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EVALUATION OF THE LOW CARBON TYPE 316 STAINLESS STEEL RECIRCULATION OUTLET SAFE ENDS AT PEACH BOTTOM UNIT 3

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1. SUMMARY

During 1985 refueling outage inspections at Peach Bottom Unit 3, significant ultrasonic (UT) indications were reported on both sides of both 28-inch recirculation outlet safe end to pipe welds 2-AS-2 and 2-BS-2. These indications suggested the presence of extensive intergranular stress corrosion cracking (IGSCC). Since the safe ends are low carbon 316 stainless steel and the weld design is uncreviced, based on extensive laboratory testing and considerable field experience, IGSCC was not expected.

In order to confirm the presence and depth of cracks reported by UT, a 1-inch diameter core sample was removed from the B-Loop safe end to pipe weldment 2-BS-2. The location of the sample was carefully selected to coincide with the region where UT signals indicated the presence of the deepest cracks in the safe end. The resulting hole was replugged and a full structural weld overlay repair of the entire joint was performed.

Following receipt of the core sample at General Electric' Vallecitos Nuclear Center special analysis and metallurgical sectioning was performed. The results are as follows:

1. Metallographic examination of the sections of the core sample at high magnification showed no intergranular stress corrosion cracking (IGSCC) in the low carbon 316 material. In two of the three samples, small lack of fusion/slag inclusion type defects were found at a distance of 5/8 inch from the I.D. (mid-wall). This coincides with the crack depth and location indicated by UT in this section.

2. Sectioning of the core confirmed the actual weld cross-section and I.D. location of the weld root. Based on this and knowledge of the UT signal paths, it was determined that the UT indications reported in the 316L heat affected zone core were actually at the weld fusion line or in the weld metal itself. This conclusion is consistent with UT data plots at various locations around the circumference of both A and B-Loop recirculation safe end to pipe welds.

3. Visual observation, metallographic evaluations and hardness measurements determined the presence of I.D. grinding with a relatively shallow level of surface cold work (0.004 inch maximum depth.). No evidence of abusive grinding was found in the core sample, which is consistent with the absence of cracking.

4. It is believed that an unusual straight sided weld root fusion line (vertical cross-section in the weld root pass for a significant distance, 1/8 inch, from the I.D.) provided a UT reflector on the inner surface that appeared to have characteristics of IGSCC. The vertical root geometry may have resulted from weld preparation modifications that could have been performed during field fit-up of these closure weld spools.

In summary, no cracking of the 316L material was found in the core sample. Evidence was found that the UT indications reported on the low carbon 316 side of the weld are actually in the weld fusion line or in the weld metal. The ultrasonic test indications previously reported as IGSCC are believed to be due to the unusual straight sided weld root geometry. In turn, the reported "crack depths" are related to small lack of fusion type defects in the 308 weld metal itself. The fact that there was no IGSCC in the low carbon 316 material is consistent with laboratory data and field performance of L-grade austenitic stainless steel piping.

2. BACKGROUND

Extensive experience has established that high carbon type 304 austenitic stainless steel which is sensitized by welding can be susceptible to intergranular stress corrosion cracking when exposed to oxygenated high temperature water environment typical of the Boiling Water Reactor coolant.[1] However, if the carbon level of the steel is reduced below 0.035%, typical of L-grade austenitic stainless steel, the steel will not sensitize during the welding process and is therefore highly resistant to IGSCC. The resistance of these steels in recirculation coolant environments has been documented thoroughly.[2] Further reduction of carbon level to ≤0.02% to obtain additional margin against sensitization was the basis for the selection of the type 316 Nuclear Grade (316NG) replacement alloy reported in Reference 2. Although the L-grade, nuclear grade and stabilized grade stainless steels are highly resistant to IGSCC in the as-welded condition, laboratory and field results have indicated that cracking can occur even in these materials under severely cold worked and/or creviced conditions even in the absence of sensitization. For example, field data did establish that cracking occurred in the crevice region of the Peach Bottom-2 recirculation inlet safe ends where the thermal sleeve was attached to the safe end.[3] This region was significantly removed from the butt weld and the heat affected zone where IGSCC typically occurs in sensitized high carbon stainless steel. Examinations also established that shallower IGSCC was associated with local areas of severe surface cold work near the attachment weld attributed to grinding or slag removal hammer peening during the fitup and welding of the thermal sleeve to the safe end.[3]

During the recent inspections of the recirculation piping system at Peach Bottom-3 (including both piping and safe end components), all of the recirculation inlet and outlet safe end to pipe butt welds were inspected as they had been at Peach Bottom-2. While all of the safe ends were manufactured

of low carbon type 316 stainless steel* considered to be conforming material by NUREG-0313, Rev. 1, the piping that was joined to it was a high carbon type 304 stainless steel that was susceptible to IGSCC. This prompted the required inspection. This inspection established that several of the high carbon type 304 heat affected zones were cracked. The inspection also established that all of the recirculation inlet safe end heat affected zones in the 316L were free of UT indications. Similar findings had been made at Peach Bottom-2 during the pipe replacement activities. These results were consistent with the expected performance of low carbon, non-sensitized austenitic stainless steels. However, the inspections of the two outlet safe end heat affected zones revealed IGSCC type UT indications in both the 304 and the 316L material.

These findings were not expected for the 316L material and contradicted laboratory and field data on the high IGSCC resistance of these steels. In particular, earlier liquid penetrant inspections at the Peach Bottom-2 plant of the same type of outlet safe end to pipe butt welds had established the outlet safe end HAZ's to be free of cracking after prepping for pipe installation. Secondly, inspections of the other outlet safe end welds where the safe end was attached to the low alloy steel nozzle at both plants did not reveal any crack-like indications.

Due to the unexpected reported occurrence of the indications in the 316L material, i.e., their presence as well as their apparent depth, a core sample was taken from one of the outlet safe end to pipe weld HAZ region to evaluate the nature of the cracking. The objective of this report is to document all the work performed in this evaluation of the apparent IGSCC in the low carbon type 316 outlet safe end material. The report will cover the following topics:

a. Initial UT Inspection Results

b. UT Evaluations

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*Material certified as Type 316 with low carbon for design purposes but is referred to in this report as 316L.

c. Core Sample Removal Procedures

d. Core Sample Evaluation

e. Reassessment of U.T. Indications

f. Reassessment of Low Carbon Stainless Steel Performance

It should be noted that following the removal of the core sample, a plug was seal welded into the hole and the outlet safe end to pipe welds were overlayed with a full structural overlay as a repair for the IGSCC type UT indications found in both the pipe and safe end heat affected zones. To complete the required repairs without extension of the outage, the weld overlays had to be applied following the core sample removal and prior to completion of the entire core sample evaluation.

3. UT EVALUATIONS

3.1 INITIAL UT EVALUATION

A cross sectional sketch of the Peach Bottom-3 recirculation outlet nozzle, safe end, and pipe configuration is displayed in Figure 3-1. The results of the weld 2-BS-2 inspections are displayed in Figure 3-2. This figure shows the depth of the indications around the circumference for both the pipe side and the safe end side of the weld.

The indications on the safe end side were originally detected and evaluated as IGSCC by General Electric, and were independently confirmed by Southwest Research Institute personnel. A total of five different examiners made the same evaluations. The indications had all the identifying characteristics for IGSCC which are the following:

- Initiation on the I.D.
- Depth
- Sharp characteristics with multiple tips
- Readily detected at transducer skew angles
- Detectable with an I.D. creeping wave
- "Crack tips" with deeper cusps detected with fracted longitudinal wave

The indications were known to be at or near the fusion line but field experience had shown that cracks in large diameter pipes would frequently occur there. This information - combined with the construction radiographic evidence also displayed in Figure 3-2 that showed the inside to be ground smooth eliminating geometric reflectors at those locations - left little doubt that the safe ends were cracked.

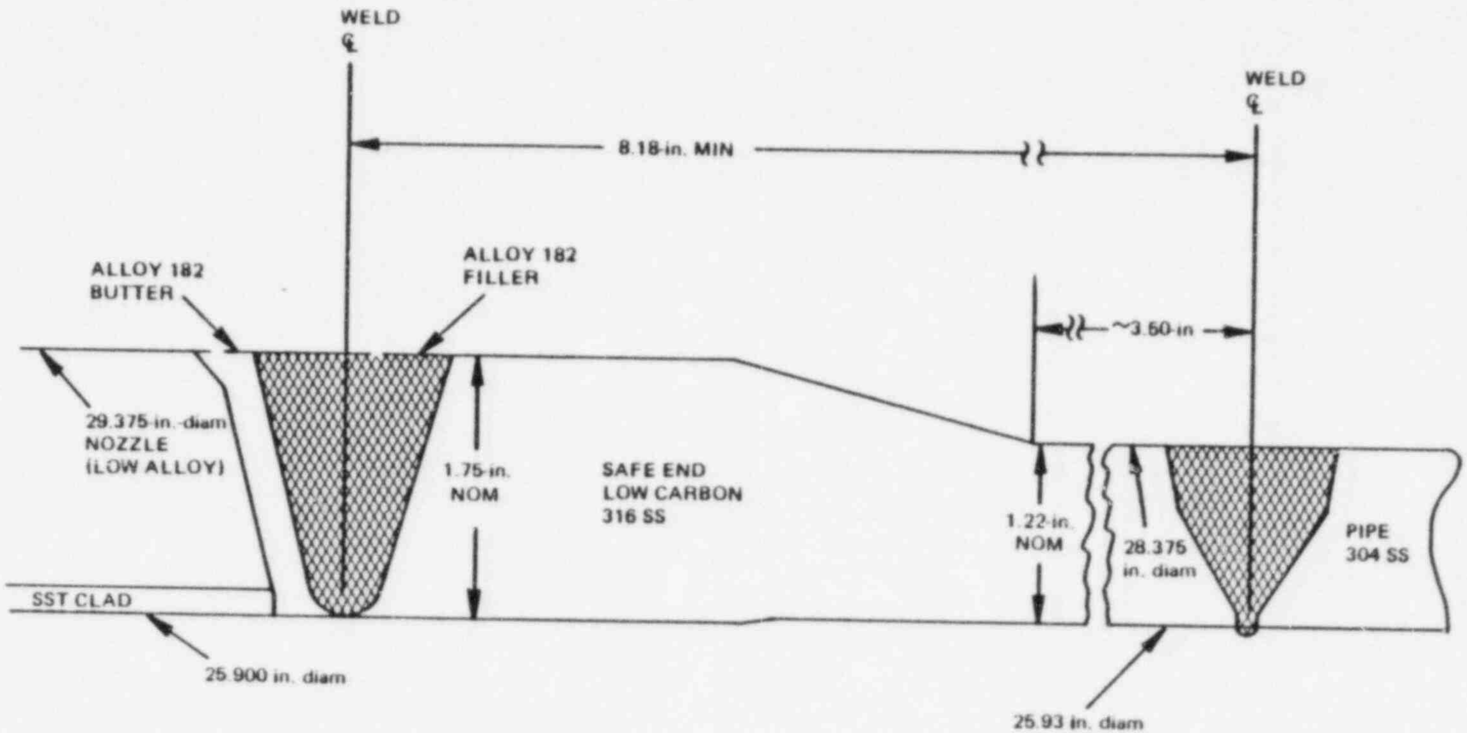


Figure 3-1. Peach Bottom-3 Recirculation Outlet Safe End Configuration

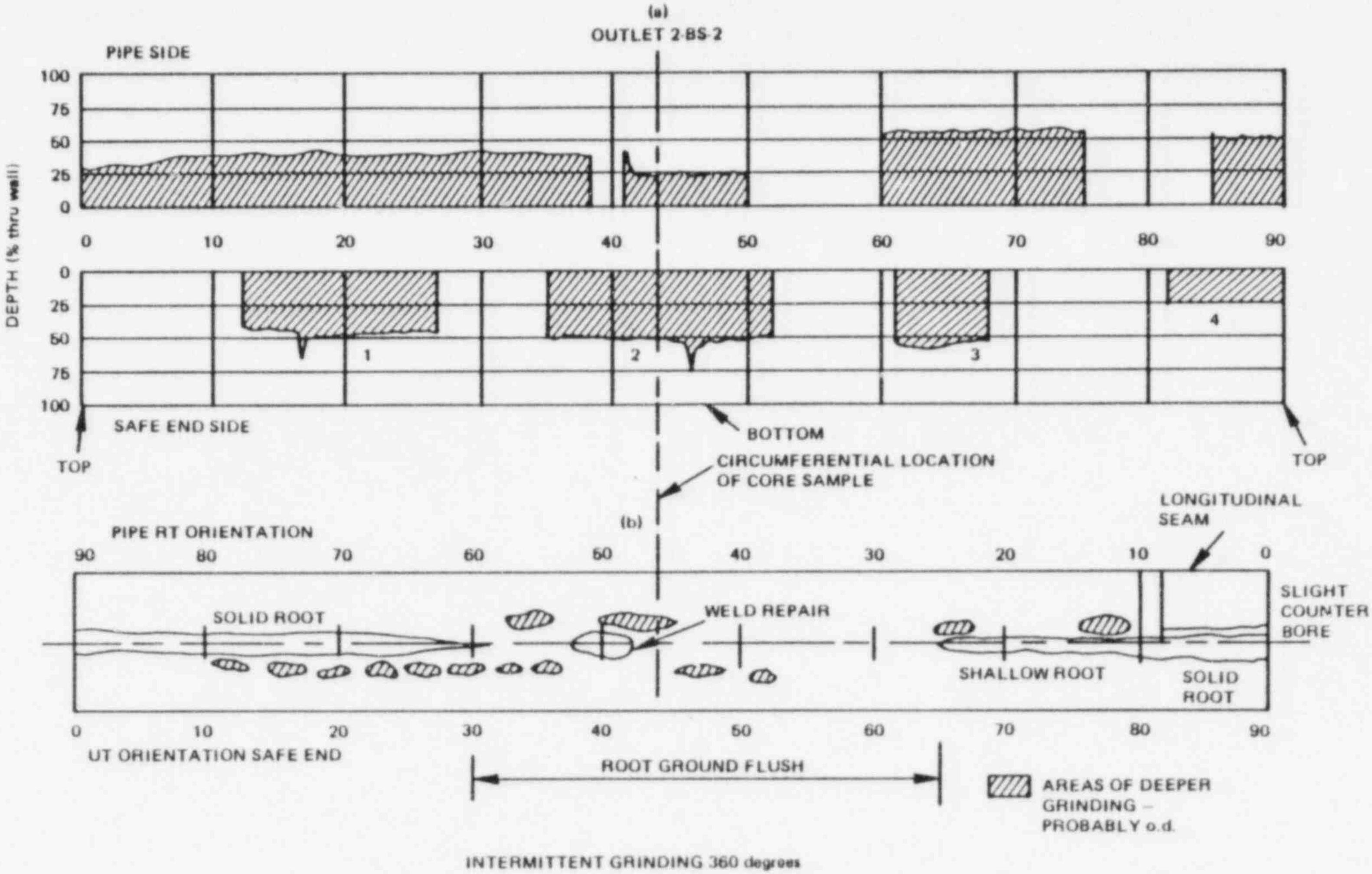


Figure 3-2. Schematic of Ultrasonic and Radiographic Records for Peach Bottom-3 Outlet Safe End to Pipe Weld 2-BS-2; (a) UT crack indications around circumference; (b) construction radiographic interpretation around circumference

The recirculation outlet safe end to pipe weld 2-BS-2 was selected for obtaining the core sample. This selection was based on both UT and construction Radiographic (RT) data. The construction radiographs showed that there had been considerable grinding on the inside surface as indicated in Figure 3-2. This was important since it was felt that cold work as a result of the grinding was the only potential method of crack initiation in this uncreviced joint. According to the radiographs weld 2-BS-2 had an area where all of the root and counterbore had been removed. This corresponded to an area indicated by UT to have a relatively long and deep crack indication on the safe end side of the weld. The layout of the UT indications for weld 2-BS-2 is also shown in Figure 3-2 and, for reference, the core sample centerline is noted. (The method of selecting the core sample location is described later in this section.)

Figure 3-3 shows cross-sectional plots of representative UT data from the safe end side of weld 2-BS-2. Similar UT examination results were observed for the companion A-Loop weld 2-AS-2. The plotting in Figure 3-3 shows the safe end crack indications to be at or near the fusion line or in the weld metal. Because the actual I.D. weld root centerline and weld cross-section geometry cannot be accurately predicted based on O.D. weld crown location, these indications were evaluated as IGSCC in the 316L heat-affected zone. Figure 3-4 shows cross-sectional plots of the pipe side indications. Note that the indications are typical of piping IGSCC and are located in the pipe heat-affected zone area, except for the indication at the 31 inch location which could be an indication of cracking on the safe end side.

The combination of the pipe side and safe end side UT data layouts gave a clear indication of apparent IGSCC on both sides of the joint. As with any field weld, typical weld cross-sections and assumed I.D. root locations can be applied to the layouts, but the data must be interpreted with the appropriate allowance for skewed weld crowns and various as-built cross-sectional geometries. Based on these allowances, and based on prior large pipe experience with IGSCC near the fusion line, the data in Figures 3-3 and 3-4 (and the IGSCC signal characteristics associated with the indications) led to the evaluation of IGSCC.

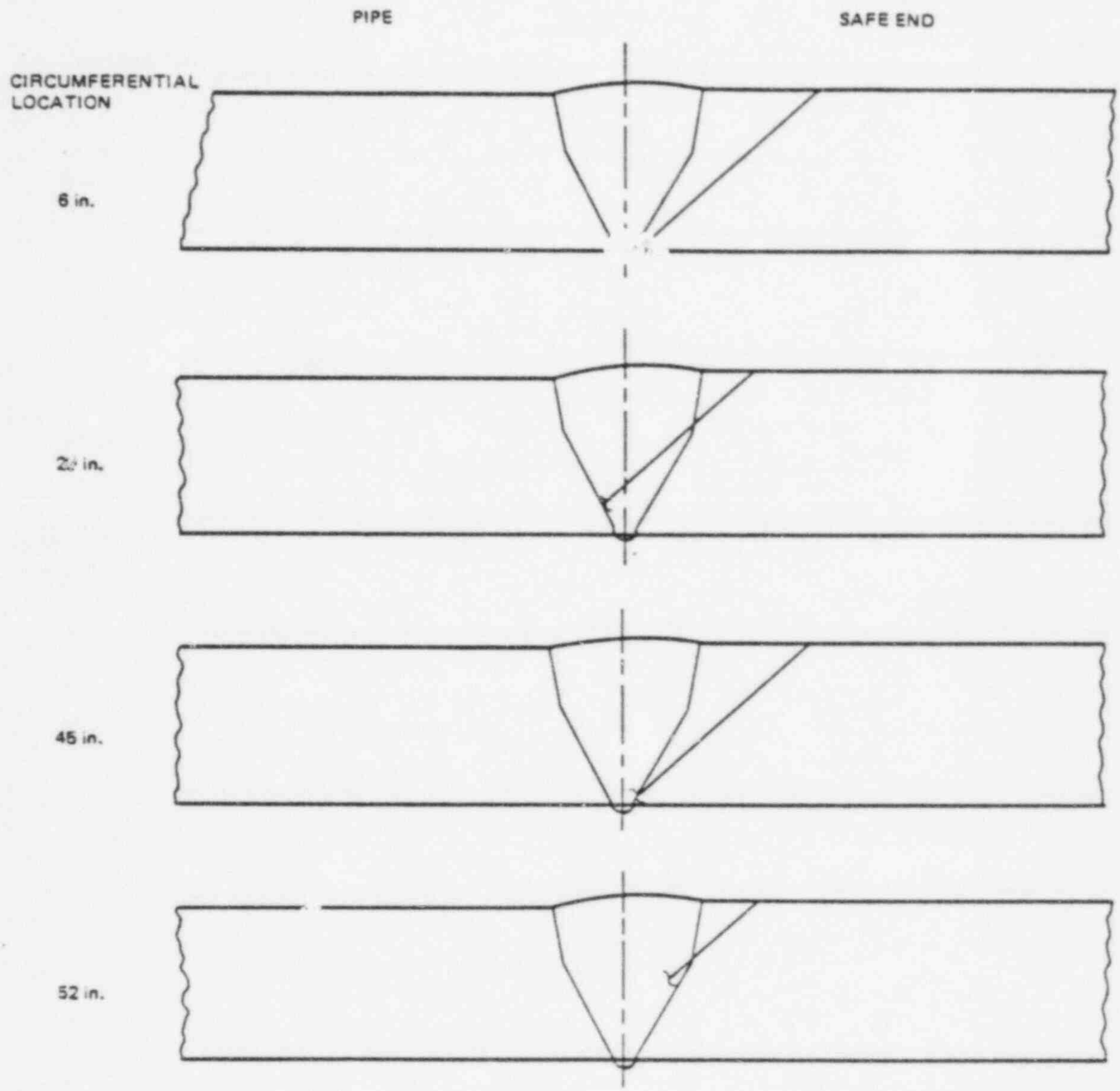


Figure 3-3. Schematic of Weld 2-BS-2 UT Plots Showing Indication Metal Path from Safe End Side at Different Circumferential Locations

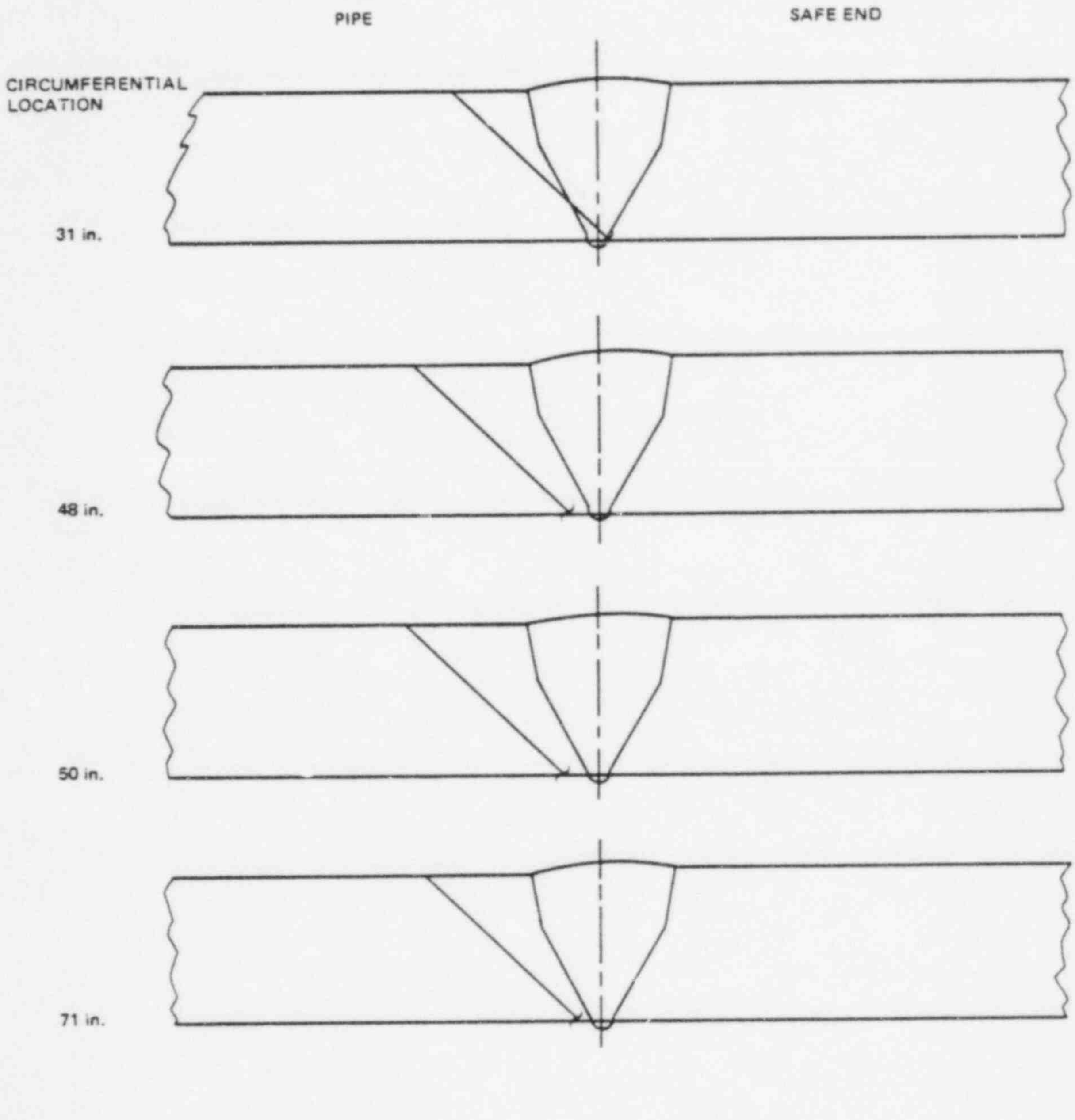


Figure 3-4. Schematic of Weld 2-BS-2 UT Plots Showing Indication Metal Path from Pipe Side at Different Circumferential Locations

3.2 CORE SAMPLE LOCATION

As described previously, the crack indication near the bottom of the 2-BS-2 joint was selected for core sample removal. A zone located from the 40 to 54 inch azimuth (clockwise looking toward vessel centerline) was selected for further evaluation. This area was selected to contain the longest, deepest crack indication on the safe end side and confirmed evidence of I.D. grinding, which was felt to be the only known mechanism for crack initiation in the low carbon material. The layout of this zone and the proposed sample location with respect to the weld centerline is shown in Figure 3-5. Note that this is only a reference location, and that final positioning of the sample centerline and the exact azimuthal location was to be determined by additional UT, which is described next.

To assure that the sample was located to contain a representative portion of the entire crack indication, and to finalize the exact location with respect to the weld centerline, additional UT examinations were performed. These included 45° shear wave and 45° refracted L-wave examinations. Using this data, the precise azimuth location and an O.D. weld centerline reference point were marked by the UT personnel performing the examination. The location selected was the 47 inch azimuth (looking clockwise toward vessel centerline). This was about the midpoint of the crack indication on the safe end side at a location showing confirmed IGSCC signals on the I.D. and a measured crack tip at 50% through-wall.

Extreme care was taken in locating the precise position for the core sample that was to be removed. A UT transducer was placed on the safe end and aimed directly at the indication. While this indication was being observed on the instrumentation, the centerline of the weld was marked with a punch directly in front of the transducer. This arrangement is shown in Figure 3-6. Next, cross-section layouts and UT data plots were prepared to determine the axial position of the core sample cutter. The primary objective was to include both the initiation and the through-wall crack tip points in the 316 side of the joint. A second objective was to include the root pass and some of the pipe side crack indications. It was decided to locate the center of

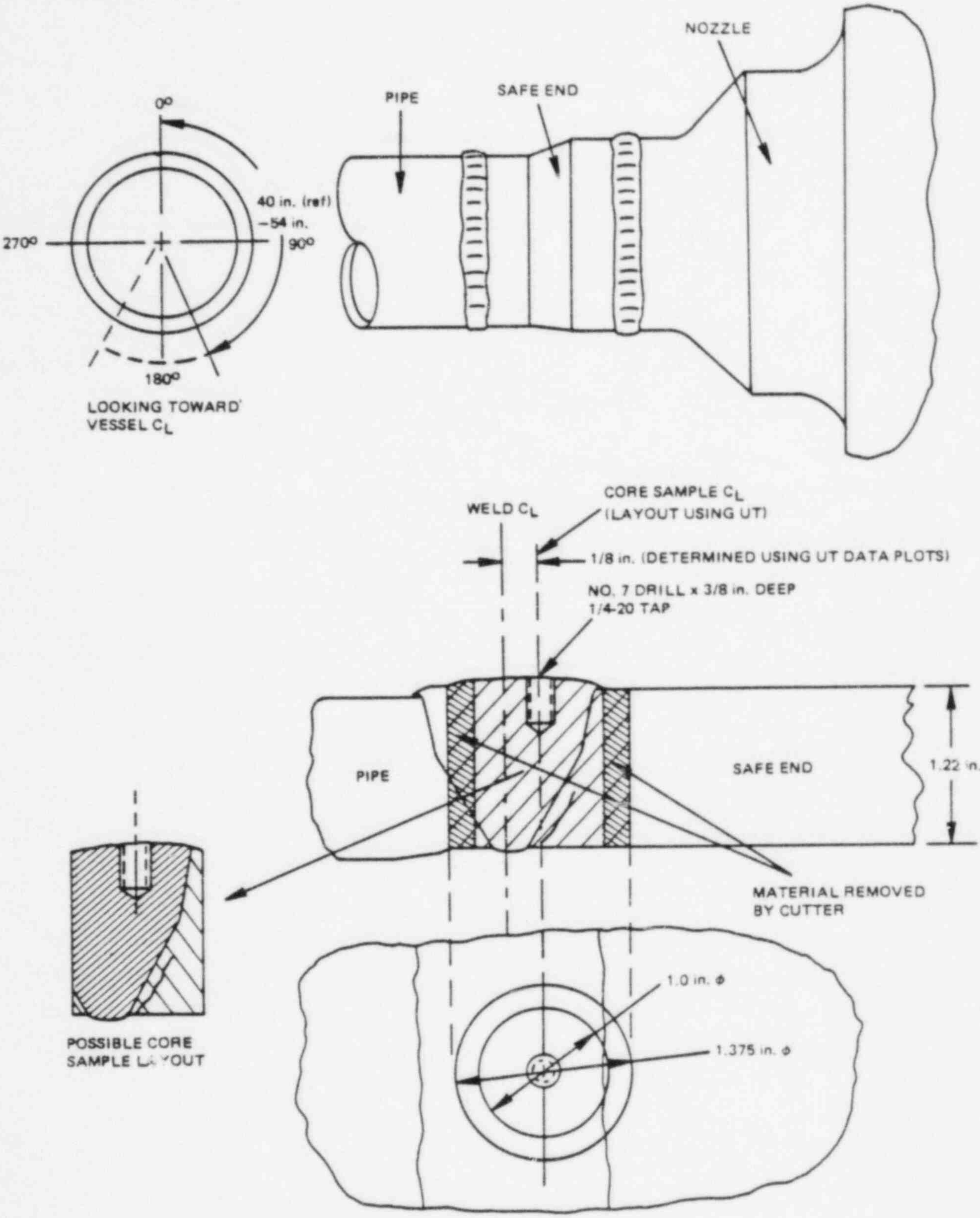


Figure 3-5. Schematic Showing Core Sample Location Plan and Top and Cross-Section Views of Possible Sample

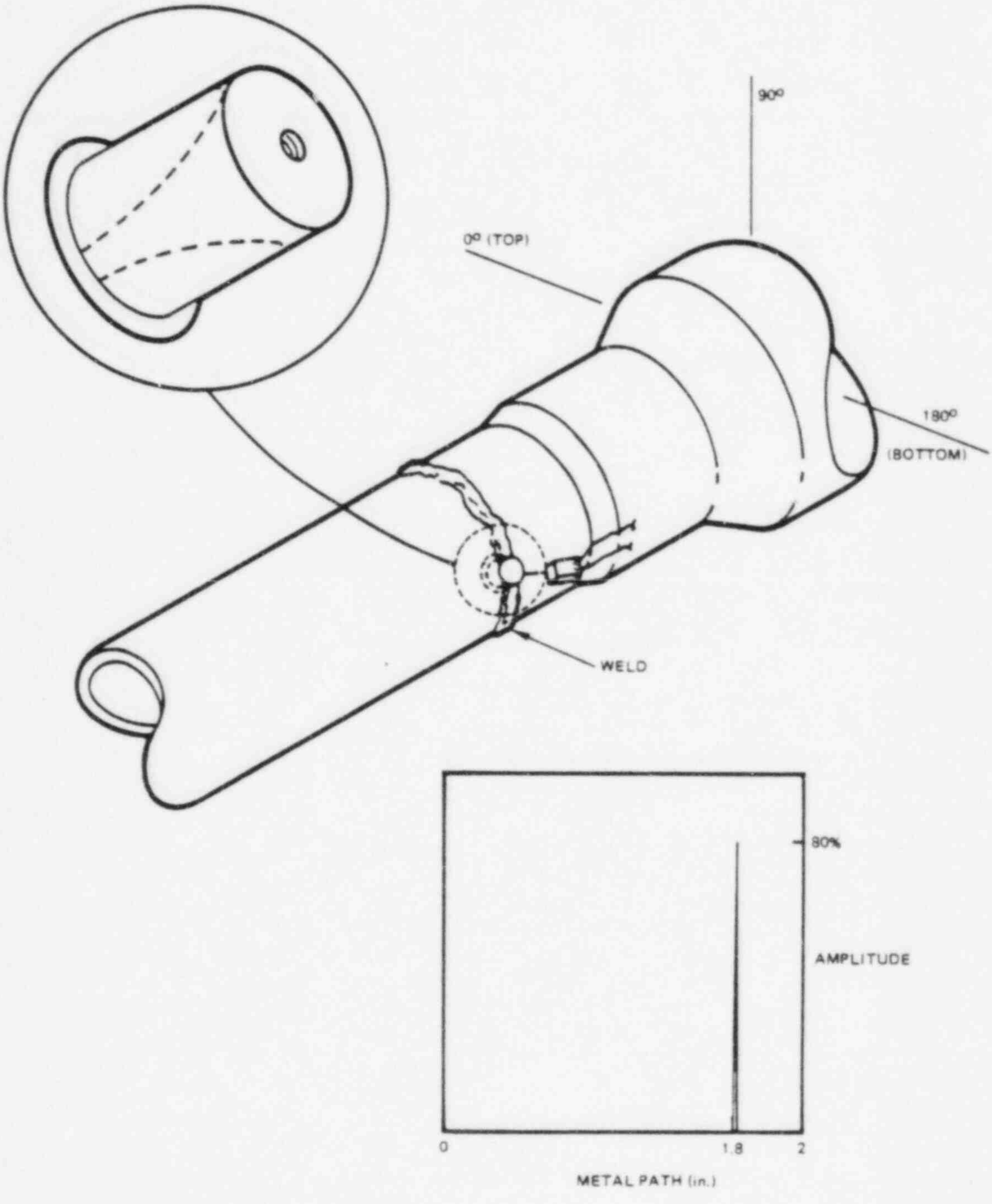


Figure 3-6. Schematic Showing Technique for Core Sample Location and Accompanying UT Signal for I.D. Crack

the core sample cutter 1/8 inch toward the safe end side of the O.D. weld centerline reference point as shown in Figure 3-5. The data plots and sample cross-section layout are shown in Figure 3-7. Note that up to 3/8 inch of material would be removed on the pipe side of the weld root centerline, and at least 5/8 inch of material would be removed on the safe end side depending on the actual location of the weld root. This location satisfied the objectives and would include more of the safe end material than the pipe. The actual core sample later verified that the location was selected properly.

It should be noted that the O.D. weld centerline was used as a reference point for UT data plotting and sample cutter location; however, it could not be assumed that this point represented the I.D. root weld centerline. The weld crown had been ground nearly flush and there was considerable O.D. mismatch between the pipe and safe end. With these conditions, as with any typical field weld, the I.D. root could actually be located on either side of this apparent O.D. weld centerline. Similarly, the UT cross-section data plots (Figure 3-7) show the crack tip in the weld metal, but a slight shift of weld centerline would place this tip right along the fusion line, typical of large diameter piping IGSCC.

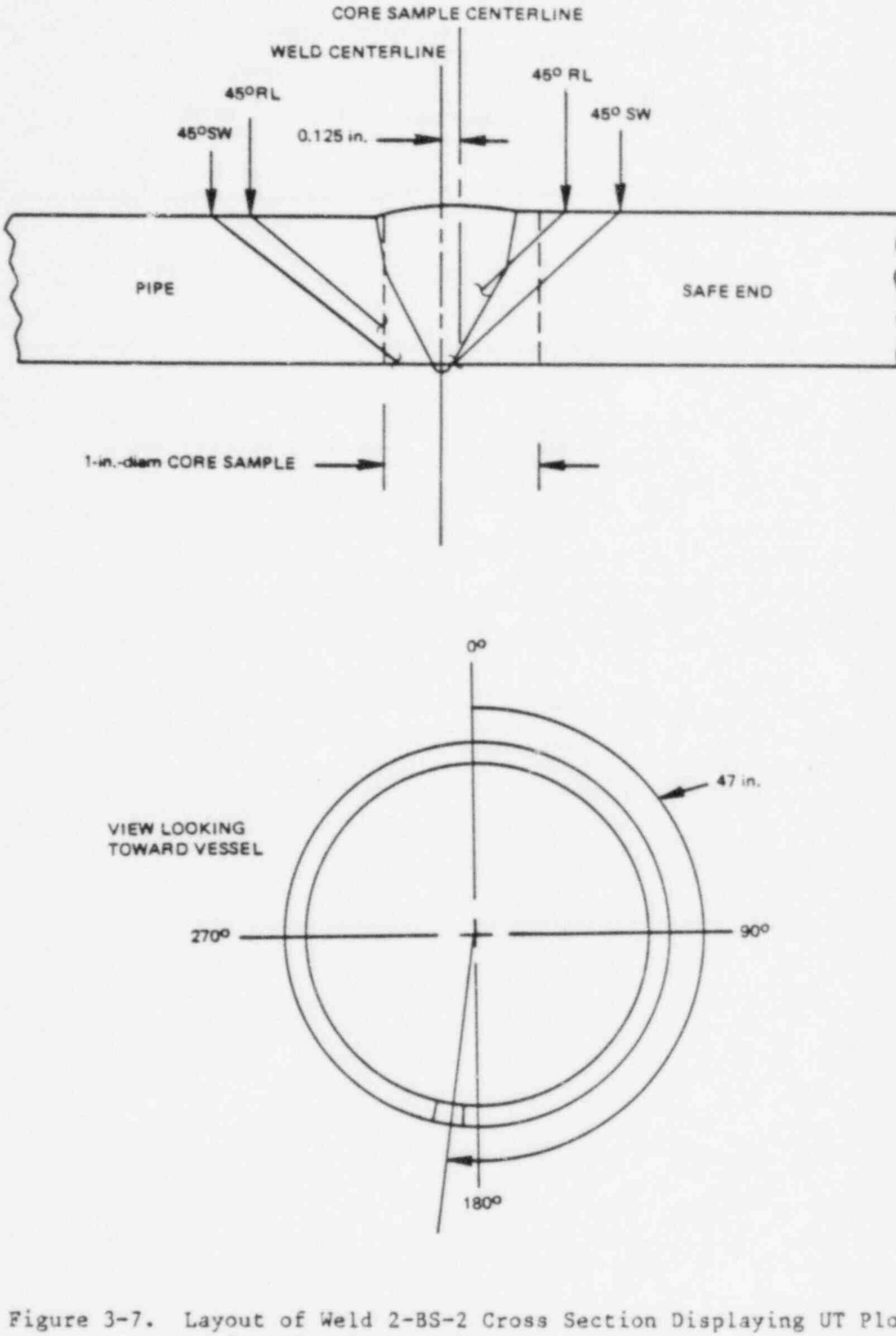


Figure 3-7. Layout of Weld 2-BS-2 Cross Section Displaying UT Plots at Core Sample Location

4. CORE REMOVAL PROCEDURES

4.1 CORE SAMPLE REMOVAL

In this section, the location and removal of a 1 inch diameter core sample from 28-inch pipe to safe end weld 2-BS-2 will be discussed.

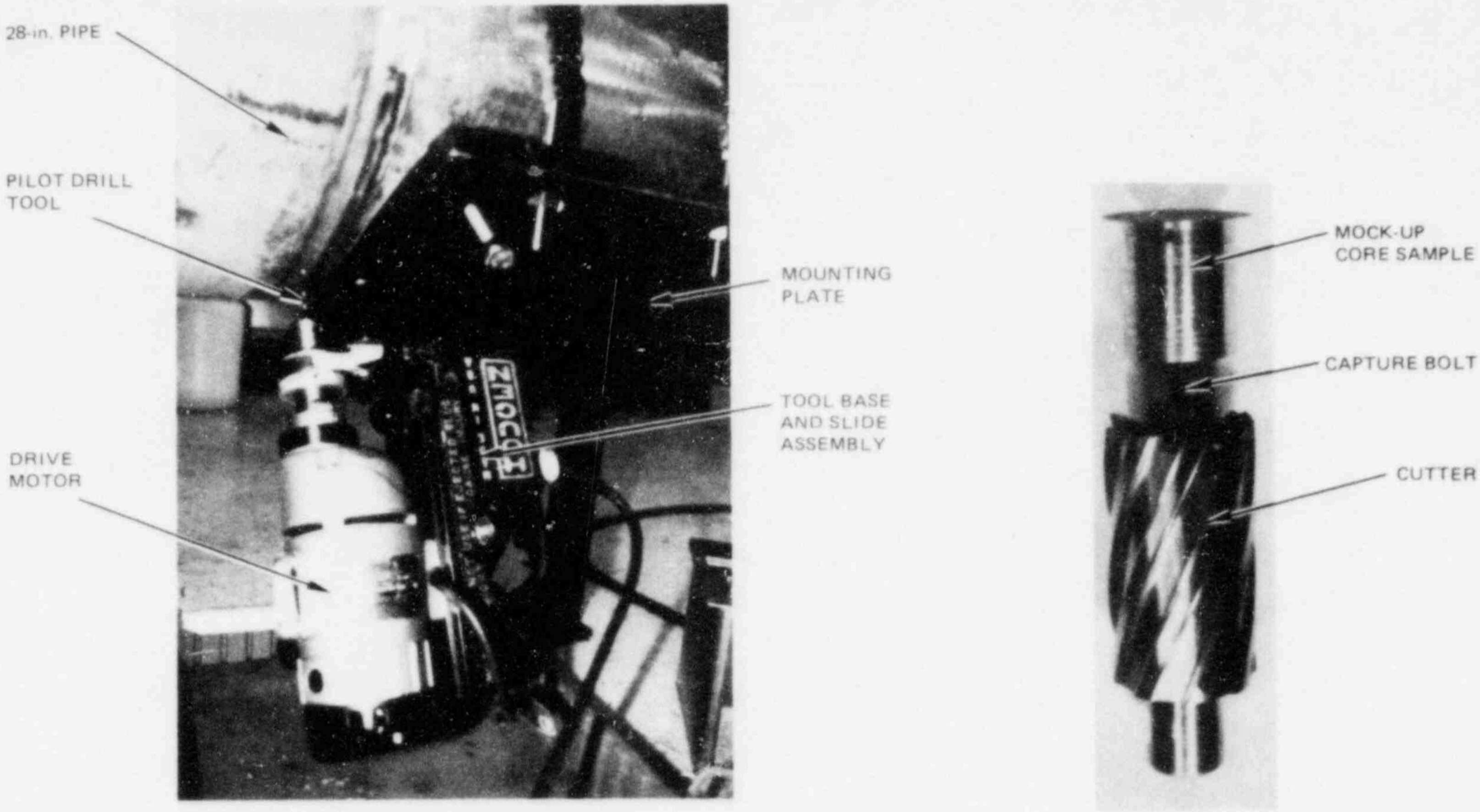
The purpose of the core sample was to metallographically confirm the crack indications in the low carbon 316 safe end material. By obtaining a through-wall sample, the exact location, extent and depth of cracking could be confirmed. In addition, the I.D. surface could be examined to determine the method of crack initiation.

Tooling Preparation

Once the need for a sample was identified, commercially available cutting tool vendors were reviewed and equipment was selected for mockup testing. The tooling selected was a special milling cutter and drive motor assembly, as shown in Figure 4-1. The tool was modified to shorten its working height to clear the 18" minimum distance between the pipe and the biological shield. The mill cutter and attachment arbor were also modified to install a capture bolt to the core sample. This assured that the sample would not inadvertently separate from the tool.

The tool was set-up and functionally tested in the GE San Jose facilities. All tests were performed using a spray coolant of de-ionized water. The tool performed very successfully, and high quality cuts could readily be made through a pipe butt weld. On-site, additional mockups were performed under full access restrictions to train craft labor crews and formally qualify the sample removal procedure.

Selection of the sample removal location was conducted by reviewing the original construction radiographs and the ultrasonic in-service-inspection results as discussed in Section 3. Following verification of the sample cutting location a small pilot hole was drilled to a depth of 3/8 inch and tapped



a) TOOLING INSTALLED ON MOCK-UP AND DRILLING PILOT HOLE

b) CORE SAMPLE CUTTER AND CAPTURE BOLT ARRANGEMENT

Figure 4-1. Core Sample Removal Tooling and Cutter Arrangement

to attach the sample capture device. The cutter was installed in the tool and the sample was removed using spray de-ionized water cooling. Sample removal went very well and required only about 15 minutes cutting time.

The sample was removed from the drywell and shipped to General Electric Vallecitos Nuclear Center for destructive examination. No decontamination was performed to preserve the specimen I.D. and crack surfaces for future residual element contamination studies.

4.2 CORE SAMPLE HOLE EXAMINATION AND REPAIR

While the hole was in the pipe, a visual examination of the inside surface of the joint was attempted by Philadelphia Electric. This examination was complicated by seepage of water through the hole due to the only practical method of draindown that could be applied for this work. Draindown was accomplished by lowering the water level in the shroud annulus using the 28-inch outlet piping B-Loop. A water level control and monitoring scheme was applied to the pipe, but remaining water in the vessel could not be drained lower than the 28-inch outlet nozzles, and therefore seepage from higher level nozzles would often cause water to run down the pipe.

Viewing was also limited by the complexity of locating and manipulating fiber optic devices in a 28-inch pipe through the 1 3/8 inch diameter core sample hole. The depth of field and magnification tradeoffs with this device, combined with the access and manipulation problems, made it impossible to perform a meaningful visual examination for cracking at other azimuth locations.

The only pertinent examination results were obtained by viewing directly through the hole to the opposite side of the pipe. With this method, a dark line was observed on the pipe side of the root pass that is believed to be the 43 inch long pipe side crack indication reported from the 85 to 38 inch UT azimuth (see Figure 3-2). No such indications were observed on the safe end side of the joint. Although this observation is by no means conclusive, it does support the overlay repair of the joint due to pipe side cracking, and

showed no anomalies on the safe end side that would contradict the subsequent core sample examination results.

The repair of the core sample hole was performed under the approved ASME Code Section XI repair program in place for the weld overlays. A circular plug was installed and seal welded in position. The vessel/pipe was then filled and a full structural overlay was applied over the joint and seal plug area. This repair was evaluated against ASME Code Section III rules for openings and reinforcement (NB-3330), and against Section III allowable stresses by a finite element analysis. Results showed that the design with the weld overlay satisfies the intent of the Section III requirements (without taking credit for the plug seal weld itself), and complies fully with ASME Code Section XI IWB-3640 requirements for evaluation of piping.

5. CORE SAMPLE EVALUATION

The core sample evaluation followed an evaluation of a boat sample cut from the O.D. of the safe end to determine the chemical and metallurigical condition of the safe end material. Following a brief discussion of these findings, the core sample evaluation will be presented.

5.1 METALLOGRAPHIC AND CHEMICAL RESULTS OF SAFE END O.D. BOAT SAMPLE

After the initial UT indications were found, a boat sample was removed from the O.D. surface of the 2-BS-2 outlet safe end. Prior to removal, Electro Chemical Potentiokinetic Reactivation (EPR) measurements using a dual scan unit established that the material was not sensitized. This sample was removed from above the uncracked region of the safe end near the top of the weld. The sample was 1/8" deep, 1-1/4" long, and 1/4" wide. The sample included both the 316L safe end material as well as the weld material. The sample was then transmitted to General Electric's Vallecitos Nuclear Center (VNC). A metallographic evaluation was made of the material for microstructure, sensitization and hardness. A chemical analysis was also performed on the material. The evaluation established that at the O.D. surface, the material was annealed, not sensitized, and had a typical grain size of ASTM 3.5. The hardness level was also typical at R_B71. The chemistry check established the heat to be 316L. Table 5-1 gives a comparison of the heat certification chemistry and the check chemistry from the boat sample.

5.2 PLAN FOR METALLURGICAL ANALYSIS

A cylindrical core sample, approximately 1-inch in diameter was removed from the safe end to pipe weld 2-BS-2 of the 28-inch recirculation outlet nozzle N1B to confirm the nature of UT indications. The sample was removed from a location near the center of the largest and deepest UT crack indication. (The depth was estimated to be 50% wall at this location.) The circumferential location of the core sample (Figure 3-2) also coincided with a location of heavy weld root grinding, as determined by the construction radiographs for the weld.

The core sample located as shown in Figure 3-5 encompassed the 316L safe end material, the weld, and the 304 SS pipe material, with 5/8 inch from the weld centerline on the 316L side and 3/8 inch from the weld centerline on 304 pipe side. The biasing of the sample location to the safe end side of the weld was for the purpose of focusing on IGSCC indications detected on the safe end side.

Attachment A is the plan for metallurgical analysis of the core sample. The plan, which included macroscopic examination, optical and scanning electron microscopy, hardness profiles and sensitization measurements was focused on (a) the determination of the nature of cracking and the identification of propagation mechanism in the 316L safe end material; (b) the verification of the degree of I.D. surface cold work and (c) the metallographic confirmation of the ultrasonic crack signals, including confirmation of crack depth relative to the weld fusion line.

5.3 VISUAL EXAMINATION OF CORE SAMPLE

Immediately following removal of the core sample from the safe end it was examined visually (Figure 5-1). Cracking or weld root fusion lines were not evident. Evidence of grinding, however, was present. A ferrite meter (for weld metal ferrite determination) was used to confirm that the core sample was taken at the desired location and the sample contained both safe end and pipe material. The sample was packaged and shipped to Vallecitos Nuclear Center for metallurgical examination.

At Vallecitos, in accordance with the established plan for analysis, the inner surface was visually examined and the macroscopic evidence of weld root grinding was photographed (Figure 5-2). The weld root region had been ground in a direction transverse to the fusion lines, obliterating the weld root. The ground surface appeared typical, with no evidence of aggressive, abusive grinding.

5.4 METALLOGRAPHIC EVALUATION

The sample was then decontaminated by ultrasonic cleaning and examined under a stereo microscope. At magnifications up to 33X evidence of cracking was not observed at any locations along the I.D. surface. The core sample was then sectioned as shown in Figure 5-3. Each cutting plane was oriented normal to the weld fusion line such that a polished and etched section would be a transverse cross section of the weld. Figure 5-4 is a polished and etched cross section of the sample. Close examination of this section, and the three other sections prepared from the core sample (Figure 5-5) clearly showed the following:

a. No IGSCC was found in the entire sample. There is no cracking in the 316L safe end material, or in the pipe material contained within the core sample.*

b. No weld heat affected zone sensitization was found on the safe end side of the weld, as expected with a 0.019 carbon content. The pipe side of the weld (0.054% carbon) did exhibit sensitization as expected. Figure 5-6 are views of the pipe side of weld (HAZ) and the safe end of the weld HAZ, respectively.

c. A replotting of the UT metal path assumptions on the actual cross sectional weld geometry showed the safe end UT I.D. indications were actually located in the weld metal/fusion line region and the crack tip indications were located well into the weld metal. This is based on the confirmed location of the root centerline on the I.D. relative to the centerline of the weld on the O.D. surface. Figure 5-7 displays a sketch of the UT metal paths sketched relative to the actual core sample cross-section.

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*At this azimuth location, the pipe side indications were up to 1/2 inch from the fusion line (outside the edge of the core sample), and were shallower and lower amplitude than at other azimuth positions. Therefore, pipe side findings at this azimuth are not necessarily representative of the remainder of the pipe side indications.

5.5 COLD WORK EFFECTS

Severe surface cold working, and increased surface hardness levels can be an important causative factor in the initiation and growth of stress corrosion cracking in 316L stainless steels. The macroscopic visual examination of the inner surface of the core sample showed that there had been some weld root grinding at the time of fabrication. The degree of surface working was judged to be normal. There was no sign of aggressive or abusive surface working, as would be evidenced by surface metal smearing and deep, short grind marks or depressions. The surface was found to be smoothly ground with shallow grind marks normal to the fusion line. The weld root was ground flush.

On the through-wall section (marked A in Figure 5-5) polished and etched to reveal the microstructure, the section view of the safe end inner surface showed a cold worked layer, with grain deformation to a depth of less than 0.004 inch. This shallow cold work layer is characteristic of light-to-moderate surface grinding (Figure 5-8). A microhardness traverse was prepared for the safe end at a location approximately 5/16 inch from the fusion line of the weld, to be outboard of the annealing effect of the weld. Figure 5-9 displays the location of indentations and gives a sketch of the hardness profile. Note that within 0.010 inch into the surface the hardness level drops from R_c 26 near the surface to less than R_c 92 for the bulk interior material.

The hardness profile found in typical grinding in Pipe Test Laboratory studies are shown in Figure 5-10 compared to the cold work in the Peach Bottom-3 outlet safe end. The figure shows the Peach Bottom-3 safe end is bounded by the Pipe Test Lab data.

5.6 UT REFLECTORS IN WELDMENT

Metallurgical analysis has shown the safe end weldment to be free of IGSCC. This finding is consistent with the metallurgically and compositionally correct 316L safe end material and 308 weld deposit. Since the weldment was found to be uncracked, later core sample evaluations focused on understanding the source of UT signals detected at the 316L/308 weld interface.

The ultrasonic (UT) signals detected on the 316/308 weld region apparently resulted from some effect other than IGSCC. The core sample sections prepared for microscopy were studied by optical microscopy, scanning electron microscopy (backscattered electron imagery) and electron microprobe (wave dispersive x-ray system) to identify possible UT reflectors.

While an obvious source of UT reflection was not identified, the following facts are apparent:

a. On the four transverse sections examined by optical microscopy, no evidence of IGSCC cracking was found, and the weld/base metal interface was metallographically normal, such that a microstructural difference would not be expected to cause a UT reflection.

b. Under optical examination at higher magnification (100 to 500X) some porosity, slag, and minor lack of fusion was found in the weld metal. The largest weld defect was a slag inclusion in the weld metal found approximately 1/8 inch from the safe end weld fusion line. The location coincided with the location where UT crack tip indication. As shown in Figure 5-11 the plane, on which this "large" defect was found, was ground to expose a new plane 0.050 inches below the original surface. The inclusion was still visible on this new surface, though much smaller in size. A rough estimate for length is 1/8 inch. In other regions in the weld small "normal" amounts of porosity were also found.

c. Following optical microscopy, the core sample pieces were radiographed (RT) to detect the possible presence of additional weld defects. Further evidence of small porosity and inclusions was found.

d. By optical microscopy, multiple non-metallic (presumably MnS) inclusions were found along the 308/316L fusion line approximately 1/8 inch from the I.D. surface. While not observed in this section,

such inclusions at sufficiently high densities could cause UT reflections similar to IGSCC. Radiography confirmed that the density of these small inclusions was low and therefore an unlikely UT reflector.

e. The weld geometry was somewhat unique in that the weld root region had vertical fusion lines for a distance of about 1/8 inch from the I.D. Although the UT signal reflection characteristics of this geometry have not been fully evaluated, false UT crack indications were found on the removed core sample as well as in a laboratory test weldment with vertical fusion lines.

f. The sectioned core sample was examined on the SEM and microprobe equipment in an effort to identify possible compositional or constituent gradients at the weld fusion line that could account for UT reflection. Results were negative.

The sample was examined on the scanning electron microscope using the back scattered electron imagery (an energy dispersive detection device). No abrupt compositional gradient other than Mo was observed at the fusion line, and no unexplainable elements, inclusions or accumulations associated with the fusion line were found.

A linearly decreasing gradient of diffused Mo was observed in the weld metal when moving from the 316L fusion line towards the pipe side fusion line. In addition, there was an enrichment of Mo in the ferritic phase of the weld. The enrichment gradient from the 316L fusion line to the 304 fusion line was linear, suggestive of mechanical mixing. Figure 5-12 is a photo of the 316L weld interface boundary and Figure 5-13 is a SEM photo of the Mo enriched ferritic phase within the austenitic matrix. Figure 5-14 is an energy scan made on the SEM with the energy dispersive X-ray detection equipment providing confirmation of Mo enrichment in the light second phase regions of Figure 5-13.

Electron microprobe (wave dispersive X-ray imagery) techniques have confirmed no compositional uniqueness associated with the fusion line, or weld deposit. The microprobe also confirmed the Mo is likely present in the weld structure in an elemental form rather than in the form of a complex carbide. This suggestion is supported by the lack of carbon enrichment in the ferritic phase, or inclusions.

The SEM studies have shown the absence of compositional or microstructural gradients or enrichment associated with the 316L fusion line that could have contributed significantly to UT reflection. The observed Mo gradient is gradual and the minor effect is probably unobservable by UT methods.

5.7 SUMMARY

No IGSCC was found in the core sample. The lack of 316L cracking is consistent with the absence of excessive cold work, and/or sensitization.

The available evidence indicates the UT indications resulted from the unique weld root geometry and the presence of small weld defects.

Table 5-1

MATERIAL CHEMISTRY VERIFICATION

	Mill Certification in Material Test Report (w/o)	Laboratory Verification* (w/o)
Carbon	0.019	0.016**
Chromium	17.05	17.20***
Nickel	13.49	13.72***
Molybdenum	2.19	2.19***
Silicon	0.80	0.28
Sulfur	0.020	0.019
Phosphorus	0.031	0.028
Manganese	1.67	1.79
Cobalt	---	0.11
Columbium	---	0.02
Copper	---	0.33
Titanium	---	0.005
Vanadium	---	0.04
Boron	---	0.005
Nitrogen	---	0.60-0.100

*By emission spectroscopic method
**0.024% by combustion method
***By X-ray fluoresence method

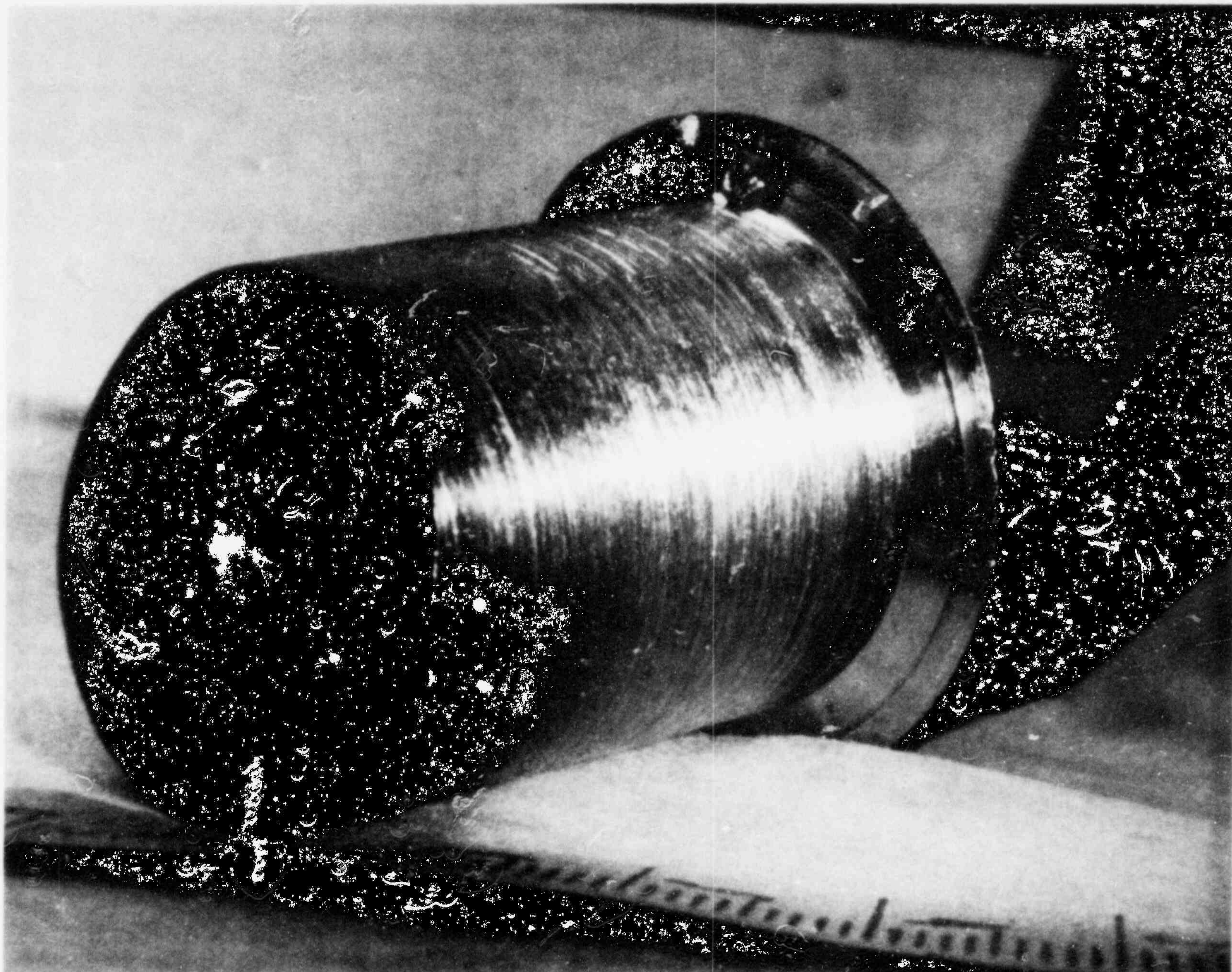


Figure 5-1. Photograph of Core Sample After Removal

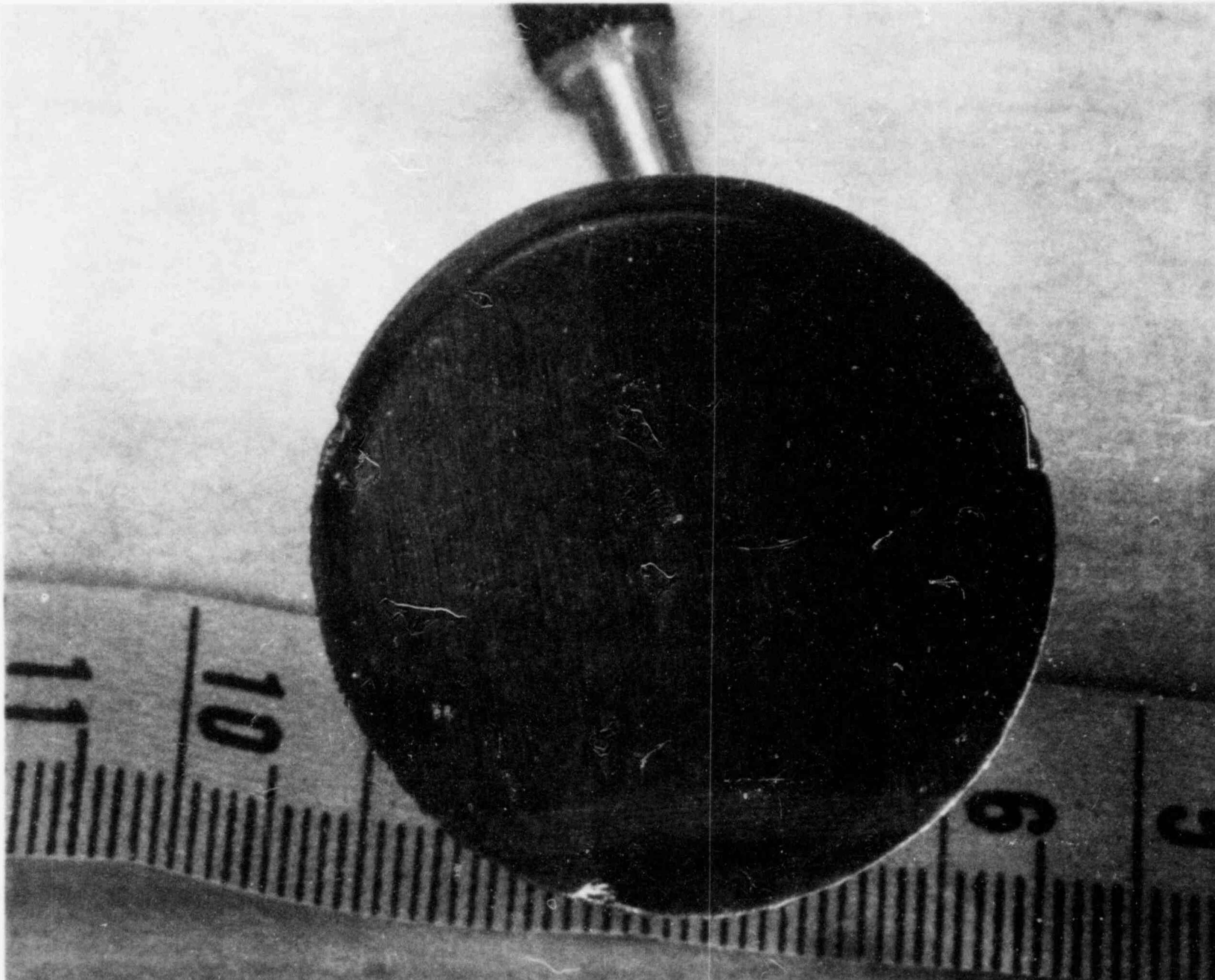


Figure 5-2. Photograph Showing Grinding on the Pipe Inner Surface

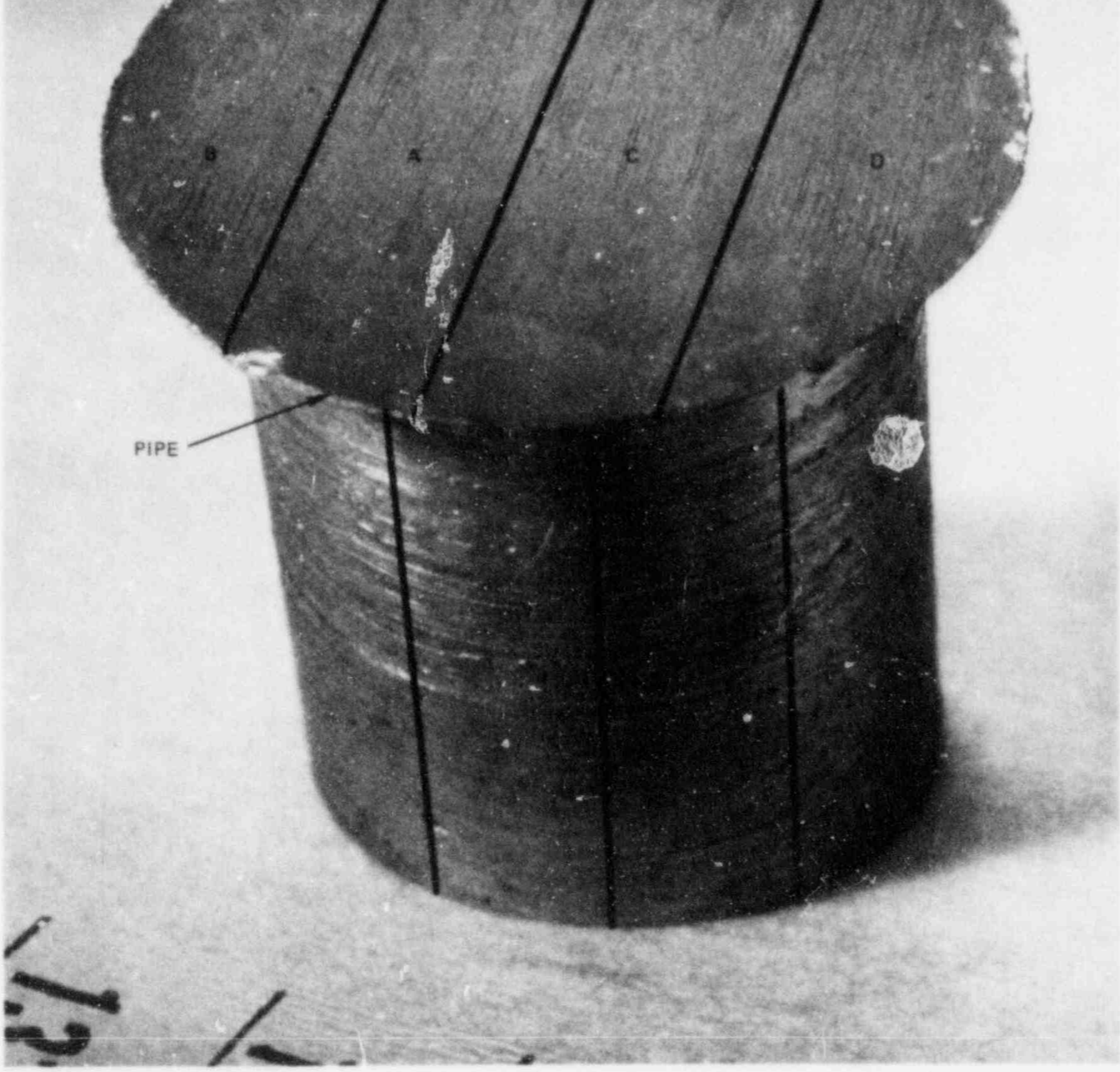


Figure 5-3. Core Sample Cutting Plan (all samples A, B C and D were mounted for optical microscopy with no cracking found in any section)

Figure 5-4. Cross Section Photomicrograph of 2-BS-2 Safe End to Pipe Weld Core Sample

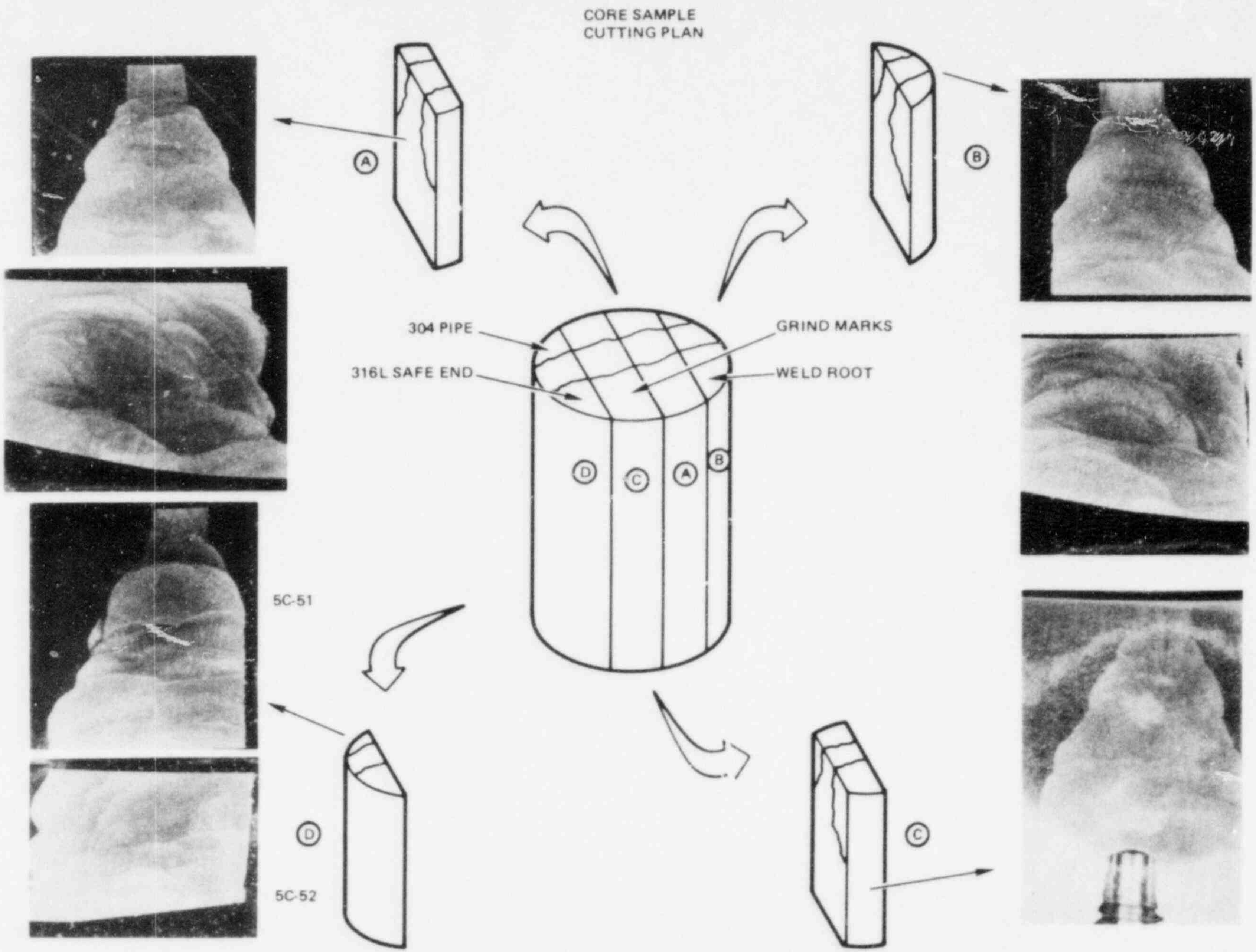
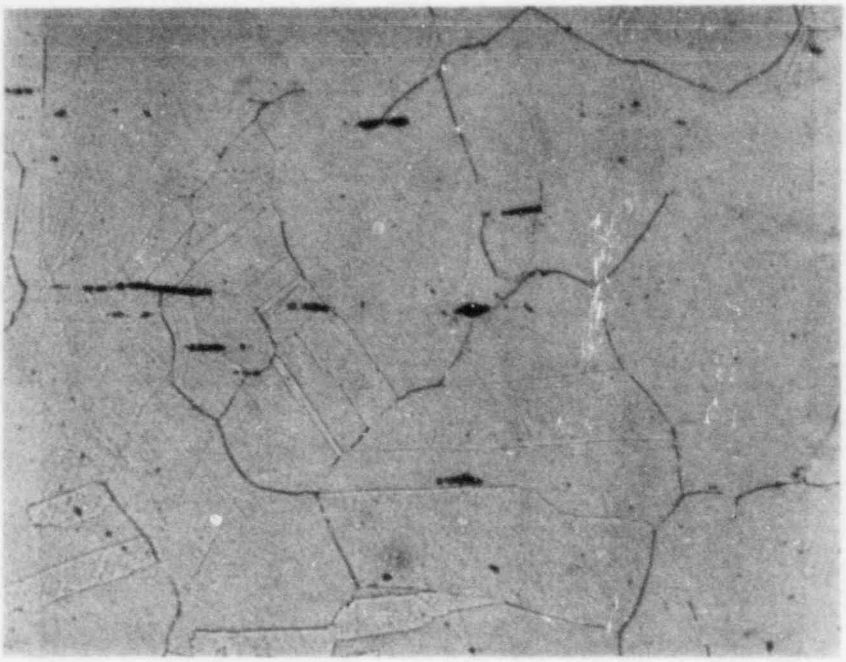
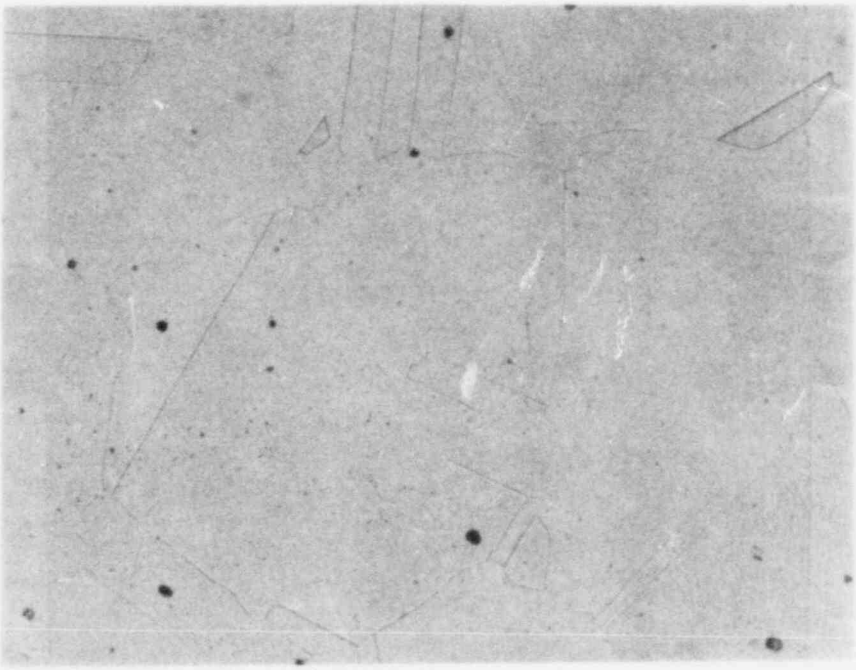


Figure 5-5. Composite Photograph Detailing Metallographic Sample Location and Results. No cracking found at any location.



(a) PIPE SIDE OF WELD (HAZ) 0.054 CARBON 304 S/S



(b) SAFE END SIDE OF WELD (NOTE NO SENSITIZATION)
0.019 CARBON 316L S/S

Figure 5-6. Photographs of Pipe and Safe End Microstructures Etched to Detect Sensitization

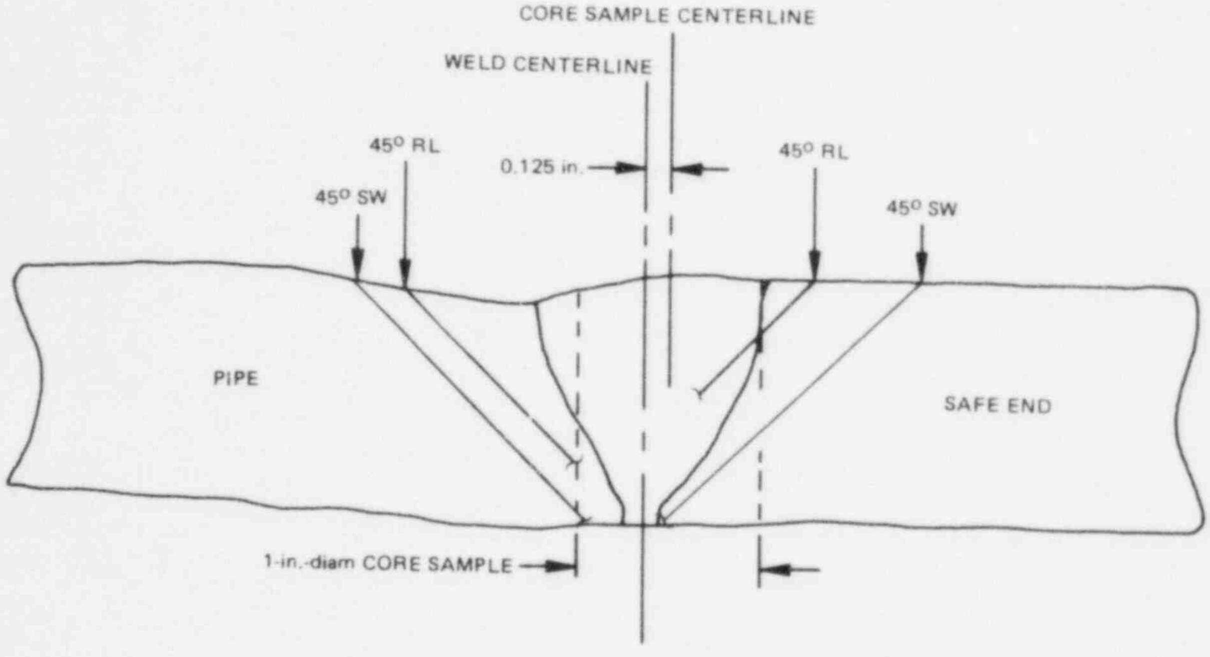


Figure 5-7. Actual Cross-Section of Weld 2-BS-2 Displaying UT Plots Used in Core Sample Selection. (Note: Plots show that indications lie in weld metal/fusion line region.)

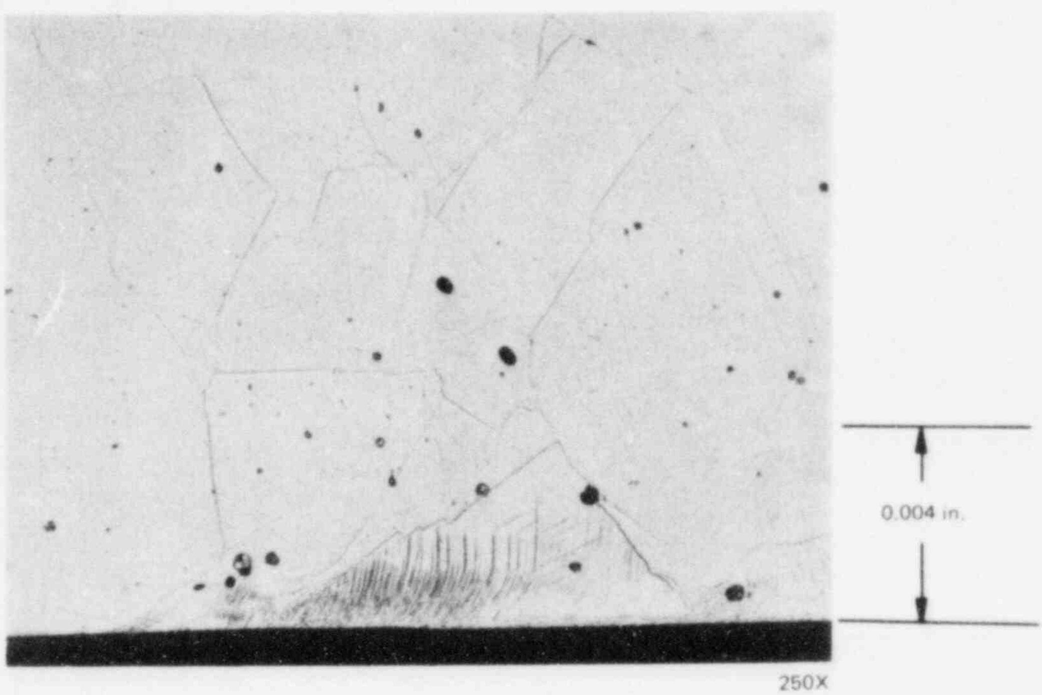
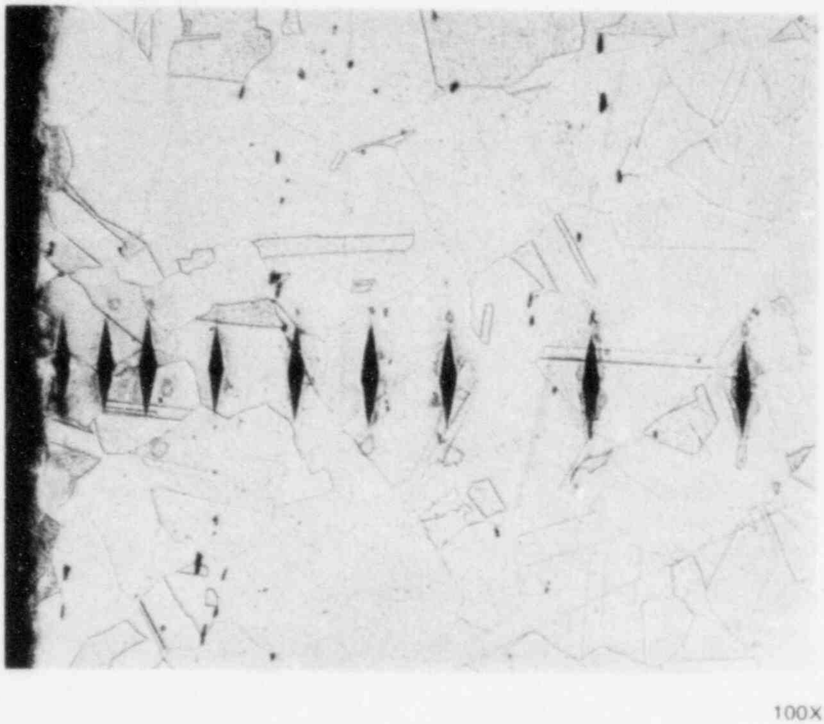


Figure 5-8. View of Cold Work on Inner Surface of Safe End. Note Depth of Grain Deformation is Less Than 0.004 inch.



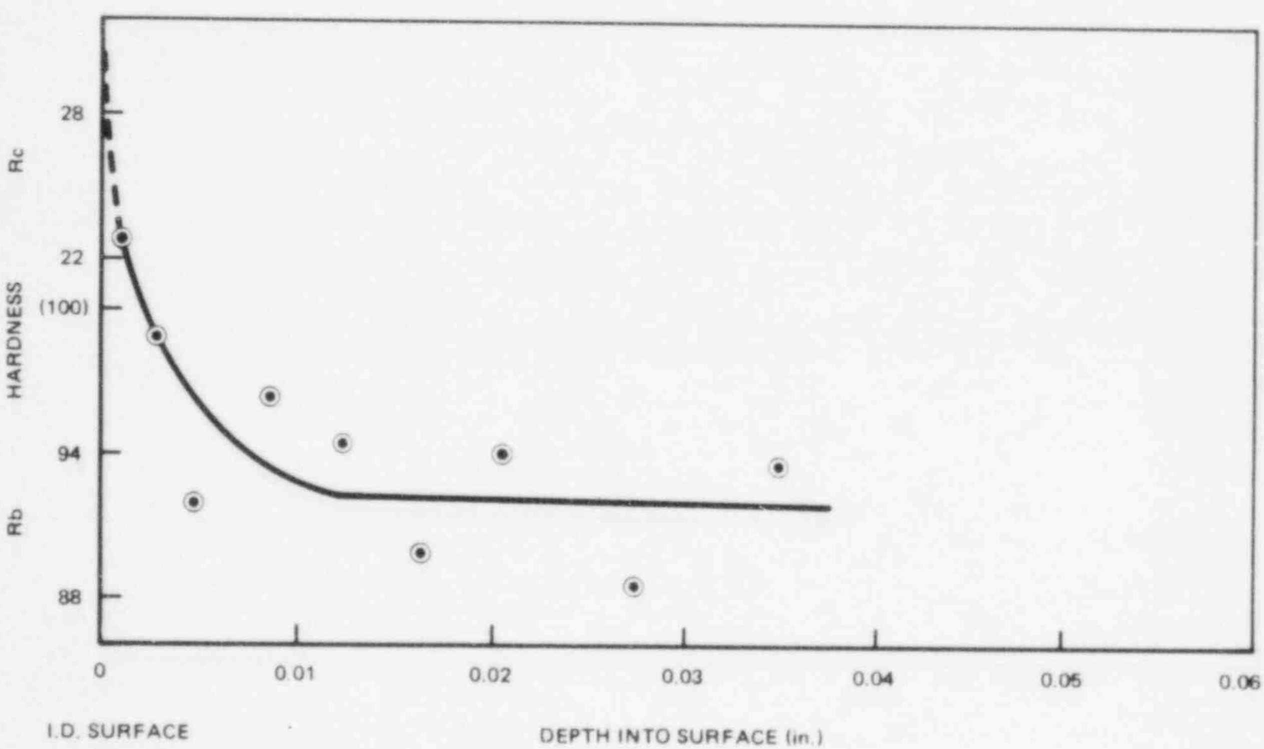


Figure 5-9. Photomicrograph and Plot of Hardness Traverse of Safe End Surface to Evaluate Cold Work

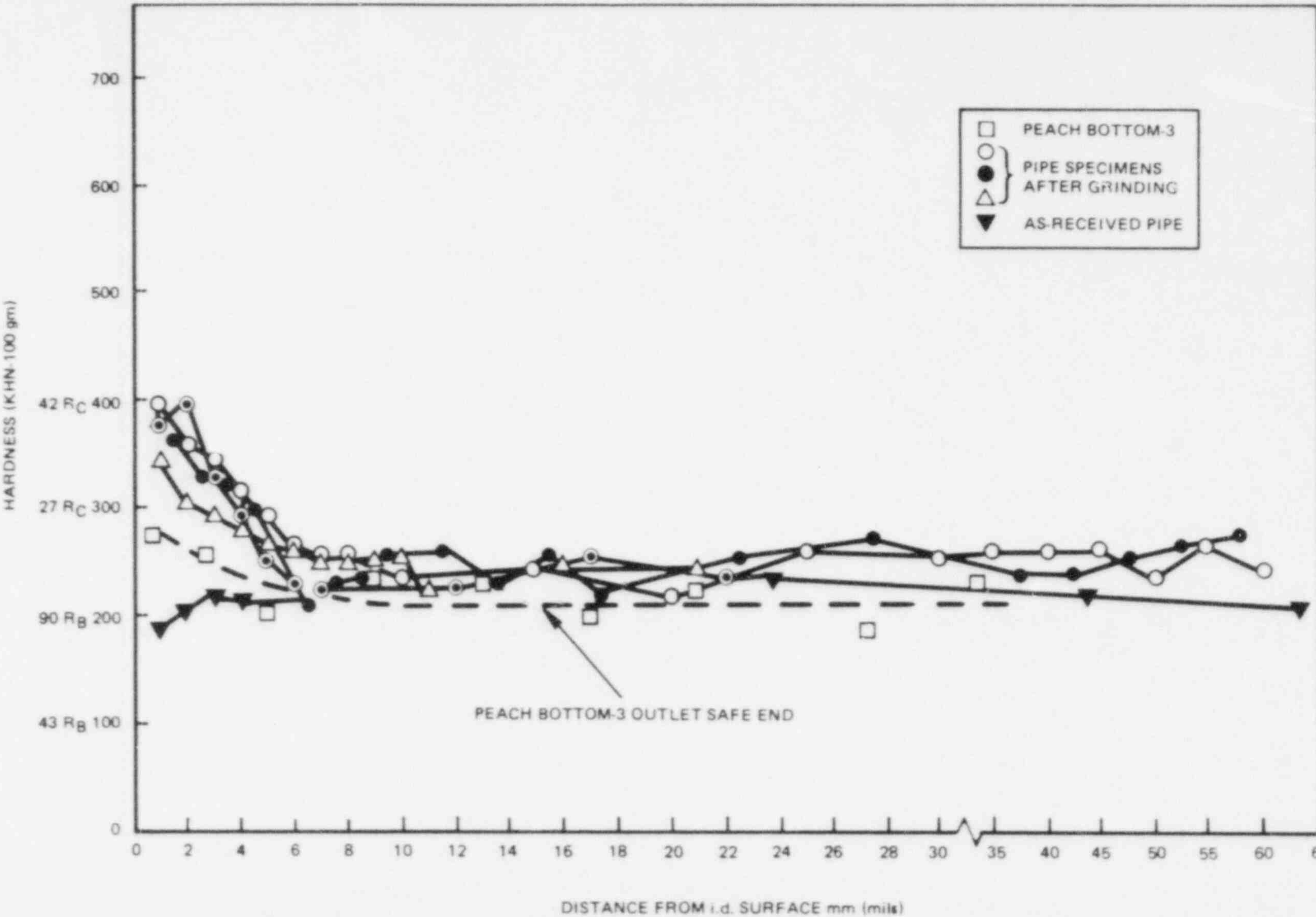


Figure 5-10. Comparison of Hardness Found in Peach Bottom-3 Safe End Core Sample with Hardness Data from General Electric Pipe Test Laboratory 4 inch Pipe Specimens that were Ground

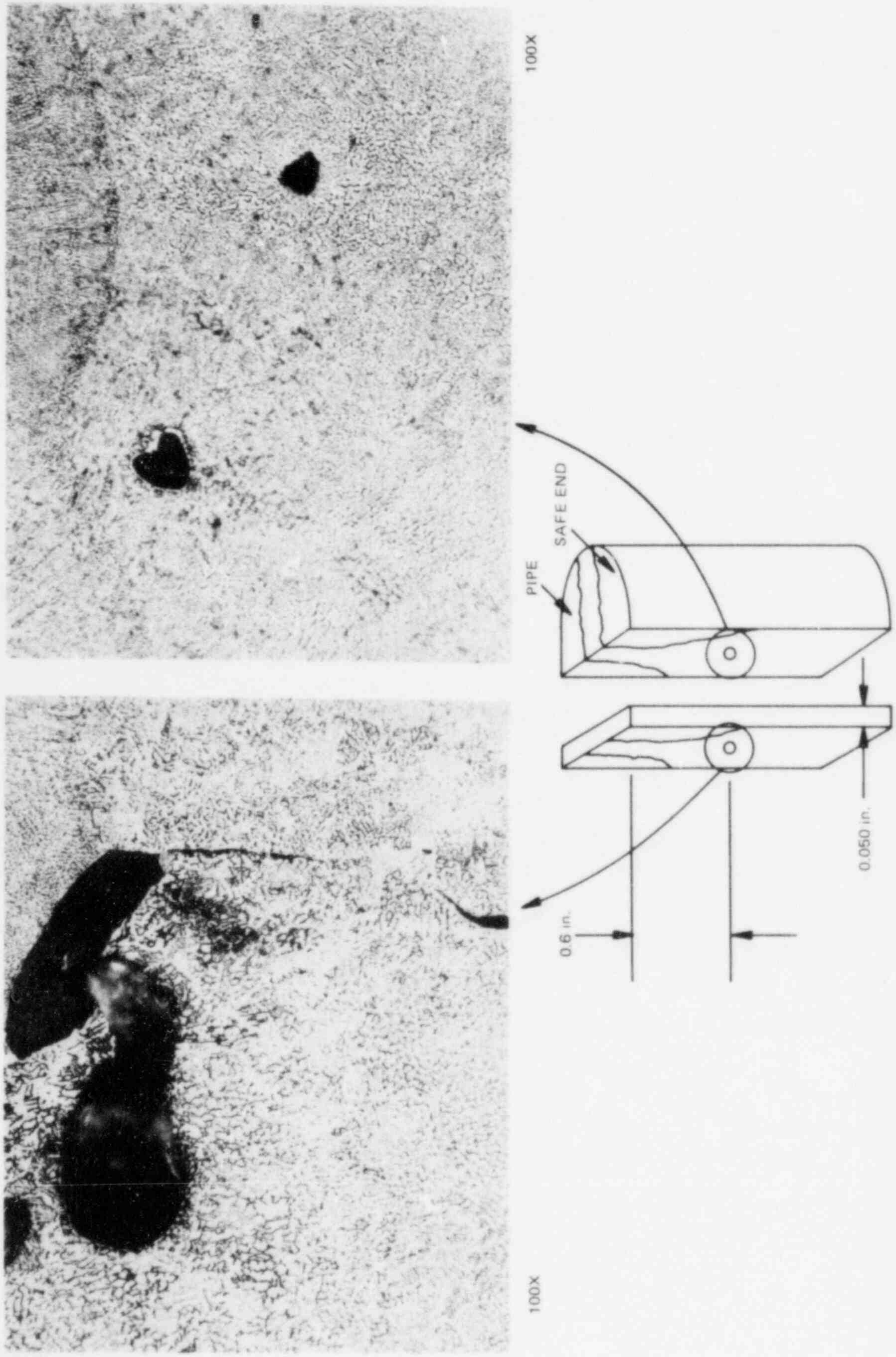


Figure 5-11. Views of Slag Inclusion on Planes Separated by 0.050 inch Length of Inclusion Estimated to be 1/8 inch.

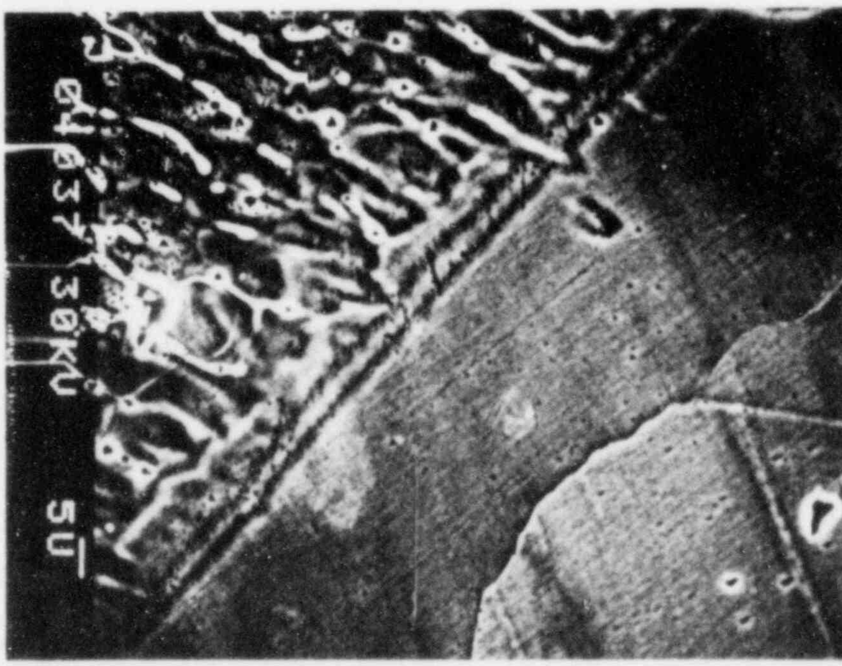


Figure 5-12. High Magnification SEM View of the 316L/308 Weld Interface (Note the Abrupt Microstructural Change and Lack of Transition Zone at the Interface)

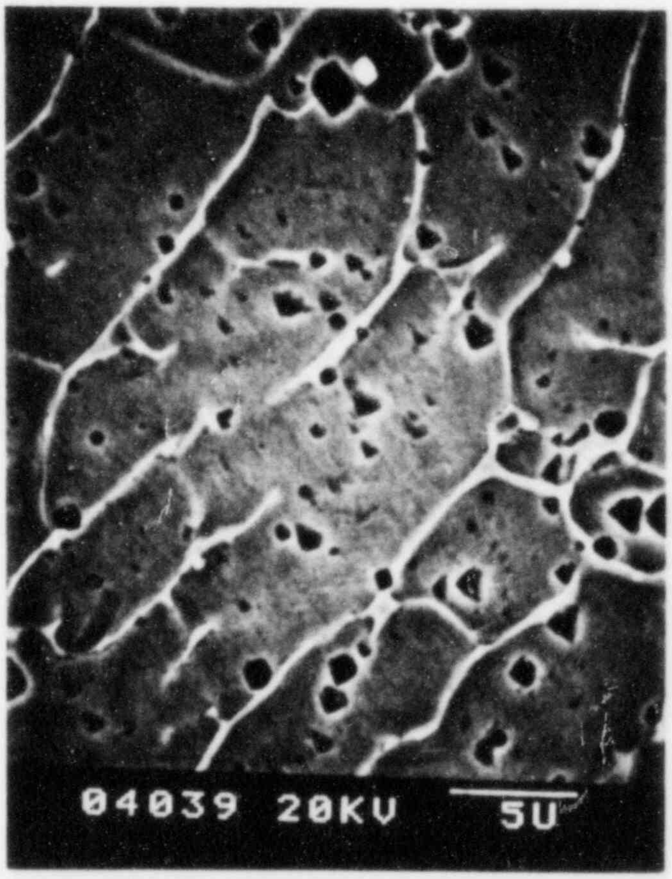


Figure 5-13. High Magnification View of the Weld Matrix Approximately 100 mils from the 316L Fusion Line. (The light phase in the dendrite boundaries has approximately a 4 to 1 enrichment of Mo over the austenitic phase.)

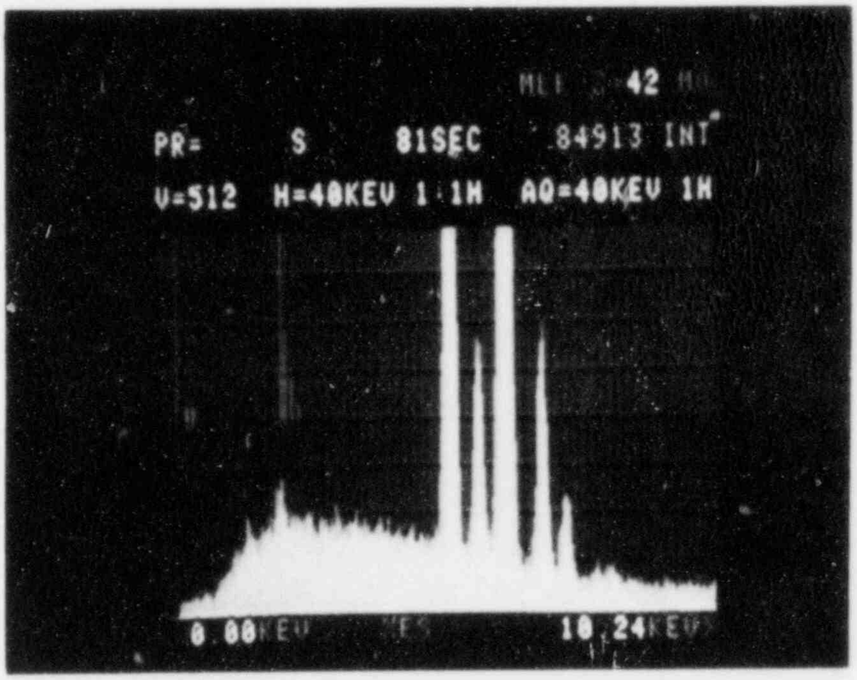


Figure 5-14. Dispersive X-ray Energy Scan Confirming the Mo Enrichment in the Light Second Phase

6. UT REASSESSMENT

6.1 NDE OF CORE SAMPLE

After the core sample was sectioned and examined metallographically further NDE was performed. Radiographs were taken of the slices which were 1/2 inch to 1/4 inch in thickness. The radiographs were taken using a 1975 KVP X-ray machine and fine grain film (Kodak type R) to maximize the sensitivity. Small discontinuities such as lack of fusion and minor inclusions were detected, but no cracks.

Additional UT was also performed on the metallographic slices. First a straight beam (0° longitudinal) was directed from the safe end side of the sample, such that the sound beam was perpendicular to the weld root. A direct reflection was obtained from the fusion line. Secondly a 45° shear wave was aimed from the face of the sample towards the weld root such that it intercepted the fusion line at the opposite face of the sample thus forming a corner trap. Again a direct reflection was obtained from the fusion line area. In both of these experiments calibration of the UT instrument was performed utilizing a 1/16 inch diameter side drilled hole at a depth of 1/2 inch in a stainless steel block. The reflection from this hole was set at 100% of full screen height. The resultant reflections from the fusion line were 50% of full screen height at a metal path of 0.4 inch in the case of the shear wave and 60% of full screen height at a metal path of 0.5 inch in the case of the straight beam. This arrangement is shown in Figure 6-1. These experiments clearly show that the source(s) of the reflections are still contained in the metallographic sample and are somehow related to the fusion line at the weld root. The only aspect noted to be unusual in this case is the long (1/8 inch), vertical side walls of the root.* The indication that was detected with refracted longitudinal waves in the field and thought to be due to diffraction at a crack tip is now believed to be related to small slag stringers with associated lack of fusion located near mid wall in the weldment. Records

*A possible explanation for this geometric condition is shown in Appendix B.

indicate and metallography shows that this is the height in the weld where a different size electrode was used and as a result slag stringers might be expected.

6.2 OTHER OCCURRENCES

This is not the only occurrence where indications similar to those expected of IGSCC have been detected from a weld root with vertical fusion lines.

Recently at a foreign BWR site UT indications were evaluated as IGSCC in 10-inch diameter, 304 SS recirculation riser welds. The evaluation was made by qualified examiners from the ISI contractor and confirmed by qualified examiners from another contractor.[4] Upon removal no cracks were found; however, the welds did have a vertical root/fusion line condition similar to that seen on the Peach Bottom core sample. Cross sections of these welds are shown in Figures 6-2, 6-3 and 6-4. Another occurrence was observed when UT was performed on a special GE weld which had vertical side walls. Again, indications were obtained which were similar to those detected at Peach Bottom.

6.3 SUMMARY

In summary, it has been shown that certain weld root or fusion line orientations or specific metallurgical conditions can result in UT signals similar to those obtained from IGSCC. Additionally, weld defects, such as lack of fusion and/or slag stringers can give indications similar to those obtained from crack tips when using refracted longitudinal waves. To overcome this situation precise cross sectional plotting of indications would be required to show that they are located in the weld metal. The root configuration and orientation would also be needed. As stated, with the weld geometry information obtained from the core sample, UT indications on the safe end side of the weld are clearly at the fusion line or in the weld itself. However, indications on the 304SS pipe side that are located away from the fusion line are obviously in the heat affected zone, and as such are indicative of

significant IGSCC, thus necessitating the weld overlay repair. From a generic standpoint it is clear that the cause or source of the indications must be determined and an effective evaluation technique developed.

6.4 RECOMMENDATIONS

A special UT procedure is needed to discriminate IGSCC from Peach Bottom-3 weld type indications. This would require mockups with vertical root welds and with IGSCC located near the root. Samples from the field might also be helpful when and if they are available. Such a study could be funded by the BWR Owners Group through EPRI. Certainly the objective of such a program would have to be to understand the source of the reflections and the qualification of discriminating techniques or methods.

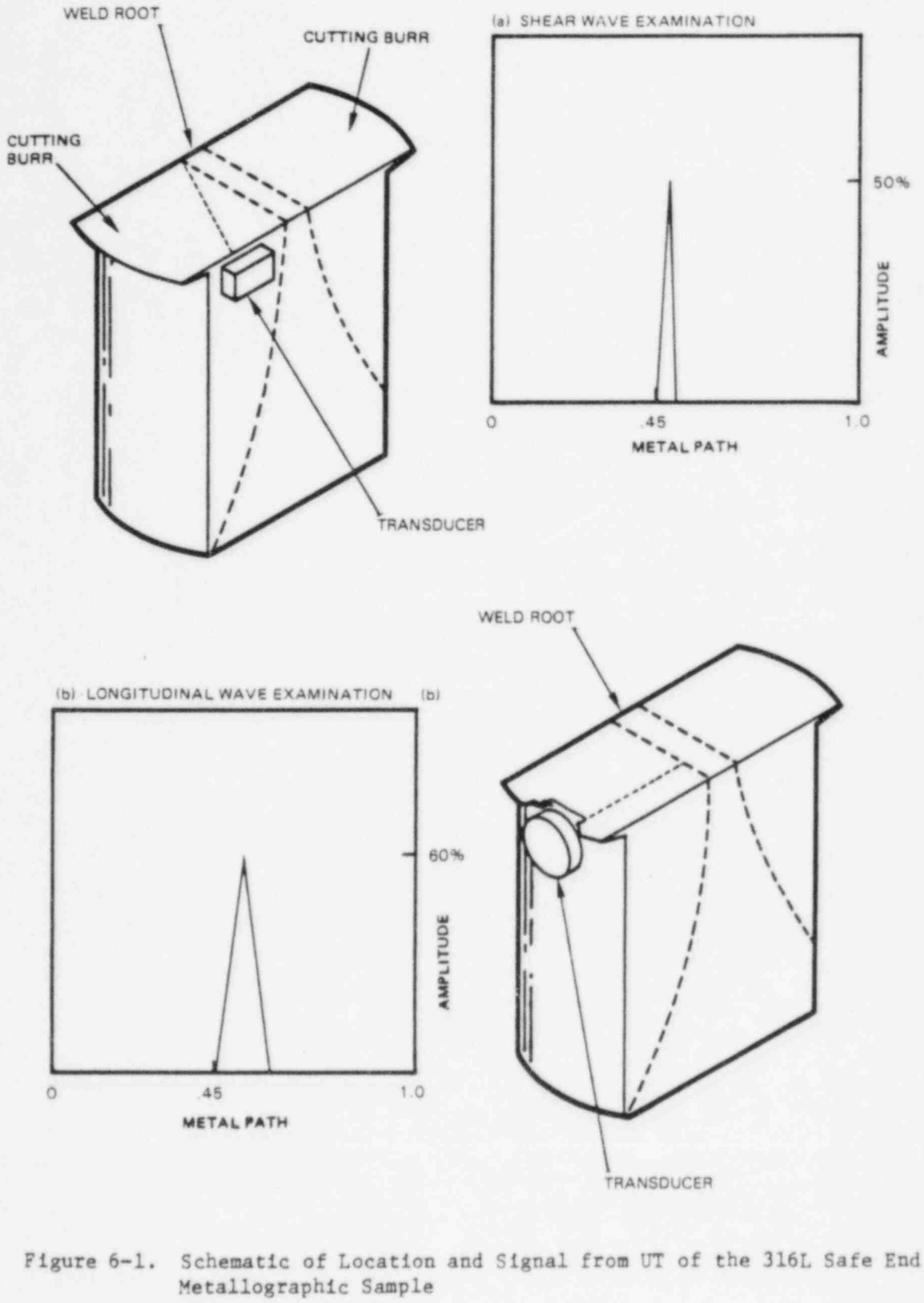


Figure 6-1. Schematic of Location and Signal from UT of the 316L Safe End Metallographic Sample

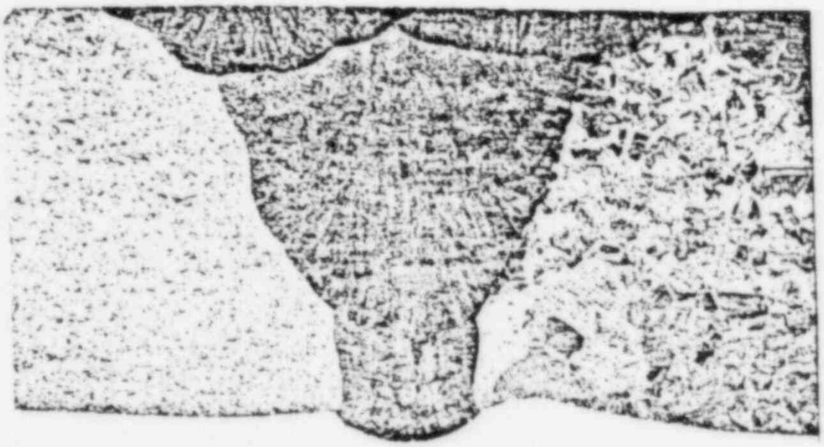


Figure 6-2. Cross Section of Weld A Associated with UT Indications

Figure 6-3. Cross Section of Weld B Associated with UT Indications

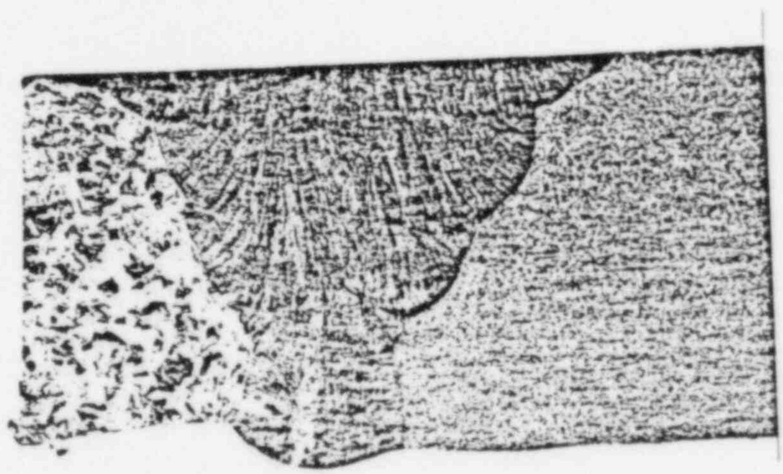


Figure 6-4. Cross Section of Weld C Associated with UT Indications

7. LOW CARBON STAINLESS STEEL PERFORMANCE

Following the confirmation of no cracking in the low carbon type 316 stainless steel outlet safe end material, the overall experience of low carbon steels was reviewed. In summary, there is a large body of field data and laboratory data that shows that nuclear grades of low carbon material are highly resistant to IGSCC in high temperature oxygenated environments. Each set of data will be briefly reviewed.

7.1 FIELD PERFORMANCE

Presently, there are approximately 1000 L-grade stainless steel pipe welds in GE BWR operating plants. One third of these L-grade welds are in small diameter piping (diameters less than 6 inches) where IGSCC generally leads to leakage in short times. None of these welds have leaked to date. In contrast, the behavior of the high carbon material in these size lines has been quite different with a significant fraction of the welds exhibiting cracks or leakage. The balance of the successful L-grade weld experience is in the larger pipe (diameter of 10 inches or greater) with over 200 of the larger welds having greater than 8 years of successful operation. The current overall experience at Peach Bottom 2 and 3 where these welds were inspected, verifies the superior cracking resistance.

7.2 SUMMARY OF LABORATORY QUALIFICATION

A laboratory qualification effort to develop alternate recirculation piping alloys was extensive as discussed in NUREG-1061[1] and Section 2.0. The majority of testing was carried out by General Electric in a program sponsored by EPRI as part of the BWR Owners Group program.[2] This program focused on low carbon austenitic stainless steels for a variety of reasons including ease of fabrication, ASME Code acceptability, ease of inspection, and familiarity. The program established that all the low carbon stainless steels of the 304 and 316 type were highly resistant to IGSCC in actual full size pipe tests conducted in oxygenated environments. A large factor of improvement over conventional high carbon type 304 stainless steel was

determined for all the alloys (greater than 55 for the 316NG material). In addition, in transient water chemistry the low carbon 316NG steel performed better than type 304. Microstructural evaluations established the difficulty in sensitizing low carbon materials. Studies also established the higher resistance of low carbon 316 materials to cold worked induced cracking.[5] However, studies in bolt loaded fracture mechanics tests did establish that all non-sensitized austenitic stainless steels including both low carbon and stabilized grades could crack in highly stressed creviced locations.[2]

7.3 SUMMARY

All of these results are consistent with the findings at the Peach Bottom 2 and 3 plants. While cracking has been found in the creviced region where the thermal sleeve was attached to the safe end, all of the non-creviced HAZs in the low carbon material have been evaluated to be free of any IGSCC.

8. REFERENCES

1. "Investigation and Evaluation of Stress Corrosion Cracking in Piping of Boiling Water Reactor Plants", U.S. Nuclear Regulatory Commission Report, NUREG-1061, August 1984.

2. "Alternative Alloys for BWR Pipe Applications", Final Report, EPRI NP-2671-LD, October 1982.

3. "Evaluation of Crevice Cracking in Peach Bottom Atomic Power Station Unit 3 Recirculation Inlet Safe Ends", General Electric Company NEDC-31086-P, September 1985.

4. Private Communication

5. J. Kuniya et al, Private Communication, 1984.

Appendix A
PLAN FOR METALLURGICAL ANALYSIS OF PEACH BOTTOM-3 CORE SAMPLE

INTRODUCTION

A cylindrical core sample, approximately 1 inch in diameter will be removed from the safe end side of the safe end-to-pipe weld 2-BS-2 of the 28 inch recirculation outlet nozzle N1B. The sample will be removed as shown in Figure 1.

1. MACROSCOPIC

   A. Visual exam of core sample inner surface. Examine, and photograph macroscopic evidence of weld root grinding.

   B. Map the fracture plane in the core sample. Identify and document the crack on both the inner surface and the cylindrical side of the core. (Note: Do not penetrant examine [PT] or use any material other than deionized water on the sample, so as to avoid masking of possible contaminants on the fracture surface.)

   C. Prepare the cutting map and prepare sections for the tests identified below. (See Figure 2.)

2. OPTICAL MICROSCOPIC

   A. On a through wall section, polished, and etched with an appropriate reagent, characterize the fracture relative to the following:

      - microstructure

      - cold work

      - sensitization (if present)

- crack morphology, which emphasis on -
  - mode, and relation to microstructure
  - branching
  - crack tip
  - oxide thickness and distribution
  - character of MnS inclusions

- microhardness profile - and changes with depth below inner pipe surface

- examine weld fusion line region for evidence of carbon diffusion or dilution of the 316L by the 308 weld deposit (See also Test 4-E)

- microhardness variations with distances from the weld fusion line

B. Prepare a second section, again on a plane normal to the crack plane. The purpose of this section is to provide a more detailed examination of the crack tip, and to provide a second plane of examination to support the results of the through wall section.

3. SCANNING ELECTRON MICROSCOPY

A. Prepare the portion of the core sample selected for surface fractography. Cool the sample in liquid nitrogen, and quickly before the sample warms to room temperature, forcibly pry open the sample to expose the fracture faces. Back cutting may be necessary to accomplish this.

B. Evaluate the macroscopic features of the fracture, with special emphasis in the regions of crack initiation, stable crack growth, and the crack tip.

C. Evaluate the microscopic features of the fracture. By noting the surface fractography, verify the fracture mode.

D. Perform an analysis of the oxide compositional gradients, from the crack mouth to the crack tip.

E. Perform a microprobe analysis of the inclusions (by the boat sample analysis, the inclusions were found to be MnS).

F. Perform a surface fractography of the pipe inner surface. The intent of this test is to identify a possible correlation between crack pattern and the surface cold work.

4. OTHER TESTS

A. Take surface hardness measurements on the pipe inner surface in the vicinity of the crack. This measurement will identify the possible presence of surface working.

B. Establish the cold work depth by making microhardness measurements on the section polished for optical microscopy. Beginning approximately 5 mils from the pipe inner surface, take hardness measurements at 10 mil increments, moving in the pipe through wall direction. At a depth of 70 mils, change the measurement spacing to 50 mils, and continue to the pipe O.D. surface.

C. Perform a sensitization measurement by the dual scan EPR method near the I.D. surface on the section polished for optical microscopy (and micro hardness measurements).

D. Establish the strain hardening profile by making microhardness traverses on a polished and etched through wall section. Beginning at the weld fusion line, make measurements at 10 mil increments (to 70 mils then at 50 mil increments out to a

distance of 0.500 inches from the weld fusion line). Make these measurements at the 25%, 50%, and 75% wall positions of the safe end.

E. Test for the possible presence of Martensite, or other magnetic phases (ferrite, or sigma) on the section prepared for optical microscopy.

F. With one of the remaining non-cracked portions of the core sample, decontaminate and perform a wet chemical analysis, with particular emphasis on Carbon, Boron, and Nitrogen.

NOTE: WHILE THIS IS THE EXPECTED PLAN FOR THE METALLURGICAL ANALYSIS OF THE PEACH BOTTOM-3 SAFE END SAMPLE, CHANGES TO THE PLAN MAY BE NECESSARY. AS WITH ANY FAILURE ANALYSIS, RESULTS OBTAINED EARLY IN THE ANALYSIS MAY SUGGEST ALTERNATE TESTS TO BE PERFORMED TO CLARIFY SOME UNFORESEEN OR UNEXPECTED FINDING.

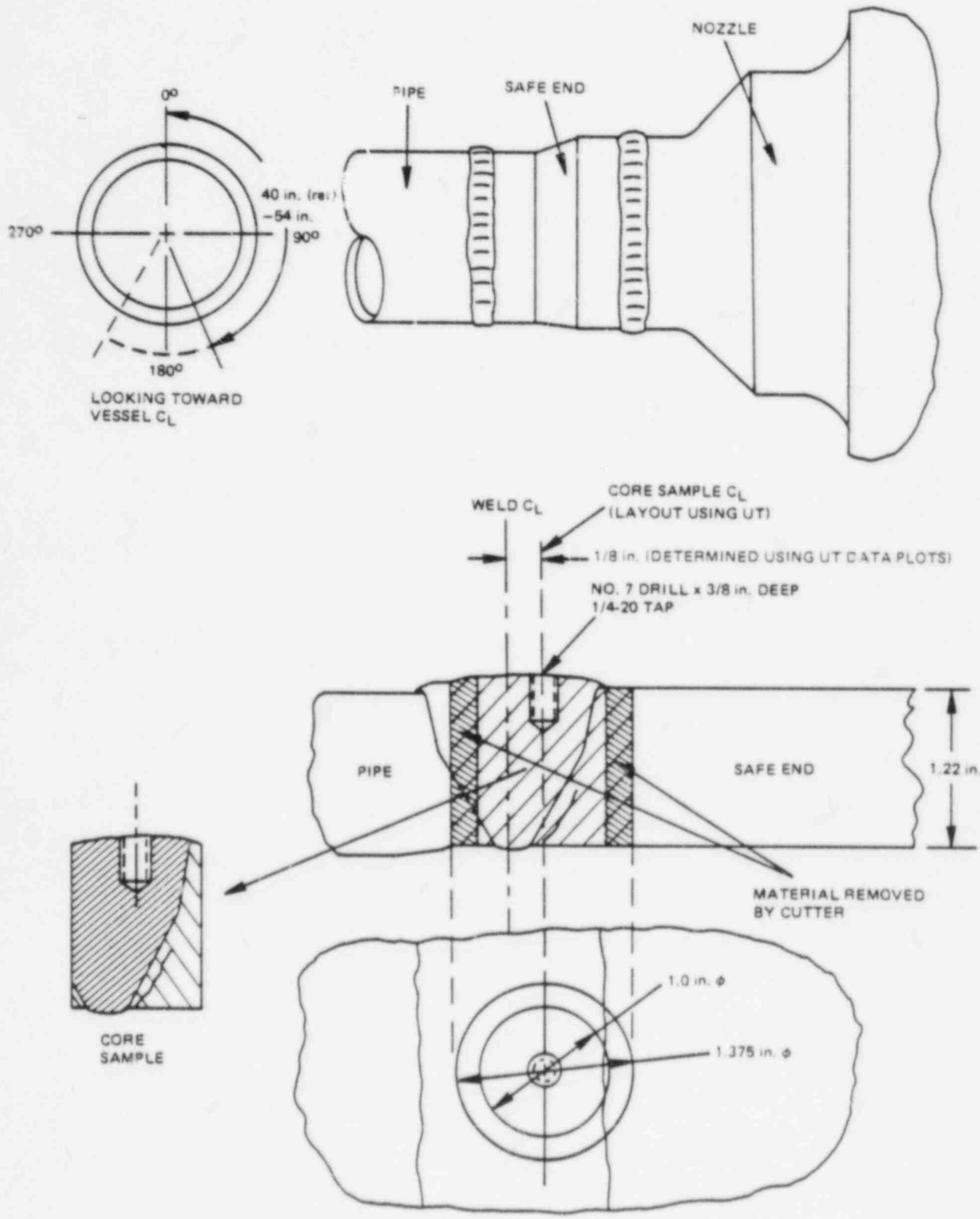

NOZZLE
PIPE
SAFE END
0°
40 in. (ref)
−54 in.
270°
90°
180°
LOOKING TOWARD
VESSEL C_L
WELD C_L
CORE SAMPLE C_L
(LAYOUT USING UT)
1/8 in. (DETERMINED USING UT DATA PLOTS)
NO. 7 DRILL x 3/8 in. DEEP
1/4-20 TAP
PIPE
SAFE END
1.22 in.
MATERIAL REMOVED
BY CUTTER
CORE
SAMPLE
1.0 in. φ
1.375 in. φ

Figure 1

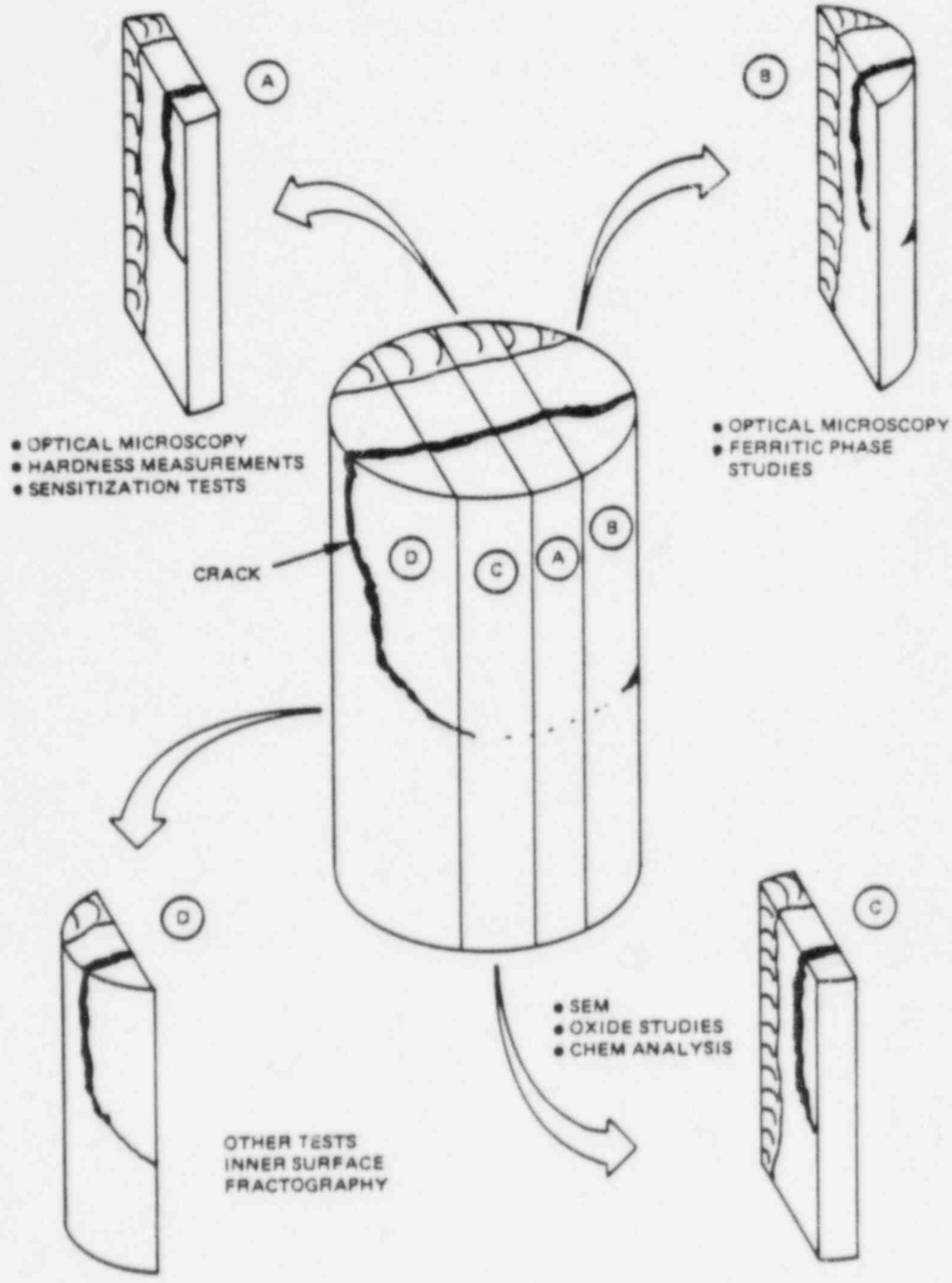


Figure 2. Suggested Cutting Plan for Core Sample

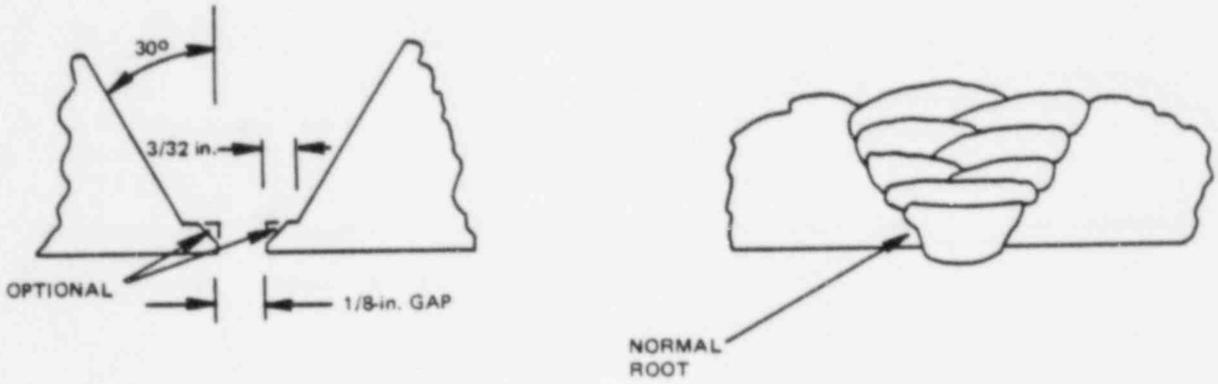
Appendix B
EFFECTS OF FIELD WELD PREPARATION ON JOINT CROSS-SECTION

The piping at Peach Bottom-3 was installed using the manual Gas-Tungsten-Arc and the Shielded-Metal-Arc welding processes. The root pass was installed using the extended land weld preparation and an "open-butt" welding technique. This technique uses a 1/8 inch minimum root gap as shown in Figure B-1(a). With the extended weld preparation and the 1/8 inch gap, a normal weld root cross-section as shown in Figure B-1(b) would be expected.

Welds 2-AS-2 and 2-BS-2 were closure welds for the 28-inch piping loop between the recirculation pump and vessel safe end. Accordingly, the closure spools (vertical segment, 90° elbow and horizontal segment) were match machined to the required dimensions using a templating technique. The installation procedure required fit-up of the spool and welding of the vertical weld first, allowing the pipe to shrink vertically until the horizontal weld joint (2-AS-2 and 2-BS-2) was axially aligned. Weld sequence on the vertical welds would also have to be controlled to maintain the 1/8 inch root gap at 2-AS-2 and 2-BS-2.

Realizing the difficulty of accurately templating and machining such a large spool piece, the need to modify the weld preparations in the field would not be unexpected. Such a modification would most likely be performed by hand grinding or filing the extended lands as shown in Figure B-2(a). In this case, the cross-section shown in Figure B-2(b) could result, which is similar to that found in the core sample.

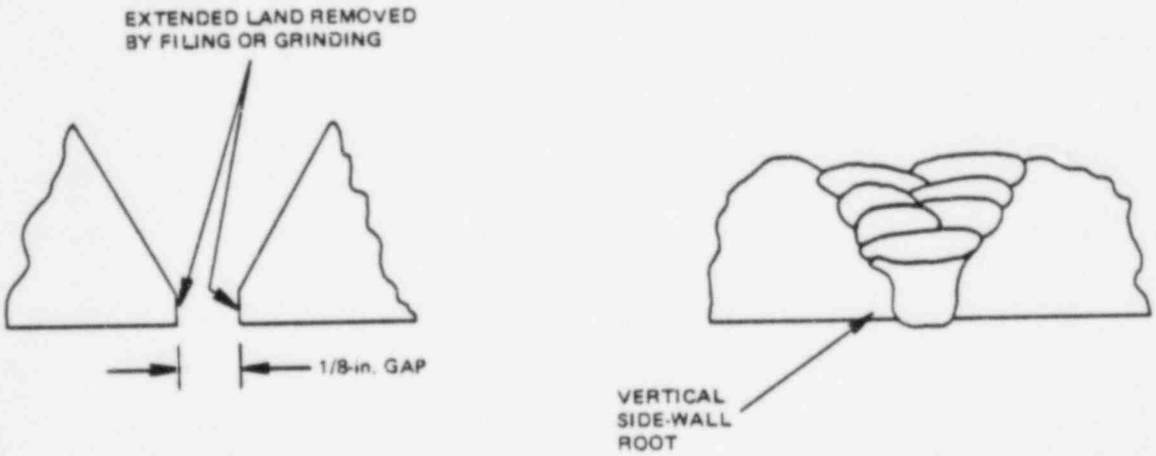
Field construction records are insufficient to show whether this actually occurred, but the practice was commonly used to help obtain the 1/8 inch minimum gap specified in the "open-butt" welding procedures. This weld prep modification could have been made anywhere on the 28-inch piping, but the closure weld spools would be the most probable locations requiring such a field modification. Based on this, the observed root cross-section and anomalous UT crack indication are not considered typical of the other 28-inch piping in the system.



(a) NORMAL EXTENDED LAND PREPARATION FOR "OPEN BUTT" WELDING (OPTIONAL REMOVAL OF SQUARE EDGES OF LAND TO OBTAIN MORE UNIFORM ROOT FUSION ALSO SHOWN)

(b) RESULTING WELD CROSS SECTION

Figure B-1. Normal Weld Preparation and Weld Cross-Section



(a) MODIFIED PREPARATION TO CORRECT JOINT FIT-UP

(b) RESULTING WELD CROSS SECTION

Figure B-2. Modified Weld Preparation and Cross-Section

GENERAL ELECTRIC