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Metallurgical Evaluation of Weld Overlaid Pipe Sections From Brunswick Unit 2 Nuclear Power Station

Prepared by
C. Czajkowski, B. Bowerman, M. Schuster,
T. Roberts, L. Milian

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Washington, DC 20555
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ABSTRACT

A metallurgical assessment of four sections of weld overlaid pipe was performed. The investigation consisted of strain gage measurements, metallographic sectioning and mounting, scanning electron microscopy, hardness and ferrite measurements, radiography and dye penetrant examinations. A review of the fabrication history and original preservice and inservice examinations was performed and comparison was made to the actual cracks revealed after sectioning. In general, the report concludes that this weld quality of the overlays was consistent with ASME quality code class welds with adequate average "as deposited" ferrite readings of FN>7. The chemical analysis of the welds were normal for the alloys used (type 304 stainless steel, type 308 weld metal). The study also concludes that the ultrasonic inspection techniques used for inservice inspection of the overlays may not accurately depict the top 25% of the pipe in all cases and that crack growth is possible after weld overlay under certain conditions.

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EXECUTIVE SUMMARY

Four pieces of radioactive stainless steel from the Brunswick Unit 2 plant were evaluated at Brookhaven National Laboratory. The pieces of pipe were 12 inch diameter, approximately 12 inches long, and each contained an overlaid weld. The four sections of pipe and their approximate crack lengths were identified as:

Vertical to Elbow	2B32 Recirc.	12"	BRJ2	2.25", 12% thru wall
Horizontal to Elbow	2B32 Recirc.	12"	BRJ3	1.75", 11% thru wall
Safe end to Horizontal	2B32 Recirc.	12"	BRG4	2.0", 14% thru wall
				1.25", 7% thru wall
Horizontal to Elbow	2B32 Recirc.	12"	BRK3	1.25", 5% thru wall

These pipes had been in service for three (3) refueling cycles prior to removal.

The proposed metallurgical assessment of the four samples was to entail the following (as applicable) steps:

- Review the fabrication history, material certifications of both original and overlay repair methods for the four weldments.
- Review the nondestructive test data (ISI/PSI) for the four weldments.
- Photograph - "as received" the four pieces of pipe and perform a visual examination of same.
- Radiograph to characterize the weldments/overlay prior to cutting the pipe.
- Strain gage measurements.
- Metallurgically examine the four samples using the following techniques:

  a) scanning electron microscopy
  b) wavelength dispersive spectroscopy (WDS)
  c) dye or fluorescent penetrant
  d) metallographic grinding/polishing/etching
  e) optical metallography
  f) microhardness measurements
  g) ferrite measurements

- Provide a chemical analysis of the overlay material original weldment and base metal for the four samples (EDS).

Dye penetrant results on the pipes' inside surfaces compared to the utility U.T. data revealed the following:

12BRG4

Three indications were noted on this pipe. They were of the following lengths: 1 inch, 7.5 inches and 1.5 inches. The utility had reported that this weld had only two indications: length 2.0 inches, 14% thru wall and 1.25 inches, 7% thru wall.

12BRK3

Two indications were noted on this pipe. They were both 1.5 inches long. The utility reported one 1.25 inches long indication at 5% thru wall for this weld.

12BRJ2

This weld showed a faint 1.5 inch long indication. The utility report one 2.25 inch indication at 12% thru wall for this weld.

12BRJ3

Two indications were seen on this weld. The first was approximately 2 inches long and the second approximately 3/8 inches long. The utility reported one 1.75 inch long indication at 11% thru wall for this weld.

Procedures were developed to determine the residual stresses of the welds in areas where cracks were identified. To accomplish this, strain gages were installed adjacent to and across selected cracks in the welds on the interior of the pipe sections and on the outer pipe circumference at locations corresponding to the interior surface strain gages. The gages were zeroed before the pipes were sectioned, then readings were taken after the pipes had been cut. In general, the pipes had reasonably high residual compressive stresses on the inside surface and residual tensile stresses on the exterior surface. Pipe 12BRG4 did have very low residual compressive stresses on its inside surface which indicated that the overlay technique may not always provide the necessary compressive stresses required on the pipes' inside diameters.

Ferrite readings performed on the four pipe sections indicated that all "as deposited" weld metal exceeded FN 7. Only four readings (on 12BRG4) were below FN 8 out of approximately 480 readings.

Optical microscopy revealed that all of the cracks were intergranular in nature. The large crack (7.5 inches long) in 12BRG4 was essentially "through wall" (original pipe) for approximately 30% of its length. This is in distinct contrast to the original inspection data which showed a two inch long 14% through wall crack and a second crack 1.25 inches and 7% through wall.

The following conclusions were drawn from the investigation:

- The chemical analyses (WDS) of the base metal/weld metal and overlay materials appeared normal for the alloys used (A240 Type 304 stainless steel, SFA 5.4 308 weld

- The ferrite numbers recorded (FN >7) for all of the overlaid welds were consistent with industry practice. One reading was below the recommended FN 7.5 minimum outlined in USNRC Generic Letter 88-01. Considering the fact that the recording was FN 7.3 and that all other ferrite measurements on this pipe were above FN 7.5 this is considered acceptable.

- The quality of the overlays was consistent with that expected in an ASME pressure boundary weld. There was no evidence of porosity, lack of fusion, lack of penetration or weld metal cracking (other than IGSCC).

- The evaluation of the ultrasonic test data coupled with the input and re-evaluations by General Electric Co., indicated that for certain overlay configurations, ultrasonic inspection may not provide an accurate picture of the top 25% (original pipe wall) of the pipe. Comparing the metallurgical sectioning of the four pipes to the dye penetrant results also gives rise to questions regarding overcalls and undercalls on IGSCC. Three indication (2 on 12BRK3 and 1 on 12BRJ2) did not reveal cracks after sectioning. The comparison of cracks to ultrasonic test data also evidences the fact that the sizing/locating of cracks (before overlay) is not an "exact science" and results of these inspections should be carefully evaluated.

- The stress calculations (based upon the strain gage measurements) indicate that crack growth (propagation) after weld overlay is a distinct possibility. This conclusion is based upon the low recorded residual compressive stresses observed on pipe 12BRG4.

- It could not be positively determined if crack growth occurred after overlay by the metallurgical tests performed.

ACKNOWLEDGEMENTS

The authors wish to thank D. Horne and K. Warburton for their tremendous help in the strain gage and microhardness measurements; the BNL Welding Shop for the radiography, A. Lopez for the first draft of this report and V. Morante for its completion. The authors also wish to thank P. Soo for his review and constant support.

1. INTRODUCTION

Weld overlay repairs on intergranular stress corrosion cracked (IGSCC) piping was initially considered as a short term repair by the U.S. Nuclear Regulatory Commission (NRC) and was accepted provided that no more than two additional fuel cycles were completed. The issuance of Generic Letter 88-01 (by the USNRC) allows weld overlay repaired piping to continue to operate as long as a satisfactory ultrasonic examination is performed on the repaired piping every other fuel cycle. This evaluation must show no significant growth (propagation) of existing cracks and no initiation of new cracks. Many overlays have been applied in boiling water reactor (BWR) plants. The NRC believed that there was a need to confirm the effectiveness of weld overlay repairs (in mitigating the IGSCC) by metallurgically examining several overlay repaired welds.

Pursuant to this end, the USNRC (Materials and Chemical Engineering Branch) contracted with Brookhaven National Laboratory (BNL) to perform the metallurgical assessment.

Prior to the placing of the contract with BNL, Carolina Power and Light (CP&L) had offered the NRC some piping which had been in service for multiple fuel cycles.

On December 6, 1989, a joint NRC/BNL team visited the Brunswick Nuclear Units. The purpose of the site visit was to elicit information from the licensee regarding sections of weld overlaid stainless steel piping to be sent to BNL for metallurgical evaluation.

Discussions with the utility personnel revolved about the size, configuration, shipping condition, radiolytic condition, and identification of the specimens to be sent to BNL from Brunswick Unit 2. The following information was gathered during the discussions:

1) Four pieces of radioactive stainless steel pipe would be sent to BNL. The pieces of pipe are 12 inch diameter, approximately 12 inches long, and each will contain an overlaid weld. The four sections of pipe and their approximate crack lengths were identified as:

Vertical to Elbow	2B32	Recirc.	12"	BRJ2	2.25", 12% thru wall
Horizontal to Elbow	2B32	Recirc.	12"	BRJ3	1.75", 11% thru wall
Safe end to Horizontal	2B32	Recirc.	12"	BRG4	2.0", 14% thru wall 1.25", 7% thru wall
Horizontal to Elbow	2B32	Recirc.	12"	BRK3	1.25", 5% thru wall

These pipes had been in service for three (3) refueling cycles prior to removal.

Figure 1 is a layout drawing showing the location of the four referenced welds. A cutaway view of the vessel and the specimens' locations relative to the riser and containment is depicted in Figure 2.

The pipe specimens chosen had interior "smearable" contamination levels of between 2000 - 4000 dpm (disintegrations per minute). These levels were determined after "fixing" the containments on the pipes' inside surfaces with water soluble glue. The actual contamination levels were considered to be much higher (factor of 2-10).

The proposed metallurgical assessment of the four samples was to entail the following (as applicable) steps:

- Review the fabrication history and material certifications of both original and overlay repair methods for the four weld overlays.
- Review the nondestructive test data (ISI/PSI) for the four weldments.
- Photograph - "as received" the four pieces of pipe and perform a visual examination of same.
- Radiograph to characterize the weldments/overlay prior to cutting the pipe (4 pieces).
- Metallurgically examine the four samples using the following techniques:

  a) scanning electron microscopy
  b) wavelength dispersive spectroscopy (WDS)
  c) dye or fluorescent penetrant
  d) metallographic grinding/polishing/etching
  e) optical metallography
  f) microhardness measurements
  g) ferrite measurements

- Provide a chemical analysis of the overlay material original weldment and base metal for the four samples (EDS).
- Perform tensile tests (if feasible) for the original weld metal, base metal, overlay/interface.

This report documents the results of the metallurgical evaluation.

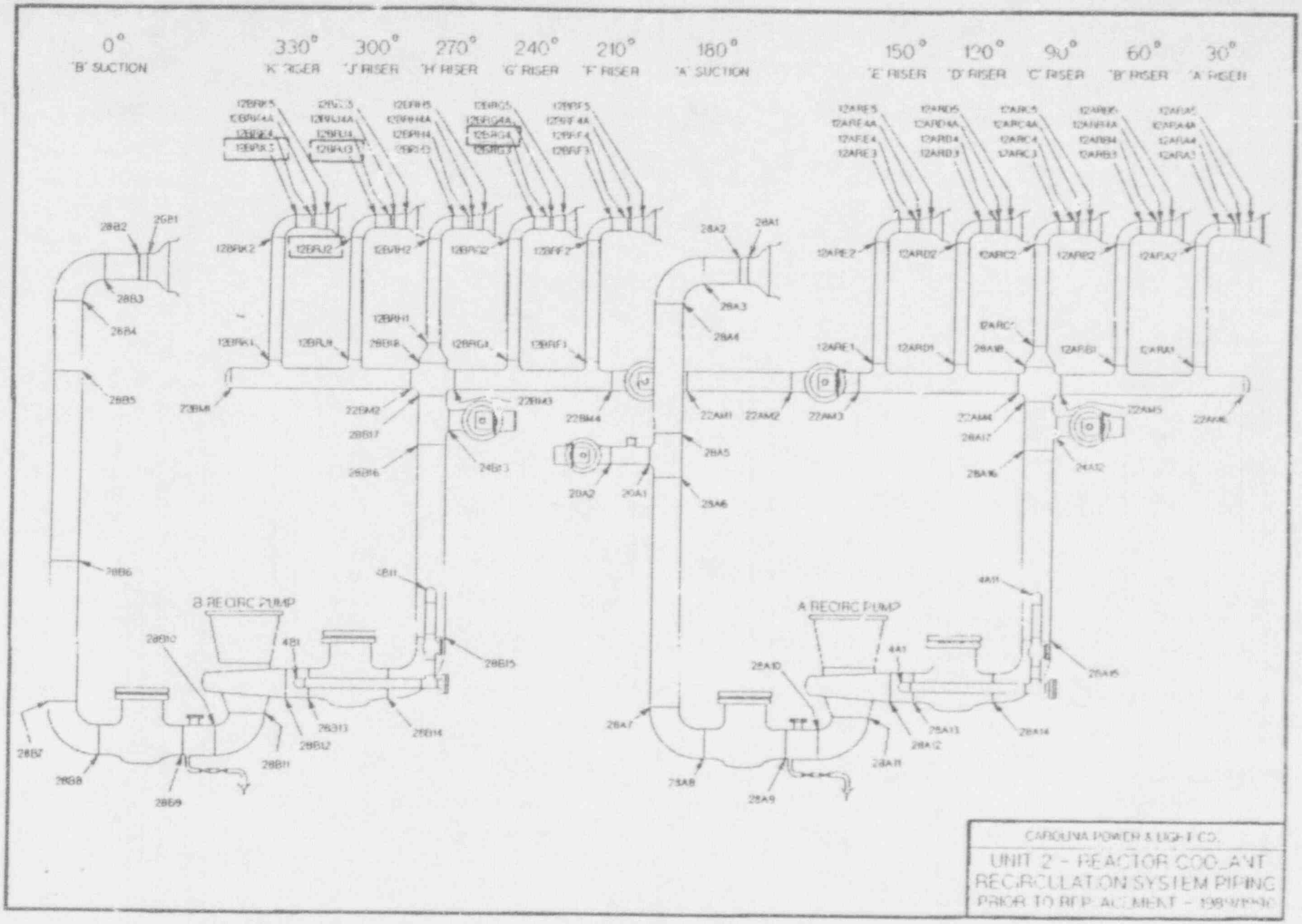


Figure 1 Layout of Reactor Recirculation System and location of the four weld samples (BRK3, BRG4, BRJ2, and BRJ3 - boxed).

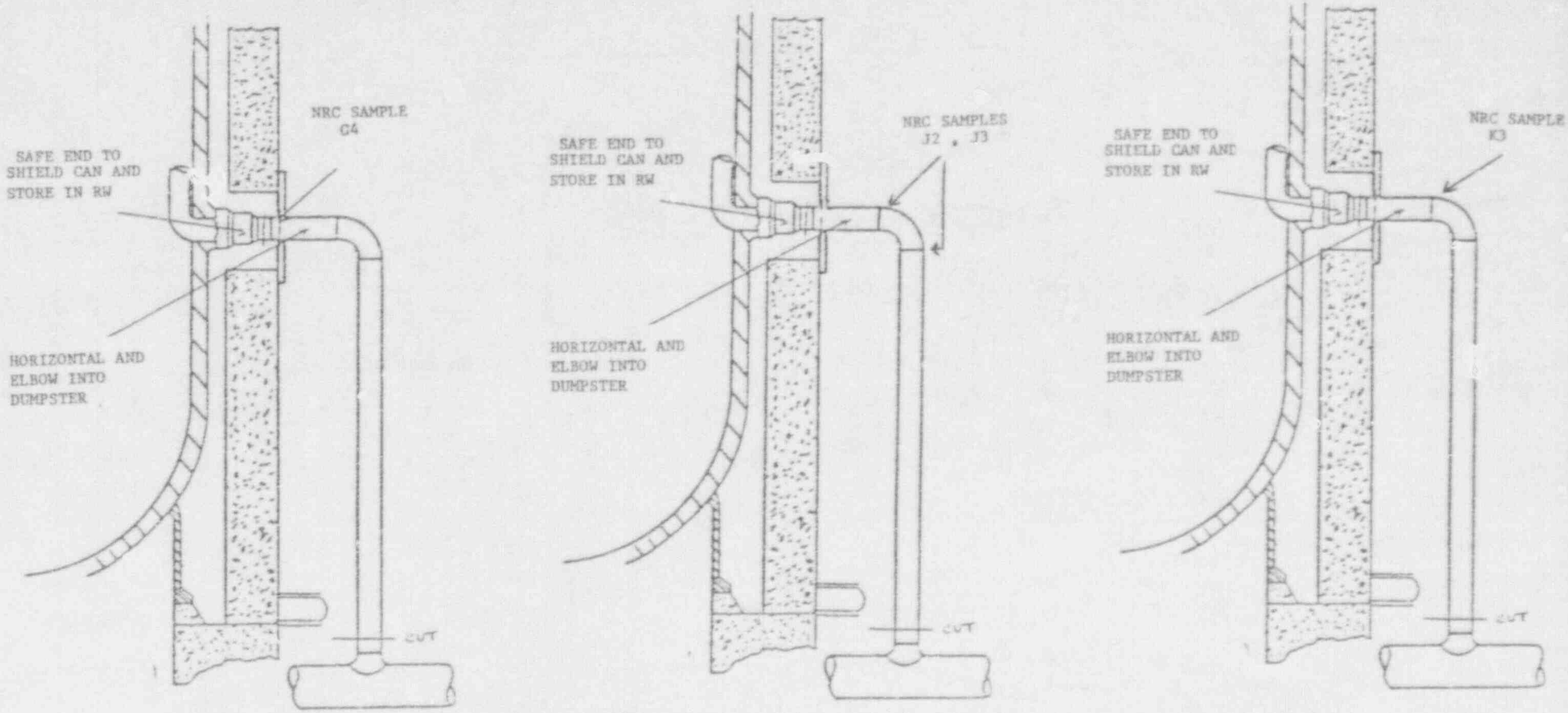


Figure 2 The relative location of the NRC sample welds is shown in the above three sketches.

2. INSPECTION BACKGROUND

A review of inspection data (supplied by CP&L) revealed the following inspection history for the welds:

Weld B32-RR-12"-BRG4 (0.7" wall thickness)

- Preservice inspection (PSI) was done on June 27, 1974, using ultrasonic examination. The inspection showed non-relevant indications due to ID geometry.
- Inservice inspection (ISI) was done using ultrasonic examinations on November 11, 1983. The inspection disclosed IGSCC at (L_1)22-24 (station numbers) 14% through wall and (L_2)23¼ - 26 (station numbers) 7% through wall (depth).
- ISI (after overlay was applied) performed on November 14, 1983. This overlay examination was conducted concurrently with bond examination. Visual inspection disclosed no apparent discontinuities. UT inspection also showed no apparent discontinuities. Penetrant examination (after overlay) showed no apparent discontinuities.
- ISI performed on March 15, 1986. Penetrant examination disclosed no apparent discontinuities (after additional overlay was applied). IGSCC indications at 22.75" and 24.75" were located prior to additional overlay by ultrasonic examination. Non-relevant indications were noted (ID geometric reflectors) by ultrasonic examination after overlay repair. Both IGSCC indications were not observed after additional overlay repair. No reportable indications were recorded in the top 25% of the base material or overlay material.
- ISI performed on January 29, 1988. Ultrasonic examination disclosed no indications associated with IGSCC. Inside surface geometric reflectors were noted by examination.

Weld B32-RR12"-BRJ2 (0.68" wall)

- PSI performed on September 17, 1974, by ultrasonic examination. No recordable indications noted.
- ISI performed on November 16, 1983, by ultrasonic examination. IGSCC noted at (L_1)38 3/4" 12% thru wall depth approximately L_1 = 2.25" in length. ID counterbore reflector noted at 22".
- No 1983 original overlay data available.
- ISI performed on March 1, 1986. Penetrant examination showed no recordable indications (after additional overlay was applied). IGSCC indication at 38" was not seen after additional overlay was applied. Ultrasonic examination showed no recordable indications in top 25% of base metal.

- ISI performed on February 4, 1988, by ultrasonic examination. No indications associated with IGSCC were seen. Non-relevant indications both up stream and down stream side of the weld were noted during the examination.

<u>B32-RR-12"-BRJ3</u> (0.68" wall thickness)

- PSI performed on September 17, 1974, by ultrasonic examination. No rejectable indications noted. ID geometric reflector identified at 27" (station marker).

- ISI performed November 10, 1983, by ultrasonic examination. IGSCC indication noted at (L_2) 14" - 15 3/4" (station markers), L = 1 3/4", 11% thru wall. After overlay inspection data showed no recordable defects (November 11, 1983).

- ISI performed on April 7, 1986, by penetrant examination. No recordable indications were noted (after additional overlay was applied). IGSCC at 14" - 15 3/4" was not observed. A new IGSCC indication was found at 23.5" to 24.5" approximately 35% thru wall. ID geometric reflectors were also noted.

- ISI performed on January 27, 1988. None of the previously recorded IGSCC indication were observed during this examination.

<u>B32-RR-12" BRK3</u> (0.71" wall thickness)

- PSI performed on September 17, 1974, by ultrasonic examination. No rejectable indications were noted. ID geometric reflector identified at 27.5.

- ISI performed on November 17, 1983, by ultrasonic examination. IGSCC indication noted at (L_1) 35.5" to 36.75"; L = 1¼"; ~5% thru wall. At (L_2) 20.12" - 25.5", an ID. Geometric reflector was noted.

- ISI performed on November 15, 1983. Overlay examination conducted concurrently with bond examination. Penetrant examination showed no apparent discontinuities. Ultrasonic examination reported no apparent discontinuities.

- ISI performed on April 8, 1986. The IGSCC indication (comment of 1986 review) was not detected after overlay. Penetrant examination showed no recordable indications (after additional overlay was applied). The IGSCC indication at 36" was not observed after additional overlay was applied. No IGSCC indications in overlay or top 25% of base metal.

- ISI performed on January 26, 1988, by ultrasonic examination. IGSCC indication was recorded at location 17.9". The indication is contained within the top 25% of the base material and does not extend into the overlay material. This indication was recorded but not reported during the previous outage. Non-relevant root geometric reflectors were also reported.

3. VISUAL INSPECTION/DYE PENETRANT EXAMINATION/RADIOGRAPHY

Four sections of radioactively contaminated pipe were received at BNL. The pipes were 12 inches in diameter and approximately 15 inches in length. The pipes were typically covered at both ends and wrapped in duct tape (Figure 3).

Removal of the end coverings and duct tape revealed that the inside surface of each of the pipes was covered with a heavy oxide coating and slag from the cutting process (Figures 4 - 7). There were no top dead center (TDC) or zero markings (station markers) readily evident on the pipe sections.

In order to preserve and not marr the features of any intergranular cracks (on the pipes' inside surfaces) the oxide was removed manually with a hammer and cold chisel. After the oxide was removed, the inside surfaces of the four pipe sections were wiped down with methanol allowed to dry, and then subjected to dye penetrant examination by the following procedure:

> The materials used for the dye penetrant were: Magnaflux - Penetrant SKL-HF/S, Developer SKD-S, and Cleaner SKC-NF/ZC-7.
>
> The procedure used for the dye penetrant inspection of the pipe follows:
>
> 1. All dye penetrant examinations were performed in a hot cell at approximately room temperature (~70°F).
> 2. Cleaner - The pipe surface to be tested was wiped clean and then allowed to dry for approximately ten minutes.
> 3. Penetrant - After the penetrant was applied, it was allowed to stand for ten minutes (dwell time).
> 4. Cleaner - The penetrant was wiped off and the area allowed to dry for an additional ten minutes.
> 5. Developer - The developer was applied and the surface examined.

The following sections describe the results of the dye penetrant examination:

<u>12BRG4</u>

An approximately one inch long indication was noted between station markers 16-17 (Figure 8). A second indication approximately 7½" in length was located between stations 34 and 25 (Figure 9). A third indication (Figure 10) approximately 1½" long was located between stations 38 and 36.

- The utility had reported that this weld had only two indications:
  length 2.0", 14% thru wall
  1.25", 7% thru wall

Figure 3 "As received" section of pipe from Brunswick Unit 2 (Typical).

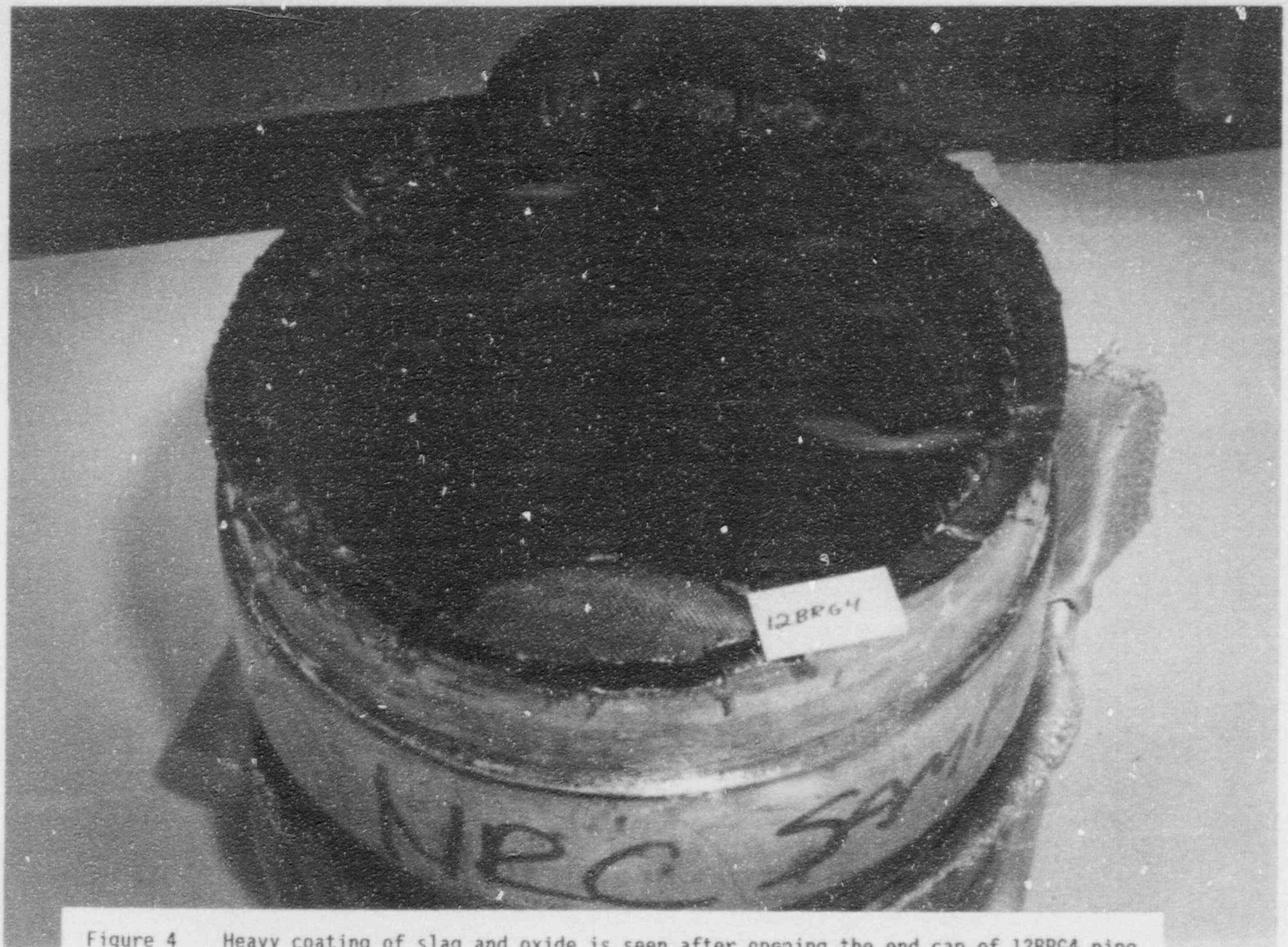


Figure 4   Heavy coating of slag and oxide is seen after opening the end cap of 12BRG4 pipe.

Figure 6 The relative thickness of the oxide coating can be seen in this photograph of 12BRJ3.

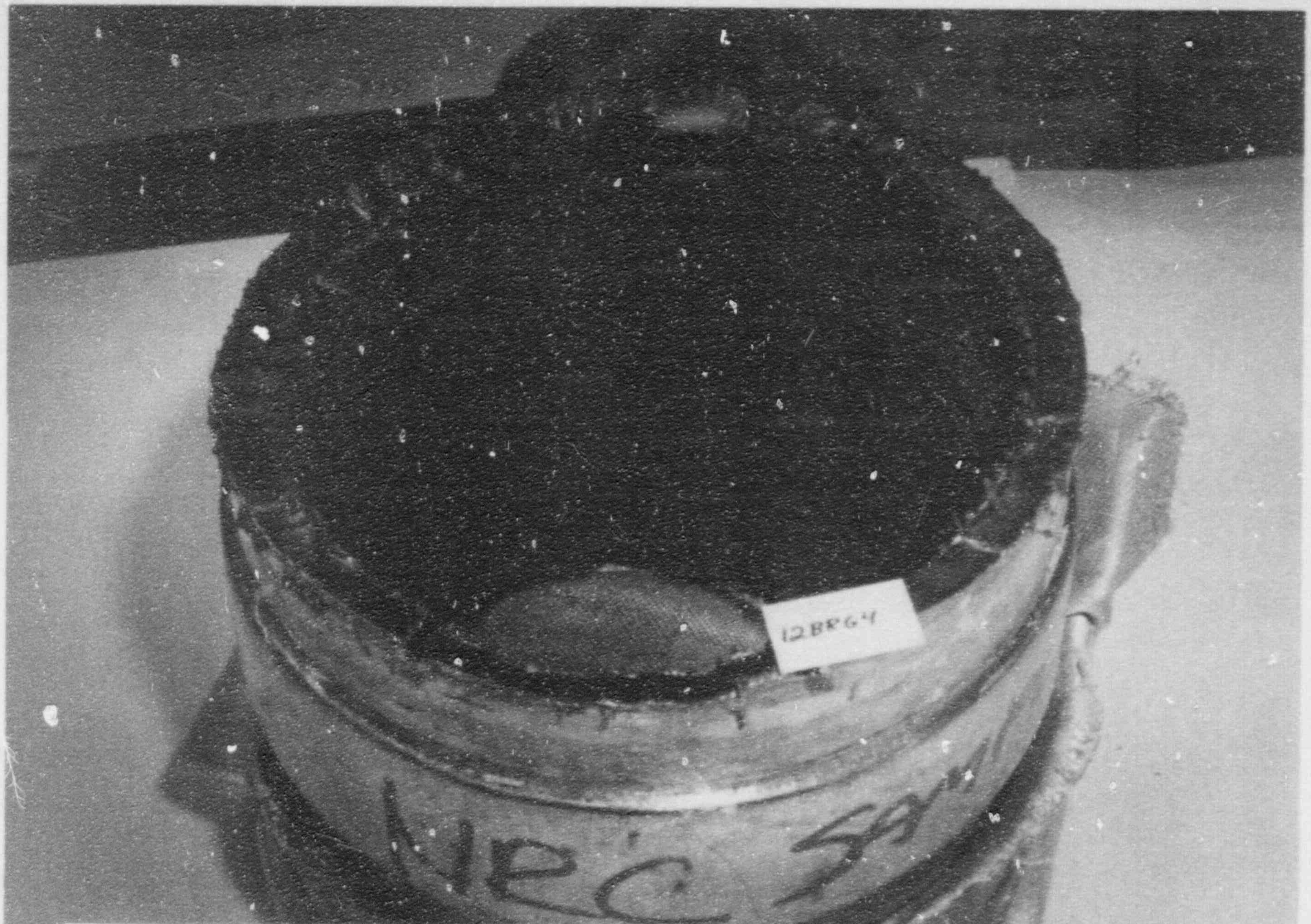


Figure 4 Heavy coating of slag and oxide is seen after opening the end cap of 12BRG4 pipe.

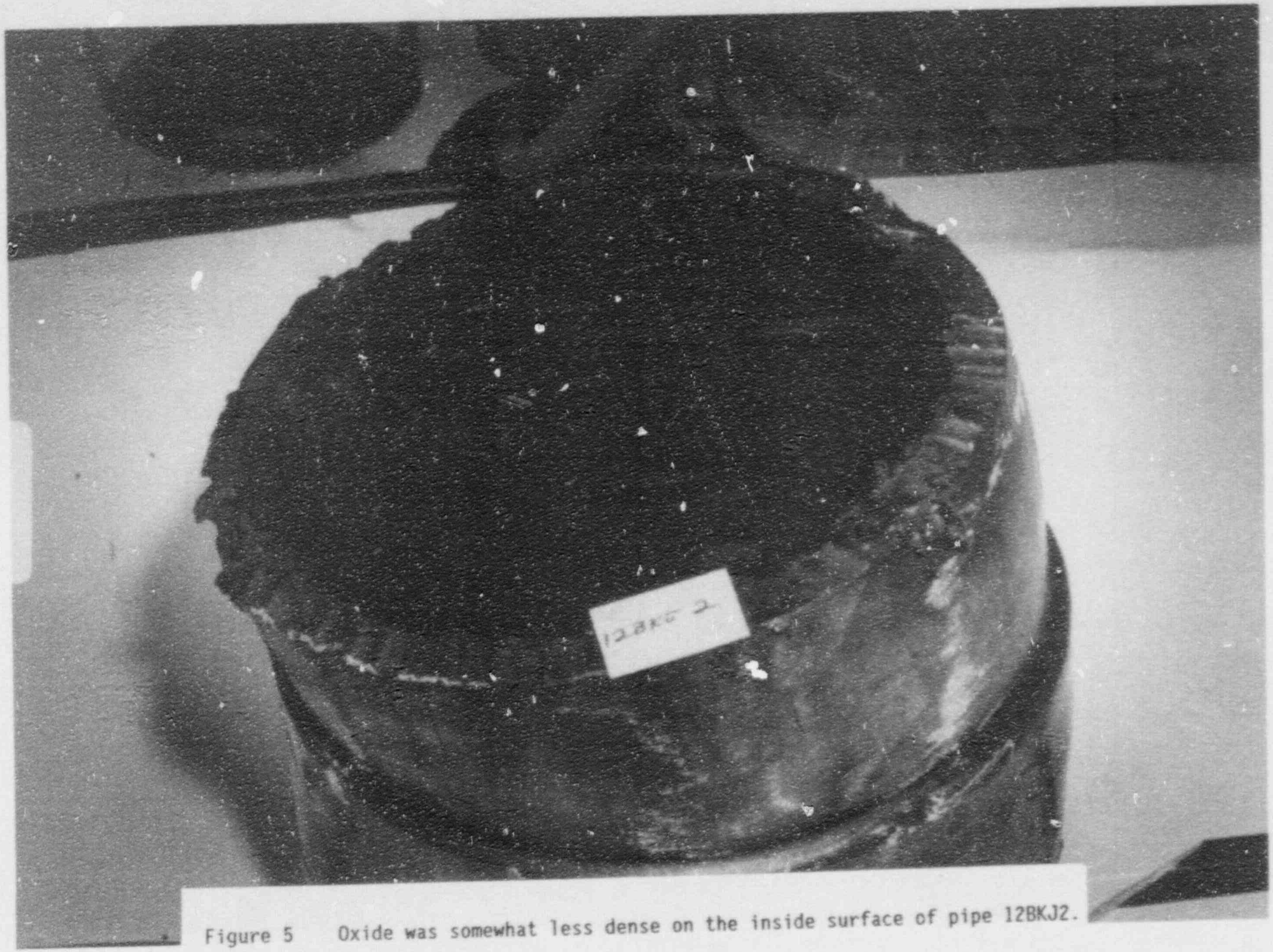


Figure 5 Oxide was somewhat less dense on the inside surface of pipe 12BKJ2.

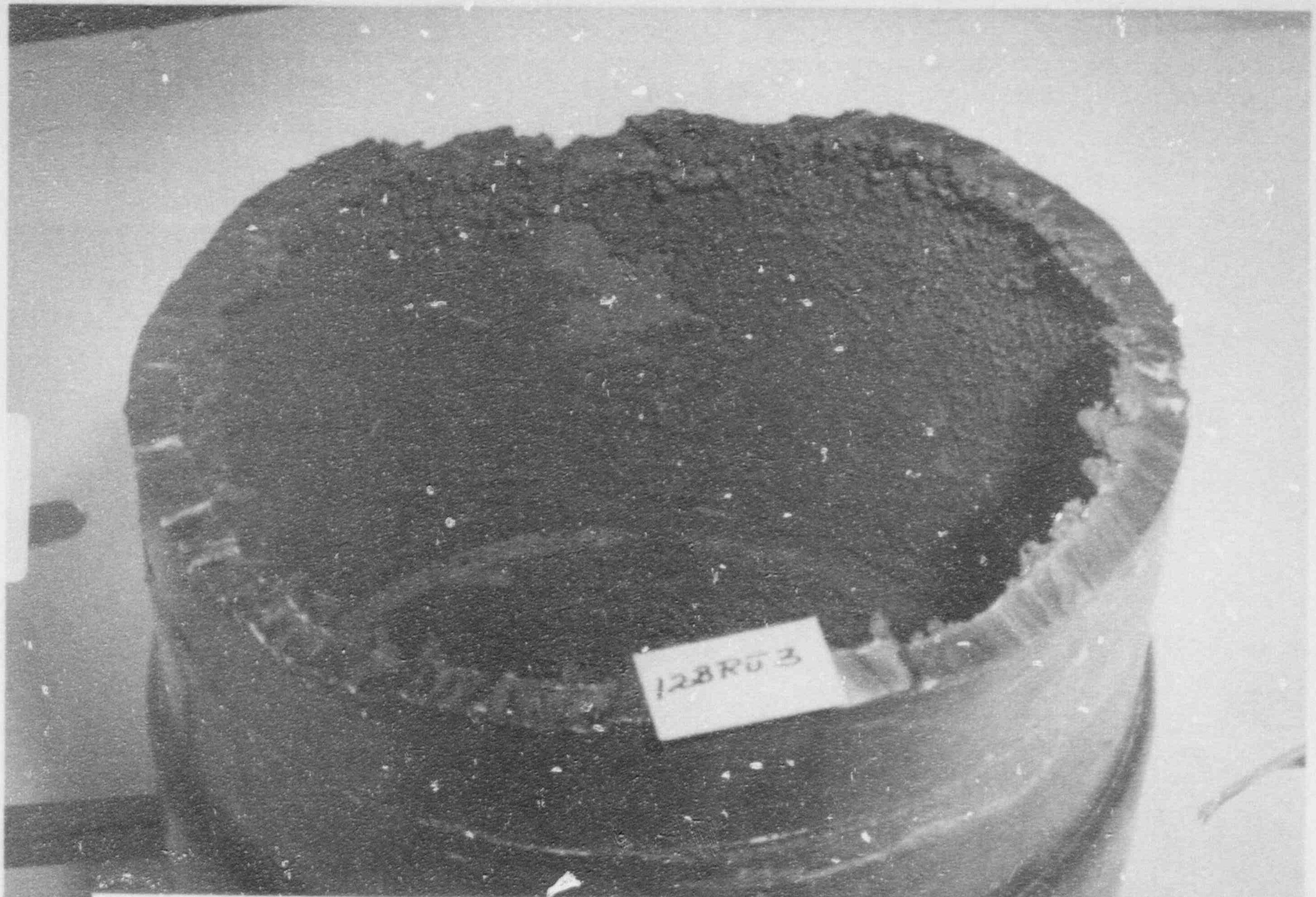


Figure 6 The relative thickness of the oxide coating can be seen in this photograph of 12BRU3.

Figure 7 A generally thinner layer of oxide was seen on the inside surfaces of 12BRK3.

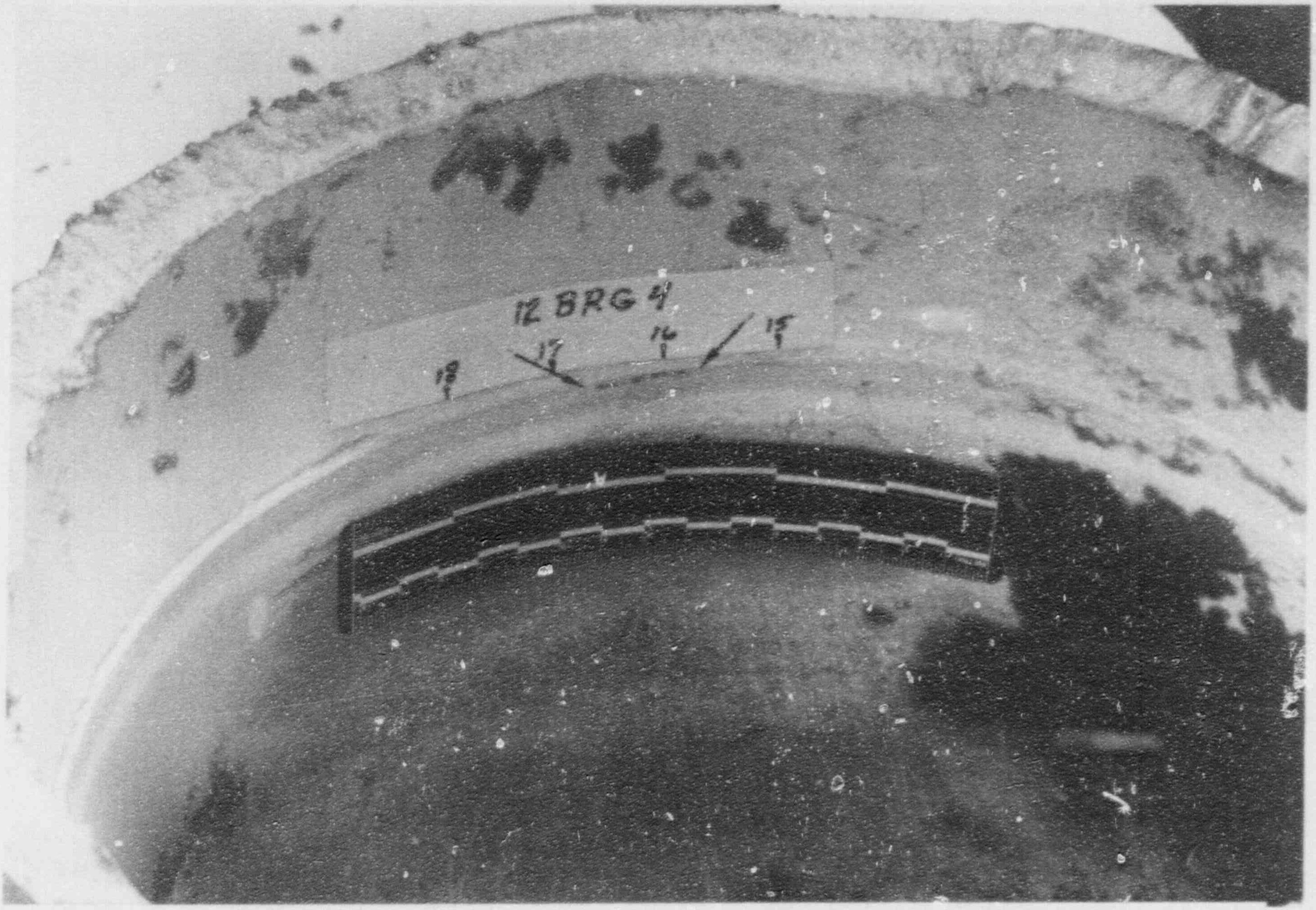


Figure 8 A linear indication (~1 inch long) is seen at stations 17-16 after dye penetrant examination of 12BRG4 (arrows).

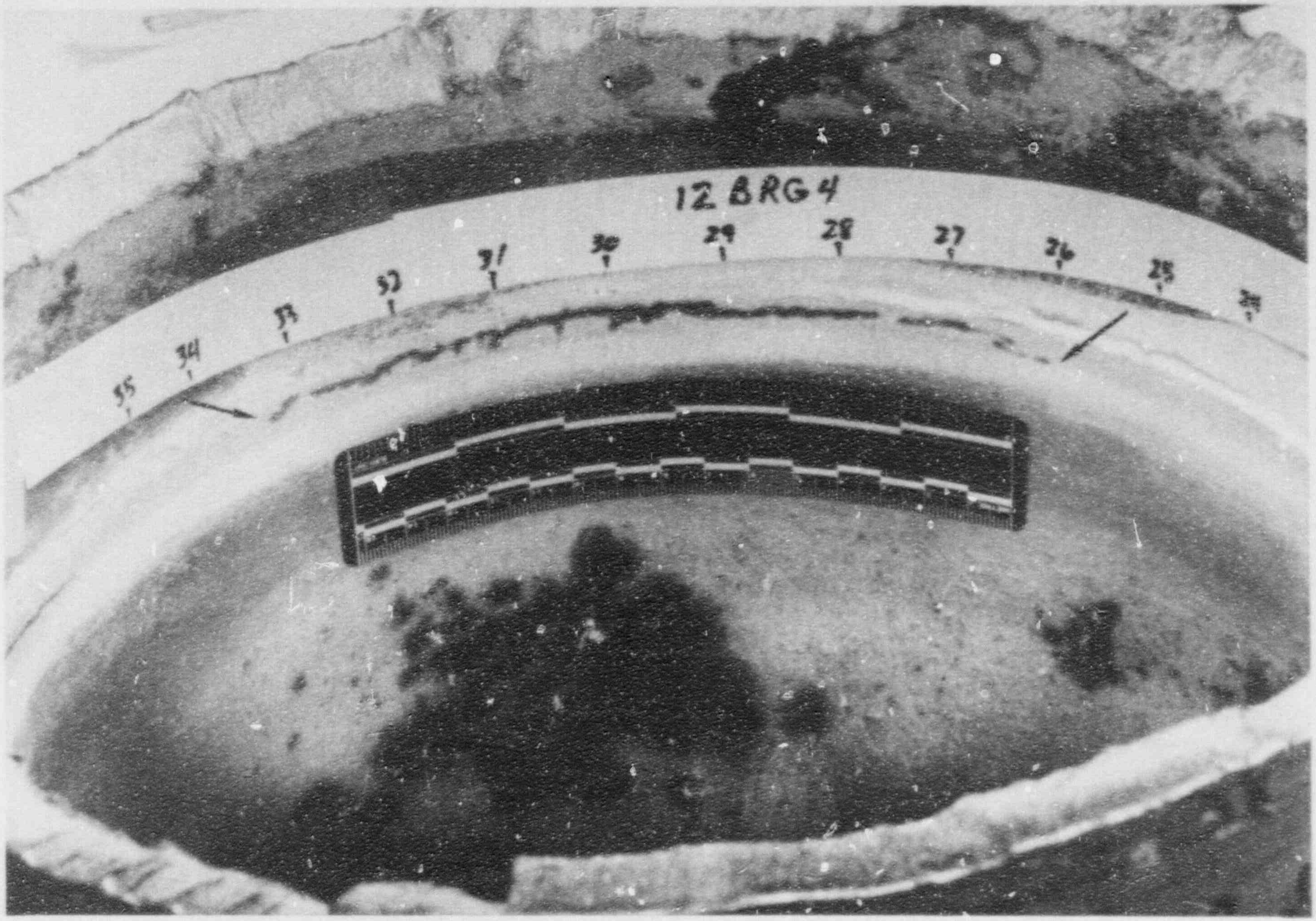


Figure 9 A 7½" long indication was noted on 12BRG4 after dye penetrant was applied (stations 34-25) (arrows).

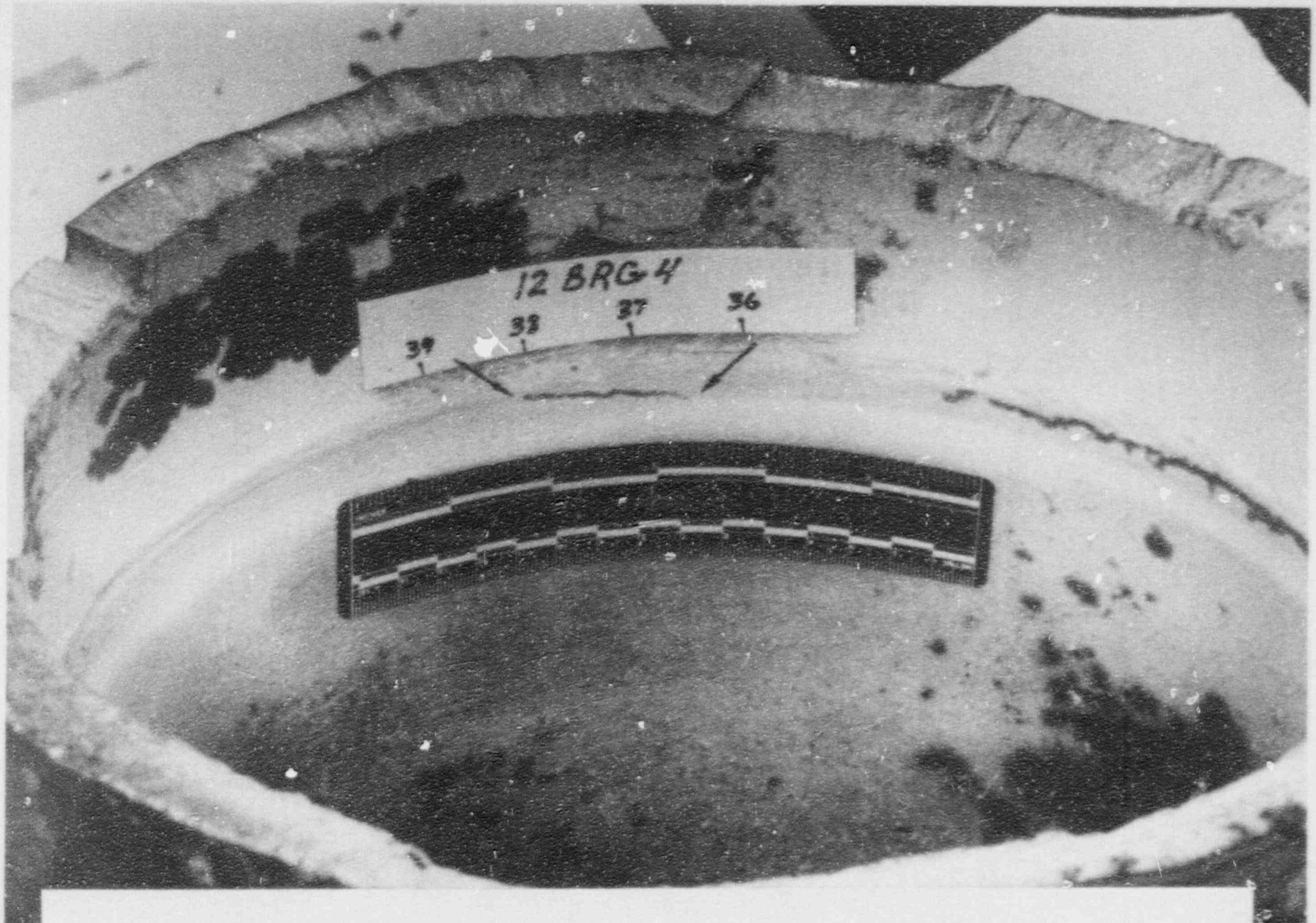


Figure 10 A third linear indication was seen (~1 3/4" long) between stations 39-36 on 12BRG4 (arrows).

12BRK3

Faint dye penetrant indications (Figure 11) were seen between areas 7-5, approximately 1½" in length (discontinuous) and at marker 32 (Figure 12), approximately 1½" in length.

- The utility reported one 1.25" long indication at 5% thru wall for this weld.

12BRJ2

This weld (Figure 13) showed a faint 1½" long indication between station markers 24-23.

- The utility reported one 2.25" long indication at 12% thru wall for this weld.

12BRJ3

Two indications (Figures 14 and 15) were seen on this weld. The first was approximately 2" long between markers 7-9 and the second approximately 3/8" long between markers 33-32.

- The utility reported one 1.75" long indication at 11% thru wall for this weld.

To further characterize the indications, radiography was performed on the four pieces of pipe. A total of 44 radiographs were made of the pipe sections (11 per pipe) and these films were interpreted and compared to the dye penetrant examination data. There was no definitive correlation noted between the radiographs and the dye penetrant indications since the IGSCC cracks do not manifest themselves conspicuously by this (radiography) nondestructive examination technique.

During these comparisons, the importance of accurate labeling of station markers became apparent if BNL was to correlate its inspections with the PSI and ISI data generated by the utility.

The locations of the cracks were identified in relation to station numbers which were marked on the outer diameter of the overlay boundary with the pipe. The station numbers were placed after selecting a zero point; station locations are spaced one inch apart starting from the zero point. The BNL examination of the pipe prior to the x-ray radiography (the first stage of the project) failed to identify clearly any zero marks which may have been used by the utility or their contractors for in situ NDE. Therefore, BNL placed an arbitrary zero mark on each overlay and assigned station numbers from this zero point. The zero mark consisted of "0>" with the ">" aligned along the pipe axis.

Figure 11   A discontinuous indication (~1½" long) was seen between stations 7-5 on 12B K3 (arrows).

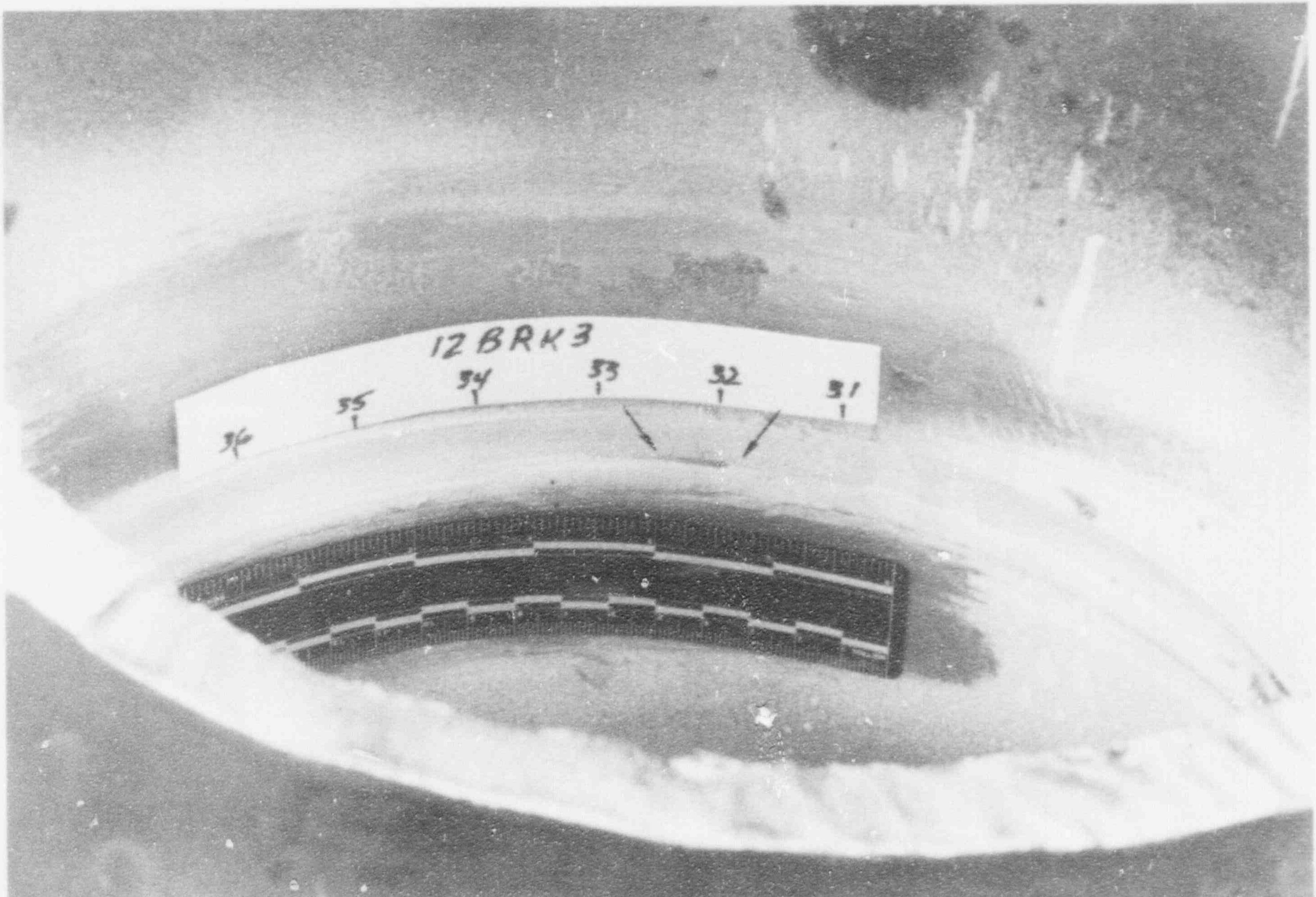


Figure 12 A small indication (~1/2" long) was seen at station marker 32 on 12BRK3 (arrows).

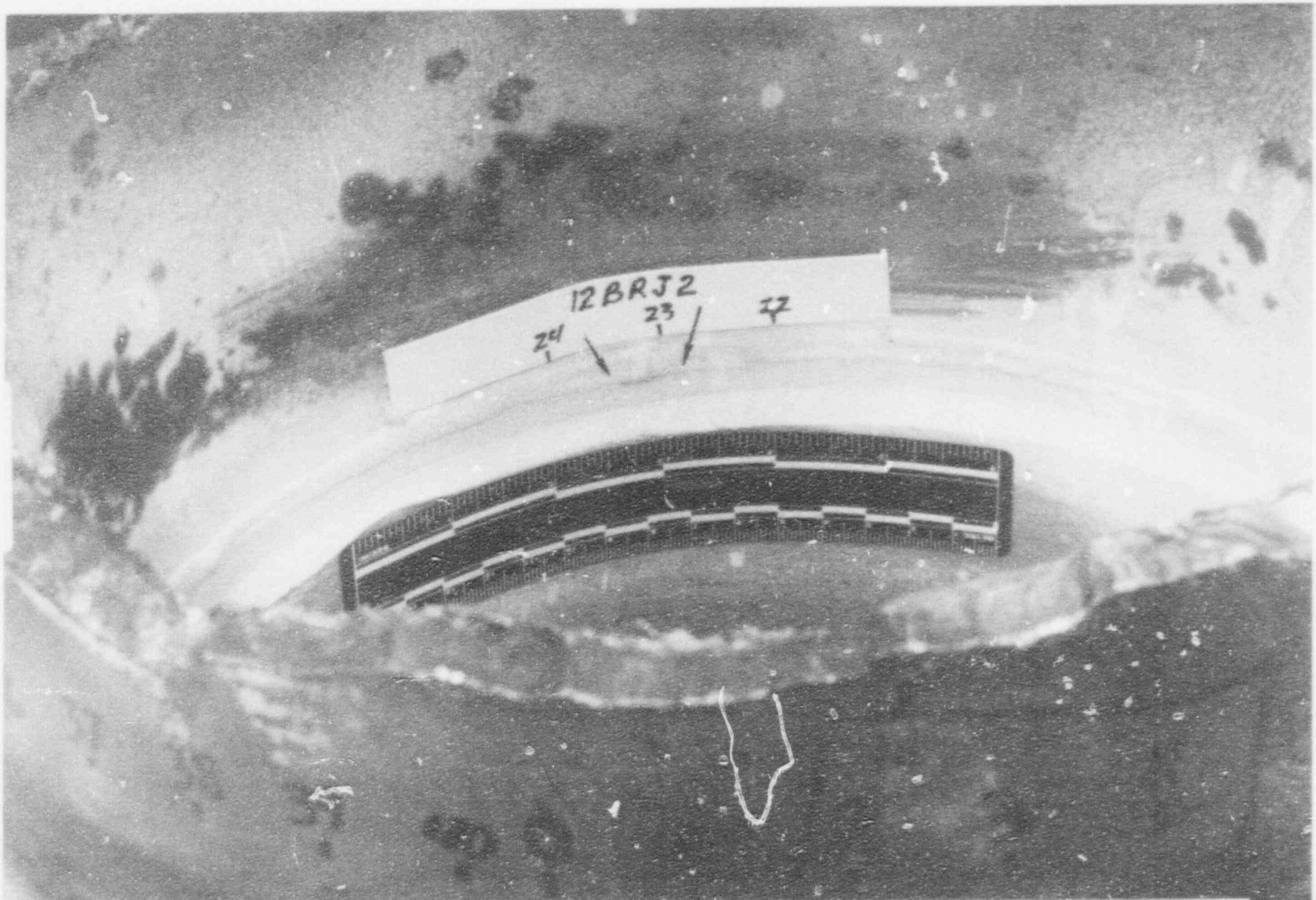


Figure 13 Pipe 12BRJ2 had one small indication (~1/2" long) located between markers 24-23 (arrows).

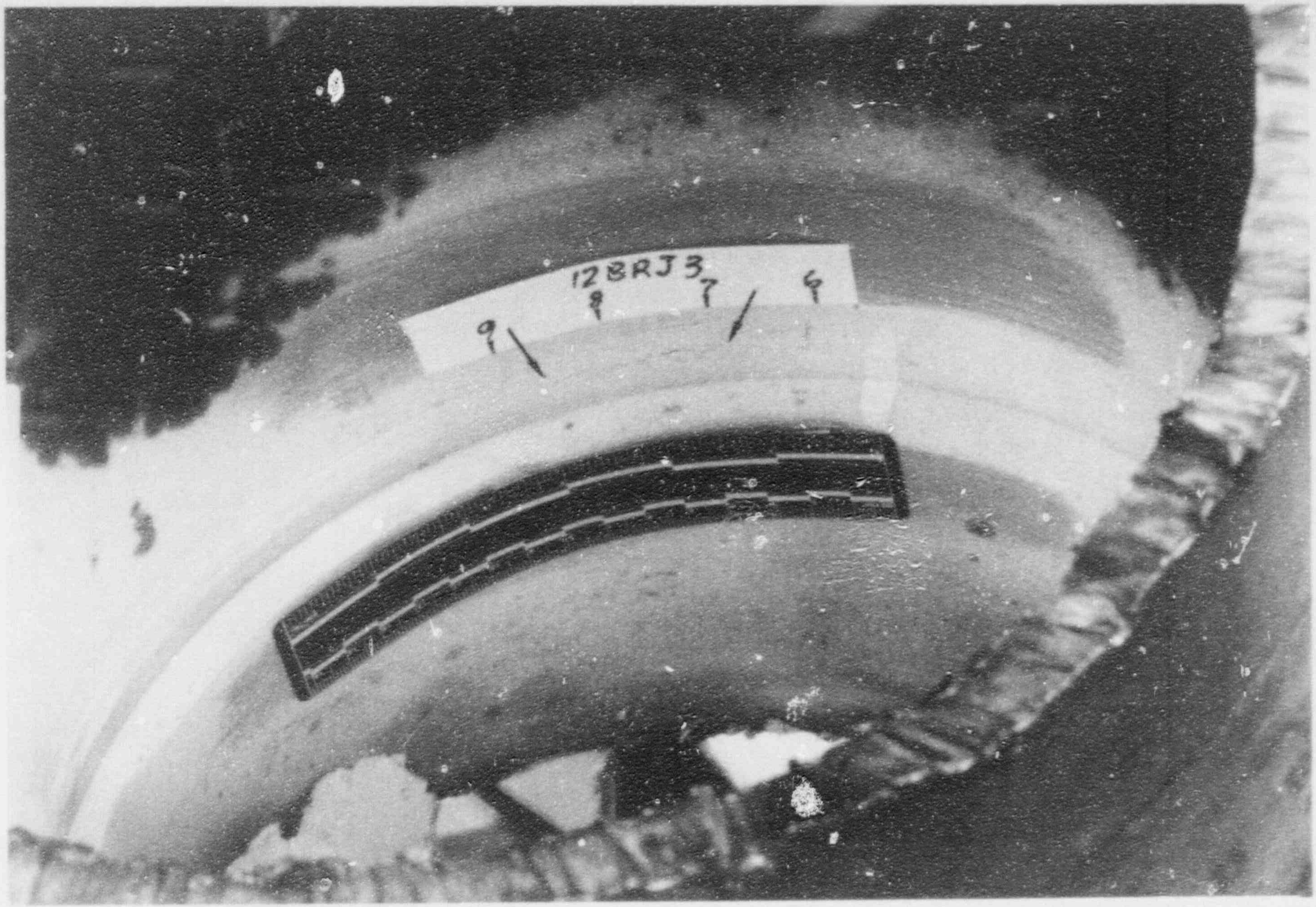


Figure 14 A "crazed" appearing indication was seen between markers 9-7 (~1 1/2" long) on 12BRJ3 (arrows).

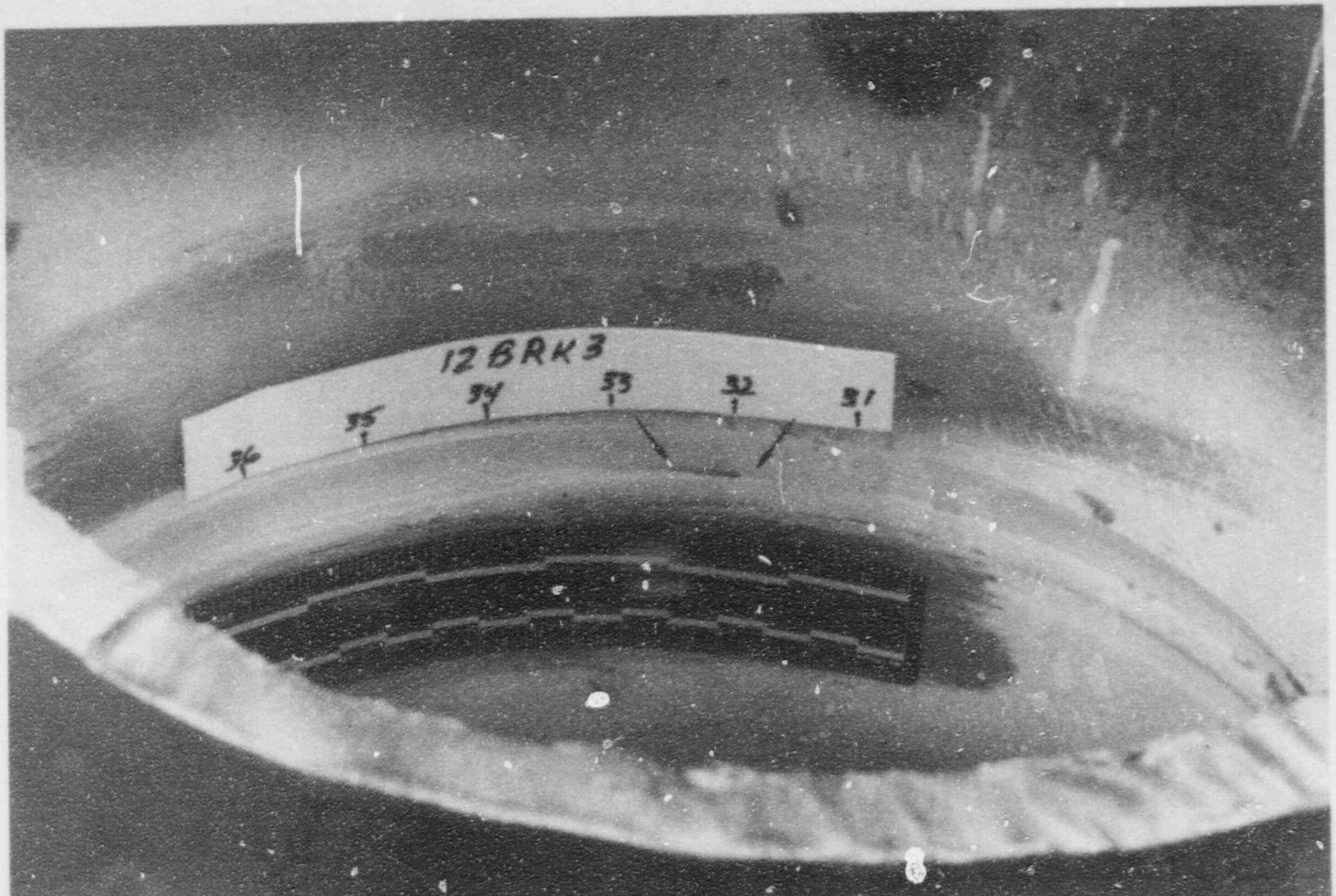


Figure 12 A small indication (~1/2" long) was seen at station marker 32 on 12BRK3 (arrows).

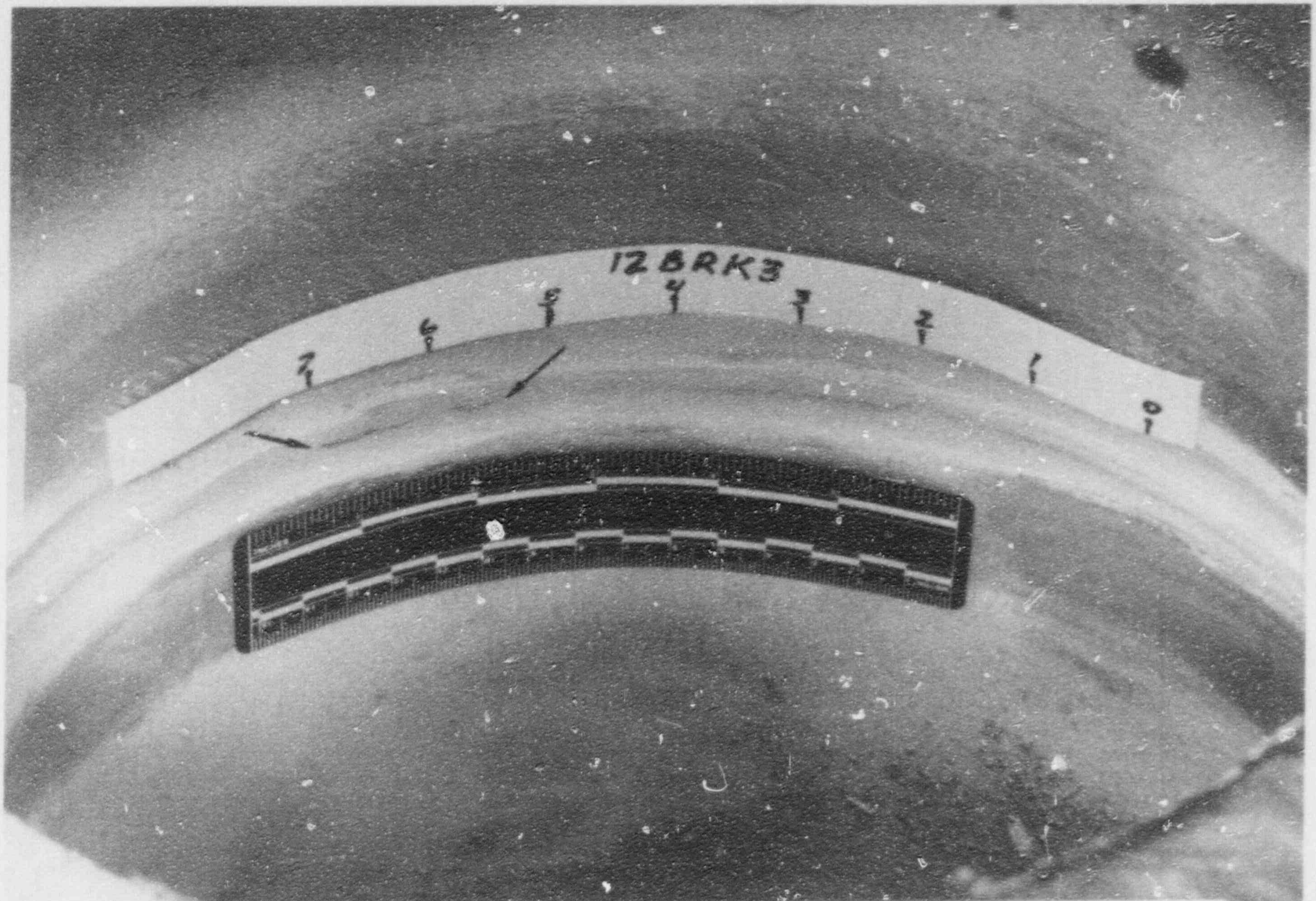


Figure 11 A discontinuous indication (~1½" long) was seen between stations 7-5 on 12BRK3 (arrows).

Figure 14 A "crazed" appearing indication was seen between markers 9-7 (~1 1/2" long) on 12BRJ3 (arrows).

Figure 13 Pipe 12BRJ2 had one small indication (~1/2" long) located between markers 24-23 (arrows).

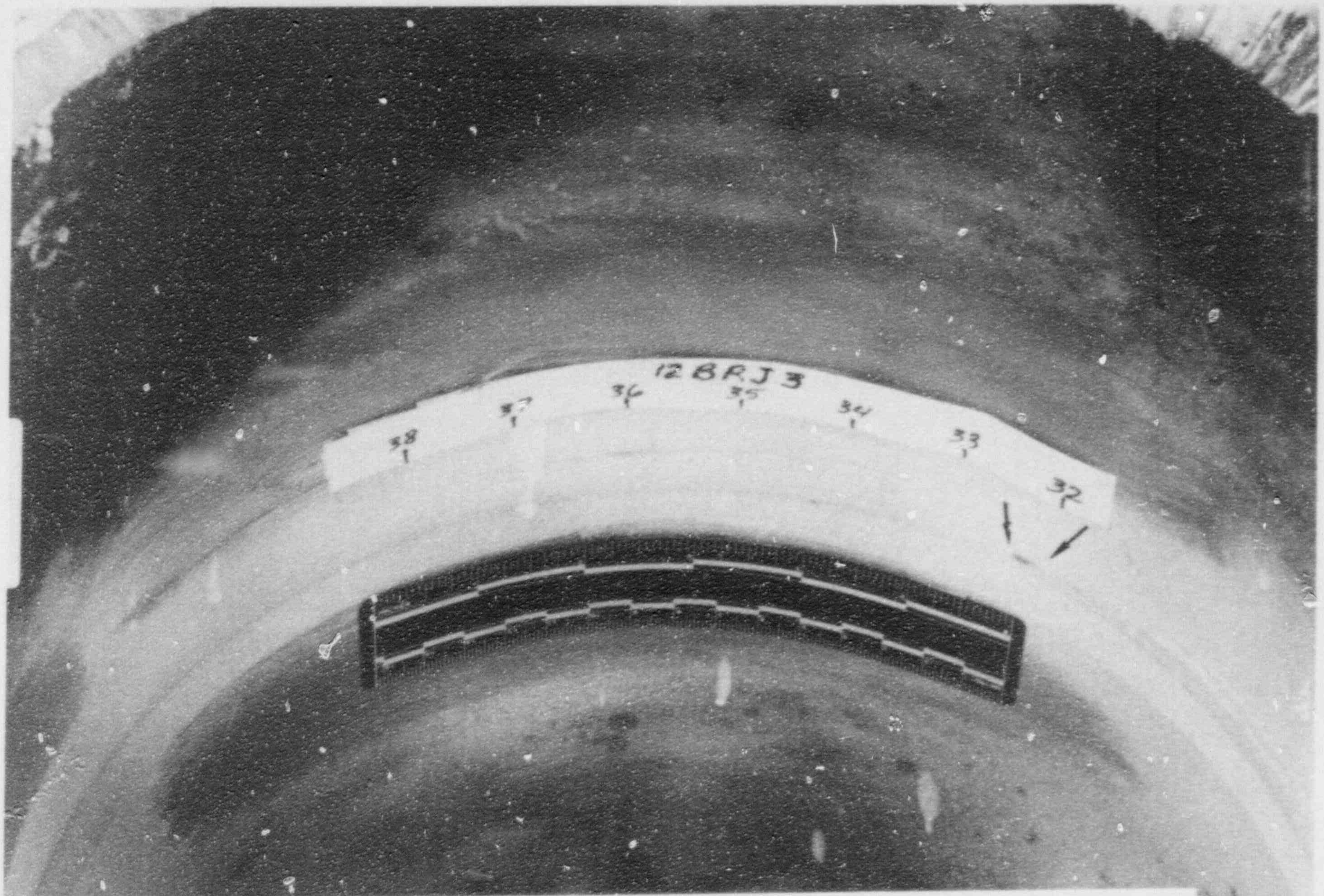


Figure 15 A second indication (~3/8" long) was seen on 12BRJ3 at station marker 32 (arrows).

After the x-ray radiography was completed, BNL repeated its inspection of the overlays and recorded the locations of all markings on the pipes which could be zero marks. Possible marks included flow direction indicators ("F" next to an arrow), a 5-dot pattern which looked like the 5 on gambling dice, and one pipe, a dotted "V."

BNL communicated with General Electric (GE), the contractor which had installed the overlays, and clarified the locations of the zero points GE had used for installing and evaluating the overlays. The original pipe had zero points which consisted of interrupted dot "V" marks, with the "V" aligned circumferentially in the direction of increasing station numbers. Unfortunately, the original zero marks were probably covered by the overlay, (according to the GE contact person). BNL pointed out that the zero mark on 12BRG4 (the straight pipe to "pup" weld) was visible, and that the overlay for the elbow welds were the main concern. The rules GE used for placement of their zero marks on elbow welds follow:

1) The zero point is along the outer radius of the elbow;
2) station numbers increase circumferentially using the right hand rule;
3) the "thumb" for the right hand rule points in the direction of water flow;
4) station numbers are placed on the downstream edge of the overlay.

According to General Electric, the 5-dot pattern markings were placed on the pipes to monitor shrinkage, and that there should be four spaced uniformly on each pipe on either side of the overlays. GE stated that the flow direction marks had been placed by the utility on the overlay-pipe sections after the sections had been removed from service.

Using the above information, two tables were prepared. Table 1 shows the GE zero point and the flow mark locations in terms of BNL station numbers and the rule (right- or left-hand) which applies to BNL station numbers. Table 2 correlates the BNL station numbers with those GE used. These numbers are approximate since the fractional space between the last mark (40 or 41) and the zero point was assumed to be one inch for this correlation. This process for correlation of station numbers was reviewed with GE personnel at San Jose and determined to be accurate when comparing the BNL numbering system to the GE labeling procedure [1].

Table 1 Mark locations and numbering rules.

Overlay	Mark or Feature	BNL Station Number	Comment
12BRJ2	F (with arrow) elbow outer radius 0> (BNL zero) BNL station nos.	2¼ 3 0	BNL Nos. left-hand to arrow. BNL Nos. right-hand to ">" upstream side of overlay.
12BRJ3	F (with arrows) elbow outer radius 0> (BNL zero) BNL station nos.	37½ 36½ 0	BNL Nos. right-hand to arrow. BNL Nos. left-hand to ">" downstream side of overlay.
12BRK3	F (with arrow) elbow outer radius 0> (BNL zero) BNL station nos.	½ 3 0	BNL Nos. left-hand to arrow. BNL Nos. left-hand to ">" downstream side of overlay.
12BRG4	F (with arrow) dotted ">" 0> (BNL zero) BNL station nos.	4½ 2 0	BNL Nos. right-hand to arrow points to station No. 3 BNL Nos. left-hand to ">" downstream side of overlay.

Table 2 Correlated station numbers[a]

Overlay 12BRJ2		Overlay 12BRJ3		Overlay 12BRK3		Overlay 12BRG4	
BNL	GE	BNL	GE	BNL	GE	BNL	GE
0	3	0	4.5	0	3	0	40
1	2	1	5.5	1	2	1	41
2	1	2	6.5	2	1	2	0
3	0	3	7.5	3	0	3	1
4	40	4	8.5	4	40	4	2
5	39	5	9.5	5	39	5	3
6	38	6	10.5	6	38	6	4
7	37	7	11.5	7	37	7	5
8	[illegible]	8	12.5	8	36	8	6
9	35	9	13.5	9	35	9	7
10	34	10	14.5	10	34	10	8
11	33	11	15.5	11	33	11	9
12	32	12	16.5	12	32	12	10
13	31	13	17.5	13	31	13	11
14	30	14	18.5	14	30	14	12
15	29	15	19.5	15	29	15	13
16	28	16	20.5	16	28	16	14
17	27	17	21.5	17	27	17	15
18	26	18	22.5	18	26	18	16
19	25	19	23.5	19	25	19	17
20	24	20	24.5	20	24	20	18
21	23	21	25.5	21	23	21	19
22	22	22	26.5	22	22	22	20
23	21	23	27.5	23	21	23	21
24	20	24	28.5	24	20	24	22
25	19	25	29.5	25	19	25	23
26	18	26	30.5	26	18	26	24
27	17	27	31.5	27	17	27	25
28	16	28	32.5	28	16	28	26
29	15	29	33.5	29	15	29	27
30	14	30	34.5	30	14	30	28
31	13	31	35.5	31	13	31	29
32	12	32	36.5	32	12	32	30
33	11	33	37.5	33	11	33	31
34	10	34	38.5	34	10	34	32
35	9	35	39.5	35	9	35	33
36	8	36	40.5	36	8	36	34
37	7	37	0.5	37	7	37	35
38	6	38	1.5	38	6	38	36
39	5	39	2.5	39	5	39	37
40	4	40	3.5	40	4	40	38
						41	39

a) Assumes that the fractional space between highest station and zero point is exactly one inch.

4. SECTIONING AND STRAIN GAGE MEASUREMENTS/FERRITE MEASUREMENT

Early in the investigation, procedures were developed to determine the residual stresses of the welds in areas where cracks were identified. To accomplish this, strain gages were installed adjacent to and across selected cracks in the welds on the interior of the pipe sections and on the outer pipe circumference at locations corresponding to the interior surface strain gages. The gages were zeroed before the pipes were sectioned, then readings were taken after the pipes had been cut.

Three non-destructive tests were conducted before the strain gages were installed: dye-penetrant examinations, ferrite measurements, and x-ray radiography. All three are described elsewhere in the report. The dye-penetrant tests revealed several probable crack locations in each pipe. The crack locations formed the basis for the pipes' initial sectioning plan; Table 3 lists the station numbers identifying the sections of interest. (The station numbers for the sectioning plan were the same as those used for the x-ray radiography tests. The numbers represent inches measured from an arbitrary zero point on the outer diameter of the pipe along the edge of the overlay.) The overlays were cut into sections with a band saw to avoid the possibility of heat affecting the strain gage measurements. The cuts were made in accordance with the attached cutting sheets (Attachments 1-4).

Table 3 Locations of section cuts[a]

Overlay Identification No.	Station Locations
12BRJ2	from 13 to 16
12BRJ2	from 22 to 26
12BRJ3	from 5 to 9
12BRJ3	from 34 to 38
12BRK3	from 4 to 8
12BRK3	from 30 to 34
12BRG4	from 15 to 18
12BRG4	from 21 to 34
12BRG4	from 34 to 39

[a] Station numbers are same as those used in x-ray radiography tests.

Precision strain gages from Measurements Group, Inc. (Micro-Measurements Division, Raleigh, NC, gage type CEA-09-250UN-120) were used to make the measurements. The gages were installed following the procedures provided by Micro-Measurements (M-M). Installation included the following steps: surface preparation, gage attachment with epoxy, and soldering electrical lead wires to the gages.

Surface preparation consisted of cleaning the area of interest with a carbide grinder, then degreasing with acetone and methanol. The areas of interest were approximately 5 cm by 5 cm (2 in. by 2 in.) squares at the middle of cracks which had been identified earlier using dye-penetrant tests. Two squares, one on the crack (pipe interior) and one on the pipe exterior surface at the same location, were prepared. The squares were large enough to install two strain gages.

Epoxy resin obtained from M-M (M-Bond AE-10) was applied to the clean metal surface and the gages, and the gages were mounted on the surface aligned perpendicularly to the crack (along the axis of the pipe) using tape (as described in M-M Instruction Bulletin B-137-11). A slight pressure load (less than 30 psi) was applied to the gages while the epoxy cured for a minimum of 12 hours. After the epoxy cured, the tape was removed and the strain gages were cleaned with the methanol. Then wire leads were soldered to the strain gages via separate terminal blocks and jumper wires (Measurements Group Technical Bulletins TT-603 and TT-609).

The strain gage measurements consisted of determining the electrical resistance of the gage before and after pipe sectioning. Before sectioning, the gages' resistances were measured ("zeroed" in a resistance bridge) with a strain gage readout device. Following sectioning, the gages' readings were obtained with the readout system, which automatically converts gage resistance to units of micro-inch/inch.

Table 4 lists the strain gage results for each overlay. Except for overlay 12BRG4, one location on each pipe was tested. Since 12BRG4 had the largest cracks, strain gage tests were made at two locations.

The strain gage readings were, for the most part, consistent with what was expected. Positive readings show that the strain gages experienced tensile stress. Conversely, negative readings indicate that the gage underwent compression. These readings are useful in that the stress state of the overlay, before the sections were cut, is opposite to the readings obtained with the gages after the cuts are made. Thus, a positive gage reading indicates a compressive residual stress, while a negative gage reading results when the overlay had a tensile compressive stress.

The strain gage readings for overlays 12BRJ2, 12BRJ3, and 12BRK3 were all consistent in showing compressive residual stresses on the inner diameter. For overlay 12BRG4, gages 17 and 18 at station 29 show compressive stresses, while at station 38, only gage 14 indicated a compressive stress. Gage 13 immediately adjacent to gage 13 had a negative value, suggesting a tensile stress. However, the reading on this gage fluctuated from -166 to -526. The reason for the instability in the reading is not n, and the results for gage 13 should be considered tentative because of the unstable reading.

Six of the ten strain gage readings on the outer diameters of the overlays were negative, corresponding to residual tensile stresses. Three of the four exceptions, gages 11, 12, and 20 were not measurable, showing open circuits when attached to the gage readout system. Gage 19 had a positive reading, indicating a compressive stress on the outer surface of the overlay.

The last column of Table 4 depicts the stress measurements obtained when the strain gage data was entered into the formula:

$$E(Modulus\ of\ Elasticity) = \frac{\sigma(Stress)}{e(Strain)}$$

The Modulus of Elasticity chosen was 27.6 X 10^6 psi [14] for 18-8 stainless steel.

It is readily evident from the table that the stress distribution in 12 BRG-4 pipe is markedly different than that seen in the other pipe sections. The reading at gage 13 shows a tensile stress in an area where residual compression should be the norm and its adjacent gage (14) only attained 3.42 ksi compression while comparable sections were in excess of 10 ksi compression on the inside pipe surface.

Table 4 Strain gage data

Pipe and Station Number	Gage No	Strain (μin/in)	Position on Pipe	Stress** (Ksi)
12BRJ2 - 14	1	751	ID	20.73C
	2	543	ID	14.99C
	3	-1164	OD	32.13T
	4	-1144	OD	31.57T
12BRJ3 - 35	5	491	ID	13.55C
	6	392	ID	10.82C
	7	-1291	OD	35.63T
	8	-1147	OD	31.66T
12BRK3 - 5	[illegible]	843	ID	23.27C
	[illegible]	897	ID	24.49C
	[illegible]	open	OD	--
	[illegible]	open	OD	--
12BRG4 - 38	13	-526*	ID	14.52T
	14	124	ID	3.42C
	15	-217	OD	5.99T
	16	-184	OD	5.08T
12BRG4 - 29	17	26	ID	7.18C
	18	319	ID	8.80C
	19	74	OD	2.04C
	20	open	OD	--

*readings fluctuated from -166 to -526.
**C = Compressive Stress
T = Tensile Stress

After the strain gage measurements were performed, the various sections were cut into smaller pieces for optical microscopy, electron microscopy and microhardness measurements.

Prior to the sectioning and strain gage measurements of the four pipe sections, ferrite measurements were done on all four pipes' outside surfaces (weld overlay area). The requirement for ferrite control and content in austenitic stainless steel welds has been documented in at least two Regulatory Guides [1,2] and is considered a first order defense against microfissuring and SCC prevention in the deposited weld metal. Additionally [3], at least one study considers the role of delta ferrite quite important in reducing the susceptibility of austenitic materials to intergranular cracking.

The instrument used to make the ferrite readings on the specimens was a Ferritescope. The ferritescope operation (according to its manufacturer) "...is based on a magneto-induction principle, whereby the relative permeability of the specimen (which bears a known relationship to its ferrite content) is measured.

When the probe is place on the material to be tested, a closed magnetic circuit is formed and excited by a low-frequency magneto-motive force. The resultant field induces a voltage in a pick-up coil (located in the probe), the magnitude of which is a measure of the relative permeability and hence the ferrite content of pick-up coil is amplified in a meter unit and the resultant amplitude indicated on a meter which is calibrated in either % Fe or WRC ferrite figures.

The configuration of the alternating field in the material is governed primarily by the construction of the probe, this being designed so as to minimize any field attenuation due to eddy currents and thus eliminate the effect of material conductivity from the measurement..."

The instrument was recalibrated after each specimen was set in order to assure accurate readings. Measurements were taken at three points of the overlay at each of the station locations. The "A" reading is on the overlay near the thinner of the two pipe sections joined; the "B" reading in the center of the overlay; and the "C" reading near the thicker of the pipe sections. Table 5 tabulates the readings by pipe and station number. It is evident that the majority of the readings are ferrite number (FN) 8.0 or greater to approximately FN 13.3. The only readings less than 8.0 were the four readings on 12BRG4: 7.3, 7.5, 7.9 and 7.9. All of the "as deposited" ferrite readings measured would be considered acceptable in making a weld overlay.

Table 5 Ferritescope data (% ferrite)

Station No.	Pipe 12BRJ2 A	B	C	Pipe 12BRJ3 A	B	C	Pipe 12BRK3 A	B	C	Pipe 12BRG4 A	B	C
0	10.3	10.8	11.9	9.3	10.5	8.7	9.8	11.3	12.3	10.0	8.7	8.3
1	9.5	11.5	11.4	10.0	10.4	9.4	9.0	10.5	10.0	8.7	8.7	8.6
2	10.2	11.0	11.5	10.8	10.0	10.7	9.1	9.3	9.6	9.1	8.2	8.0
3	10.2	10.8	12.1	10.8	11.0	10.8	10.3	11.7	9.2	8.4	9.2	9.0
4	10.2	11.0	12.2	10.2	10.0	11.5	10.3	11.6	8.8	8.7	9.0	7.3
5	10.0	11.6	11.5	10.3	10.2	9.7	9.8	9.4	10.3	8.7	8.3	7.9
6	9.9	11.0	11.4	10.1	10.4	10.0	9.7	10.6	9.7	8.5	9.3	9.2
7	9.5	11.6	10.9	11.5	11.2	12.9	9.2	9.9	8.8	9.2	8.7	8.1
8	10.0	10.8	10.7	10.8	10.4	12.8	9.6	11.2	9.3	9.2	8.4	7.9
9	9.5	11.1	10.8	11.0	12.0	11.8	9.7	11.3	9.3	8.9	8.7	8.1
10	9.5	10.9	11.0	11.0	11.0	12.5	9.8	9.8	9.4	8.6	8.4	9.0
11	10.3	11.2	11.6	10.5	11.3	11.7	9.4	9.5	9.2	9.8	8.2	8.2
12	10.3	10.5	12.5	10.5	10.7	13.2	9.8	11.5	8.7	11.2	9.5	9.3
13	*	10.8	11.3	10.5	10.2	13.2	9.3	11.3	9.7	10.3	9.7	8.2
14	9.0	10.5	12.5	11.9	10.6	12.8	9.1	11.3	8.7	10.7	9.0	8.6
15	9.2	SG	11.8	10.7	9.8	12.0	9.0	10.6	9.9	10.0	9.2	7.5
16	10.5	10.8	12.2	10.3	9.7	13.0	9.5	11.5	9.0	10.8	9.4	9.2
17	10.5	11.2	12.2	9.5	13.0	12.7	10.6	10.8	9.9	10.4	9.4	9.0
18	9.3	10.7	12.0	11.2	10.5	13.2	9.8	12.3	10.6	10.6	8.7	10.3
19	9.6	11.3	11.8	10.2	9.9	13.0	10.3	10.6	10.0	10.7	8.8	9.6
20	10.7	10.4	12.5	10.4	11.8	13.3	10.0	11.2	9.5	11.5	8.2	8.9
21	8.3	10.7	12.6	10.7	12.4	12.4	10.2	11.2	8.8	10.9	8.3	8.4
22	9.2	11.7	12.1	9.7	12.5	11.3	10.1	10.8	10.3	11.7	8.9	9.2
23	10.2	11.0	12.8	10.3	12.1	11.3	10.6	12.1	10.5	11.8	8.8	10.6
24	10.0	10.0	12.8	10.3	11.5	9.3	10.2	11.5	9.7	10.7	9.6	10.7
25	11.1	11.7	12.4	9.6	12.1	8.7	10.8	12.0	9.4	10.3	9.3	10.0
26	10.7	10.2	12.5	9.9	11.6	9.8	10.7	11.2	10.0	10.2	8.3	8.9
27	11.1	11.2	12.0	9.9	11.9	9.2	10.2	11.7	8.8	11.1	9.5	10.5
28	11.3	11.4	12.7	9.8	9.8	9.7	10.7	11.7	10.0	9.8	9.1	10.5
29	13.2	11.8	13.0	10.0	11.4	10.2	10.6	10.8	8.4	9.0	9.2	11.4
30	9.3	11.7	11.9	10.0	10.8	9.7	10.1	11.6	9.2	8.5	9.2	11.2
31	11.4	10.0	13.3	9.3	10.5	10.7	10.1	11.7	8.5	8.4	8.4	10.2
32	9.7	11.2	12.6	8.9	10.0	10.0	10.9	11.8	9.4	8.9	9.8	11.1
33	9.2	11.3	12.4	10.5	9.2	10.1	10.2	10.8	9.7	9.7	9.0	9.3
34	8.7	10.9	12.3	9.7	9.6	9.1	10.6	11.2	9.7	10.0	8.7	9.0
35	11.1	12.2	12.6	9.3	10.9	10.5	10.0	11.9	9.4	10.3	10.0	9.0
36	10.5	10.1	13.2	10.0	10.3	10.2	10.4	11.3	8.9	10.4	8.8	8.5
37	11.2	11.6	12.6	10.2	11.0	9.3	10.5	11.3	9.7	9.7	9.9	9.6
38	9.3	11.0	12.5	9.9	11.0	9.3	10.0	12.7	9.2	10.6	9.3	9.4
39	9.7	10.3	12.3	10.0	10.8	9.1	10.0	11.2	9.6	9.0	8.7	8.6
40	9.8	10.5	12.3	9.2	11.7	9.1	9.1	11.0	12.6	9.4	8.6	8.1
41										9.2	8.7	9.6

5. OPTICAL MICROSCOPY

The various cut sections (resulting from the strain gage measurements) were further sectioned into smaller specimens suitable for optical microscopy. These specimens were ground, metallurgically polished using ASTM A-262, Practice A oxalic acid etching.

Intergranular corrosion is commonly defined as a local attack on the grain boundaries of a metal by a corrosive media.

In stainless steel, susceptibility to intergranular corrosion is enhanced by the sensitization process. Sensitization can be described as the formation of chromium carbide precipitates in the grain boundaries of an austenitic stainless steel and the resultant depletion of Cr, brought about by heating the steel in the temperature range 500-800°C [4,5].

This temperature range is achieved readily during the welding process where the normal temperature of welding exceeds 1600°C during fusion welding. Therefore, the welded base material could receive a sensitizing heat treatment in the critical range (500-800°C) at some point outward from the weld fusion line which would be maintained long enough to precipitate Cr carbide at the grain boundaries. This is not to say that the welding process alone will induce a sensitization effect on the base material, as the degree of material sensitization is a cumulation of the material's prior thermal and mechanical treatments, weld cycle history, (number of passes, heat input, etc.) material chemistry, thickness and thermal conductivity, and time at temperature in the sensitization range.

In order to measure a materials' degree of sensitization, the American Society for Testing and Materials (ASTM) has published Standard A-262, "Standard Recommended Practices for Detecting Susceptibility to Intergranular Attack in Stainless Steels." This standard includes a rapid screening test: Practice A - Oxalic Acid Etch Test for Classification of Etch Structures of Stainless Steels. This practice is described in A-262 as: "1.3 The oxalic acid etch test is a rapid method of identifying, by simple etching, those specimens of certain stainless steel grades which are essentially free of susceptibility to intergranular attack associated with Cr carbide precipitates. These specimens will have low corrosion rates in certain corrosion tests and therefore can be eliminated (screened) from testing as 'acceptable.'"

For purposes of this investigation, the polished specimens were etched with a current density of ~1 A/cm^2 for 1.5 min. in a 10% oxalic acid + demineralized water solution. The cathode used for the etching was a piece of 304 stainless steel while the polished specimen was used as the anode. The welded cross sections were then examined on a metallograph.

The results of the etching are shown in the metallurgical cross sections photographed in this part of the report. In all cases, the structures observed had at least one grain completely "ditched" which would have classified the structure as sensitized.

Table 6 is a listing of all of the cross sectioned examined and the location (marker number) where each section was cut. The twenty-one sections which were polished were removed from sections where the dye penetrant examination had indicated that a discontinuity was present. Eleven cracked cross sections were revealed from the twenty-one sections cut. Of the four pipes examined, only 12BRK3 had no cracks evident after sectioning.

Table 6 Identification of metallurgical sections cut for metallography.

Specimen Identification	Location	Comments
G4B1 (Pipe 12BRG4)	16	Cracked
G4B2	16-17	Cracked
G4D1	25	Not cracked
G4D2	28½	Cracked
G4D3	28½-29	Cracked
G4d4	30	Cracked
G4D5	30-31	Cracked - examined by SEM
G4D6	31-32	Cracked
G4E1	38	Cracked
G4E2	38-39	Cracked
J2B (Pipe 12BRJ2)	14½	Not cracked
J2C	14½-15	Not cracked
J2E1	22	Cracked
J2E2	23	Not cracked
J3B1 (Pipe 12BRJ3)	7½	Not cracked
J3B2	7½-8	Not cracked
J3D	32	Cracked
K3B1 (Pipe 12BRK3)	6 3/4	Not cracked
K3B2	6 3/4 - 7	Not cracked
K3D1	32½	Not cracked
K3D2	32½-33	Not cracked

Pipe 12BRG4

With the exception of two axial cracks (Figure 21) all of the cracks associated with this weld were circumferential in direction. The cracks were intergranular in appearance (Figures 16 - 23) and all were associated with the heat affected zone (HAZ) of the original weld. The cracks all initiated on the inside surface of the subject weld and were located on the pipe side (not pup piece) of the weld.

The nominal wall thickness for this pipe was approximately 0.7" (18mm). The cracks examined ranged from a minimum (0.132", 13.5mm) between stations 16-17 to a maximum of 0.738" (18.7mm) at station 29. The longest crack (Figure 18) propagated through the entire thickness of the pipe and stopped just short (less than 0.010", 1.25mm) of the weld overlay in the section examined. Some of the cracks examined (Figures 19, 20, 21) penetrated into the original weld metal (not the overlay) for a few grains. A circumferential crack (Figure 20) had two axial cracks associated with it (Figure 21). These cracks ranged in depth from 0.246" (6.25mm) deep (penetrated a few microns into the weld) to 0.282" (7.2mm) deep.

One crack was seen on 12BRG4 (Figure 22) which was not seemingly associated with the pipe's inside surface. This crack was 0.308"(7.8mm) in length and did not intersect the inside pipe wall at the location of the section (marker 31).

A 0.584" (14.8mm) long crack was located at marker 38 on 12BRG4 (Figure 23). This crack barely penetrated the weld zone (etched structure).

12BRJ2

A 0.200" (5.1mm) long array of intergranular cracking (Figure 24) was associated with this weld at marker 22. The crack was exceedingly branched and initiated at the fusion zone (original weld root) and heat affected zone interface. The crack had the appearance of entering the weld metal (original weld) and then traveling some distance through wall until it entered the weld metal further along the crack path.

12BRJ3

Figure 25 is a photomicrograph of a 0.328" (8.3mm) long crack associated with the weld's heat affected zone. This crack was located at marker 28½; was circumferential in direction and appeared to have started to propagate into the original weld metal deposit.

Some additional ferrite readings were performed on selected cross-sections. These were performed on the overlay area, the original weld metal and the base metal. Table 7 is a tabulation of the data. The readings (all above 7.0 for original weld metal on overlay) indicate that there was probably excessive weld metal to base metal dilution during the welding process at those locations where the cracks entered the original weld metal.

12BRK3

No cracks evident after cross sectioning and metallurgically polishing.

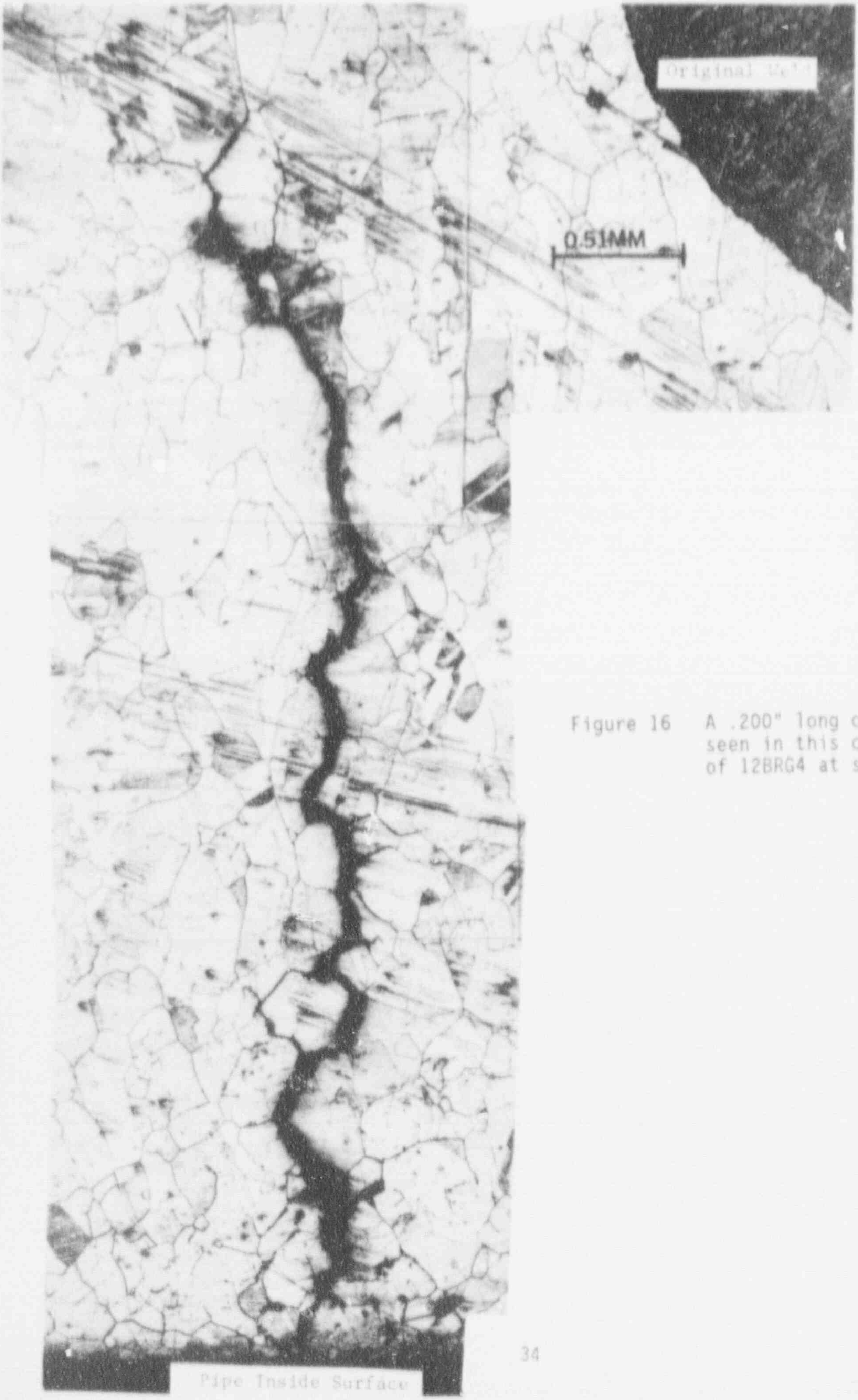
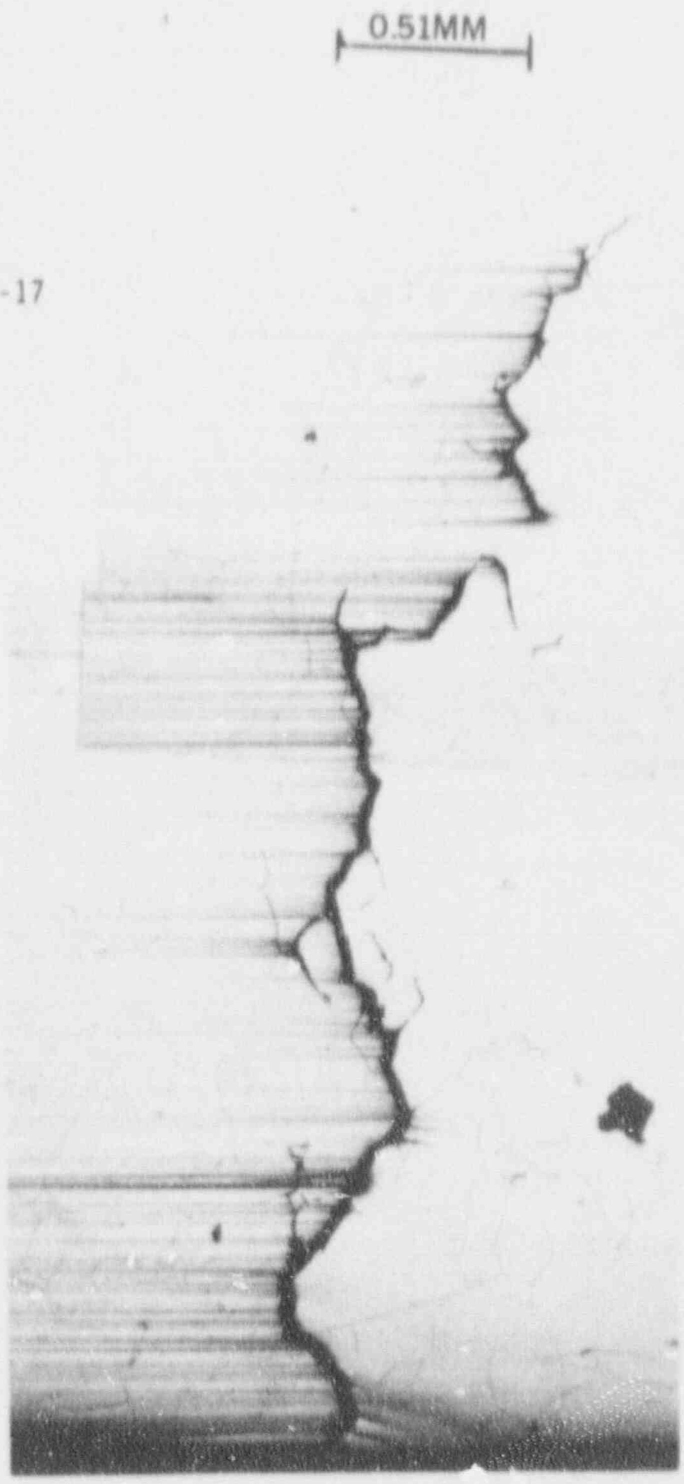


Figure 16 A .200" long crack was seen in this cross section of 12BRG4 at station 16.

Figure 17 A crack .132" long was seen between stations 16-17 on 12BRG4.



Pipe Inside Surface

Figure 18 A crack essentially "through wall" (up to weld overlay) was seen at station 29 on 12BRG4. The crack was .738" long.

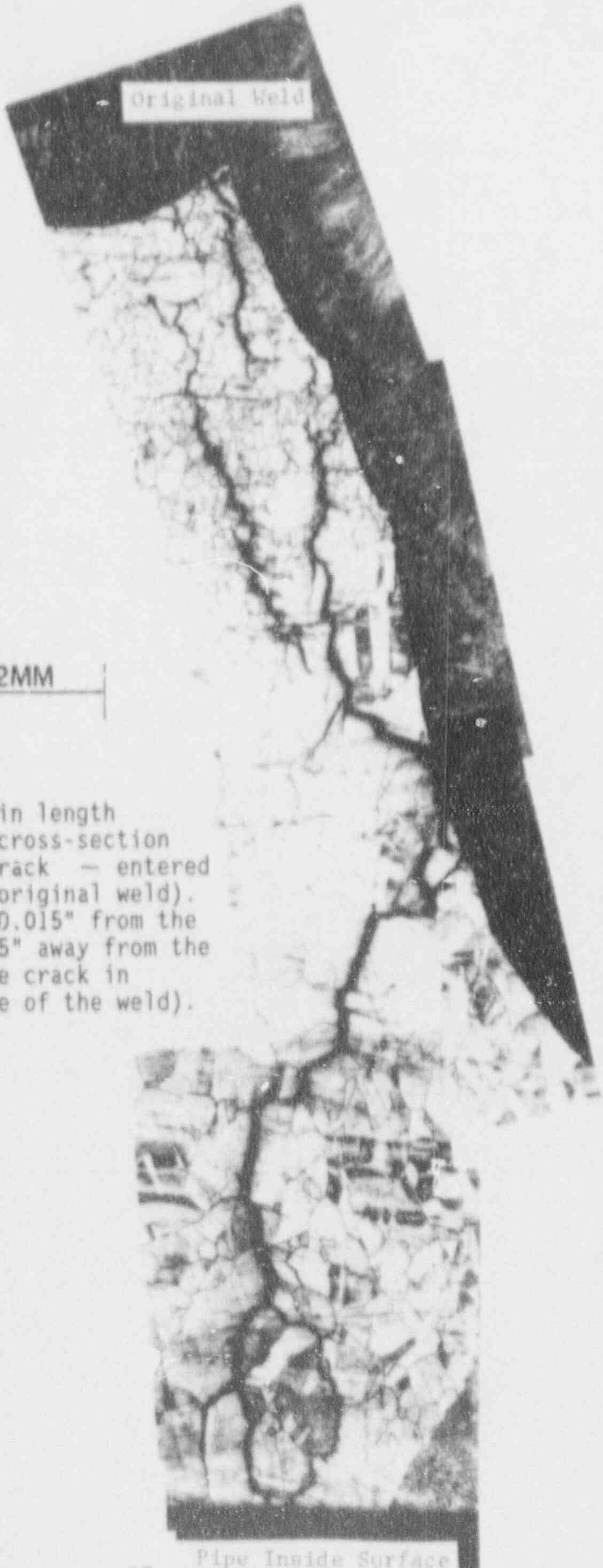


Figure 19 A second crack .266" in length was seen on the same cross-section at marker 29. This crack — entered into the weld metal (original weld). This crack initiated 0.015" from the weld root and was .255" away from the initiation site of the crack in Figure 18. (Same side of the weld).

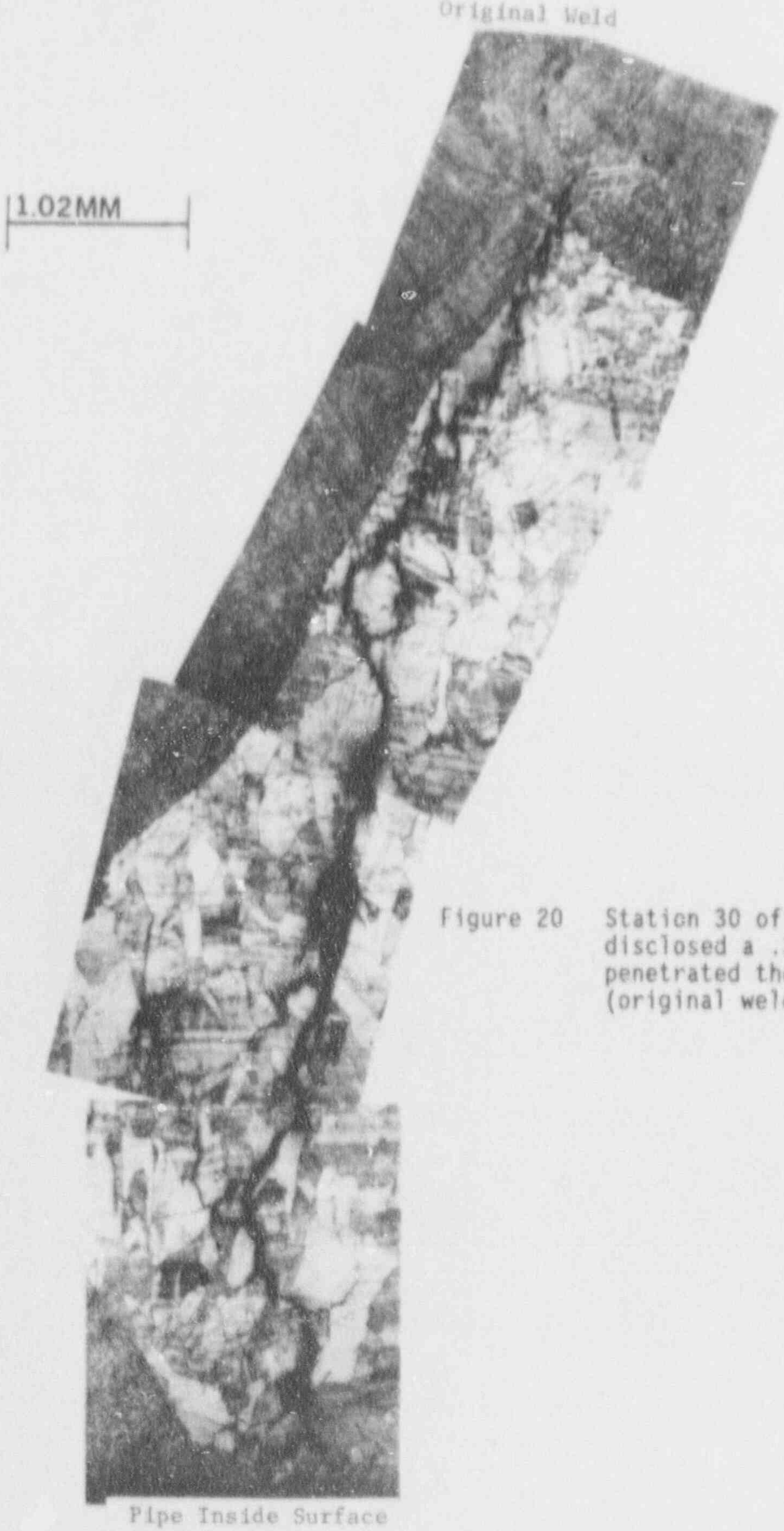


Figure 20 Station 30 of 12BRG4 cross section disclosed a .302" long crack which penetrated the weld metal deposit (original weld).

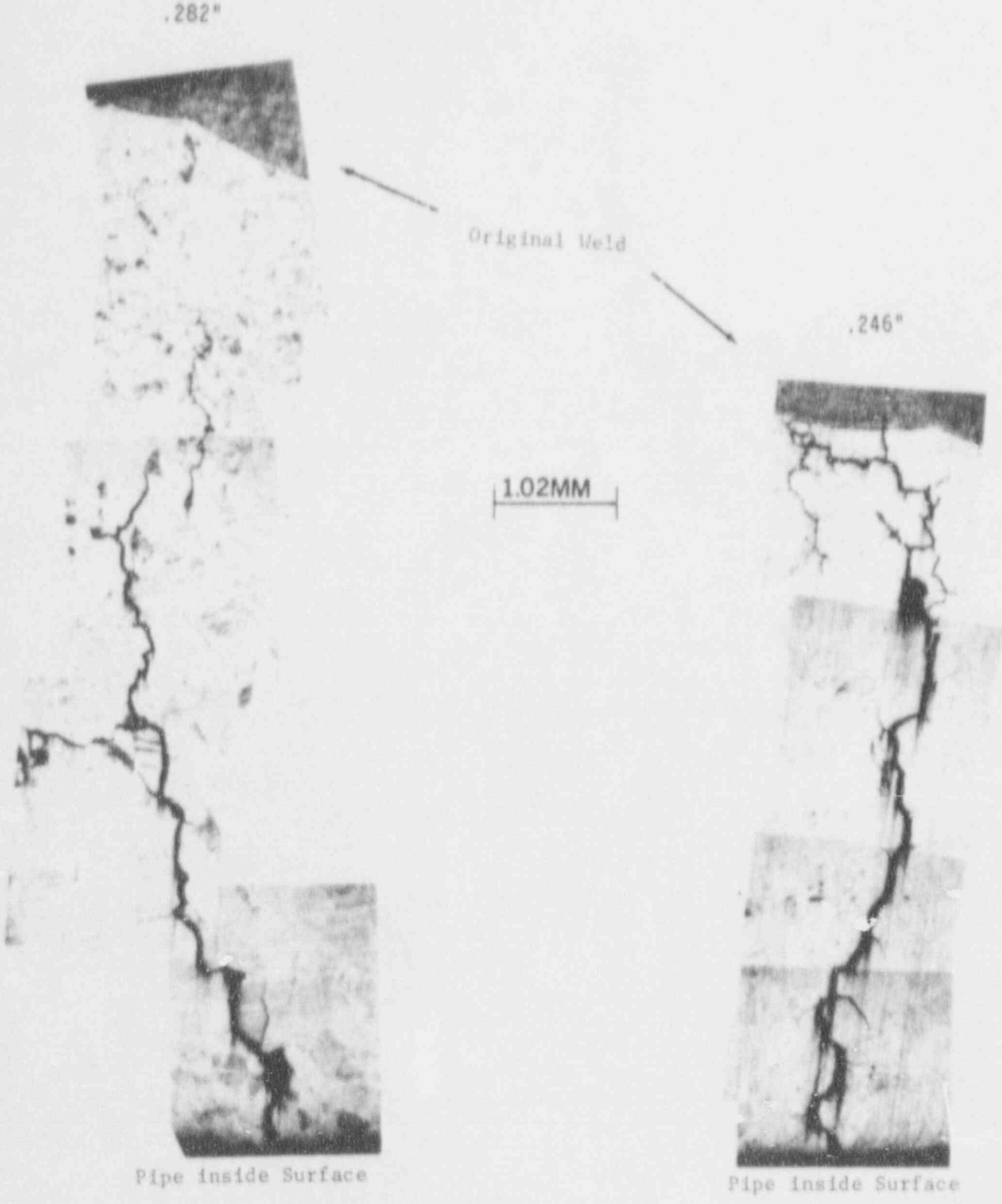


Figure 21 Two axial components were seen on a polished face perpendicular to the crack in Figure 20.

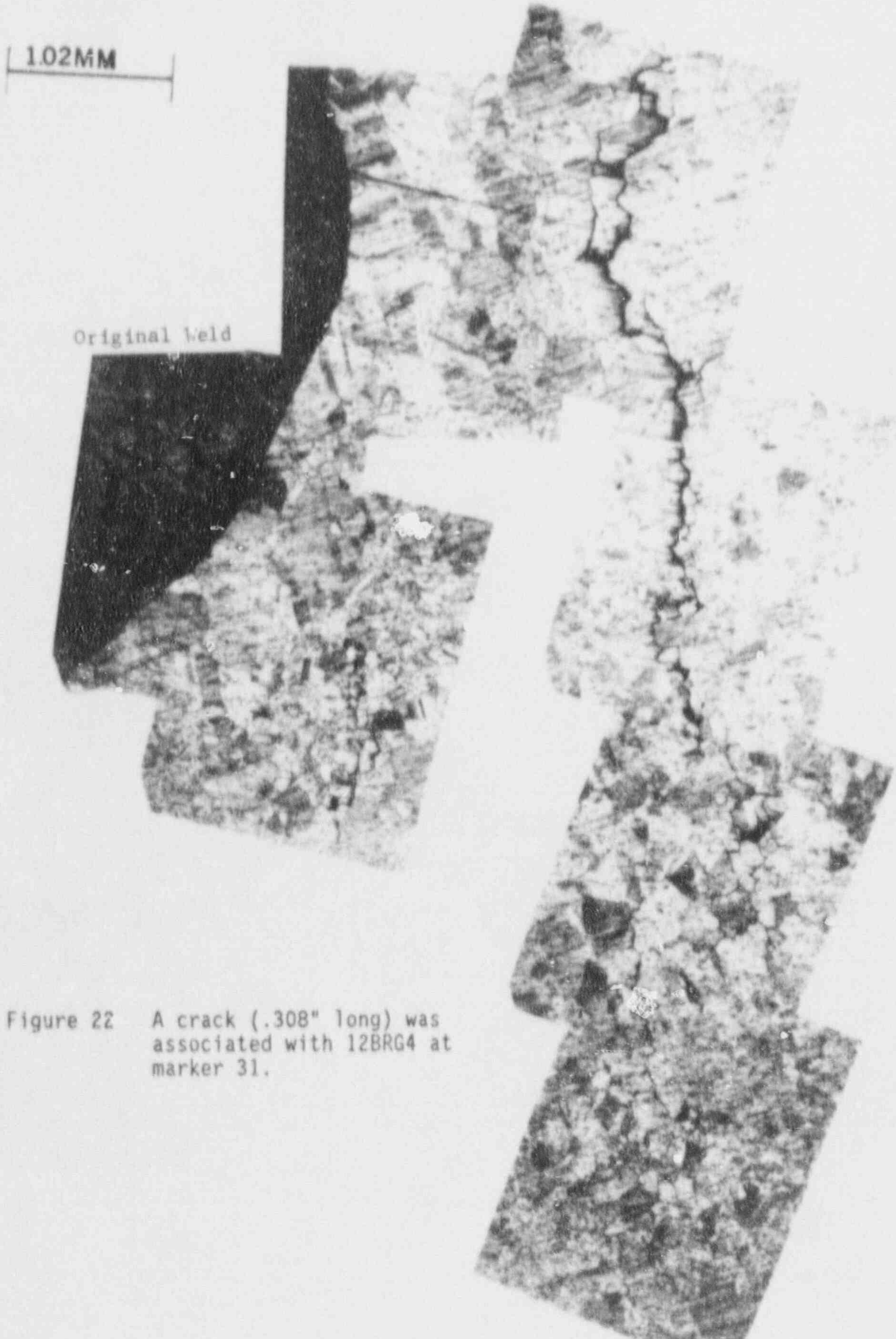


Figure 22 A crack (.308" long) was associated with 12BRG4 at marker 31.

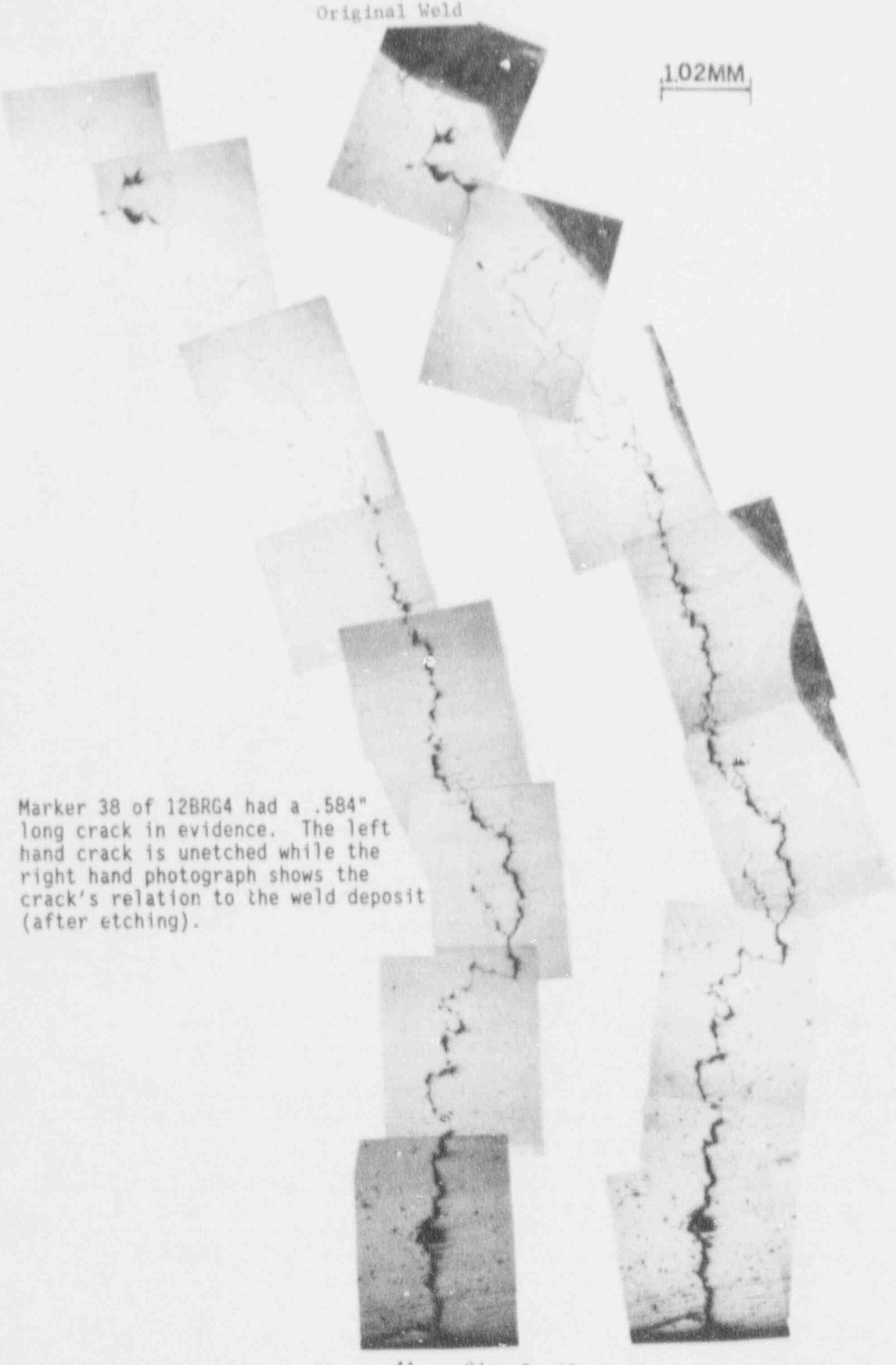


Figure 23 Marker 38 of 12BRG4 had a .584" long crack in evidence. The left hand crack is unetched while the right hand photograph shows the crack's relation to the weld deposit (after etching).

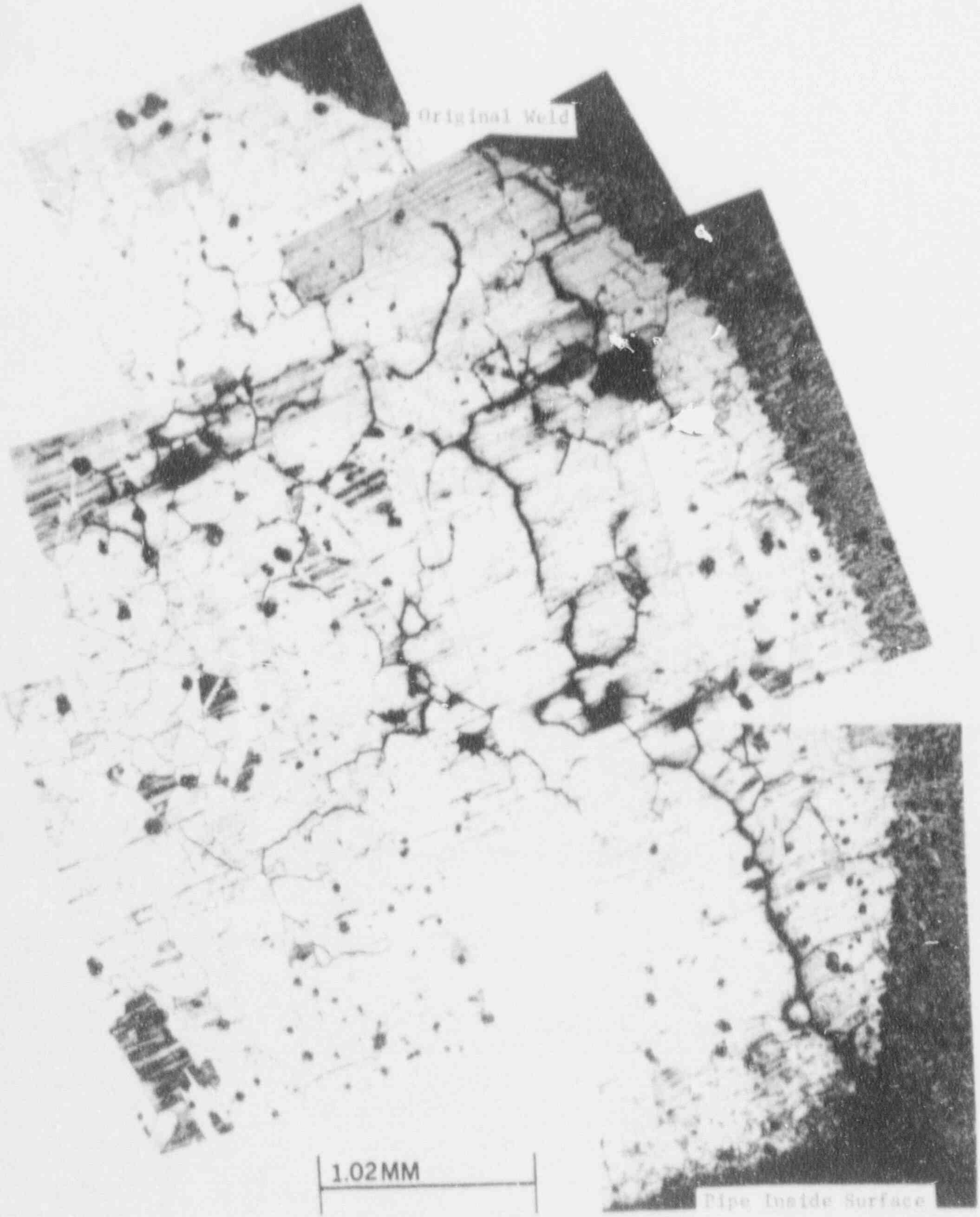


Figure 24 A .200" long array of cracks was seen at marker 22 of pipe 12BRJ2.

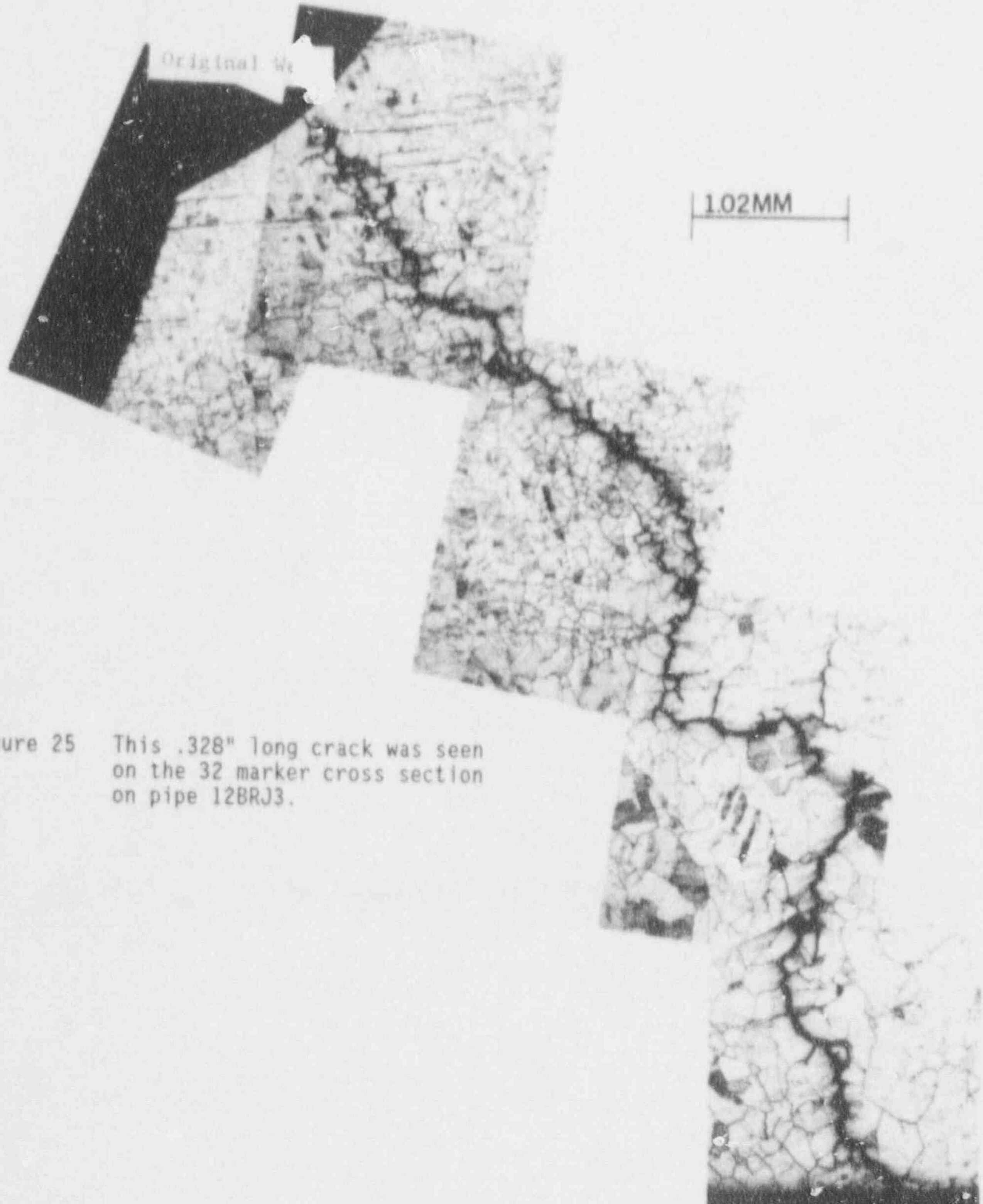


Figure 25 This .328" long crack was seen on the 32 marker cross section on pipe 12BRJ3.

Table 7 Ferrite readings on metallurgical cross sections

Pipe	Cross-section (marker location)	Ferrite Number
12BRG4	30	overlay - 10.5, 9.3, 10.7 original weld - 11.7 base metal - 0.1
12BRG4	16	overlay - 11.7, 11.2, 10.5, 9.6, 10.7 original weld - 7.2 base metal - 0.0, 0.5
12BRG4	28½	overlay - 9.4, 11.0, 9.9, 9.3, 10.5, 10.9 original weld - 11.4 base metal - 0.1

6. CHEMICAL ANALYSIS (BY WAVELENGTH DISPERSIVE SPECTROSCOPY)

Various methods of decontamination and cleaning operations (including metallurgical grinding and polishing) were performed on samples cut from the pipes in order to send out specimens for elemental chemical analysis. The piping material was radioactively activated (not contaminated). After cleaning it was found that these levels of activation precluded the offsite shipment of the samples for evaluation. The alternate chemical analysis technique of wavelength dispersive spectroscopy (WDS) was considered adequate to evaluate the alloying additions in the specimens.

WDS is an analytical technique, capable of performing elemental analysis of microvolumes, typically on the order of a few cubic microns in bulk samples and considerably less in thinner sections. Analysis of x-rays emitted from a sample is accomplished by crystal spectrometers which separate the x-rays from the individual elements present according to their characteristic wavelengths.

The feature of electron beam microanalysis that best describes this technique is its mass sensitivity. For example, it is often possible to detect less than 10^{-16} grams of an element present in a specific microvolume of a sample. The minimum detectable quantity of a given element or its detectability limit varies with many factors, and in most cases is less than 10^{-16} grams/microvolume. (Note: WDS will only detect elements with atomic numbers greater than 11 so certain light elements will not be detected.)

Twelve specimens from the four pipes (three from each section) were cut out. The specimens consisted of a sample from the individual overlay, base metal and original weld metal.

Each of the specimens were metallurgically ground, polished and analyzed by WDS. Each specimen was analyzed in three locations with the average composition for each sample recorded in Table 8. With the exception of the 12BRJ2 overlay (only 7.66% Ni), and the 12BRG4 weld metal (only 7.29% Ni) all the readings were within the range of values expected for the Type 304 stainless steel and type 308 weld metal. The typical values for the alloys are included in the table.

Table 8 Wavelength dispersive spectroscopy results

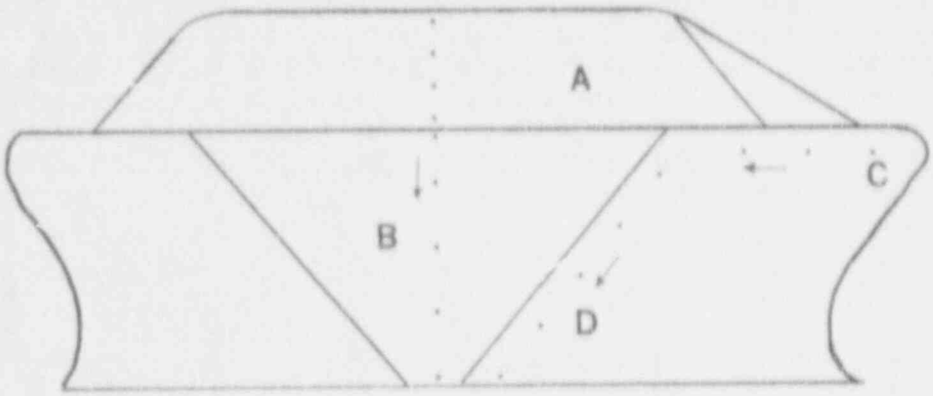
ANALYSIS OF STAINLESS STEEL (WEIGHT %)					
Sample	Fe	Cr	Ni	Mn	Si
J2S2 OVERLAY	67.93	21.92	7.66	1.62	0.87
J2S3 RING	69.85	18.89	8.50	1.82	0.94
J2S2 25-26	69.91	18.99	8.06	2.02	1.02
J3 RING A+32	69.72	19.20	8.03	1.98	1.06
J3S2 OVERLAY	67.21	20.44	9.59	1.87	0.90
J3S1 33-34	68.65	19.86	8.97	1.31	1.23
G4811 RING	70.88	19.12	7.29	1.80	0.91
G4S6 OVERLAY	67.38	20.70	9.18	1.90	0.84
G4S3 39-40	68.87	19.00	8.92	1.76	1.22
K3S3 34-35	68.14	19.85	9.09	1.94	0.98
K3S3 OVERLAY	67.43	19.36	10.64	1.85	0.88
K3S7 RING	69.23	18.91	9.40	1.35	1.12

Typical ASME 5.4, 308 Weld	Balance	18-21	9-11	0.5-2.5	0.90
Typical ASTM A240, Type 304SS	Balance	18-20	8-12	2.0	1.0

7. MICROHARDNESS MEASUREMENTS

In order to obtain an insight into the mechanical properties of a typical overlay weldment, one section of pipe 12BRG4 was cut, metallurgically ground and polished and then tested for microhardness. Table 9 shows a sketch of the specimen and the readings taken at various locations. With the exception of one hard spot near the outside edge of the overlay (overlay/pipe interface) the remainder of the readings were reasonably consistent for 304 stainless steel and for the type 308 overlay material.

Table 9 Microhardness readings



A - overlay
B - original weld
C - overlay/base metal interface (HAZ)
D - original weld HAZ

Arrows indicate direction of impression taking (1 ...N)
Impressions taken ~0.020"

<u>Area A</u> -	1 - 237.8	<u>Area B</u> -	1 - 217.4
	2 - 184.0		2 - 234.2
	3 - 196.9		3 - 228.4
	4 - 189.0		4 - 226.2
	5 - 193.3		

<u>Area C</u> -	1 - 342.6	<u>Area D</u> -	1 - 220.6
	2 - 202.4		2 - 206.2
	3 - 205.4		3 - 212.2
	4 - 202.4		4 - 231.8
			5 - 216.4

<u>Vickers hardness Numbers</u>:

6 - 193.3	11 - 205.4	16 - 220.6	21 - 217.4
7 - 187.3	12 - 211.2	17 - 215.4	22 - 222.8
8 - 195.1	13 - 226.2	18 - 215.4	23 - 225.0
9 - 196.9	14 - 222.8	19 - 211.2	
10 - 200.6	15 - 212.2	20 - 210.2	

8. SCANNING ELECTRON MICROSCOPY EVALUATION

Various specimens (with cracks in them) were notched and chilled to liquid nitrogen temperature. A counter force was applied to the notched area while one part of the specimen was locked in a vise. This method will open fractures with minimum damage to the fracture face.

One of the goals for this project was to determine if crack growth could have continued after weld overlay. Various methods of oxide stripping were tried to accomplish this end; to no avail. It was decided that the fractures to be examined would be deoxidized using an electrolytic process (described below) before further SEM examinations were done:

> A working solution of Endox-214 is prepared by adding 8 ounces of Endox-214 powder to 1000 ml of cold water and stirring until it is completely dissolved. A small amount of Photoflow is added to the solution to aid the wetting of the specimen and eliminate some of the featuring during the electrochemical cleaning step. A glass beaker with 500 ml of the Endox-214 solution is placed in an ultrasonic cleaner. The specimen is made the cathode, and a platinum wire loop is the anode. A current density of approximately 250 mA/cm^2 is applied for 15 seconds. Remove the specimen from the electrolyte and ultrasonically wash it in a detergent solution consisting of Alconox and Photoflow for one minute, then rinse in clean water, dip in methanol and dry in hot air. The above procedure comprises one cycle. It may be necessary to repeat the above cycle several times before removing all the corrosion products. It is not possible to predetermine the exact number of cleaning cycles for any given specimen, since it depends upon the severity of the oxidation, roughness of surface, and the physical size of the sample. Observe the specimen optically after each cycle so that the process can be discontinued after the oxide or the corrosion product is removed and the specimen surface looks clean. After the specimen is thoroughly dry, examine it immediately or store in a desiccator.

Figure 26 shows a fracture face after the treatment. The fracture was entirely intergranular (Figure 27). There was no evidence of beach marks (where crack growth may have ceased due to overlay) or any evidence that the crack did or did not propagate during service (after overly applied). The crack itself appeared to have just entered into the overlay (Figures 28a - c) and had sharp features to all of the intergranular facets. There was no definitive evidence of crack blunting; although the overlay ferrite values (recorded earlier) would indicate that blunting should have occurred or would eventually occur.

One of the smaller cracks on 12BRG4 was also examined (Figure 29). This crack was also entirely intergranular with no evidence of beach marks, etc.

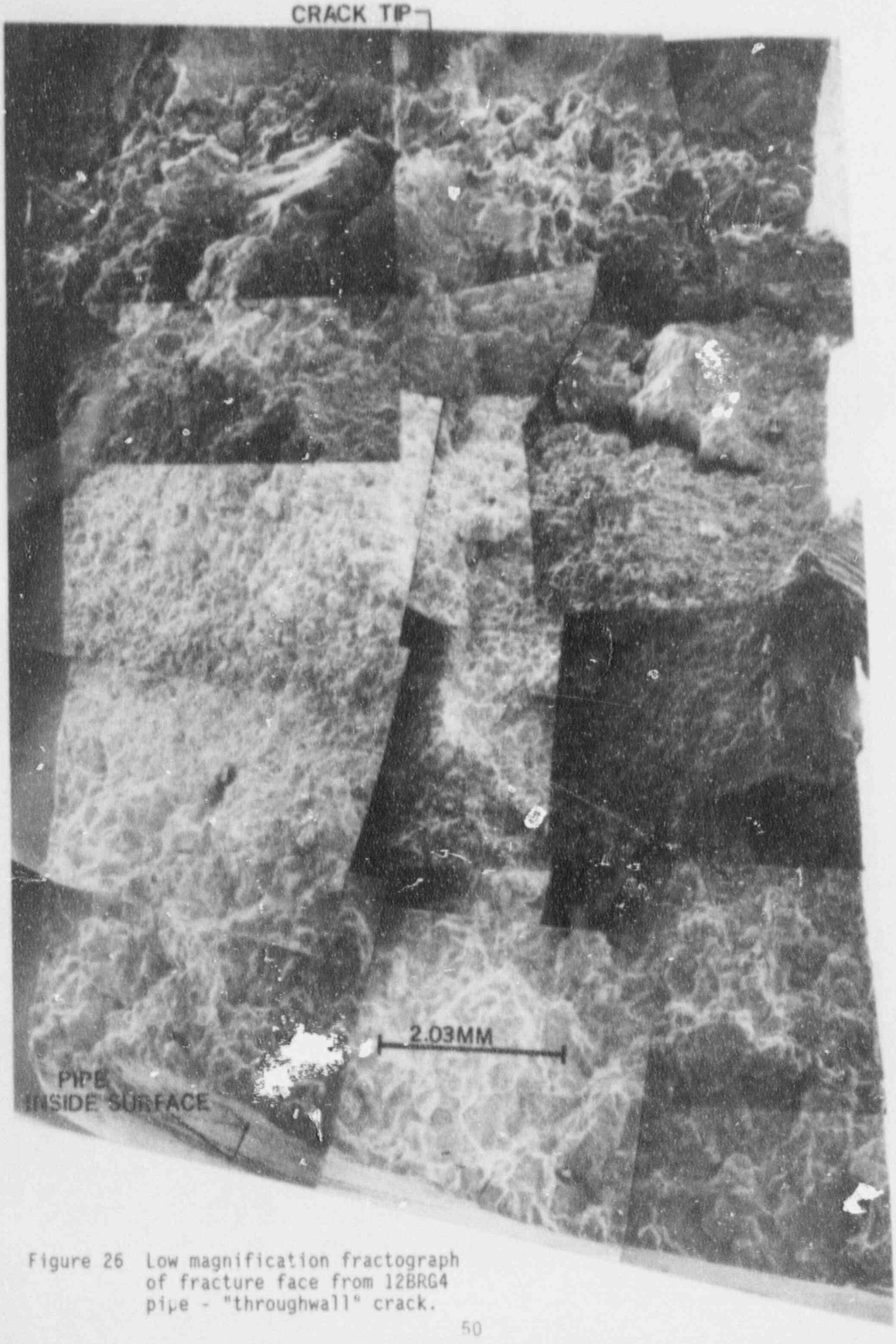


Figure 26 Low magnification fractograph of fracture face from 12BRG4 pipe - "throughwall" crack.

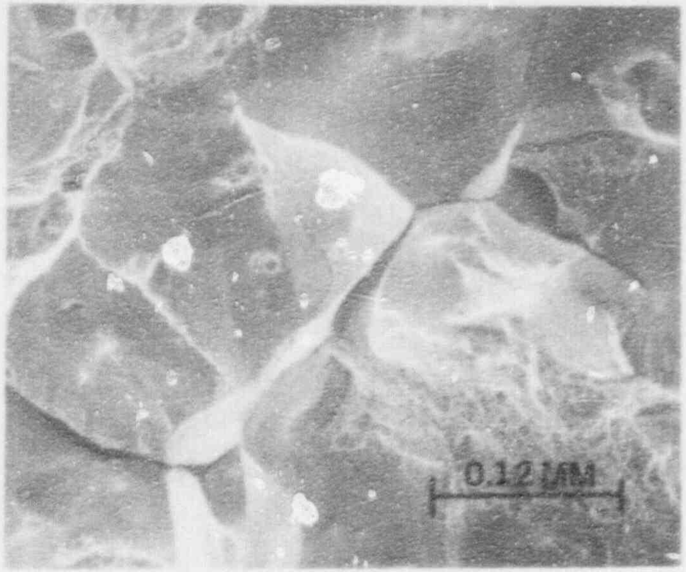


Figure 27 Crack seen in Figure 26 was intergranular in appearance.

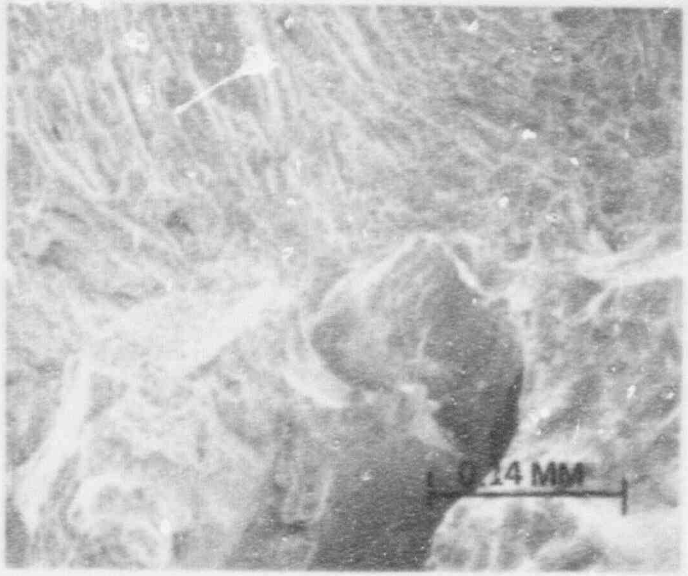


Figure 28a No evidence of crack blunting was seen at the crack/overlay interface.

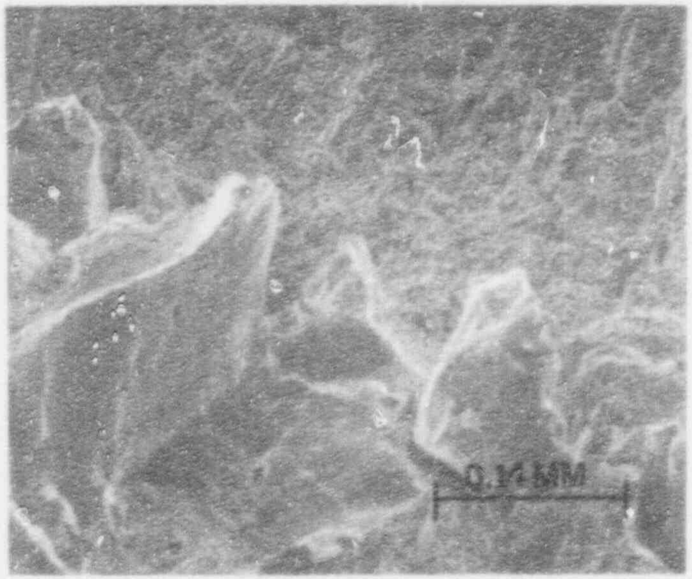


Figure 28b Sharp intergranular facets are evident in the same interface.

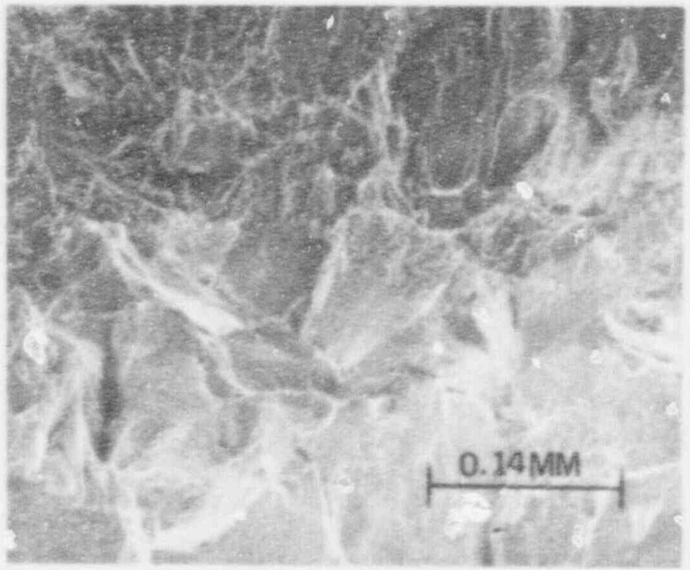


Figure 28c A third area showing no definite crack blunting.

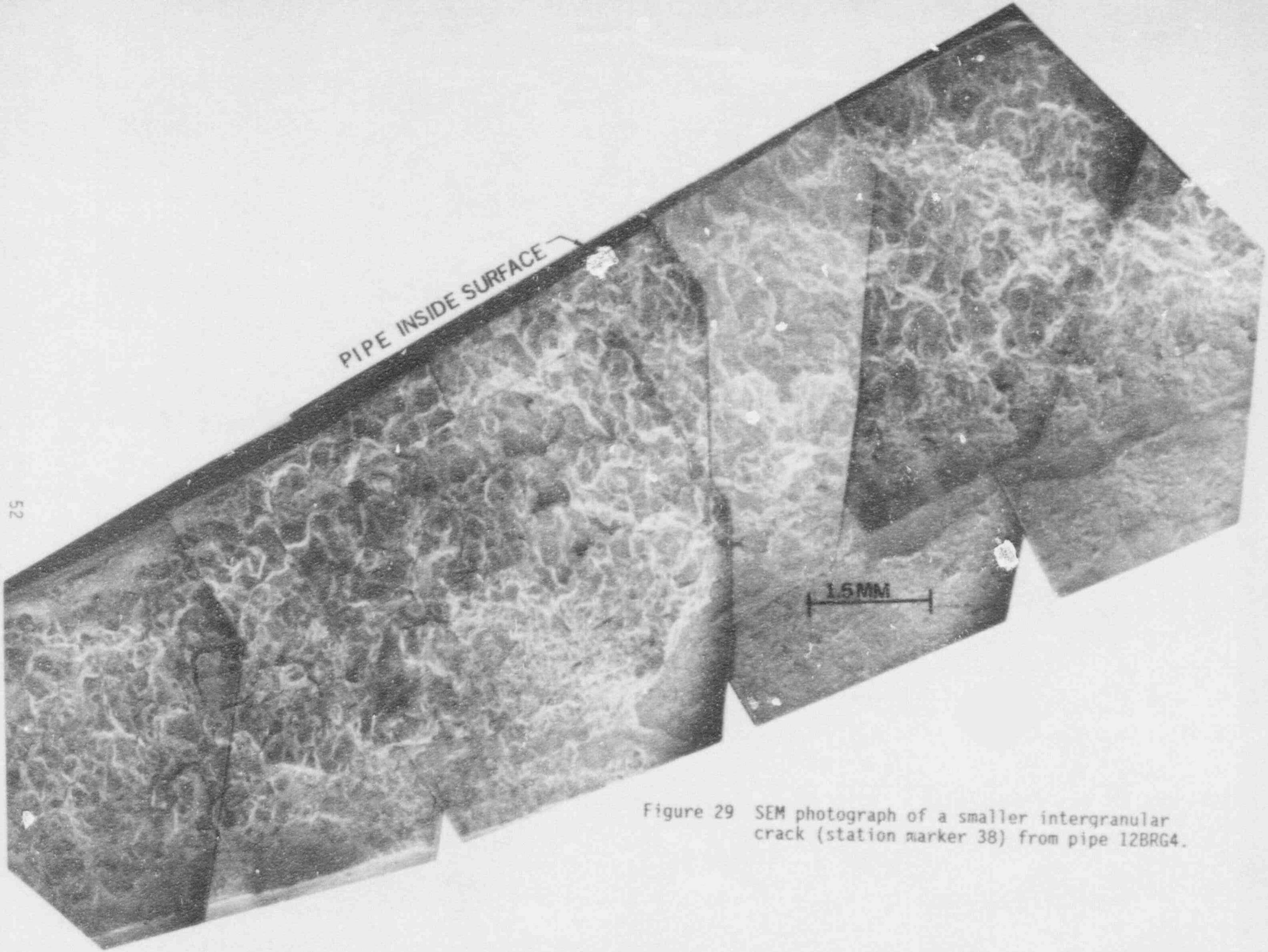


Figure 29 SEM photograph of a smaller intergranular crack (station marker 38) from pipe 12BRG4.

A fracture face from BRJ2 pipe (typical of other cracks examined) is shown in Figure 30. This crack was entirely intergranular (Figure 31a and 31b) with no evidence of beach marks or discontinuous crack growth.

Discussion

For intergranular stress corrosion cracking to occur, three conditions must be present. They are:

a) a susceptible microstructure
b) a corrosive environment
c) tensile stress (applied or residual).

In the case of austenitic stainless steel, the susceptible microstructure is termed "sensitized." This condition (as previously described) is easily obtained during the welding process of stainless steel piping.

The second condition needed to cause IGSCC is a corrosive environment. In light water reactors (LWRs), the corrosive species responsible for most IGSCC is oxygen. This has been well documented [6,7] and will not be discussed in this report.

The third condition required is tensile stress. For the cracks investigated the stresses were probably the residual tensile stresses induced by welding. Various instances have been cited [8] of residual tensile stresses (in Type 304 stainless steel heat affected zones) of higher than 40 ksi. The direction and amount of tensile stresses developed in piping seem to be closely related to the pipe's diameter. Chrenko [9] has postulated that the inner cross sections of smaller diameter pipes provide a less efficient heat sink and a more flexible surface during welding. The heat transferred by welding is then distributed over a larger area with an increased weld shrinkage area resulting in larger axial stresses.

As previously mentioned, the resistance of an austenitic stainless steel to IGSCC increases with an increase in ferrite content of the material. Additionally a ferrite level of at least 3FN will effectively eliminate hot cracking (fissuring) in E316 and E316L weld metal [10]. In either instance, a critical minimum of ferrite must be present in order to assure a sound, trouble free weld.

In order to mitigate the IGSCC phenomenon, various remedies [11,12] have been developed to alter the residual tensile stress distribution and producing compressive residual stresses on the pipes' inside surfaces. This would tend to reduce the stress corrosion cracking initiation and propagation potential in a given weldment.

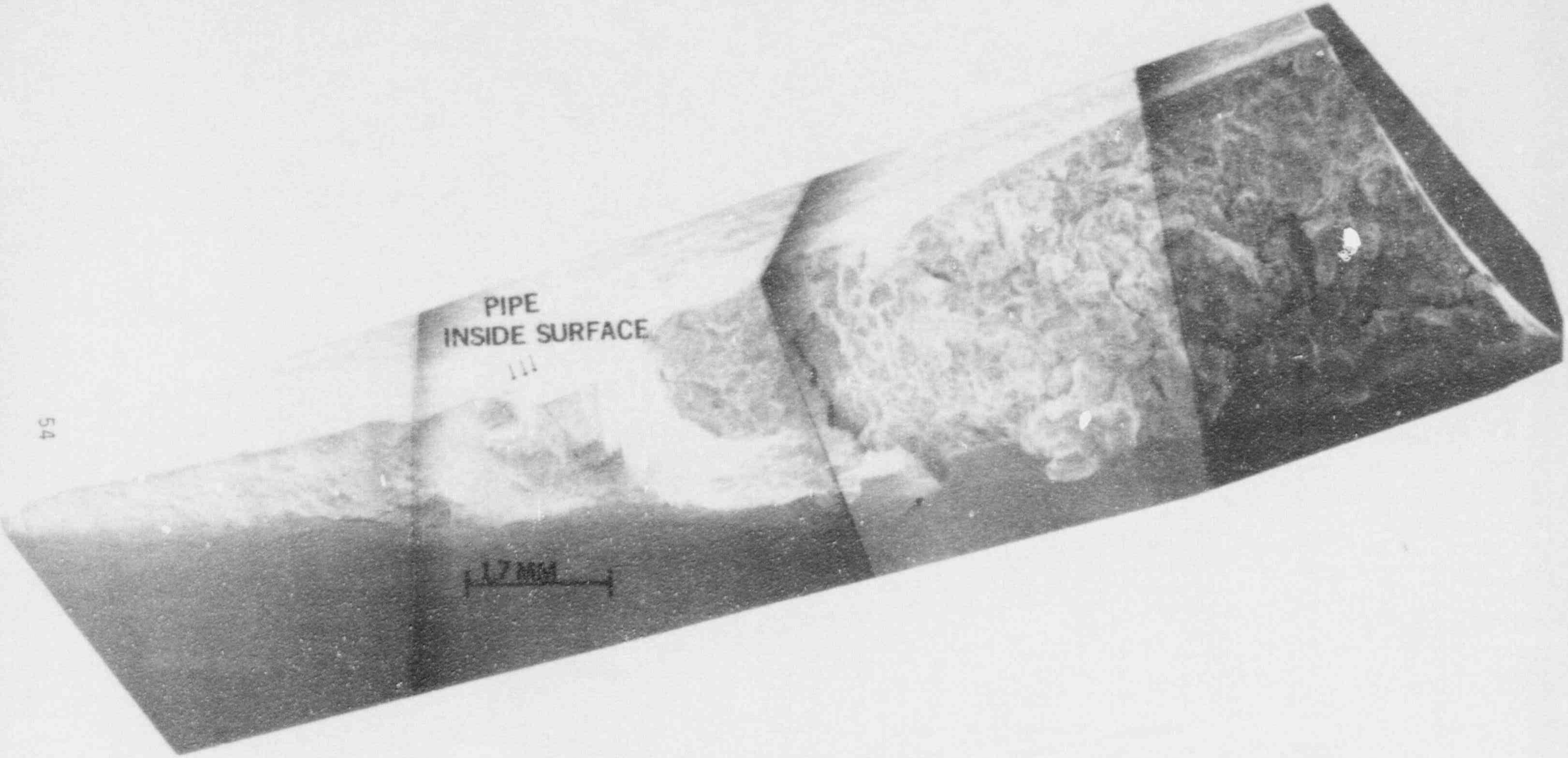


Figure 30 Low Magnification fractograph of intergranular crack from BRJ2 station marker 22.

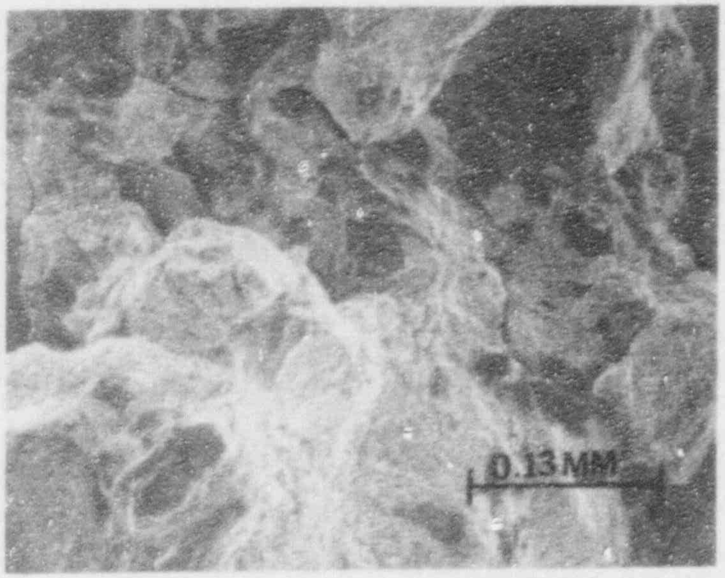


Figure 31a Higher magnification SEM photo of fracture face on BRJ2 (station marker 22).

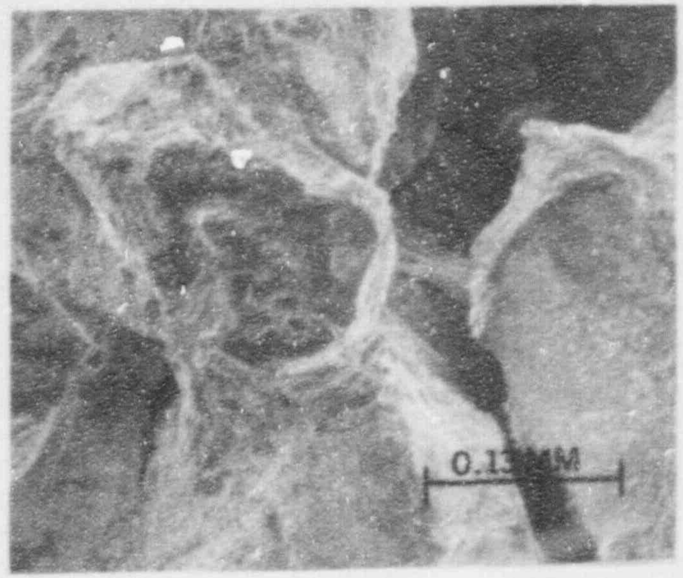


Figure 31b Second intergranular area (typical) seen on BRJ2 (station marker 22).

For purposes of this discussion, the method of repair/stress redistribution is the continuous weld overlay. This method of mitigation consists of welding a continuous (360 degrees) band of 308L (stainless steel) weld metal directly onto the outside surface of a cracked pipe (weld directly over a defect area). The normal process utilized for depositing a uniform weld layer is automatic gas tungsten arc welding (GTAW). This method of mitigation produces a high toughness weld deposit resistant to stress corrosion cracking (normally deposited metal has a ferrite number greater than 8). The weld overlay process also tends to produce compressive residual stresses on the affected pipes' inside surfaces and partially through the wall thickness.

The two overlay designs [13] used for the four evaluated weldments; 12BRG4, 12BRJ2, 12BRJ3 and 12BRK3 are seen in Figures 32 and 33. Pipes 12BRJ2, 12BRJ3 and 12BRK3 were overlaid using the design in Figure 32. This design essentially centers the weld below the overlay to obtain a uniform stress distribution over the affected weld. There is also a reasonably good access for the ultrasonic inspection of these welds since there are no close welds to interfere with the ultrasonic signal.

The design of the overlay for 12BRG4 (Figure 33) was configured differently from the other three examined welds. The difference resulted from the addition of a "pup" piece of stainless steel between the original pipe and the safe end. This configuration shifted the overlay off center - away from the "pup piece." This shifting might result in misleading or erroneous ultrasonic inspection data. The importance of this issue lies in the "inspectability" of weld overlaid joints.

This investigation has identified visible cracks in locations and sizes which differ from those reported by the utility and its contractors:

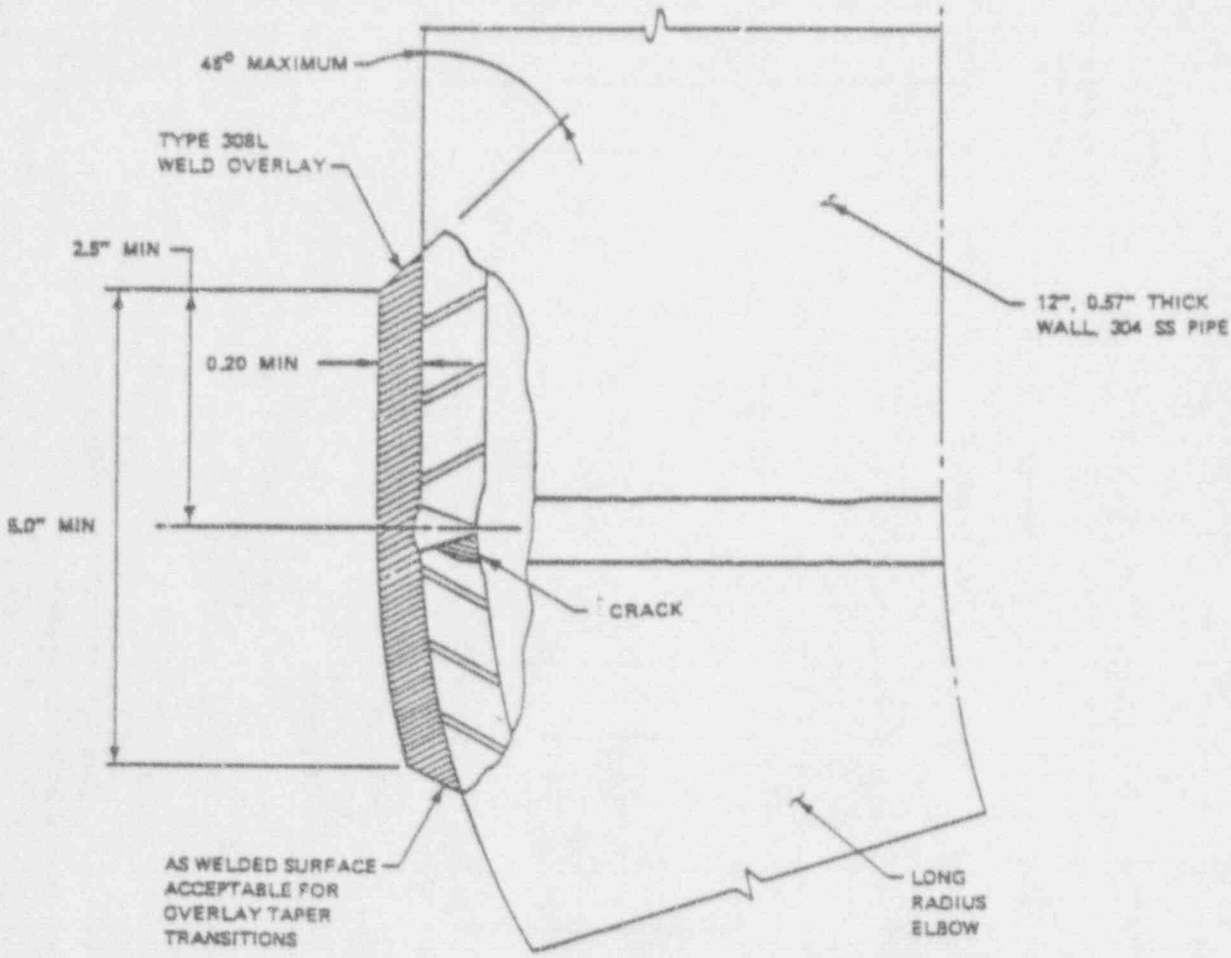
Vertical to Elbow	2B32	Recirc. 12" BRJ2	2.25", 12% thru wall
Horizontal to Elbow	2B32	Recirc. 12" BRJ3	1.75", 11% thru wall
Safe end to Horizontal	2B32	Recirc. 12" BRG4	2.0", 14% thru wall
			1.25", 7% thru wall
Horizontal to Elbow	2B32	Recirc. 12" BRK3	1.25", 5%thruwall

Locations of the cracks found at BNL are compared with these crack locations (reported by the inspection contractor) in Table 10. Comparisons for each individual weld are shown in Tables 11-14.

It is also seen that some indications which are seen visually and by dye penetrant will not be crack related as evidenced by no cracks in the metallurgical cross sections removed from 12BRK3 and 12BRJ3 (Tables 12 and 13).

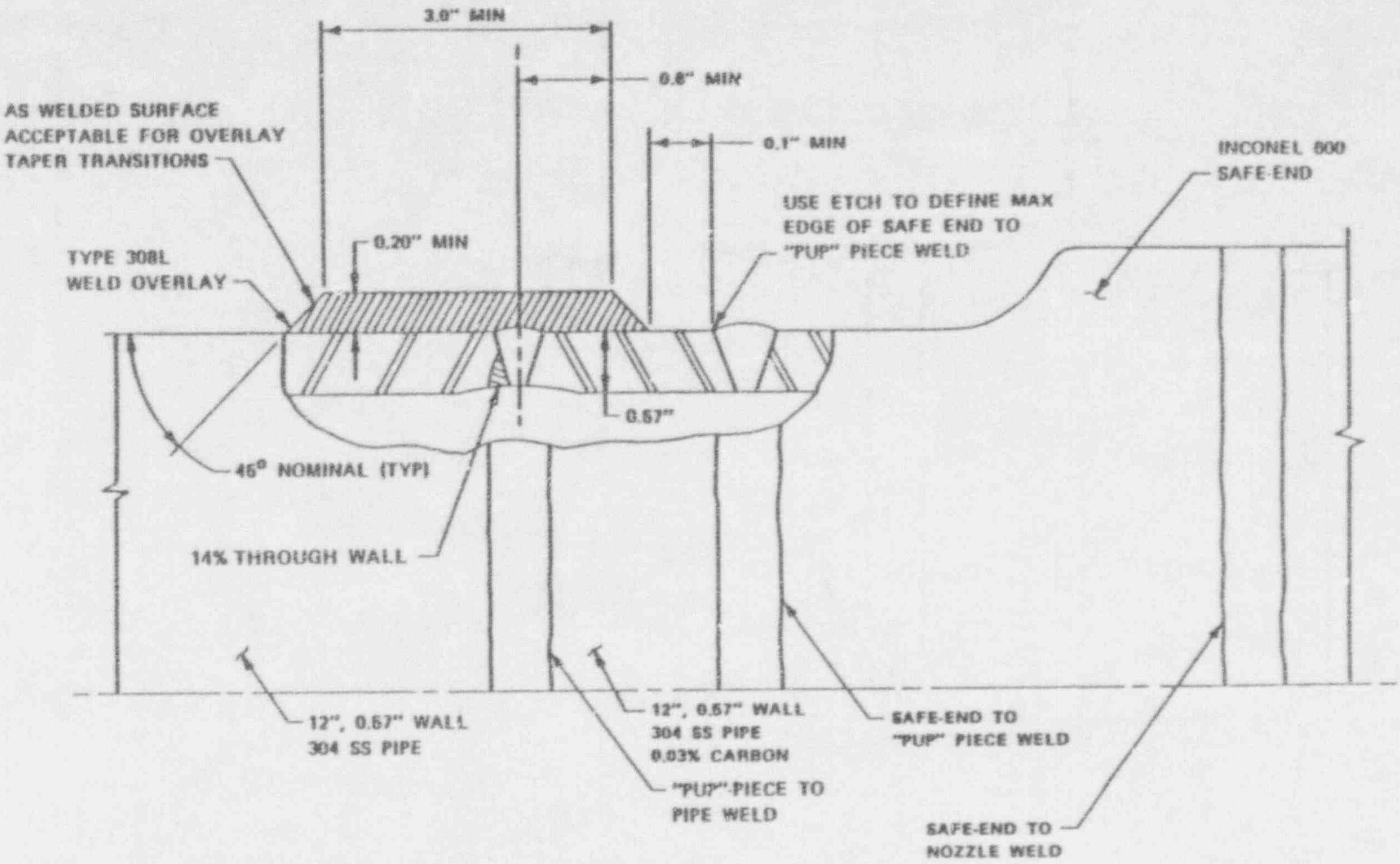
These observations lead to one of two possible scenarios:

1) That the crack on BRG4 was pre-existing in a 7 1/2" length and virtually "through wall" in depth and was neither located nor sized by the ultrasonic inspection system used; the GE Smart System; or
2) That crack growth occurred in the "through wall" crack after weld overlay was applied.



CONFIGURATION OF 12"
ELBOW TO PIPE WELD OVERLAY

Figure 32 Sketch of weld overlay design for pipes 12BRJ2, 12BRJ3, and 12BRK3.



CONFIGURATION OF SAFE END TO PIPE WELD OVERLAY
(THERMAL SLEEVE CMITTED)

Figure 33 Sketch of weld overlay design for pipe 12BRG4.

Table 10 Crack location data
BNL (visual) vs. Utility/Contractor
V = visual (BNL)
U = ultrasonic (GE)
PT = dye penetrant indications

Overlay 12BRJ2			Overlay 12BRJ3			Overlay 12BRK3			Overlay 12BRG4		
BNL	GE	Indication	BNL	GE	Indication	BNL	GE	Indication	BNL	GE	Indication
0	3		0	4.5		0	3		0	40	
1	2		1	5.5		1	2		1	41	
2	1		2	6.5		2	1		2	0	
3	0		3	7.5		3	0		3	1	
4	40		4	8.5		4	40		4	2	
5	39	U	5	9.5		5	39	PT	5	3	
6	38	U	6	10.5	PT/V	6	38	PT	6	4	
7	37	U	7	11.5	PT/V	7	37	PT, U	7	5	
8	36		8	12.5	PT/V	8	36	U	8	6	
9	35		9	13.5	PT/V	9	35	U	9	7	
10	34		10	14.5	U	10	34		10	8	
11	33		11	15.5	U	11	33		11	9	
12	32		12	16.5		12	32		12	10	
13	31		13	17.5		13	31		13	11	
14	30		14	18.5		14	30		14	12	
15	29		15	19.5		15	29		15	13	
16	28		16	20.5		16	28		16	14	PT/V
17	27		17	21.5		17	27		17	15	PT/V
18	26		18	22.5		18	26		18	16	PT/V
19	25		19	23.5	U	19	25		19	17	
20	24		20	24.5	U	20	24		20	18	
21	23		21	25.5		21	23		21	19	
22	22	PT/V	22	26.5		22	22	U	22	20	
23	21	PT/V	23	27.5		23	21		23	21	
24	20	PT/V	24	28.5		24	20		24	22	U
25	19		25	29.5		25	19		25	23	U
26	18		26	30.5		26	18	U	26	24	U, PT/V
27	17		27	31.5		27	17	U	27	25	U, PT/V
28	16		28	32.5		28	16		28	26	PT/V
29	15		29	33.5		29	15		29	27	PT/V
30	14		30	34.5		30	14		30	28	PT/V
31	13		31	35.5		31	13		31	29	PT/V
32	12		32	36.5	PT/V	32	12	PT	32	30	PT/V
33	11		33	37.5	PT/V	33	11	PT	33	31	PT/V
34	10		34	38.5		34	10		34	32	
35	9		35	39.5		35	9		35	33	
36	8		36	40.5		36	8		36	34	PT/V
37	7		37	0.5		37	7		37	35	PT/V
38	6		38	1.5		38	6		38	36	PT/V
39	5		39	2.5		39	5		39	37	
40	4		40	3.5		40	4		40	38	
									41	39	

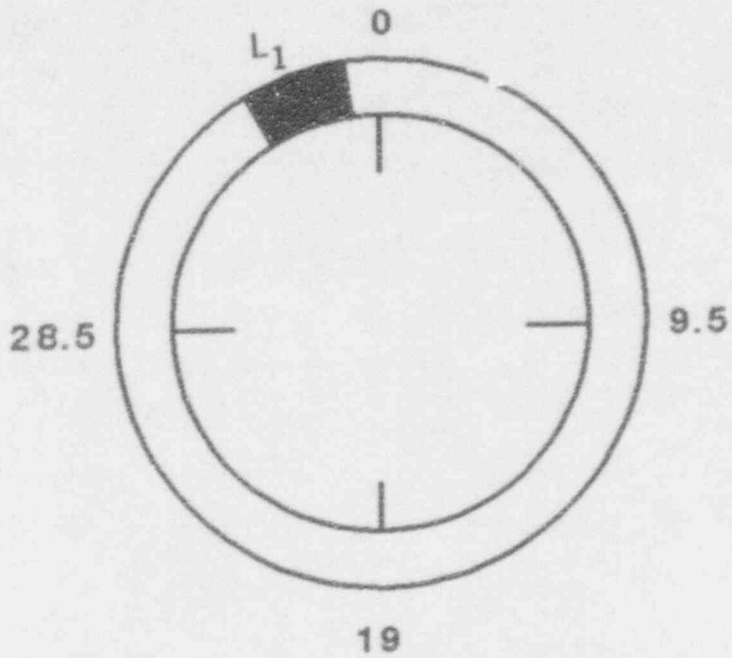
*No cracks detected by BNL after metallographic sectioning in any location.

TABLE 11

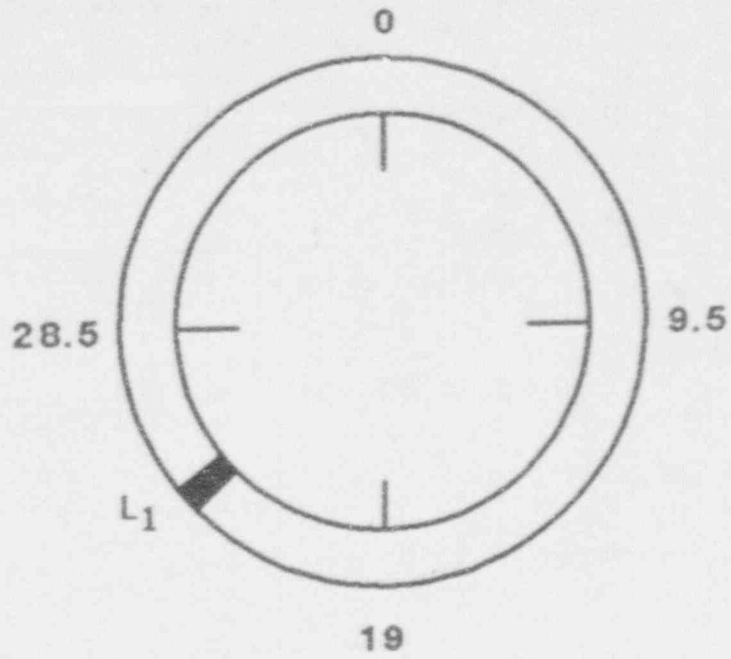
Comparison of NDE Data

12BRJ2

Utility Ultrasonic Tests	BNL Dye Penetrant Tests/ Metallurgical Sectioning



- 1983 ISI - L_1 = 2.25" long; 12% through wall (0.08 deep)
  - Circumferential



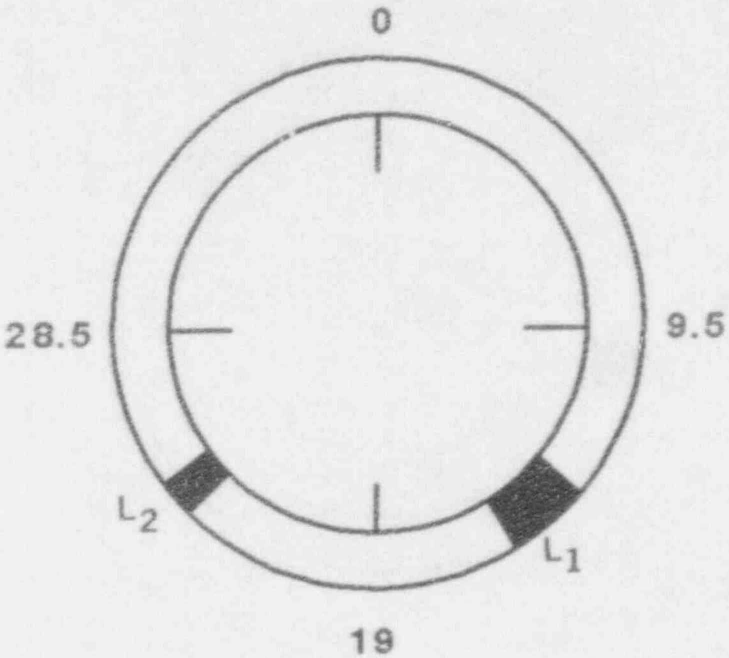
- L_1 = 0.500" long crack; 29% through wall (0.200" deep)
  - Circumferential

TABLE 12

Comparison of NDE Data

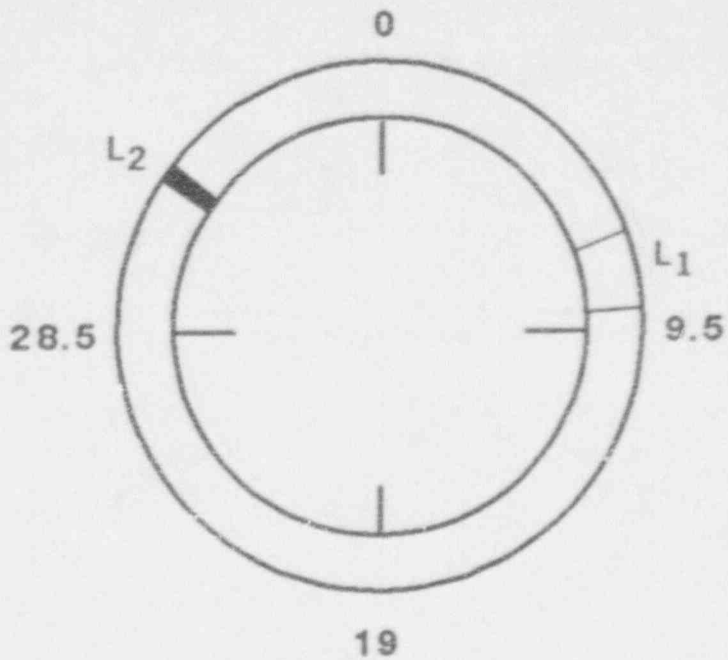
12BRJ3

Utility Ultrasonic Tests



- 1983 ISI - L_1 = 1.75" Long, 11% through wall (0.07"deep).
- 1986 ISI - L_2 = 1.0" long, ~30% through wall (0.204" deep).
  - Circumferential

BNL Dye Penetrant Tests/ Metallurgical Sectioning



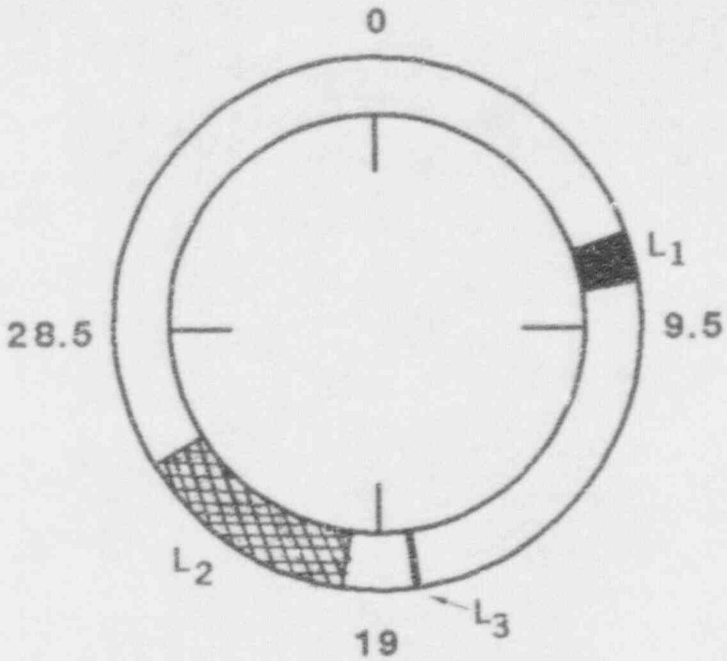
- Two indications located by dye penetrant L_1 = 1.5"long; L_2 = 0.375" long.
- L_2 = 0.375" long crack; 48% through wall (0.328"deep).
  - Circumferential

TABLE 13

Comparison of NDE Data

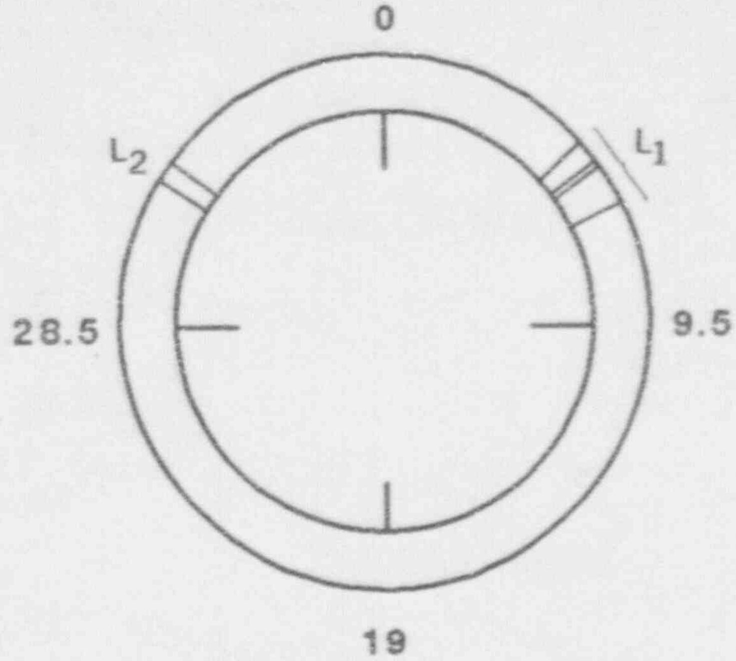
12BRK3

Utility Ultrasonic Tests



- 1983 ISI - L_1 = 1.25" long; 5% through wall (0.036" deep); L_2 = ID Geometric Reflector.
  - Circumferential
- 1988 ISI - IGSCC recorded at top 25% of base metal (L_3).
  - Circumferential

BNL Dye Penetrant Tests/ Metallurgical Sectioning



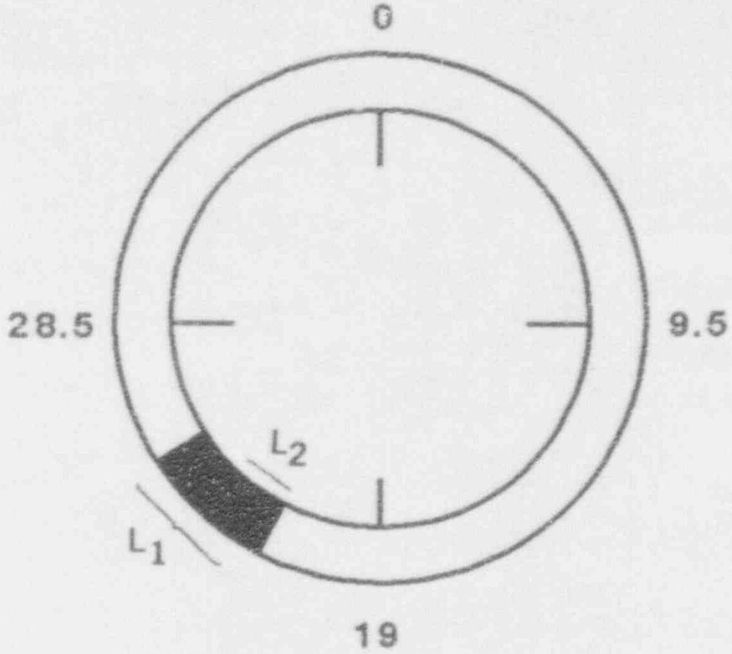
- Two indications located by dye penetrant - L_1 = 1.5" long (discontinuous); L_2 = 0.5" long
  - Circumferential
- No cracks present after sectioning.

TABLE 14

Comparison of NDE Data

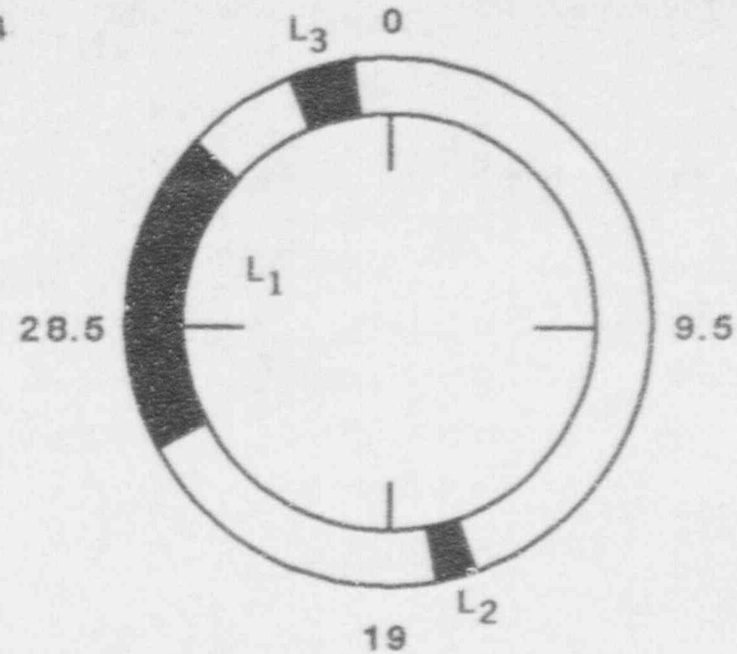
12BRG4

Utility Ultrasonic Tests



- 1983 ISI - L_1 - 2.0" long; 14% through wall (.100" deep; L_2 = 1.25" long; 7% through wall (.050" deep) - Split signals on UT
  - Both Circumferential

BNL Dye Penetrant Tests/ Metallurgical Sectioning



- L_1 = 7.5" long (essentially through wall for 30% length).
  - Circumferential and axial components
- L_2 = 1.0" long; 29% through wall (.200" deep)
  - Circumferential
- L_3 = 1.75" long; 83% through wall (~20% of length - .538" deep)
  - Circumferential

In order to enhance this report's data base, both the Electric Power Research Institute's, J.A. Jones (Nondestructive Evaluation) NDE Center and General Electric Company (San Jose, California) were invited to participate in performing additional ultrasonic examination of the four pipe pieces prior to their being sectioned. Both EPRI (by telephone) and GE (formally - Attachment 6) declined the invitation.

The BNL investigator had a meeting with the appropriate cognizant GE inspection personnel where both image data and video CRT display data from the original inspection of the four overlays were reviewed. The data and displays were reviewed in an effort to correlate the BNL observations to the UT signals recorded. Attachment 7 is a letter documenting this comparison. The UT results, although somewhat more definitive, were "inconclusive."

GE was kept informed during the various stages of the investigation. In fact, subsequent discussions with GE revealed that due to the problem of access to weld 12BRG4 (Attachment 8) ultrasonic examination may have been severely limited. The scenarios that an almost "through wall" crack may not have been detected prior to overlay became a distinct possibility. At this stage of the evaluation, GE was requested to review the collected inspection reports for the overlay of 12BRG4 for objective evidence that the pipe (during overlay) was filled with water (necessary to obtain criterion compressive stresses) and that there was no evidence of a weld "blow through" from a "through wall" crack being welded with a back pressure of water in the pipe.

GE was also requested to re-evaluate the possibility that crack growth could have occurred on 12BRG4 after weld overlay was applied. This request resulted in GE (Attachment 9) performing a series of fracture mechanics analyses using weld residual stress assumptions. The analysis concluded:

> "In conclusion, the results generally show that the flaw growth for the bounding assumptions are consistent with the UT findings and destructive examination. It does point out that without the full benefit of compressive stress from the thermal treatment, some crack growth in the original pipe cannot be ruled out. However, the industry standard is for full structural overlays which take no credit for the original pipe wall thickness and are made of a material resistant to Intergranular Stress Corrosion Cracking. Therefore, even with the observed growth, the overlay will meet the ASME Code structural margin requirements."

An amended letter was sent to BNL by GE (Attachment 10). Although, it did not change the original conclusions, it expanded on the previous history of weld overlay and axial cracking. Discussions with GE personnel at this time disclosed no evidence of "blow through" on 12BRG4 during the welding of the overlay which was of concern at the onset of the investigation.

9. CONCLUSIONS

The aforementioned documentation review, nondestructive testing, metallurgical assessment and utility/contractor (CP&L/GE) discussions have led to the following conclusions:

- The chemical analyses (WDS) of the base metal/weld metal and overlay materials appeared normal for the alloys used (A240 Type 304 stainless steel, SFA 5.4 308 weld metal). The hardness values were also consistent with those expected in this type of weldment.

- The ferrite numbers recorded (FN>7) for all of the overlaid welds were consistent with industry practice. One reading was below the recommended FN 7.5 minimum outlined in USNRC Generic Letter 88-01. Considering the fact that the recording was FN 7.3 and that all other ferrite measurements on this pipe were above FN 7.5, this is considered acceptable.

- The quality of the overlays was consistent with that expected in an ASME pressure boundary weld. There was no evidence of porosity, lack of fusion, lack of penetration, or weld metal cracking (other than IGSCC).

- The evaluation of the ultrasonic test data coupled with the input and re-evaluations by GE indicated that for certain overlay configurations, ultrasonic inspection may not provide an accurate picture of the top 25% (original pipe wall) of the pipe. Comparing the metallurgical sectioning of the four pipes to the dye penetrant results also gives rise to questions regarding overcalls and undercalls on IGSCC. Three indications (2 on 12BRK3 and 1 on 12BRJ3) did not reveal cracks after sectioning. The comparison of cracks to ultrasonic test data also evidences the fact that the sizing/locating of cracks (before overlay) is not an "exact science" and results of these inspections should be carefully evaluated.

- The stress calculations (based upon the strain gage measurements) indicate that crack growth (propagation) after weld overlay is a distinct possibility. This conclusion is based upon the low recorded residual compressive stresses observed on pipe 12BRG4.

- It could not be positively determined if crack growth occurred after overlay by the metallurgical tests performed.

10. REFERENCES

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7. USNRC NUREG-0531, February 1979.

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9. Fox, M., Proceedings: Seminar on Countermeasures for Pipe Cracking in BWR's, EPRI, Vol. 1, Workshop Report, May 1980, Paper No. 1.

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12. Gilman, J.D., Giannuzzi, A.J., Childs, W.J., Paper 130, Corrosion 83 (NACE) Conference, Anaheim, CA, 1983.

13. EPRI NN-2033-SY-LD, Project T119, September 1981.

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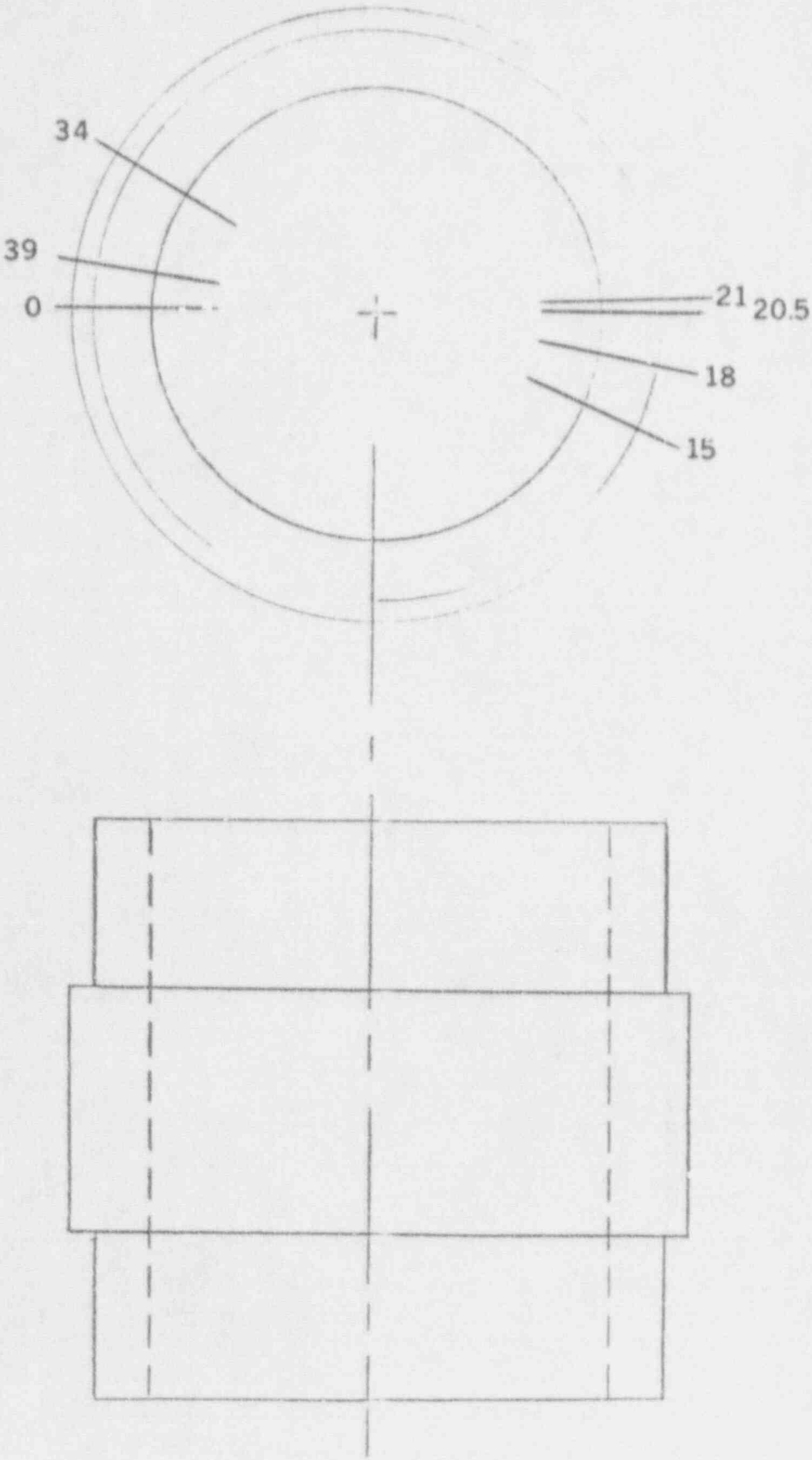
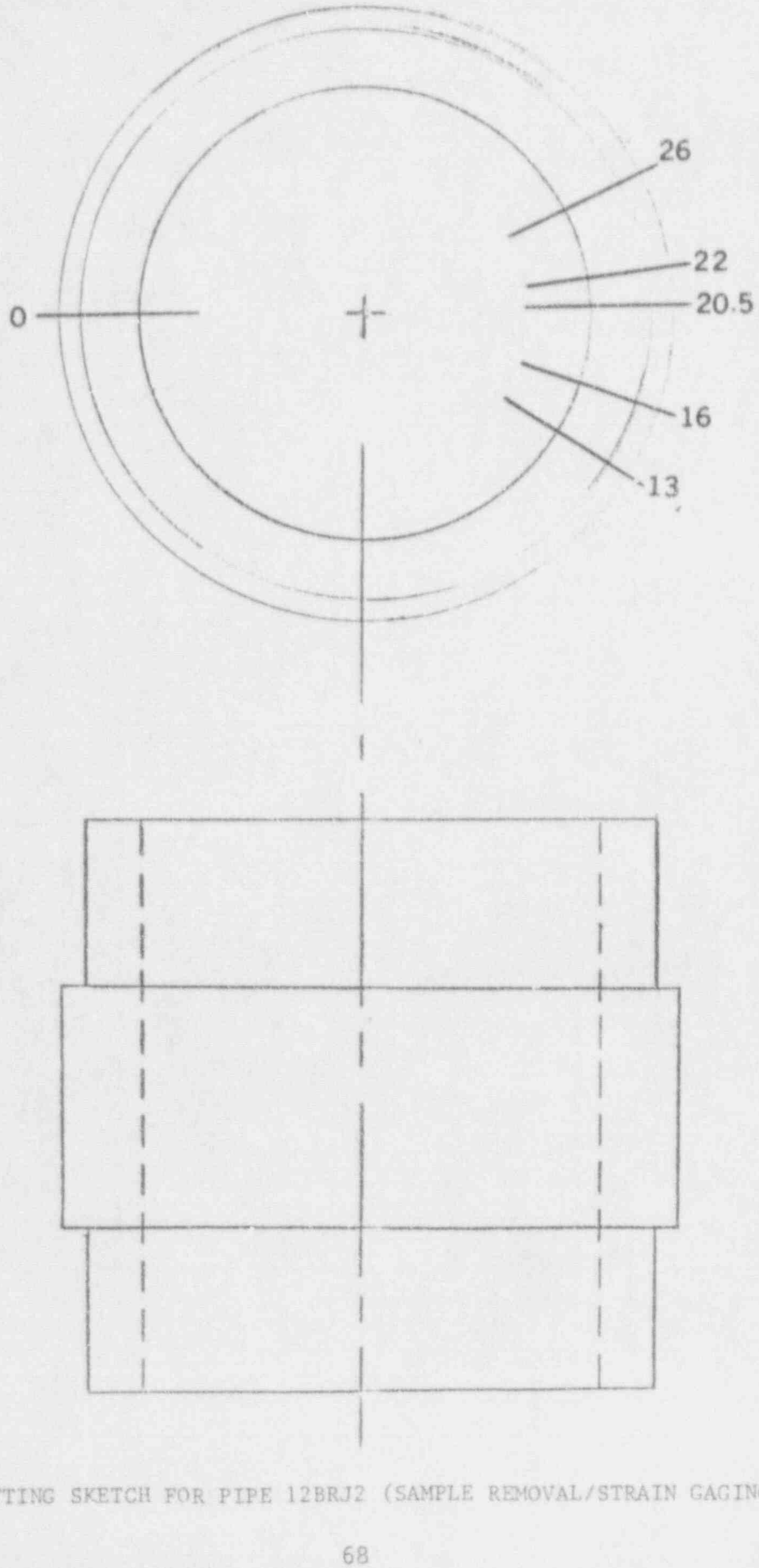
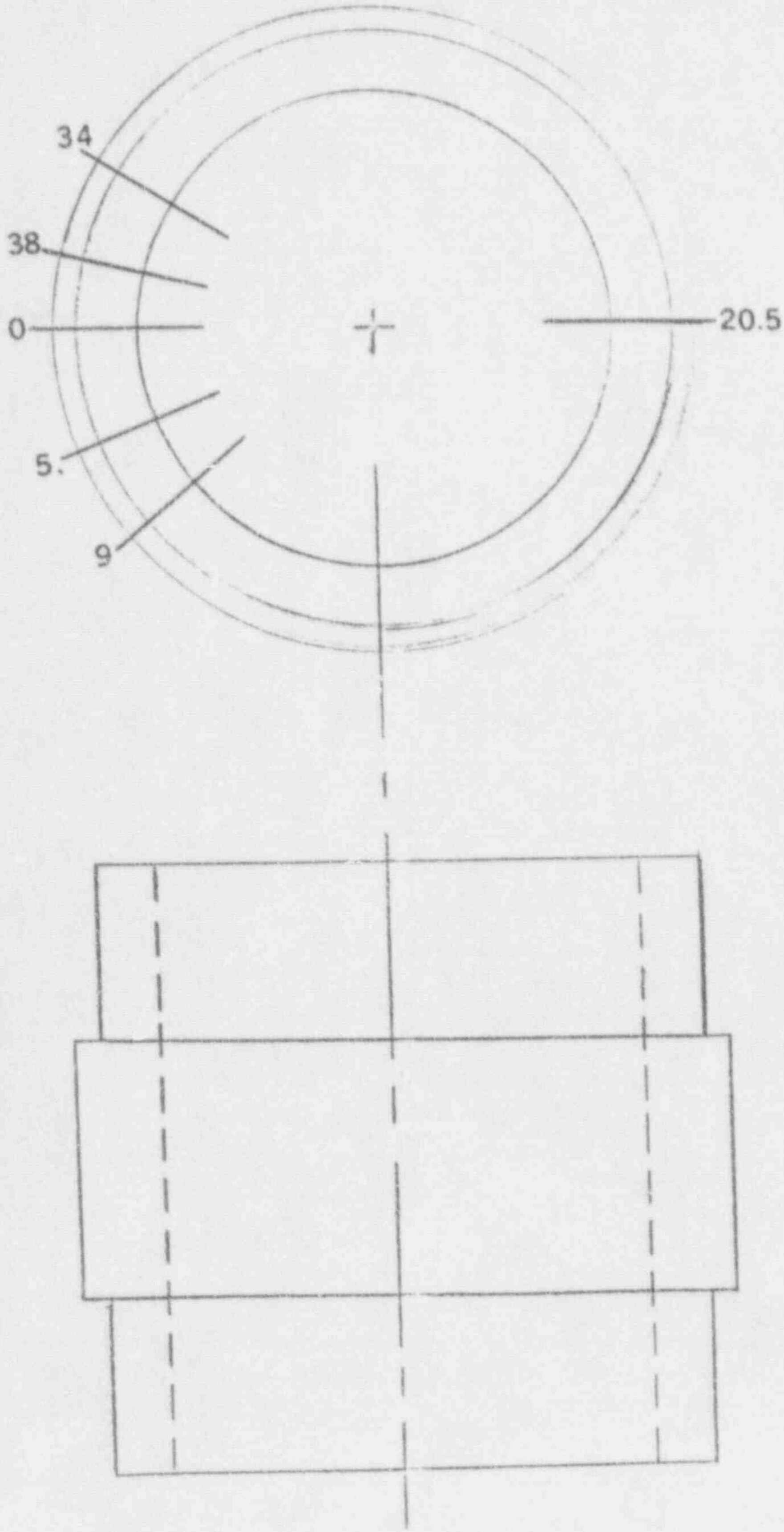


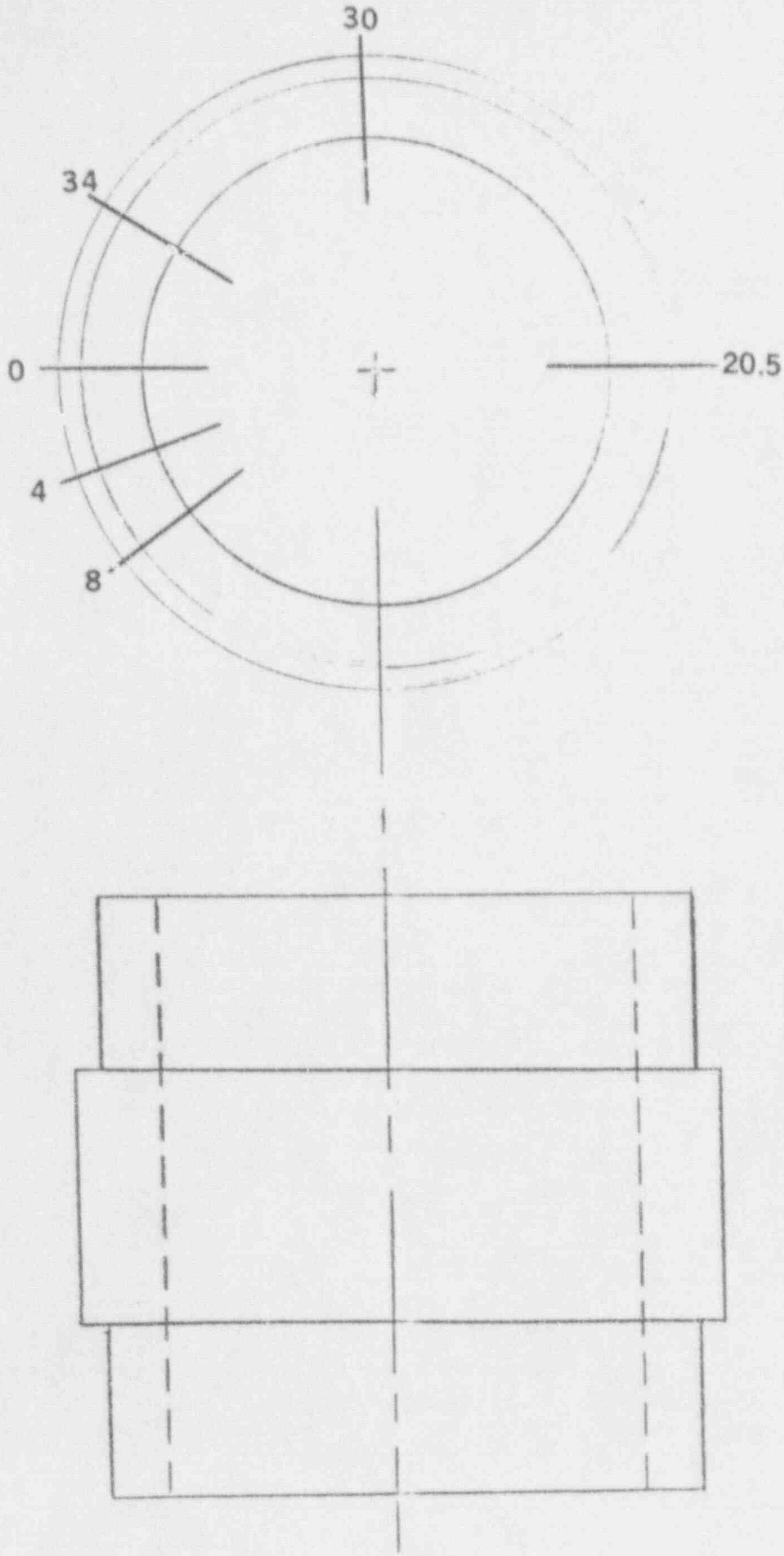
CUTTING SKETCH FOR PIPE 12BRG4 (SAMPLE REMOVAL/STRAIN GAGING)



CUTTING SKETCH FOR PIPE 12BRJ2 (SAMPLE REMOVAL/STRAIN GAGING)



CUTTING SKETCH FOR PIPE 12BRJ3 (SAMPLE REMOVAL/STRAIN GAGING)



CUTTING SKETCH FOR PIPE 12BRK3 (SAMPLE REMOVAL/STRAIN GAGING)

GE Nuclear Energy

General Electric Company
175 Curtner Avenue, San Jose, CA 95125

ATTACHMENT 5

August 24, 1990

Mr. C. Czajkowski
Brookhaven National Laboratory
Building 830
Upton, New York 11973

Subject: Brunswick Pipe Overlay Samples

Dear Mr. Czajkowski:

As we discussed recently, we have concluded that any ultrasonic tests prior to sample cutting would not be useful due to known limitations in inspecting the the inner wall of the pipe through weld overlays. Therefore, we recommend you proceed with the strain gage residual stress program as planned.

We are interested in providing technical support related to analysis of the ultrasonic examination data. We believe our input may be of particular value in understanding the ultrasonic examination techniques for examination of the welds and in interpreting the data from both the pre- and post-overlay examinations. We will provide you a summary of the prior examinations, and would like to participate with you in evaluating any differences between the UT and destructive metallographic results.

We have begun collecting the ISI data reports and expect to have completed the process in the near future. We have also assigned Doug Henry from my organization as the the Project Engineer. When our review of this prior examination data is complete, Doug will contact you. However, if any specific questions develop as your work progresses please feel free to call me at (408) 925-6771, or Doug at (408) 925-3398.

Sincerely,

T. L. Chapman, Manager
Reactor & Fuel Examination Technology

cc: R. Herman, NRC
R. Jones, EPRI
S. Walker, EPRI NDE Center
G. Gordon, GE
D. Henry, GE

TLC90106

GE Nuclear Energy

General Electric Company
175 Curtner Avenue San Jose CA 95125

ATTACHMENT 6

November 20, 1990

Carl J. Czajkowski
Brookhaven National Laboratory
Department of Nuclear Energy
Building 830
30 Railroad Avenue
Upton, NY 11973

Dear Mr. Czajkowski:

This letter transmits the results of the SMART UT ultrasonic examination data review performed during your visit on November 14 and 15, 1990, in support of the metallurgical examination of overlayed pipe weld samples from Brunswick Unit 2. Both the Image data and the video CRT display data were included in this review.

Depth estimates have been provided where they could be reasonably ascertained, however, it should be noted that the depth measurements show these indications to be at the accepted threshold of detectability using this technique. Nevertheless, we hope this information has been helpful to your metallurgical examination.

We look forward to meeting with you again in January following completion of your metallurgical examination.

If you have any additional questions or if we can be of further assistance, please do not hesitate to call me at (408) 925-3398.

Sincerely,

Douglas Henry

Douglas Henry

cc: T. L. Brinkman
T. L. Chapman
J. P. Clark
D. E. Delwiche
E. R. Dykes
G. M. Gordon
D. W. Sandusky

PROJECT: BROOKHAVEN NATIONAL LABORATORY METALLURGICAL INVESTIGATION OF OVERLAY WELDS FROM NORTH CAROLINA POWER & LIGHT BSEP - UNIT 2: REVIEW SMART UT RESULTS FROM 1988 OUTAGE

SUBJECT: GENERAL ELECTRIC SMART UT ULTRASONIC DATA FOR OVERLAY WELDS: 2B32-RR-12-BR-J3
2B32-RR-12-BR-K3
2B32-RR-12-BR-G4
2B32-RR-12-BR-J2

PREPARED BY: DOUG EDGEL, G.E. DE

DATE: NOVEMBER 16,1990

On November 15 and 16, 1990 a review of the SMART UT data including the video CRT display data, for the above mentioned welds was performed. An effort was made to correlate SMART UT data with penetrant indications which the Brookhaven examination had recorded. As a result, indications recorded for this review include both indications which were previously recorded as relevant or non-relevant. The following indications were noted during this data review (see 1988 SMART UT Data for correlation):

WELD NO./EXAM	LOCATION	DEPTH from O.D.
2B32-RR-12-BR-G4/ 60 RL	19" to 22.2" LKDN	I.D.
	23.3" TO 24.6" LKDN	I.D.
	23" TO 24" LKUP	I.D.
	8" TO 10" LKUP	I.D.
	23.8" UPST	.62"
2B32-RR-12-BR-K3/ 60 RL	.4" TO 1.7" LKDN	I.D.
	8.6" TO 12" LKDN	I.D.
	32.4" TO 33.3" LKDN	I.D.
	34.4" TO 36.5" LKDN	I.D.
	21.3" TO 23.5" LKDN	I.D.
	1.2" TO 1.9" LKUP	I.D.
	8.9" TO 9.5" LKUP	I.D.
	10.2" TO 11.6" LKUP	I.D.
	19.4" TO 21" LKUP	I.D.
	17.9" UPST	.62"
2B32-RR-12-BR-J2	19.3" TO 19.4" LKUP	.73"
2B32-RR-12-BR-J3	7.9" TO 8.1" LKUP	I.D.

UPST = Upstream side of weld (Axial indication)
LKUP = Looking upstream
LKDN = Looking downstream

GE Nuclear Energy

General Electric Company
175 Curtner Avenue, San Jose, CA 95125

ATTACHMENT 7

April, 1, 1991

Mr. C. Czajkowski
Department of Nuclear Energy
Brookhaven National Laboratory
Upton, New York 11973

Dear Mr. Czajkowski:

Pursuant to our discussion today on your investigation of Brunswick 2 overlayed pipe sample BR-G4, we are providing background technical information related to the ultrasonic examination data and possible crack growth scenarios. We believe this input may be of particular value in understanding the results of ultrasonic examinations performed in 1986 and 1988.

Figure 1 illustrates the coverage limitation on BR-G4 due to the offset of the weld under the overlay as compared with the coverage which would be obtained on a weld centered under the overlay. Referring to Figure 1 (a), the angle beam examination looking in the upstream direction would be the most likely to detect the crack based on orientation; however, due to the offset, the area of the heat affected zone (HAZ) containing the crack cannot be scanned in this direction. While the area of the HAZ containing the weld can be scanned by the angle beam looking downstream, the orientation of the crack is not such that the soundbeam will be reflected back toward the transducer. If the weld were centered under the overlay, a sufficient scan path would exist for detection of a similar crack in the upper 25% of the original pipe wall on either side of the weld, as shown in Figure 1 (b) and (c).

A second factor considered was the crack growth during the period from the 1988 examination to the removal of the pipe from the system in 1989. While Ultrasonic examination techniques for overlay examination may detect smaller flaws, they are primarily relied upon for detection of cracks which have propagated to 75% or more of the original pipe wall thickness. In order to evaluate the crack growth, a fracture mechanics analysis was performed to determine if the flaw in Weld BR-G4 could grow from less than 74% to 98% of the original wall thickness between 1988 and 1989 while starting from a flaw depth of less than 50% in 1983.

A crack growth analysis was performed to determine the depth of the crack after approximately four 18 month operating cycles. The Buchalet-Barford polynomial fit method was used to calculate the stress intensity factors. Crack Growth was determined using the upper bound weld sensitized crack growth.

The two following analyses were performed:

1) the first used a pressure stress of 4 ksi, a thermal stress of 6 ksi, and a linear weld residual stress distribution of -5 ksi on the inside diameter and 30 ksi on the outside diameter.

2) the second used a pressure stress of 4 ksi, a thermal stress of 6 ksi, and a linear weld residual stress distribution of -10 ksi on the inside diameter and 30 ksi on the outside diameter.

The results of analysis 1 are shown in Figure 2 and of analysis 2 are shown in Figure 3. These figures show that both analyses result a growth of less than 74% to 100% between 1988 and 1989 while starting from a flaw depth of less than 50% in 1983.

If any further questions develop as your work progresses please feel free to call me at (408) 925-3398.

Sincerely,

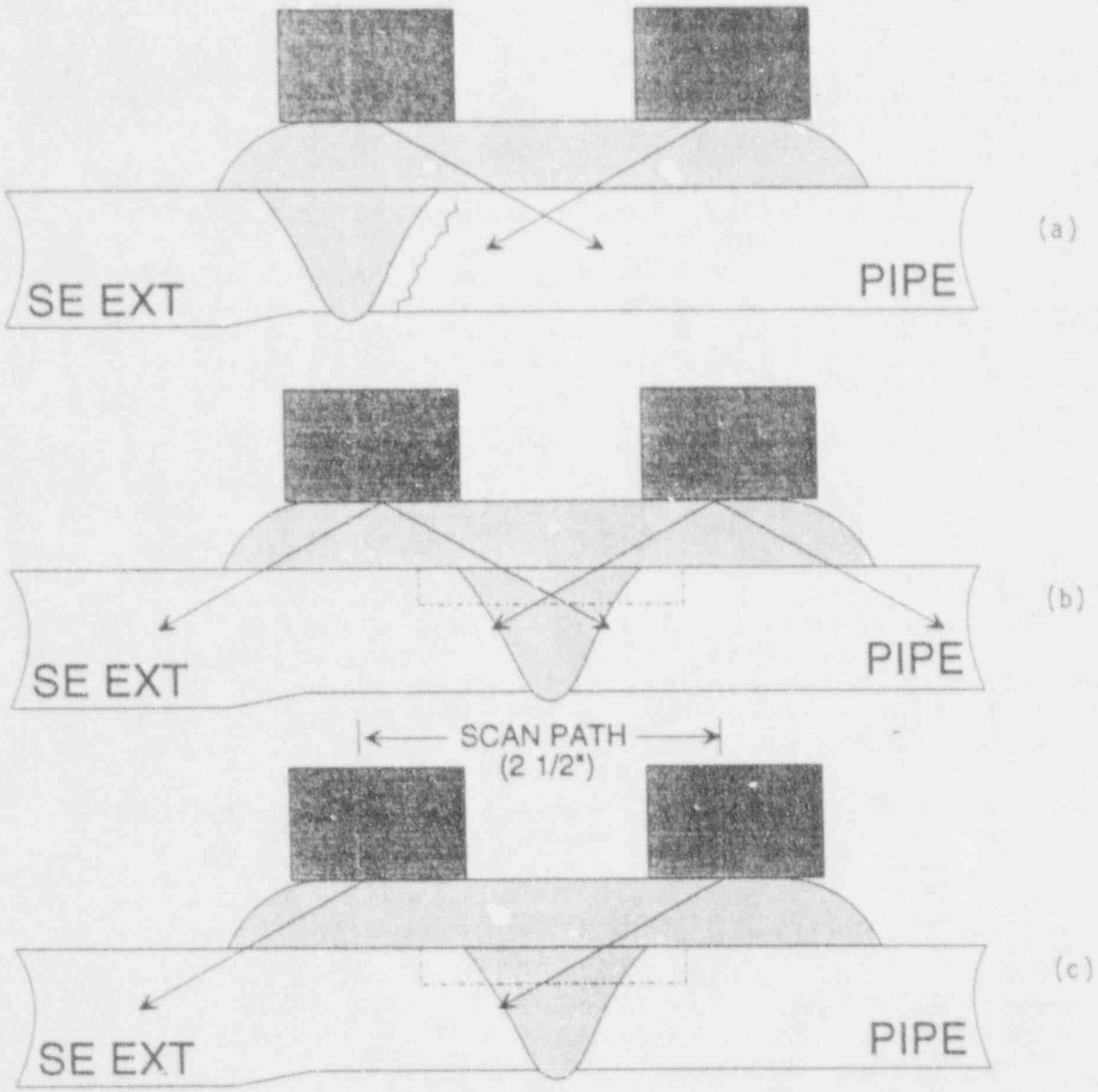
D. O. Henry

D. O. Henry

Attachments

cc: B. J. Branlund
T. L. Brinkman
T. L. Chapman
J. P. Clark
G. M. Gordon
E. Kiss

FIGURE 1. Ultrasonic Examination Coverage



(a) Offset Weld Showing Coverage Limitation For Weld BR-G4

(b) Coverage at Ends of Scan Path For Weld Centered Under Overlay

(c) Scan Path On Overlay With Same Length as BR-G4 For Centered Weld

Figure 2 Residual Stress of – 5 to 30 ksi

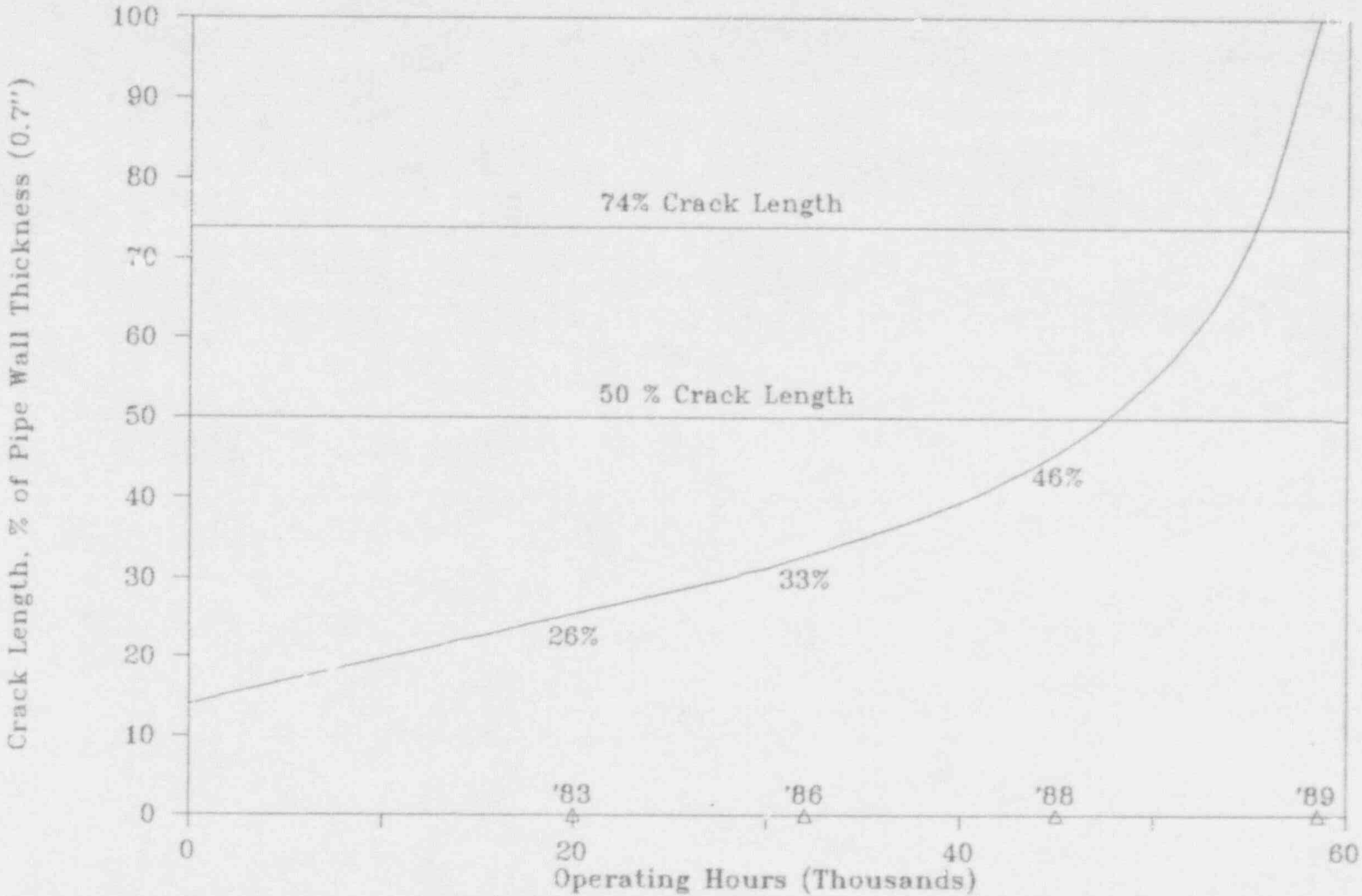
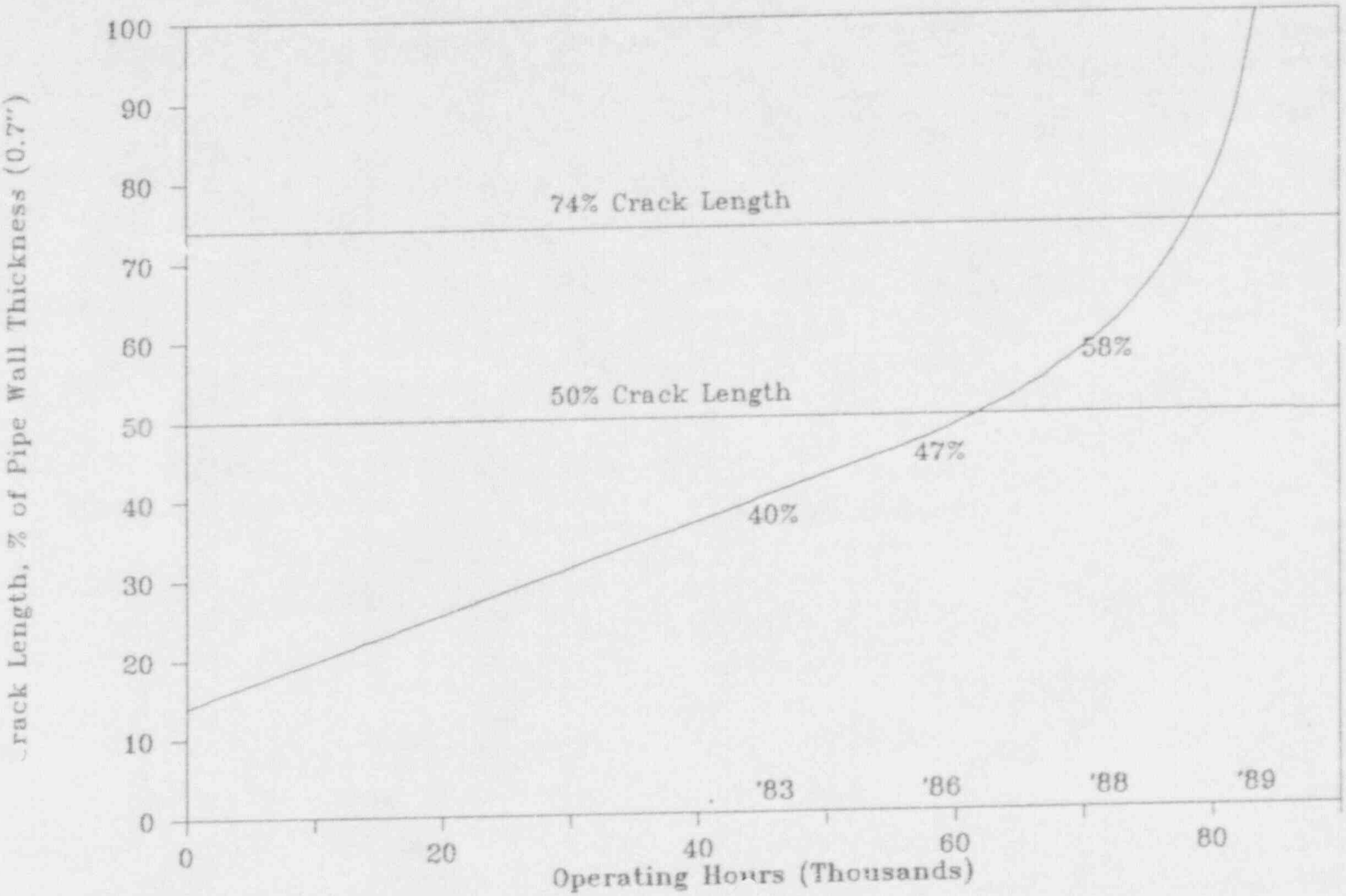


Figure 3 Residual Stress of -10 to 30 ksi



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ATTACHMENT 8

BWR Technology
Materials Monitor & Structural Analysis Services

April 15, 1991
BJB-9105

Mr. C. Czajkowski
Department of Nuclear Energy
Brookhaven National Laboratory
Upton, New York 11973

Subject: Fracture Mechanics Analysis of the Flaw in Weld 12BRG4-29 for Brunswick Unit 2

Reference: Letter to Mr. C. Czajkowski from D. O. Henry dated April 1, 1991

Dear Mr. Czajkowski:

As discussed in the reference letter, destructive examination of Weld 12BRG4-29 by Brookhaven National Laboratories revealed a flaw approximately 98% through the original pipe wall thickness (hereafter [illegible]ed "through the pipe wall"). This weld was removed from the B[illegible]wick Unit 2 Power Plant during a piping replacement in 1989. An ultrasonic examination (UT) of the weld in 1988 showed no observable flaw in the outer 25% (i.e. a flaw depth of 75% or more) of the original pipe wall thickness. UT examination is generally [illegible]ied upon to detect flaws that have propagated to 75% or more of the original pipe wall thickness.

Per your recent request, the purpose of this letter is to provide additional information related to the flaw growth for Weld 12BRG4-29. The analysis presented in this letter addresses the following three findings:

- 1) Destructive examination revealed a flaw nearly 100% through the pipe wall in 1989.
- 2) UT observed no flaw in 1988 (i.e. The flaw size was less than 75% through the pipe wall).

- 3) UT observed a flaw less than 50% through the pipe wall in 1983. Also, flaws greater than 50% typically grow through the pipe wall during overlay application. There was no indication of through-wall flaw growth during the overlay application in 1983.

A series of fracture mechanics analyses were performed using a reasonable set of weld residual stress assumptions. The weld residual stress resulted from the thermal treatment of the weld; the thermal treatment was a result of the weld overlay applied on Weld 12BRG4-29. The two following considerations were used to choose the residual stress distributions to be analyzed:

- The strain data shown in Table 1 for Weld 12BRG4-29 may not be reliable, since cracking of the section may have relieved much of the residual stress that had existed in the section prior to the destructive examination.

- The strain data shown in Table 1 provides an estimate of the residual stress in Welds 12BRJ2-14 and 12BRJ3-35; this data can only be used to estimate the residual stress on the inside and outside diameter of the pipe and says nothing about the through-thickness distribution. Therefore, this data was used to estimate the magnitude of residual stress in Weld 12BRG4-29 before any flaw growth had occurred; in the absence of through-thickness data a linear distribution was used.

There were six residual stress distributions used to bound the data. For each stress distribution an applied stress of 10 ksi (pressure stress = 4 ksi and thermal stress = 6 ksi) was superimposed on each of the six residual stress distributions. The six cases and the rationale for choosing the distribution are shown in Table 2.

Figures 2 through 6 show the results of the analysis for Cases 2 through 6, respectively. As expected, Case 1 resulted in no growth of the flaw. The results of Cases 2, 3, 5, and 6 demonstrated that any partial benefit produced results that were consistent with the findings of the UT inspection and the destructive examination. The results of Case 4, while not in total agreement with the findings, were still very close.

In conclusion, the results generally show that the flaw growth for the bounding assumptions are consistent with the UT findings and destructive examination. It does point out that without the full benefit of compressive stress from the thermal treatment, some crack growth in the original pipe cannot be ruled out. However, the industry standard is for full structural overlays which take no credit for the original pipe wall thickness and are made of a material resistant to Intergranular Stress Corrosion Cracking. Therefore, even with the observed growth, the overlay will meet the ASME Code structural margin requirements.

Details of the calculations are contained in DRF 137-0010, Report No. SASR 91-32. If you have any questions, feel free to call me at (408) 925-1472.

Sincerely,

B. J. Branlund

B. J. Branlund

Attachments
cc: T. L. Brinkman
T. L. Chapman
J. P. Clark
G. M. Gordon
E. Kiss
D. O. Henry
S. Ranganath

Table 1 - Strain Gage Data

Pipe and Station Number	Gage No	Strain (μin/in)	Stress* (ksi)	Position on Pipe
12BRJ2-[illegible]	1	751	-23	ID
	2	543	-16	ID
	3	-1164	35	OD
	4	-1144	34	OD
12BRJ3-35	5	491	-15	ID
	6	392	-12	ID
	7	-1291	39	OD
	8	-1147	34	OD
12BRG4-29	17	26	-1	ID
	18	319	-9	ID
	19	74	-2	OD
	20	open		OD

---

* A modulus of elasticity of 30×10^3 ksi was used to calculate stress.

Table 2 List of Linear Stress Distributions

Case	Residual Stress ID (ksi)	Residual Stress OD (ksi)	Rationale
1	-30	30	This case represents full benefit from the thermal treatment.
2	- 5	30*	This case represents a marginal lack of benefit from the thermal treatment.
3	-10	30*	This case represents some benefit from the thermal treatment and is a conservative representation of the strains measured in Welds 12BRJ2-14 and 12BRJ3-35.
4	- 5	- 2*	This case represents a best estimate of the weld residual stress measured in 12BRG4-29. It should be re-emphasized that this data may be unreliable.
5	- 5	5	This case represents a minimum benefit from the thermal treatment.
6	0	0	This case represents no compressive stress benefit from the thermal treatment.

---

* The resultant force of a residual stress distribution is zero, (i.e. for a linearized stress, the magnitude of the stress on the inside and outside surface should be equal and opposite in sign). However, around the circumference there can be localized variations in the residual stress, such that the sum of the stresses around the circumference has a resultant force of zero.

Figure 2 Residual Stress of - 5 to 30 ksi

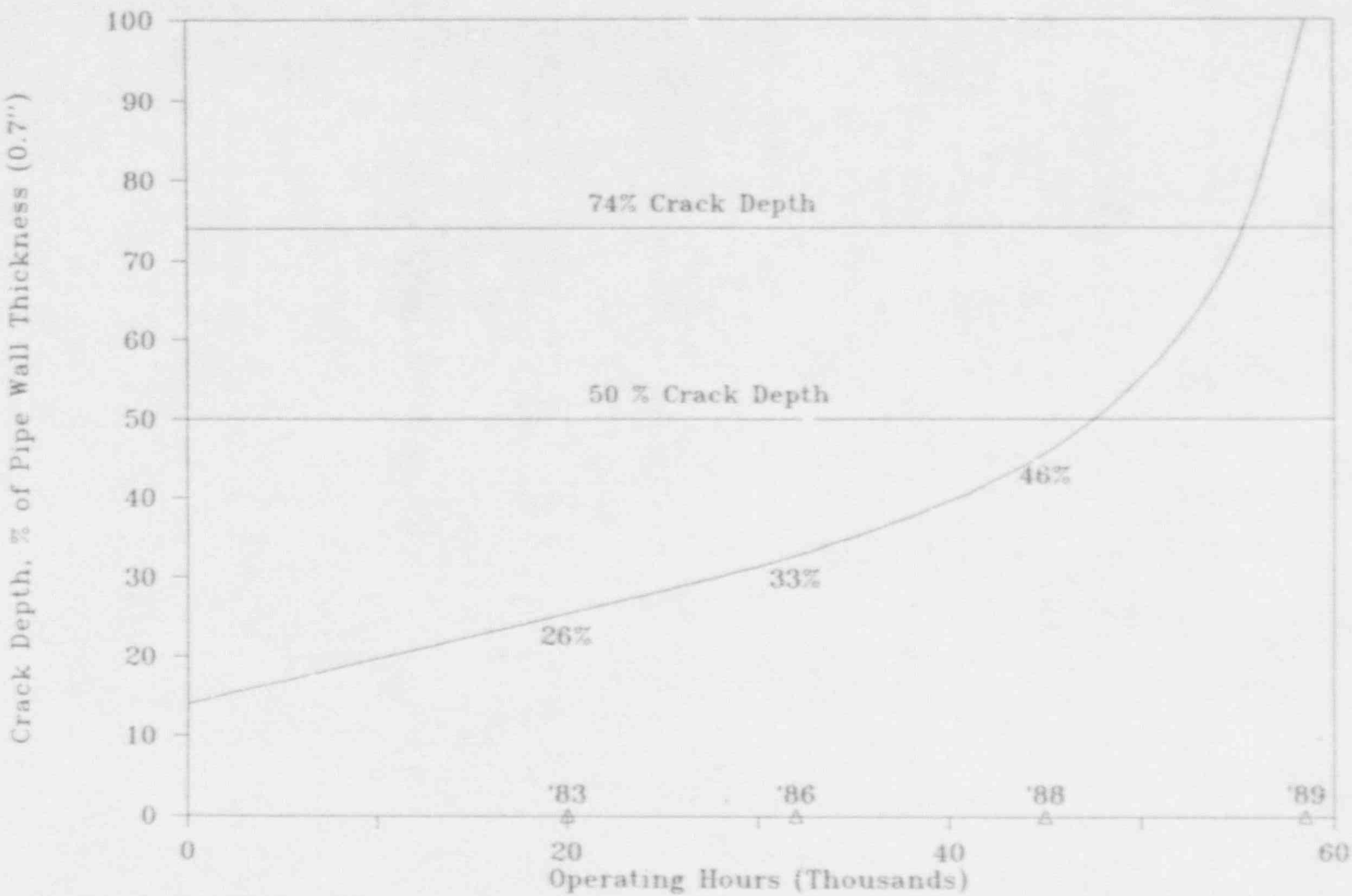


Figure 3 Residual Stress of −10 to 30 ksi

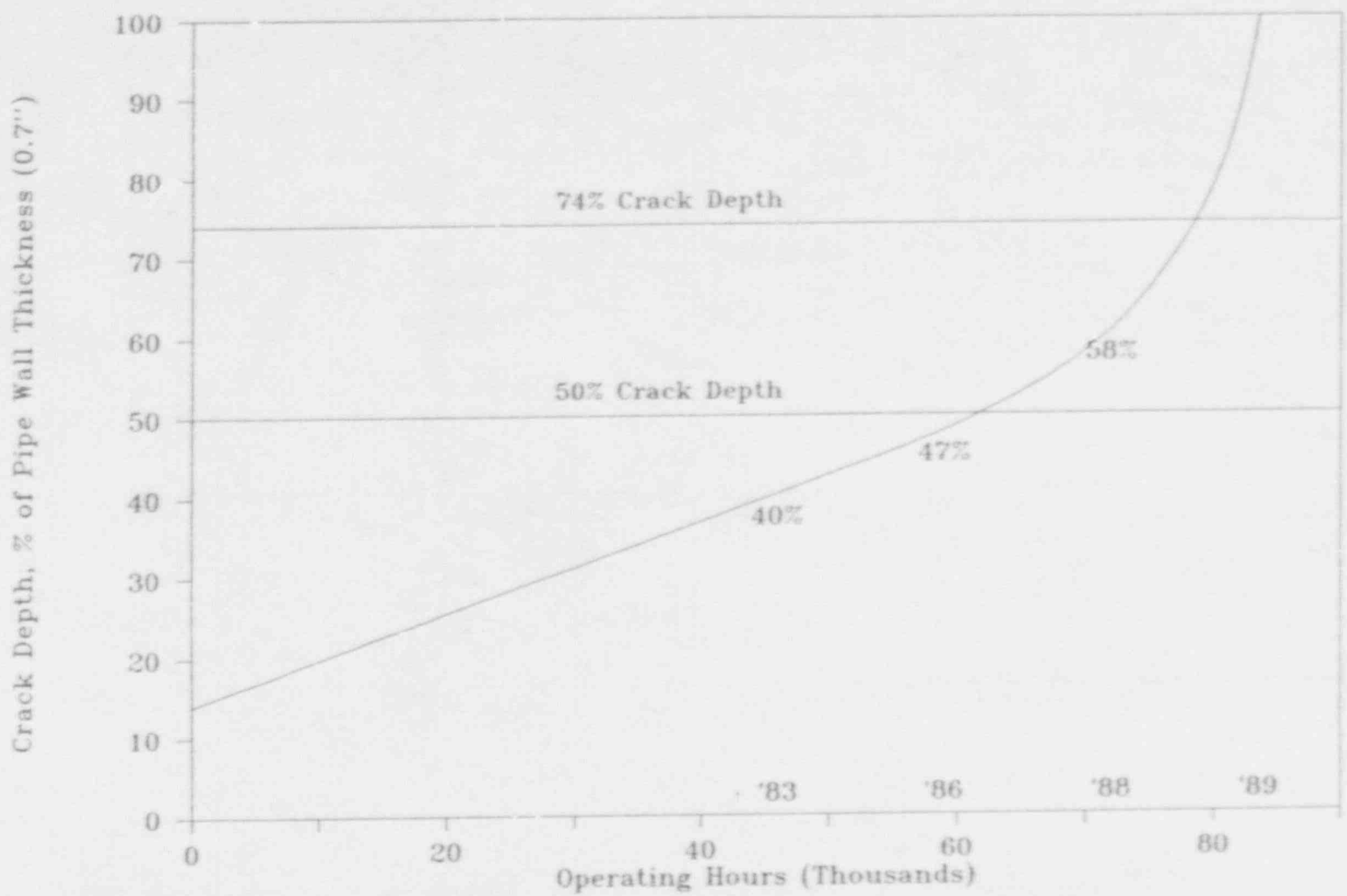


Figure 4 Residual Stress of −5 to −2 ksi

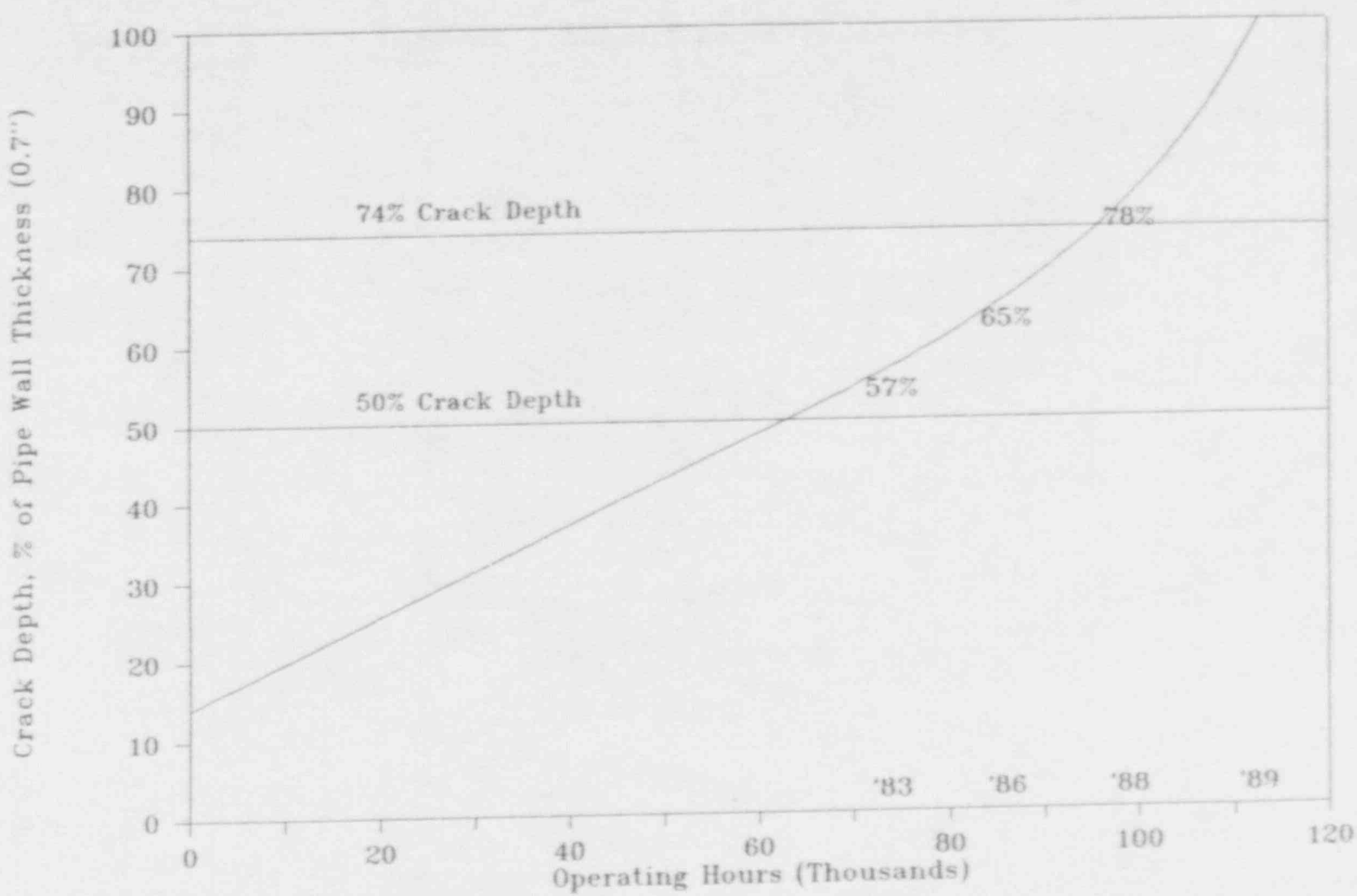


Figure 5 Residual Stress of – 5 to 5 ksi

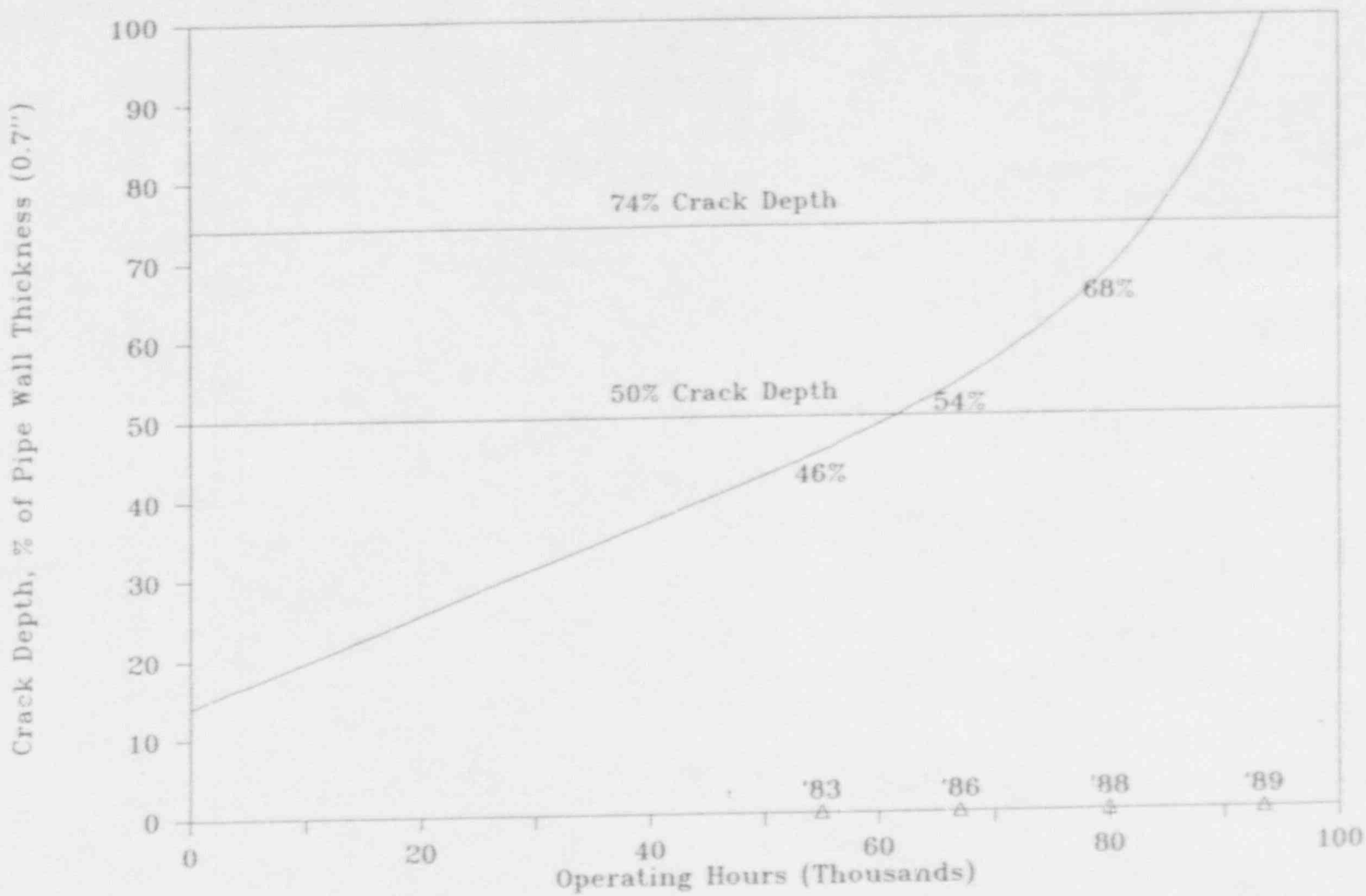
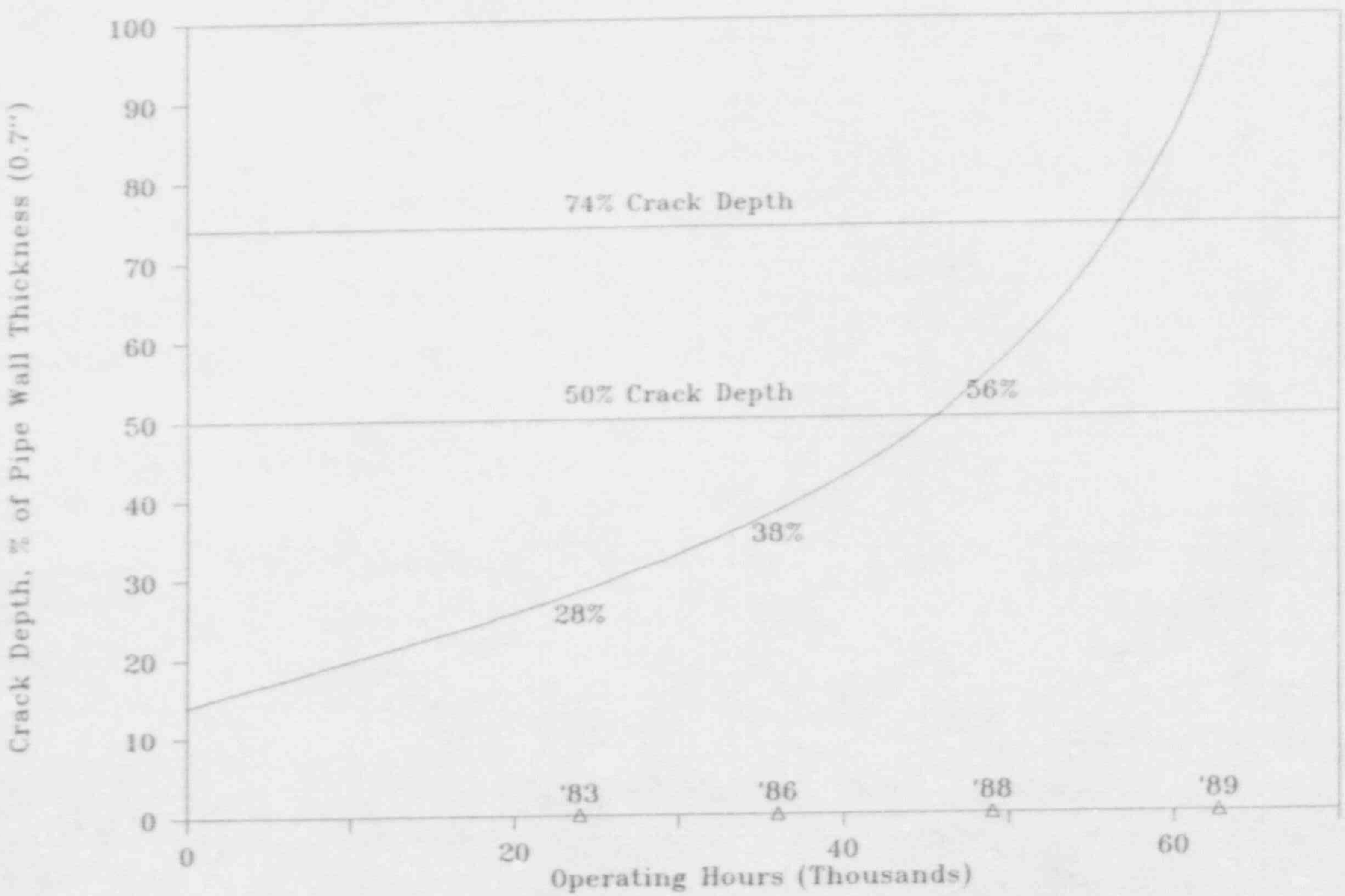


Figure 6 No Residual Stress



GE Nuclear Energy

General Electric Company
175 Curtner Avenue, San Jose, CA 95125

ATTACHMENT 9

BWR Technology
Materials Monitor & Structural Analysis Services

April 17, 1991
BJB-9106

Mr. C. Czajkowski
Department of Nuclear Energy
Brookhaven National Laboratory
Upton, New York 11973

Subject: Fracture Mechanics Analysis of the Flaw in Weld 12BRG4-29 for Brunswick Unit 2

Reference: Letter to Mr. C. Czajkowski from B. J. Branlund dated April 16, 1991 (BJB-9105)

Dear Mr. Czajkowski:

As well as sending the reference letter to you on April 16, 1991, an additional copy was sent to the GE weld overlay application experts. Based on their comments, we wish to clarify and correct one statement made in the referenced letter. Specifically, the assertion that "...flaws greater than 50% typically grow through the pipe wall during overlay application".

There has been no analytical data or field experience indicating that flaws >50% through-wall grow during the overlay application. There have been cases where axial cracks have grown through-wall and leaked when the first overlay layer was deposited. In some cases, these cracks (which are often difficult to size by ultrasonics due to their short aspect ratio and tip location relative to the edge of the weld crown) could have been reported to be 50% through-wall. However, experience with axial cracks and weld overlay application is that the cracks had to be nearly through-wall prior to overlay application. In this case, the heating/melting from the welding combined with the water pressure in the pipe, would cause a "blow through" or leak during the overlay welding. It was this experience with axial cracks that led to the confusion on our part in the referenced letter.

Therefore, a corrected finding 3) is provided in the revised letter enclosed herein. It should now read:

3) UT observed a flaw less than 50% through the pipe wall in 1983.

Since this revision to finding 3) does not contribute to the conclusions, this revision will not influence any of the results or conclusions of the reference letter.

Sincerely,

B. J. Branlund

B. J. Branlund
Engineer, Materials Monitoring &
Structural Analysis Services

Attachment:

cc: T. L. Brinkman
T. L. Chapman
J. P. Clark
G. M. Gordon
E. Kiss
D. O. Henry
S. Ranganath

GE Nuclear Energy

General Electric Company
175 Curtner Avenue San Jose CA 95125

ATTACHMENT 10

BWR Technology
Materials Monitor & Structural Analysis Services

April 17, 1991
BJB-9105, Revision 1

Mr. C. Czajkowski
Department of Nuclear Energy
Brookhaven National Laboratory
Upton, New York 11973

Subject: Fracture Mechanics Analysis of the Flaw in Weld 12BRG4-29 for Brunswick Unit 2

Reference: Letter to Mr. C. Czajkowski from D. O. Henry dated April 1, 1991

Dear Mr. Czajkowski:

As discussed in the reference letter, destructive examination of Weld 12BRG4-29 by Brookhaven National Laboratories revealed a flaw approximately 98% through the original pipe wall thickness (hereafter called "through the pipe wall"). This weld was removed from the Brunswick Unit 2 Power Plant during a piping replacement in 1989. An ultrasonic examination (UT) of the weld in 1988 showed no observable flaw in the outer 25% (i.e. a flaw depth of 75% or more) of the original pipe wall thickness. UT examination is generally relied upon to detect flaws that have propagated to 75% or more of the original pipe wall thickness.

Per your recent request, the purpose of this letter is to provide additional information related to the flaw growth for Weld 12BRG4-29. The analysis presented in this letter addresses the following three findings:

- 1) Destructive examination revealed a flaw nearly 100% through the pipe wall in 1989.
- 2) UT observed no flaw in 1988 (i.e. The flaw size was less than 75% through the pipe wall).

* 3) UT observed a flaw less than 50% through the pipe wall in 1983.

A series of fracture mechanics analyses were performed using a reasonable set of weld residual stress assumptions. The weld residual stress resulted from the thermal treatment of the weld; the thermal treatment was a result of the weld overlay applied on Weld 12BRG4-29. The two following considerations were used to choose the residual stress distributions to be analyzed:

* The strain data shown in Table 1 for Weld 12BRG4-29 may not be reliable, since cracking of the section may have relieved much of the residual stress that had existed in the section prior to the destructive examination.

* The strain data shown in Table 1 provides an estimate of the residual stress in Welds 12BRJ2-14 and 12BRJ3-35; this data can only be used to estimate the residual stress on the inside and outside diameter of the pipe and says nothing about the through-thickness distribution. Therefore, this data was used to estimate the magnitude of residual stress in Weld 12BRG4-29 before any flaw growth had occurred; in the absence of through-thickness data a linear distribution was used.

There were six residual stress distributions used to bound the data. For each stress distribution an applied stress of 10 ksi (pressure stress = 4 ksi and thermal stress = 6 ksi) was superimposed on each of the six residual stress distributions. The six cases and the rationale for choosing the distribution are shown in Table 2.

Figures 2 through 6 show the results of the analysis for Cases 2 through 6, respectively. As expected, Case 1 resulted in no growth of the flaw. The results of Cases 2, 3, 5, and 6 demonstrated that any partial benefit produced results that were consistent with the findings of the UT inspection and the destructive examination. The results of Case 4, while not in total agreement with the findings, were still very close.

In conclusion, the results generally show that the flaw growth for the bounding assumptions are consistent with the UT findings and destructive examination. It does point out that without the full benefit of compressive stress from the thermal treatment, some crack growth in the original pipe cannot be ruled out. However, the industry standard is for full structural overlays which take no credit for the original pipe wall thickness and are made of a material resistant to Intergranular Stress Corrosion Cracking. Therefore, even with the observed growth, the overlay will meet the ASME Code structural margin requirements.

Details of the calculations are contained in DRF 137-0010, Report No. SASR 91-32. If you have any questions, feel free to call me at (408) 925-1472.

Sincerely,

B. J. Branlund

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Engineer, Materials Monitoring &
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Attachments

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D. O. Henry
S. Ranganath

Table 1 - Strain Gage Data

Pipe and Station Number	Gage No	Strain (μin/in)	Stress* (ksi)	Position on Pipe
12BRJ2-14	1	751	-23	ID
	2	543	-16	ID
	3	-1164	35	OD
	4	-1144	34	OD
12BRJ3-35	5	491	-15	ID
	6	392	-12	ID
	7	-1291	39	OD
	8	-1147	34	OD
12BRG4-29	17	26	-1	ID
	18	319	-9	ID
	19	74	-2	OD
	20	open		OD

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* A modulus of elasticity of 30×10^3 ksi was used to calculate stress.

Table 2 List of Linear Stress Distributions

Case	Residual Stress ID (ksi)	Residual Stress OD (ksi)	Rationale
1	-30	30	This case represents full benefit from the thermal treatment.
2	- 5	30*	This case represents a marginal lack of benefit from the thermal treatment.
3	-10	30*	This case represents some benefit from the thermal treatment and is a conservative representation of the strains measured in Welds 12BRJ2-14 and 12BRJ3-35.
4	- 5	- 2*	This case represents a best estimate of the weld residual stress measured in 12BRG4-29. It should be re-emphasized that this data may be unreliable.
5	- 5	5	This case represents a minimum benefit from the thermal treatment.
6	0	0	This case represents no compressive stress benefit from the thermal treatment.

* The resultant force of a residual stress distribution is zero, (i.e. for a linearized stress, the magnitude of the stress on the inside and outside surface should be equal and opposite in sign). However, around the circumference there can be localized variations in the residual stress, such that the sum of the stresses around the circumference has a resultant force of zero.

Figure 2 Residual Stress of – 5 to 30 ksi

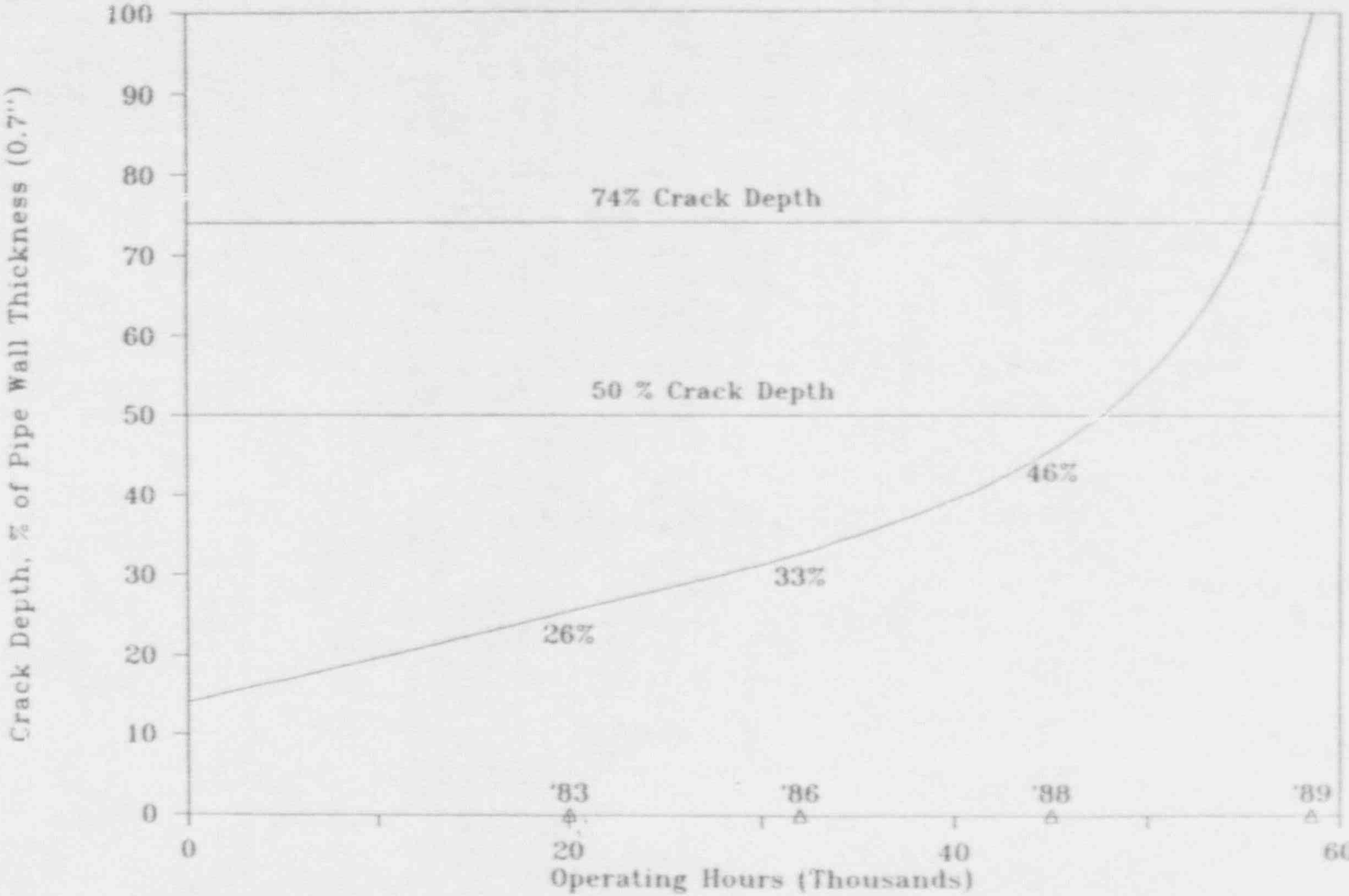


Figure 3 Residual Stress of −10 to 30 ksi

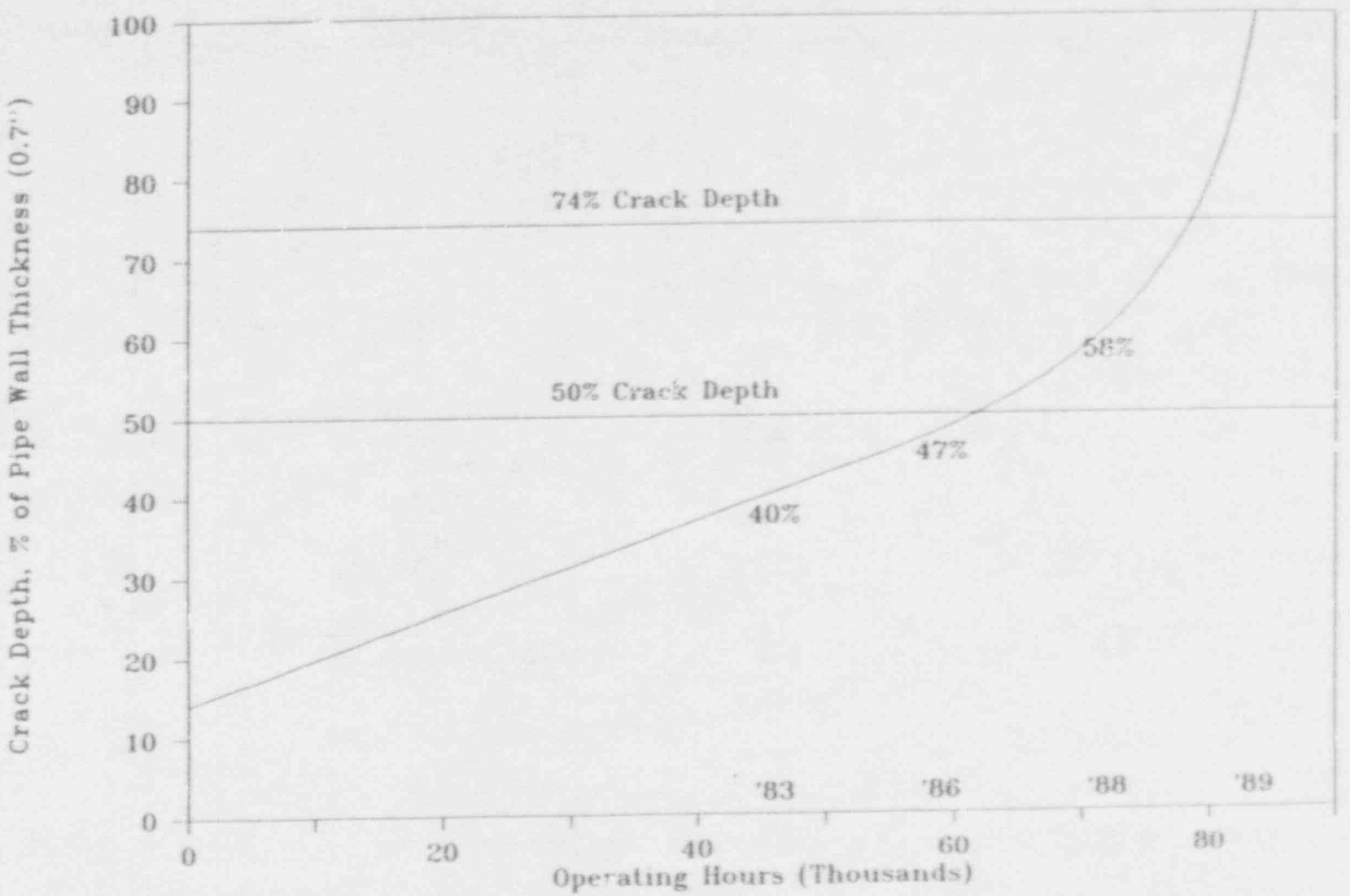


Figure 4 Residual Stress of −5 to −2 ksi

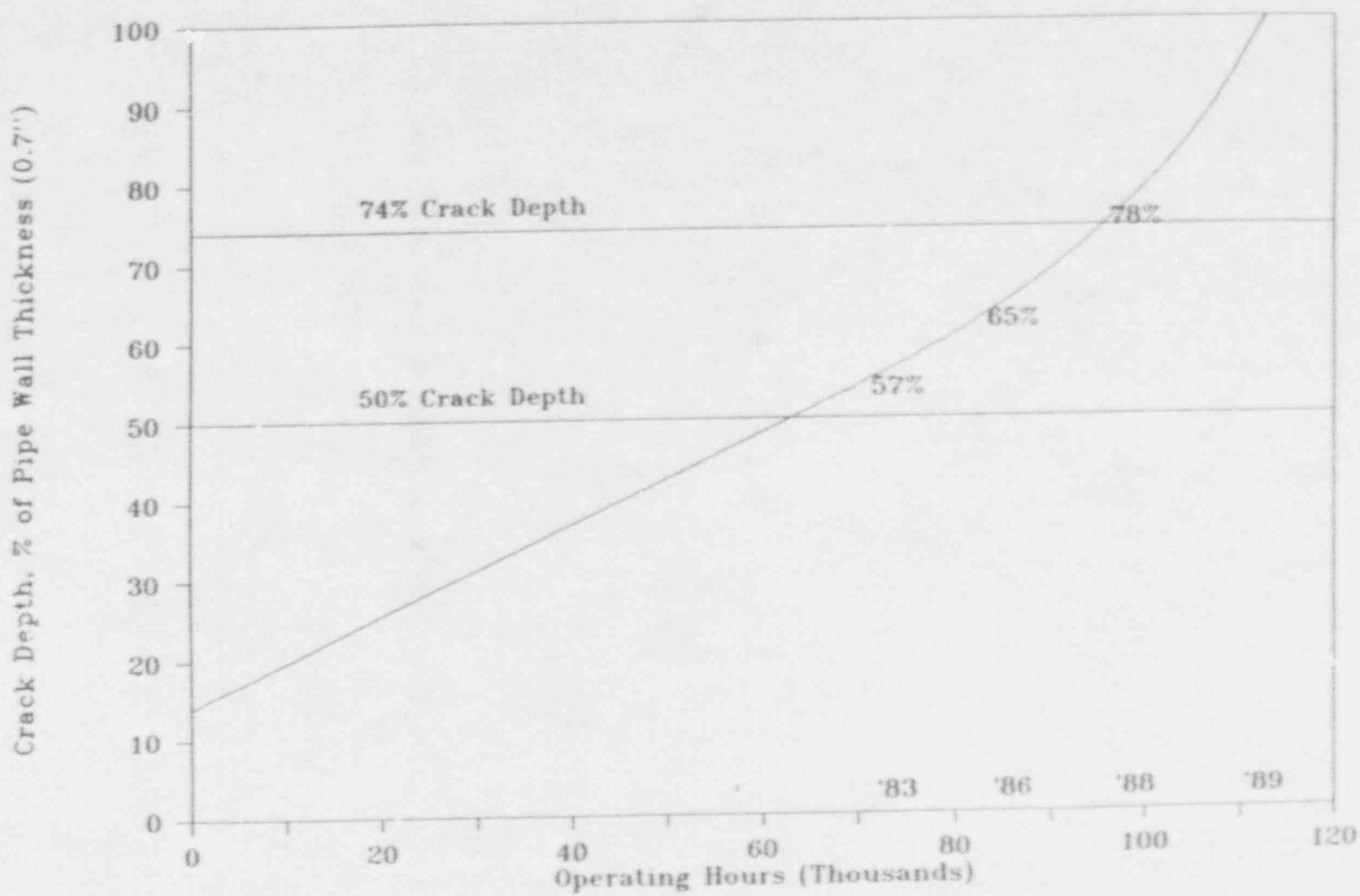
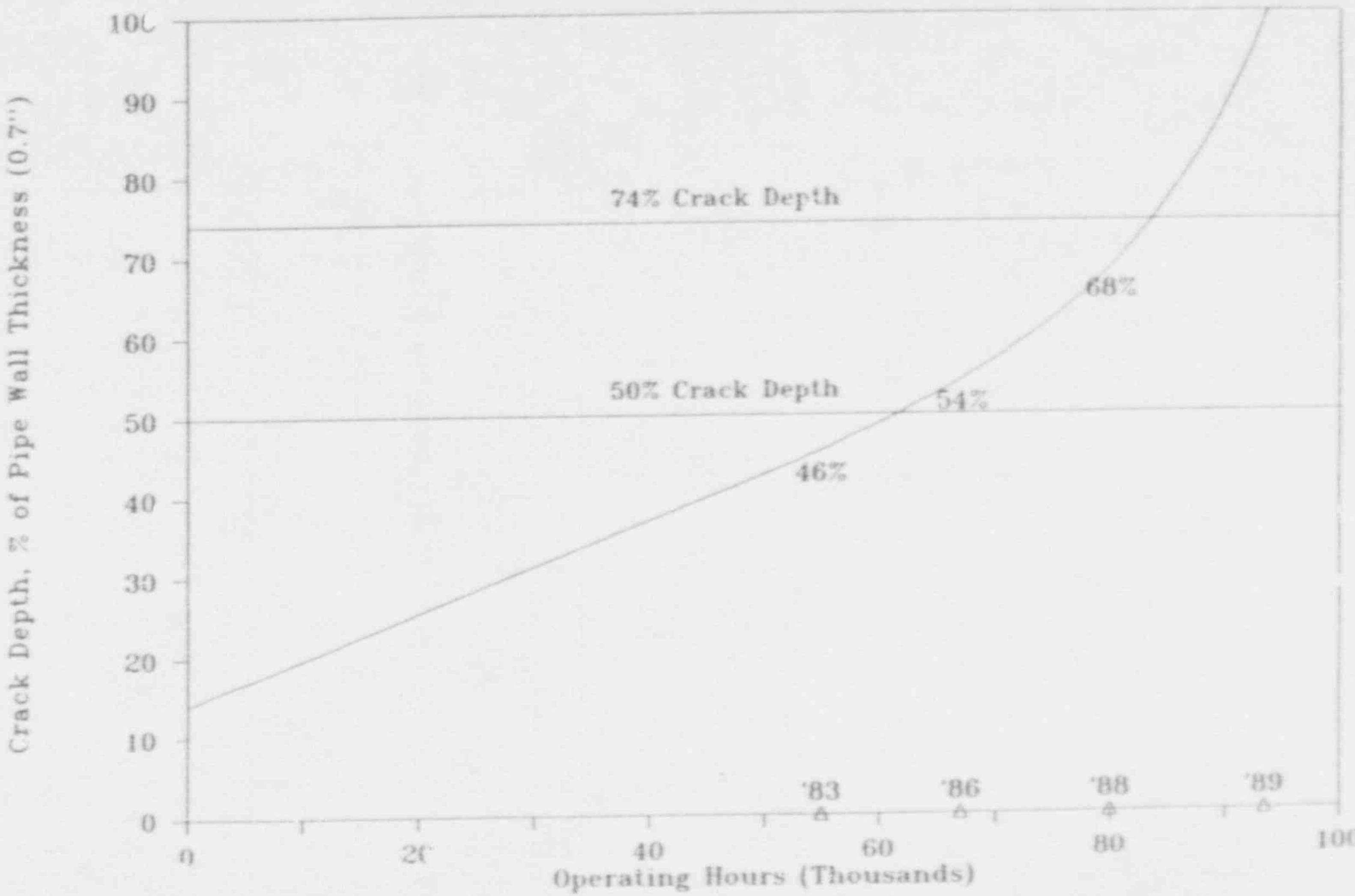


Figure 5 Residual Stress of − 5 to 5 ksi



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11. ABSTRACT (200 words or less)

A metallurgical assessment of four sections of weld overlaid pipe was performed. The investigation consisted of strain gage measurements, metallographic sectioning and mounting, scanning electron microscopy, hardness and ferrite measurements, radiography and dye penetrant examinations. A review of the fabrication history and original preservice and inservice examinations was performed and comparison was made to the actual cracks revealed after sectioning. In general, the report concludes that this weld quality of the overlays was consistent with ASME quality code class welds with adequate average "as deposited" ferrite readings of FN>7. The chemical analysis of the welds were normal for the alloys used (type 304 stainless steel, type 308 weld metal). The study also concludes that the ultrasonic inspection techniques used for inservice inspection of the overlays may not accurately depict the top 25% of the pipe in all cases and that crack growth is possible after weld overlay under certain conditions.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

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