniques for inspecting the HPI nozzles at the Davis-Besse plant. This report summarizes the capabilities of the techniques. During the conduct of the program, techniques were identified which would permit inspection of the critical areas of the HPI nozzle. The techniques developed and qualified for use at Davis-Besse are a subset of those identified and were selected based on inspecting the portions of the nozzle affected by the failed thermal sleeve. This program has successfully developed, qualified and demonstrated techniques with sufficient coverage and accuracy to be reliably used as the bases for judgements relative to continued operation.

Toledo Edison contracted the EPRI NDE Center to provide assistance with examination planning (including ultrasonic modeling), mockup fabrication (including crack implantation), overview of examination design, and performance demonstration to the USNRC.

Two program status meetings were held to review the program status with representatives of the NRC. At both NRC status meetings, an NRC consultant (Battelle Pacific Northwest Laboratory) was represented. This document provides a synopsis of the information presented at these two meetings.

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1. INTRODUCTION

During the 5th Refueling Outage at Davis-besse Unit 1, the thermal sleeve in the High Pressure Injection (HPI)/Makeup nozzle on the Reactor Coolant System (RCS) was found broken. Subsequent dye penetrant inspection of the nozzle found indications near the nozzle mouth where it had been exposed to flow of cold makeup water. Based upon the results of manual ultrasonic examinations and analysis at that time, it was concluded that any flaws represented by the indications were contained in the cladding, and that growth of postulated small cracks, approximately 0.3 inch total depth, would not challenge the pressure boundary integrity for the remainder of the forty year design life of the station.

The Nuclear Regulatory Commission (NRC) approved restart and operation for one fuel cycle contingent upon Toledo Edison identifying follow-up actions for the subsequent refueling outage. As part of those actions, Toledo Edison Company contracted the B&W Nuclear Service Company (BWNS) to develop an enhanced ultrasonic examination system for the re-examination of the Davis-Besse Unit 1 HPI/Makeup nozzle during th[illegible] Refueling Outage. Toledo Edison also contracted with the EPRI NDE Center to provide assistance with examination planning, mockup fabrication (including crack implantation), overview of the examination design, and performance demonstration to the NRC.

This document provides a summary of the program conducted by BWNS for the Toledo Edison Company to develop enhanced ultrasonic examination techniques for the inspection of the HPI/Makeup nozzle. This report focuses primarily on the development of techniques for detecting, locating and sizing flaws penetrating from the inside surface into the carbon steel base metal. Some supplemental evaluations of techniques to detect and locate flaws contained entirely within the cladding are also discussed.

2. SUMMARY AND CONCLUSIONS

The principal objective of the development of an Enhanced Ultrasonic Examination System was to provide maximum capability to detect, locate and size small thermal fatigue cracks initiated from the inside surface of the nozzle or adjacent RC pipe. Sizing resolution of the system needed to be adequate to permit subsequent structural analysis to show that any flaws found remain within safe structural limits. In order to meet the functional objectives, it was decided to use automated scanning from outside the nozzle in combination with the BWNS ACCUSONEX[R] system for enhanced data acquisition and analysis.

The ultrasonic examination techniques were qualified for the specific nozzle geometry using representative flaws installed in test blocks and a replica mockup of the nozzle and adjacent RC piping. A plan for automated scanning was developed. The ACCUSONEX® system was further enhanced to handle the specific nozzle geometry.

As a result of the systematic development process, it was possible to demonstrate reliable detection of all flaws penetrating 1/8th inch or more into the carbon steel base material of the nozzle or the adjacent RC pipe wall.

Sizing capability was demonstrated for most of the flaw orientations within the examination region using tip diffraction techniques. The statistical performance and error levels for these flaws fell well within bounds needed to support subsequent structural evaluations.

Axial flaws in the nozzle bore near the blend radius with the RC piping required the use of amplitude-based sizing techniques. Should axial flaws be detected in this region, the examination will be locally augmented.

Although not required to confirm the structural integrity of the nozzle and the RC pressure boundary, on a limited basis, techniques were evaluated for detecting flaws contained entirely within the cladding.

It was concluded that the enhanced ultrasonic examination system as developed meets the need for reliable detection, location and sizing of flaws in the carbon steel base metal within the region of concern.

3. BACKGROUND

While conducting a combined ASME Section XI and pre-fueling visual inspection during the 5th Refueling Outage at Davis-Besse Unit 1, loose parts were discovered in the reactor vessel. Among these loose parts were two metallic pieces resembling half cylinders approximately three inches in length. These pieces were identified as portions of the thermal sleeve which normally protrudes from the HPI/Makeup nozzle (nozzle A1) into the RCS cold leg. This failure and the subsequent action by the Toledo Edison Company leading to approval by the NRC to return to operation for one additional fuel cycle are described in the submittal to the NRC, Serial No. 1580, dated September 14, 1988. Figure 1 illustrates the location of thermal sleeve in the nozzle after the failure. Figure 2 illustrates the replacement thermal sleeve design for the HPI/Makeup Nozzle.

The failure of the thermal sleeve permitted cold makeup water to impinge directly upon the cladding in the nozzle from the point of failure of the thermal sleeve past the nozzle blend

radius with the RC pipe. Inspection of the HPI/Makeup nozzle revealed linear indications in the nozzle in the area exposed to the cold water flow. Physical limitations did not permit dye penetrant examination to extend beyond the knuckle region of the nozzle, however, ultrasonic examination from the outside surface detected no flaws either in the base metal of the nozzle or adjoining RC piping. That examination, and additional fracture mechanics analysis led to the conclusion that the crack-like indications were limited to the cladding, and that such flaws would not grow to a size which could affect integrity of the pressure boundary.

In a submittal to the NRC, Serial No. 1664, dated June 19, 1989, Toledo Edison committed to re-route the makeup flow path to an alternate HPI nozzle (Nozzle A2) in the adjacent RC cold leg; to inspect the makeup thermal sleeve in nozzle A1, and to develop enhanced ultrasonic examination techniques which would be used during the 6th Refueling Outage to confirm the condition of the HPI/Makeup Nozzle (A1) and to obtain baseline information on the alternate nozzle (Nozzle A2) for use in any necessary future examinations.

4. PROGRAM DESCRIPTION

4.1 Objectives

The overall objective of the program was to develop an enhanced ultrasonic examination system capable of detecting, locating and sizing thermal fatigue type flaws penetrating the inner surface of the nozzle, the blend radius at the nozzle mouth, and the adjacent RC pipe inner surface. The emphasis of the development was upon small flaws, penetrating only short distances into the base metal.

Specific criteria for the development included the following:

(1.) The examination must cover the zone of concern potentially affected by cold makeup water following the failure of the thermal sleeve as discovered in the 5th Refueling Outage. (This zone encompasses all dye penetrant indications found in the HPI/Makeup nozzle during the 5th Refueling Outage.)

(2.) The system must be sufficiently sensitive to detect, locate and size flaws penetrating 1/8 inch or more beyond the cladding into the base metal within the zone of concern.

(3.) The system must be capable of detecting flaws oriented in a manner representative of those found in the dye penetrant examination in the 5th Refueling

Outage and consistent with similar observations from other events in the industry. It is necessary to detect and size flaws oriented essentially in the axial and circumferential directions within the nozzle and knuckle radius, and radially and circumferentially surrounding the nozzle opening on the adjacent RC pipe inner surface.

(4.) Sizing resolution shall be determined. A goal of ± 0.1 inch was established.

(5.) Automated scanning must be used along with an enhanced display and analysis system to enhance detection and sizing, to ensure consistent and repeatable results, and to minimize errors of interpretation.

(6.) For reasonable access, the examination must be conducted from the outside surface of the nozzle.

An additional objective, although not required for subsequent structural evaluation, was to detect flaws located entirely within the cladding.

4.2 <u>Program Structure</u>

The structure of the program was based on selecting the regions to be examined, then developing the capability to detect, locate and size flaws in that region.

The program structure included five basic parts:

(1.) Determination of the boundary of the region to be examined.

(2.) Development of the scanning plan for the specific nozzle/RC piping geometry.

(3.) Selection of automated scanning equipment, and development of application software. (This includes proof of capability to function within the space limitations within the Davis-Besse plant.)

(4.) Development of the ACCUSONEX® data acquisition and display system software for effective use with the specific nozzle geometry.

(5.) Development of examination techniques (scanning and data analysis) and qualification against test blocks and a replica mockup.

Figure 3 is a flow chart depicting the major activities of the program.

Following trials for initial selection of examination techniques, development of automated scanning hardware and the enhanced ACCUSONEX[R] analysis software proceeded in parallel with the accuracy testing of the techniques.

Initial trials of candidate techniques were made on clad test blocks fabricated by BWNS and a forged makeup nozzle containing electro-discharge machine (EDM) notches which was obtained from another utility. A tentative decision was made to proceed with various angled shear wave transducers at this point.

Parallel efforts proceeded on defining requirements for the robotic scanning equipment. Space is limited in the region of the HPI nozzles at Davis-Besse Unit 1, and careful consideration had to be given both to access and available operating space. Reviews of dimensions were made, and the decision was made to construct a full-scale mockup of the area and piping in the immediate locale. Figure 4 is a photograph of the access mockup.

From these studies, decisions were made on selection of the PUMA Model 262 robot to perform the automated scanning functions. Work needed to adapt the robot for the scanning function, to develop a support system, and to program the control software for the specific geometric configuration proceeded in parallel with the remaining technique development efforts.

Detailed evaluations of selected techniques were performed on two sets of clad test blocks and a replica mockup of the nozzle in a section of RC piping. These test blocks were scanned and analyzed without prior knowledge of flaw locations and sizes, thereby providing a basis to quantify the results of the program.

The replica mockup was fabricated to be geometrically and materially identical to the HPI nozzles at Davis-Besse Unit 1. This nozzle/pipe mockup was used to confirm the adequacy of the scanning plan, and further quantify the ability to detect and size flaws in the base metal and cladding. This mockup also served to demonstrate the automated scanning techniques to be used at the plant.

4.3 Equipment and Software Development

To properly scan and image the data from the HPI nozzle, a new scanner needed to be developed. A new software package was also needed for the ACCUSONEX[R] analysis system to correct the data display for the complex nozzle geometry.

4.3.1 Selection of Scanning Equipment

The scans required for nozzle geometry are somewhat complex, particularly when scanning from the RC pipe side. Here the transducer must be held such that the sound beam is directed toward the centerline of the nozzle while the transducer is scanned along various trajectories. The trajectory forms a straight line when scanning along the RC pipe surface parallel to the pipe axis. The trajectory is a circular arc when scanning on the RC pipe surface around the circumference. (This is a line formed by an intersection of the pipe surface with a plane perpendicular to the pipe axis.) The trajectory follows one of a variety of elliptical paths when scanning along the surface in an orientation between these extremes.

An x-y pipe scanner was evaluated for this application but would not adequately conform to the desired trajectories. A six-axis robot was then evaluated and determined to have the desired capability. Development was initiated with a 500 series PUMA robot which had been previously used to scan complex geometries. Although this robot could perform the desired scans a review of the access restrictions indicated that it was too large for the available space. A smaller robot in the same family was then evaluated and selected for this application. This robot is a 200 series PUMA robot. The robot weighs 29 pounds and has a length of 8 inches in each of the two arm segments for a total reach of 16 inches when the two arms are positioned in line. The robot has a positioning capability repeatable to within 0.002 inch. This robot is adequate to scan a quadrant of the nozzle or RC pipe region with a single setup.

The nozzle and pipe surface geometry is programmed into the robot controller. System setup requires that the robot be moved to the location of four points on the pipe. This is adequate to teach the robot the position of the pipe and the nozzle with respect to the base of the robot. With this setup, all scans on both the pipe and nozzle can be accomplished repeatedly within the area that the robot can reach.

The software is flexible enough to allow the operator to specify the range for the scan, the index increment between the scan lines and the increment along each scan line at which ultrasonic data will be acquired. For this application, data are acquired at 0.050 inch increments.

4.3.2 ACCUSONEX^R Development

ACCUSONEX^R is an ultrasonic data acquisition and display system. This system has been in use since 1986 on reactor vessel, piping, and reactor coolant pump casing examinations. The system digitizes the ultrasonic wave form and stores either peak data or the full wave form. The data is then recalled by the analysis system and displayed.

ACCUSONEX^R provides the data images in the form of an engineering drawing with simultaneous display of the C-Scan (top view), B-Scan (side view), and rotated B-Scan (end view) views. The system can provide an image of the complete data set or zoom in for a detailed image of any portion of the data set. In order to improve the analyst's ability to interpret data, corrections for the transducer angle are also included in the software. The data are then displayed at the actual location in the component where the echo originated. This type of imaging is useful for both detection and sizing of indications. For tip diffraction sizing, a geometrically correct view shows the echo from the corner trap and the flaw tip in correct relationship to each other. This greatly improves the analyst's ability to correctly locate and size indications.

To use ACCUSONEX^R for the HPI nozzle examination, modifications were made to allow the system to interface with the PUMA robot and to provide images that were corrected for the nozzle geometry. The system had previously been used with another model PUMA robot, so only minimal modifications were required to the data acquisition portion of the system. The data analysis portion of the system was modified to provide a more complete geometric model of the nozzle and reactor coolant pipe. The geometric corrections allowed data that were acquired during radial or tangent scans while the transducer was being scanned along an elliptical path on the RC pipe to be imaged in a

geometrically correct location. This improves the analyst's ability to detect and size flaws in the mockup nozzle bore that were detected while scanning on the pipe. An option was also added to provide polar plots of the data acquired with a radial scan. This allows data in the knuckle area of the nozzle to be more accurately imaged. These enhancements allow the analyst to easily distinguish between geometric reflectors and implanted flaws in the mockup.

5. EXAMINATION REGION

The boundaries of the region to be examined were selected to cover the zone potentially affected by cold makeup water following the failure of the thermal sleeve as discovered in the 5th Refueling Outage. (This zone encompasses all dye penetrant indications found in the HPI/Makeup nozzle during the 5th Refueling Outage.)

5.1 Area Affected by Cold Water Impingement

Figure 1 is a representation of the nozzle/thermal sleeve configuration following failure of the thermal sleeve during the 5th Fuel Cycle.

The configuration of the thermal sleeve originally installed in Davis-Besse Unit 1 included:

(1.) A hard rolled region in the safe end of the nozzle.

(2.) A region over most of the nozzle bore which separated the cold makeup water from the nozzle by a 1/8 inch annular space filled with still RCS water.

(3.) A collar serving to locate the discharge end of the thermal sleeve radially in the nozzle, and

(4.) An end section which extended two inches into the RC pipe bore.

During the 5th Fuel Cycle, the thermal sleeve end section broke off at the collar in two half-cylinders. As a result, cold makeup water flowing from the thermal sleeve contacted the exposed downstream portion of the nozzle, the nozzle blend radius, and some distance along the RC pipe as the cold water was carried along in the RC flow stream.

5.2 Nozzle Dye Penetrant Examination Results

Figure 5 is an illustration of the indications found in the nozzle mouth by dye penetrant examination.

At the time of the first examination following the discovery of the sleeve failure, signs of wear from the thermal sleeve collar were clearly visible on the nozzle inner wall. No dye penetrant indications were found in the nozzle bore extending beyond the mid-point of these collar wear indications. This fixes the furthest upstream point of the indications as 0.50 inch upstream of the weld buttons on the nozzle bore. The indications extend downstream from this location as far as the examination was performed. The tooling and techniques available at the time did not allow the examination to be continued around the nozzle knuckle region into the RC pipe. Thus the indications in this limited examination did not extend further than about half way around the knuckle radius at the nozzle mouth.

5.3 Examination Volume

The cold water influence was impeded from extending back into the nozzle beyond the thermal sleeve collar due to the narrow clearance (0.010 to 0.015 inch diametral clearance) and lack of a driving head. Thus, the collar functioned as an obstruction to flow back into the nozzle. The thermal sleeve was hard rolled into the safe end and remained firmly in place following the failure. Hence there was no leakage path to permit the cold water to enter the closed annular space behind the collar. The arrangement of the original thermal sleeve collar is shown in Figure 1. Absence of any dye penetrant indications from the collar region back to the nozzle safe end supports the conclusion that there was no cold water influence on the nozzle beyond the thermal sleeve collar.

Considering the potential effects of the cold water around the nozzle knuckle radius and into the RC pipe bore, the zone of examination for the inside surface of the RC pipe was selected as the area within an 8-inch radius of the nozzle centerline. Provisions exist to extend the examination further in the downstream direction along the reactor coolant pipe wall should indications be found to extend beyond the nominal examination boundary.

The examination volume varies slightly for the various scanning techniques. As a minimum, the inspection volume extends from a point in the nozzle approximately 1/2 inch beyond (upstream of) the last dye penetrant indication to a location in the RC pipe which is 8 inches from the centerline of the nozzle bore. Figure 6 illustrates the examination region in relation to the initially installed thermal sleeve. This volume is considered adequate to cover the zone of concern.

The specifics of coverage of each scan are discussed in more detail in the following sections.

6.0 SCANNING PLAN

The examination volume includes areas in the nozzle bore and knuckle area that cannot be reached by scanning with beam angles and techniques normally used for weld inspections. For this reason, an extensive development program was undertaken to evaluate the effectiveness of scanning with a wide range of beam angles. One of the significant accomplishments of this program was the development of a technique using high angle shear wave transducers from the pipe side to look for axial flaws in the nozzle bore. This technique proved very effective in detecting flaws in the nozzle bore because the beam angle was close to perpendicular to the plane of the flaw. The beam angle for this scan, however, made tip diffraction sizing difficult and, therefore, amplitude-based sizing techniques were used for this region. A discussion of the technique development is included in Section 7.0. The scans that were developed from this effort are summarized in Table 1. Figures 7 through 14 illustrate details of the examination to be performed.

These examinations will be conducted using shear waves for the initial detection scans. Shear waves were shown to be most effective for detecting flaws that penetrated through the cladding into the base metal. The weld deposited cladding attenuates, scatters, and redirects shear waves much more than longitudinal waves. The clad layer is relatively transparent to longitudinal waves so supplemental scans with longitudinal waves will be used to enhance detection of flaws entirely contained within the cladding in the segment of the nozzle and RC pipe most likely to have been affected by the cold makeup water following the thermal sleeve failure in 1988. The discussion and implementation of scanning techniques for flaws contained entirely within the cladding is described in section 7.5.

6.1 Circumferential Flaws Extending from the Nozzle Bore

Circumferential flaws in the nozzle bore will be detected by scanning from the tapered portion of the HPI nozzle (see Figure 7). This scan will detect circumferential flaws in the base metal as shown in Figure 9. Scans separate from those used for detection will be used to size circumferential flaws in the nozzle bore. Sizing will be performed by scanning from the shoulder of the nozzle (see Figure 8). Figure 9 shows the transducer locations and the coverage provided for the sizing scans.

6.2 Axial Flaws in the Nozzle Bore

Flaws which are located axially along the nozzle bore will be detected and sized using "tangent" scans from the RC

pipe (see Figure 12 and 13). The sizing techniques will vary depending on the exact location of the flaw. Flaws which extend through the knuckle radius, forming a corner flaw as shown in Figure 14, have two measurable dimensions, one of which lies along the RC pipe wall and the other along the nozzle wall. These dimensions form two legs of a right triangle. Sizing of this type of flaw will be performed by a "geometric" technique. In this case the depth of the corner flaw will be constructed assuming a triangular geometry using the dimensions which lie along each wall at a right angle to each other.

Axial flaws in the nozzle bore which do not extend into the RC pipe will be sized using amplitude-based techniques. These sizing techniques will be supplemented on-site by other techniques based on the location of the indication.

6.3 Radial Flaws in the RC Pipe

Flaws which extend radially outward from the nozzle opening will be detected and sized by different scans as a function of their distance from the center of the nozzle bore. The use of circular scans from the RC pipe (Figure 10) and tangential scans from the RC pipe (Figures 12 and 13)provide overlapping coverage for radial flaws. Sizing of radial flaws in this region will be based on tip diffraction techniques.

6.4 Circumferential Flaws in the RC Pipe

Circumferential flaws in the RC pipe (oriented at 90 degrees to a line extending radially outward from the nozzle opening) will be detected and sized by radial scans (Figure 11) and tangent scans (Figures 12 and 13) from the RC pipe. These two types of scans provide overlapping coverage for circumferential flaws in the RC pipe.

Sizing of flaws in this category will be based on tip diffraction techniques.

7. TECHNIQUE DEVELOPMENT

The technique development included numerous mockups and several iterations. The initial techniques were based on an engineering review of the nozzle and pipe geometry. A 3-D CAD drawing of the nozzle and pipe was created. Planar sections were then extracted from the 3-D model. These were used to evaluate transducer angles required to provide scan coverage of the nozzle and pipe. Engineering review indicated that high angle shear-wave transducers (50 to 75 degrees) would be required to provide the desired scan coverage in some regions

of the nozzle. The engineering review also indicated that, to obtain the desired coverage in the nozzle bore, it would be necessary to take into account the beam spread of the transducers. Based on this engineering review, a technique development plan was developed. This plan consisted of making a preliminary evaluation of transducer detection and sizing capability by scanning a series of notches in a test block. The transducers and angles selected from this preliminary evaluation were then tested by scanning two sets of blocks. One set of test blocks was obtained from the EPRI NDE Center and the other from Battelle Pacific Northwest Laboratories (PNL). The examiners did not have prior knowledge of the number, location, or size of flaws in these test blocks. The final step in the technique development was to confirm that the results obtained from the above evaluations could also be obtained using the actual geometry of the nozzle and pipe. This was accomplished with the nozzle mockup that contained a series of notches and cracks.

The following sections provide a description of each set of mockups, including the purpose, results, and conclusions of scanning the blocks. The technique development focused primarily on flaws with small depths of penetration into the base metal in keeping with the expectation that any flaws represented by the dye penetrant indications found in the Davis-Besse makeup nozzle do not extend beyond the cladding.

7.1 BWNS Test Blocks

The BWNS test blocks were used to develop information to support initial decision making on technique selection and scanning strategy. These particular blocks were selected based on their immediate availability and characteristics which most closely matched the needs of the project. The parameters addressed using these blocks included:

- o Transducer angle limits.
- o Coverage provided by each scan angle.
- o Effects of the cladding/base metal interface.
- o Effects of cladding inclusions.
- o Transducer parameters most effective for detection and for sizing.
- o Evaluation of detection capability for flaws contained in the cladding.

Figure 15 is an illustration typical of the types of reflectors used for this portion of the program. One

block has four EDM notches (0.0625 inch wide) with depths of 0.2 inch, 0.25 inch, 0.3 inch and 0.35 inch. The cladding thickness is 0.25 inch and the base metal thickness is 3 inches. Thus, one notch is entirely contained within the cladding (80% of clad thickness), one notch penetrated to the clad fusion line (100% of clad thickness), and the remaining two notches penetrated 0.050 inch and 0.10 inch into the base metal.

The other block has five EDM notches (0.015 inch wide) with depths of 0.1 inch, 0.2 inch, 0.3 inch, 0.4 inch, and 0.5 inch. The nominal cladding thickness is 0.55 inch and the base metal thickness is 3 inches. Therefore all of these notches are contained in the clad layer.

The preliminary conclusions from this block were:

- o Shear wave transducers could be used for detection and sizing of flaws penetrating the base metal.
- o Shear wave transducers provided the best results for notches penetrating into the base metal.
- o Sizing accuracy for both the shear wave and longitudinal wave transducers was within 0.050 inch of the actual flaw depth dimension.
- o Coverage of flaw orientations of up to ± 15 degrees from normal to the scan direction could be expected for sizing and detection.
- o The cladding/base metal interface tended to mask the crack tips when sizing with shear wave unless the flaw penetrated into the base metal a minimum distance (approximately 0.05 inch).
- o Cladding inclusions could not always be distinguished from flaws located entirely within the cladding.
- o Longitudinal waves provide less interaction with the clad layer than shear waves.
- o The flaw depth must be greater than approximately 0.15 inch in order to be able to classify the flaw as a planar flaw when using longitudinal waves. Otherwise the reflector cannot be distinguished from other inclusions or metallurgical reflectors within the clad layer.

7.2 <u>EPRI Test Blocks</u>

The EPRI test blocks were used to provide statistically

significant data on the capabilities of the techniques to detect, locate and size both cracks and notches existing in the carbon steel base material of blocks clad with stainless steel. Both notches and cracks were installed in the blocks to allow evaluation of the validity of using notches as a standard.

Figure 16 illustrates the basic parameters of the EPRI test blocks. The defects were installed in the base material and then cladding was applied over the defects. Two test blocks were provided. The test blocks contained 24 flaws which were oriented within ± 15 degrees of the scans. The flaws included 16 EDM notches and 8 cracks. The 16 notches varied in depth (clad/base metal interface to tip) from approximately 0.15 inch to 0.46 inch. The 8 cracks varied in depth from 0.185 inch to 0.49 inch. The cracks were installed using a process developed to simulate tight flaws such as those which might be expected due to thermal fatigue.

BWNS personnel did not have prior knowledge of the location number or size of flaws in these test blocks; i.e. blind. The blocks were scanned and data analysis provided for eight different techniques which were under consideration at the time. The techniques included combinations of the following:

- o Nominal angles of 40, 45, 57, and 60 degrees.
- o Longitudinal and shear waves.
- o Relative arrival time and absolute arrival time tip diffraction sizing techniques.
- o The data analysts selected data they considered as most representative of the actual flaw depth.
- o The results from the selected technique (as well as from the other techniques) were forwarded to the EPRI NDE Center for evaluation.

The results were as follows:

- o The techniques were successful in detecting 100% of the flaws within ± 15 degrees of normal to the beam. All flaws up to 45 degrees off axis were also detected in the scans.
- o No indications were analyzed as flaws in non-flawed areas of the blocks; i.e., no false calls.

- o The longitudinal wave transducers did not detect as many flaw tips as compared to an equivalent shear wave angle. However, all flaws were detected with both the longitudinal and shear waves.

- o Tip diffraction sizing with longitudinal waves resulted in larger sizing errors than with shear waves.

- o Figure 17 presents the results for the EDM notches using selected techniques. Evaluation of the sizing of the 16 notches yielded an RMS error of 0.057 inch.

- o Figure 18 presents the results for the cracks using selected techniques. Evaluation of the sizing of the 8 cracks yielded an RMS error of 0.064 inch.

It was concluded that flaws penetrating into the base material by more than 0.15 inch oriented with ± 15 degrees of normal to the beam will be detected. Performance in detection and sizing of installed notches and cracks was essentially the same.

7.3 Battelle Blocks

The purpose of examining the blocks provided by PNL was to have a data base on actual thermal fatigue cracks that extend through the cladding into the base metal. The results of these examinations would serve as another benchmark of the system's detection and sizing capability.

The 9 blocks (see Figure 19) provided by PNL consisted of carbon steel base material with stainless steel cladding. A centrally located, full penetration weld ran the width of each block. All of the flaws except one are located in the weld metal. The installed flaws are representative of thermal fatigue flaws and extended through the cladding into the base material. The set of flaws in these blocks ranges from 0.27 to 0.89 inch in depth. As these flaws are thermal fatigue cracks, true depth had been defined by PNL based upon manual ultrasonic measurements of the installed cracks. Plates were welded over the cladding to ensure that scanning would be blind.

Similar to the EPRI blocks, each block was examined using eight different techniques. The analyst selected the results that he determined as representing the best estimate of flaw size. The results of the individual techniques as well as the best estimate were submitted to PNL for evaluation.

The results were as follows:

- o All seven of the known flaws were detected.

- o Flaw orientation was essentially parallel to the weld and perpendicular to the surface.

- o In addition, two flaws were detected in one block which PNL had not recorded as having flaws. At the request of the PNL representative, the backing plate was removed, revealing that two flaws did exist in the block. These flaws had been correctly identified by the ultrasonic system.

- o Of the seven known (to PNL) flaws, five closely matched the dimensions established by PNL using tip diffraction techniques. The sizing results for the entire flaw population are shown in Figure 20. The results of the selected technique for the seven flaws deviated from PNL's baseline ultrasonic sizing by an RMS error of 0.247 inch. A review of the data showed that, for the two flaws, which did not closely match the PNL dimensions, reflections from porosity or inclusions in the weld may have been used for sizing rather than the tip signals. This either occurred during the baseline examination to establish the flaw depth or during the analysis with ACCUSONEX®. Further investigation is required in order to determine the source of the discrepancy.

- o During the examination, the analysts had identified a number of the reflectors in the weld material which were deemed as either porosity or inclusions. It was noted in the sizing results submitted to PNL for evaluation that some of the reflectors were positioned such that they could be interpreted as the flaw tip or could interfere with the detection of the flaw tip. It should be noted that the weld indications may also have interfered with the initial determination of the true flaw depths. This is one possible reason for the difference in accuracy between the measurements on the EPRI blocks and the Battelle blocks.

- o Most of the region of interest in the examination of the HPI/Makeup nozzle at Davis-Besse Unit 1 lies outside of a weld zone. In these areas, sizing will not be affected by extraneous indications. Results of the PNL block evaluation more appropriate to the Davis-Besse situation are shown in Figure 21. These results from the five flaws where flaw tips were not interfered with deviates from PNL's baseline ultrasonic sizing by an RMS error of 0.145 inch.

- The longitudinal wave transducers did not detect as many flaw tips as compared to an equivalent shear wave angle. However, all flaws were detected with both the longitudinal and shear waves.

The following conclusions were reached:

- Demonstrations conducted in this program increased the confidence of detecting flaws penetrating the base material in the plant. The set of flaws in these blocks ranged from 0.33 inch to 0.83 inch in depth from the ID surface.

- Flaws which are not located in a region with extraneous reflectors can be reliably sized.

7.4 Nozzle/RC Pipe Mockup

A replica mockup of the nozzle/RC pipe assembly, geometrically identical to the HPI nozzle installation at Davis-Besse, was fabricated in order to complete the development of the examination techniques, confirm the adequacy of the scanning plan, and demonstrate the performance of the automated scanning system.

- It was necessary to demonstrate the ability of the ultrasonic system to detect, locate and size flaws representative of those small flaws expected in Davis-Besse Unit 1, on an ultrasonically identical component.

- It was necessary to demonstrate that the system and selected examination techniques could cover the required examination region.

- It was necessary to demonstrate the practical operability of the automated scanning system for a component configuration geometrically identical to that at Davis-Besse Unit 1.

The Nozzle/RC pipe mockup is illustrated in Figures 22 and 23. Care was taken in the design and construction of the mockup to make it sufficiently similar in configuration, material, and manufacturing process to conclude that it is ultrasonically identical to the HPI nozzles at Davis-Besse Unit 1. Cracks and notches were implanted in the mockup at the EPRI NDE Center. The sizes and locations of these flaws are such that a determination can be made of the detection, location and sizing capability for small flaws spanning the examination region.

Tight, welding-induced cracks simulating thermal fatigue cracks were installed in the cladding using a process

developed by the EPRI NDE Center. This process was limited to the depth of the stainless steel cladding and could not produce cracks extending into the carbon steel base material.

Since no other means of generating controlled thermal fatigue cracks in the HPI nozzle configuration was readily available, and data existed to judge that narrow EDM notches could be used to represent the flaws, the decision was made to use narrow EDM notches to represent flaws penetrating into the base metal. The assembled mockup, with defects, was shipped to BWNS for scanning.

In order to construct the mockup, a nozzle from a cancelled BWNS contract was obtained. Nozzle identification numbers, applicable records, drawings and specifications were compared with the Davis-Besse Unit 1 HPI nozzle specifications and drawings. It was concluded that, for purposes of the mockup, the nozzles were essentially identical.

A section of clad carbon steel, 28-inch diameter cold leg pipe from a cancelled contract was identified and obtained from the B&W Mount Vernon facility.

The nozzle/safe end assembly was welded to the RC pipe section in an orientation and location representative of the HPI nozzle at Davis-Besse Unit 1. The specification controlling the manufacture was designed to ensure the suitability of the resultant mockup for use in developing an enhanced ultrasonic examination technique. Considerations included geometry, material specifications and manufacturing processes. The specified NDE included radiographic and ultrasonic examinations. The nozzle/RC pipe mockup was fabricated at the B&W Mount Vernon facility which had been used for the same steps in the Davis-Besse NSSS fabrication process.

Figure 24 provides the details of the flaws inserted in the mockup.

Five weld-induced cracks were implanted in the cladding by the EPRI NDE Center at various depths and locations. Each crack penetrated either 50% or 90% through the cladding, with cladding thickness varying from 0.190 to .725 inch. The .725 inch clad was at the nozzle inside radius.

Twelve EDM notches were also placed in the mockup. The notches were 0.014 inch wide. The EDM electrodes used to implant the notches had pointed tips and were crinkled to simulate cracking. One notch was contained entirely within the cladding. The other 11 notches penetrated through the cladding to various depths.

The population of all implanted defects penetrated no further than 0.31 inch into the carbon steel base metal. The depth of the flaws was kept shallow in order to demonstrate the required sensitivity of detection and accuracy of sizing of flaws consistent with the expectations for Davis-Besse Unit 1.

In general, the implanted flaws were installed to ensure the information obtained in the examination at Davis-Besse Unit 1 would adequate to support any subsequent structural analysis which might prove necessary. The implanted flaws include flaws which are representative of the axial and circumferential flaw orientations seen in the dye penetrant examination which took place during the 5th Refueling Outage. However, flaw dimensions were set to ensure that:

(1) The minimum detection resolution would be demonstrated for flaws penetrating more than 0.125 inch into the base metal.

(2) The range of penetration was sufficient to ensure that a range of larger flaws would be detected and sized.

(3) That the extent of the examination region would be defined.

In the latter case, for example, the long axial notch in the bore of the mockup nozzle (flaw G of Figure 24) was placed to ensure that the system could detect axial flaws extending into the nozzle to the bounds of the required examination region. In actuality, only short axially oriented indications were found in the Davis-Besse nozzle by dye penetrant examination.

The flaw location selection process intentionally placed many flaws in the mockup nozzle bore in the most difficult locations for examination.

The examination of the nozzle/RC pipe mockup proceeded initially with the development of scanning hardware, development of scanner controller software, and development of ACCUSONEX[R] software for adaptation to the complex nozzle geometry. Different display techniques were tried in order to provide the best advantage for the data analyst. Finally, after all areas of concern in the mockup were scanned with the selected techniques, and the detection and sizing data were analyzed, the results were compared to the true locations and sizes of the implanted flaws.

It was demonstrated that the entire region of concern could be examined with the scanning techniques including the high-angle shear wave scan from the RC pipe surface.

No non-flawed areas were identified as containing flaws.

All flaws penetrating greater than 0.100 inch into the base metal were detected, including those in the difficult to examine nozzle bore.

Of the four flaws penetrating the base metal 0.050 inch or less, two were detected. The two flaws that were detected penetrated the base metal by 0.027 inch and 0.037 inch respectively. The two flaws which were not detected penetrated the base metal by 0.035 inch and 0.050 inch.

Six flaws were totally contained within the cladding. Three of these (90% through the clad) were detected. Of the three undetected flaws, two were 50% (0.093 inch and 0.095 inch deep) into the clad and one was 90% (0.207 inch deep) into the clad.

It should be noted that the above-mentioned detection results were obtained with shear wave search units. Shear waves produced readily detectable signals from all of those flaws which penetrated greater than 0.100 inch into the base metal. Due to the shear wave scattering at the clad-to-base metal interface, some of the very shallow base metal flaws were detected and some were not. The interaction of the shear waves with the cladding only permitted detection of three cladding flaws.

A similar analysis was performed of the sizing results. Other than one cladding crack, all detected flaws were sized.

The sized flaws in the mockup were separated by component location, the flaws in the RC pipe were sized by tip diffraction techniques and (for the most part) the flaws in the nozzle bore were sized by amplitude-based and geometric shape techniques since time-based tip diffraction sizing was not feasible due to the geometry and flaw/ultrasound interactions.

Figure 25 shows the results for flaws located in the RC pipe. The flaws detected in the RC pipe were sized with tip diffraction techniques resulting in an RMS error of 0.081 inch.

Figure 26 shows the results for flaws located in the nozzle bore. All but one of the detected flaws were sized. The sizing was performed with amplitude-based and

geometric-shape techniques due to configuration. The sizing estimate yielded an RMS error of 0.279 inch.

Detection scans with shear waves were performed on the mockup. Each flaw which penetrated greater than 0.100 inch into the base metal was detected. Additionally, two flaws with shallower penetrations and three flaws within the cladding were detected. Longitudinal waves are less affected by the relatively coarse grain of the clad and the irregular clad-to-base metal fusion line. In an effort to better detect flaws completely contained within the clad and those with very shallow penetration into base metal, similar scans were performed using longitudinal waves. An additional flaw was detected which had not been previously detected with the shear wave examination. This flaw penetrated the base metal by 0.035 inch. It is anticipated that longitudinal wave search units may enhance detection of flaws in the cladding or very near the cladding interface.

Sizing scans with shear waves were also performed on the mockup. Those flaws which were in locations allowing tip diffraction sizing were sized with a an RMS error of 0.081 inch.

Those flaws which were in locations which did not allow tip diffraction sizing were sized with amplitude-based and geometric shape techniques. Those flaws were sized an RMS error of 0.279 inch. Sizing of flaws in these regions in the Davis Besse HPI nozzle will be augmented with local techniques for optimum tip diffraction sizing.

7.5 Cladding Examinations

The development program included efforts to detect and size flaws which were completely contained within the cladding. The BWNS test block contained one notch that did not penetrate into base material. The nozzle/pipe mockup contained five cracks and one notch which were contained within the cladding.

Detection of flaws in the cladding is more difficult than in the base material because the stainless steel cladding is a coarse grain material. Reflections are received from the clad/base metal interface and from the grain structure in the cladding. Shear waves tend to be reflected and scattered at the clad/base metal interface. Longitudinal waves provide better penetration into the cladding than shear waves. Shear waves proved to be very effective in discriminating between imperfections in the cladding and flaws that extended into the base material. For this reason, shear waves are being used as the primary

inspection technique. Shear waves, however, were not as effective as longitudinal waves in detecting cladding flaws, particularly in areas of the nozzle and pipe with relatively thick cladding. As a result, a series of scans using longitudinal waves are planned. These scans will look for cladding flaws in the nozzle bore and in the portion of the reactor coolant pipe downstream of the nozzle mouth.

TABLE 1

TRANSDUCER SELECTION TABLE

Nominal Beam Angle (Degrees)	Detection Diameter/ Frequency (Inch) (MHz)	Sizing Diameter/ Frequency (Inch) (MHz)	Element	Application
45 S	3/8 1.5	N/A	Single-Flat	Axial Scan on Taper
45 S 60 S	N/A N/A	3/8 5.0 3/8 5.0	Single-Flat Single-Flat	Axial Scan on Shoulder of Nozzle
45 S 45 S	3/8 2.25 3/8 2.25	3/8 5.0 3/8 5.0	Single-Flat Single-Flat	Radial Scan on Main Pipe Circular Scan on Main Pipe
57 S&L 66 S&L 75 S&L	1/2 2.25 1/2 2.25 1/2 2.25	1/2 5.0 1/2 5.0 1/2 5.0	Single-Flat Single-Flat Single-Flat	Tangential Scan on Main Pipe

S = SHEAR WAVE MODE L = LONGITUDINAL WAVE MODE

Makeup/HPI Nozzle Original Thermal Sleeve Design

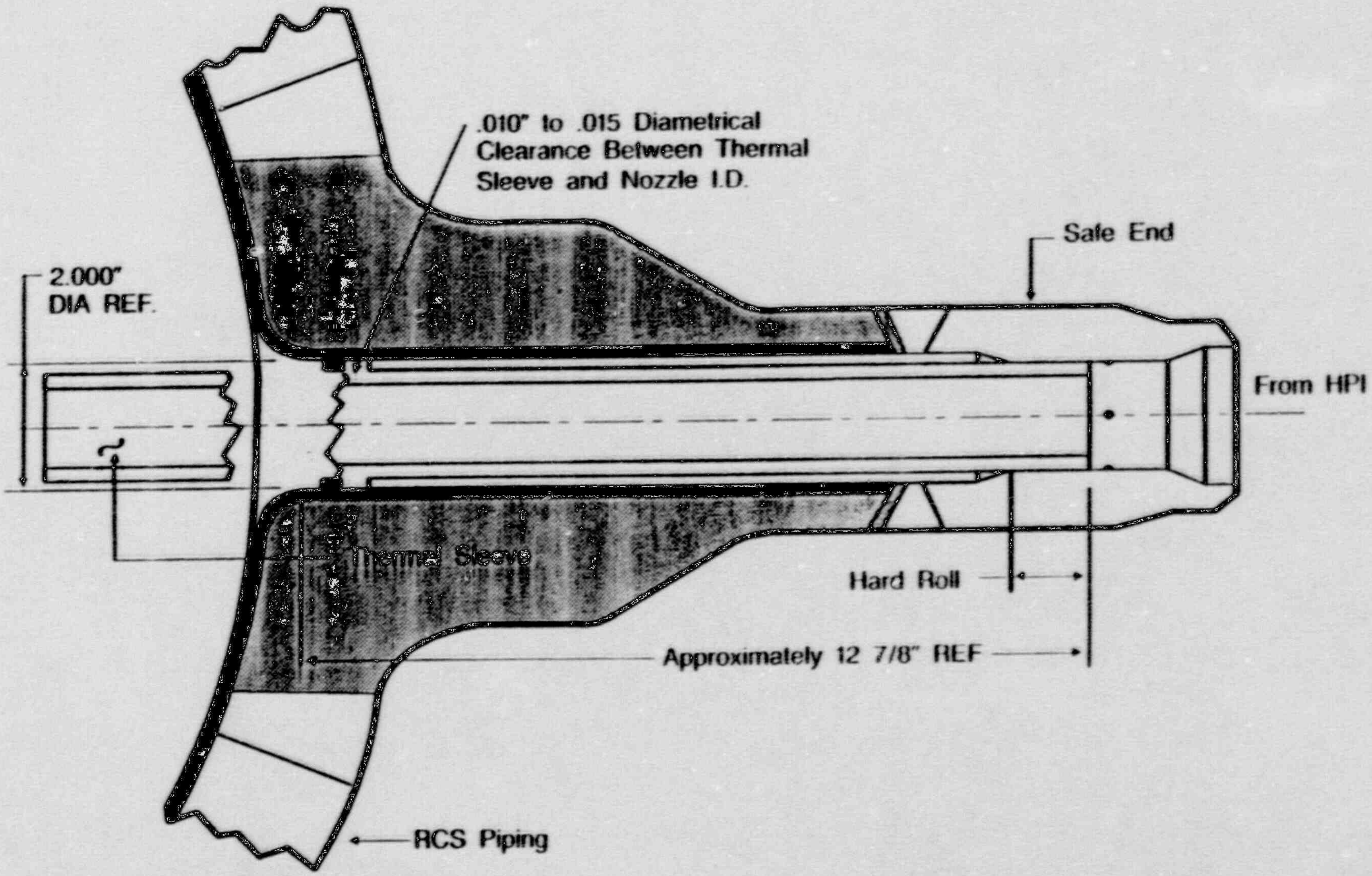


FIGURE 1

Makeup/HPI Nozzle Replacement Thermal Sleeve Design

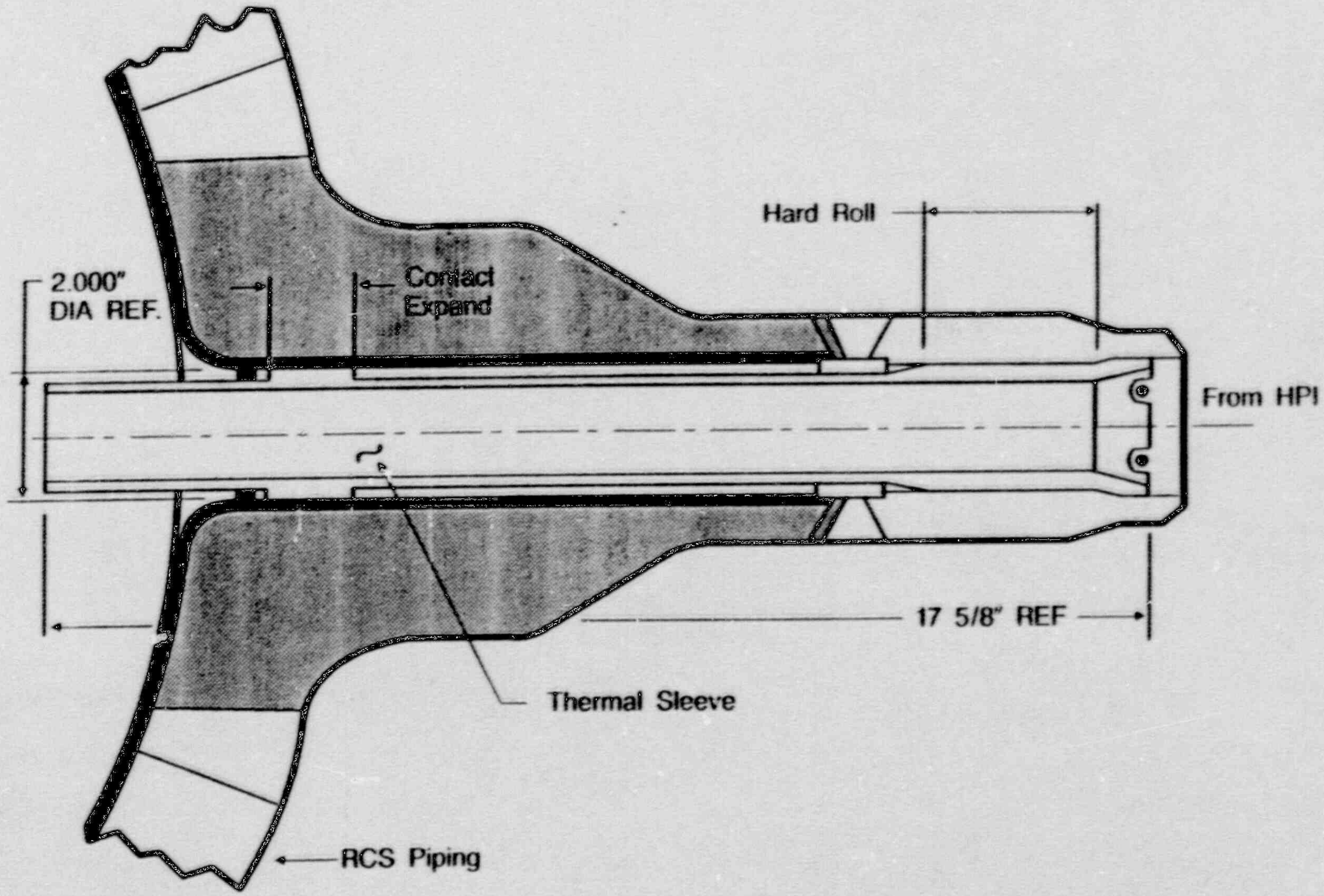


FIGURE 2

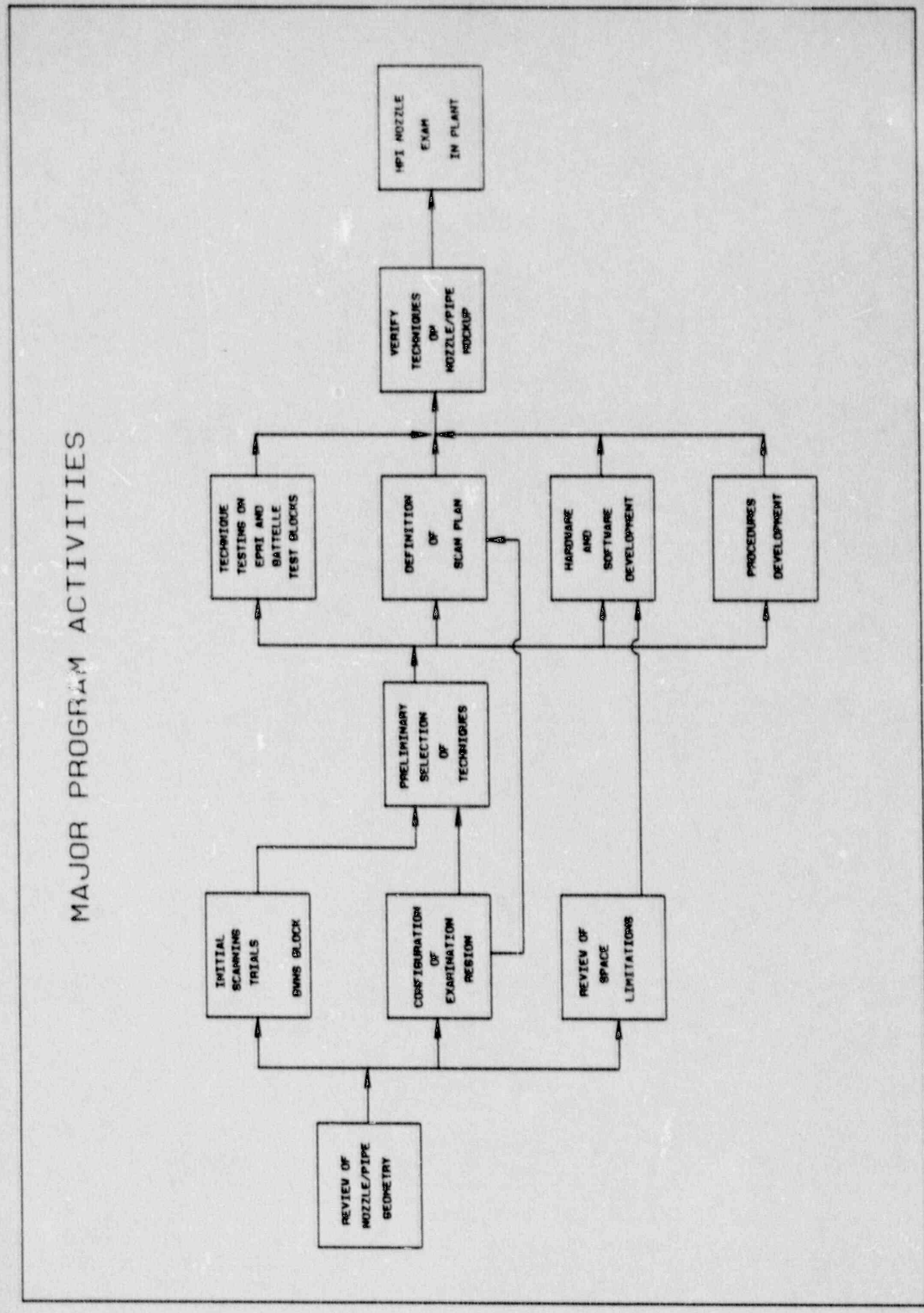
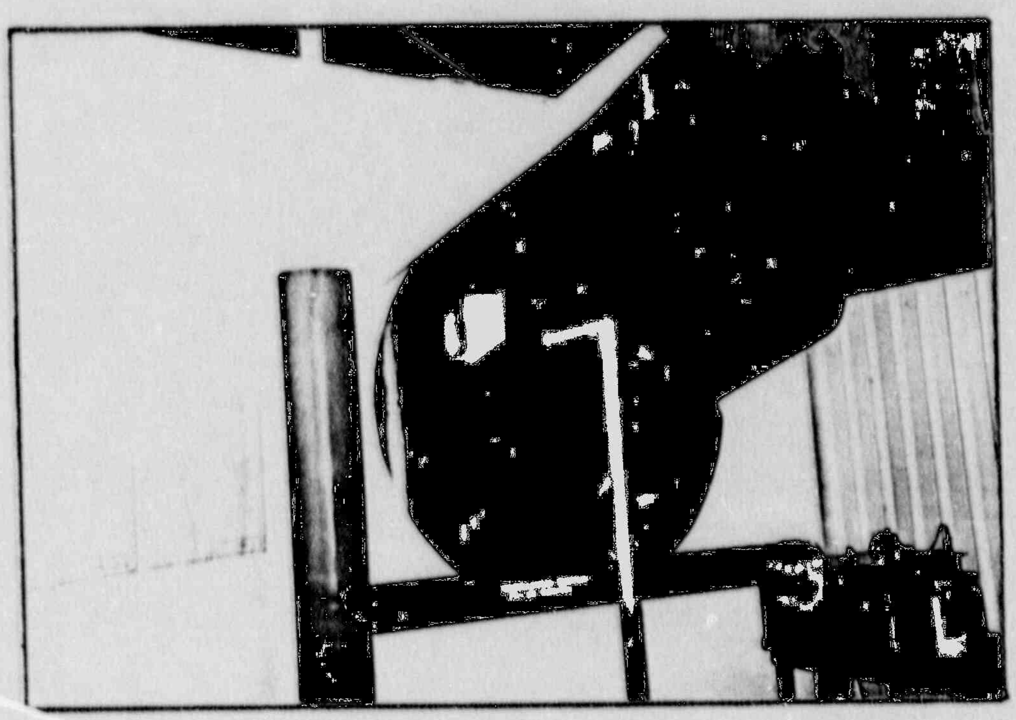

MAJOR PROGRAM ACTIVITIES
REVIEW OF NOZZLE/PIPE GEOMETRY
INITIAL SCANNING TRIALS
DWHS BLOCK
CONFIGURATION OF EXAMINATION REGION
REVIEW OF SPACE LIMITATIONS
PRELIMINARY SELECTION OF TECHNIQUES
TECHNIQUE TESTING ON EPRI AND BATTELLE TEST BLOCKS
DEFINITION OF SCAN PLAN
HARDWARE AND SOFTWARE DEVELOPMENT
PROCEDURES DEVELOPMENT
VERIFY TECHNIQUES ON NOZZLE/PIPE MOCKUP
HPI NOZZLE EXAM IN PLANT

FIGURE 3



ACCESS MOCKUP PHOTOGRAPH

FIGURE 4

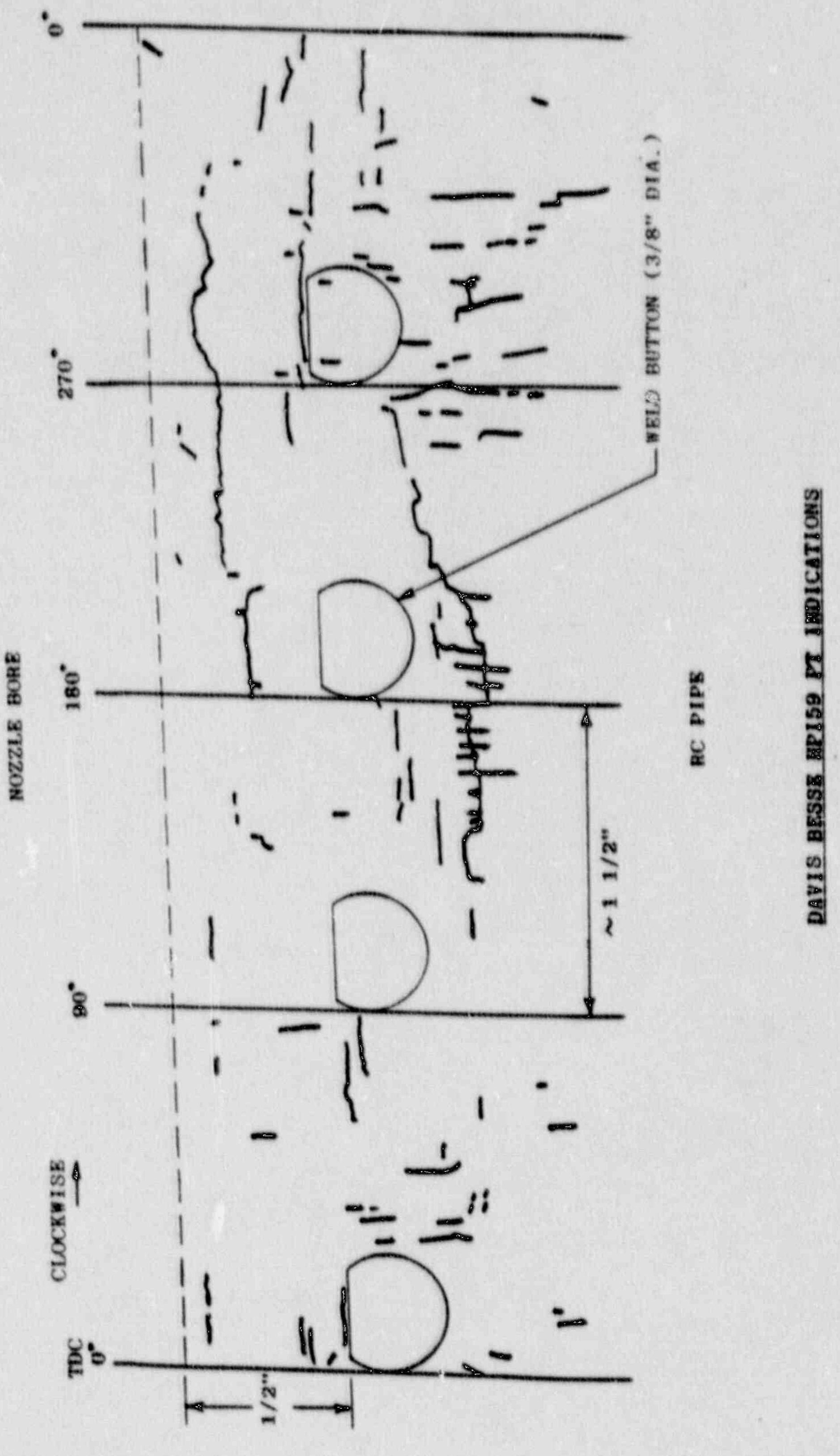

NOZZLE BORE
TDC 0°
CLOCKWISE
90°
180°
270°
0°
1/2"
~1 1/2"
WELD BUTTON (3/8" DIA.)
RC PIPE
DAVIS BESSE HPI59 PT INDICATIONS

FIGURE 5

HPI NOZZLE EXAMINATION REGION

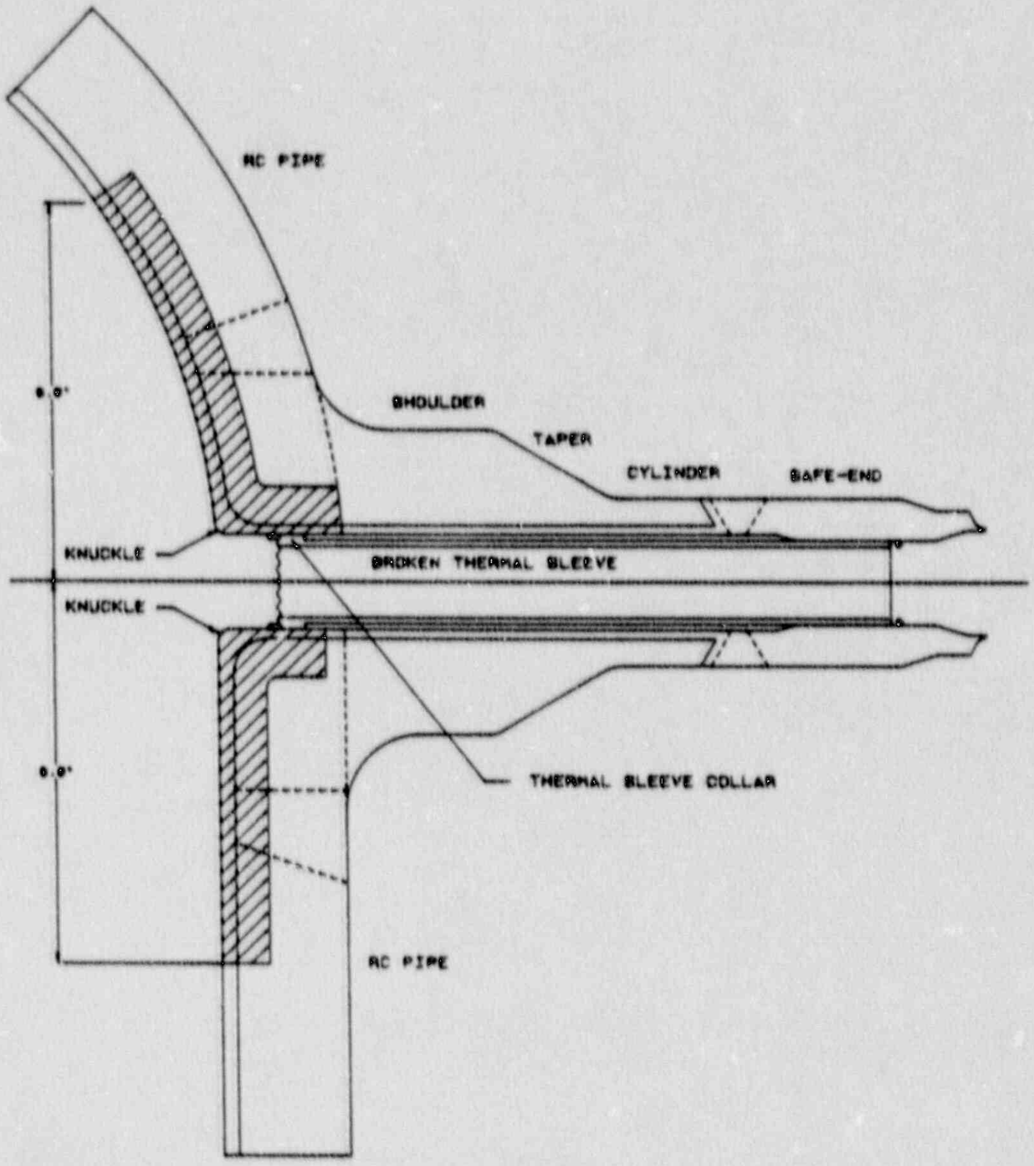
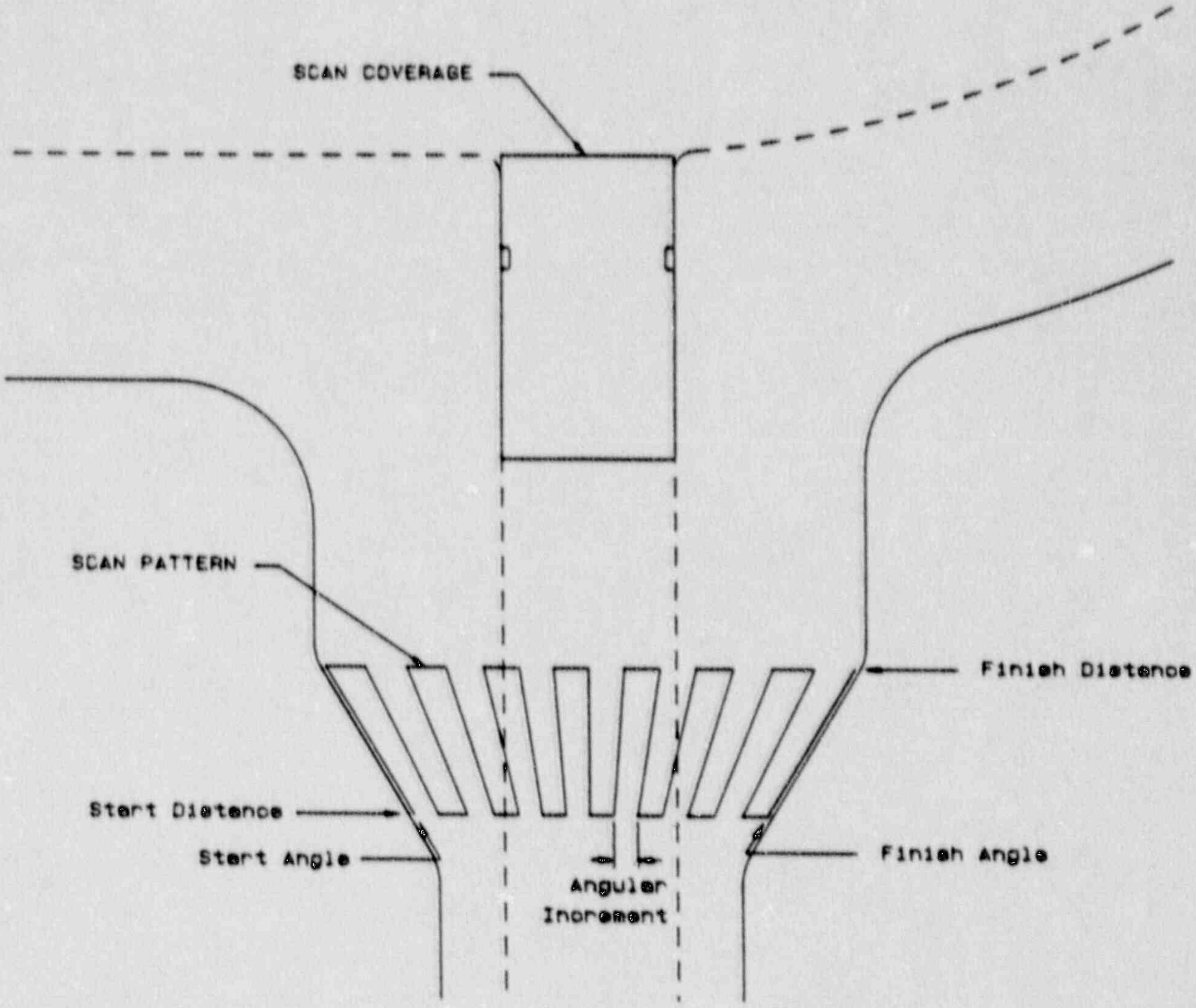


FIGURE 6

AXIAL TAPER SCAN

(For Detection of Circumferential Flaws in the Bore)

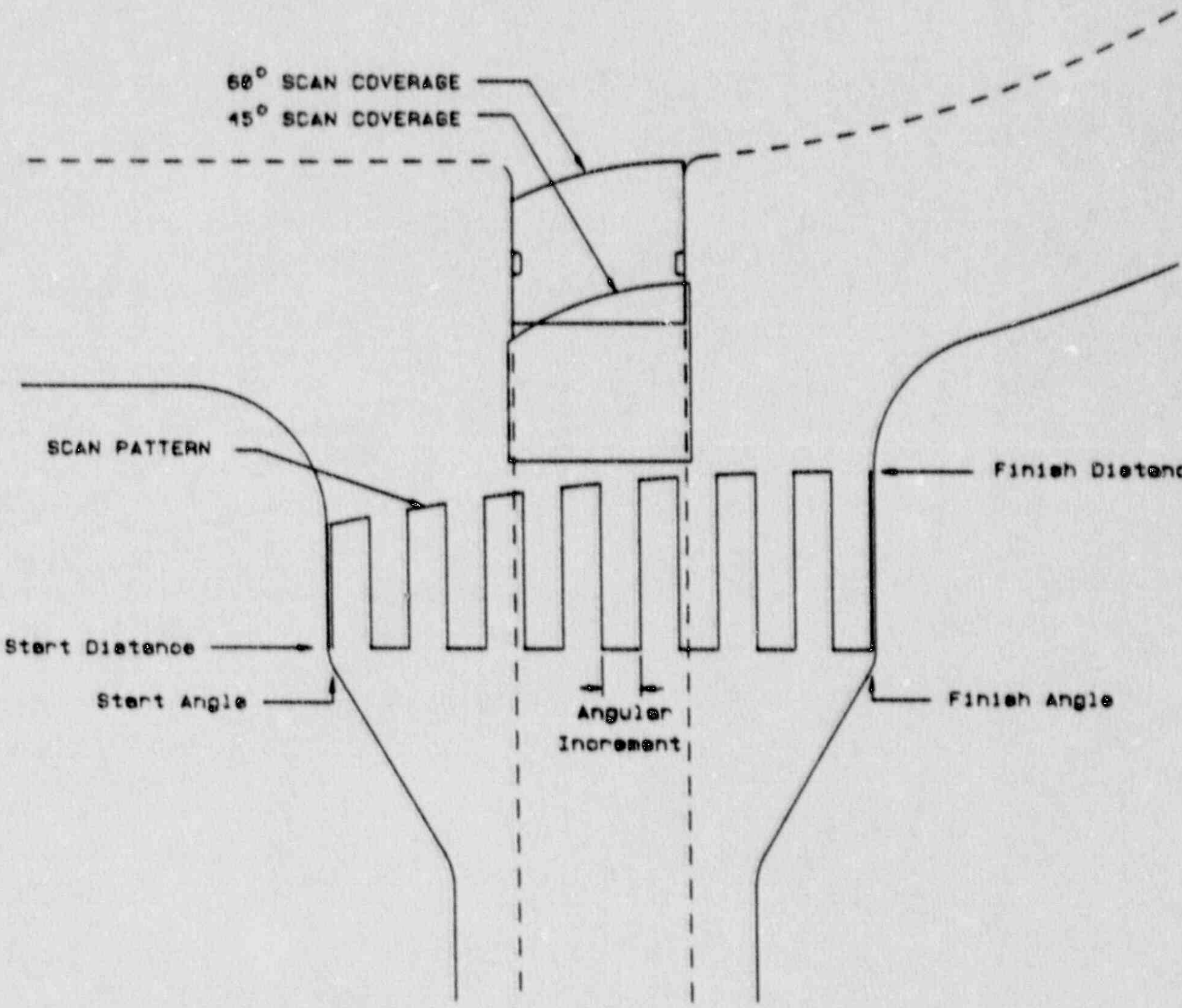


Nominal Beam Angle(s) : 45
Wave Mode : Shear
Detection Transducer :
Diameter : 3/8 inch
Frequency : 1.5 MHz

FIGURE 7

AXIAL SHOULDER SCAN

(For Sizing of Circumferential Flaws in the Bore)



Nominal Beam Angle(s)	:	45, 60
Wave Mode	:	Shear
Sizing Transducer	:	
Diameter	:	3/8 inch
Frequency	:	5 MHz
Sizing Technique	:	Tip Diffraction

FIGURE 8

AXIAL SCAN COVERAGE FROM NOZZLE

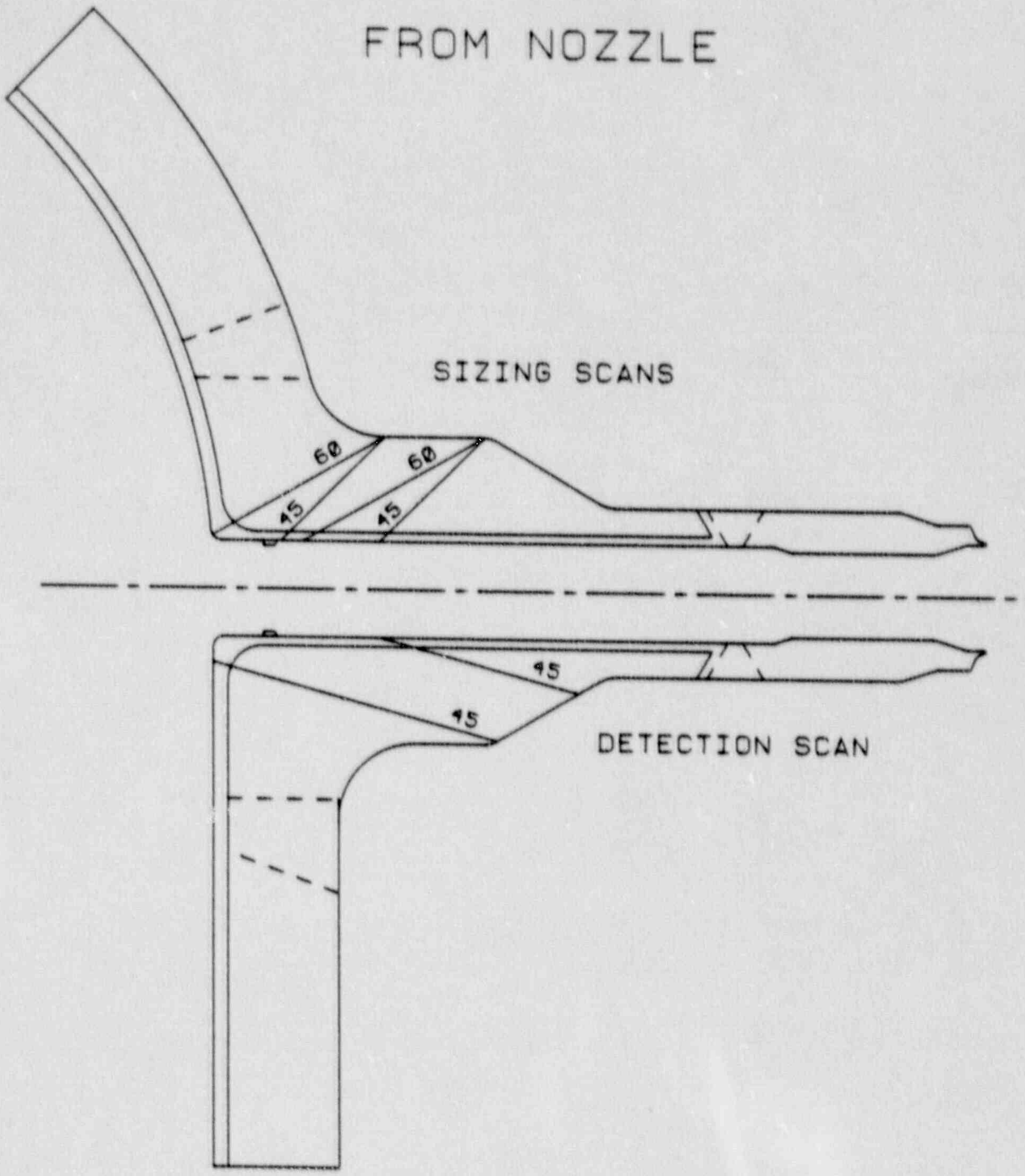
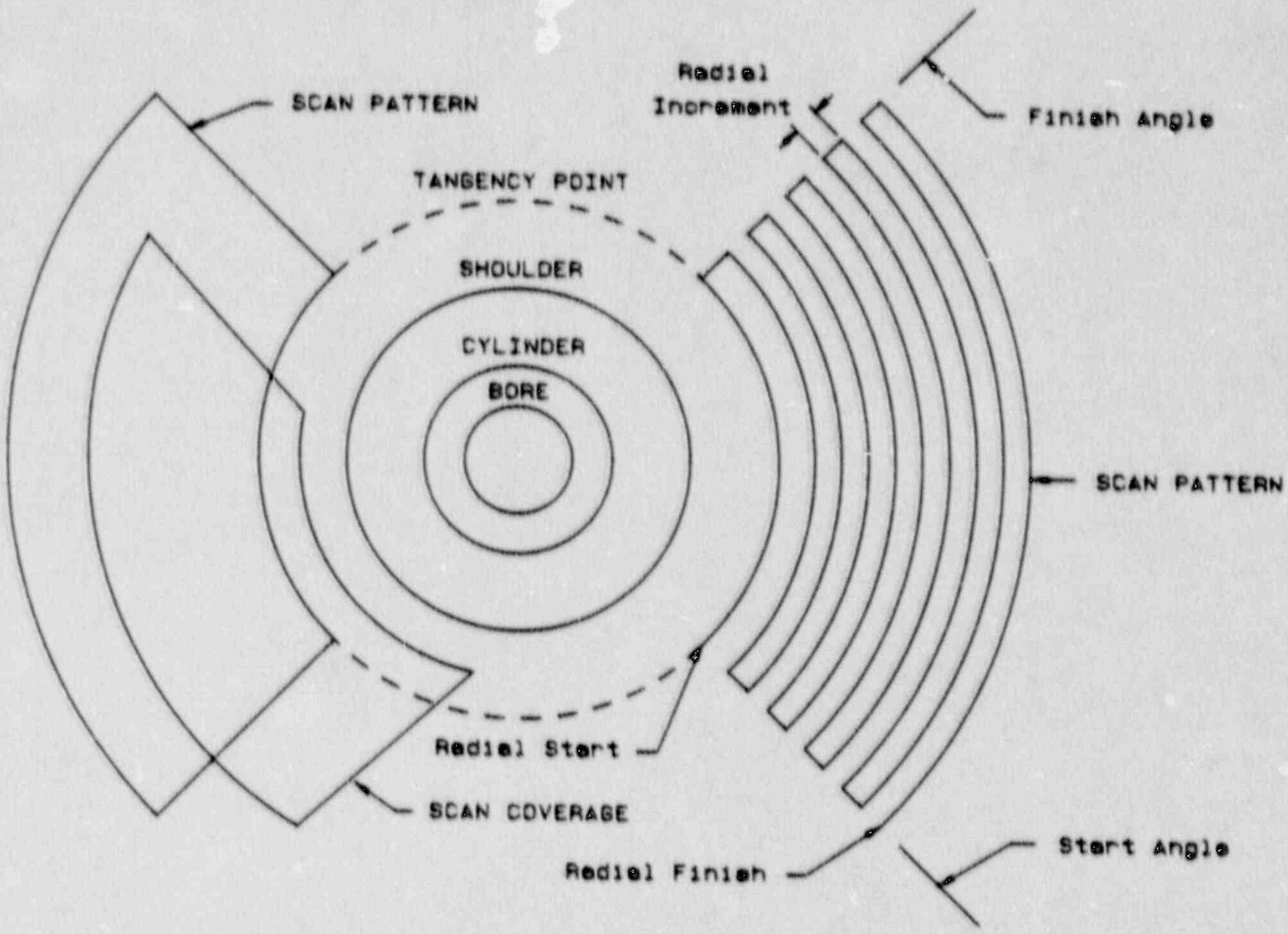


FIGURE 9

CIRCULAR SCAN

From RC Pipe Surface

(Pipe Side Radial Flaws)



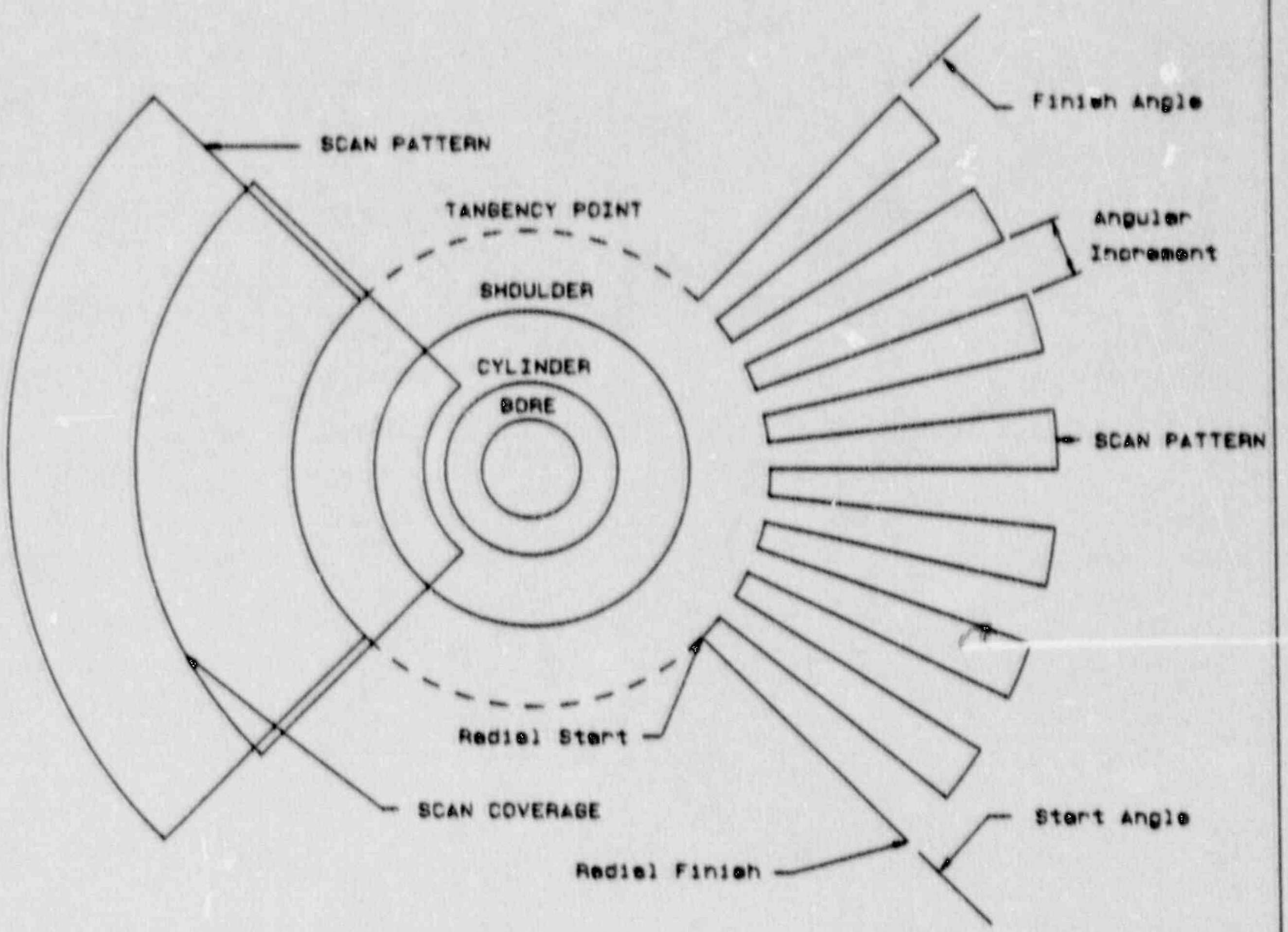
Nominal Beam Angle(s)	:	45
Wave Mode	:	Shear
Detection Transducer	:	
Diameter	:	3/8 inch
Frequency	:	2.25 MHz
Sizing Transducer	:	
Diameter	:	3/8 inch
Frequency	:	5 MHz
Sizing Technique	:	Tip Diffraction

FIGURE 10

RADIAL SCAN

From RC Pipe Surface

(Pipe Side Circumferential Flaws)



Nominal Beam Angle(s)	:	45
Wave Mode	:	Shear
Detection Transducer	:	
Diameter	:	3/8 inch
Frequency	:	2.25 MHz
Sizing Transducer	:	
Diameter	:	3/8 inch
Frequency	:	5 MHz
Sizing Technique	:	Tip Diffraction

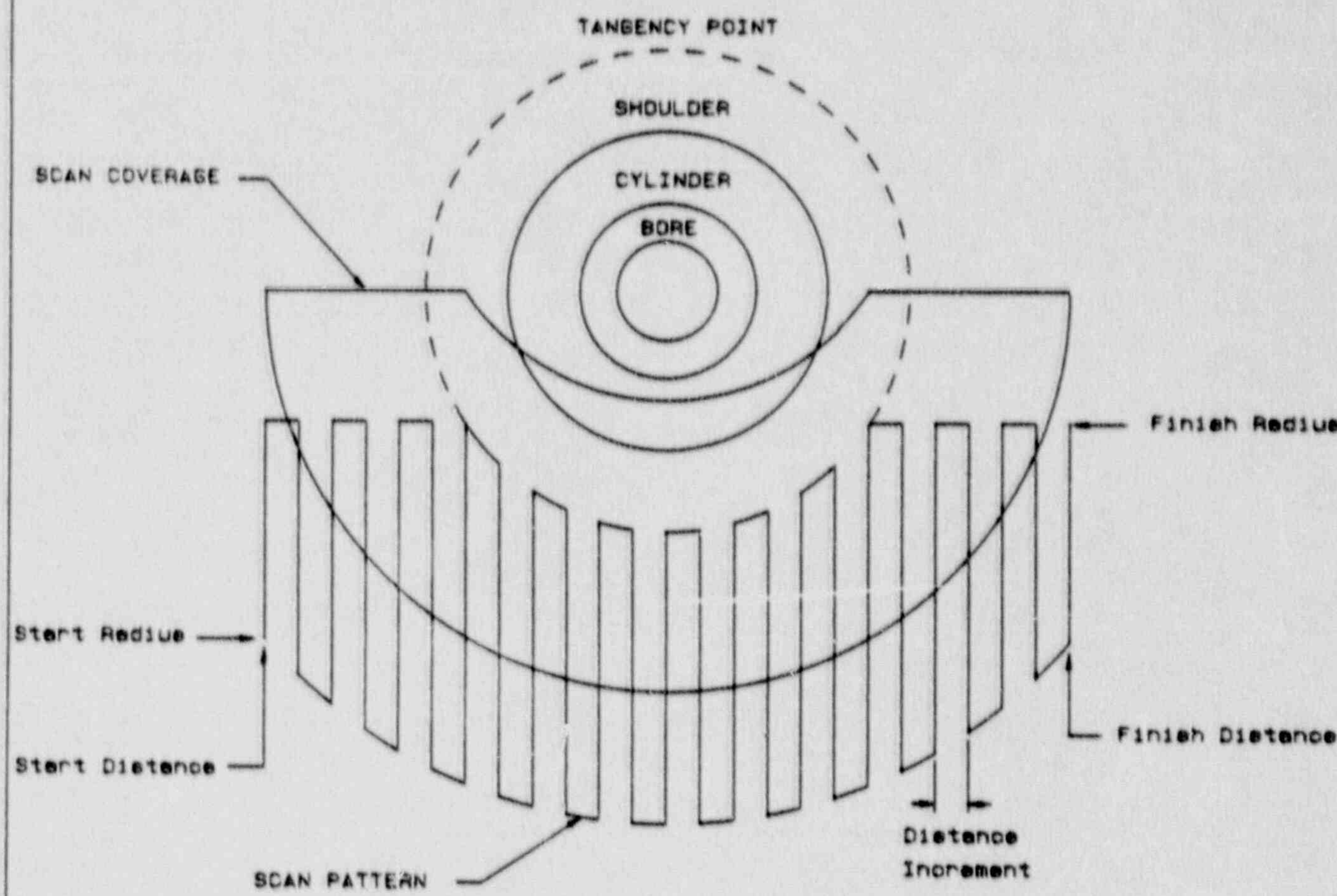
FIGURE 11

TANGENT SCAN

From RC Pipe Surface

(Axial Flaws in the Nozzle Bore)

(Radial and Circumferential Flaws in the Knuckle)



Nominal Beam Angle(s)	:	57, 66, 75
Wave Mode	:	Shear
Detection Transducer	:	
Diameter	:	1/2 inch
Frequency	:	2.25 MHz
Sizing Transducer	:	
Diameter	:	1/2 inch
Frequency	:	5 MHz
Sizing Technique	:	See Figure 14

FIGURE 12

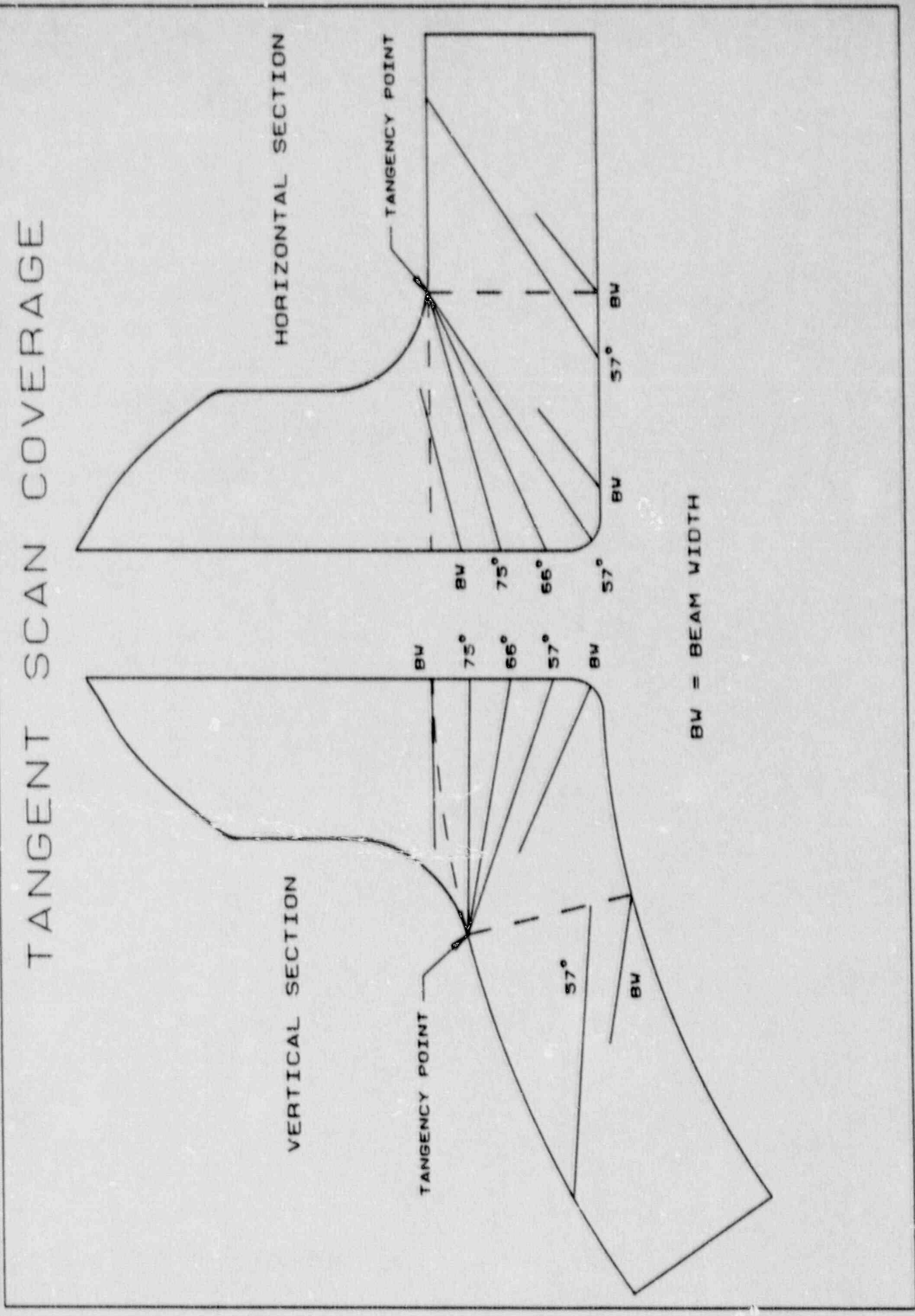
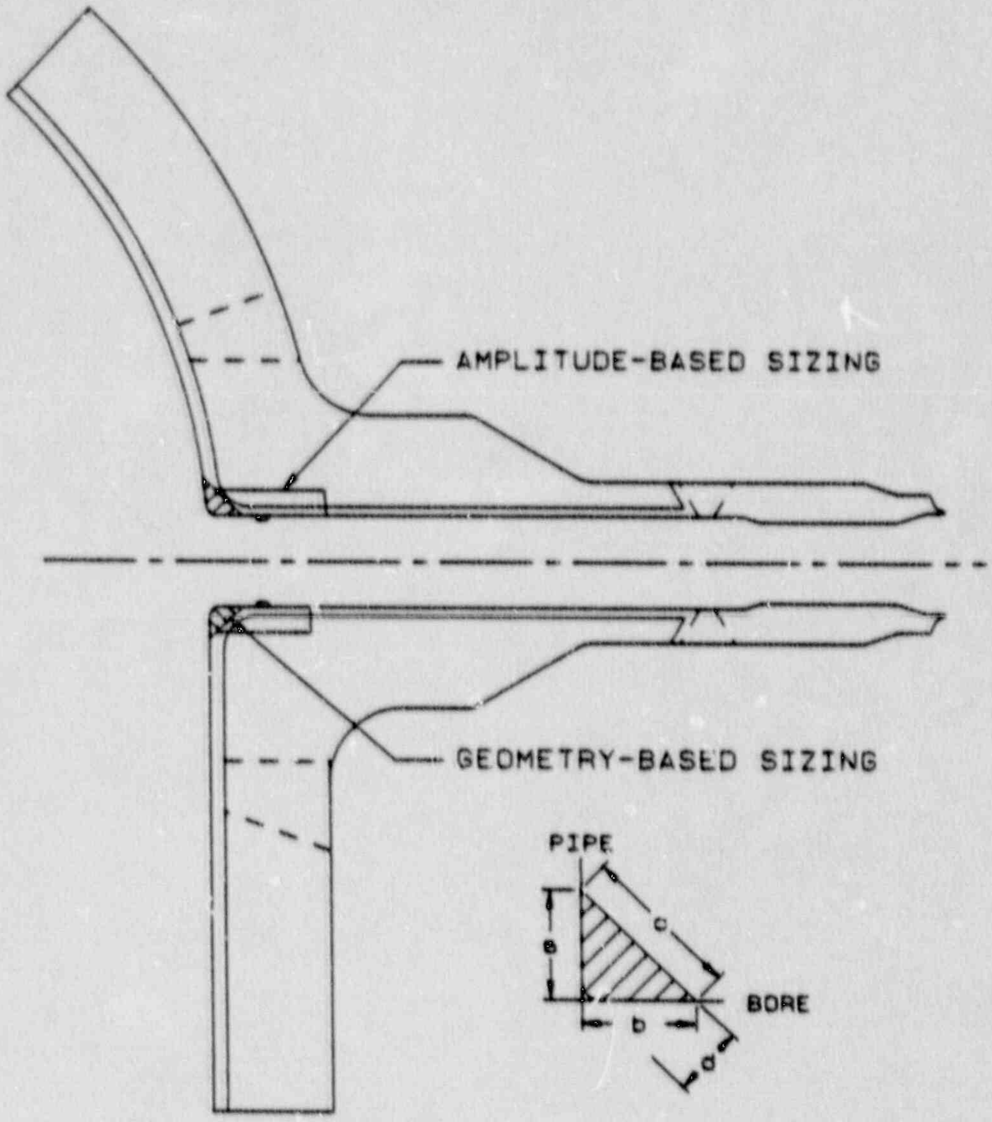

TANGENT SCAN COVERAGE
VERTICAL SECTION
HORIZONTAL SECTION
TANGENCY POINT
TANGENCY POINT
BW
75°
66°
57°
BW
57°
BW
BW
75°
66°
57°
BW
57°
BW
BW = BEAM WIDTH

FIGURE 13

SIZING TECHNIQUES



- TIP DIFFRACTION SIZING USED THROUGHOUT EXCEPT AS NOTED
- AMPLITUDE-BASED SIZING USED FOR AXIAL FLAWS IN THE BORE
- GEOMETRY-BASED SIZING USED FOR AXIAL FLAWS IN THE KNUCKLE
- SUPPLEMENTAL SIZING TECHNIQUES WILL BE APPLIED ON A CASE BY CASE BASIS FOR ANY DETECTED FLAWS

FIGURE 14

BWNS TEST BLOCK

- DEVELOP DETECTION TECHNIQUE
- DEVELOP SIZING TECHNIQUE
- DEFINE TRANSDUCER PARAMETERS
- DETERMINE DETECTABILITY AS A FUNCTION OF FLAW ORIENTATION

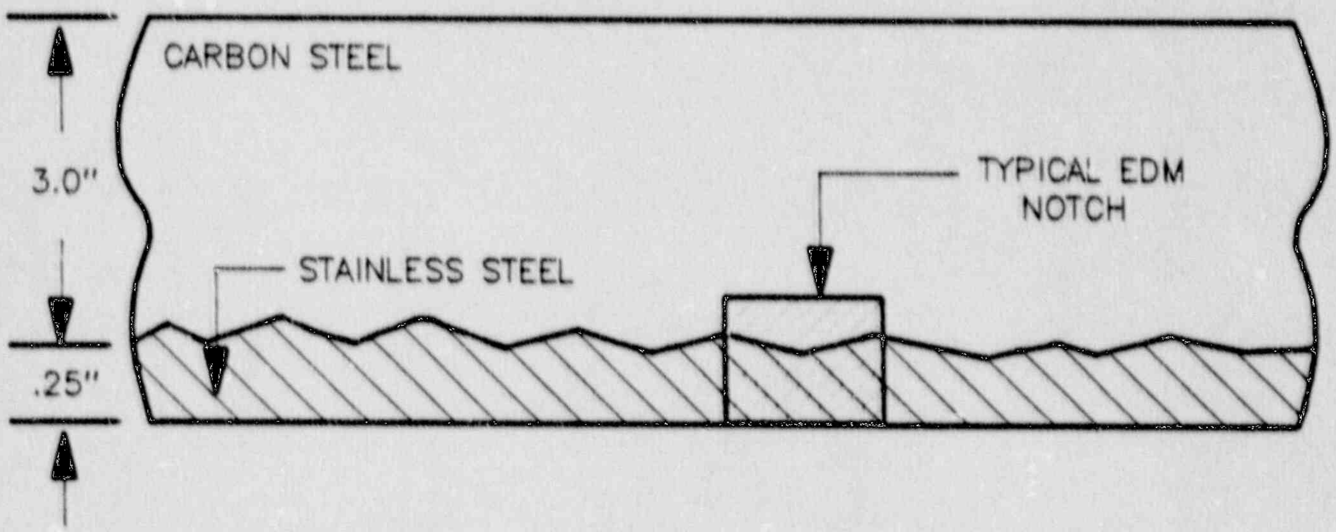


FIGURE 15

EPRI NEAR SURFACE TEST BLOCKS (2)

- "FINE TUNE" DETECTION/SIZING TECHNIQUES
- DETERMINE DETECTION PROBABILITIES
- DETERMINE FALSE CALL PROBABILITIES
- DETERMINE SIZING ACCURACY

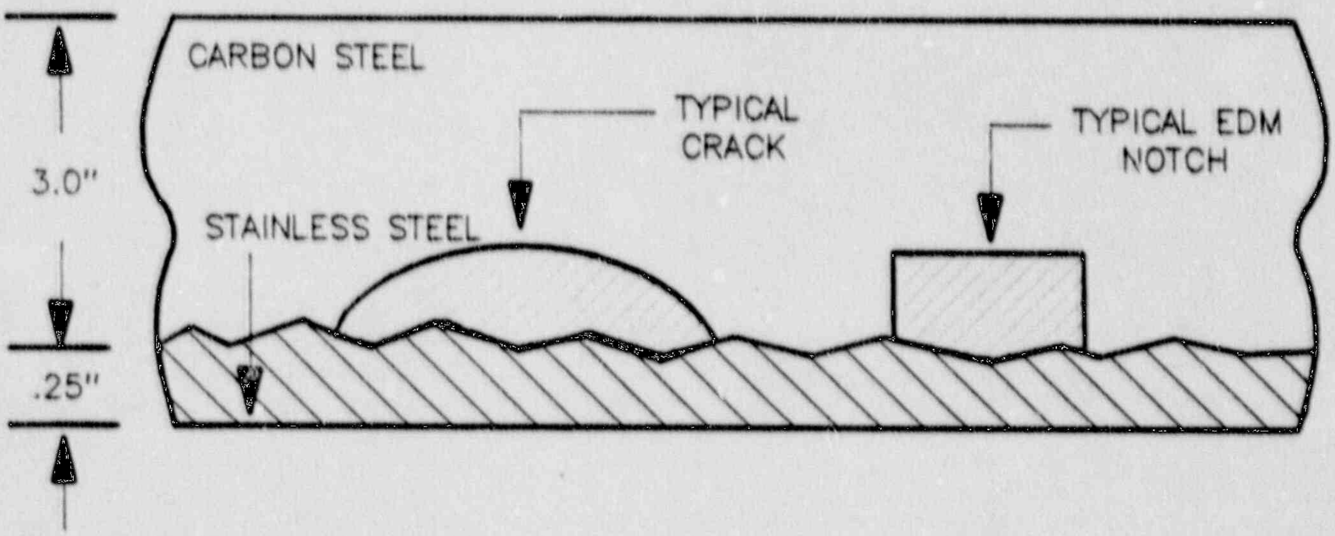
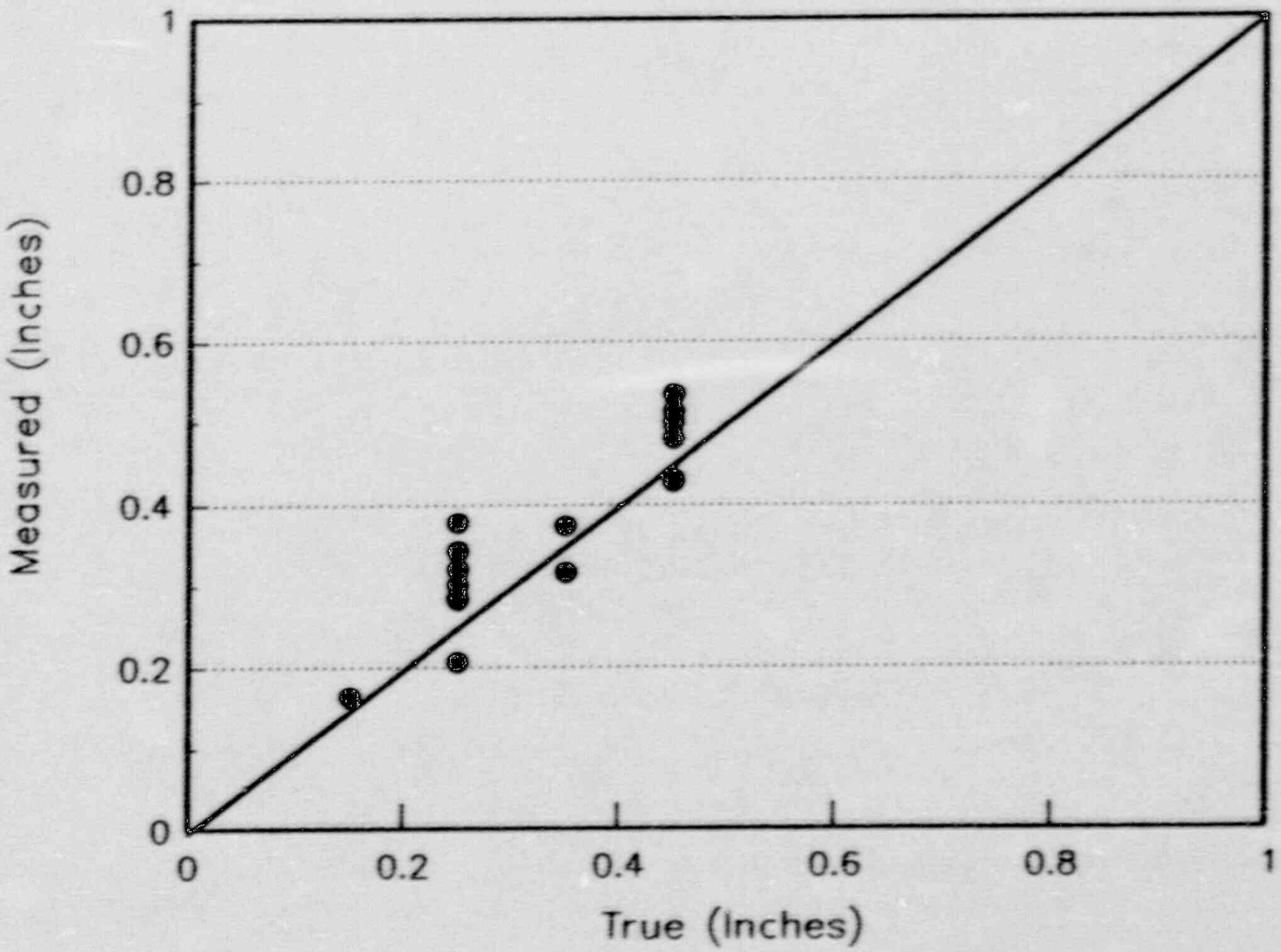


FIGURE 16

EPRI TEST BLOCKS

SELECTED TECHNIQUE
POPULATION: 16 NOTCHES



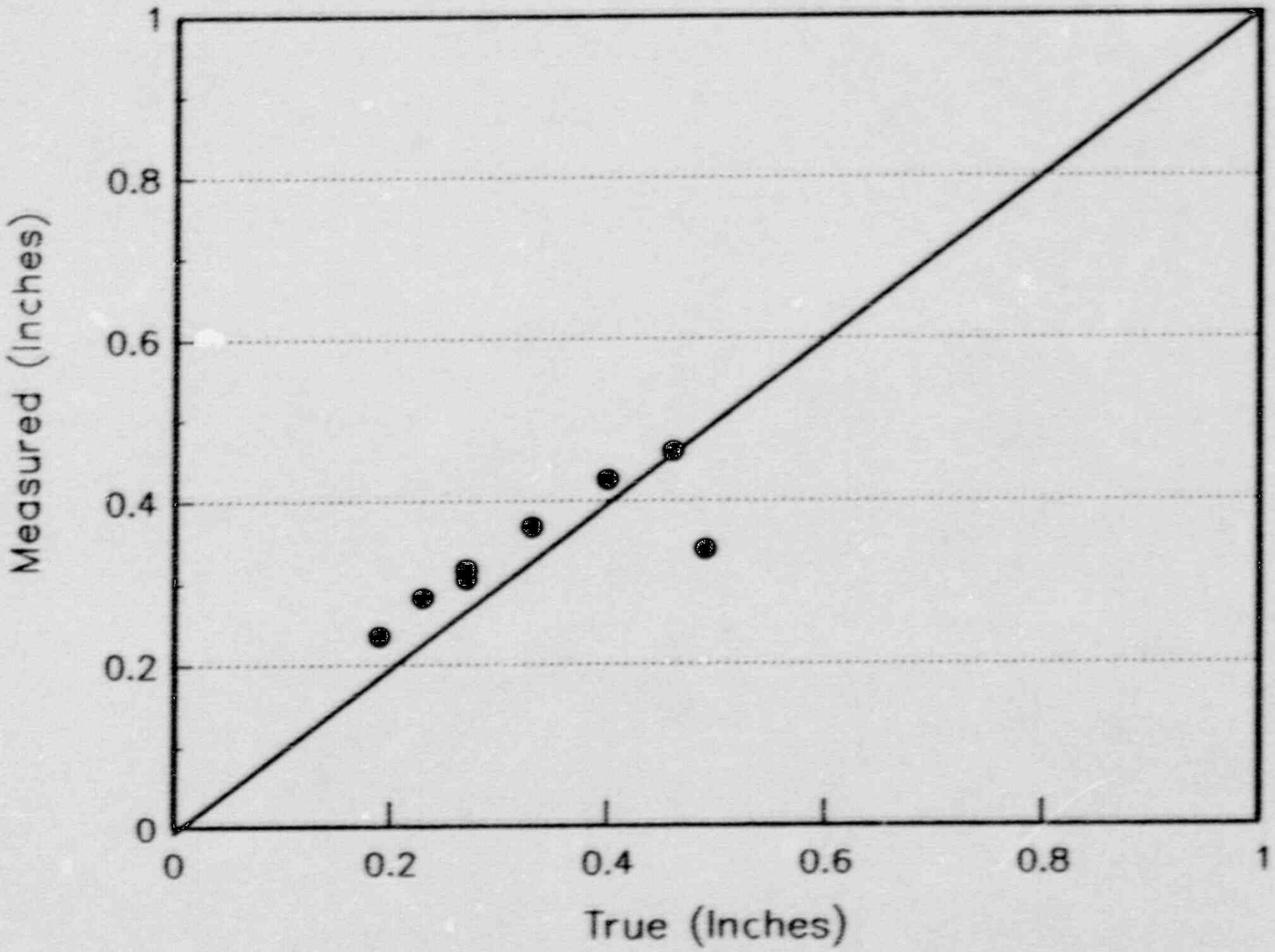
RMS Error .057 Inch

FIGURE 17

EPRI TEST BLOCKS

SELECTED TECHNIQUE

POPULATION: 8 CRACKS



RMS Error .064 Inch

FIGURE 18

BATTELLE PIPING TEST BLOCKS

- DETERMINE DETECTION PROBABILITIES
- DETERMINE FALSE CALL PROBABILITIES
- DETERMINE SIZING ACCURACY

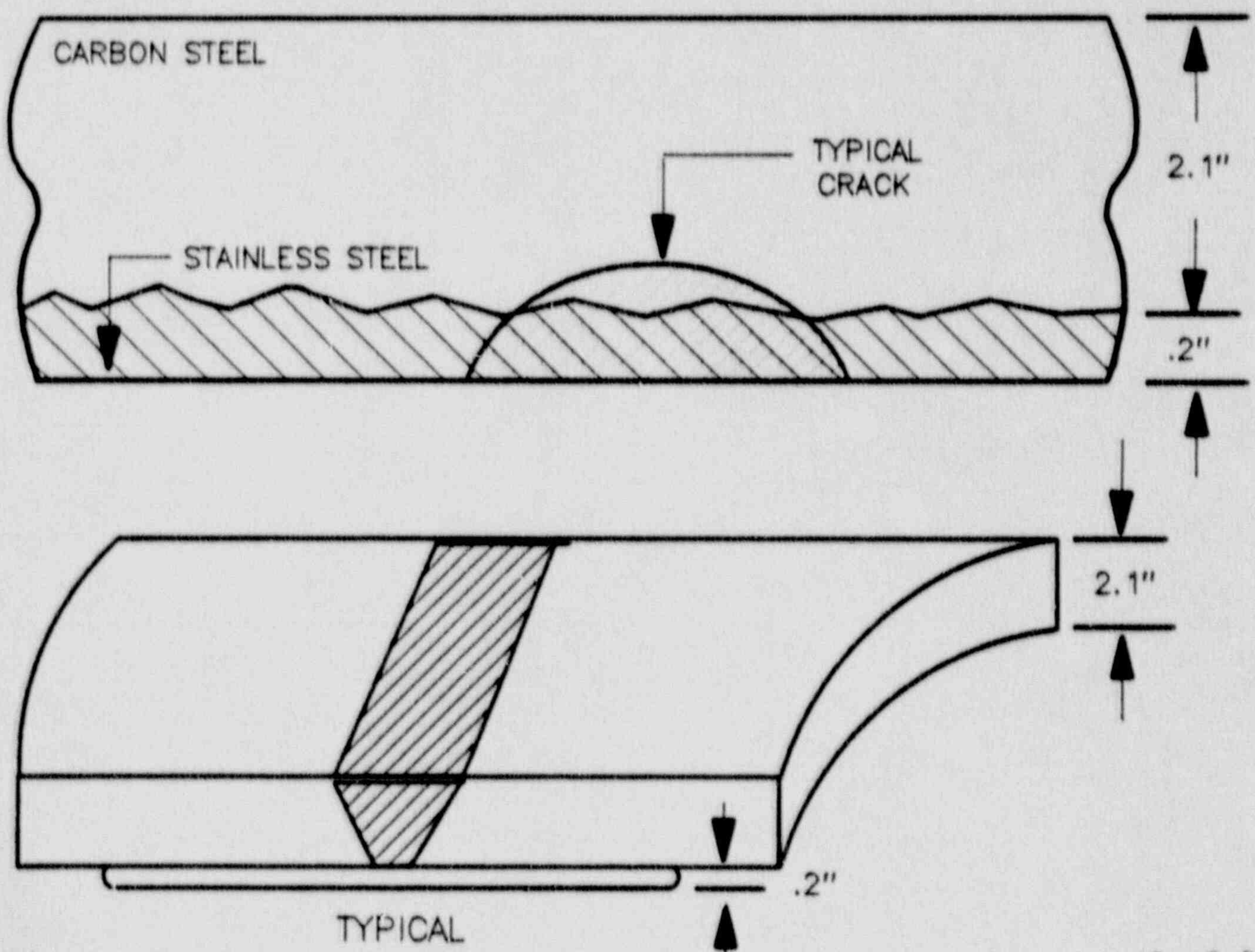
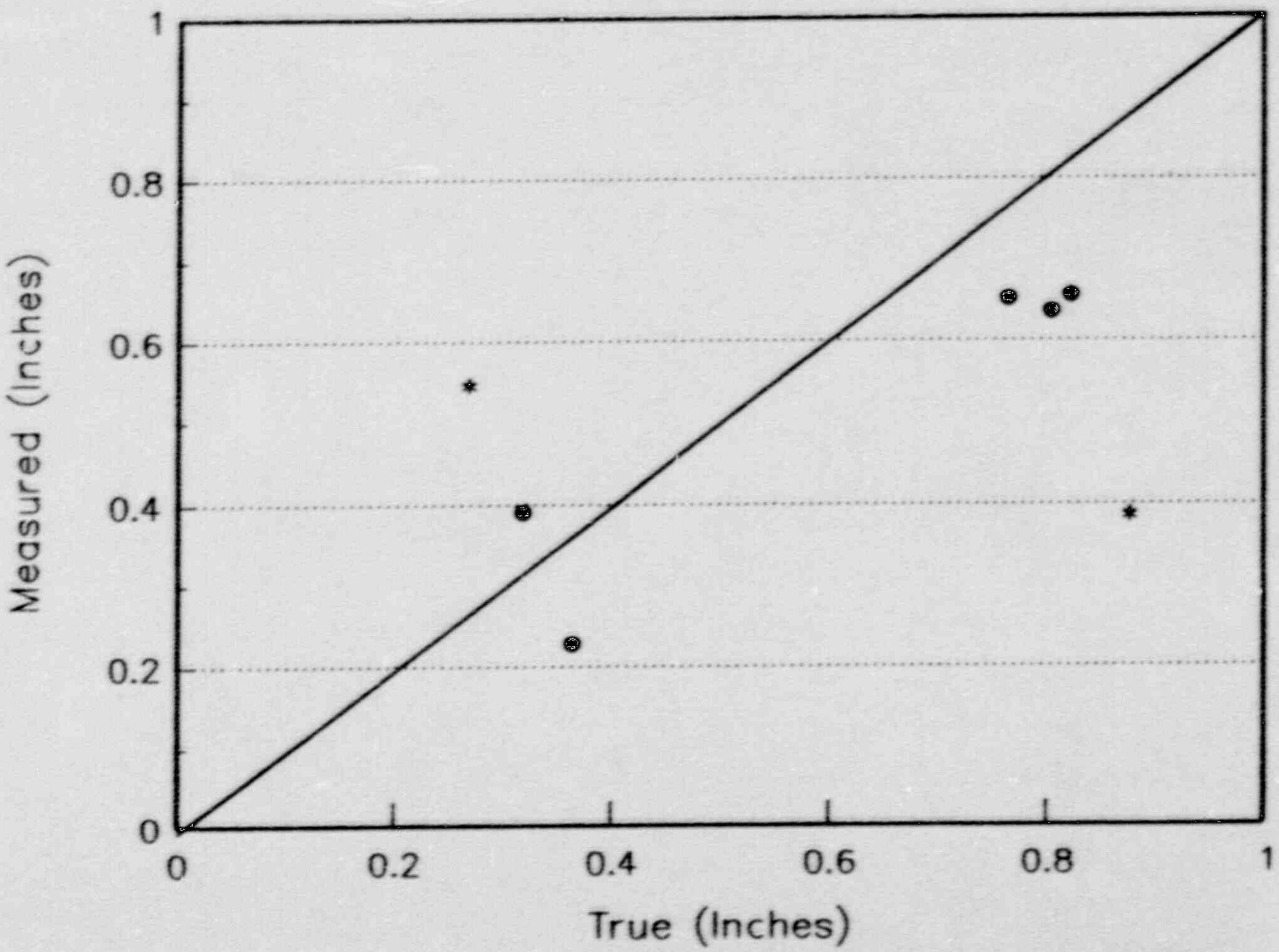


FIGURE 19

BATTELLE TEST BLOCKS

SELECTED TECHNIQUE

POPULATION: 7 CRACKS



RMS Error .247 Inch

* Invalid measurements due to interference from weld inclusions

FIGURE 20

BATTELLE TEST BLOCKS

SELECTED TECHNIQUE

POPULATION: 5 CRACKS

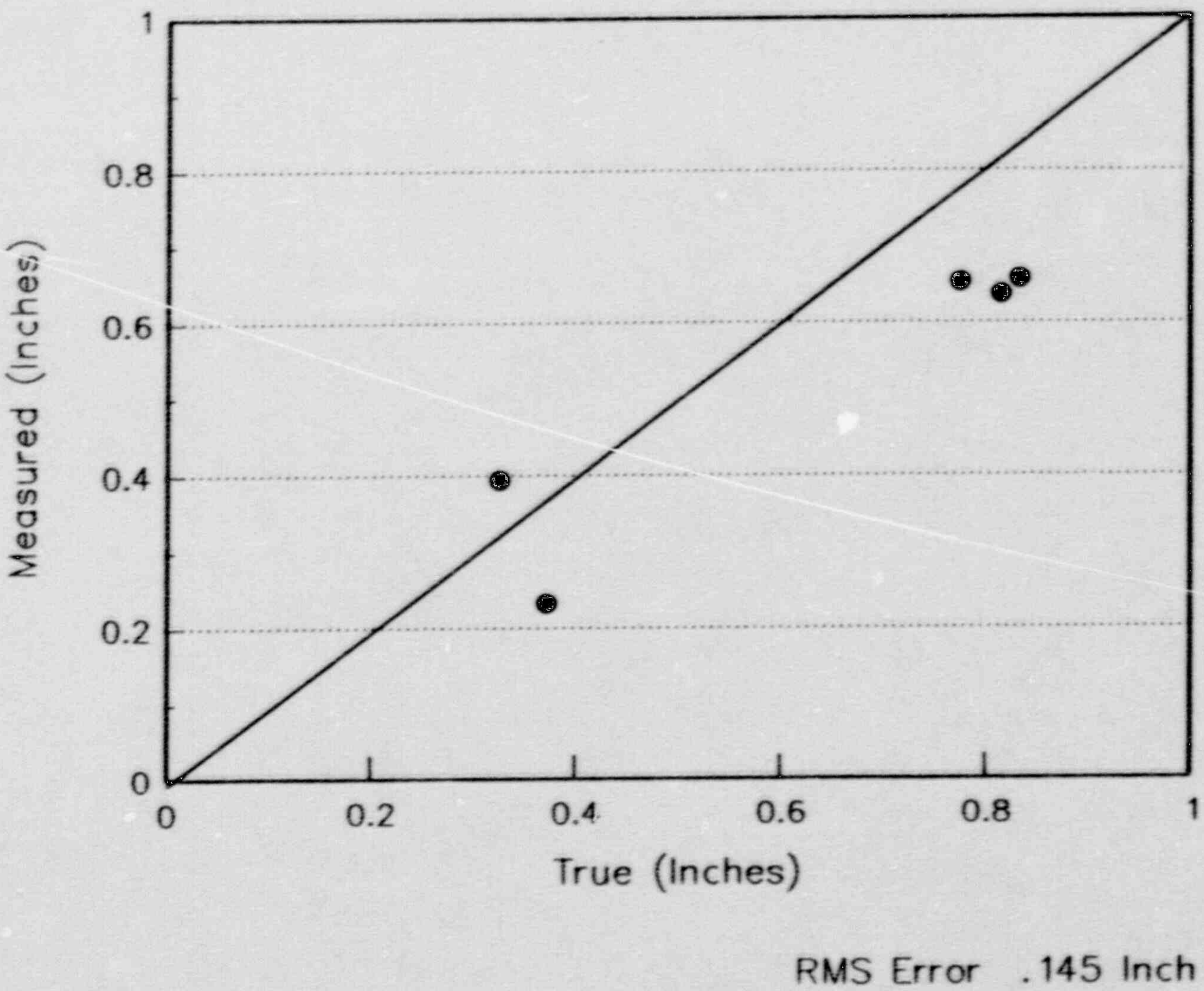
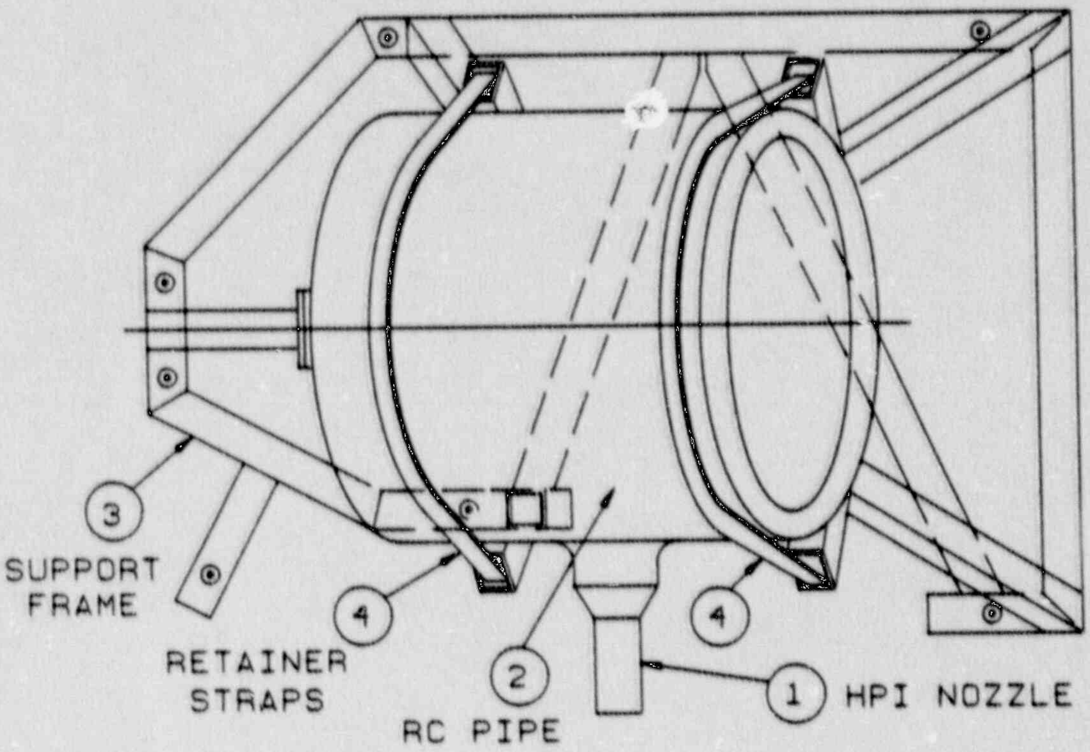
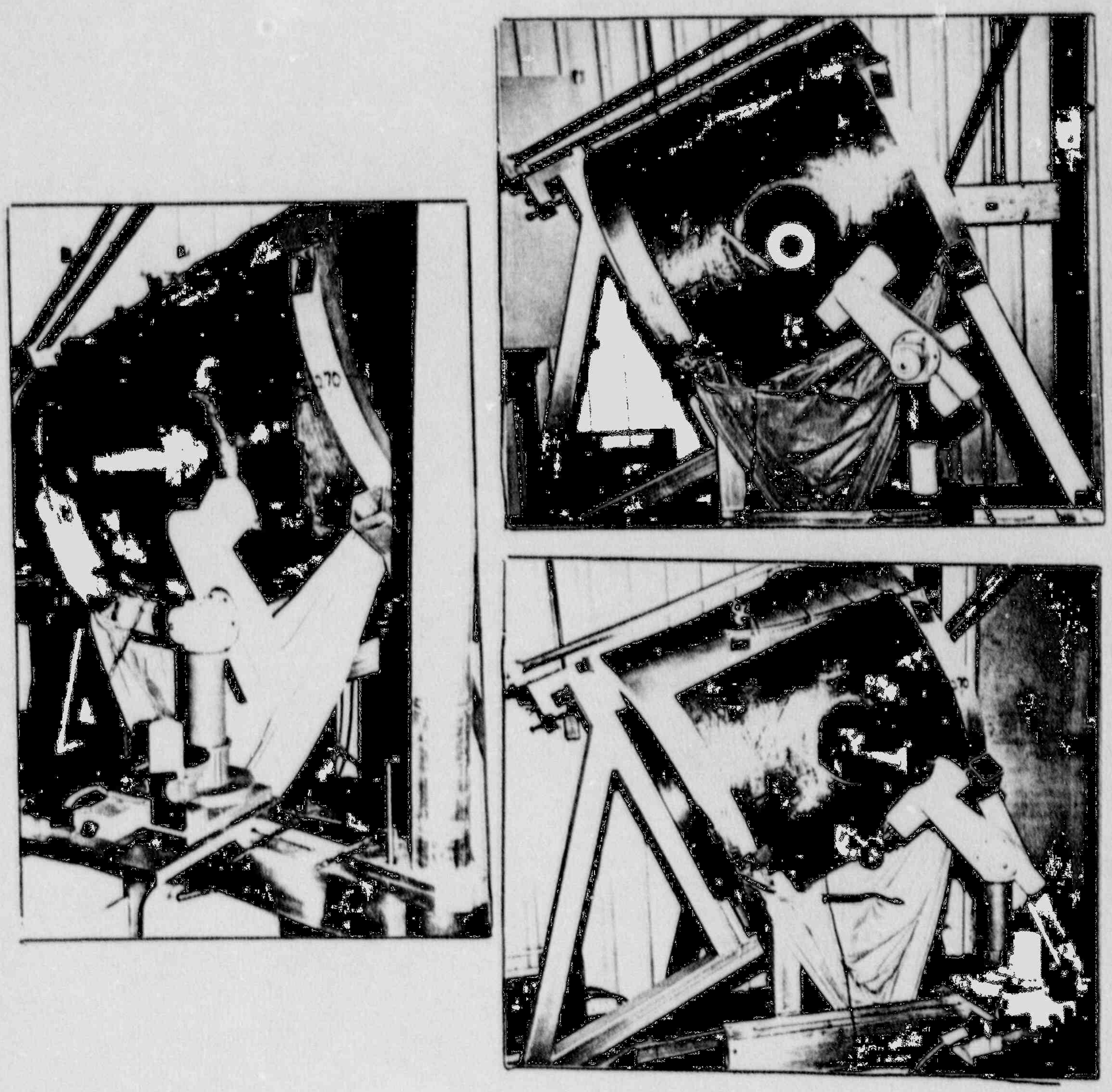


FIGURE 21



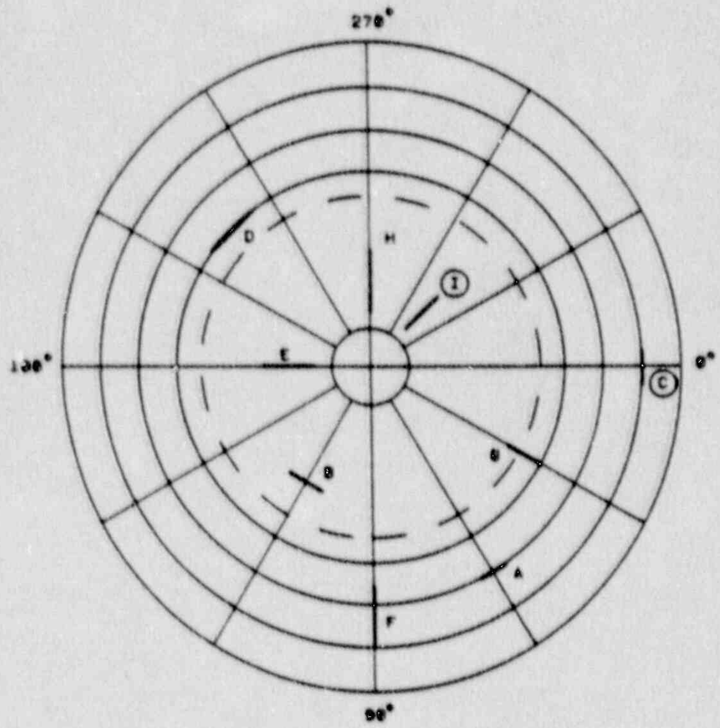
NOZZLE / RC PIPE MOCKUP

FIGURE 22



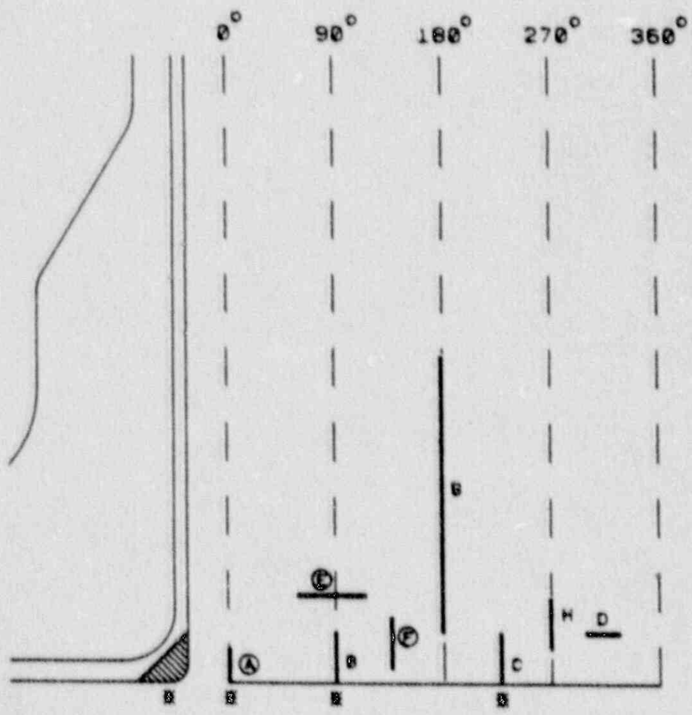
NOZZLE / RC PIPE MOCKUP PHOTOGRAPHS

FIGURE 23



DESIGNATION	DESCRIPTION	ORIENTATION	DESIGN	
			LENGTH	DEPTH
A	EDM NOTCH	90° OFF-RADIAL	0.75"	T+.05"
B	EDM NOTCH	90° OFF-RADIAL	1.00"	T+.15"
(C)	CRACK	90° OFF-RADIAL	0.90"	.50 T
D	EDM NOTCH	90° OFF-RADIAL	1.50"	T+.30"
E	EDM NOTCH	RADIAL	1.35"	T+.05"
F	EDM NOTCH	RADIAL	1.50"	T+.30"
G	EDM NOTCH	RADIAL	1.00"	.50 T
H	EDM NOTCH	RADIAL	1.05"	T+.15"
(I)	CRACK	RADIAL	1.2"	.90 T

NOTE : EDM NOTCH WIDTH IS .014"
T REPRESENTS CLADDING THICKNESS



DESIGNATION	DESCRIPTION	ORIENTATION	DESIGN	
			LENGTH	DEPTH
(A)	CRACK	AXIAL	1.00"	.90 T
B	EDM NOTCH	AXIAL	2.00"	T+.15"
C	EDM NOTCH	AXIAL	2.00"	T+.05"
D	EDM NOTCH	CIRCUM.	0.50"	T+.15"
(E)	CRACK	CIRCUM.	1.00"	.90 T
(F)	CRACK	AXIAL	0.75"	.90 T
G	EDM NOTCH	AXIAL	4.00"	T+.15"
H	EDM NOTCH	AXIAL	0.75"	T+.05"

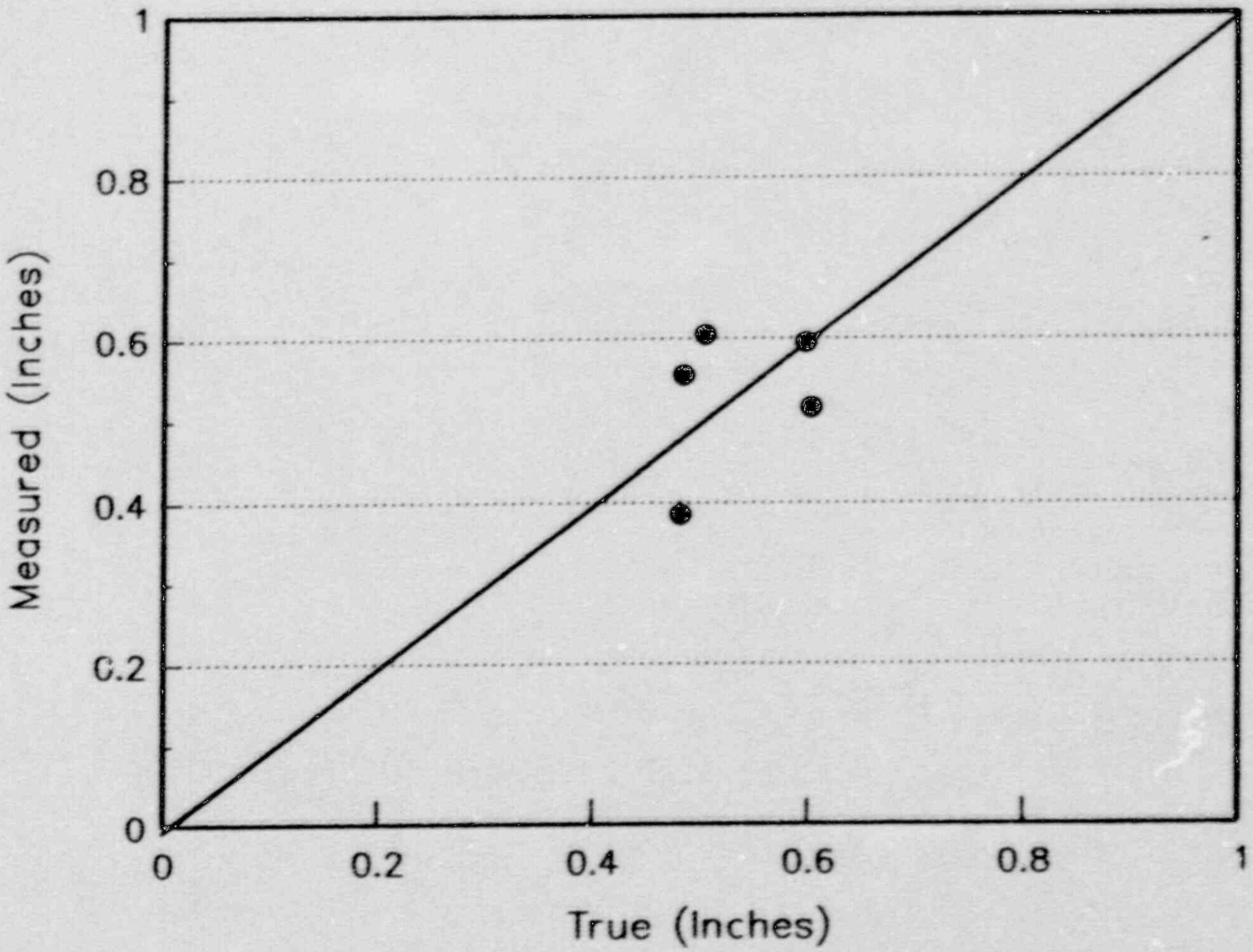
NOTE : EDM NOTCH WIDTH IS .014"
T REPRESENTS CLADDING THICKNESS

FIGURE 24

HPI NOZZLE MOCKUP

SELECTED TECHNIQUE

POPULATION: 5 RC PIPE NOTCHES



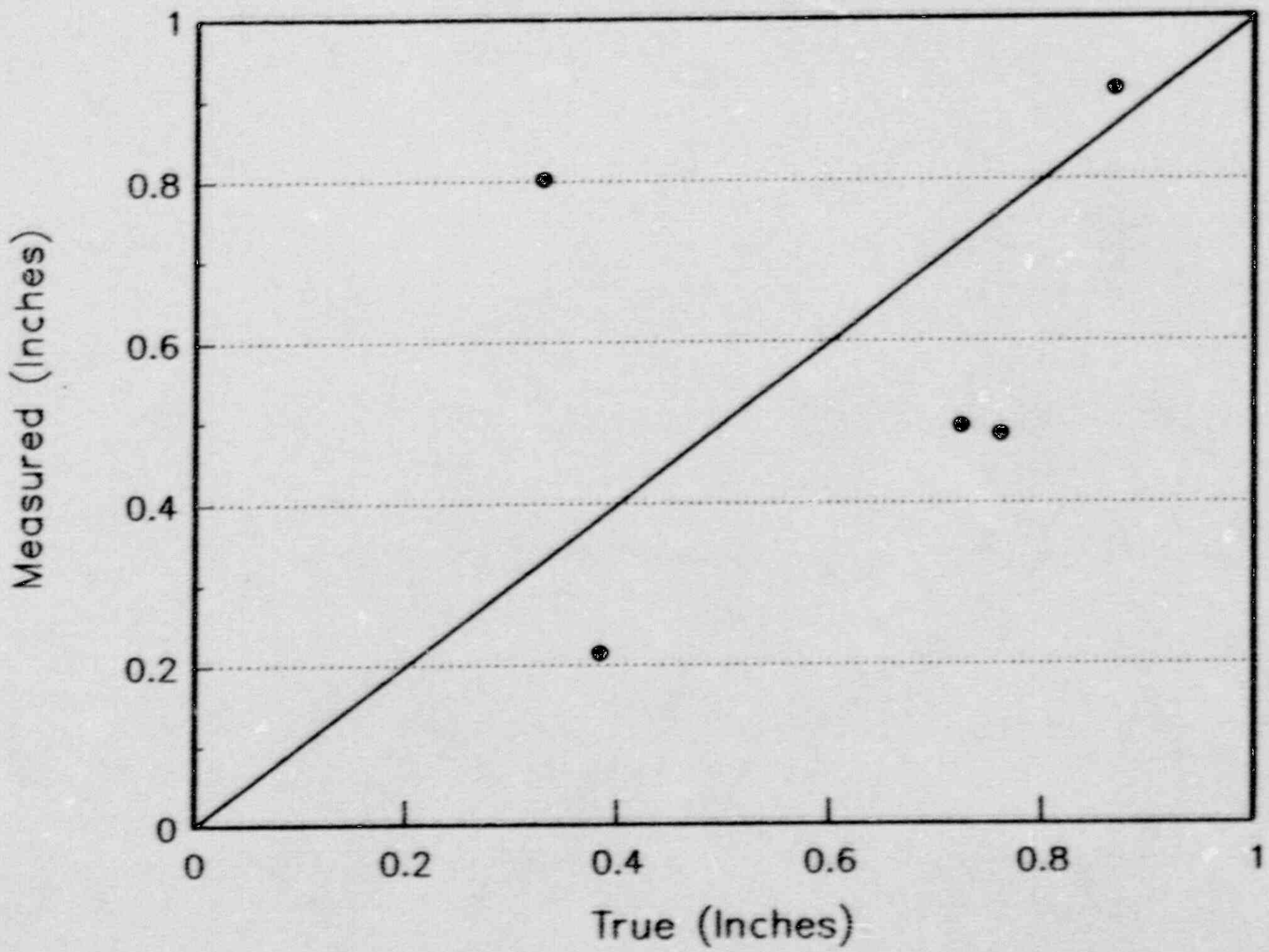
RMS Error .081 Inch

FIGURE 25

HPI NOZZLE MOCKUP

SELECTED TECHNIQUE

POPULATION: 5 BORE CRACKS AND NOTCHES



RMS Error .279 inch

FIGURE 26