Investigation of Intergranular

Stress Corrosion Cracking at

Three Mile Island - Unit 1

JCP&L / GPU

Met-Ed / GPU

GPU

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Investigation of Intergranular

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ABSTRACT

Intergranular stress corrosion cracking (IGSCC) has occurred at circumferential pipe welds in various borated water systems at Three Mile Island's (TMI) Unit 1 Pressurized Water Reactor (PWR). Extensive UT inspections and metallurgical studies were undertaken to define the scope of the problem and develop an understanding of the mechanism causing IGSCC in these systems.

One part of this investigation has directly led to the development of a 60°/2.25 MHZ UT technique capable of detecting IGSCC in the HAZ of stainless steel pipe welds with the ability to overlook most geometric reflectors. A detailed evolution with justification of this technique is presented in Section 1 of this report.

Metallurgical studies and data analysis were conducted to provide a fairly comprehensive understanding of IGSCC in the borated water systems at TMI-1 and p-ovide direction as to what remedial measures should be utilized to minimize or alleviate this problem. Highlights of these studies include: 1) The mechanism of failure has been identified as intergranular stress corrosion cracking in the weld sensitized structure in the heat-affected-zone of circumferential butt welds. 2) As of this date, no specific corrodent has been identified as being responsible for cracking, however, work is continuing in this area. 3) Increased susceptibility to IGSCC has been associated with specific heats, field welds, especially repaired field welds, high carbon heats and aerated stagnant lines. The specifics of these studies and analyses are detailed in Sections 2 and 3 of this report.

Since the basic cracking mechanism is related to sensitization, it was felt that much of the work conducted by EPRI in studying alternate solutions to the BWR pipe cracking phenomenon would be applicable. Such solutions included changing to the low carbon 304L SS or 316L SS material, weld cladding the I.D. surface at the weld joint of susceptible materials, heat sink welding, O.D. weld overlay cladding, etc. The repair scheme to be utilized at TMI-1 includes 1) the use of 304L SS for all replacement material, 2) all existing 304 SS pipe will be I.D. buttered to provide a more resistant material in the HAZ and 3) a low heat input weld procedure will be used for the circumferential butt welds of the pipe. The analysis of the repair alternatives and the impact of various parameters on the design consideration of the borated water systems are presented in Sections 4 and 5 of this report.

While this document represents a significant effort in characterizing the IGSCC in borated water systems at TMI, work is continuing in many areas to better understand this phenomenon. Such areas include the identificat'on of the cracking environment, material and structure sensitivity to IGSCC, improvement of UT techniques in detecting IGSCC, implementation of operating and process variables to mitigate IGSCC, the development of novel repair fixes and many other items. Therefore, it is this future work that will provide the insight required to completely define this problem and develop the remedial measures necessary to mitigate the IGSCC problem in borated water systems.

Section 1: DEVELOPMENT OF ULTRASONIC INSPECTION TECHNIQUES FOR THE DETECTION OF INTERGRANULAR STRESS CORROSION CRACKS AT THREE MILE ISLAND UNIT 1

1.1 INTRODUCTION

On April 4, 1979 an operator noted a build-up of boric acid crystals near a weld in the Spent Fuel cooling system. This system is a low temperature, low pressure system containing aerated borated water and was constructed from eight(8) inch (203 mm) schedule 40 Type 304 austenitic stainless steel. This leak prompted further investigations of this piping system. The initial investigation involved the following:

1) A visual walk-down of the entire system which revealed four(4) more thru-wall leaks.
2) Metallographic studies of the first thru-wall leak (pipe to valve weld at SF-V-17).
3) An unsuccessful attempt to define the extent of cracking in several weld joints by radiography.

On the fifth of May the GPU System Materials Lab reported that a crack in the sample sent to them for study was a stress assisted intergranular crack similar to those reported in various Boiling Water Reactor systems. By the end of May it had been determined that the development of an ultrasonic inspection technique capable of resolving incipient IGSCC was a necessary prerequisite to an extensive investigation of this problem. The following sections document the development of this UT inspection technique.

1.2 INITIAL STAGES

After some initial attempts with several different transducers and coupling blocks, a 1/4" by 1/4" 5 MHz transducer mounted on a 50°

(in stainless steel) block was selected. This combination was selected for several reasons:

1) This frequency is more easily reflected from small discontinuities than are lower frequencies.

2) The disadvantageously high attenuation factor at this frequency is partially compensated for by the very short metal path used (1/2 V path).

3) All nominal pipe thicknesses to be examined were thin enough to be penetrated satisfactorily with this frequency.

4) The relatively small angle of divergence of sound waves at this frequency allowed an examination concentrated on the area of interest.

5) For the typical weld geometries used, the 50° angle and a shortened coupling block provided the optimum combination for examining the heat affected zone next to the weld root (See Figure 1.1).

6) The 50° angle can still make use of the enhanced signal returned from any corner reflector that might be formed when a crack breaks the inner wall.

In conjunction with the transducer/coupling block combination, past experience with the Sonic FTE Mark I instrument suggested that a cleaner screen presentation could be obtained by setting the instrument for 1 MHz operation with the transducer connected to the receive terminal. This unusual instrument setting has little or no effect on the transmitted or received frequency spectrum and has not worked with any other instrument tested to date. All these elements were

embodied in Universal Testing Laboratories (UTL) procedure UTL-UT-SP-10 Rev. 0 (Appendix 1.1). This procedure was qualified by comparison with radiographs of pipes containing crack-like indications.

1.3 PROCEDURE IMPROVEMENTS (PHASE I TECHNIQUE)

During the latter part of June, five(5) weld joints with UT indications were cut from the system. One was sent (a thru wall leak) to Battelle's Pacific Northwest Laboratory for examination, (see Appendix 2.2). The four(4) remaining samples were retained by Met-Ed/GPU for examination. Table 1-1 summarizes and compares the results of various tests performed on these samples. (For a detailed report of these tests see Section 2 and Appendix 2.3.)

It was during the initial comparison of Liquid Penetrant Test (PT) results with the UT indications in these samples that the need for several major procedural improvements was warranted. Revisions 1 and 2 (Appendix 1.2) to UTL-UT-SP-10, here after designated as the Phase I procedures, contained the following improvements.

1) Extensive detailing of the calibration procedure.
2) Extension of the calibration procedure to materials greater than .500" thick (Rev. 2 only).
3) Extensive detailing of the method to be used for examination.
4) A change in the acceptance criteria from "all indications exceedin 25% of full screen height at a screen metal path equal to 1.4 times the thickness"...to..." any discernable reflector violating the inner wall in the Heat Affected Zone."

The most significant of these changes was the reporting criteria and because of this change all welds inspected with the Rev. 0 procedure were eventually re-inspected with the revised (Phase I) procedure. At this point it is important to note that the Phase I procedures were all used on a production basis and that they did not require a detailed mapping of indications, therefore there was no effort made to exclude reflections from weld geometry and other welding related anomalies. This procedural deficiency was not recognized until several indications were reported in the normally dry Building Spray piping inside the containment building. The reliability studies that were precipitated by the discovery of indications in dry piping are detailed in Section 1.6. Section 1.4 describes the efforts which were directed toward the development of an inspection technique which did not suffer from the same inability to differentiate reflections as did the Phase I procedures.

1.4 SCREENING PROCEDURE

Toward the latter part of July it became evident that the large number of reported indications were not all IGSCC. This conclusion was reached after radiographs of 10 weld joints in normally dry piping (3 in Building Spray System and 7 in Fuel transfer canal suction line) and 6 weld joints in the High Pressure Injection lines provided no confirmation of IGSCC. The next obvious step was the development of a screening technique capable of discriminating against non-relevant reflectors. Experimentation began with a technique which used two transducers arranged in a "pitch-catch" configuration. This method was rejected because it was too cumbersome to use in the field. Further experimentation revolved around changes in transducer frequency, incident

angle, and calibration. The result of this effort is embodied in Revision 3 to UTL-UT-SP-10 and includes the following:

1) A 2.25 MHz 1/4" by 1/4" Harisonics transducer
2) A 60° (in stainless steel) coupling block
3) An evaluation criteria which required at least a 30% of full screen height screen presentation in the area of interest before the reflection was considered reportable.

Justification for this new technique is based upon the fact that welding related anomalies, such as machining marks in the counterbore area are not detrimental to the structural integrity of the weld/pipe, therefore the screening technique need not be able to detect these reflections. This, of course, means that reflections from small discontinuities may also be missed.

The selection of a 60° coupling block and a 2.25 MHz transducer was the direct consequence of this effort to eliminate the detection of geometric type reflectors. The following is a brief explanation of how this combination functions.

1) Increasing the incident angle to 60° causes geometric type reflectors to "disappear" as the transducer is scanned inward toward the weld, (see Figure 1.1)
2) The 60° angle does not make use of corner reflectors, thus a discontinuity with some depth is required before a return signal can be generated.
3) The greater beam spread of the 2.25 MHz transducer was necessary to prevent relevant reflections from also "disappearing" as the transducer is scanned inward (see Figure 1.1)

4) The greater penetrating power of the 2.25 MHz transducer was advantageous for use over the slightly longer metal path that results from using the 60° angle.

5) The 2.25 MHz frequency is not as easily reflected from small discontinuities, but it is also not as sensitive to metal noise. (Note "metal noise" is defined as multiple reflections from grain boundaries which add together to give non-relevant indications.)

Revision 4 to UTL-UT-SP-10 (Appendix 1.3), which differs from Revision 3 only in its method of calibration, was qualified by testing three pipe samples with known cracks. Table 1.2 summarizes this qualification and compares the results with the 50°/5.0 MHz technique.

The ability of the screening procedure to discriminate against non-relevant reflections has also been confirmed by testing seven(7) crack free weld joints. These joints all had indications using the Phase I procedure but neither Liquid Penetrant tests nor the screening procedure disclosed any cracks.

1.5 EPRI SPONSORED R&D GROUP VISIT

On August 14, 1979 a research and development group for the development of an electronic method of interpreting ultrasonic indicators visited Three Mile Island. This EPRI sponsored group brought with them their prototype call confirmer for testing on several of Met-Ed's IGSCC samples. Appendix 1.4 details this visit but the following is a summary of the conclusions reached during this visit.

1) The 60°/2.25 MHz transducer utilized by the screening procedure was more accurate at determining IGSCC in the samples than was the group's 45°/1.5 MHz dual mounted transducers.

2) Machine marks in the counterbore area were indistinguishable from cracks for the Call Confirmer.

3) The Call Confirmer was sensitive to signal levels.

4) The Call Confirmer was incapable of using any information obtained while the transducer is in motion.

1.6 RELIABILITY AND VERIFICATION STUDIES

As mentioned in Section 1.3, the discovery of indications in normally dry piping prompted a reliability study. In fact two reliability studies have been conducted, one utilizing the 50°/5.0 MHz Phase I technique and one utilizing the 60°/2.25 MHZ screening technique.

The first study revealed a lack of correlation for inspections done with the Rev 0 procedure. This lack of correlation provided additional incentive for the reinspection of all the welds previously inspected with Rev 0.

The results of the second study were very satisfactory especially when the random nature of the human element is considered. This study used a 50% Poisson probability to show that 95.5% of the recorded results would be repeated by a single reinspection. A further examination of the study indicated that most non-repeatable results would probably involve marginal cases. However, this does not guarantee that a significant flaw will always be detected on the first inspection.

In addition to the reinspection of welds for the reliability studies, the following efforts were made to ensure the quality of the inspections.

1) Each Level II* technician was given extensive training in these procedures.
2) The Level III* technician, who was also the author of most of these procedures, frequently spot checked the performance of the technicians in the field.
3) On four different occasions the inspection process was witnessed by a qualified independent auditor.
4) During the reinspections, care was taken to ensure that a technician did not reinspect his own work.
5) The progress of the inspections was carefully followed by continually updating a set of system isometric drawings.

1.7 COMPARISONS OF UT TECHNIQUES

The question of why the UTL-UT-SP-10 series procedures are superior to ASME Section XI has been asked on several occasions by other organizations. The attached sample examination data sheets (Appendix 1.5) provide the formal documentation comparing these techniques. The following is a summary of the results.

1) The ASME technique easily detected a 10% notch, but did not give a reportable indication for a known 25% thru wall IGSCC. The 60°/2.25 MHz Rev 4 procedure gave a 100% full screen height response for the same crack.

*As defined by SNT-TC-1A, "Recommended Practice for Nondestructive Testing Personnel Qualification and Certification," ASNT.

2) Geometric reflectors gave rejectable indications with the ASME technique but were easily distinguished or not observed with the 60°/2.25 MHz technique.

3) For cracks greater than 25% thru wall the ASME technique could not define the full circumferential length of the crack. The 60°/2.25 MHz technique could.

4) With the ASME technique, indications had to be plotted in order to classify them. The 60°/2.25 MHz technique does not require plotting to differentiate between most indications.

5) The ASME technique requires much more time than the UTL-UT-SP-10 procedures.

1.8 SUMMARY AND CONCLUSIONS

The techniques described in the previous sections were derived in a relatively short period of time and did not have extensive support testing. They have to date proven themselves to be superior to anything previously available, but they are by no means infallible.

The 50°/5.0 MHz technique is extremely sensitive to incipient cracks, but is hampered by geometric reflectors and can provide little or no information about the crack's axial length.

The 60°/2.25 MHz technique gains its ability to overlook most geometric reflectors at the cost of becoming extremely sensitive to welding inclusions and lack of fusion. This technique can give some <u>relative</u> circumferential crack length information but no <u>actual</u> crack depth data can be derived from this or any other presently available nondestructive test. The examination of future IGSCC samples may

improve the confidence in this relative crack depth information but the many variables involved in this type inspection make it doubtful that actual crack penetration information will ever be available from this type of testing.

A brief attempt at a theoretical explanation of these techniques is given in the previous sections but the June 1978 Electric Power Research Institute's Key Phase Report NP-761 entitled Evaluation of Ultrasonic Techniques for Detection of Stress Corrosion Cracks in Stainless Steel Piping provides some additional empirically derived support for the 60°/2.25 MHz approach used in UTL-UT-SP-10 Rev 4. Again remember that this EPRI report was not used or available during the development of this technique.

The data gathered during these inspections is summarized and analyzed in the following sections. However, it should be noted that the results of any given UT inspection is not positive proof of the presence or absence of IGSCC. Even radiography may not be able to detect small, tight cracks. Therefore these ultrasonic testing procedures shall be considered only as a meaningful tool to be utilized for the detection of IGSCC.

For More Details
See Appendix 2.3

TABLE 1-1

PIPE SECTION	INDICATION	U.T. INDICATION		P.T. TEST	R.T. TEST	METALLOGRAPHY
		SCREEN B/L	AMPL			
#1 (SF-209)	I-1	7.6	70%FSH	YES	-	YES (Lack of Fusion)
	I-2	7.0	30%FSH	YES	-	YES (Lack of Fusion)
	I-3	7.8	60%FSH	YES	-	YES (Lack of Fusion)
#2 (SF-201)	I-1	6.4	20%FSH	YES	-	YES (Weld Root Irregularity)
	I-2	6.8	10%FSH	YES	-	YES (Weld Root Irregularity)
	I-3	6.2	15%FSH	YES	-	-
	I-4	6.2	25%FSH	YES	-	YES (Weld Root Irregularity)
	I-5	7.0	35%FSH	YES	-	- Surface Roughness
#3 (SF-12)	I-1	6.0	40%FSH	YES	-	YES (IGSCC)
	I-2	6.4	65%FSH	YES	-	YES (IGSCC)
	I-2 Twin Peak	6.5	25%FSH	YES	-	YES (IGSCC)
	I-3	6.5	75%FSH &	YES	-	YES (IGSCC)
		5.6	25%FSH	YES	-	YES (IGSCC)
		5.4	100%FSH	YES	YES	YES (IGSCC)
	I-4	6.0	20%FSH	YES	-	YES (IGSCC)
#4 (SF-42B)	I-1	5.6	15%FSH	YES	-	YES (IGSCC .010 deep)

Definitions:

B/L - Baseline Position
P.T. - Liquid Penetrant Test
R.T. - Radiographic Test

TABLE 1-2

SAMPLE ID. NO.	UT ID. NO.	APPROX. CRACK DEPTH (% THRU-WALL)	60°/2.25 MHz AMPL. @ MEASURED DEPTH LOCATION	60°/2.25 MHz MAX. AMPL.	LOCATION OF MAX. AMPLITUDE ORIGIN @ LEFT EDGE	LENGTH OF RECORDABLE INDICATION	50°/5.0 MHz MAX. AMPL.
Sample 3 IND. 2	SF-12	25%	60%FSH	100%FSH + 5dB	.5"	.875"	65%FSH
Sample 3 IND. 3	SF-12	50%	100%FSH + 1dB	100%FSH + 12dB	.5"	3"	100%FSH
SF-29	SF-35	100%	100%FSH+9 to 11dB	100%FSH + 11dB	6"	Full Length of Sample	95%FSH

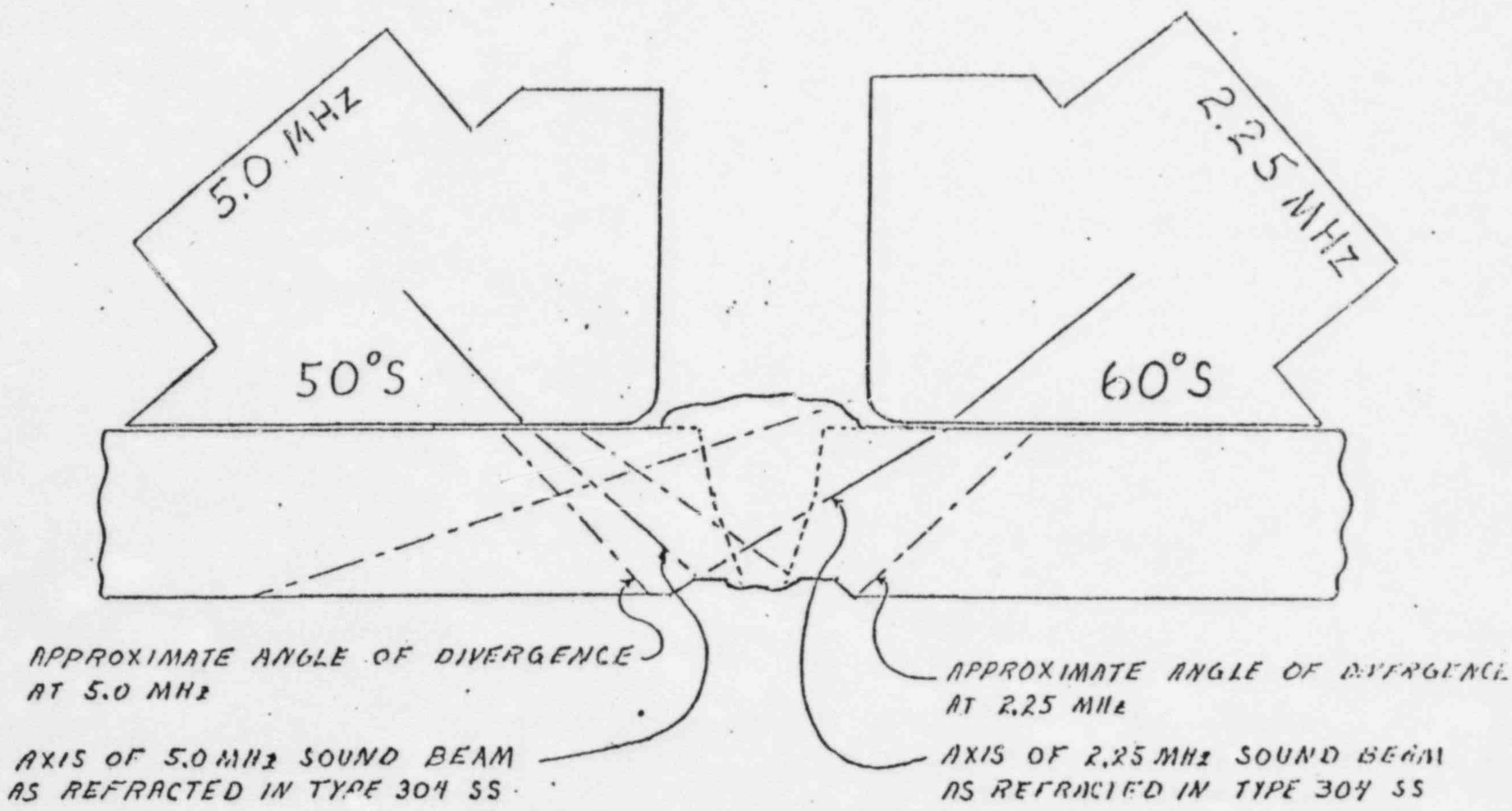

5.0 MHz
2.25 MHz
50°S
60°S
APPROXIMATE ANGLE OF DIVERGENCE
AT 5.0 MHz
AXIS OF 5.0 MHz SOUND BEAM
AS REFRACTED IN TYPE 304 SS
APPROXIMATE ANGLE OF DIVERGENCE
AT 2.25 MHz
AXIS OF 2.25 MHz SOUND BEAM
AS REFRACTED IN TYPE 304 SS

Figure 1-1

Appendices: Section 1

UNIVERSAL TESTING LABORATORIES, INC.

ubject: Special Procedure for Ultrasonic Examination of Austenitic Welds

Procedure #: UTL-UT-SP 10

pproval/Concurrence: J Piet (MET-ED)

Date Issued: 6/4/79

roject: TMI-Unit 1

Effective Date: 6/4/79

ate: 6/4/79

Revision #: 0

repared By: Neal Goodenough, Level III

IST OF EFFECTIVE PAGES	REVISION	DATE
1	0	6/4/79
2	0	6/4/79
3	0	6/4/79
ATTACHMENT		
1	0	6/4/79
2	0	6/4/79
3	0	6/4/79
4	0	6/4/79

1.0 SCOPE

1.1 This procedure provides the requirements and method for performing examination of austenitic welds for the detection of inner granular stress corrosion cracking.

1.2 This procedure is implemented to examine the weld heat affected zones only. This procedure is designed to examine welds from 1/8" to 2" thick.

2.0 REFERENCES

2.1 ASME Section XI 1974 edition, Summer 1975 Addenda, paragraph IWA-2240.

2.2 ASME Section XI, Appendix III for Instrument Linearity checks if a DAC is required on a specifc examination.

3.0 PROCEDURE QUALIFICATION

3.1 This procedure will be considered qualified by satifactory calibration checks before and after examinations and/or by comparison with radiographs from welds with known defects.

4.0 PERSONNEL QUALIFICATIONS

4.1 Personnel performing and interpreting ultrasonic examinations shall be qualified in accordance with UTL Personnel Qualification Manual which meets SNT-TC-1A 1975 edition.

5.0 INSTRUMENTS

5.1 Ultrasonic pulse-echo type of instrument shall be used which shall be capable of transmitting and receiving synchronized sound energy in frequenc of 1-10 mhz.

5.2 50° pulse-echo probes and/or 45° transmit-receive probes may be used. Frequency shall be 1.5 mhz. Other frequencies may be used if necessary. (i.e., 5 mhz probe - 1 mhz on machine. This combination yields the best signal response for (T304 S/S) stress corrosion examination.)

6.0 CALIBRATION

6.1 Sweep range shall be determined using IIW blocks or step wedge.

6.2 Amplitude calibration shall be determined using 5% notches and/or side drilled holes. Some thinner material may require a 10% notch to obtain an indication response.

NOTE: Because screen width represents 1/2V or less to remove geometrical reflectors, amplitude shall be approximately 100% FSH from the 10% notch on thickness to be examined. No DAC curve is required.

.0 CALIBRATION BLOCK

7.1 The calibration block shall be of a material acoustically similar to the material being examined. Blocks in excess of 1/2" thick shall contain side drilled holes as well as notches.

.0 EXAMINATION

8.1 All pipe and fittings to be examined, shall be measured with a straight beam to provide actual wall thickness, in order to properly interpret reflectors.

8.2 Examine the weld perpendicular from both sides when possible with a 50° pulse-echo or focused probe. Scan distance need only be for a distance of approximately equal to the heat affected zone. (i.e., 1/2T.) Scan overlap should be a minimum of 10%.

RECORDING

9.1 All indications exceeding 25% of FSH located at a screen metal path equal to 1.4 times the thickness shall be considered a crack and reported.

9.2 Instrument calibration reports shall be maintained on forms provided. (See attachments 1, 2, 3 & 4) Supplemental forms and sketches shall be used to clearly report the inspection.

UNIVERSAL TESTING LABORATORIES, INC.

410 POMPTON AVENUE CEDAR GROVE NEW JERSEY 07009

Procedure: UTL-UT-SP
Rev. 0 - 6/4/79
(Attachment 1)

TECHNIQUE CALIBRATION AND QUALIFICATION RECORD

S NO.	PROCEDURE NO.	DATE(S)
E NO.	LABORATORY	TECHNICIAN & LEVEL
P NO.	SYSTEM	CUSTOMER

'UT' TEST EQUIPMENT

UT INSTRUMENT	MAKE	MODEL	SERIAL NO.	CAL. DUE DATE
COUPLANT	TYPE			
CABLES	IDENTIFICATION			
SHOES	TYPE			
CALIBRATION BLOCK	SERIAL NO.	MATERIAL	DRAWING NO.	REVISION

SEARCH UNIT	MAKE	S/N	ANGLE	SIZE	EXIT PT.	MATERIAL	FREQUENCY

PRIOR TO EXAMINATION:

TEMPERATURE: CAL. BLOCK ________________°F

SPECIMEN TESTED________________°F

TIME: ____________________

SIGNATURE

SYSTEM CALIBRATION AND QUALIFICATION RECORD

NO.	PROCEDURE NO.	DATE(S).
NO.	LABORATORY	TECHNICIAN & LEVEL
NO.	SYSTEM	CUSTOMER

RECORD:

START OF EXAMINATION EVERY 4 HOURS	EVERY PERSONNEL CHANGE END OF EXAMINATION

E	TIME	DAC (RECORD AMPLITUDE)	SWEEP RANGE

TRANSFER	
CK db	COMPONENT db

AMPLITUDE LINEARITY			
TIME	-db	HIGH	LOW
START	-6db -12db		
	-6db -12db		
	-6db -12db		
	-6db -12db		
	-6db -12db		

CAL. BLOCK SENSITIVITY CHECK

TIME	GAIN SETTING			
	db	DAMP	COARSE	FINE

SONIC INSTRUMENT CALIBRATION RECORD

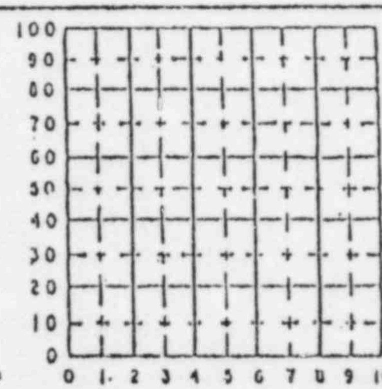
PROJECT No.:	SITE:	DATE (DAY-MON.-YR.)	TIME: (24 HR. CLOCK)	SHEET No.
1) EXAMINER:		INSTRUMENT:	SERIAL No.	CALIBRATION VERIFICATION
2) EXAMINER		COUPLANT: GLYCERINE		TIME: / INITIALS

SEARCH UNITS			
NOMINAL ANGLE			
MEASURED ANGLE			
BRAND	SERIAL NUMBER		
SIZE:			
NOMINAL FREQUENCY (MHZ):			

VERIFICATION BLK S/N:

EXAMINATION AREA(S):

INSTRUMENT SETTINGS			
REJECT:			
DEC:			
FINE dB:			
COARSE dB:			
FREQUENCY:			
DELAY:			
MAT'L CAL:			
RANGE:			
DAMPING:			
REP RATE:			
VIDEO:			
FILTER:			



___ SCREEN DIVISIONS: ___ INCHES OF METAL

BASIC CALIBRATION BLOCK No.:

REMARKS:

DATE:

JOB NO.	PROCEDURE NO.	DATE
NDE NO.	LABORATORY	TECHNICIAN & LEVEL
RWP NO.	SYSTEM	CUSTOMER

Appendix 1.2

UNIVERSAL TESTING LABORATORIES, INC.

Subject: Special Procedure for Ultrasonic Examination of Austenitic Welds

Approval/Concurrence: [signature] 7/19/79

Project: TMI-Unit 1

Date: 7/18/79

Prepared By: [signature] Level III

Approved By: [signature] Level III

Procedure #: UTL-UT-SP 10
Revision: 2
Date Issued: 7/18/79

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LIST OF EFFECTIVE PAGES	REVISION	DATE
1	2	7/18/79
2	2	7/18/79
3	2	7/18/79
4	2	7/18/79
5	2	7/18/79
6	2	7/18/79
ATTACHMENT		
1	2	7/18/79
2	2	7/18/79
3	2	7/18/79
4	2	7/18/79
5	2	7/18/79

0 SCOPE

1.1 This procedure provides the requirements and method for performing examination of austenitic welds for the detection of inter granular stress corrosion cracking.

1.2 This procedure is implemented to examine the weld heat affected zones only. This procedure is designed to examine welds from 1/8" to 2" thick.

1.3 See attachment #5 for weld joints.

.0 REFERENCES

2.1 ASME Section XI 1974 edition, Summer 1975 Addenda, paragraph IWA-2240.

.2 ASME Section V, Article 4, 1977 Edition, Summer Addenda

.0 PROCEDURE QUALIFICATION

3.1 This procedure will be considered qualified by satisfactory calibration checks before and after examinations (Ref. 6.3) and/or by comparison with radiographs from welds with known defects.

.0 PERSONNEL QUALIFICATIONS

4.1 All Level II personnel shall be qualified in accordance with UTL Personnel Qualification Manual which meets SNT-TC-1A 1975 Edition.

4.2 Level I and (or) Level IT personnel shall assist in operations and obtaining data.

.3 All interpretation and evaluation as well as calibration shall be performed by Level II personnel only.

.0 INSTRUMENTS

5.1 Ultrasonic pulse-echo type of instrument shall be used which shall be capable of transmitting and receiving synchronized sound energy in frequencies of 1-10 mhz.

5.2 Probes may consist of pulse echo and/or transmit-receive types.

5.3 Transducer angles shall be within the range of 45^0-55^0.

5.4 Transducer size shall be 1/4" to 1/2" wide for angle beam inspection. A straight beam transducer shall be 3/8" Ø to 3/4" Ø, for determining wall thickness.

5.5 Transducer frequency within the range of 2 mhz and 5 mhz may be used in conjunction with varied machine settings.

5.6 Cables shall not exceed 12' in length.

5.7 Couplant shall consist of Hamikleer, Exosen #20, or equivalent to ensure continous coupling contact.

6.0 CALIBRATION DESCRIPTION

6.1 Sweep range shall be determined using IIW blocks or step wedge.

6.2 Amplitude calibration shall be determined using 5% or 10% notches and/or side drilled holes.

NOTE: Amplitude shall be approximately 100% FSH from the 5% or 10% notch on applicable test standard. No DAC curve is required.

6.3 As per frequency of calibration verification.
Calibration shall be verified at the beginning of each examination, not more than every 4 hours, any change in equipment, change in personnel and at the end of examination.

7.0 SYSTEM CALIBRATION (SWEEP RANGE)

7.1 Full screen width shall represent .5" depth for thicknesses of .100 to .500 to be inspected.

7.1.1 Full screen width shall represent 2.5" depth for a thickness of .900 to 1.3" to be inspected.

7.1.2 Full screen width shall represent 1.0" depth for thicknesses over .500 to .900 to be inspected.

7.2 Position search unit for a maximum response from the corner of .2" on step wedge. Adjust left edge of this signal to line 4 on the screen with the delay control.

7.2.1 Position search unit for a maximum response from the corner of .4" step wedge. Adjust left edge of this signal to line #8 on the screen with the material calibration.

7.2.2 Repeat delay and material calibr[illegible] trol adjustments until the two signals start at precisely [illegible] 8.

7.2.3 Check corner reflectors on .3 wedge and a .5 wedge. These should now break the base line at Lines 6 and 10.

7.2.4 Each division on the sweep now is equal to .050 metal depth.

7.2.5 For wall thickness of .9 to 1.3" the corner of the IIW bl[illegible]k will be used in conjunction with the .5 step wedge.

7.2.6 Position search unit for maximum response from bottom corner of IIW block. Adjust left edge of signal to line #4 on the screen with delay control.

7.2.7 Position search unit for maximum response from the top corner of IIW block on full "V" path. Adjust the left edge of this signal to line #8 with the material calibration.

7.2.8 Repeat delay and material calibration control adjustments until the two signals start at precisely lines 4 and 8.

7.2.9 Each division on the sweep now is equal to 1/8" (.125) metal depth.

7.2.10 For wall thicknesses of .500 to .900 position search unit for maximum response from the corner of the .500 step wedge. Adjust left edge of this signal to line #5 on the screen with the delay control.

7.2.11 Position search unit for maximum response from the corner of the 1.0" block. Adjust left edge of this signal to line #10 on the screen with the material calibration.

7.2.12 Repeat delay and material calibration control adjustments until the two signals start at precisely lines 5 and 10.

7.2.13 Check corner reflectors on various other step blocks to determine accuracy.

7.2.14 Each screen division is now equal to .100 metal depth.

7.3 System Calibration (sensitivity)

7.3.1 Sensitivity shall be obtained from the 10% or 5% notch cut on the I.D. of the applicable standard.

Standards are as follows:

.100 to .300 Wall Thickness - Block SE-28-W-3C
.300 to .500 Wall Thickness - Block SF-29-W-3C
.500 to .900 Wall Thickness - Block SF-29-W-3C
.900 to 1.3 Wall Thickness - Block MET-ED-019

7.3.2 Position search unit to obtain maximum response from 10% notch on the first leg of "V" path.

7.3.3 Adjust gain control to bring signal amplitude to 100% FSH. Scanning will be performed at this level. This is to refrain from over saturation of material.

7.4 Directions and Extent of Examination

7.4.1 The heat affected zone shall be examined from both sides of the weld where possible. Where configuration or adjacent parts of the component are such that scanning from both sides is not feasible, this fact shall be included in the report of the examination.

7.4.2 The angle beam search unit shall be aimed at right angles to the weld axis, with the search unit being oscillated approximately 20° off the normal.

7.4.3 Scan shall consist of a minimum 10% overlap at a rate of six (6) inches per sec. maximum speed.

7.4.4 Scan coverage shall consist of 2T each side of weld, where applicable. See 7.4.1.

7.4.5 All scan surfaces are to be measured with a straight beam transducer to provide actual wall thickness, in order to properly evaluate reflectors.

7.4.6 All surfaces shall be free of loose scale, dirt, weld spatter or anything that would inhibit the transmission of ultrasound.

8.0 EVALUATION

8.1 Any discernable reflector violating the inner wall, in the Heat Affected Zone, will be evaluated as Stress Corrosion Cracking.

9.0 RECORDING

9.1 For each ultrasonic examination the following information shall be recorded on Attachments #1 - #4 as applicable.

9.2 Procedure

9.3 UT equipment

9.4 Examination Personnel and Levels

9.5 Calibration Sheet identify

9.6 Weld identification and location

9.7 Surface of examination

9.8 Calibration block number

9.9 Record of indications

9.10 Date and time of examination

9.11 Couplant

9.12 Frequency

9.13 Surface condition

9.14 Special equipment

TECHNIQUE CALIBRATION AND QUALIFICATION RECORD

	PROCEDURE NO.	DATE(S)
NO.	LABORATORY	TECHNICIAN & LEVEL
NO.	SYSTEM	CUSTOMER

'UT' TEST EQUIPMENT

UT [IN]STRUMENT	MAKE	MODEL	SERIAL NO.	CAL. DUE DATE
[CO]UPLANT	TYPE			
[C]ABLES	IDENTIFICATION			
SHOES	TYPE			
[CALI]BRATION [BLO]CK	SERIAL NO.	MATERIAL	DRAWING NO.	REVISION

[SEARCH] UNIT	MAKE	S/N	ANGLE	SIZE	EXIT PT.	MATERIAL	FREQUENCY

PRIOR TO EXAMINATION:

TEMPERATURE: CAL. BLOCK ______________ °F

SPECIMEN TESTED ______________ °F

TIME: ______________

____
SIGNATURE

579 POMPTON AVENUE CEDAR GROVE NEW JERSEY 07009

SYSTEM CALIBRATION AND QUALIFICATION RECORD

	PROCEDURE NO.	DATE(S).
	LABORATORY	TECHNICIAN & LEVEL
	SYSTEM.	CUSTOMER

RECORD:

START OF EXAMINATION EVERY 4 HOURS	EVERY PERSONNEL CHANGE END OF EXAMINATION

	TIME	DAC (RECORD AMPLITUDE)	SWEEP RANGE

TRANSFER	
db	COMPONENT db

AL. BLOCK SENSITIVITY CHECK

ME	GAIN SETTING			
	db	DAMP	COARSE	FINE

AMPLITUDE LINEARITY			
TIME	-db	HIGH	LOW
START	-6db -12db		
	-6db -12db		
	-6db -12db		
	-6db -12db		
	-6db -12db		

SONIC INSTRUMENT CALIBRATION RECORD

PROJECT No.:	SITE:	DATE (DAY-MON.-YR.)	TIME: (24 HR. CLOCK)	SHEET No.

1) EXAMINER:		
2) EXAMINER:		

INSTRUMENT:	SERIAL No.
COUPLANT: GLYCERINE	

CALIBRATION VERIFICATION					
TIME:					
INITIALS:					

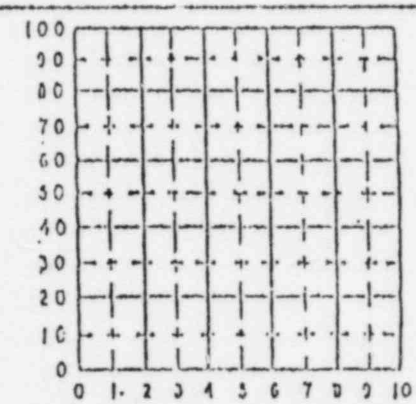
SEARCH UNITS

NOMINAL ANGLE			
MEASURED ANGLE			
BRAND	SERIAL NUMBER		
SIZE:			
NOMINAL FREQUENCY (MHZ):			

VERIFICATION BLK S/N:

INSTRUMENT SETTINGS

REJECT:			
DEC:			
FINE dB:			
COARSE dB:			
FREQUENCY:			
DELAY:			
MAT'L CAL:			
RANGE:			
DAMPING:			
REP RATE:			
VIDEO:			
FILTER:			



___ SCREEN DIVISIONS: ___ INCHES OF METAL

BASIC CALIBRATION BLOCK No.

EXAMINATION AREA(S):

REMARKS:

DATE:

NEW JERSEY

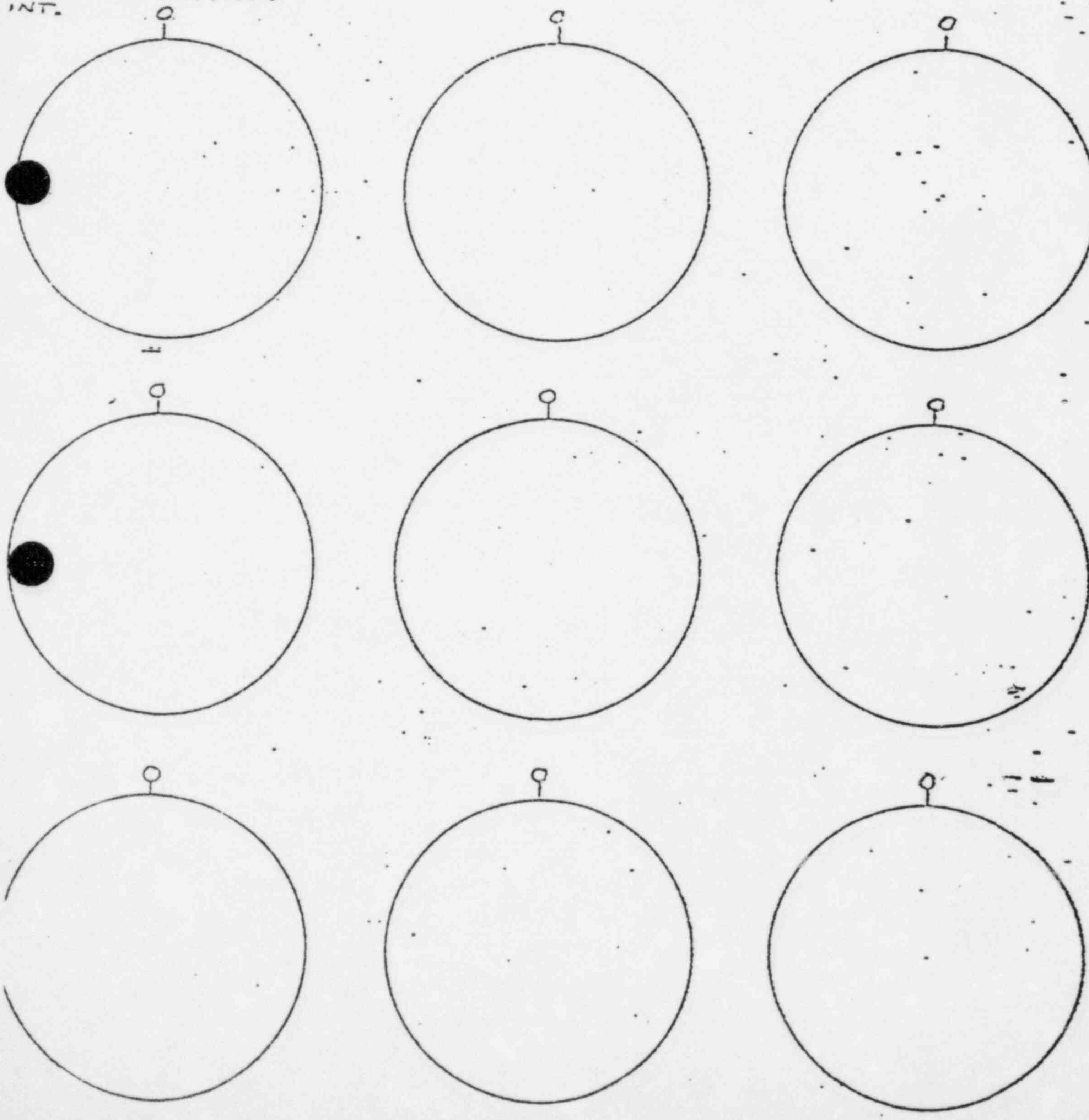
SHEET 10 of 1

Procedure: UTL-UT-SP
Rev. 2 - 7/18/79
(Attachment #4)

JOB NO. INVESTIGATION EXAMINATION	PROCEDURE NO.	DATE
NDE NO.	LABORATORY U.T.L.	TECHNICIAN & LEVEL
RWP NO.	SYSTEM	CUSTOMER. MET-ED T.M.I. (UNIT-1)

TE!
ROW ON WELD NO.
NTIFICATION ON
PC - 15 0 INDICATION
INT.

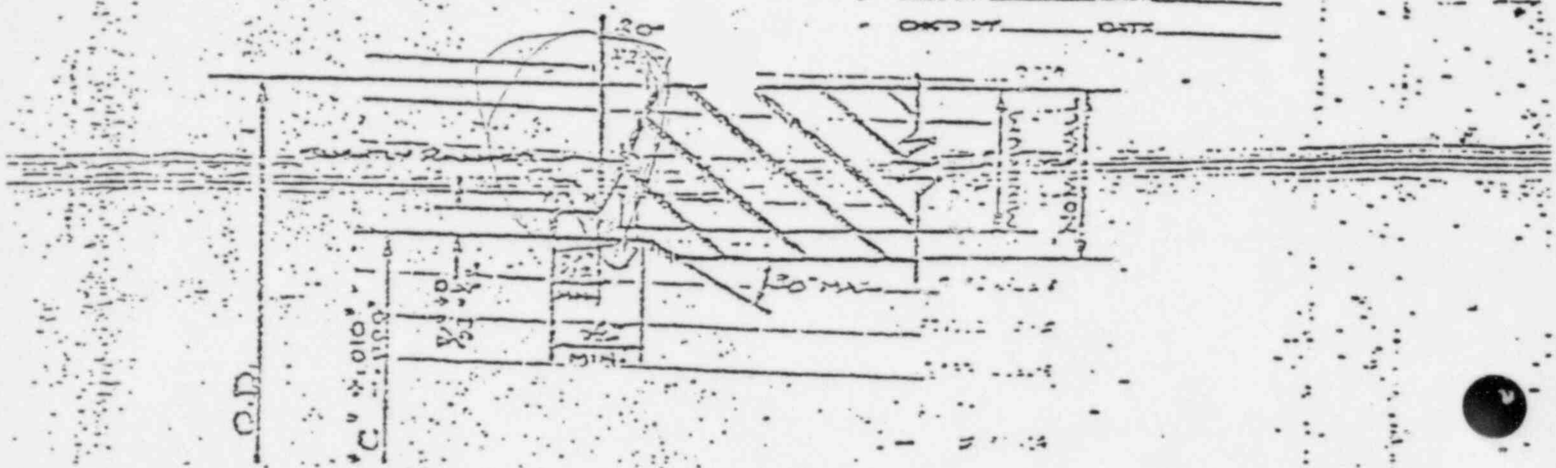
INDICATION REPORT SHEET



GRINNELL

P. O. No. 94174
ORDER OR CONT. No. 51-H-494
NAME METROPOLITAN EDISON CO. UNIT #1
LOCATION THREE MILE ISLAND NUCLEAR STATION

PROVIDENCE I P D
DRWN BY CE DATE 6-15-69
CHKD BY [illegible] DATE [illegible]
REV. BY ______ DATE ______
CHKD BY ______ DATE ______



SIZE	SCH	O.D.	NOM. WALL	tm	C
16"	40S	16.000	.375	.227	15.437
14"	-	14.000	.375	.207	13.437
12"	-	12.750	.375	.159	12.187
10"	-	10.750	.365	.159	10.206
8"	-	8.625	.322	.129	8.123
6"	-	6.625	.280	.093	6.197
4"	-	4.500	.237	.067	4.117
3"	-	3.500	.216	.117	3.153
24"	3/8" W.	24.000	.375	.040	23.437

END PREPARATION FOR S.40S STAINLESS STEEL INERT GAS ROOT PASS SHOP AND FIELD WELDS

PRIORITY		RADIOGRAPHY		ULTRASONIC		LIQ. PENT.	
STRESS RELIEVE		MAG. PARTICLE INSPECTION		ASME PARTIAL DATA REPORTS		MILL TEST CERTIFICATES	

P.O.
D.W. FIG.
F.L.

SYSTEM DECAY HEAT REMOVAL

DWG. NO. 8-301-001 IV PIECE MARK

SKETCH DH-D1

P. O. No. 94174 GRINNELL
ORDER OR CONT. No. 51-H-494
NAME METROPOLITAN EDISON CO. UNIT #1
LOCATION THREE MILE ISLAND NUCLEAR STATION

UNIVERSAL TESTING LABORATORIES, INC.

Appendix 1.3

Special Procedure for Ultrasonic Examination of Austenitic Welds

PROCEDURE: UTL-UT-SP 10

REVISION: 4

DATE ISSUED: 8/17/79

EFFECTIVE DATE: 8/17/79

Approval/Concurrence: [signature] 8/17/79

PROJECT: TMI-Unit 1

Date: 8/17/79

PREPARED BY: [signature] Level III

APPROVED BY: [signature] Level III

LIST OF EFFECTIVE PAGES	REVISION	DATE
1	4	8/17/79
2	4	8/17/79
3	4	8/17/79
4	4	8/17/79
5	4	8/17/79
6	4	8/17/79
7	4	8/17/79
ATTACHMENTS		
1	4	8/17/79
2	4	8/17/79
3	4	8/17/79
4	4	8/17/79
5	4	8/17/79
6	4	8/17/79

1.0 SCOPE

1.1 This procedure provides the requirements and method for performing examination of austenitic welds for the detection of inter granular stress corrosion cracking.

1.2 This procedure is implemented to examine the weld heat affected zones only. This procedure is designed to examine welds from 1/8" to 1.25" thick.

1.2.1 See attachment #5 for weld joints.

1.3 This procedure provides a two step screening disposition.

1.3.1 Step one entails a highly sensitive technique, susceptible to reflectors very small in size of numerous origins.

1.3.2 Step two entails a highly sensitive technique which is not as susceptibl to small reflectors (as step #1) nor is it as vulnerable to geomet

2.0 REFERENCES

2.1 ASME Section XI, 1974 edition, Summer 1975 Addenda, paragraph IWA-2240.

2.2 ASME Section V, Article 4, 1977 Edition, Summer Addenda

2.3 SNT-TC-1A, 1975 Edition.

3.0 PROCEDURE QUALIFICATION

3.1 This procedure will be considered qualified by satisfactory calibration checks before and after examinations (Ref. 6.3) and/or by comparison with radiographs from welds with known defects.

4.0 PERSONNEL QUALIFICATIONS

4.1 All Level II personnel shall be qualified in accordance with UTL Personnel Qualification Manual which meets SNT-TC-1A 1975 Edition.

4.2 Level I and (or) Level II personnel shall assist in operations and obtaining data.

4.3 All interpretation and evaluation as well as calibration shall be performed by Level II or Level III personnel only.

5.0 INSTRUMENTS

5.1 Ultrasonic pulse-echo type of instrument shall be used which shall be capable of transmitting and receiving synchronized sound energy in frequencies of 1-10 mhz.

5.2 Probes may consist of pulse echo and/or transmit-receive types.

5.3 Transducer angles shall be within the range of 45° - 60° ($\pm$ 2°).

5.3.1 Angles of 45° and 50° shall be used for step one screening where applicable.

5.3.2 A 60° transducer shall be used for step two screening. (See 8.0 evaluation.

5.4 Transducer size shall be 1/4" to 1/2" wide for angle beam inspection. A straight beam transducer shall be 1/4" ϕ to 3/4" ϕ, for determining wall thickness.

5.5 Transducer frequency within the range of 2 mhz and 5 mhz may be used in conjunction with varied machine settings.

5.6 Cables shall not exceed 12' in length.

5.7 Couplant shall consist of Hamikleer, Exosen #20, or equivalent to ensure continous coupling contact.

6.0 CALIBRATION DESCRIPTION

6.1 Sweep range shall be determined using IIW blocks or step wedge.

6.2 Amplitude calibration shall be determined using 5% or 10% notches and/or side drilled holes.

NOTE: Amplitude shall be approximately 100% FSH from the 5% or 10% notch on applicable test standard. No DAC curve is required.

6.3 As per frequency of calibration verification. Calibration shall be verified at the beginning of each examination, not more than every 4 hours, any change in equipment, change in personnel and at the end of examination.

7.0 SYSTEM CALIBRATION (SWEEP RANGE)

7.1 Full screen width shall represent .5" depth for thicknesses of .100 to .500 to be inspected.

7.1.1 Full screen width shall represent 2.5" depth for a thickness of .900 to 1.3" to be inspected.

7.1.2 Full screen width shall represent 1.0" depth for thicknesses over .500 to .900 to be inspected.

7.2 Position search unit for a maximum response from the corner of .2" on step wedge. Adjust left edge of this signal to line 4 on the screen with the delay control.

7.2.1 Position search unit for a maximum response from the corner of .4" step wedge. Adjust left edge of this signal to line #8 on the screen with the material calibration.

7.2.2 Repeat delay and material calibration control adjustments until the two signals start at precisely Lines 4 and 8.

7.2.3 Check corner reflectors on .3 wedge and a .5 wedge. These should now break the base line at Lines 6 and 10.

7.2.4 Each division on the sweep now is equal to .050 metal depth.

7.2.5 For wall thickness of .9 to 1.3" the corner of the IIW block will be used in conjunction with the .5 step wedge.

7.2.6 Position search unit for maximum response from bottom corner of IIW block. Adjust left edge of signal to line #4 on the screen with delay control.

7.2.7 Position search unit for maximum response from the top corner of IIW block on full "V" path. Adjust the left edge of this signal to line #8 with the material calibration.

7.2.8 Repeat delay and material calibration control adjustments until the two signals start at precisely lines 4 and 8.

7.2.9 Each division on the sweep now is equal to 1/8" (.125) metal depth.

7.2.10 For wall thicknesses of .500 to .900 position search unit for maximum response from the corner of the .500 step wedge. Adjust left edge of this signal to line #5 on the screen with the delay control.

7.2.11 Position search unit for maximum response from the corner of the 1.0" block. Adjust left edge of this signal to line #10 on the screen with the material calibration.

7.2.12 Repeat delay and material calibration control adjustments until the two signals start at precisely lines 5 and 10.

7.2.13 Check corner reflectors on various other step blocks to determine accuracy.

7.2.14 Each screen division is now equal to .100 metal depth.

7.3 System Calibration (sensitivity)

7.3.1 Sensitivity shall be obtained from the 10% or 5% notch cut on the I.D. of the applicable standard.

Standards are as follows:

.100 to .300 Wall Thickness - Block SE-28-W-3C
.300 to .500 Wall Thickness - Block SF-29-W-3C
.500 to .900 Wall Thickness - Block SF-29-W-3C
.900 to 1.3 Wall Thickness - Block MET-ED-019

7.3.2 Position search unit to obtain maximum response from 10% notch on the first leg of "V" path.

7.3.3 Adjust gain control to bring signal amplitude to 100% FSH. Scanning will be performed at this level. This is to refrain from over saturation of material.

7.4 Directions and Extent of Examination

7.4.1 The heat affected zone shall be examined from both sides of the weld where possible. Where configuration or adjacent parts of the component are such that scanning from both sides is not feasible, this fact shall be included in the report of the examination.

7.4.2 The angle beam search unit shall be aimed at right angles to the weld axis, with the search unit being oscillated approximately 20^{o} off the normal.

7.4.3 Scan shall consist of a minimum 10% overlap at a rate of six (6) inches per sec. maximum speed.

7.4.4 Scan coverage shall consist of 2T each side of weld, where applicable. See 7.4.1.

7.4.5 All scan surfaces are to be measured with a straight beam transducer to provide actual wall thickness, in order to properly evaluate reflectors.

7.4.6 All surfaces shall be free of loose scale, dirt, weld spatter or anything that would inhibit the transmission of ultrasound.

8.0 <u>EVALUATION</u>

8.1 Any discernable reflector violating the inner wall, in the Heat Affected Zone, will be evaluated as Stress Corrosion Cracking.

8.1.1 Evaluation (screening) will be performed using a 60^{o} ($\pm$ 2^{o}) shear wave of 2.25 mhz nominal frequency.

8.2 All information obtained will be recorded on Attachments #3 and #6 where applicable.

8.3 Calibration for 60^{o} screening shall be obtained from 10% machined notch in:

A. .250 - IGA-#2

B. .500 - IGA-#1

8.3.1 Position search unit for maximum response from 10% notch on IGA-#2. Adjust left edge of signal to division #5 on the screen with delay control.

8.3.2 Position search unit for maximum response from 10% notch on IGA-#1. Adjust left edge of this signal to division #7 on the screen with the material calibration.

8.3.3 Repeat delay and material calibration control adjustments until the two signals start at precisely divisions #5 and #7.

8.3.4 Position search unit for maximum response from 10% machine notch on either block. Adjust gain control until signal response is 50% full screen height (FSH).

8.3.5 Position search unit for maximum response from 10% machine notch on the opposite block used in step 8.3.4. Any difference > 10% of referenced level shall be brought to the attention of the Level III.

8.4 All indications exceeding 30% FSH in the area of concern will be recorded on Attachment #6.

RECORDING

9.1 For each ultrasonic examination the following information shall be recorded on Attachments #1 - #4 as applicable. (50° only)

9.2 Procedure

9.3 UT equipment

9.4 Examination Personnel and Levels

9.5 Calibration sheet identity

9.6 Weld identification and lcoation

9.7 Surface of examination

9.8 Calibration block number

9.9 Record of indications

9.10 Date and time of examination

9.11 Couplant

9.12 Frequency

9.13 Surface condition

9.14 Special equipment

UNIVERSAL TESTING LABORATORIES.

410 POMPTON AVENUE CEDAR GROVE NEW JERSEY 07009

Sheet 8 8/17/79
Procedure: UTL-UT-SP
Rev. 4
(Attachment #1)

TECHNIQUE CALIBRATION AND QUALIFICATION RECORD

NO.	PROCEDURE NO.	DATE(S).
E NO.	LABORATORY	TECHNICIAN & LEVEL
P NO.	SYSTEM	CUSTOMER

'UT' TEST EQUIPMENT

UT STRUMENT	MAKE		MODEL		SERIAL NO.		CAL. DUE DATE
COUPLANT	TYPE						
CABLES	IDENTIFICATION						
SHOES	TYPE						
RATION BLOCK	SERIAL NO.		MATERIAL		DRAWING NO.		REVISION
SCH UNIT	MAKE	S/N	ANGLE	SIZE	EXIT PT.	MATERIAL	FREQUENCY

PRIOR TO EXAMINATION:

TEMPERATURE: CAL. BLOCK ________________°F

SPECIMEN TESTED________________°F

TIME: ______________________________

____

SIGNATURE

SYSTEM CALIBRATION AND QUALIFICATION RECORD

[illegible]	PROCEDURE NO.	DATE(S)
[illegible]	LABORATORY	TECHNICIAN & LEVEL
[illegible]	SYSTEM	CUSTOMER

RECORD:

START OF EXAMINATION EVERY 4 HOURS	EVERY PERSONNEL CHANGE END OF EXAMINATION

	TIME	DAC (RECORD AMPLITUDE)	SWEEP RANGE

TRANSFER	
K db	COMPONENT db

AMPLITUDE LINEARITY			
TIME	-db	HIGH	LOW
START	-6 db -12 db		
	-6 db -12 db		
	-6 db -12 db		
	-6 db -12 db		
	-6 db -12 db		

CAL. BLOCK SENSITIVITY CHECK

IME	GAIN SETTING			
	db	DAMP	COARSE	FINE

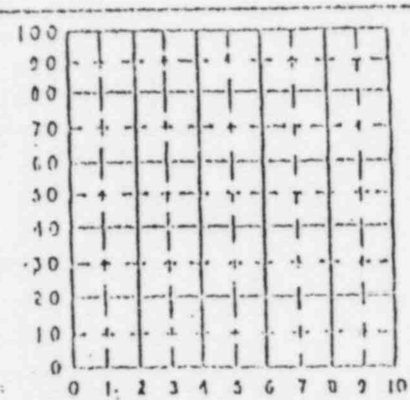
SONIC INSTRUMENT CALIBRATION RECORD

PROJECT No.:	SITE:	DATE (DAY-MON.-YR.)	TIME: (24 HR. CLOCK)	SHEET NO.
1) EXAMINER:		INSTRUMENT:	SERIAL NO.	CALIBRATION VERIFICATION
2) EXAMINER:		COUPLANT: GLYCERINE		TIME:
				INITIALS:

SEARCH UNITS			
NOMINAL ANGLE			
MEASURED ANGLE			
BRAND	SERIAL NUMBER		
SIZE:			
NOMINAL FREQUENCY (MHZ):			

INSTRUMENT SETTINGS			
REJECT:			
DEC:			
FINE dB:			
COARSE dB:			
FREQUENCY:			
DELAY:			
MAT'L CAL:			
RANGE:			
DAMPING:			
REP RATE:			
VIDEO:			
FILTER:			

VERIFICATION BLK S/N:



___ SCREEN DIVISIONS: ___ INCHES OF METAL

BASIC CALIBRATION BLOCK No.:

EXAMINATION AREA(S):

REMARKS:

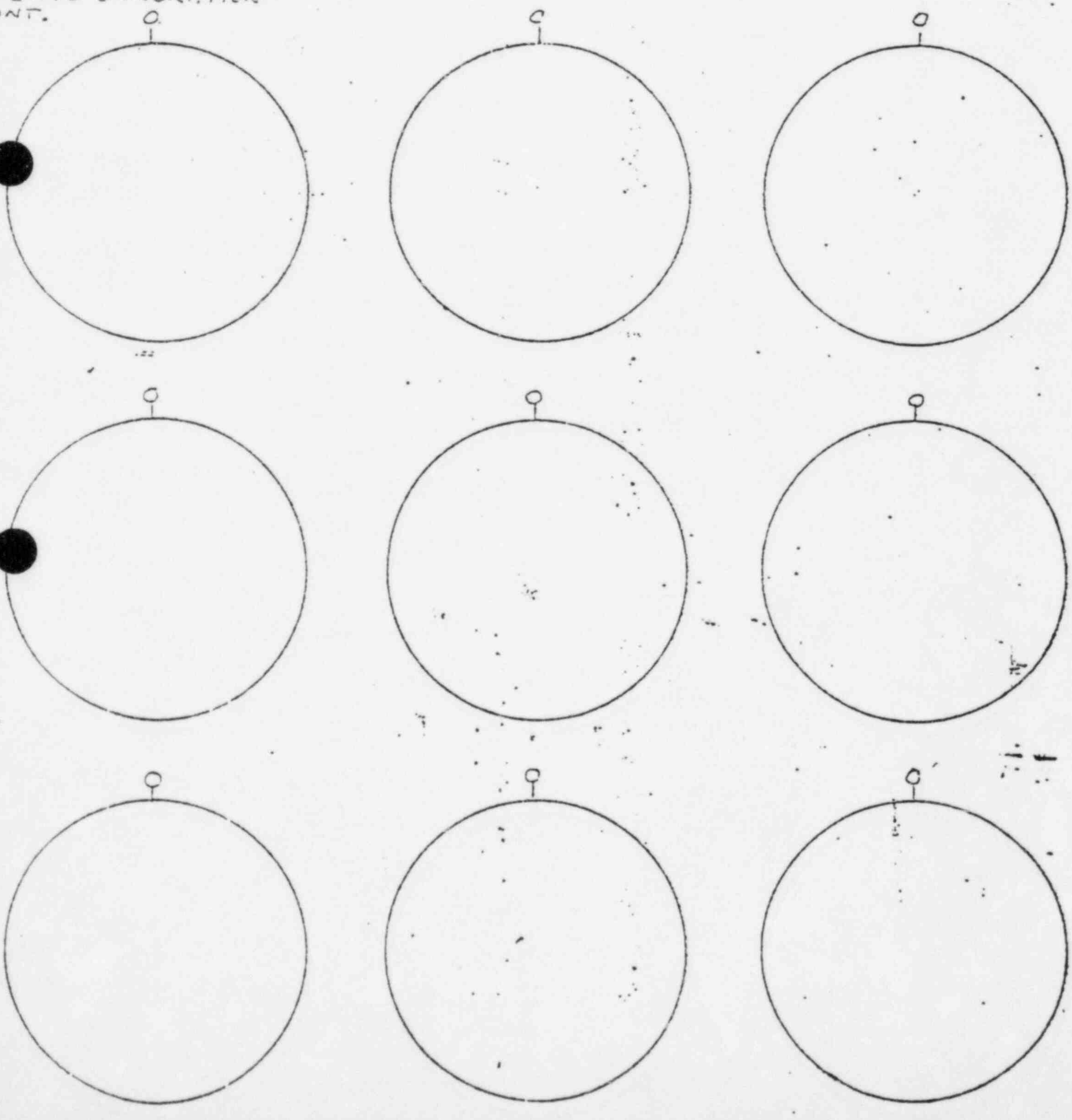
DATE:

Rev. 4 8/17/79
(Attachment #3)

JOB NO. INVESTIGATION EXAMINATION	PROCEDURE NO. UTL- UT-SP-10	DATE
NDE NO.	LABORATORY U.T.L.	TECHNICIAN & LEVEL
RWP NO.	SYSTEM	CUSTOMER MET-ED T.M.I. (UNIT-1)

OTE!
RROW ON WELD NO.
ENTIFICATION ON
IPE - IS O INDICATION
OINT.

INDICATION REPORT SHEET



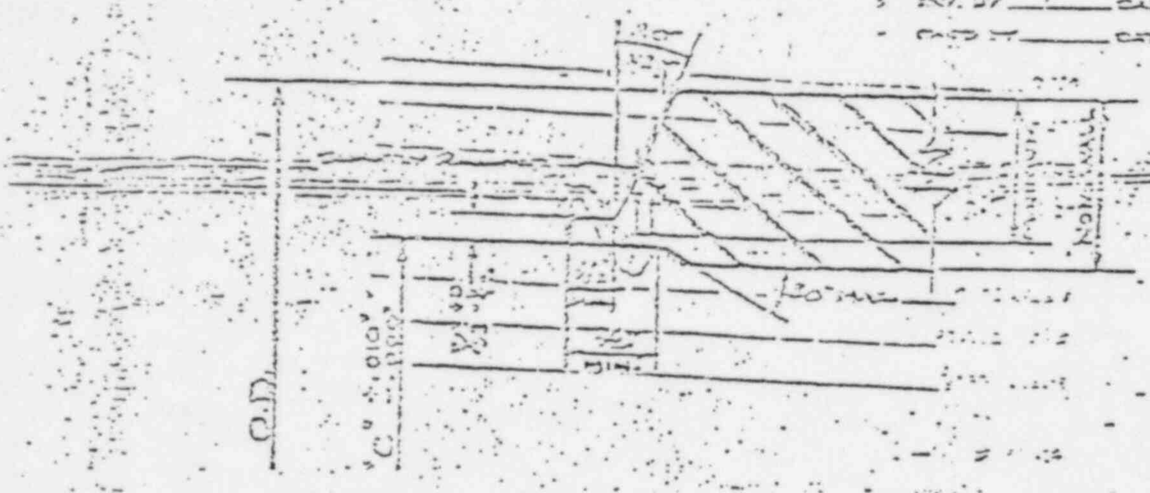
ATTACHMENT 5

Sheet 12
Procedure: UTL-U
Rev. 4 8/17/79

GRINNELL

P. O. No. 94174

PROVIDENCE I P D



SIZE	SCH	O.D.	NOM. WALL	[illegible]	C
16"	40S	16.000	.375	.227	15.437
14"	-	14.000	.375	.207	13.437
12"	-	12.750	.375	.159	12.187
10"	-	10.750	.365	.154	10.2[illegible]
8"	-	8.625	.322	.129	8.123
6"	-	6.425	.280	.093	6.197
4"	-	4.500	.237	.067	4.117
3"	-	3.500	.216	.117	3.153
24"	[illegible]	24.000	.375	.020	23.437

END PREPARATION FOR S.40S STAINLESS STEEL INERT GAS ROOT PASS SHOP AND FIELD WELDS

DECAY HEAT REMOVAL

DH-D1

P. O. No. 94174

GRINNELL

ORDER OR CONT. No. 51-H-494

NAME METROPOLITAN EDISON CO.

THREE MILE ISLAND

LOCATION NUCLEAR STATION

UNIT #1

579 POMPTON AVENUE

UTL-UT-SP 10
SHEET 13
Rev. 4 8/17/79
(ATTACHMENT #6)

JOB NO.	PROCEDURE NO.	DATE
NDE NO.	LABORATORY	TECHNICIAN & LEVEL
RWP NO.	SYSTEM	CUSTOMER

ELD I.D.__________ CROWN WIDTH__________ PIPE DIA.__________

REFLECTOR NO.	PS/FS	ANGLE	% F.S.H.	W MAX.	L_1	L-MAX	L_2	REMARKS

METROPOLITAN EDISON COMPANY Subsidiary of General Public Utilities Corporation

Subject: Investigation/Comparison Study by Electric Power Research Institute (EPRI) Sponsored Equipment (Ultrasonic) of Piping Samples Illustrating Intergranular Stress Corrosion Cracking (IGSCC).

Location: TMI Nuclear Stat Middletown, PA

To: N. C. Kazanas

Date: September 6, 1979

GQM - 3016

INTRODUCTION

Due to the need for additional input into the problem of accurately identifying the indication (s) of IGSCC, a research and development program (R & DP) underway by EPRI was utilized at Three Mile Island (TMI) for the purpose of assisting in the interpretation of indications (IGSCC & Geometric Type Reflectors). The EPRI/ R & DP utilized personnel specializing in ultrasonics as well as specialized electronics.

PERSONNEL	ORGANIZATION	/ GROUP
C. D. Rowe	MET/ED	QC
J.J. Potter	MET/ED	QC
D. Smith	GPUSC	Materials Eng.
J. Godleski	GPUSC	QA
R. Skibinski	GPUSC	QA
E. P. Jernigan, Jr.	USNRC	I & E
G. A. Walton	USNRC	I & E
R. F. Palmer	UTL	LIII UT
G. R. Stromer	B&W	ISI LIII
M. J. Avioli, Jr.	UII	Mech. Engr.
Y. H. Jeong	UII	Mech. Engr.
J. Rose	UII	Lead Engr.

PROGRAM & EVENTS

On August 14, 1979 the EPRI Group for R & D (UII) in relation to ultrasonic evaluation of IGSCC utilizing a "Call Confirmer" met with MET/ED personnel to demonstrate the development of their system.

The following equipment was set-up in the Quality Control Department for the demonstration:

1. Manual Analog Call Confirmer
   A prototype built by Zeger-Abrams, Inc.

2. Ultrasonic Transducer Analyzer
   A prototype built by Aerotech Laboratory

3. Dual 1.5 MHZ Transducers (.375 x .75 by Aerotech)
   Mounted on a 45° shoe

4. One 1.5 MHZ Transducer mounted on a 45° shoe

5. Tektronix Type 422 OSCILLOSCOPE

6. Various CAL Blocks (IIW Block, Step Wedges & System Pipe Samples)

Basically the Call Confirmer and the Oscilloscope were connected to the output of the Transducer Analyzer and the Transducers were connected to the Analyzer's input.

The first test performed was the comparison of the gains and signal to noise ratios for several transducers. The Oscilloscope screen presentations for each Transducer was photographed for later analysis, however little difference in gain was noted.

The second test involved the testing of various known samples with the Call Confirmer using the dual mounted 45° transducers. The results were inconclusive but the following was noted:

1. Machine marks in the counterbore were called cracks by the "Call Confirmer".

2. Changing the gain settings on the Transducer Analyzer could change the call. (A screen amplitude less than a threshold value or above a saturation value caused inconclusive calls.)

The third test was a repeat of this second test except that U.T.L.'S single 2.25 MHZ Transducer mounted on a 60° shoe was utilized. This test had much better results but was still calling machine marks in the counterbore as cracks. For cracks and root geometry the correct call was obtained 80% of the time.

The final testing involved the photographing of the Transducers RF signal and of an envelope signal generated by the Call Confirmer for several known cracks and machine marks. This data was taken in an effort to develop a method of distinguishing between cracks and machine marks.

IN CONCLUSION:

1. The 60°(mounted) Transducer utilized by U.T.L. was more accurate on IGSCC type cracks.

2. Machine marks are indistinguishable from cracks for the Call Confirmer.

3. The Call Confirmer was sensitive to signal levels.

4. The Call Confirmer was incapable of using any information obtained while the Transducer is in motion.

Respectfully,

C. D. Rowe
Quality Control Specialist

CDR:mlg

cc: J. J. Potter
D. Smith
J. Godleski
R. Skibinski
E. P. Jernigan, Jr.
G. A. Walton
R. F. Palmer
G. R. Stromer
M. J. Avioli, Jr.
Y. H. Jeong
J. Rose
Reading File (2)
Q.C. File (1)

IGSCC SAMPLE EXAMINATION DATA SHEET

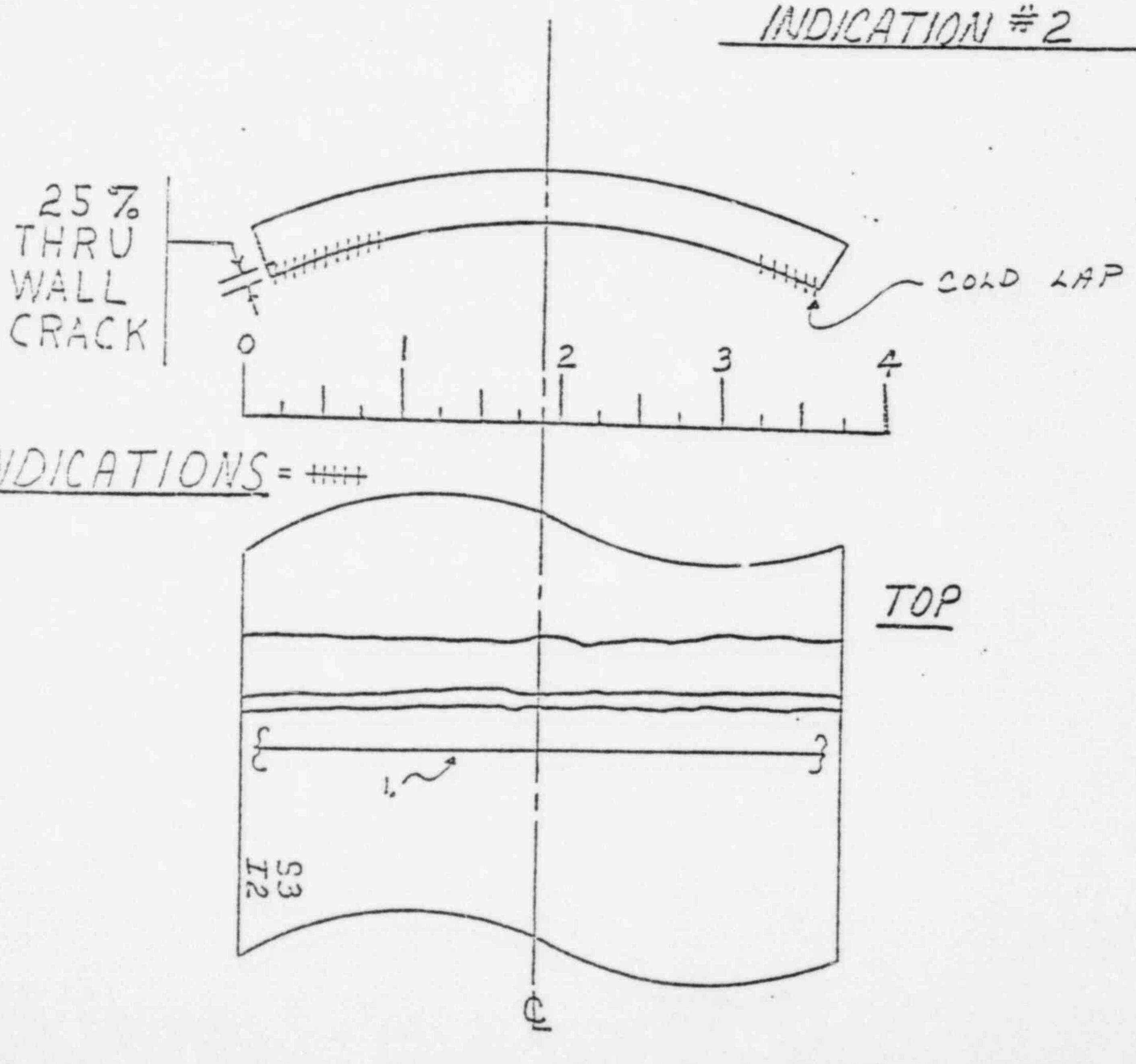
1300-1E REV 5
SECTION XI EXAM

CALIBRATION DATA

SEARCH UNIT	Scan Angle 45°	INSTRUMENT SETTINGS	Comments on Scan(s)
ze & Shape :	1/4" x 1/4"	Mfg./Model No.: Sonic MK-1	RELEVANT INDICATIONS
requency :	2.25	Serial No. : 790 837	NO ≥ 100% DAC IND
erial No./Brand :	SONIC - S790266	Sweep Length : 5 7	NO ≥ 50% DAC IND
easured Angle :	44°	Sweep Delay : 1.24/9.16	
able Type & Length :	6'	Pulse Length or Damping: 0	1. RECORDABLE REFLECTOR
ouplant Used :	EXOSEN #20	Frequency: 2 Filter: Hi	EVALUATED TO BE
		Rep Rate: 3K Video: N Jack: R	GEOMETRY
		Dac/Gate Switch: / Range:)	
		Mode Select: N Reject: 0	
		Gain (coarse): 70 (fine): 1	

SAMPLE #3

INDICATION #2



IGSCC SAMPLE EXAMINATION DATA SHEET

UTL-UT-SP-10 REV

CALIBRATION DATA

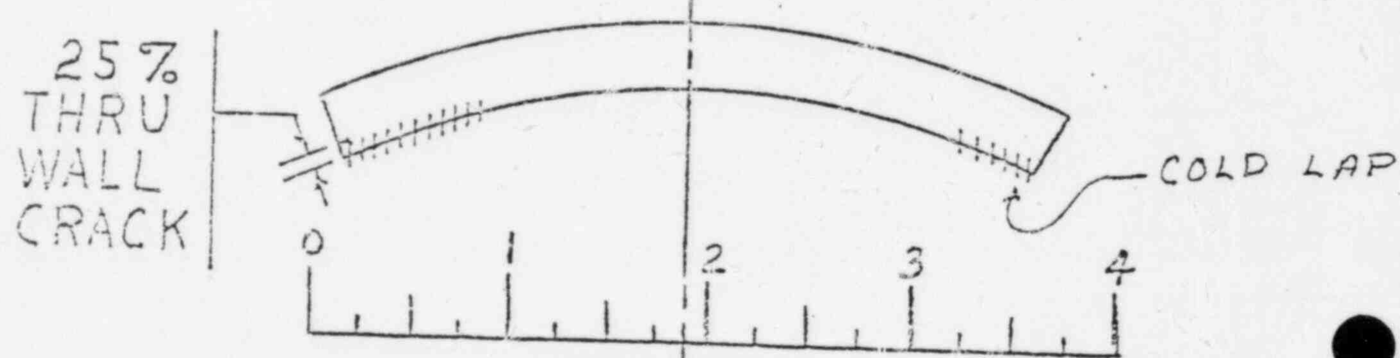
SEARCH UNIT	Scan Angle 60°
Size & Shape	1/4" x 1/4"
Frequency	2.25
Serial No./Brand	harisonic #19
Measured Angle	60°
Cable Type & Length	6'
Couplant Used	EXOSEN #20

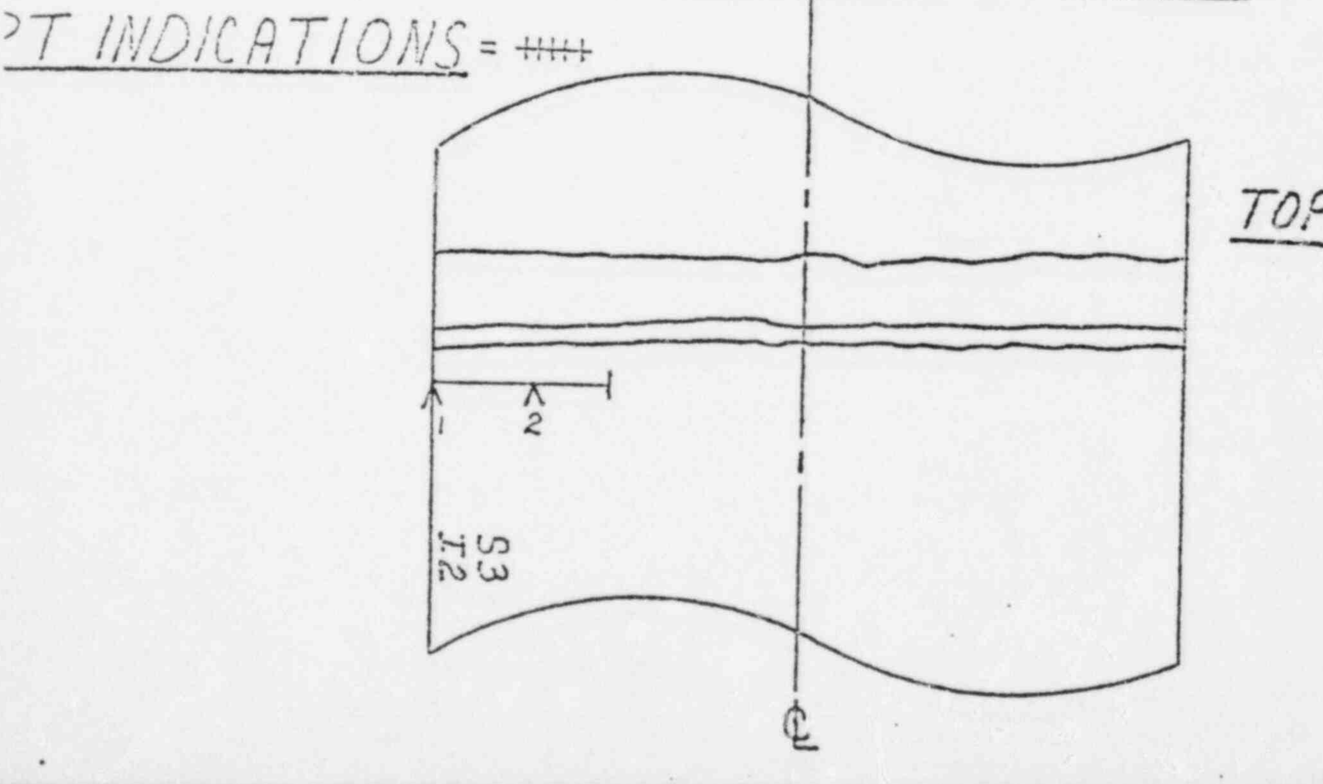
INSTRUMENT SETTINGS	
Mfg./Model No.	Sonic MK-1
Serial No.	280 837
Sweep Length	1 1/4"
Sweep Delay	1.6 / 6.98
Pulse Length or Damping	0
Frequency: 2	Filter: HL
Rep Rate: 3K Video: N	Jack: R
Dec/Gate Switch: 1	Range: 1
Mode Select: N	Reject: 0
Gain (coarse): 60	(fine): 2

Comments on Scan(s)
1. 80% F.S.H (END OF PIPE)
2. 100% F.S.H + 5 dB (MI... AR...)
END POINT AT 30% F.S.H

SAMPLE #3

INDICATION #2





IGSCC SAMPLE EXAMINATION DATA SHEET

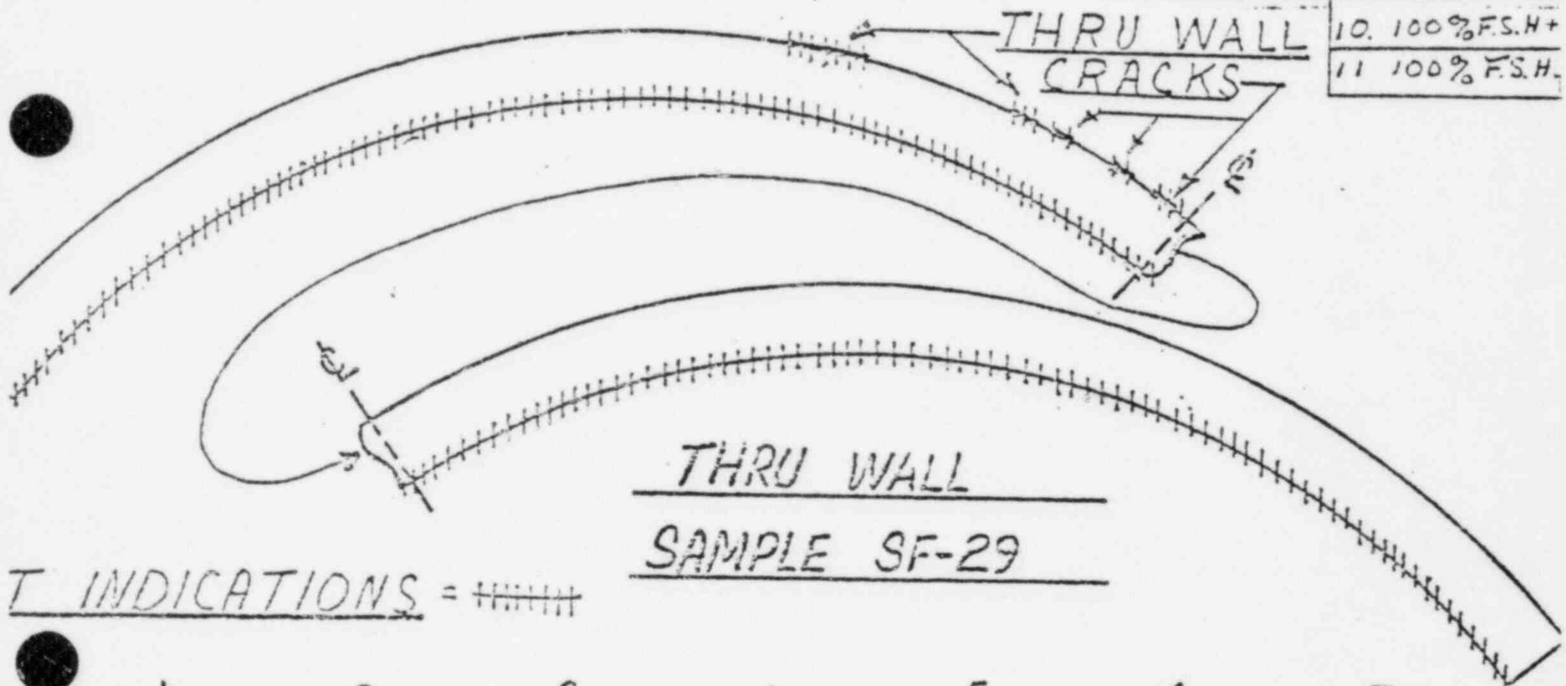
CALIBRATION DATA

UTL-UT-SP-10 REV 4

SEARCH UNIT	Scan Angle 60°
...e & Shape :	1/4" X 1/4"
...equency :	2.25
...ial No./Brand :	harisonic #19
...asured Angle :	60°
...ble Type & Length :	6'
...uplant Used :	EXOSEN #20

INSTRUMENT SETTINGS
Mfg./Model No.: SONIC MK-1
Serial No. : 780 837
Sweep Length : 1 1/4"
Sweep Delay : 1.6 / 6.93
Pulse Length or Damping: 0
Frequency: 2 Filter: H/L
Rep. Rate: 3K Video: N Jack: R
Dec/Gate Switch: 1 Range: 1
Mode Select: N Reject: 0
Gain (coarse): 60 (fine): 2

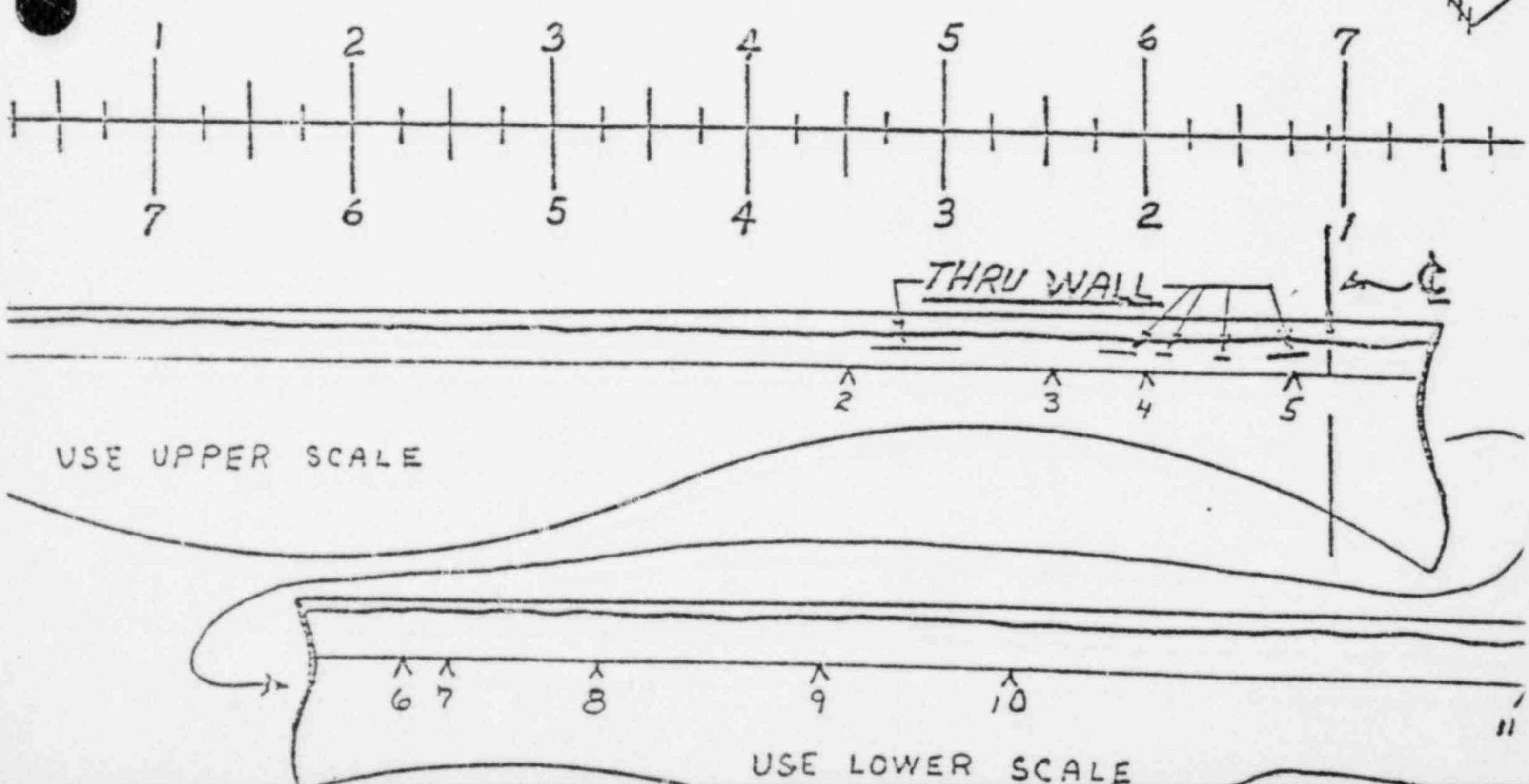
Comments on Scan(s)
HOT "SPOTS"
1. 80% F.S.H (END POINT)
2. 100% F.S.H + 2dB
3. 100% F.S.H + 9dB
4. 100% F.S.H + 11dB
5. 100% F.S.H + 2dB
6. 100% F.S.H + 3dB
7. 100% F.S.H + 2dB
8. 100% F.S.H.
9. 100% F.S.H
10. 100% F.S.H +
11 100% F.S.H.



THRU WALL

SAMPLE SF-29

UT INDICATIONS = ++++++



IGSCC SAMPLE EXAMINATION DATA SHEET

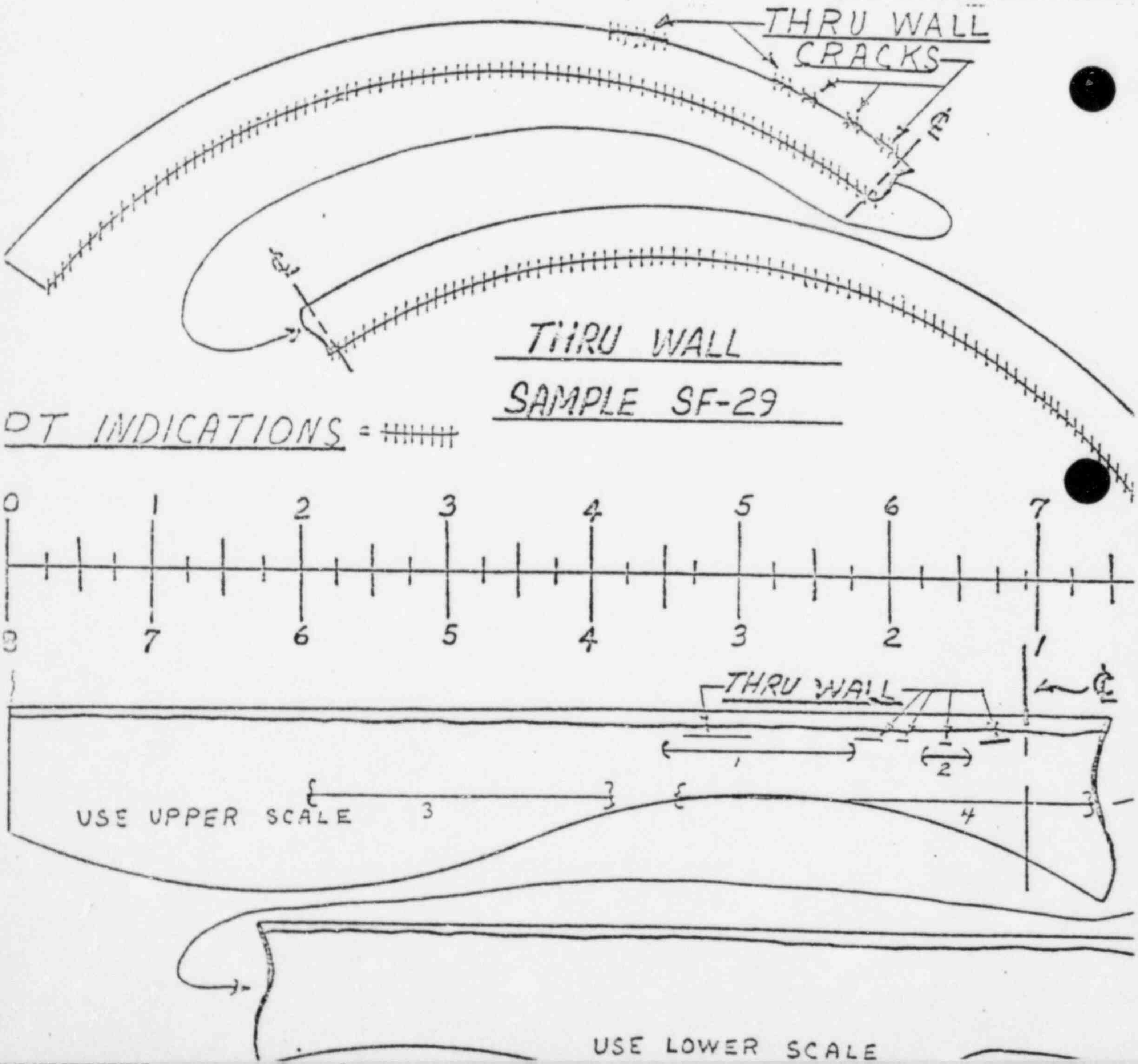
1300-IE REV 5
SECTION XI EXA

CALIBRATION DATA

SEARCH UNIT	Scan Angle 45°
Size & Shape :	1/4" x 1/4"
Frequency :	2.25
Serial No./Brand :	SONIC 5790266
Measured Angle :	44°
Cable Type & Length :	6'
Couplant Used :	EXOSEN #20

INSTRUMENT SETTINGS
Mfg./Model No. : SONIC MK-1
Serial No. : 780 837
Sweep Length : 5T
Sweep Delay : 1.24 / 9.16
Pulse Length or Damping : 0
Frequency : 2 Filter: NC
Rep Rate: 3K Video: N Jack: R
Dec/Gate Switch: 1 Range: 1
Mode Select: N Reject: 0
Gain (coarse): 70 (fine): 1

Comments on Scan(s)
RELEVANT INDICATIO
NO ≥ 100% DAC IND
1 & 2 ≥ 50% DAC IND
3 & 4 RECORDABLE
REFLECTORS EVALUATE
TO BE GEOMETRY



IGSCC SAMPLE EXAMINATION DATA SHEET

CALIBRATION DATA

UTL-UT-SP-10 REV 4

SEARCH UNIT	Scan Angle 60°
& Shape	1/4" x 1/4"
quency	2.25
al No./Brand	harisonic #19
sured Angle	60°
le Type & Length	6'
plant Used	EXOSEN #20

INSTRUMENT SETTINGS	
Mfg./Model No.:	SONIC MK-1
Serial No.	780 837
Sweep Length	1 1/4"
Sweep Delay	1.6 / 6.98
Pulse Length or Damping:	0
Frequency: 2	Filter: H
Rep Rate: 3K	Video: N Jack: R
Dec/Gate Switch: 1	Range: 1
Mode Select: N	Reject: 0
Gain (coarse): 60	(fine): 2

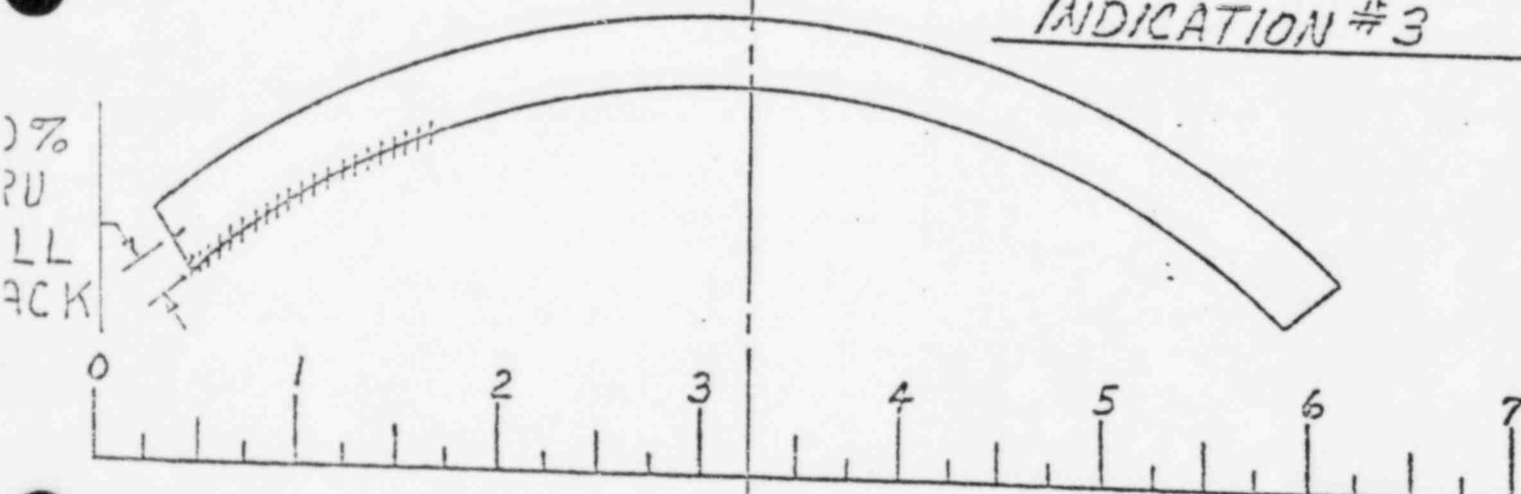
Comments on Scan(s)

1. 100% + 1dB F.S.H (END OF PIPE)
2. 100% + 12dB F.S.H (MAX AMPL)

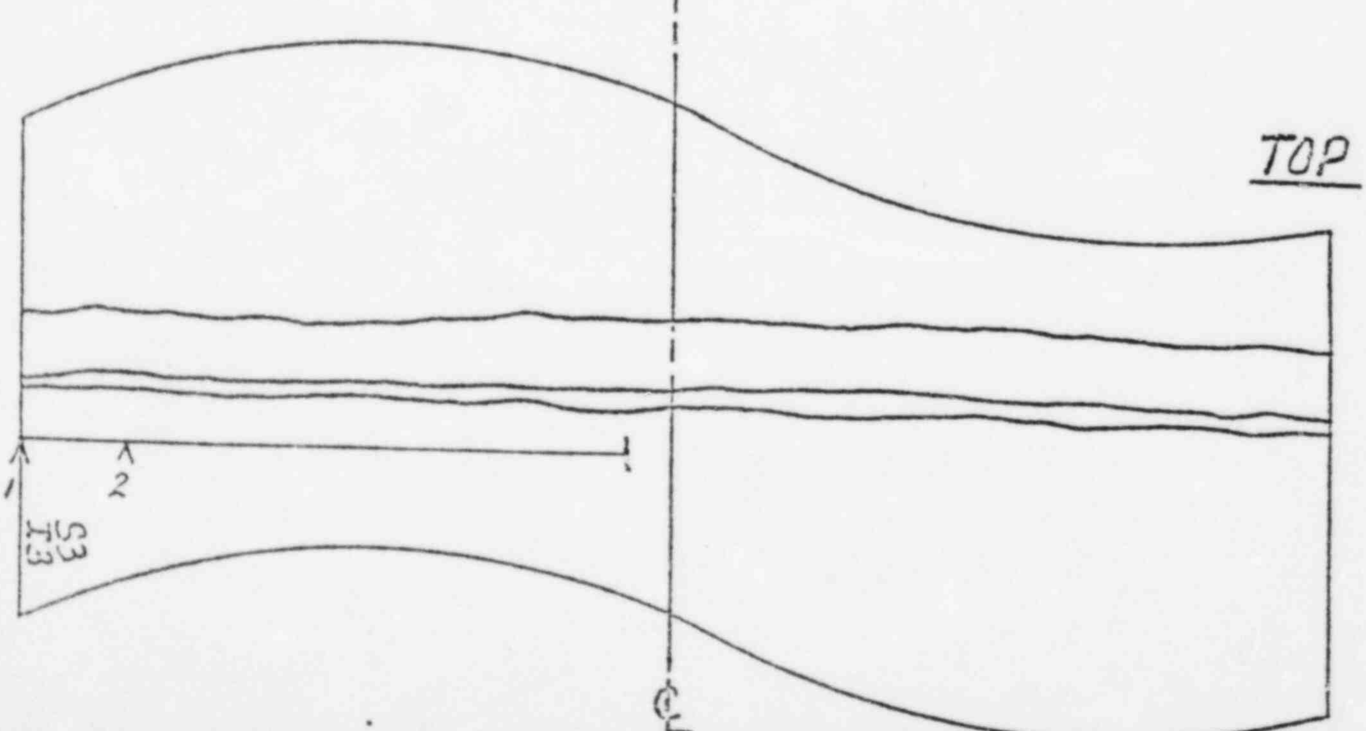
END POINT AT 30% FSH

SAMPLE #3

INDICATION #3



INDICATIONS = HHHHH



IGSCC SAMPLE EXAMINATION DATA SHEET

1300-IE REV 5
SECTION XI EX

CALIBRATION DATA

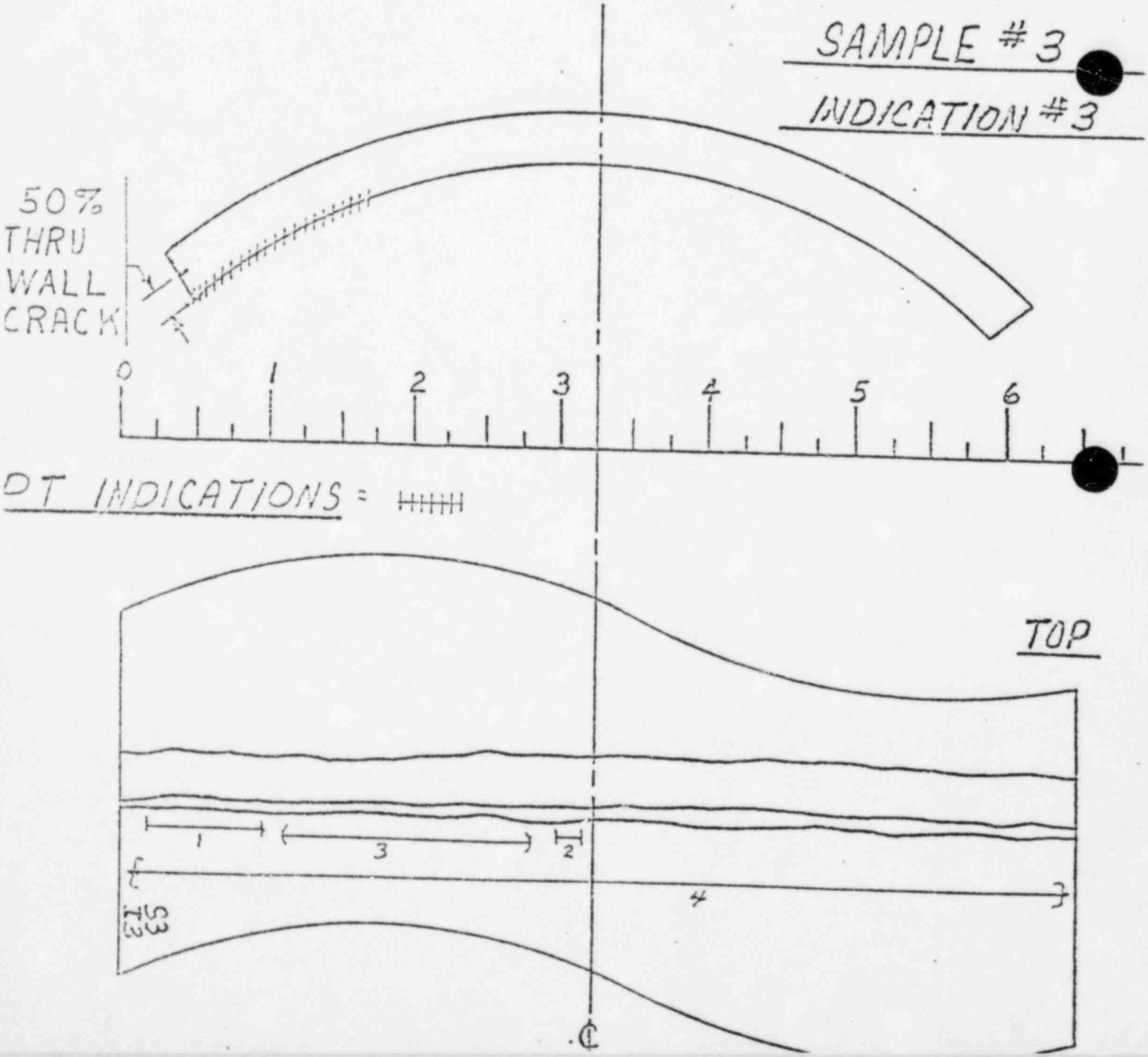
SEARCH UNIT	Scan Angle 45°
Size & Shape :	1/4" x 1/4"
Frequency :	2.25
Serial No./Brand :	SONIC - S 790266
Measured Angle :	44°
Cable Type & Length:	6'
Couplant Used :	EXOSEN #20

INSTRUMENT SETTINGS	
Mfg./Model No.: SONIC MK-1	
Serial No. : 780 837	
Sweep Length : 5T	
Sweep Delay : 1.24 / 9.16	
Pulse Length or Damping: 0	
Frequency: 2	Filter: HC
Rep Rate: 3K Video: N	Jack: R
Dec/Gate Switch: 1	Range: 1
Mode Select: N	Reject: 0
Gain (coarse): 70	(fine): 1

Comments on Scan(s)
RELEVANT INDICATIO
1 & 2 ≥ 100% DAC IND
3 ≥ 50% DAC IND

4. RECORDABLE
REFLECTOR EVALUATI
TO BE GEOMETRY

SAMPLE #3
INDICATION #3



CALIBRATION DATA

UTL-UT-SP-10 REV 4

SEARCH UNIT		Scan Angle 60 °
e & Shape	:	1/4" x 1/4"
equency	:	2.25
ial No./Brand	:	harlsonic #19
asured Angle	:	60°
ble Type & Length	:	6'
uplant Used	:	EXOSEN #20

INSTRUMENT SETTINGS	
Mfg./Model No.: SONIC MK-1	
Serial No. : 780 837	
Sweep Length : 1 1/4"	
Sweep Delay : 1.6 / 6.98	
Pulse Length or Damping: 0	
Frequency: 2	Filter: HL
Rep Rate: 3K Video: N	Jack: R
Dec/Gate Switch: /	Range: 1
Mode Select: N	Reject: 0
Gain (coarse): 60	(fine): 2

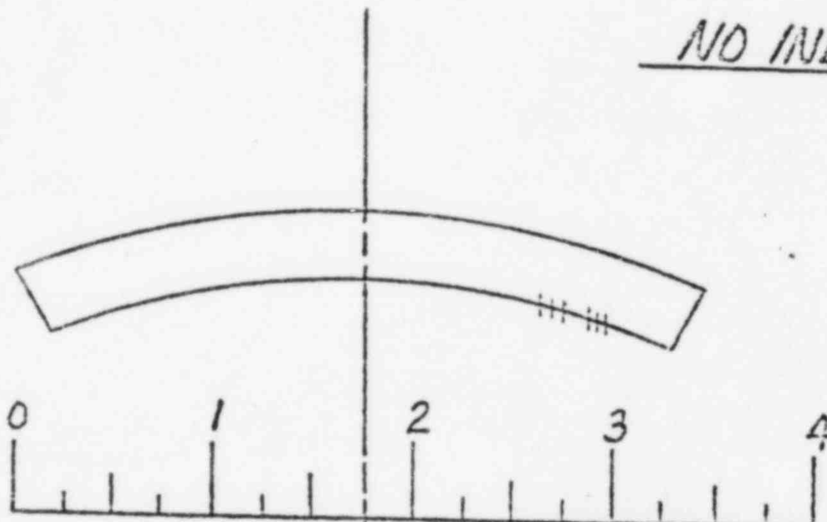
Comments on Scan(s)

NO INDICATIONS ABOVE 30% F.S.H.

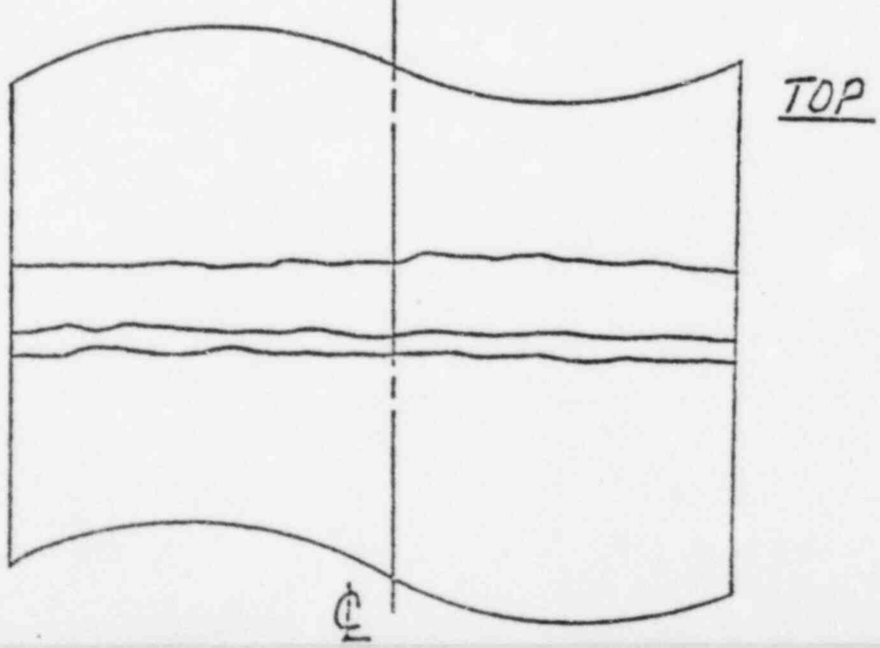
UT INDICATIONS OF APPROX. 25% F.S.H. OBSERV AT LOCATION OF P.T. INDICATIONS

SAMPLE #3

NO INDICATIONS



T INDICATIONS = ||||



IGSCC SAMPLE EXAMINATION DATA SHEET

1300-1E REV 5
SECTION XI EXAM

CALIBRATION DATA

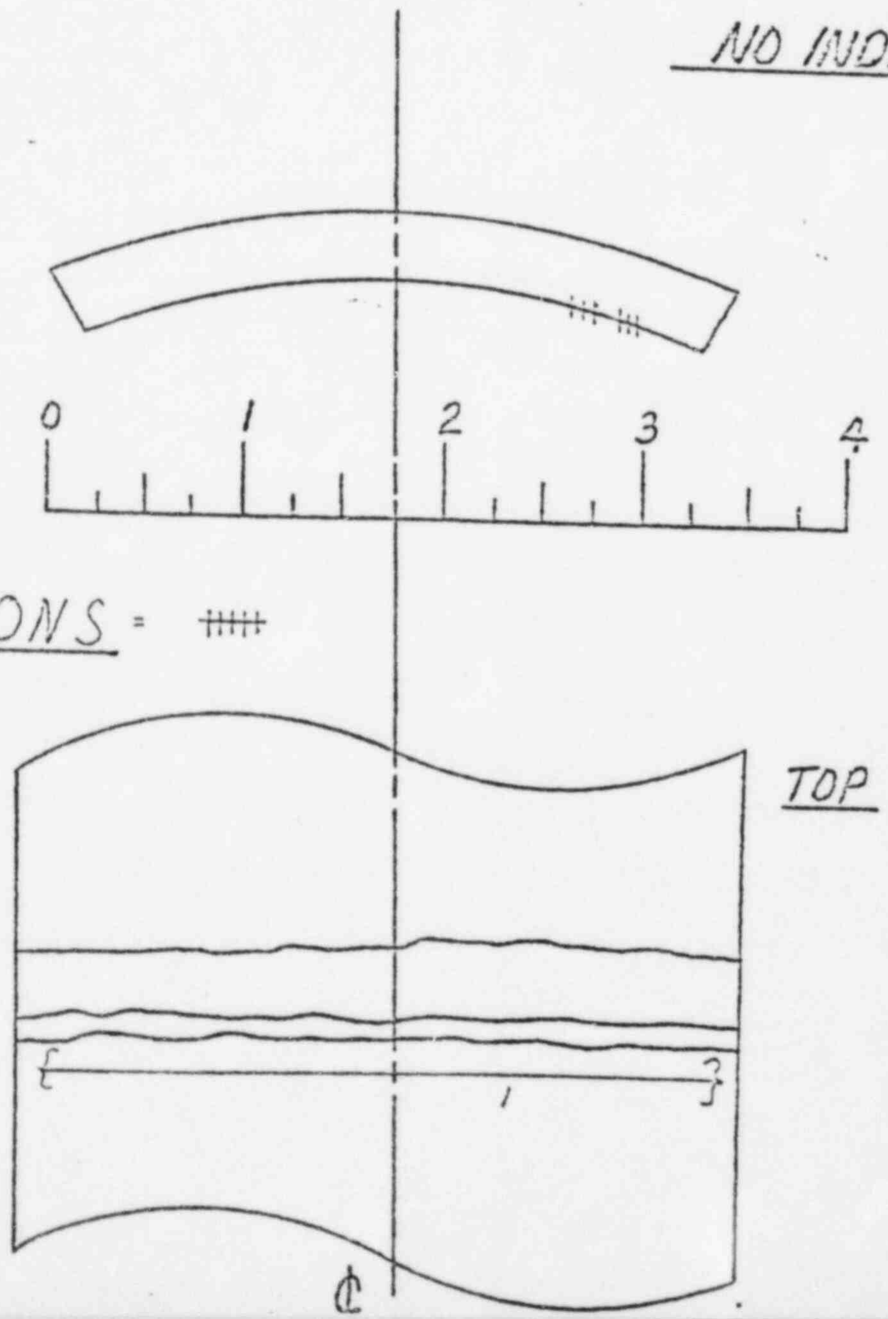
SEARCH UNIT	Scan Angle 45°
Size & Shape	1/4" X 1/4"
Frequency	2.25
Serial No./Brand	SONIC S 790266
Measured Angle	44°
Cable Type & Length	6'
Couplant Used	EXOSEN #20

INSTRUMENT SETTINGS	
Mfg./Model No.:	SONIC MK-1
Serial No.	780 837
Sweep Length	5T
Sweep Delay	1.24 / 9.16
Pulse Length or Damping	0
Frequency: 2	Filter: HC
Rep Rate: 3K Video: N	Jack: R
Dec/Gate Switch: /	Range: 1
Mode Select: N	Reject: 0
Gain (coarse): 70	(fine): 1

Comments on Scan(s)
RELEVANT INDICATIONS
NO ≥ 100% DAC IND
NO ≥ 50% DAC IN
1 RECORDABLE
REFLECTOR EVALUAT
TO BE GEOMETRY

SAMPLE #

NO INDICATIONS



PT INDICATIONS = ||||

Section 2: METALLURGICAL AND CORROSION STUDIES

2.1 INTRODUCTION

In April 1979 during a routine visual inspection of piping in the spent fuel system a small leak was observed at a weld joint in an 8.00" diameter schedule 40, 304 SS pipe. Subsequent visual examination detected four additional leaks identified by a buildup of boric acid crystals on the pipe O.D. surface. The location and orientation of these cracks was identified as being in the weld heat-affected-zone (HAZ) adjacent to girth welds, running in the circumferential direction. Several months later a leak was detected in a 10" diameter pipe in the decay heat system and another leak was observed in the spent fuel system.

In order to characterize the cracking mechanism, the decision was made to remove one of the initial failures (SF35) for laboratory investigation. The results of that investigation are contained in GPU Materials Laboratory Report, attached, as Appendix 2-1.

In essence, the failure was a result of intergranular stress corrosion cracking (IGSCC) in the sensitized structure of the weld HAZ. Cracking had initiated on the I.D. surface in the machined counterbore and then propagated in an irregular path through the wall thickness. The non-specific directionality of the crack is believed to be a result of the varying residual weld stress patterns which were estimated to be the primary stresses responsible for cracking. Additional characteristics which were observed and may have participated in the cracking phenomenon were a fine grain structure at the counterbore I.D. surface which was a result of recrystallization of the cold worked metal by the weld

heat input, sharp transition angles in the counterbore, and variations in the degree of sensitization. The fine grain structure serves to increase the grain boundary area which increases the number of potential sites for crack initiation. Sharp transition angles act as stress risers, providing an enhanced site for crack initiation, and the degree of sensitization will affect the electrochemical reaction at the grain boundaries. The more sensitized structures either reaching a threshold for intergranular attack or assuming no discernable threshold exists, the more highly sensitized the structure (higher degree of chromium depletion) the shorter the time for crack initiation.

Having identified the basic cracking mechanism as one being related to sensitization, it was felt that much of the work conducted by EPRI in studying alternate solutions to the BWR pipe cracking phenomenon would be applicable. Such solutions would include changing to the low carbon 304L SS or 316L SS material, weld cladding the I.D. surface at the weld joint of susceptible materials, heat sink welding and O.D. weld overlay cladding. These items will be discussed later in Section IV of the main report.

In regard to the environmental conditions responsible for cracking, this is an area where investigative work is still required. At this time there is no clear cut corrosive species identified. Typical water chemistry, as measured in the fuel pool itself, would contain 13,000 ppm boric acid, would be air saturated, have an average pH of 5.5 with chloride and fluoride levels of less than .1 ppm. However, there were chloride readings which were in the 12-18 ppm range. These levels, however, were not measured in other locations where cracking was ob-

served. There does appear to be a tendency for cracking to favor stagnant lines or lines which are only circulated on occasion, but this observation is based on a limited amount of data. This would suggest, though, that concentration of contaminant may have occurred in these stagnant areas in the past and been responsible for crack initiation.

2.2 CORROSION TEST PROGRAM

A corrosion test program was established, through the help of EPRI, to identify the environmental factors necessary to produce IGSCC. The test program would include a series of Constant Extension Rate Tests (CERT) utilizing actual pipe samples removed from the spent fuel systems. These tests would be conducted in pure, aerated and deaerated boric acid, followed by tests with aerated 1.3% boric acid with 15 ppm chloride. Tests would be conducted at several extension rates ranging from 1.2×10^{-4} in./min. to 4×10^{-5} in./min. In addition, polarization studies will be conducted to determine if electrochemically the environment responsible for cracking can be identified. If this can be identified, the effects of varying oxygen levels and other environmental factors such as pH, chlorides and sulfates can be studied. In any event, these factors will be studied in the CERT tests.

To date, the tests shown in Table 2-1 have been conducted. The results of these tests are too preliminary to make any accurate assessment regarding the cracking phenomenon; however, they do seem to indicate that crack initiation is a critical factor in view of the fact that two tests conducted under identical conditions, one failed by IGSCC and one failed ductilely and the only difference was the ductile failure occurred in a specimen with the original I.D. surface removed.

2.3 BATTELLE N.W. FAILURE ANALYSIS

In July 1979, a contaminated sample of a cracked spent fuel pipe (SF210) was sent to Battelle Northwest for failure analysis. Because this sample had not gone through a decontamination process it was hoped that corrosive species might be identified in internal deposits. Near the crack mouth deposits were observed. EDAX analysis of these deposits showed them to contain Al, Si, S, Cr, Ni, Fe and at one discrete area, chlorides. As you progressed deeper into the cracks, the deposits became less dense and chlorides were not detected. Auger spectroscopy was also performed. This was conducted on a fracture face from a crack opened in the dry nitrogen with some air. Again, as in the case of the EDAX analysis, trace chlorides were only detected at one location at the crack mouth. Sulfur and boron appeared as an overall contaminant on the fracture surface. The results of these analyses were inconclusive in identifying a corrosive species.

The failure analysis conducted by Battelle confirmed the GPU Lab results that failure was a result of IGSCC in the sensitized structure of the weld HAZ. The preliminary Battelle report is attached as Appendix 2-2.

2.4 CORRELATION OF UT DATA WITH METALLOGRAPHY

During the initial developmental stages of the ultrasonic examination to detect cracks, it was felt that correlation between UT indications and the actual defect present was required in order to qualify the UT technique. This correlation is contained in Appendix 2-3 and represents the inspection performed with the original UT procedure with a 50° angle beam transducer. The results of this investigation showed that

a consistent correlation was not being achieved between UT indications and IGSCC. Geometric reflectors other than IGSCC were being detected. Out of the four samples investigated which contained a total of thirteen indications, three indication were lack of fusion, three were weld root irregularites one was I.D. surface roughness, one showed no defect and five were IGSCC. The correlation did show, however, that IGSCC tended to give screen presentations which indicated short metal path distances; i.e., screen baseline was broke at 6.4 or lower for all cracks.

As a result of this comparison, modifications were made to the UT procedure to minimize the influence of spurious geometric signals and improve the ability to identify actual cracks.

2.5 CONCLUSION

Failure analyses conducted by Battelle Northwest Laboratory and GPU Materials Technology Laboratory have identified the mechanism of failure in the 304 SS borated water piping systems as intergranular stress corrosion cracking in the weld sensitized structure in the heat-affected-zone of circumferential butt welds.

As of the date of this report, no specific corrosive specie has been identified as being responsible for cracking; however, dilute chlorides have been identified in various stagnant lines in the building spray system and as such may indicate possible contamination by chlorides in other systems in the past. The role of chlorides as well as other contaminants is being studied in laboratory corrosion tests sponsored by EPRI. It is the purpose of these tests to identify the environment which can induce this mode of failure.

In addition to environment, the presence of weld induced sensitization also is a critical factor in the cracking phenomenon. It is in this area where the emphasis has been placed in defining solutions to the cracking problem. Low carbon, (304L) stainless steel materials known for their inherent resistance to sensitization are to be utilized whenever possible as replacment spool pieces. In addition, weld processes using low heat input (35,000 joules/in. max.) and filler metals containing a minimum of 5% ferrite are being used. I.D. buttering as defined in NUREG-0313 is also being employed.

The correlation between metallographic data and UT inspection data provided a much needed insight into this inspection program. As a result of this correlation, several very important items were either learned or confirmed:

1) All UT signals were not IGSCC because geometric reflectors could look like cracks.
2) Joint geometries varied greatly in shape, adding an additional interpretive problem when performing UT scans.
3) Screen amplitude could not be used as an indicator of crack depth.
4) The original UT procedure was very sensitive, finding cracks <.010" in depth. However, it was so sensitive that rough grinding marks would give rejectable signals. Some of this sensitivity would have to be sacrificed in order to improve detection accuracy and reliability.

The work conducted to date has provided definite insight into the cracking phenomenon. Data collected has definitely indicated that

certain high carbon heats of material are more likely to have IGSCC and that stagnant conditions favor cracking. However, because so many variables are involved in such a corrosion phenomenon, it may take years before the mechanism is accurately defined. EPRI should be encouraged to continue to study this problem.

In the meantime TMI will continue to employ the best state-of-the-art techniques to mitigate this problem.

TABLE 2-1

CORROSION TEST PROGRAM

	Laboratory	Test Type	Environment	O_2 Level	Cl^- Level	Extension Rate (In./Min.)	Results
1.	Battelle N.W.	CERT	Borated Water(1)	Air Saturated	<.01 ppm	4×10^{-5}	Test discontinued at 37% elong. IGSCC 2-3 grain deep (2).
2.	Battelle N.W.	CERT	Borated Water(1)	Air Saturated	15 ppm	4×10^{-5}	Substantial IGSCC observed on fracture face (2).
3.	Battelle N.W.	CERT	Borated Water(1)	Air Saturated	15 ppm	$4.x\ 10^{-5}$	No IGSCC (3).
4.	Battelle Columbus	CERT	Pure Water	Air Saturated	<.01 ppm	$1.2.x\ 10^{-4}$	No IGSCC (3).
5.	Battelle Columbus	CERT	Borated Water(1)	Air Saturated	<.01 ppm	$1.2.x\ 10^{-4}$	No IGSCC (3).
6.	Battelle Columbus	CERT	Borated Water(1)	Deaerated	<.01 ppm	$1.2.x\ 10^{-4}$	No IGSCC (3).
7.	Battelle Columbus	CERT	Borated Water(1)	Air Saturated	<.01 ppm	$6.x\ 10^{-5}$	No IGSCC (4).
8.	Ohio State	Polarization	Borated Water(1)	Air Saturated	<.01 ppm	--	No active regions.

NOTES: (1) Borated Water = pH 5.0 - 5.4, Cond. 12 umhos/cm., Boric Acid 13,000 ppm.

(2) Test specimens were made from actual pipe welds with original I.D. surface intact.

(3) Test specimens were made from actual pipe welds with original I.D. surface removed.

(4) Test specimen was made from 304 SS welded to 304L SS.

Appendices: Section 2

Appendix 2-1

GPU Materials Technology Laboratory

Failure Analysis

GPU MATERIAL TECHNOLOGY LABORATORY

INTERGRANULAR STRESS CORROSION CRACKING OF 304 STAINLESS STEEL PIPING IN TMI #1 SPENT FUEL POOL SYSTEM

SECOND REPORT

R. L. MILLER

F. S. GIACOBBE

October 12, 1979

Abstract

Intergranular stress corrosion cracking (IGSCC) initiating on the pipe I.D. at circumferential butt welds is responsible for leaks in the 304 SS spent fuel pool piping. The cracks have occurred in the sensitized structure of the weld heat affected zone.

To date seven through wall leakers have been observed, with an additional 35 ultrasonic indications which are believed to be relevant. Ambient temperature borated water, possibly coupled with dilute chlorides, appears to be the environment responsible for failure. Limited data also suggests that stagnant conditions favor cracking.

Repair procedures and materials which address minimizing of sensitization in the weld heat affected zone will be utilized.

Introduction

Visual inspection of the borated water piping at Three Mile Island Unit Number 1 (TMI-1) has revealed seven coolant leaks, six in spent fuel and one in the decay heat system. Close examination of these leaks has shown them to be circumferential cracks in the heat-affected zones of girth welds. The exact locations of these visible leaks in the piping are shown by sketches in Section 3. In addition, the type of weld joint used in the leaking areas is included in this appendix.

The SFP is divided into two loop systems, A and B. Through wall cracks, adjacent to welds, have been confined to System A, a redundant cooling loop which is normally stagnant, and in piping connected to the transfer canal which is used at refueling times only. System B, a circulating loop normally used for cooling the SFP, has no known cracks at this time.

A pipe section containing two through wall cracks at a single weld joint was removed from the transfer canal piping, decontaminated and forwarded to GPU System Laboratory in an effort to determine the cracking mechanism. This pipe section was assigned Laboratory Request Number 54148.

The pipe section submitted for metallurgical examination was an 8" Sch. 40, Type 304 SS welded grade pipe which was purchased to ASTM-A-358. As shown in Appendix I, the pipe section was labeled SF-35 and was welded to valve number SFV-17. The type of weld joint utilized on the pipe/valve was a standard single "V" bevel with a counter bore on the pipe inside diameter for fit-up (alignment) purposes. A consumable insert ring was used at the weld root. The pipe section was removed from the SFP by cutting through the pipe/valve weld and through the pipe wall at a 6" distance up the pipe length.

The pipe section's history was fifty-four months' accumulated exposure to boric acid solutions averaging 75°F with a peak temperature of 100°F. The fluid flow in this pipe was stagnant except during reactor refueling periods. A typical water chemistry for the SFP is listed in Table I. The effluent for this analysis was withdrawn from a circulating portion of the SFP System and may not be typical of stagnant areas.

A more complete listing of the SFP chemistry covering the operational years is given in Appendix II.

Investigation

A. Non-destructive Testing of Pipe Section

The decontaminated pipe section was radiographed around its circumference in the weld joint region to determine the extent of cracking. Two indications were revealed as shown in Figure 1. Each crack was approximately 3" long and appeared to be in the base metal adjacent to the circumferential pipe/valve weld.

A sketch, shown in Figure 2, was prepared from these radiographs and located the cracks with respect to the pipe's original orientation in the SFP. The north-south directions, clockwise numbering sequence, and the longitudinal pipe weld are meaningful markers to interested personnel at TMI as to the pipe's original position in the SFP. The two views show one crack to be approximately 150° around the pipe circumference in a clockwise direction from the other when the south direction was utilized as a 0° start position.

Investigation (Continued)

B. Examination of Pipe Section by Scanning Electron & Optical Microscopy

The radiographed pipe section was cut in half lengthwise with a crack lying in each segment. Visual examination of each pipe half on the inside diameter surface showed each crack to be approximately 3" long. Also both cracks were in the counterbore adjacent to the weld and displayed a very irregular crack path. These features are shown in Figure 3. Dye penetrant examination was necessary to reveal through wall crack locations on the out side diameter of the pipe halves.

All metallurgical specimens were cut from the same half of the pipe section. These specimens contained a weld, recessed groove and full wall thickness section. The specimen numbers and their locations in the pipe section are shown in Figure 4. Also, physical measurements of the weld joint are shown in this figure.

The topography of the pipe's inside diameter in the crack region on Specimen Number 1 was examined in the Scanning Electron Microscope (SEM). (NOTE: Specimen Number 1 was examined in three distinct locations; namely, the weld root, counterbore and pipe's inside diameter surfaces.) As can be seen in Figure 5, cracks were observed running in the counterbore as well as along the edge of the weld. The crack paths were very irregular but progressed basically in the circumferential direction.

Several types of particles deposited in the crack vicinity were analyzed qualitatively by the SEM Energy Dispersive X-ray Analysis attachment. The spherical particles shown in Figure 5 were primarily composed of Fe, Cr and Ni with no detectable trace of Cl. Several irregular shaped, fluorescent particles (Figure 6A) were observed at the weld root. EDAX of one particle (Figure 6B) showed its composition to be primarily Fe, Cr and Ni with traces of Ca and Cl.

The surface of the counterbore next to the crack is shown in Figure 7A. The surface shows machining marks plus what appear to be additional crack locations. EDAX of this region (Figure 7B) revealed the basic stainless steel constituents (Fe, Cr and Ni) plus traces of Ca and Cl.

Intergranular corrosion of the pipe's inside diameter surface away from the counterbore is shown in Figure 8A. This is most likely due to pickling during pipe manufacturing. EDAX spectrum, shown in Figure 8B, displayed Type 304 SS major alloy elements plus traces of Ca and Cl.

Specimen number 2 was cut from the TMI-1 pipe section and the crack contained therein was split open to study its features. As shown in Figure 9A, the main crack path was intergranular with little, if any, corrosion of the grain boundary facets. Secondary cracks can also be seen in this figure. EDAX spectrum (Figure 9B) for this area revealed no identifiable corrodents, only stainless steel alloy elements (Fe, Cr and Ni).

Specimen number 3 was cut from the SFP pipe section and mounted in bakelite such that pipe circumference was normal to the viewing plane. The specimen was polished and subsequently etched with the following mixture: six parts glycerine, five parts HNO_3, and three parts HCl. The three distinct parts of specimen number 3, namely, the weld root, counterbore and the pipe's full wall thickness, are shown in Figure 10 along with through-wall cracks. As can be seen, multiple cracks have initiated on the I.D., however only one has propagated through to the O.D. in this location.

Investigation (Continued)

A typical crack starting on the pipe's inside diameter and progressing through the 304 SS is shown in Figure 11. This micrograph displayed the intergranular path of a typical crack. Another microstructural feature shown in Figure 11 was sensitization; i.e., precipitation of chromium carbides in grain boundaries in the weld heat affected zone. Other metallographic observations not shown include the existence of incipient cracks in the HAZ.

C. Susceptibility of Type 304 SS to Intergranular Corrosion

A specimen was cut from the SFP pipe section and its composition analyzed chemically. The results shown in Table II meet the 304 SS specification limits set forth by ASTM-A-358. Subsequently, certain element concentrations were plotted on a Cihal diagram. (NOTE: This thermodynamic diagram predicts whether Type 304 SS will or will not sensitize upon heating in the 800°F to 1600°F range and thereby become susceptible to intergranular corrosion.) As shown in Figure 12, the TMI-1 SFP pipe material is highly susceptible, primarily due to its high carbon content.

To substantiate the Cihal Diagram Prediction and the optical microscopy observation that the 304 SS pipe was sensitized in the HAZ, ASTM-A-262, Practice A* was performed on Specimen number 4. The grain boundaries in the HAZ were completely ditched (grooved) by this oxalic acid test as shown in Figures 13A and 14. Thus the SFP pipe was sensitized in the HAZ. The base metal (Figure 13B) away from the HAZ, however, showed little evidence of sensitization, indicating the material had been properly solution annealed by the pipe manufacturer.

*(Detecting Susceptibility to Intergranular Attack in Stainless Steel; Oxalic Acid Etch Test for Classification of Etch Structures of Stainless Steel)

Conclusions

Metallurgical examination of the Spent Fuel Pool pipe has revealed the following:

(1) An intergranular stress corrosion cracking (IGSCC) mechanism produced the leaks in the pipes.

(2) The cracks were located in the weld heat affected zone in the counterbore area. Crack propagation was from I.D. to O.D. Grain boundaries in the HAZ were sensitized as determined by ASTM-A-262, Practice A.

(3) Chemical analysis of the pipe confirmed its 304 SS composition. This composition was plotted on a Cihal diagram which showed this material to be highly succeptible to sensitization. All known leakers to date have been in heats of material which had carbon levels over .07%. Six were in the same heat of material.

(4) SEM Energy Dispersive Analysis has revealed traces of chlorine at various locations on the pipe's inside surface. These Cl traces could be a result of decontamination procedures utilized on the pipe's surfaces and not necessarily a result of contamination in the borated water systems. At this time it can only be postulated that stagnant borated water possibly contaminated with dilute chloride was responsible for the intergranular corrosion.

(5) Sensitization of the spent fuel pipe in the counterbore was caused by welding. The degree of sensitization is believed to be rate controlling with respect to crack initiation. Higher degrees of sensitization would favor shorter initiation times.

Conclusions (Continued)

(6) Stresses responsible for cracking are believed to be primarily residual welding stresses, as the calculated applied stresses are below 15,000 psi.

(7) Besides the main through wall cracks, incipient cracks were noted at several locations in the weld HAZ.

(8) Cracking of the piping has been primarily confined to the stagnant "A" SFP System and the transfer canal piping. This fact may indicate a mechanism by which corrodents are concentrated in stagnant fluid areas.

(9) The SFP pipe cracking mechanism is a unique phenomenon in that IGSCC generally has not been observed below 140°F service temperature.

Recommendations

The metallurgical examination of the 8" Sch. 40, Type 304 SS SFP pipe section has led to the following recommendations.

(1) Substitute 304L SS for failed 304 SS pipe. The 304L material contains 0.03 wt. % C maximum as compared to 0.08 wt. % C for 304 SS. This lower carbon content will reduce the degree of sensitization in the HAZ upon welding the pipe into the SFP. If available, the nuclear grade 304L containing .02% C max. should be used.

(2) Procedures such as I.D. weld clad, as defined in NUREG-0313, are to be utilized when making welds to 304 SS piping. Joint geometries whenever possible should not include a counterbore on the I.D.

(3) Non-destructive examination of austenitic stainless steel weld joints in other systems in contact with borated water should be performed to determine if incipient cracks are present. Test techniques should include radiography and ultrasonics, ultrasonics being the preferred technique for finding small cracks.

(4) If concentration of corrodents is occurring in stagnant fluids areas, periodic fluid flow should eliminate this and help prevent additional cracking in the sensitized material. Whether existing cracks will not propagate, even though the corrodent has been removed, is not known at present. Those systems which cannot be periodically circulated must be flushed and drained.

(5) Since GPU Sytem Lab was unable to verify the existence of contaminants which may have been responsible for the IGSCC, arrangements have been made with Battelle Northwest Laboratory to perform a surface chemical analysis on a section of pipe which has not been decontaminated.

(6) If incipient cracks at numerous weld joints are discovered by non-destructive test methods, an in-service inspection (I.S.I.) plan could be set up in lieu of immediate pipe replacement, as catastrophic failures would not be expected, but rather a leak before break would apply. Crack growth could be monitored and replacement made at an appropriate time based on a determination of an acceptable flaw size for the system in question.

(7) EPRI should be encouraged to continue the laboratory investigations to reproduce and identify the environment and parameters necessary to produce IGSCC of austenitic stainless steel in low temperature boric acid solutions.

TABLE I

Typical Chemistry of Spent Fuel Pool Water

pH	5.5
Conductivity (micro-mhos/cm)	12
Boron (ppm)	2000
Chlorine (ppm)	.01
Flourine (ppm)	<.02
Beta-gamma (microcuries/ml)	6×10^{-2}
Tritium (ppm)	4×10^{-2}
Turbidity (ppm)	.01

(The known weekly water chemistry results and temperature records for the SFP's lifetime are tabulated in Appendix II.)

TABLE II

Chemical Analysis of 8" Sch. 40

Type 304 SS Spent Fuel Piping

Element	Wt. %
Manganese	1.48
Phosphorus	0.023
Sulfur	0.012
Silicon	0.56
Chromium	18.05
Nickel	8.72
Bal. Iron	----
Carbon.	0.073
Nitrogen	0.118

FAB EXPLOSION

P. O. No. 94174

ORDER OR CONT. No. 51-[illegible]

NAME METROPOLITAN EDISON CO. UNIT #1

LOCATION THREE MILE ISLAND NUCLEAR STATION

GRINNELL

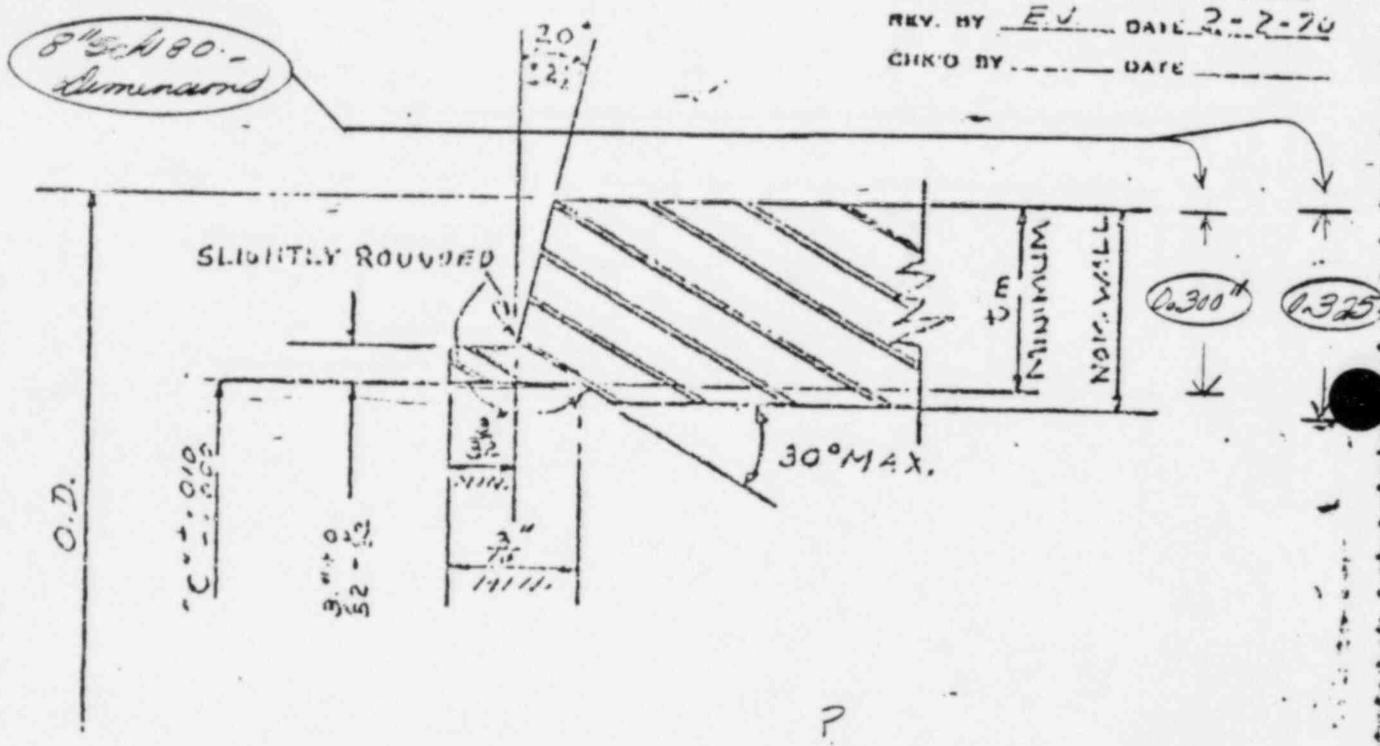
DEPT. PROVIDENCE I P

DRWN BY H R E DATE [illegible]

CHK'D BY PM DATE [illegible]

REV. BY E J DATE 2-2-70

CHK'D BY ____ DATE ____



SIZE	SCH	O.D.	NOM WALL	tm	C
6"	40S	[illegible]	[illegible]	0.0237	[illegible]
8"	"	[illegible]	.280	0.0229	[illegible]
4"	"	[illegible]	.237	0.0164	4.117
3"	"	[illegible]	[illegible]	(.075)	[illegible]
10"	"	[illegible]	.365	0.0372	[illegible]

END PREPARATION FOR S.40S STAINLESS STEEL INERT GAS ROOT-PASS SHOP AND FIELDS WELDS.

PICKLE AT		RADIOGRAPHY		BLASTING		LIQ. PENT.	
STRESS RELIEVE		MAG. PARTICLE INSPECTION		ASME PARTIAL DATA REPORTS		MILL TEST CERTIFICATES	

PIPE

B.W. FIGS

SYSTEM SPENT FUEL COOLING

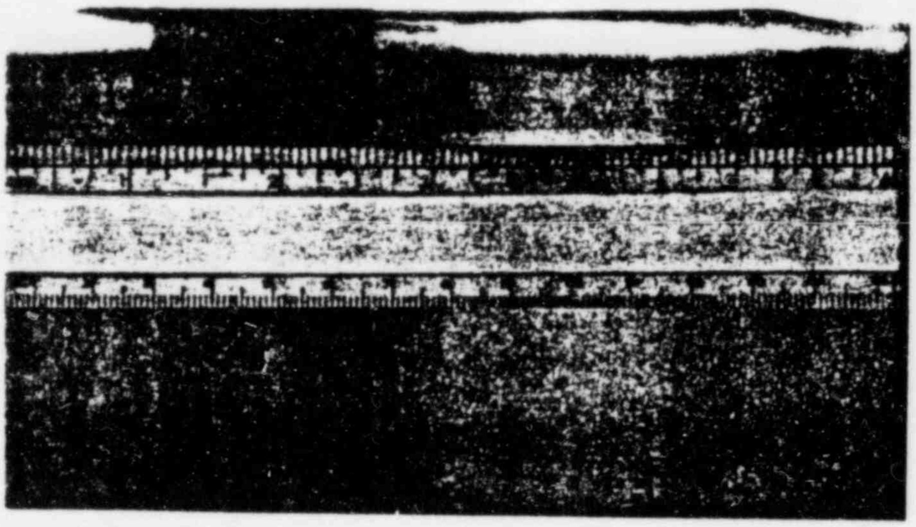
FOR OLDER LIST MATERIAL AND OPERATIONS SEE SUMMARY SHT. NO. ____

REF. DWG. NO. [illegible] PIECE MARK ____

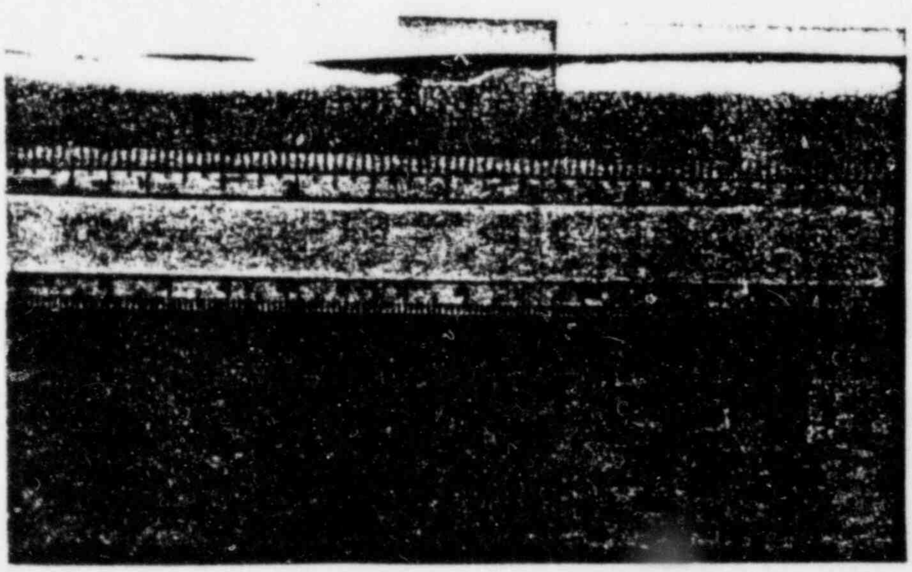
NO. REQ'D ____

SKETCH NO. SS-01

FIGURE 1. Radiographs showing cracks at two locations in SFP pipe section next to a circumferential weld (8" Sch. 40, Type 304 SS).



A. Near S marker in Figure 2.



B. Near N marker in Figure 2.

FIGURE 2. Locations of cracks in Spent Fuel Pool Pipe Section.

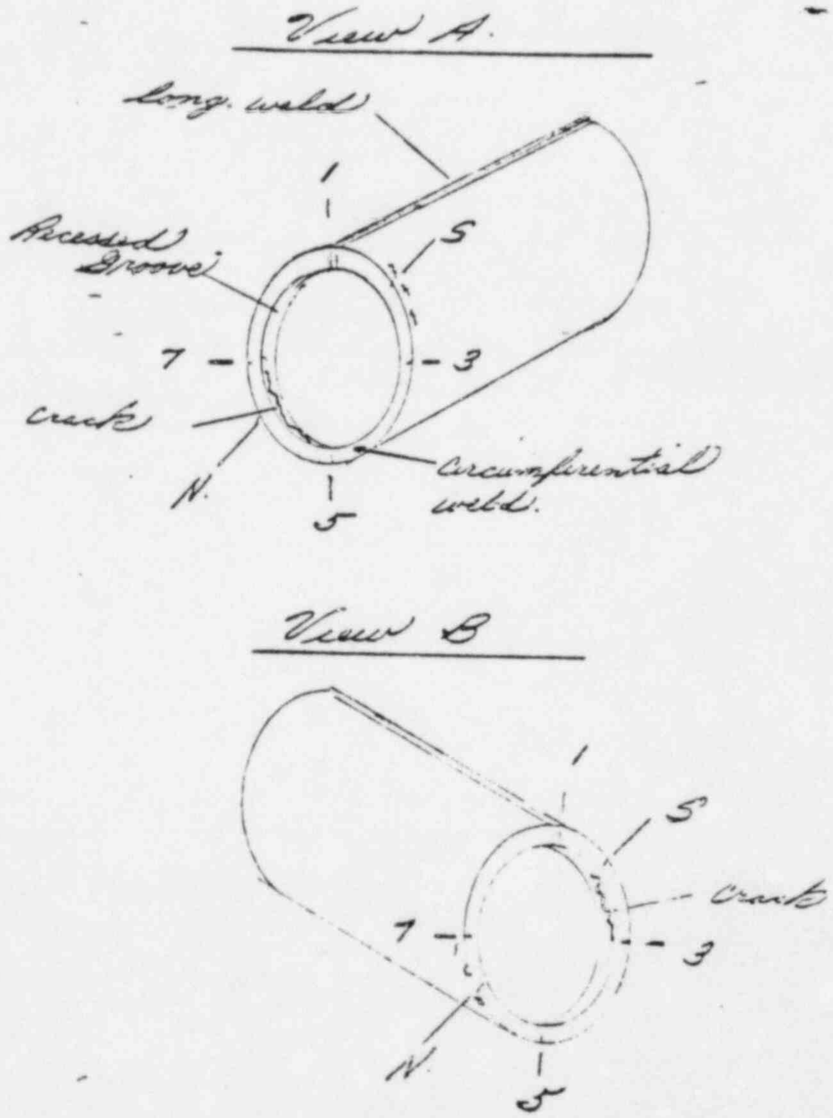
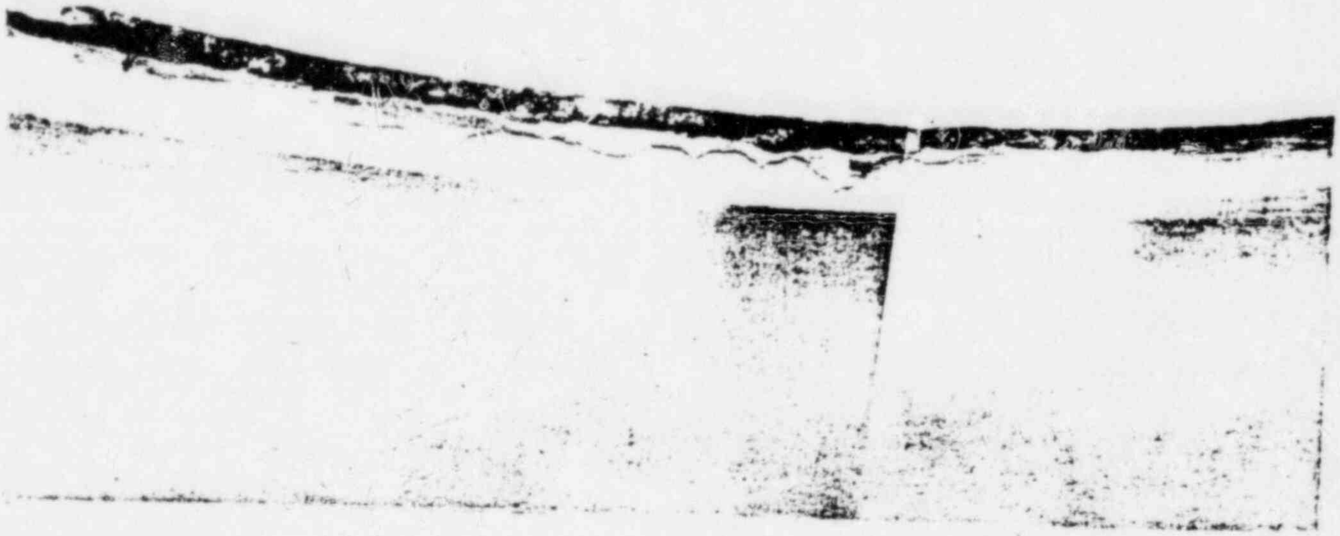


FIGURE 3. Cracks located on the I.D. surface of 8" Sch. 40, Type 304 SS Spent Fuel Pool Pipe.

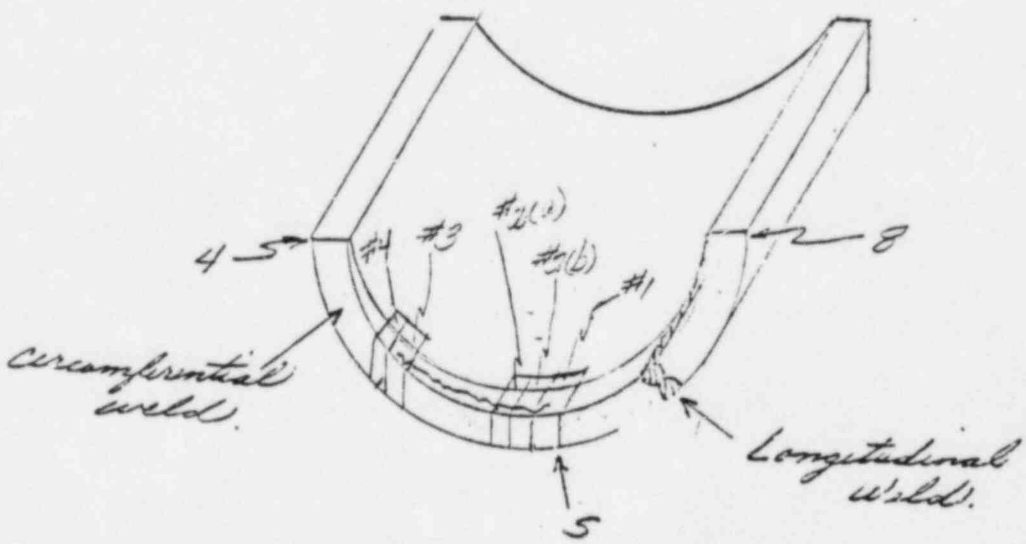


A. Crack lying near south marker. (Figure 2)

B. Crack lying near north marker. (Figure 2)

FIGURE 4. Metallurgical specimens removed from cracked pipe and weld joint dimension.

Met. Specimens



Dimension

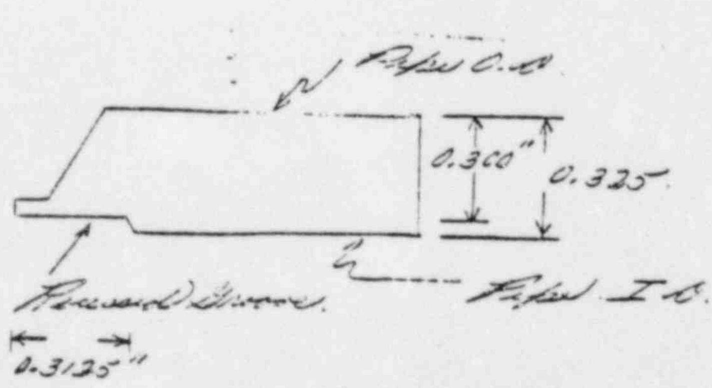
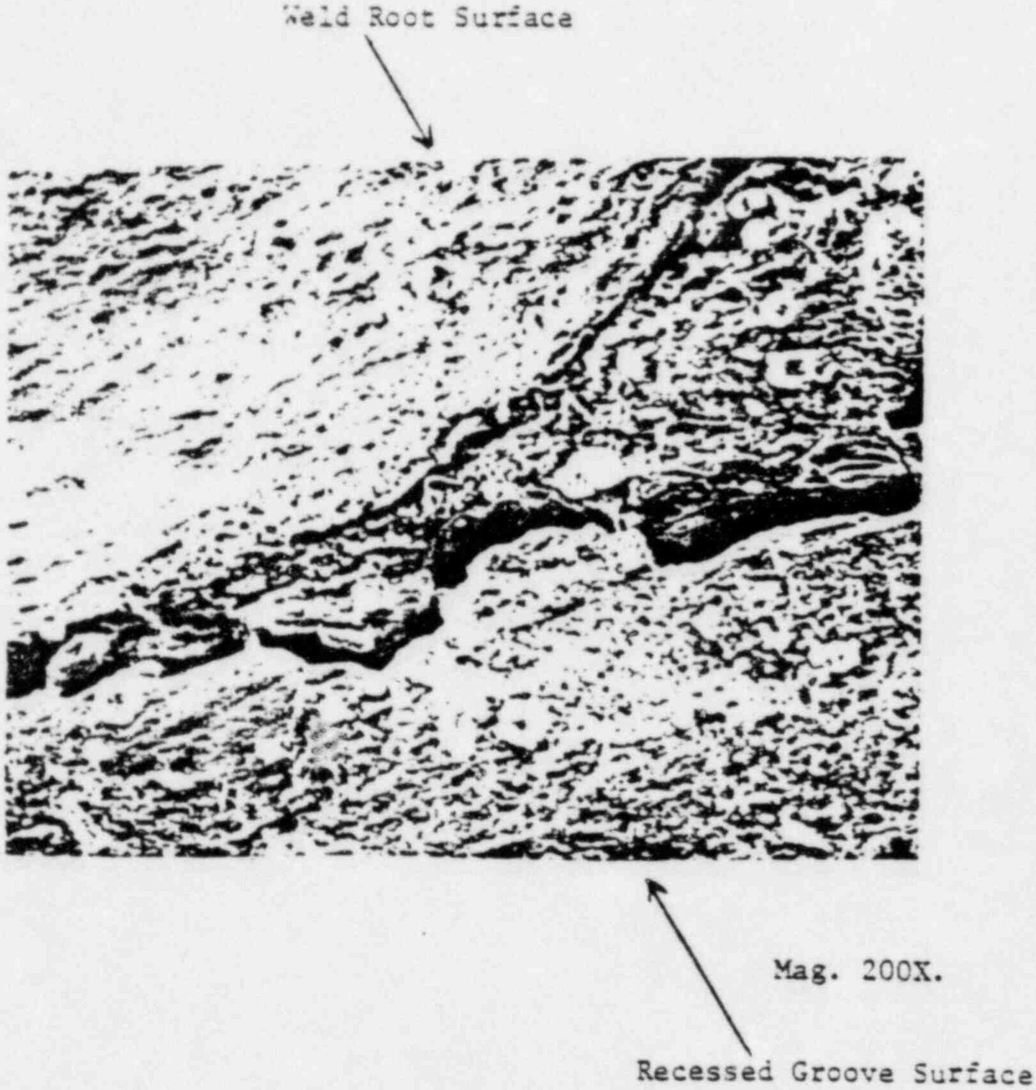
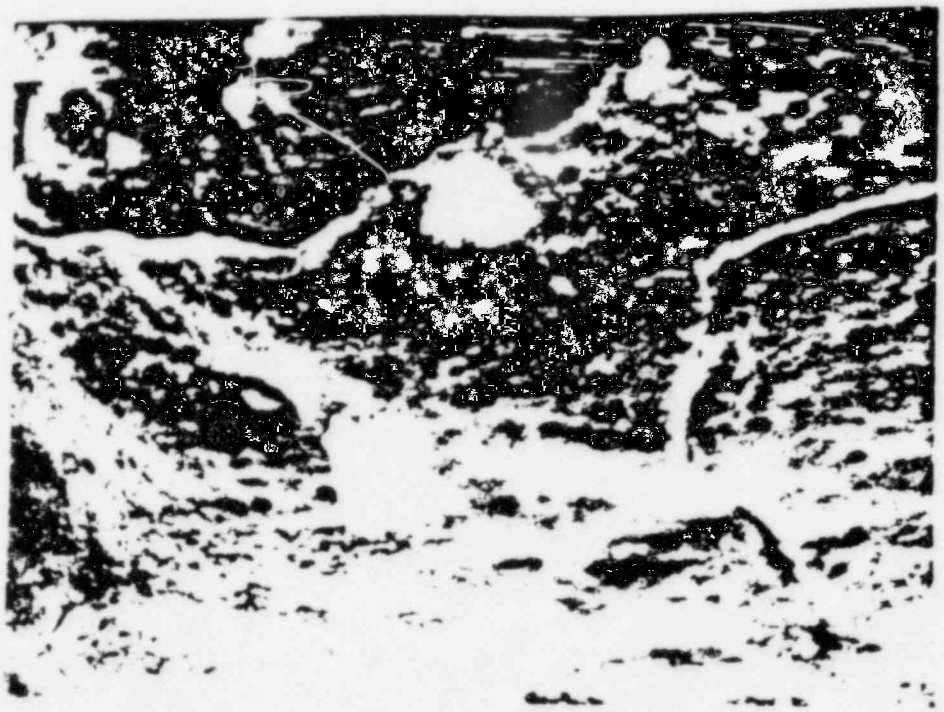


FIGURE 5. SEM Micrograph showing cracks located on the I. D. surface of TMI-1 Spent Fuel Pool Pipe (8" Sch. 40, Type 304 SS) in recessed groove next to weld root.



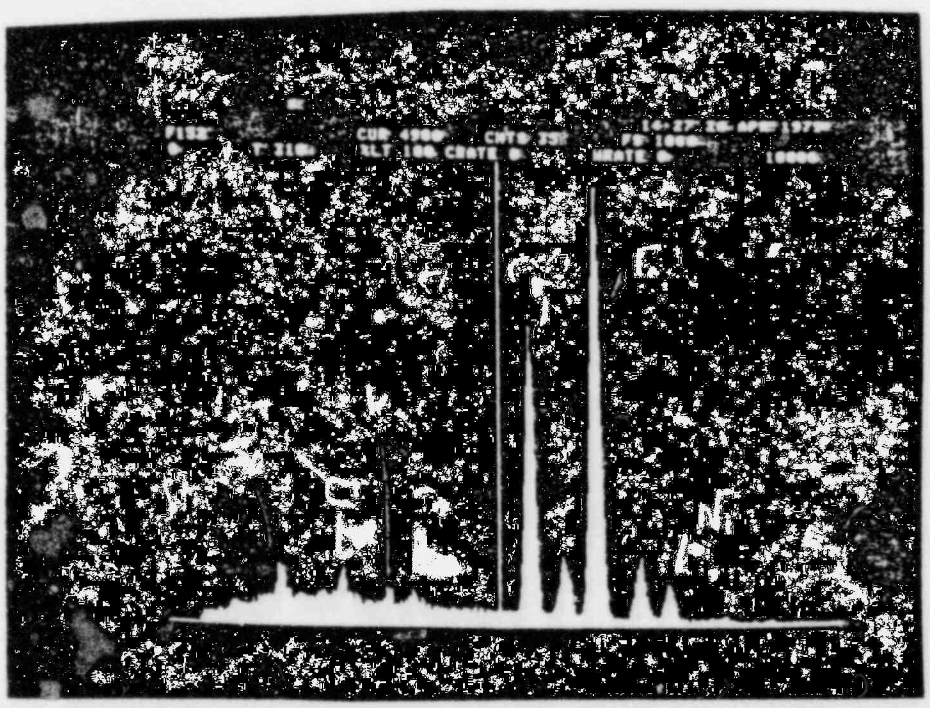
(NOTE: Fine crack follows weld root.)

FIGURE 6. Irregular shaped particles and their composition by EDAX.



Mag. 2000X

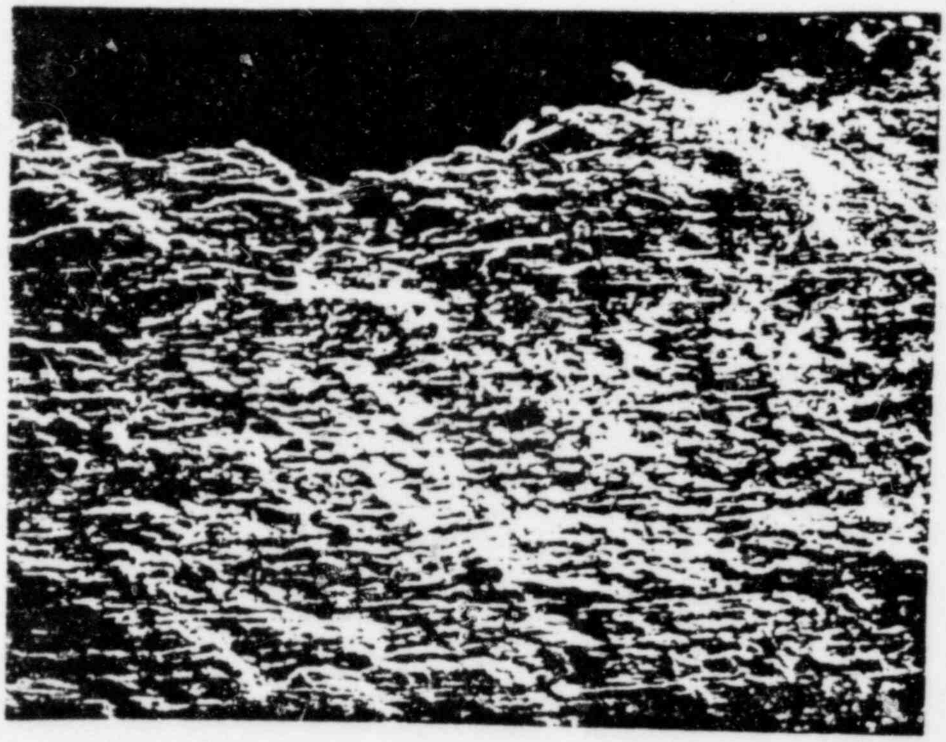
A. Fluorescent particles at weld root.



B. Energy spectrum of particle.

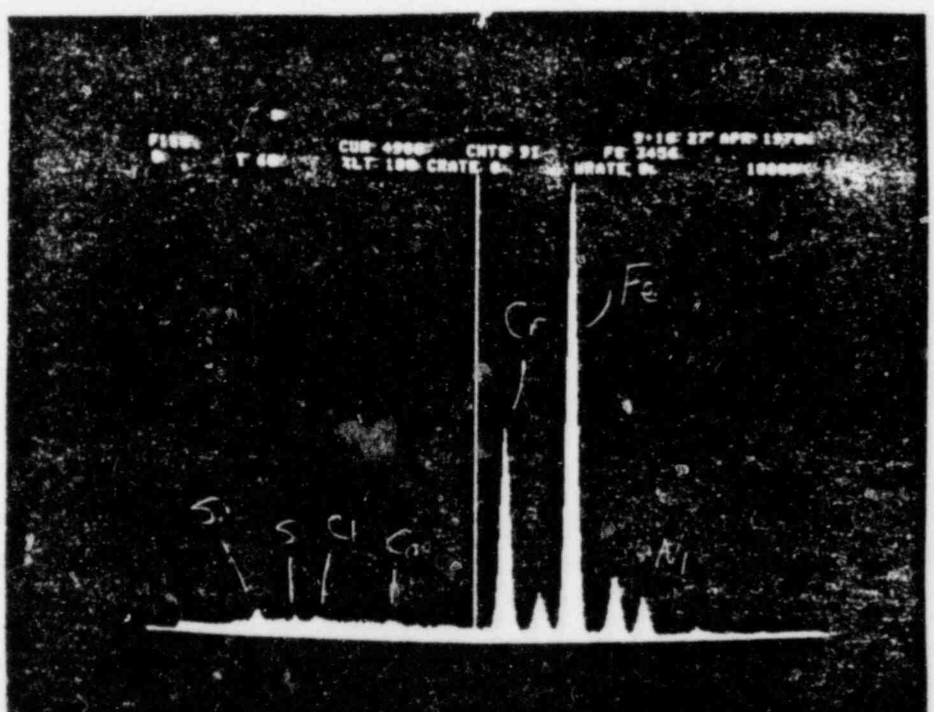
FIGURE 7. SEM And EDAX near main crack.

Crack Edge



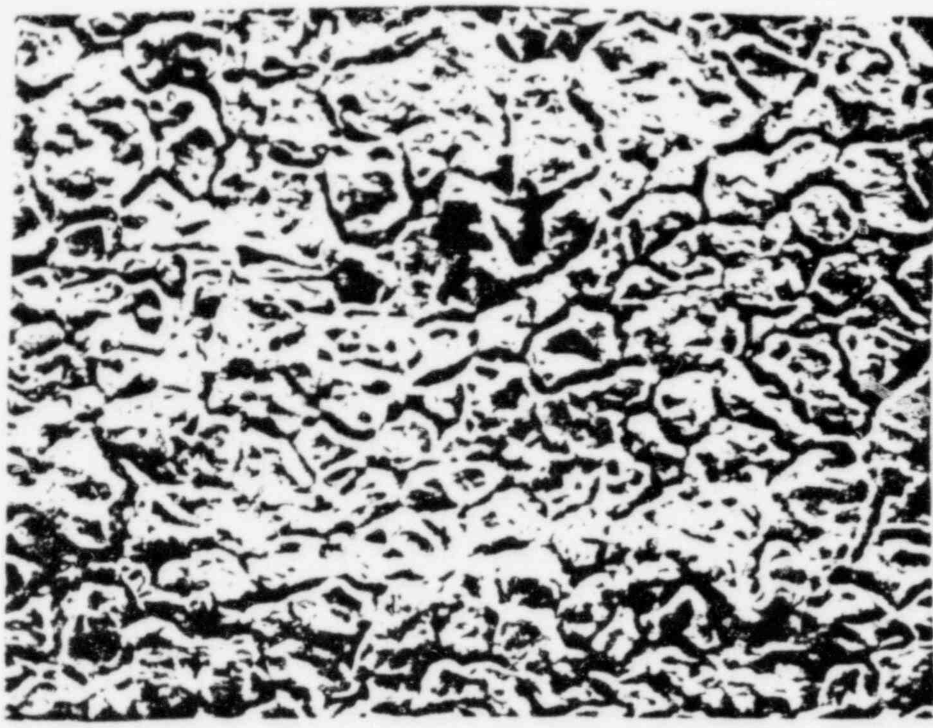
Mag. 300X

A. Topography of recessed groove on inside diameter surface of Type 304 SS SFP pipe.



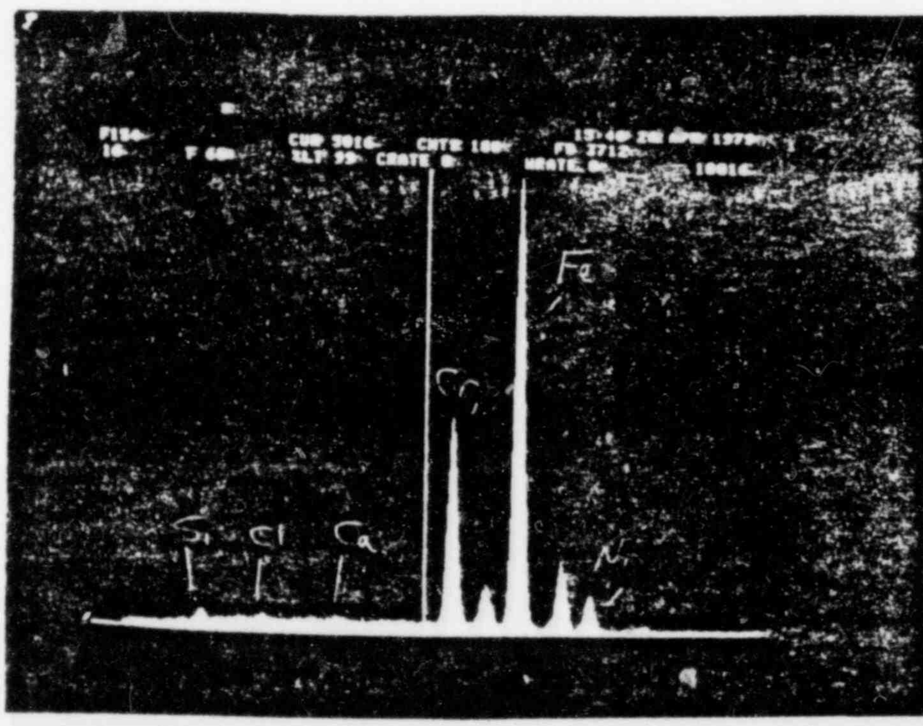
B. EDAX spectrum of recessed groove surface.

FIGURE 8. SEM and EDAX Spectrum of Type 304 SS Spent Fuel Pool Pipe Adjacent to Recessed Groove.



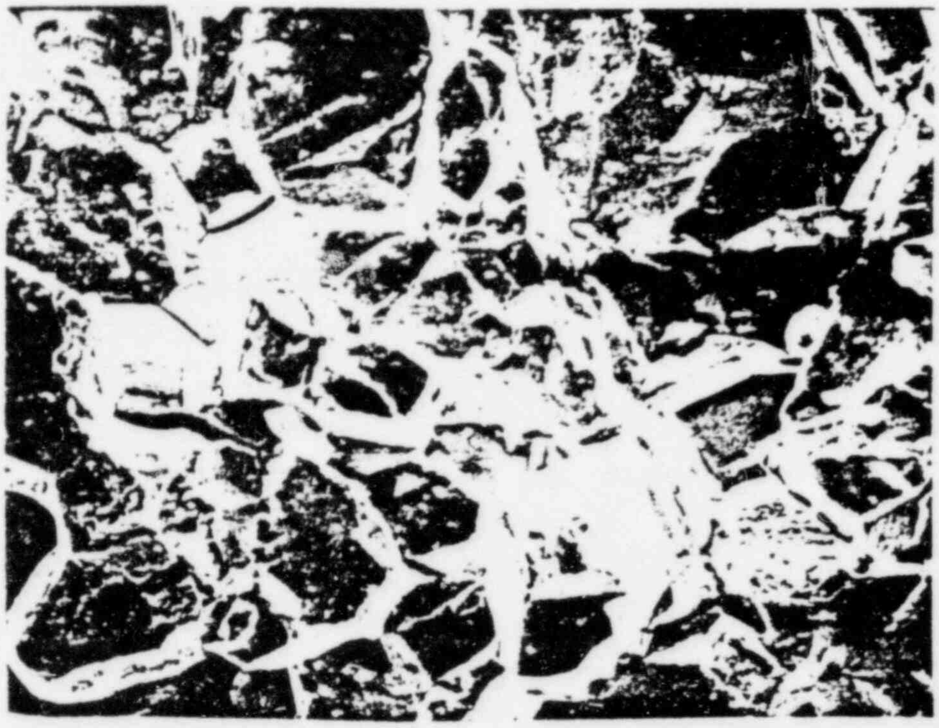
Mag. 300X.

A. Intergranular attack of Type 304 SS SFP Pipe. Penetration is less than one grain deep.



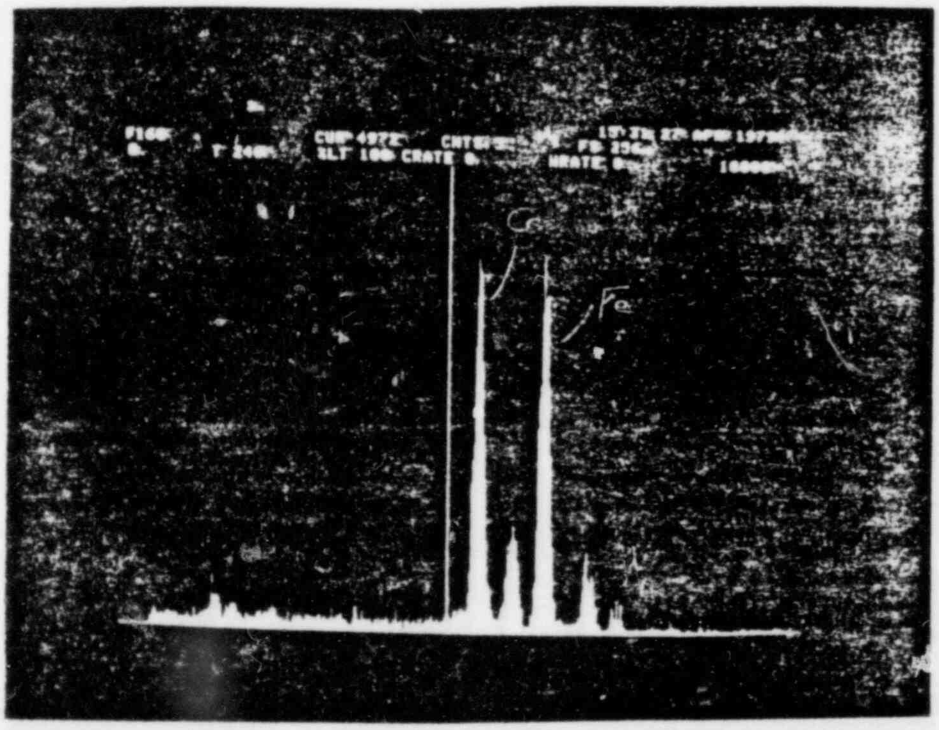
B. Energy spectrum of corroded Type 304 SS material pictured above.

FIGURE 9. Crack Topography and Associated EDAX Spectrum.



Mag. 420X

A. Features of Through Wall Crack in Type 304 SS, SFP Pipe.



B. EDAX Spectrum for above pictured area.

FIGURE 10. Metallographic Cross Section Showing Through Wall Cracks in 8" Sch. 40, Type 304 SS SFP Pipe. See Figure 14 for higher magnification photo.

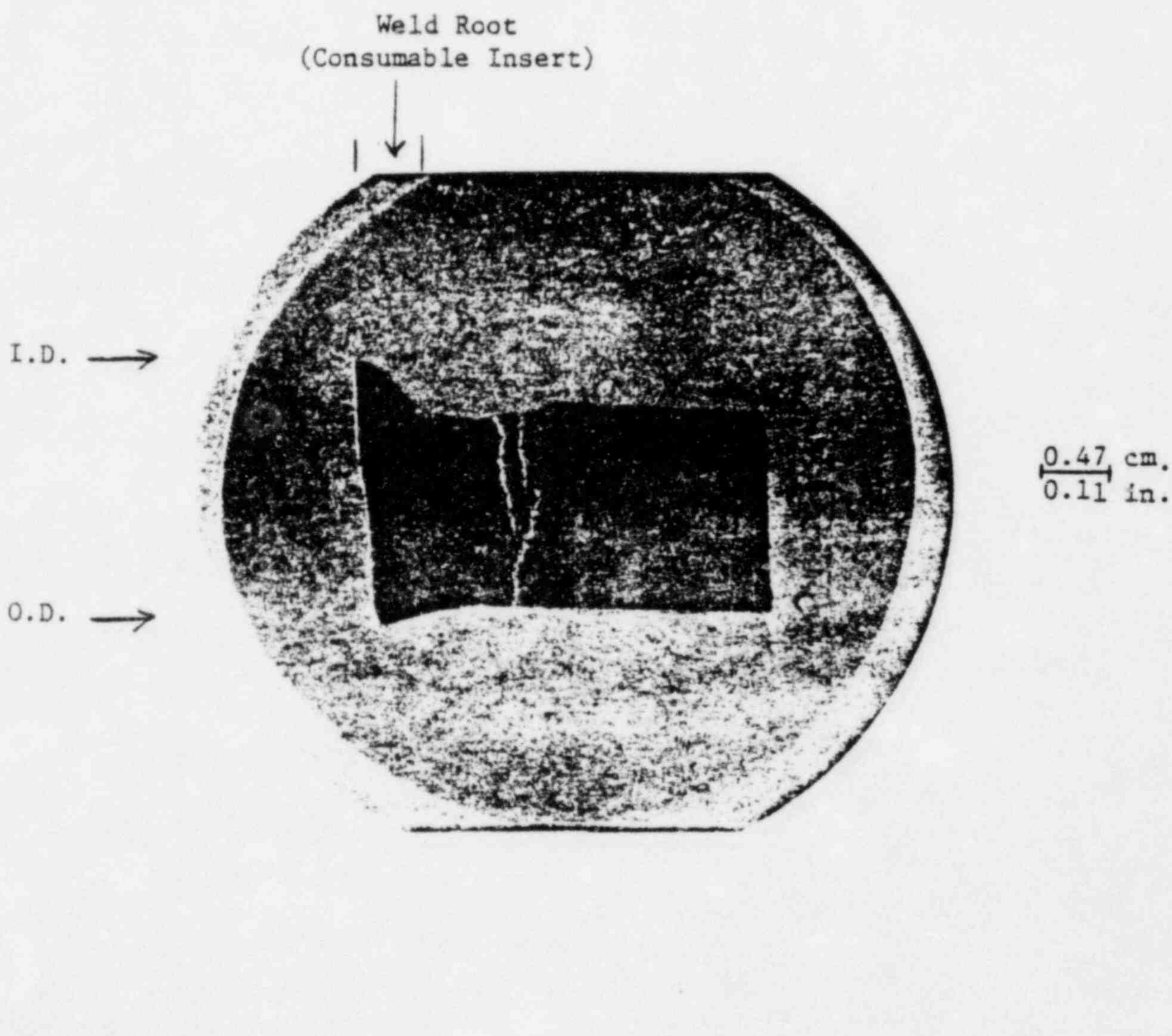
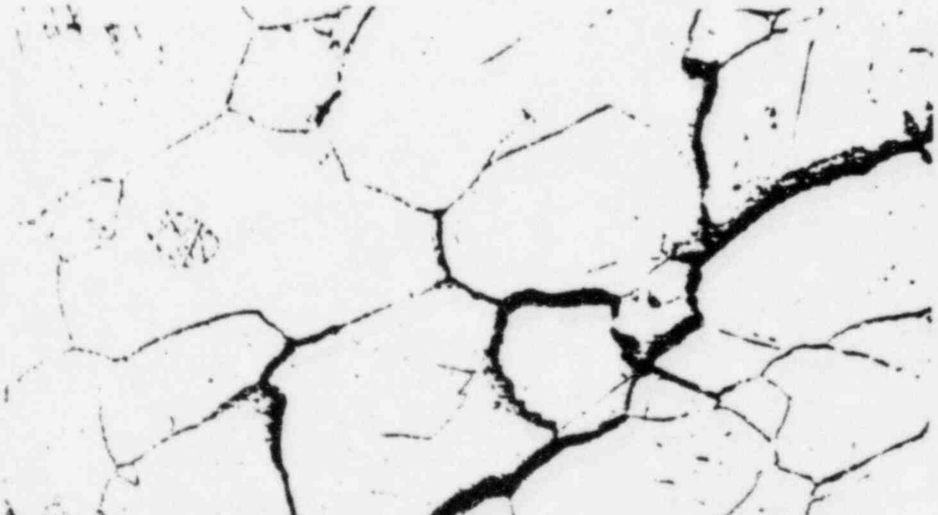


FIGURE 11. Typical Crack in Type 304 SS 8" Sch. 40, SFP Pipe.

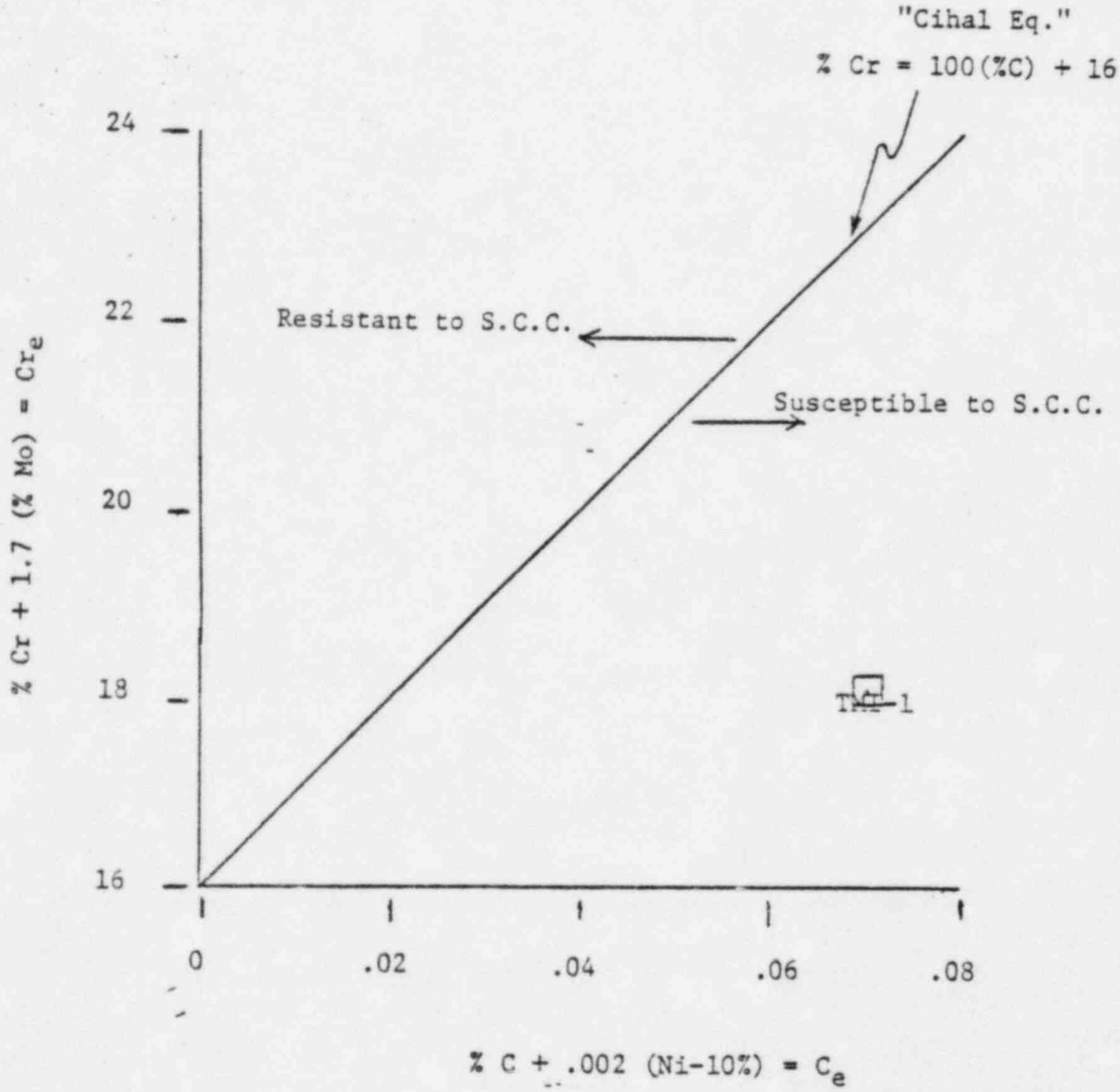
Pipe I.D.

Mag. 50X



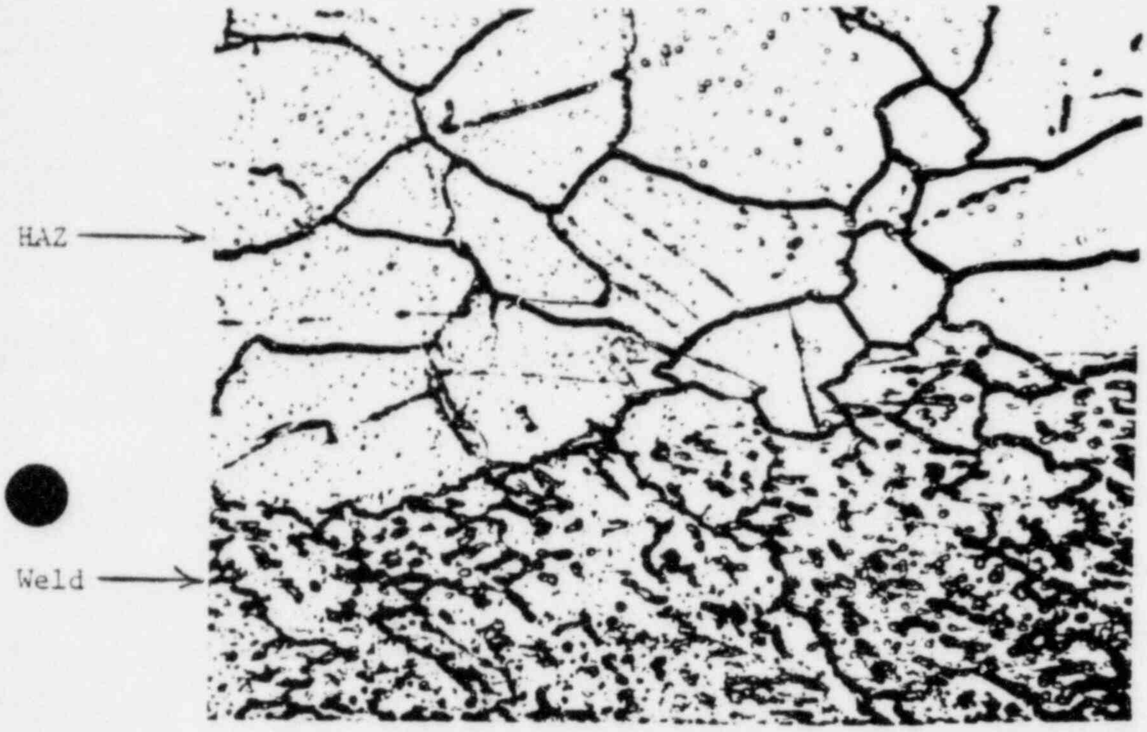
Mag. 400X.

FIGURE 12. "Susceptibility of Type 304 SS to Sensitization and hence Intergranular Corrosion/Stress Corrosion Cracking".



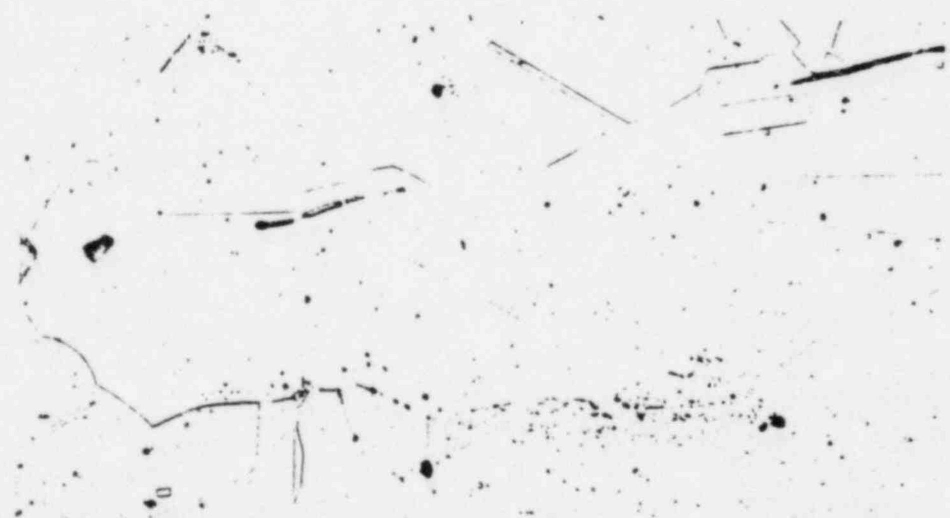
Ref. Gordon, B. M. and Armijo, V. S., "A Comparison of Type 316, 304 & 304L Stainless for Small Diameter BWR Piping".

FIGURE 13. ASTM-A-262A; Oxalic Acid Ditching Test Results.



Mag. 400X.

A. Ditching in Weld/HAZ at pipe I.D.



Mag. 400X.

B. Base Metal away from Weld Region.

weld

I.D.

FIGURE 14

Mag. 50X.

Etch: Oxalic Acid Electrolytically

Photomicrograph on left shows I.D. surface in the counterbore where cracks initiated. Photomicrograph on right shows multiple crack propagation from I.D. to O.D.

Appendix I

Location of TMI-1

Spent Fuel Pool

Leaks and Weld

Joint Configurations

Appendix II

Chronological Listing of

TMI-1 Spent Fuel Pool

Chemistries and

Temperatures

TMI #1 SPENT FUEL POOL CHEMISTRY

Year: 1979

Date	pH	Cond.	Boron	Cl^-	F^-	β - γ	H^3	Turb.	Li
	ppm		ppm	ppm	ppm		ppm.	ppm.	ppm.
5/5	5.32	10.62	2384	0.04	<0.02	2.96E-2			
4/28	5.26	11.8	2362	0.17					
4/24	5.34	11.5	2396						
3/6			2363			2.37E-2			
3/3	5.35	9.1	2361	0.055	<0.02	0.0375	0.0851	0.08	
2/17	5.4	11.5	2378	0.00	0.012	4.34E-2	0.0467	0.09	
2/10	5.39	11.3	2328	0.00	<.1	5.74E-2	0.00146	0.15	
2/3	5.45	11.3	2397	0.05	0.026	5.71E-2		0.17	
1/20	5.42	23	2384	0.0	0.037	6.19E-2	0.0529	0.1	
1/6	7.0	15	2360	0.00	0.042	9.22E-2	0.0289	0.11	

Cond. ↓ micromhos/cm

β - γ ↓ microcuries/ml

TMI #1 SPENT FUEL POOL CHEMISTRY

Year: 1978

Date	pH	Cond.	Boron	Cl^-	F^-	β - γ	H^3	Turb.	Li
12/16	5.4	13.5	2311	0.08	0.070	5.39E-2	0.0541	0.12	
11/22	5.55	11.7	2323	0.00	<0.1	8.16E-2	0.0577		0.26
11/11	5.45	14	2308	0.0	0.059	6.27E-2	0.0578	0.15	0.25
11/4	5.41	13	2266	0.0	0.031	8.31E-3	0.058		
9/30	5.42	13.5	2312	0.07	0.035	8.58E-2	0.0609	0.15	
9/21	5.43	14	2317	0.06		5.78E-2	0.0650	0.13	
9/16	5.42	13.0	2299	0.03	<.02	7.74E-2	0.0628	0.12	
9/9	5.5	11.5	2273	0.0	<.02	4.7E-2	6.3E-2	0.1	
9/2	5.56	9.1	2304	0.0	0.038	9.0E-2	6.59E-2	0.15	
8/26	5.49	13.5	2279	0.0	0.053	67.91E-2	6.61E-2	0.10	
8/19	5.58	13.5	2285	0.0	<.02	6.58E-2	6.61E-2	0.08	
8/12	5.46	14.0	2269	0.0	<.02	6.38E-2	1.07E-2	0.12	
8/5	5.56	15	2280	0.06	0.041	5.68E-2	6.84E-2	0.11	
7/29	5.5	14	2270	0.05	0.043	7.25E-2	5.93E-2	0.1	
7/22	5.55	9.95	2249	0.0	<.02	7.26E-2	2.73E-2	0.2	
7.15	5.58	14	2239	0.035	<.02	7.1E-2	7.5E-2	0.1	
7/8	5.49	12.9	2262	0.04	<.02	7.82E-2	7.59E-2	0.1	
7/1	5.5	13.5	2249	0.02	<.019	7.64E-2	7.65E-2	0.09	
6/24	5.61	10.5	2283	1.4	<.02	9.9E-2	7.81E-1	0.1	
6/17	5.57	13	2280	0.0	<.02	7.55E-2	8E-2	0.09	

(Continued)

TMI #1 SPENT FUEL POOL CHEMISTRY Year: 1978 (Cont'd)

Date	pH	Cond.	Boron	Cl^-	F^-	$\beta - \gamma$	H^3	Turb.	Li
6/10	5.75	14.5	2238	0.0	<.02	9.36E-2	8.15E-2	.23	
6/3	5.89	12	2238	0.0	<.02	9.35E-2	8.14E-2	.10	
5/27	5.72	11.5	2463	0.06	<.02	1.12E-1	7.03E-2	.11	
5/20	5.48	13.5	2269	0.08	<.019	7.67E-2	9.38E-2	0.9	
5/6	5.55	10.05	2221	0.06	<.019	5.98E-2	9.73E-2	0.11	
4/29	5.49	15	2217	0.09	<.02	6.27E-2	9.03E-2	.01	
4/24	5.51	13.5	2276	.09	<.02				
4/6			2252						
3/31			2189						
3/30			2181						Na^+ 1.23
3/30			2187						
3/30			2179						
3/29			2175						
3/29			2181			7.41E-2			
3/29			2181						
3/28			2185						
3/28			2181						
3/28			2181						
3/27			2193						
3/26			2207						

MI #1 SPENT FUEL POOL CHEMISTR

Year: 1978 (Cont'd)

Date	pH	Cond.	Boron	Cl^-	F^-	$\beta - \gamma$	H^3	Turb.	Li
3/25	5.36	8.4	2223	0.11	<.02	$5.82E^{-3}$	2.69E-2	0.075	
3/21			2221	0.00	<.02				
3/11	5.72	8.25	2228	0	<.019	7.36E-3	2.74E-2	.07	
3/4	5.37	9.7	2211	0	<.02	7.7E-3	2.7E-2	.26	
2/25	5.90	9.2	2234	0	<.019	7.53E-3	2 E-2	.007	
2/21			2218						
2/18	5.22	9.3	2216	0	<.019	6.04E-3	2.69E-2	0.25	
2/11	5.36	6.75	2209	0.06	<.019	7.73E-3	2.62E-2	0.1	
2/4	5.35	8.6	2215	0.04	<.02	6.96E-3	2.68E-2	0.12	
1/29				0.04					
1/28				.09					
1/28	5.38	7.9	2217	0.075	<.019	8.54E-3	2.68E-2	0.35	
1/22	5.45	9.85	2216	0.14	0.026	7.63E-3	2.67E-2	0.56	0.21
1/14	6.69	9.1	2213	0.0025	0.035	6.19E-3	6.420E-4	0.08	
1/7		8.4	2195	0.05	0.03	4.0 E-3	2.85E-2	0.11	

TMI #1 SPENT FUEL POOL CHEMISTRY

Year: 1977

Date	pH	Cond.	Boron	Cl^-	F^-	β - γ	H^3	Turb.	Li
12/31	5.9	7.80	22.08	0.04	0.032	6.6E-4	4.3E-4	0.11	
12/24	5.40	7.50	2194	0.07	0.048	6.1E-3	6.35E-4	0.13	0.18

I #1 SPENT FUEL POOL CHEMISTR

Year: 1976

Date	pH	Cond.	Boron	Cl^-	F^-	β - γ	H^3	Turb.	Li
10/23	5.6	13.5	2102	0.09	<.019	2.3E-3	2.6E-2	0.10	
10/16	5.52	13.5	2095	.3	<.019	2.4E-3	2.72E-2	.08	Cl^-(Titratión)
10/9	5.71	14.7	2074	0.08	.016	2.41E-3	2.72E-2	0.12	
10/2	5.3	11	2084	0.1	.024	3.5E-3	2.8E-2	0.028	
9/25	5.2	15	2120	0.1	.021	2.6E-5	2.48E-2	0.1	
9/18	5.70	14.5	2/10	0.05	0.020	1.85E-3	2.5E-2	0.1	
9/11	5.69	15.4	2114	.08	.015	2.86E-3	2.5E-2	.15	
9/4	5.75	14	2082	.06	.022	1.34E-3	$2.5E^{-2}$	.125	
8/28	5.69	14.5	2140	.05	.017		2.57E-2	.23	
8/21	5.65	14	2132	.03	.015	2.01E-3	2.61E-2	.14	
8/14	5.7	15.7	2122	.06	.013	2.13E-3	2.55E-2	.16	
8/7	5.75	14.5	2108	0.0	.015	1.78E-3	2.6E-2	.35	
7/24	5.68	18.4	2140	.07	.015	3.57E-3	2.7E-2	.075	
7/17	5.71	15.5	2096	.04	.015	2.86E-3	2.86E-2	.15	
7/3	5.7	17.5	2087	.08	.022	1.29E-3	2.74E-2		
6/26	5.72	14.5	2069	.03	.015	2.192E-3	2.74E-2	.15	
6/19	6.09	15.0	2060	.155	.012	2.28E-3	2.73E-2	.11	
6/12	5.4	14.5	2064	.09	.032	3.0E-3	2.77E-2	.14	
5/22	5.60	12.5	2073	.03	.004	3.8E-3	1.29E-1	.13	
4/24	5.83	16.5	2134	.07	.016	4.814E-3	3.576E-2	.04	

(Continued)

TMI #1 SPENT FUEL POOL CHEMISTRY

Year: 1976 (Cont'd)

Date	pH	Cond.	Boron	Cl^-	F^-	β - γ	H^3	Turb.	Li
4/15	5.75	8.5	2132	.02		1.04E-2	4.8E-2	.14	
4/13	5.38	9.2	2148	0.00	0.018	1.09E-2	1.896E-1	.15	
3/30	5.26	9.0	2136	.06	0.018	7.47E-3	5.30E-2	.13	
3/26	5.21	8.26	2113	0.015	0.015	1.31E-2	5.33E-2	.1	
3/22	5.12	7.4	2106					.011	
3/20	5.35	2.9	2106	0.0	0.017	1.18E-2	5.49E-2	.13	
3/13	5.44	8.25	2104	.03	.013	1.064E-2	5.8E-2		.0005
3/8	4.97	6.58	2065	0.0	.015		5.17E-2		
3/6	5.12	5.55	1995	.0125	.01	1.1E-2	4.45E-2	3.4	
3/5	5.04	6.25	1999	.05	.014	1.65E-2		.25	
3/2	5.06	5.6	1993	.01	.017	1.08E-2		.35	
1/10	4.92	6.0	2039	0.0	.038	2.89E-4	1.61E-3		
1/3	4.47		1936	0.03	.012	1.13E-3	6.62E-4		

MI #1 SPENT FUEL POOL CHEMISTR

Year: 1975

Date	pH	Cond.	Boron	Cl^-	F^-	$\beta - \gamma$	H^3	Turb.	Li
11/22	5.26	3.55	1126	0.0	0.01	3.15E-5	1.06E-4		
11/15	5.43	2.57	847	0.00	0.02	2.01E-4	7.14E-5		

TMI #1 SPENT FUEL POOL CHEMISTRY

1976

Date	Temp.
10/31	64
11/6	66
11/11	60
11/19	60
12/5	52
12/12	63
12/19	54

1977

Date	Temp.	Date	Temp.
1/2	52	7/3	85
9/9	49	7/10	85
1/16	57	7/17	89
1/23	60	7/24	91
1/30	66	7/31	83
2/6	62	8/7	88
2/13	66	8/14	85
2/20	60	8/21	81
2/27	50	8/28	80
3/6	50	9/4	86
3/13	52	9/11	79
3/20	45	9/	70
4/3	60	10/2	67
4/10	63	10/9	68
4/17	65	10/16	62
4/24	73	10/27	
5/1	62	11/6	77
5/9	74	11/13	66
5/15	75	11/20	56
5/22	84	11/27	55
5/29	84	12/4	60
6/6	78	12/11	64
6/12	73	12/18	70
6/19	84	12/25	57
6/25	82		

1978

Date	Temp.

1979

Date	Temp.
1/7	79
1/14	61
1/21	70
1/28	68
2/4	68
2/11	70
2/18	50
2/25	48
3/4	70
3/12	58
3/18	63
3/25	71
4/15	53
4/22	58

NOTE: These temperatures [illegible]

Appendix 2-2

Battelle Northwest Laboratory

Failure Analysis

THREE MILE ISLAND NO. 1
SPENT FUEL POOL PIPE CRACKING ANALYSIS
INTERIM REPORT

By
A. B. Johnson, Jr.
R. H. Jones

August 13, 1979

PACIFIC NORTHWEST LABORATORY
BATTELLE MEMORIAL INSTITUTE
RICHLAND, WASHINGTON 99352

The following observations are the result of analysis performed to date on the TMI-1 pipe/weld/elbow section received on July 7, 1979. The pipe/elbow specimen received contained a weld between a pipe (HT.334165) and elbow (HT.17616) which joined section MI48 to MH 440 as shown on isometric drawing number C-312-681-1. The specimen is shown in Figure 1. This piping was from the spent fuel cooling water piping, which contained water with 2200 ppm boron. The boric acid was added in April 1974 and the first failure was detected in March 1979. The pH varied from 4.47 to 7.0 from November 15, 1975 to May 5, 1979 while the water temperature varied from 45°F to 90°F (7.2°C - 32.8°C). Prior to sectioning, visual, NDT and photographic records were made with the following observations:

Visual:

1) Circumferential grinding on ID near weld
2) Residue from dye penetrant - OD surface
3) Felt pen lines - OD surface
4) Crack on ID 0.1-0.2 inches from weld root; 2.3 inches long at 315° to 345° (10:30 to 11:30) when viewed from elbow end

NDT: Four indications were recorded; so far, only one is identified as a crack. It was at 315° to 345° (10:30 to 11:30) on the pipe side. Presumably this is the crack observed at the reactor. This indication is labelled NDT-1 while NDT-2, 3, and 4 were at 60° CW (2:00) on the pipe side and 345°(11:30) on the elbow side. NDT-2 and 3 were thought to be associated with the weld while NDT-4 extended 3 inches circumferentially and was near the weld root.

Photography: The attached photographs show the pipe section and the ground surfaces on the ID. Also note the oxidation in the weld root area (Figure 1b).

Specimens were sectioned for metallography, SEM/EDX, Auger Electron Spectroscopy of a fracture surface, bulk chemical analysis and X-ray

diffraction of deposit on ID of pipe. The location of these specimens is identified in Figure 2. The following observations have been made:

Metallography

1) One major crack emanating from the ID and propagating ~80% through the pipe wall was located ~ 0.15 inches from the weld root (Figure 3a,b).
2) Several other crack segments located between the major crack noted above and the weld root (Figure 3b).
3) Intergranular cracks, with only a few exceptions as noted in Figure 4d.
4) Large density of grain boundary precipitates in the HAZ. The HAZ extended to beyond the major crack. These precipitates are presumably carbides (Figure 5).
5) Some suggestion of intergranular corrosion on the inner surface near the weld root (Figure 6). This region will be examined more carefully with an unetched specimen. If intergranular corrosion did occur, it appears to be very shallow.
6) Nonuniform grain size from mid-section of pipe to ID and OD. The grain size was much finer at mid-section than at the ID and OD. Also, there were inclusion/defects aligned with the longitudinal (pipe extrusion) direction (Figure 7). The significance of these observations to the fracture problem is not evident.

SEM/EDX

1) Corrosion product buildup was evident on ground inner surface of pipe near major crack and on the fracture surface (Figure 8). Energy dispersive X-ray analysis (EDX) of areas 1, 2, 3, and 4 of Figure 8C showed the following elements:

   a) Si (small amount), Fe, Cr, Ni
   b) Al, Si, S, Cl all small amounts, Cr, Fe
   c) Si, Si, both large amounts, Cr, Fe
   d) Al, Si, K, Cr, Fe, large amounts, Ni, small amount

2) The corrosion product was the densest near the crack origin at the inner surface of the pipe. There was some evidence of crack initiation being associated with the grinding marks (Figure 9a arrow). The elements detected with EDX on the fracture surface of Figure 9b were:

a) Fe, Cr with a little Ni
b) Fe, Cr with a little Ni
c) Al, Si, S, Cr-small amounts, Fe large

3) Deeper within the crack the fracture surface was much freer of deposits (Figure 10). The intergranular nature of the fracture is very evident.

4) The inner surface (ID) of the pipe away from the circumferential weld showed features which are associated with the pickling and grinding of the longitudinal pipe weld (Figure 11).

EDX analysis of areas 1, 2 and 3 of Figure 11a showed the following elements:

1) Mg, Al, Si - moderate amounts
S, Cl, Ti - small amounts
Fe, Cr, Ni - large amounts
2) Al, Si - large amounts
K - small amount
Fe, Cr, Ni - large amounts
3) Fe, Cr, Ni only - large amounts

<u>Auger Electron Spectroscopy (AES)</u>

An attempt was made to fracture a specimen taken from the pipe in the AES. This specimen contained a crack which had propagated partially through the wall. It was hoped that by opening the crack in the AES, the prior atmospheric exposure did not contaminate the crack front. However, the specimen was difficult to separate in the AES impact system and was exposed to dry nitrogen two times prior to AES analysis.

Analysis for chlorine was the primary purpose for the AES work. It was felt that the absence of chlorine would demonstrate its absence from the water environment while the presence of chlorine would not conclusively prove its presence in the water environment because of the atmospheric exposure.

Chlorine was observed at only one location on the fracture surface and this was a very small trace.* This location was near the origin of the crack and therefore saw the most atmospheric exposure. The AES results suggest that chlorine was not present in the water environment.

Boron was present on all the fracture surfaces except a small region which was fractured in the Auger. Sulfur was also present on all the fracture surfaces including the small region fractured in the AES. The boric acid is a probably source for the boron while the sulfur may have come from the atmosphere, handling or the material. The source of the sulfur needs further investigation.

Chemical Analysis

1) Surface swipes - X-ray flouresence analysis was performed on swabs taken on interior surfaces. The analysis did not detect chlorine* but did reveal a detectable lead content (0.13 μg/cm²). Swipes from the weld root and pipe surfaces were the same.

2) X-ray flouresence of bulk specimen ID - Chlorine was not detected** on the inner surface of the pipe by bulk X-ray flouresence; however, manganese was high. The results showed 5.6 wt% manganese when normalized to 19 wt% chromium in the specimen.

SUMMARY

Intergranular cracks were observed emanating from the ID of the 3-inch spent fuel pool 304 stainless steel pipe from the TMI No. 1 fuel transfer canal. This cracking was observed on the pipe side only and not in the weld or elbow material. The cracks were within 0.15 inch of the weld where considerable grain boundary precipitation (sensitization) occurred. The HAZ appeared to be severely sensitized. There was one major crack which apparently penetrated the pipe, through the penetration was only 80% in the metallographic specimen examined. There were several smaller crack segments between the major crack and the weld.

---

* Detection limit - <2 μg/cm²

** Detection limit - <.0039 at %

Analysis by SEM/EDX, Auger and X-ray flouresence revealed the following:

* By AES, boron and sulfur were consistent contaminants on the inner crack surfaces; chloride was minor or absent.
* By SEM, Al, Si, S, K, and Cl were detectable on the pipe inner surface near the crack mouth; Al, Si and S were associated with corrosion products inside the crack; away from the crack tip, the pipe ID surface had indications of Mg, Al, Si, S, Cl, K and Ti; Al, Mg, and Si were more prominent; S and Cl were minor.
* X-ray flouresence did not detect Cl, but did detect lead, which was absent in AES and EDX scans.

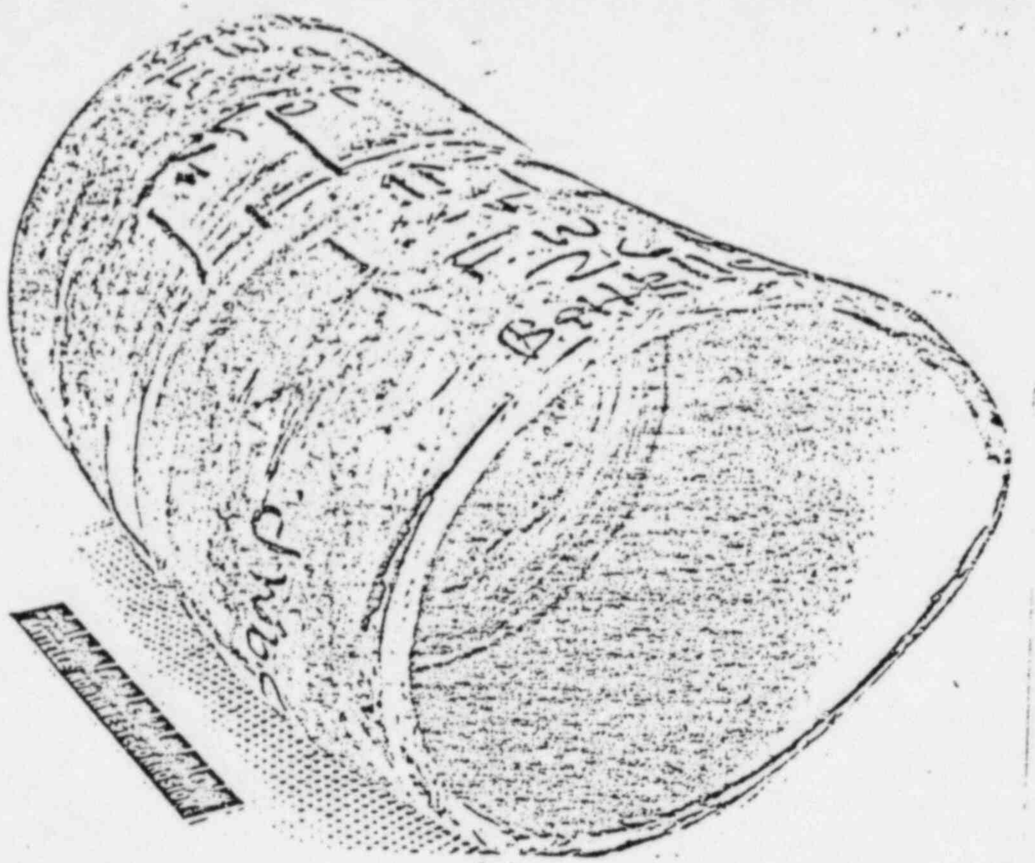
In summary, sulfur appears to be the most consistent contaminant. It is not yet clear whether it is present above the normal contamination level for 304 SS. Chlorine was detected, but was not a major contaminant. It was almost absent on inner crack surfaces examined by AES and seemed to occur only in discrete particles by EDX. Boron in the crack probably came from boric acid, which was transported through the crack and formed deposits on the other crack surface.

The interpretation of chlorine and sulfur indications is compromised somewhat by the fact that both are contaminants in the dye penetrant used to inspect the pipe.

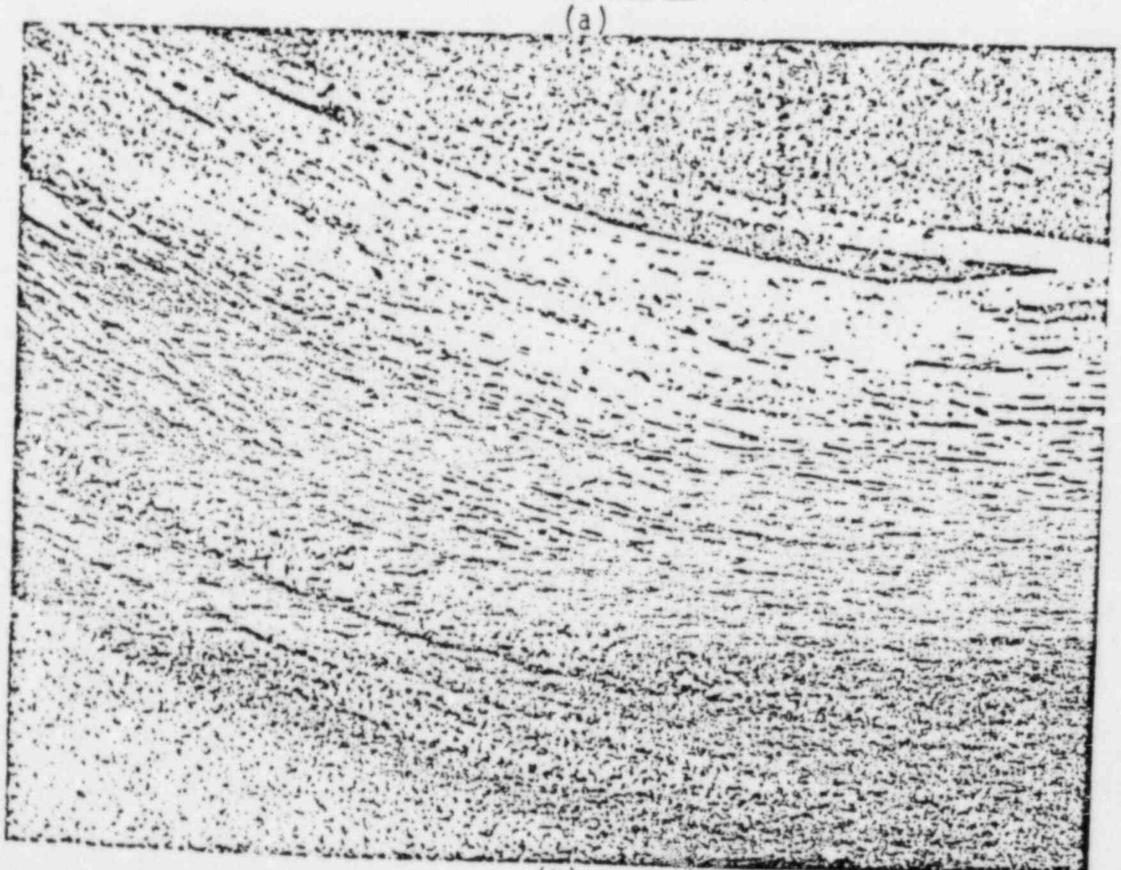
Possible sources and consequences of the other contaminants should be considered through there currently is no consistent evidence that any contributed to the cracking phenomenon.

Independent analysis of carbon in the pipe and elbow sections indicated levels about 0.01 wt% lower than the original pipe certification levels.

RHJ/ABJ:tf



(a)



(b)

Figure 1. Photographs showing a) as received pipe/elbow specimen and b) color photograph of weld root/pipe ID.

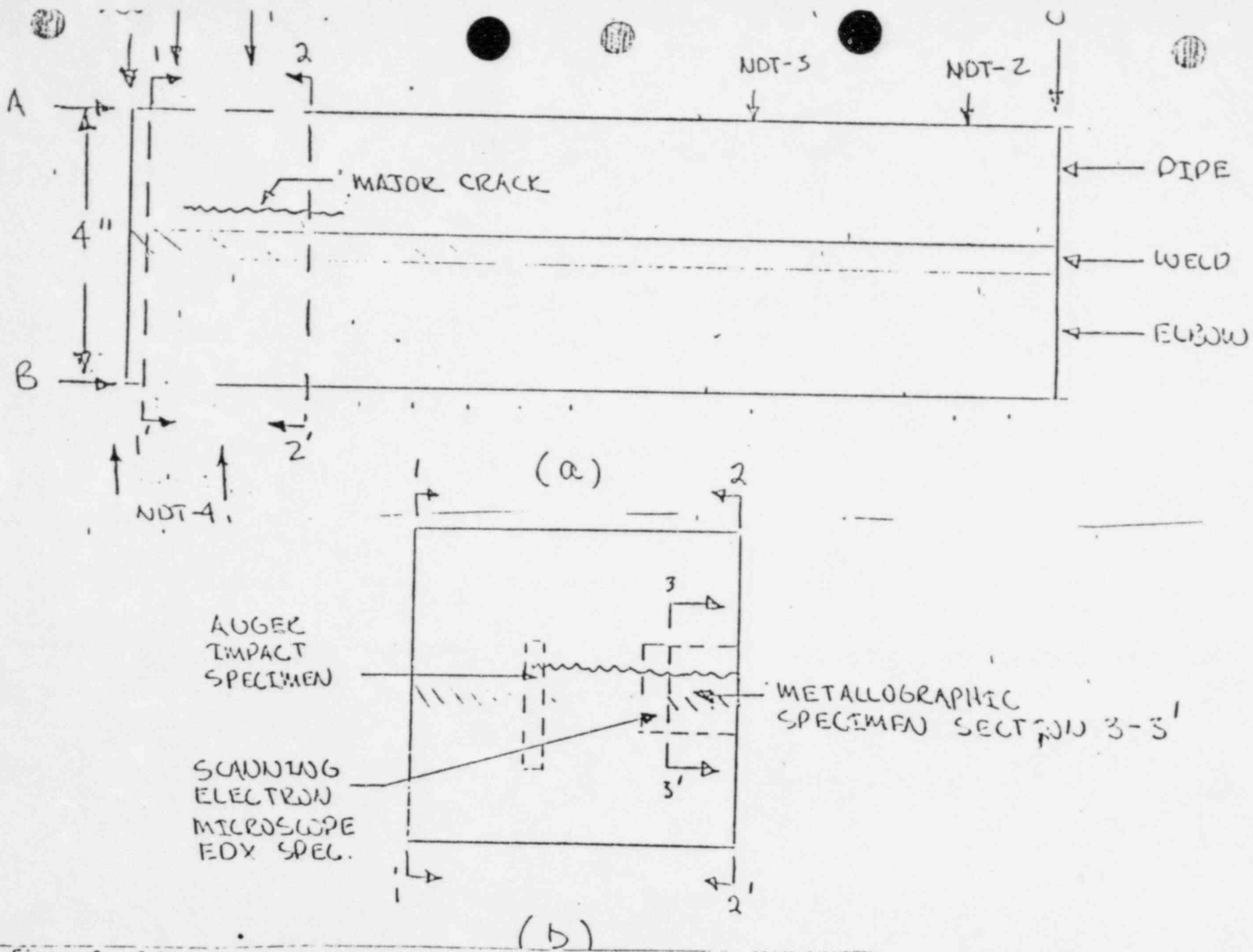
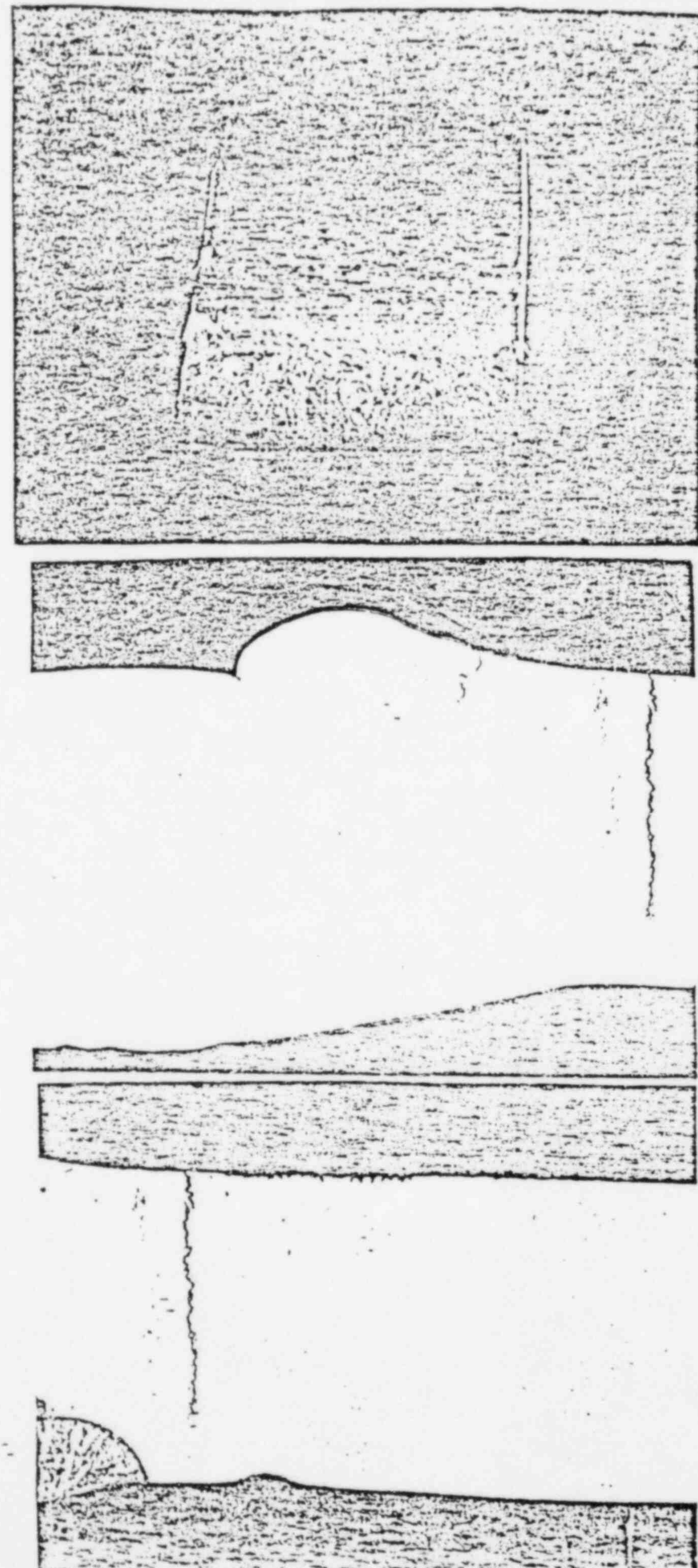


Figure 2. Schematic of pipe/weld/elbow section A-B in Figure 1 rolled out from a cut at 0° (12:00) showing locations of major crack, NDT indications and analysis specimens.



a) Macrophotograph of inner surface of pi showing major crack ~0.15 in. from weld root

b) Transverse section through pipe/weld/ elbow. Section 3-3' Unetched 6.3X 4P 1078A

c) Same as (b) Etched 6.3X 4P 1078H

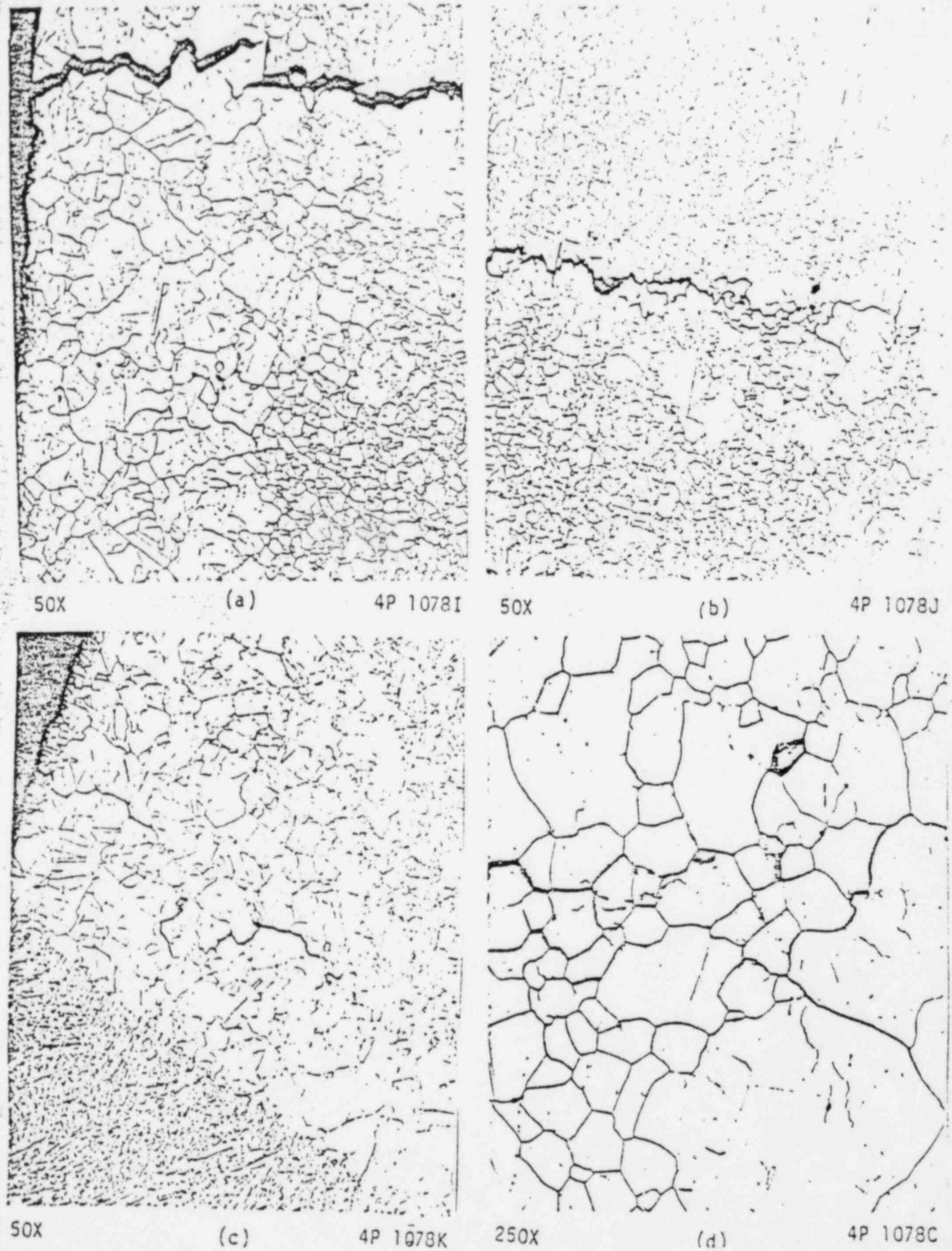


Figure 4. Optical micrographs of section 3-3' showing cracks emanating from the ID (left) towards OD (right). 4b shows end of major crack in 4a. Transgranular corrosion or stress corrosion, 4d.

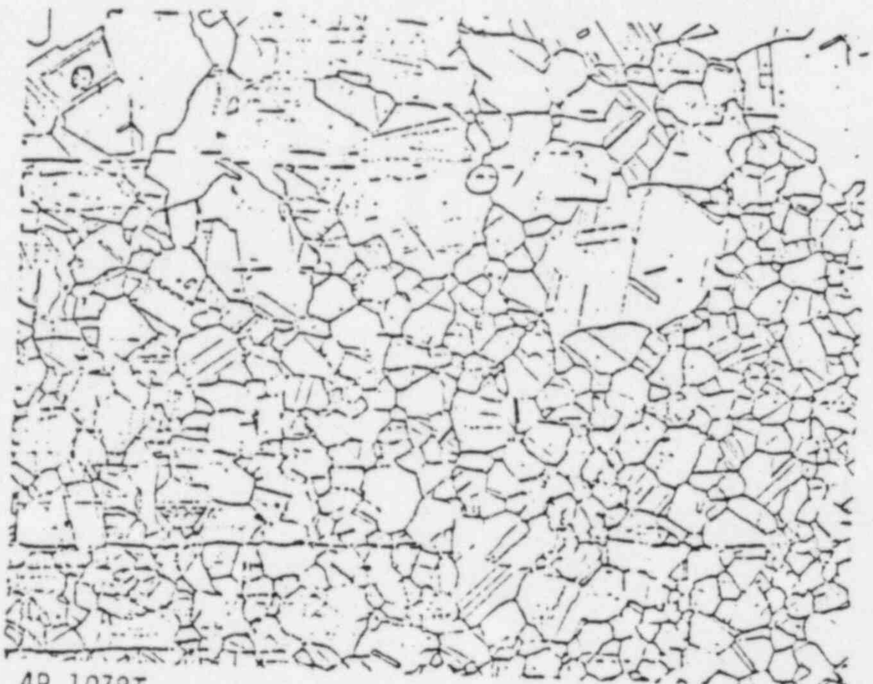
Close to weld (10
4P 1078V

~0.2 in from weld (500
beyond the major
crack
4P 1078P

Far from HAZ (105
4P 1078X

Figure 5. Optical micrographs showing grain boundary carbide precipitation at three locations relative to the weld. Section 2-2'

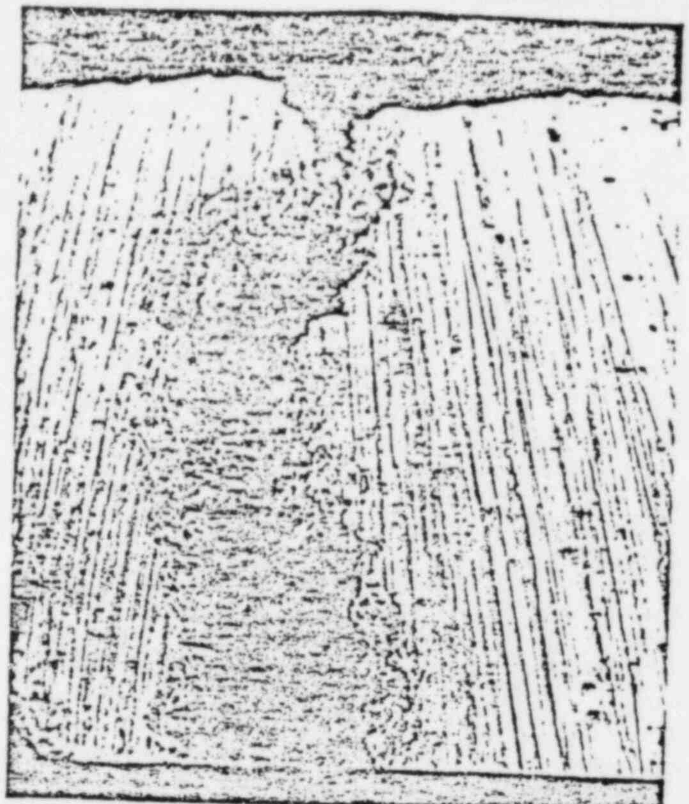
Figure 6. Optical micrographs showing inner surface of pipe from weld root to major crack. Section 3-3'.



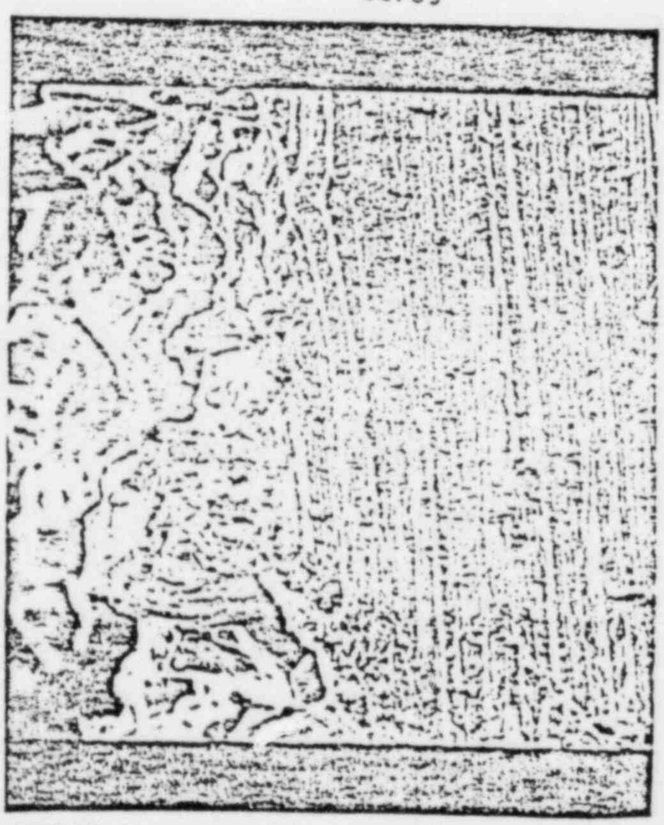
4P 1078T

100X

Figure 7. Optical Micrograph of Pipe Section Showing Non-uniform Grain Size and Longitudinal Defects.



S6739 a 20X



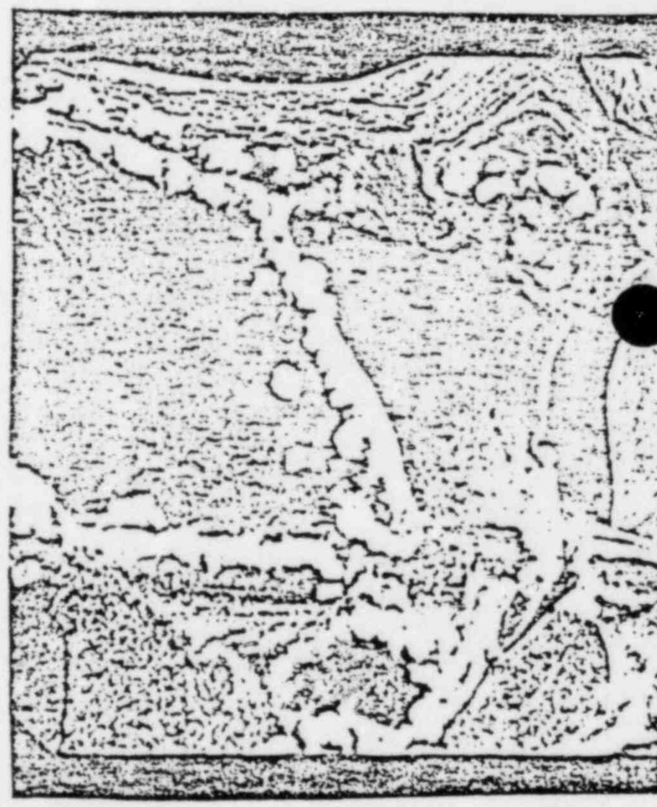
S6740 b 200X

S6741 c 800X

Figure 8. Scanning Electron Micrographs of Inner Surface of Pipe
(Near the origin of the major crack)

S6762 a 150X

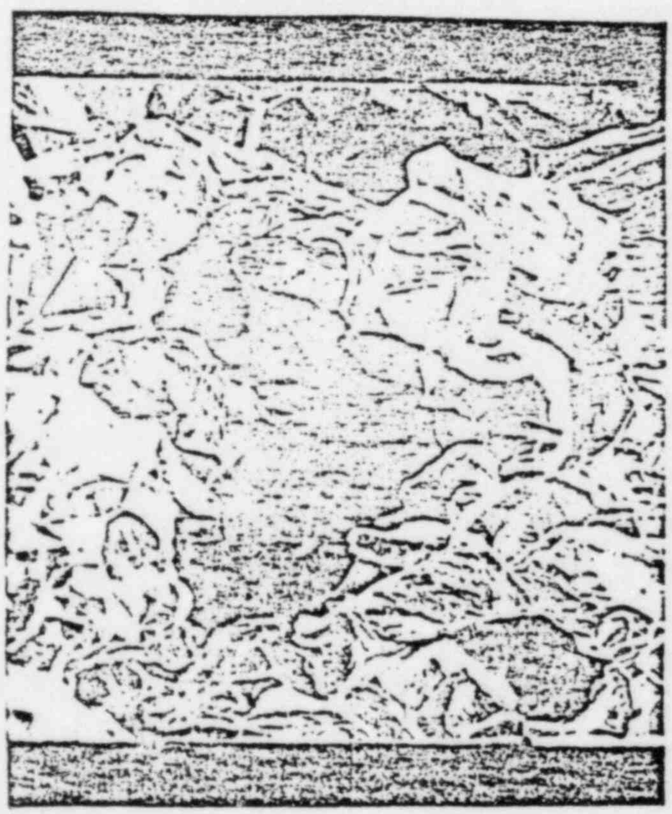
S6750 b 300X



S6761 c 1200X

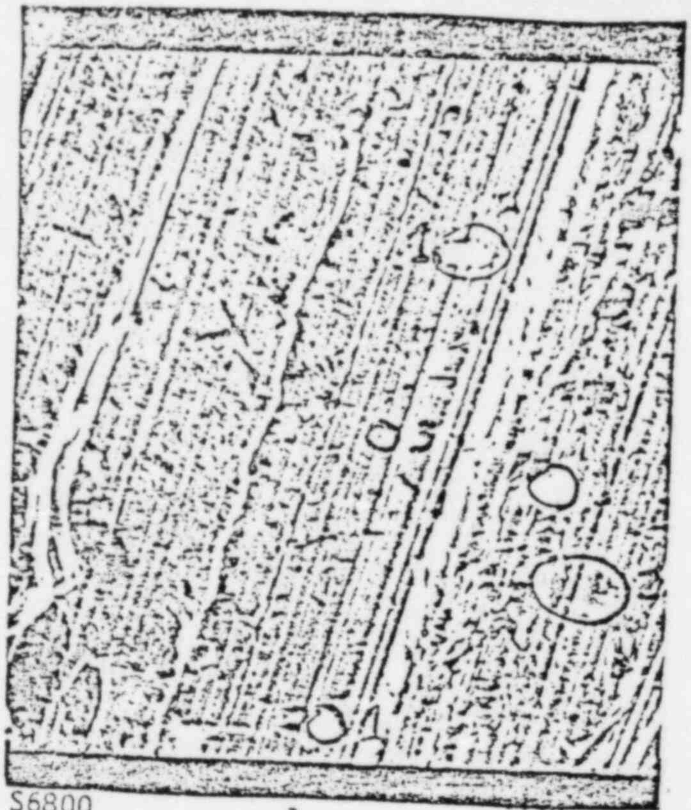
Figure 9. SEMs Showing Inner Surface and Crack Origin (a) and Corrosion Product Buildup

S6749 a 300X



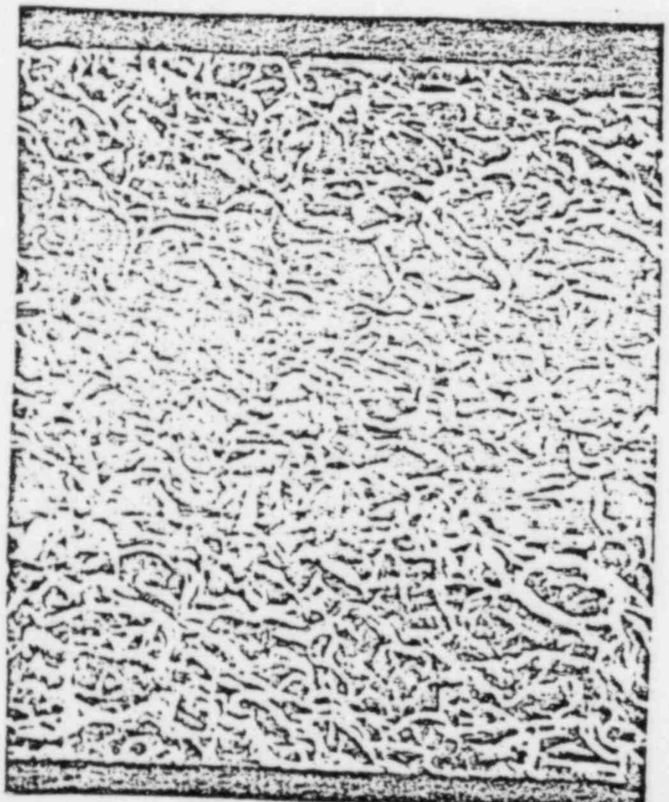
S6748 b 400X

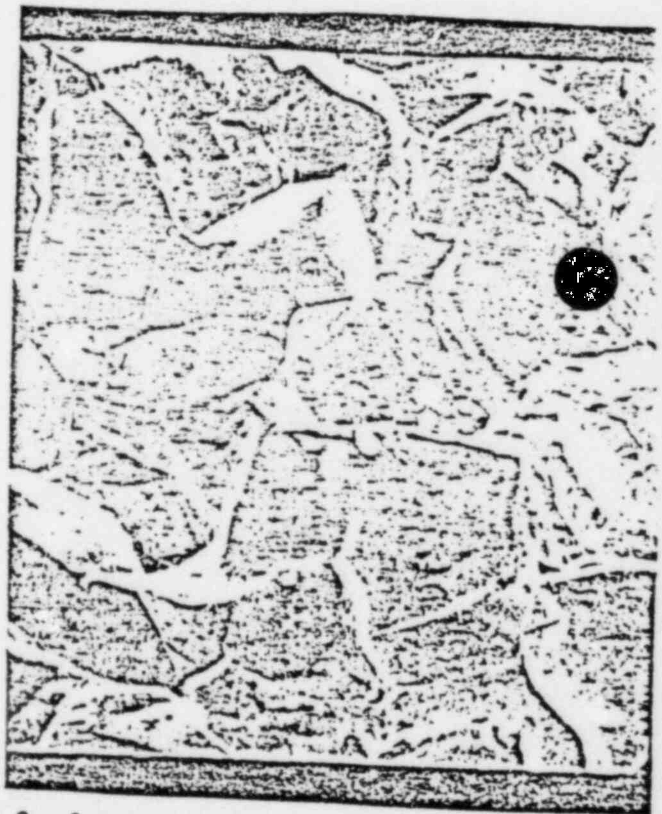
Figure 10. SEMs of the Fracture Surface far Removed From the ID



S6800 a 300X

Longitudinal Grinding Marks





S6795 b 300X Pickled Surface c 1500X S6797

Figure 11. SEMs of the Inner Surface (ID) of the Pipe Away From the Circumferential Weld

Appendix 2-3

Correlation Between UT

and Metallographic Data

SUMMARY OF UT/METALLOGRAPHIC DATA

Indication	UT Data		Metallographic Data			
	Screen B/L	Amplitude	Depth	Length	Location	Description
1 I 1	7.6	70	.010"	6-1/4"	Fitting	Lack of root fusion
1 I 2	7.0	30	.006"	1-1/2"	Fitting	Lack of root fusion
1 I 3	7.6	60	.015"	5-7/8"	Fitting	Lack of root fusion
2 I 1	6.4	20	.005"	1/4"	Pipe	Weld root irregularity
2 I 2	6.8	10	---	1/4"	Pipe	Weld root irregularity
2 I 3	6.2	15	---	1/4"	Pipe	No defect found
2 I 4	6.2	25	---	1"	Pipe	Weld root irregularity
2 I 5	7.0	35	---	1/4"	Fitting	Surface roughness
3 I 1	6.0	40	.043"	1"	Pipe	IGSCC
3 I 2	6.4	65	.062"	1-1/2"	Pipe	IGSCC
3 I 3	5.4	100	.110"	2-1/2"	Pipe	IGSCC
3 I 4	6.0	20	.047"	1/8"	Pipe	IGSCC
4 I 1	5.6	15	.010"	3/32"	Pipe	IGSCC

PIPE SECTION I (SF 209)

Heat Numbers:

Pipe Side: Ht. 48985
Fitting Side: Ht. 1401

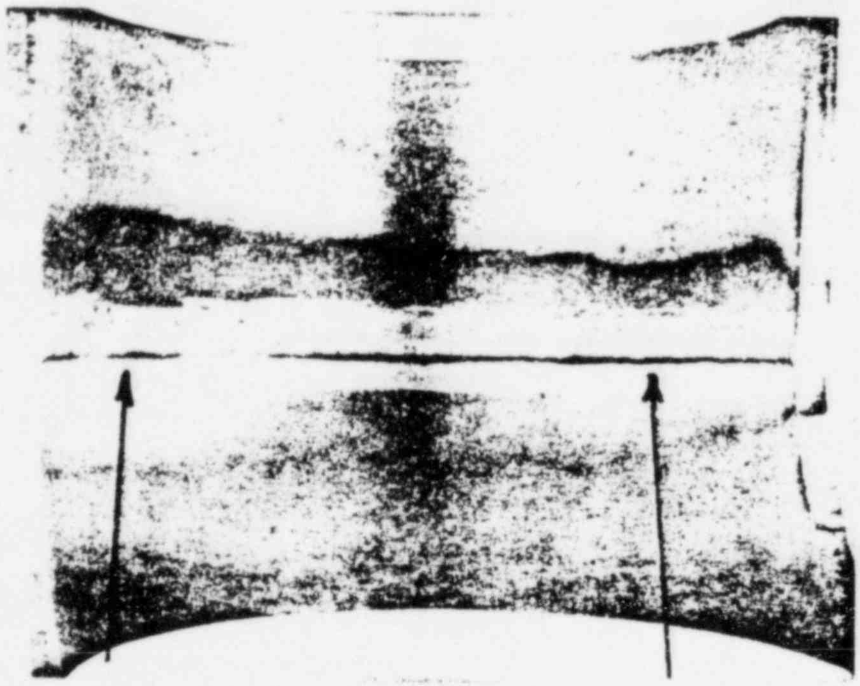
Type of Weld:

Shop

Description:

Joint geometry on this section showed little counterbore on either the fitting or pipe side. There appears to be mismatch of the I.D. surfaces which resulted in lack of root fusion on the fitting side. This lack of fusion produced the UT indications.

Location of Indications	Length	Depth
1 I 1 - fitting side	6-1/4"	.010"
1 I 2 - fitting side	1-1/2"	.006"
1 I 3 - fitting side	5-7/8"	.015"



I2 I1

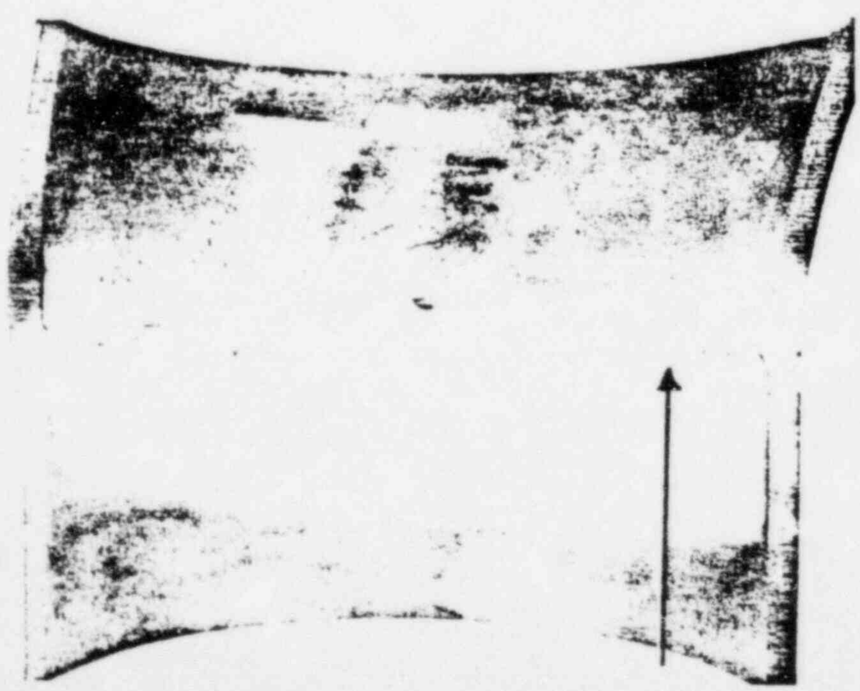
Pipe

FIGURE 1

Sample #1

I.D. surface showing Indication 1 & 2.

Fitting



I3

Pipe

FIGURE 2

Sample #1

I.D. surface showing Indication 3.

Fitting

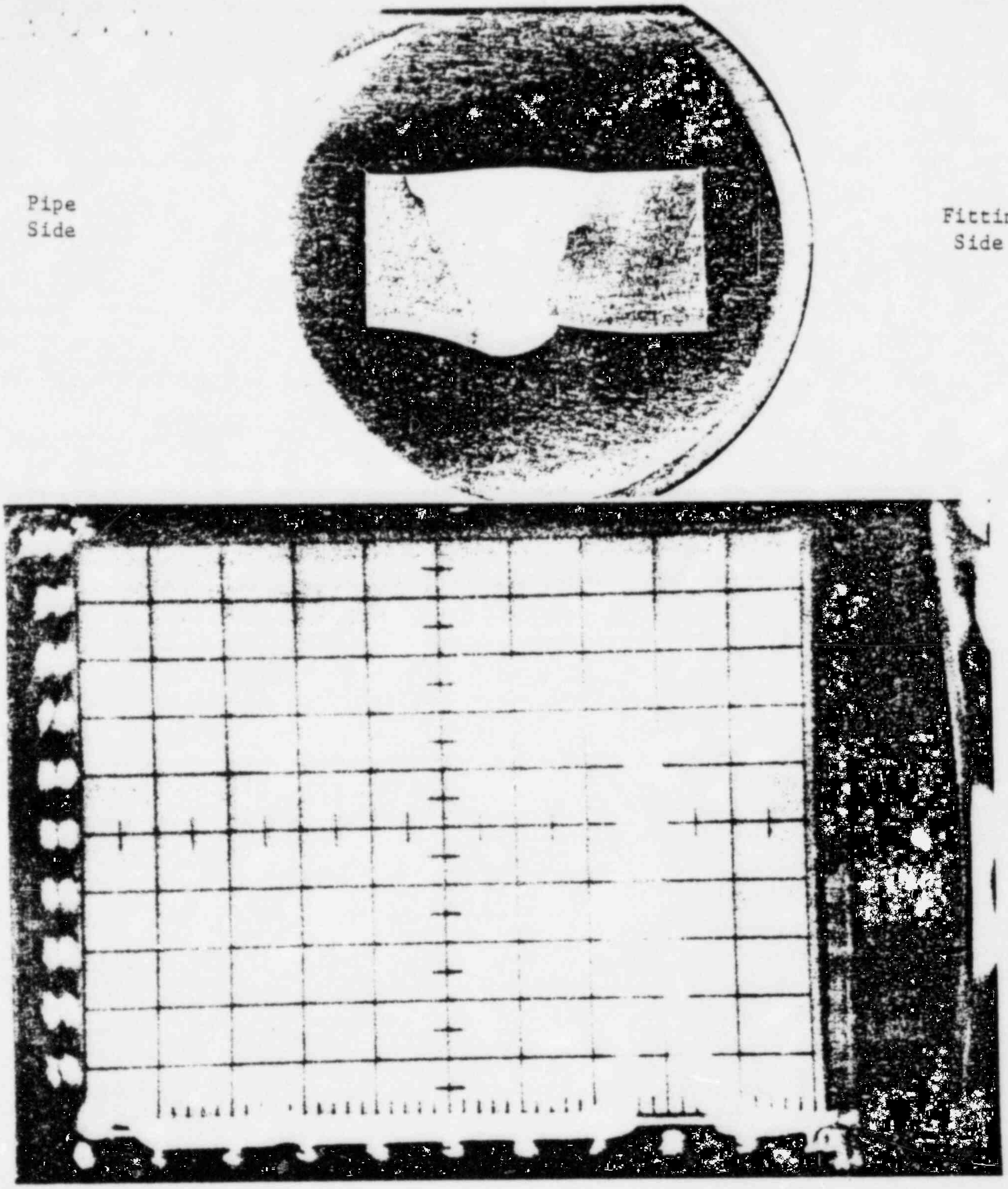
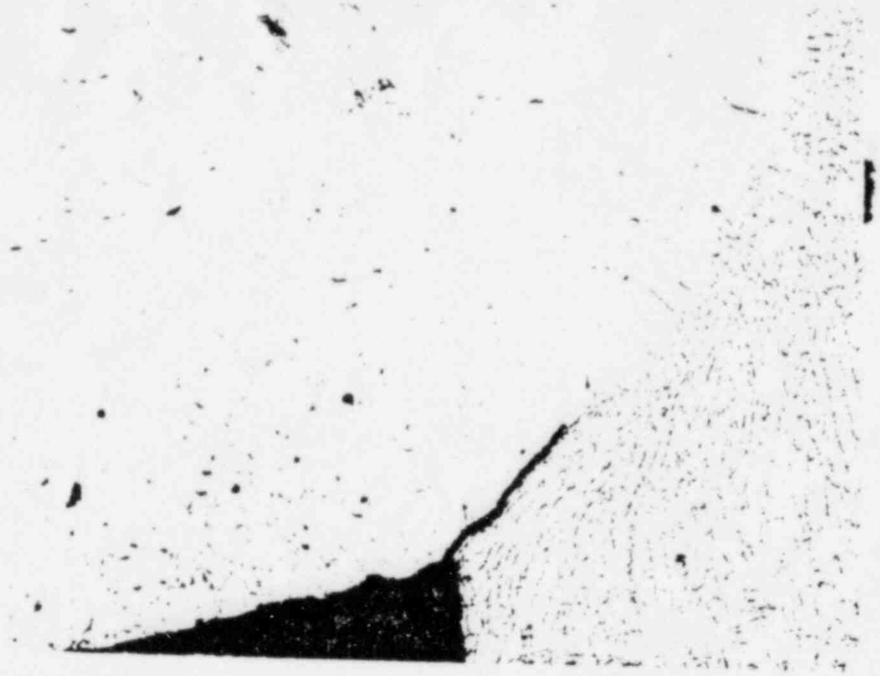


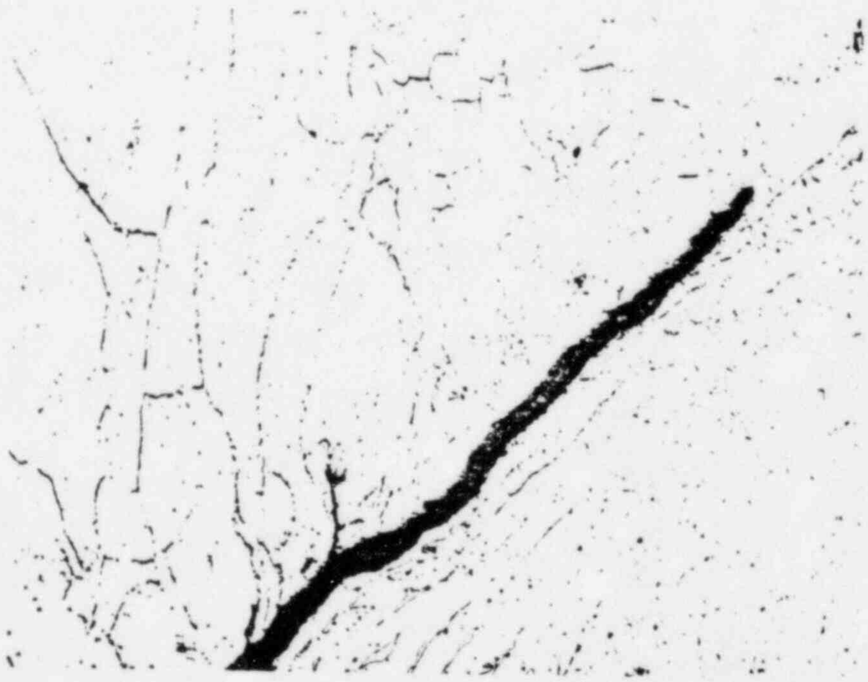
FIGURE 3

Indication 1 I 1

Joint geometry and resulting UT screen presentation produced by lack of root fusion defect seen in Figure 4.



Mag. 100X



Mag. 400X

FIGURE 4

Indication 1 I 1

Lack of root fusion defect. Depth is approximately .010".

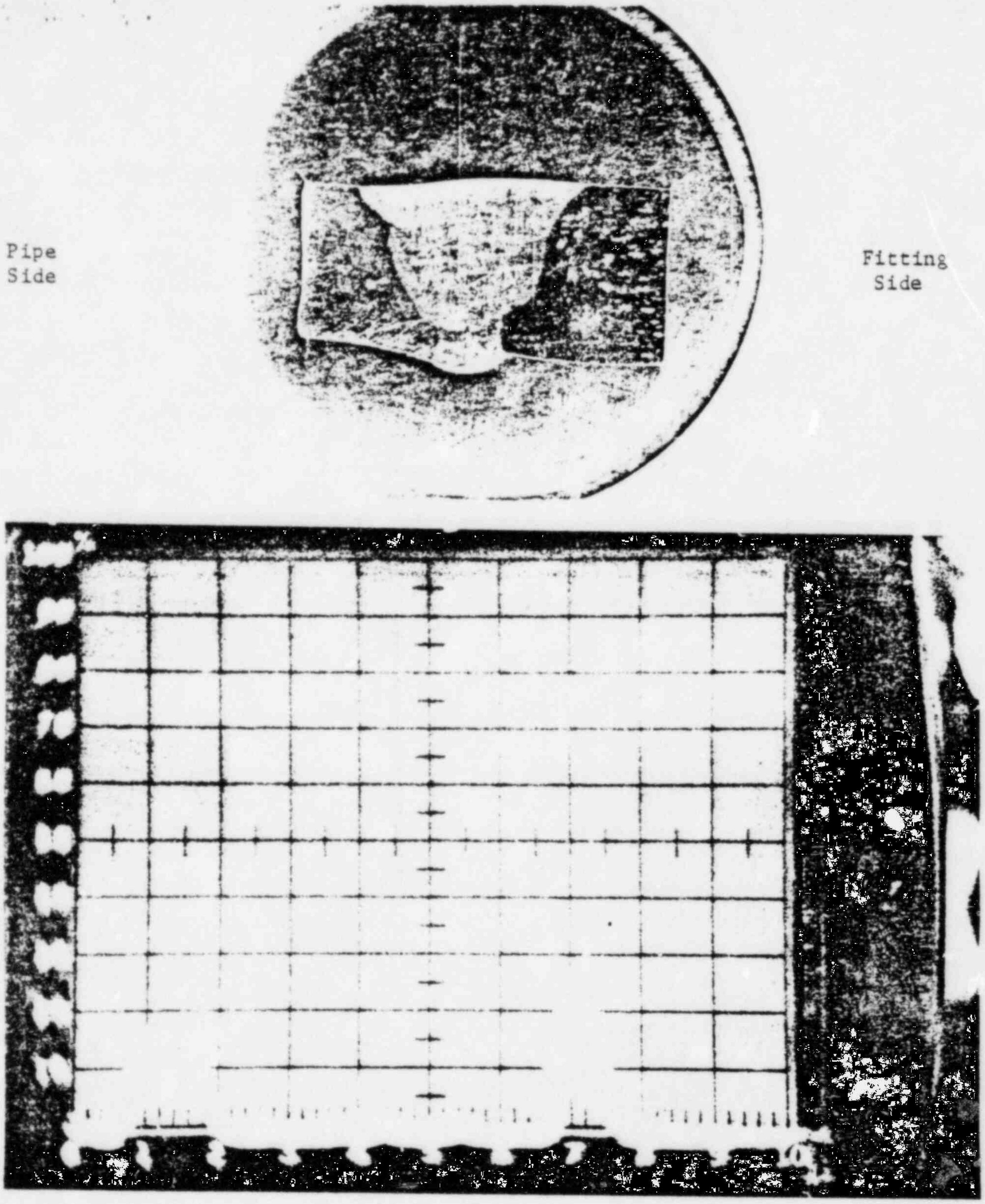


FIGURE 5

Indication 1 I 2

Joint geometry and resulting screen presentation produced by lack of root fusion defect seen in Figure 6.

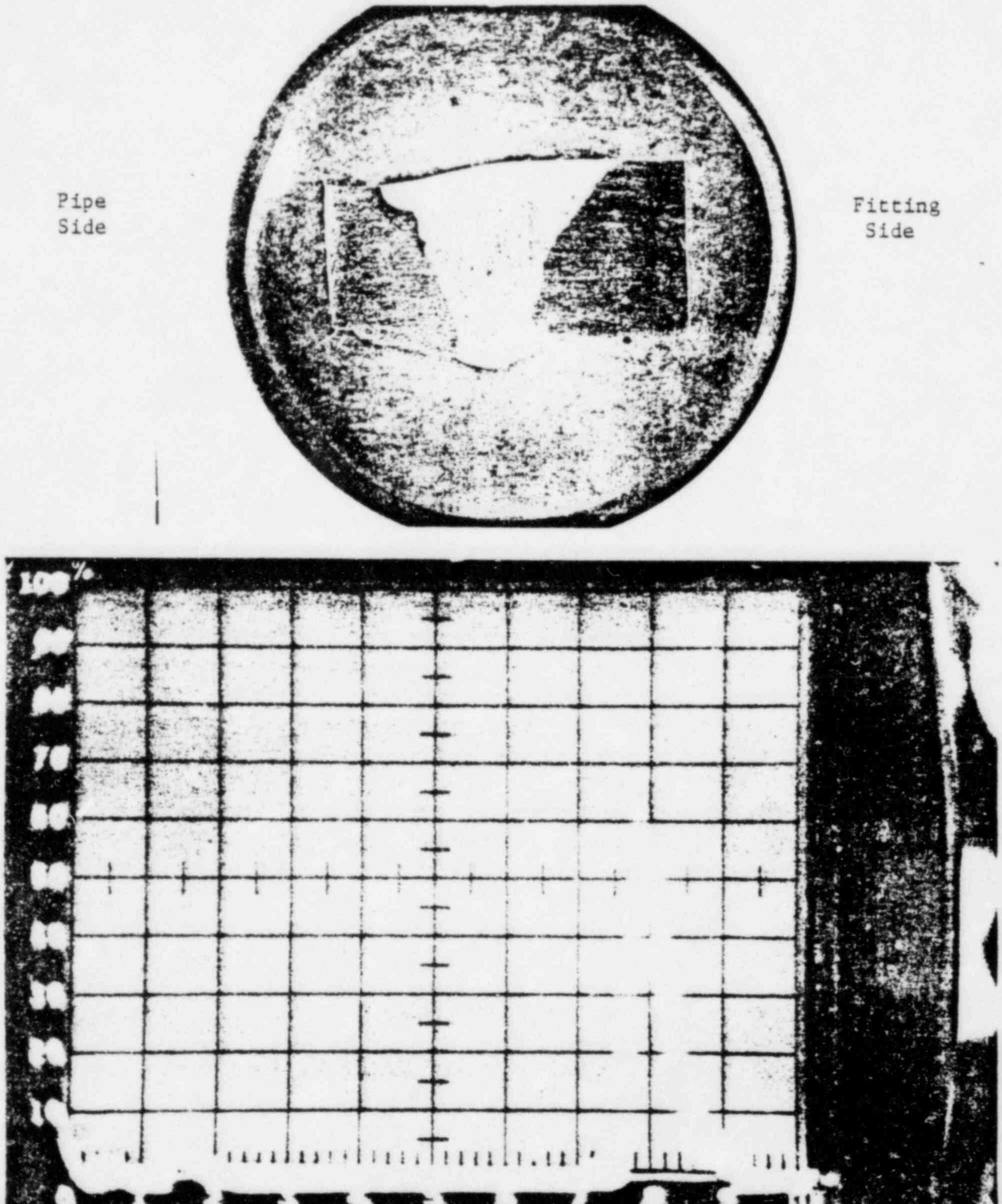
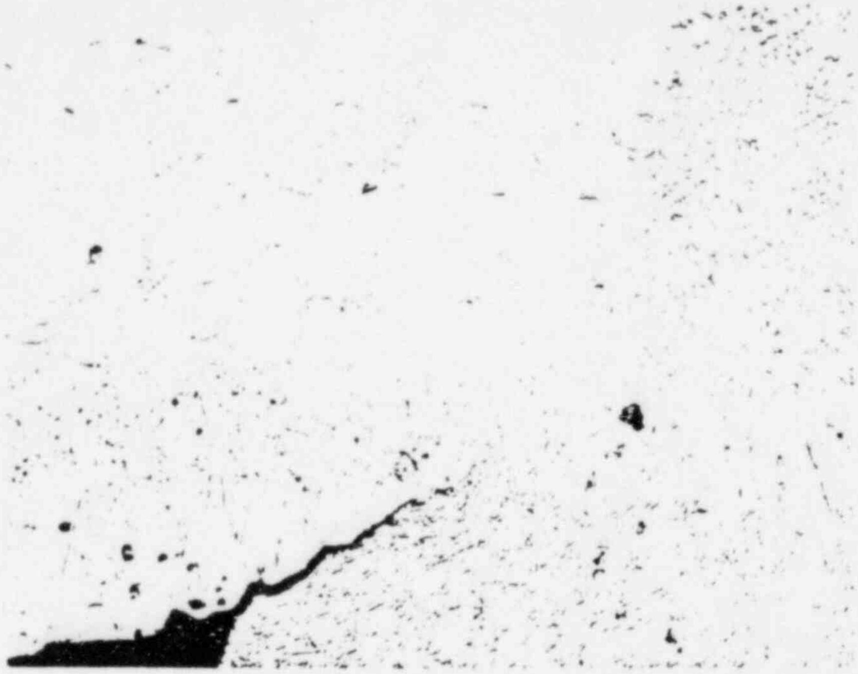


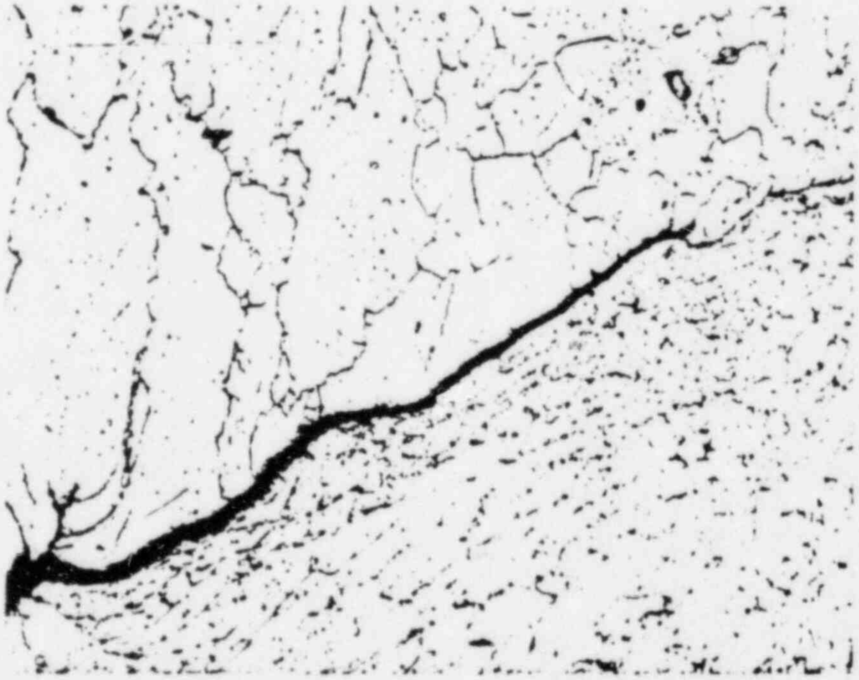
FIGURE 7

Indication 1 I 3

Joint geometry and UT screen presentation produced by lack of root fusion seen in Figure 8.



Mag. 100X



Mag. 400X

FIGURE 8

Indication 1 I 3

Defect at weld fusion line. Depth is approximately .015".

PIPE SECTION 2 (SF 201)

Heat Numbers

Pipe Side: Ht. 334165
Fitting Side: Ht. 17616

Type of Weld:

Field

Description:

This sample is characterized by sharp angular changes in the joint counterbore on the pipe side which acted as geometric reflectors. In addition, weld root irregularities existed which acted as reflectors.

No cracks were found, therefore, it must be concluded that the above account for the UT indications.

Location of Indications	Length
2 I 1 - pipe & fitting side	1/4"
2 I 2 - pipe side	1/4"
2 I 3 - pipe side	1/4"
2 I 4 - pipe side	1"
2 I 5 - fitting side	1/4"

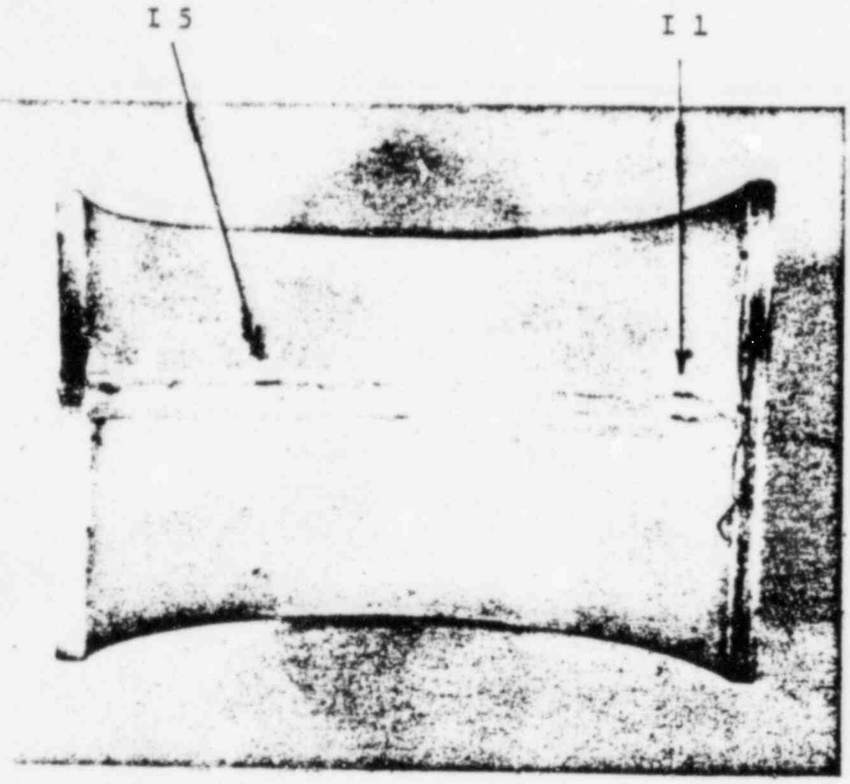


FIGURE 9

Sample #2

I.D. Surface showing Indications 1 & 5.

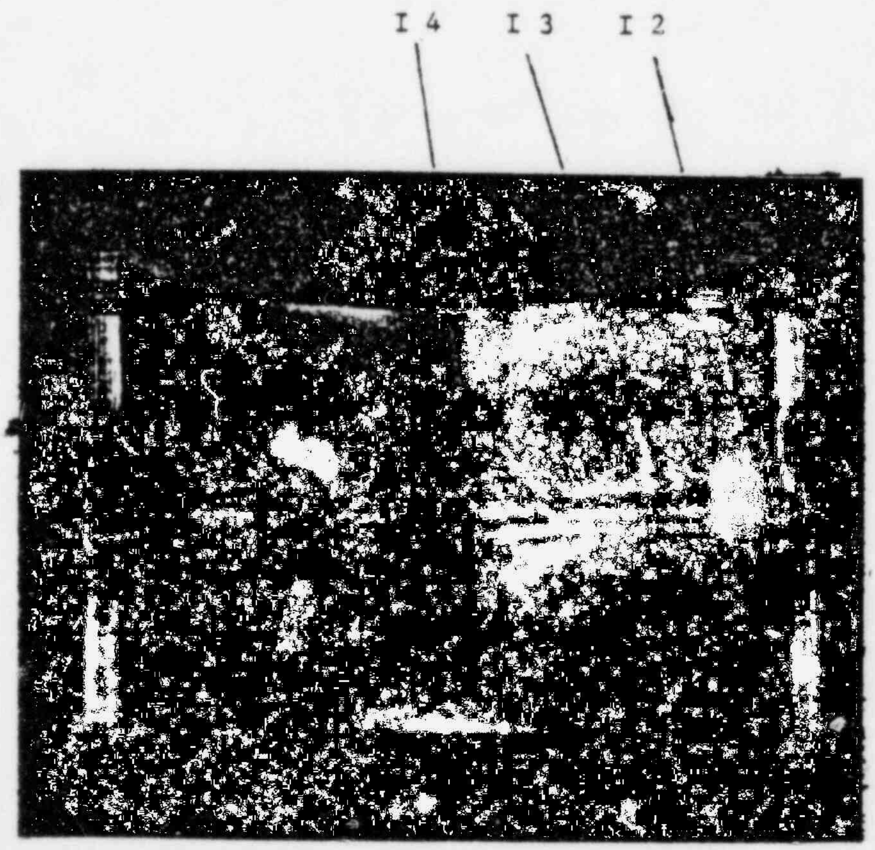


FIGURE 10

Sample #2

I.D. Surface showing Indications 2, 3 & 4.

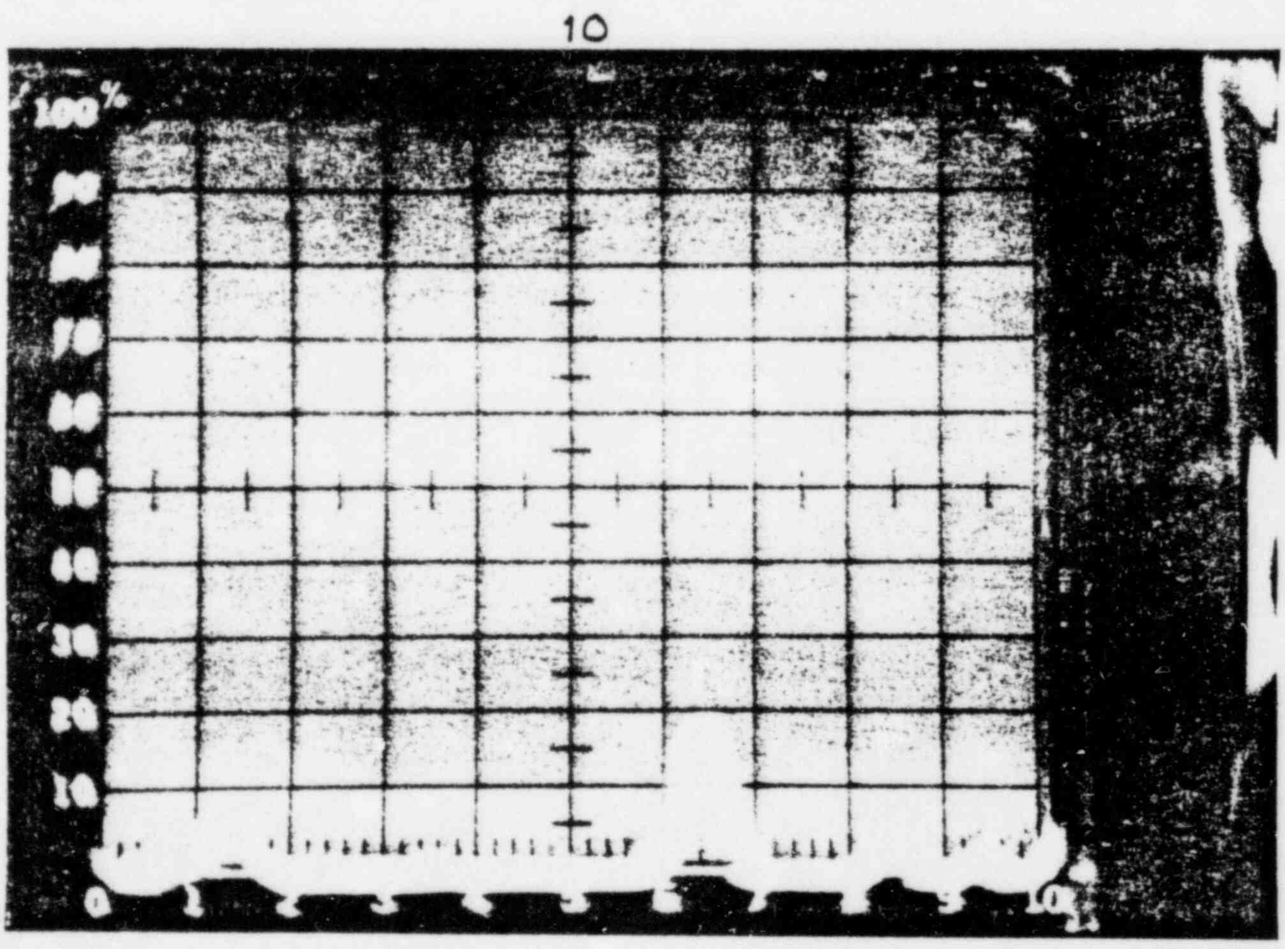
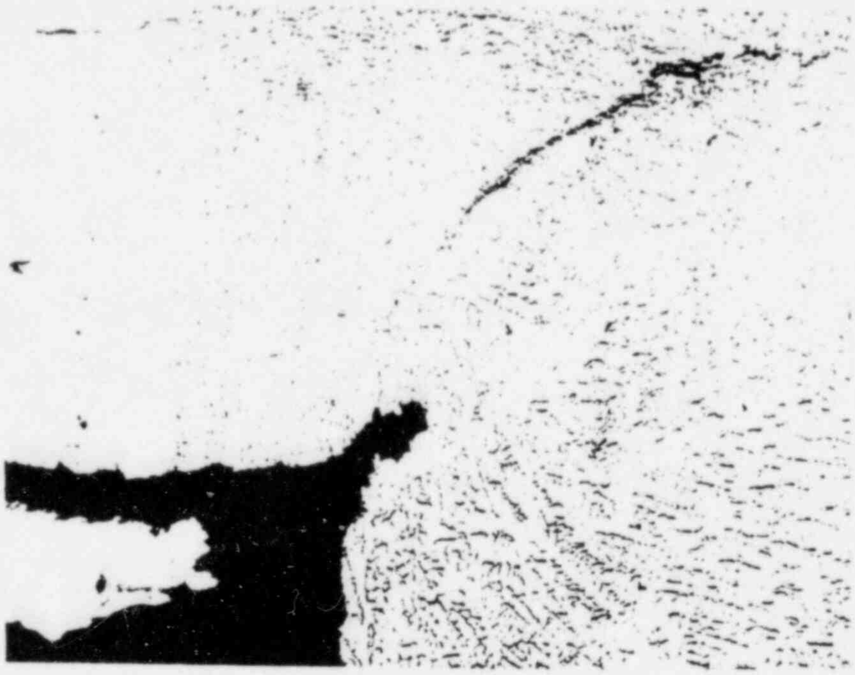


FIGURE 11

Indication 2 I 1

Joint geometry and UT screen presentation produced by weld root irregularity.



Mag. 100X

Mag. 400X

FIGURE 12

2 I 1

Weld root irregularity most likely responsible for UT indications.

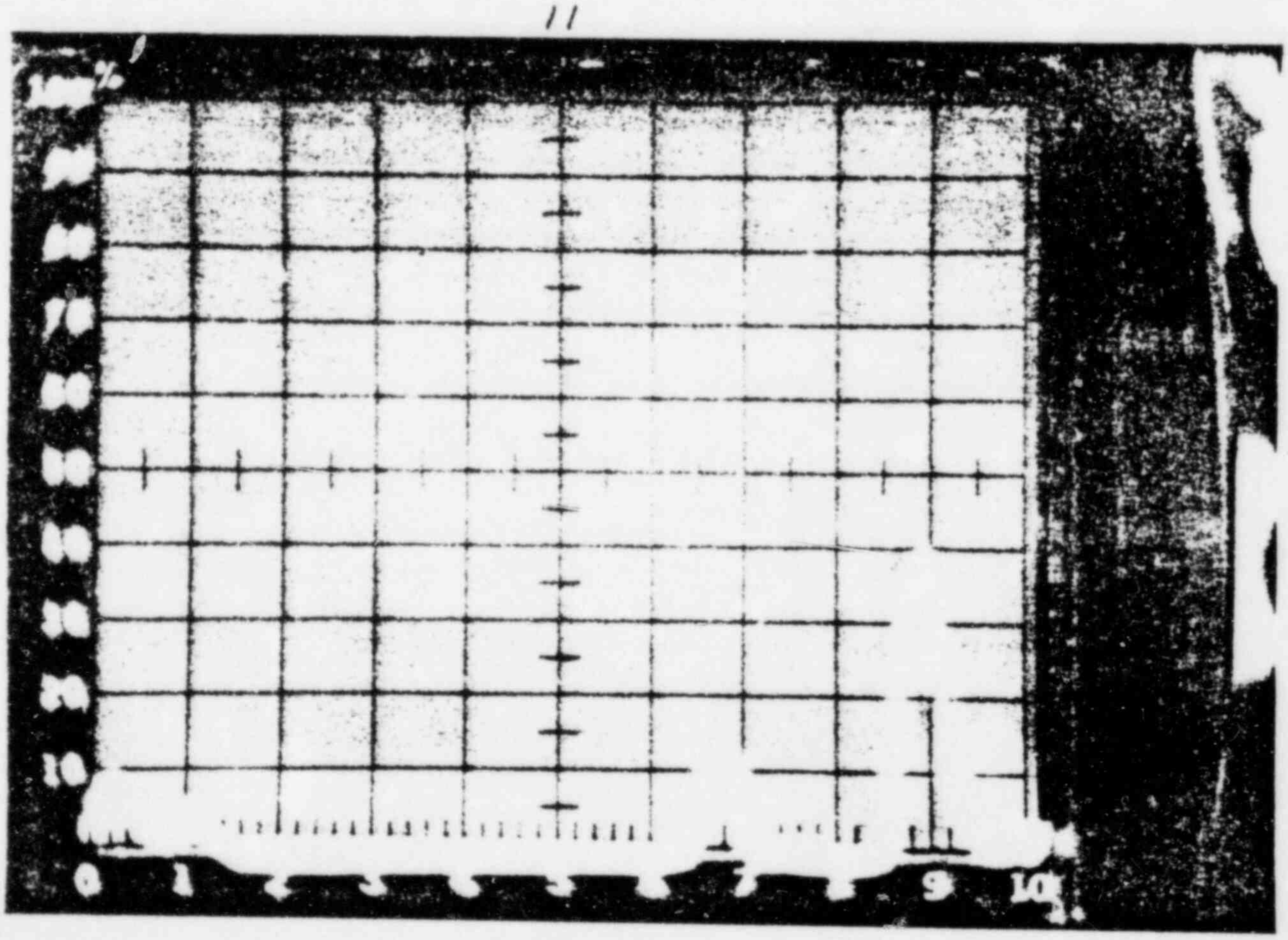
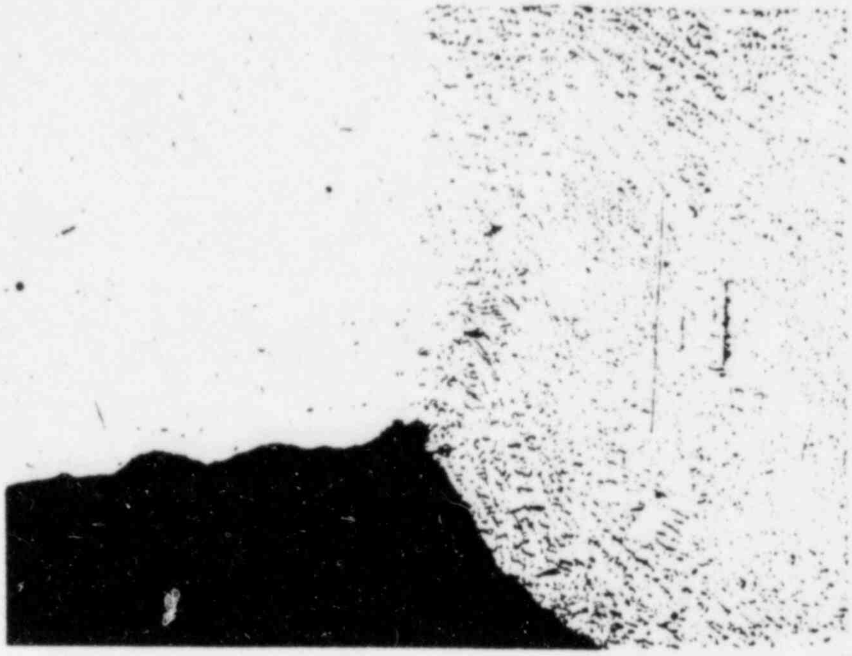


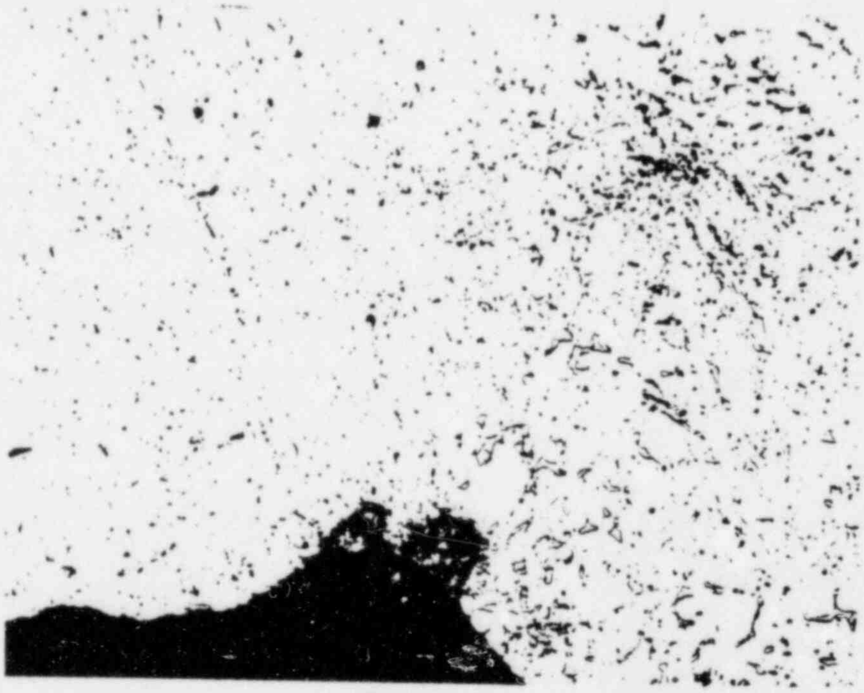
FIGURE 13

Indication 2 I 2

Joint geometry and UT screen presentation. Produced no clear p.t. indication on I.D.



Mag. 100X



Mag. 400X

FIGURE 14

2 I 2

No defects were found in this sample except for some weld geometry irregularities shown above.

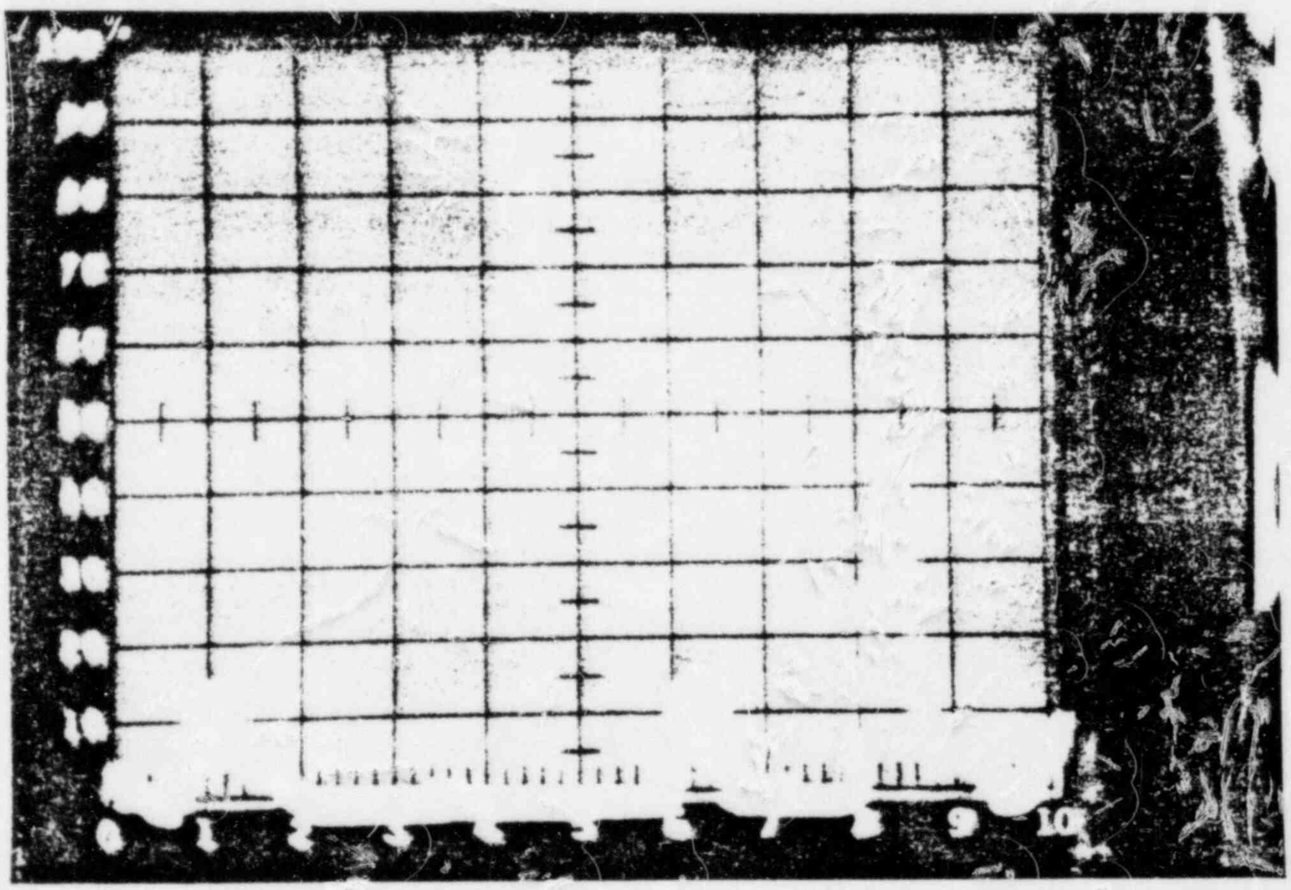
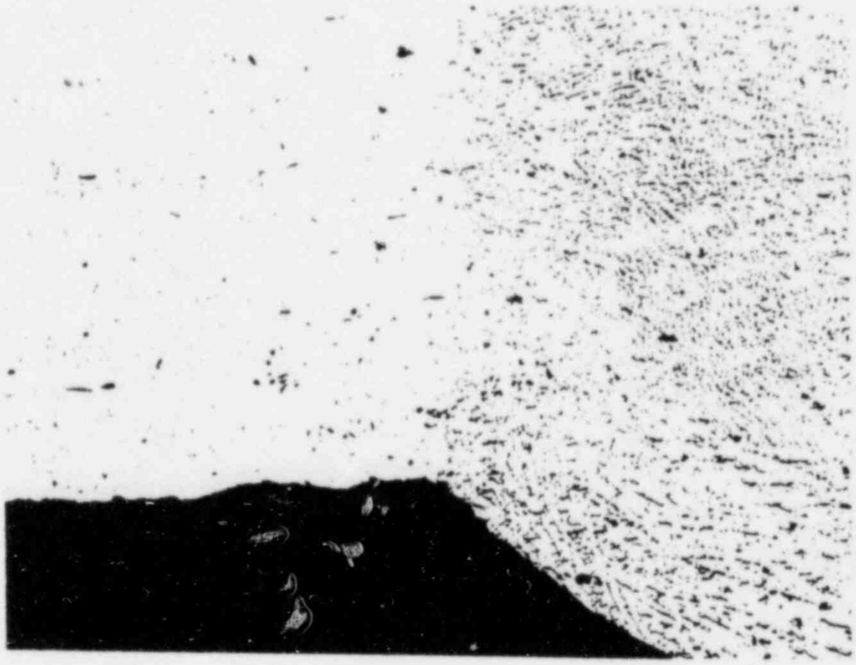


FIGURE 15

Indication 2 I 3

Joint geometry and UT screen presentation most likely produced by sharp change in joint geometry. No p.t. indication on I.D. surface.



Mag. 100X

FIGURE 16

2 I 3

No defects found on pipe or fitting side. Pipe side of joint is shown above.

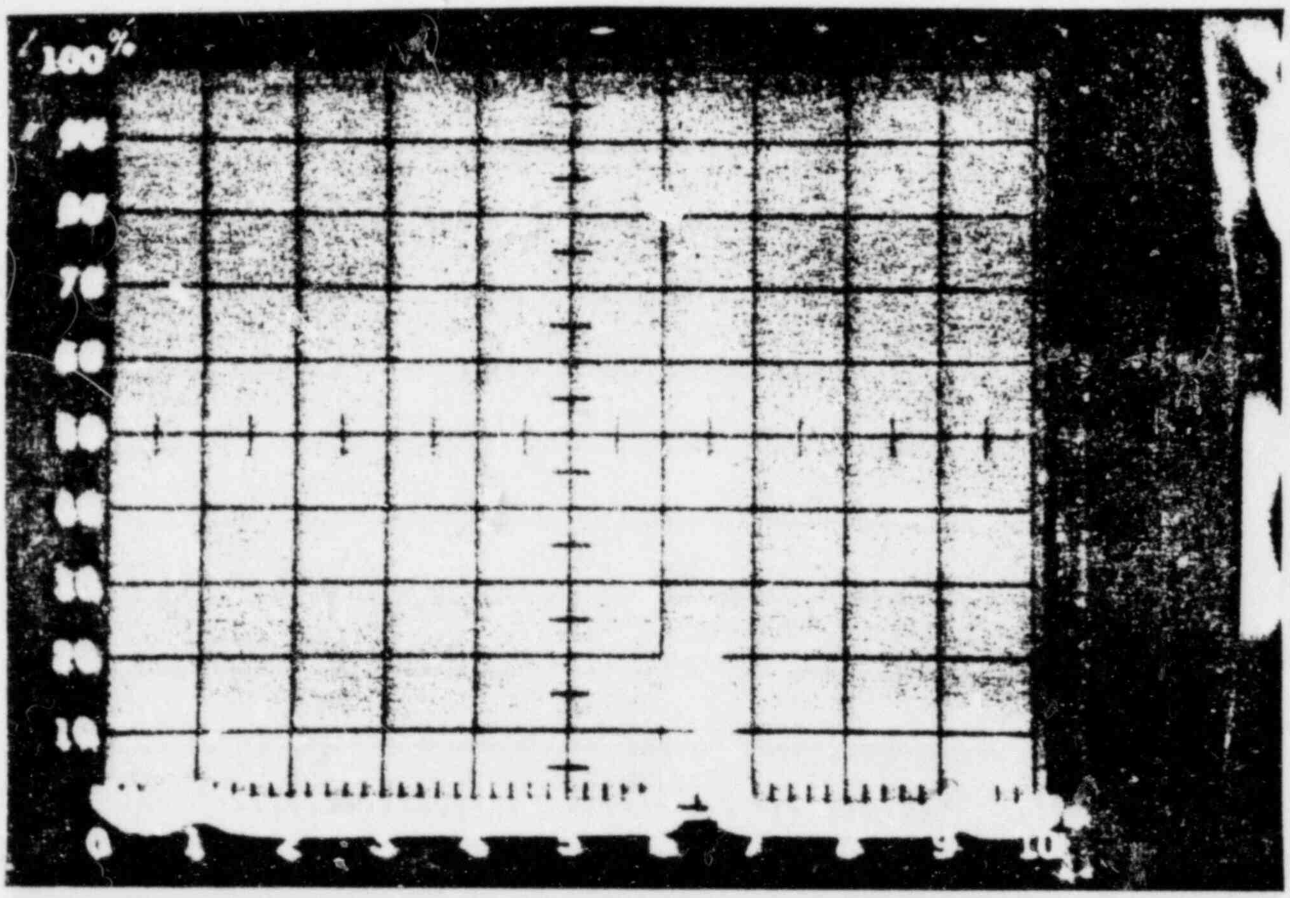
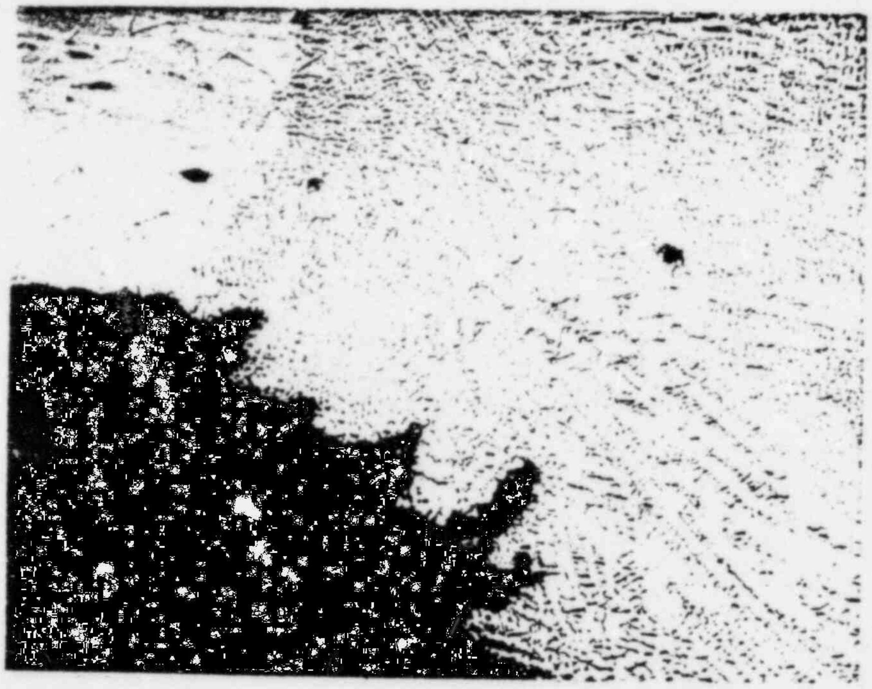


FIGURE 17

2 I 4

Joint geometry and UT screen presentation produced by weld irregularities at the root.



Mag. 100X

Mag. 400X

FIGURE 18

2 I 4

Weld root irregularities on pipe side of joint.

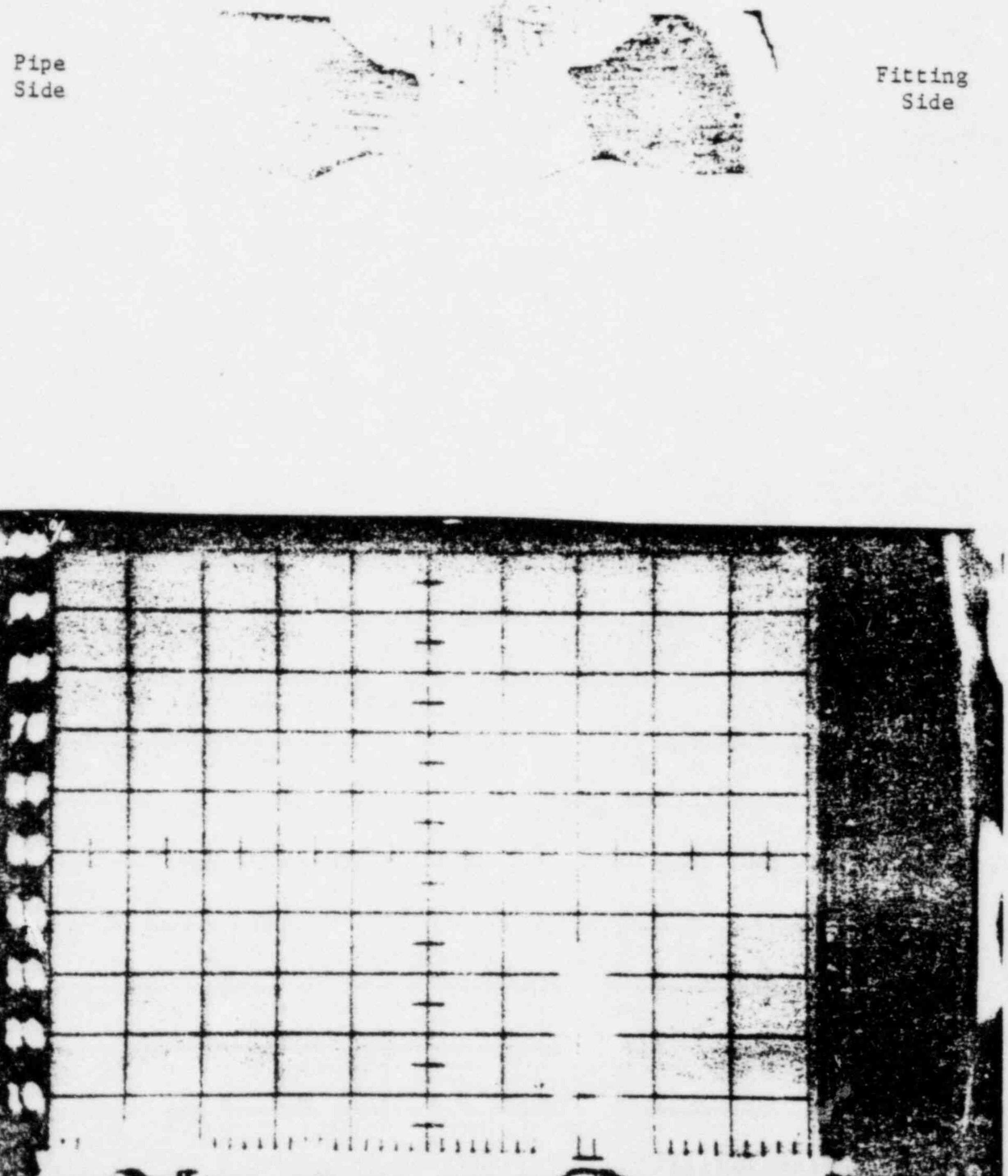


FIGURE 19

2 I 5

Joint geometry and UT screen presentation produced by rough counterbore surface. P.T. indications seen on fitting side.

Mag. 100X

Mag. 400X

FIGURE 20

2 I 5

No defects were found other than surface roughness in counterbore on fitting side shown above.

PIPE SECTION 3 (SF 12)

Heat Numbers:

Pipe Side: Ht. 334165
Fitting Side: Ht. 17616

Type of Weld:

Field

Description:

This sample contained four areas of definite intergranular cracking on the pipe side. Indication 4 had two small (≈1/8" long) parallel indications at an angle of approximately 45° to the weld bead with a depth of .045". Joint counterbore on the pipe side had a sharp transition angle which may have acted as a stress riser for crack initiation.

Location of Indications	Length	Depth
3 I 1 - pipe side	1 "	.043"
3 I 2 - pipe side	1.5"	.062"
3 I 3 - pipe side	2.5"	.110"
3 I 4 - pipe side	1/8"	.047"

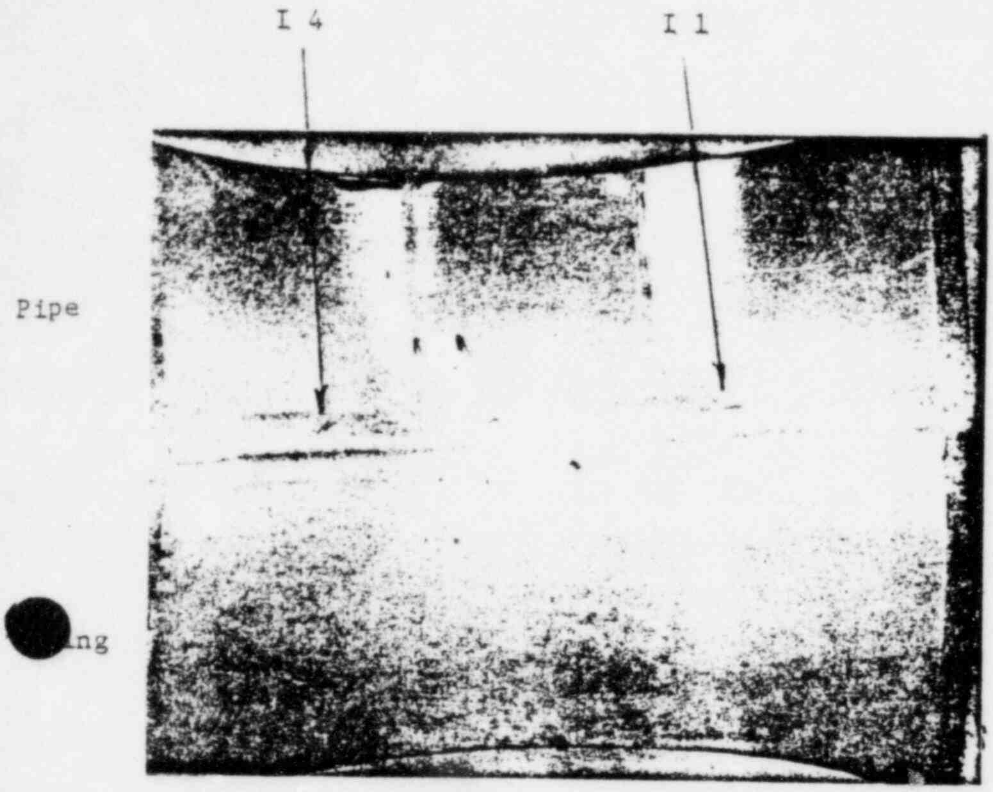


FIGURE 21

I.D. surface of Sample #3 showing Indications I 1 and I 4.

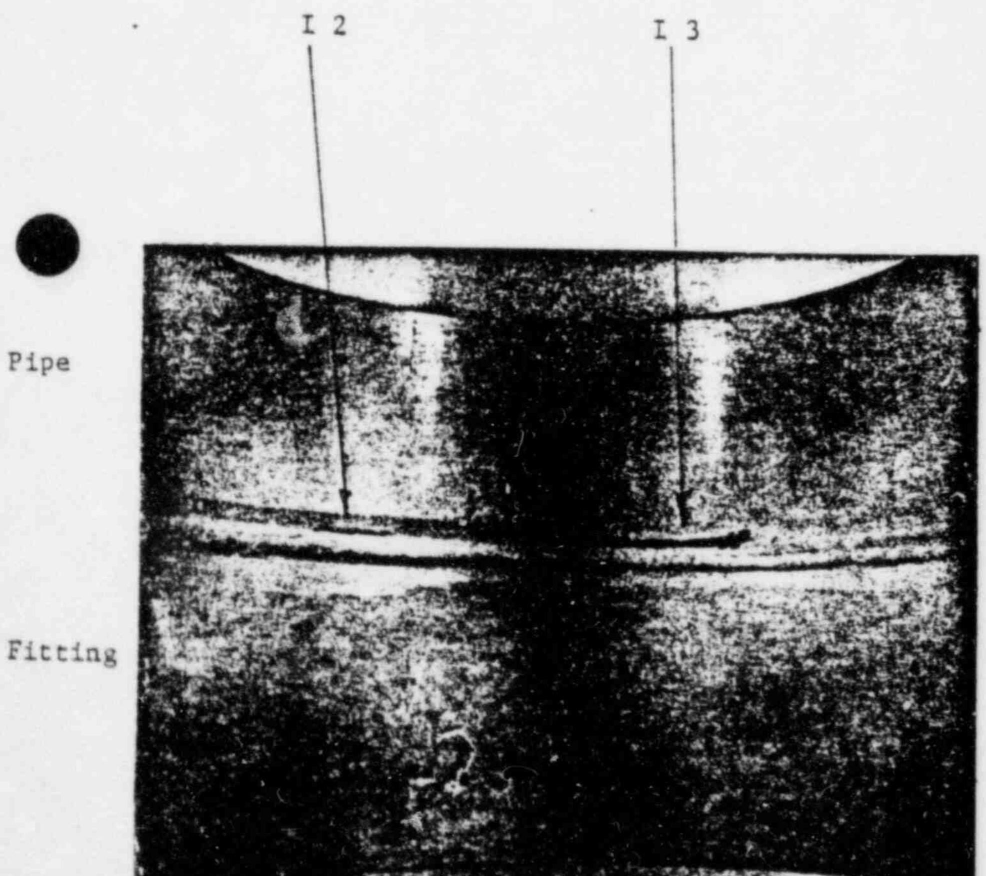


FIGURE 22

I.D. surface of Sample #3 showing Indications I 2 and I 3.

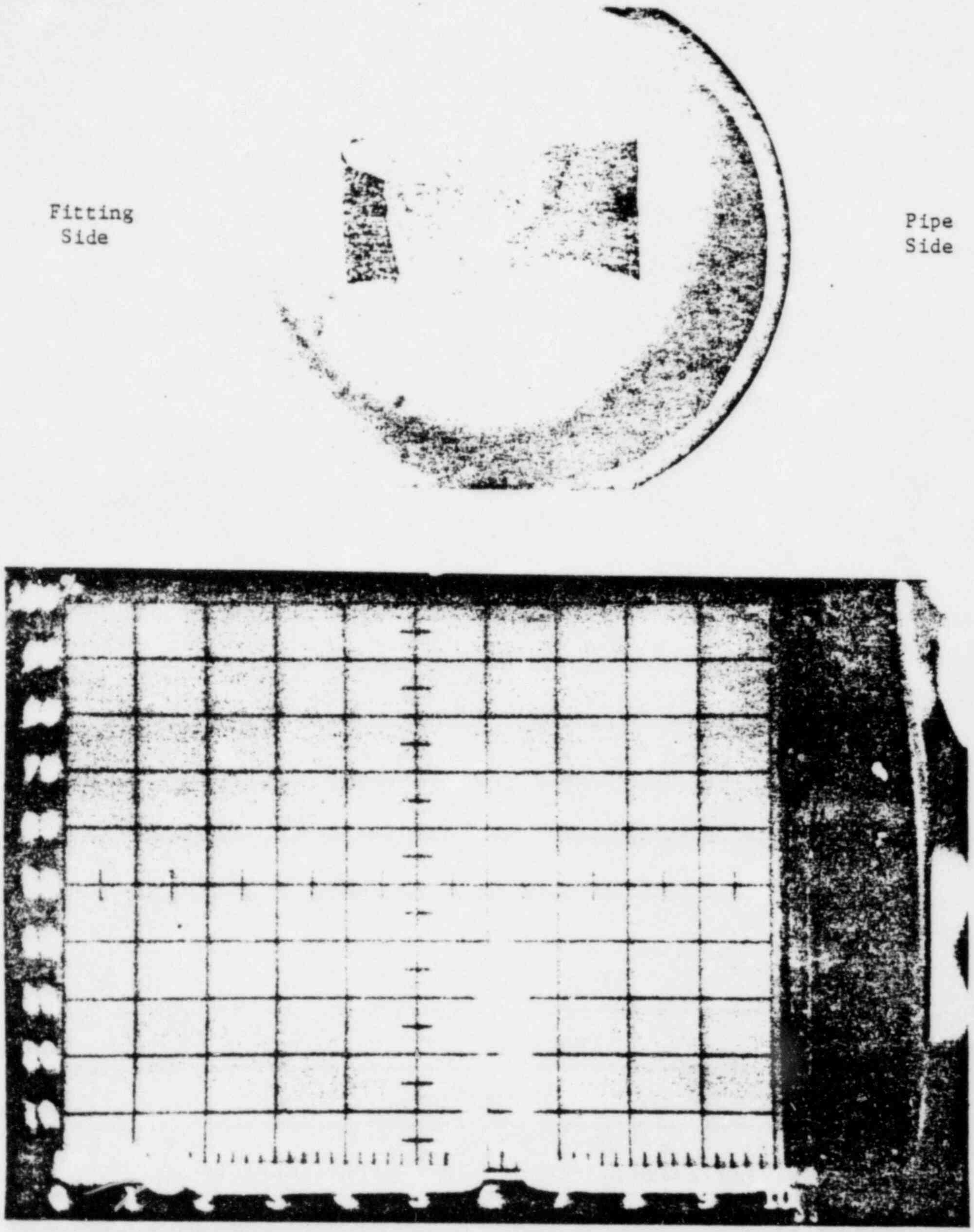
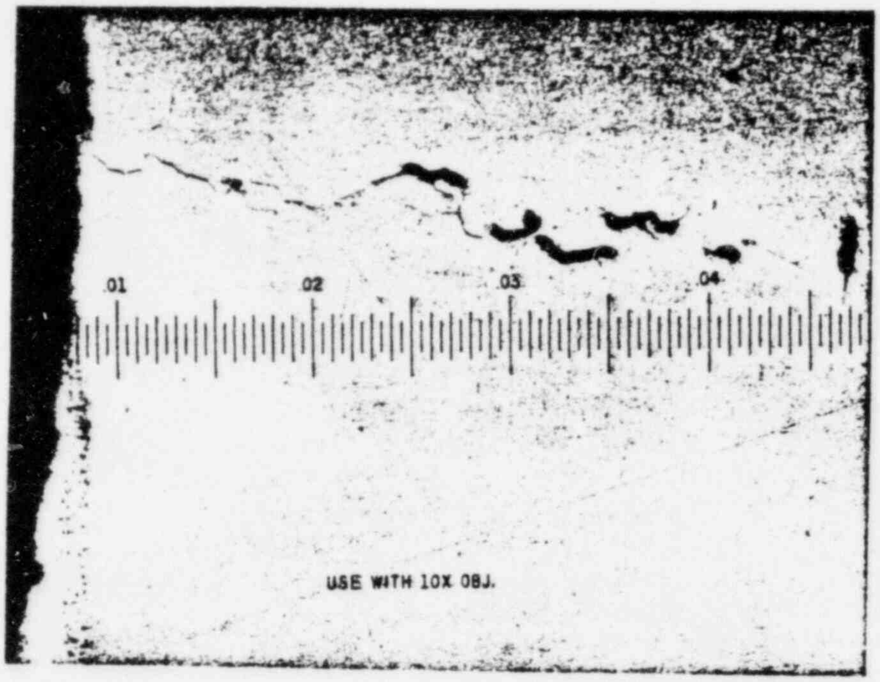


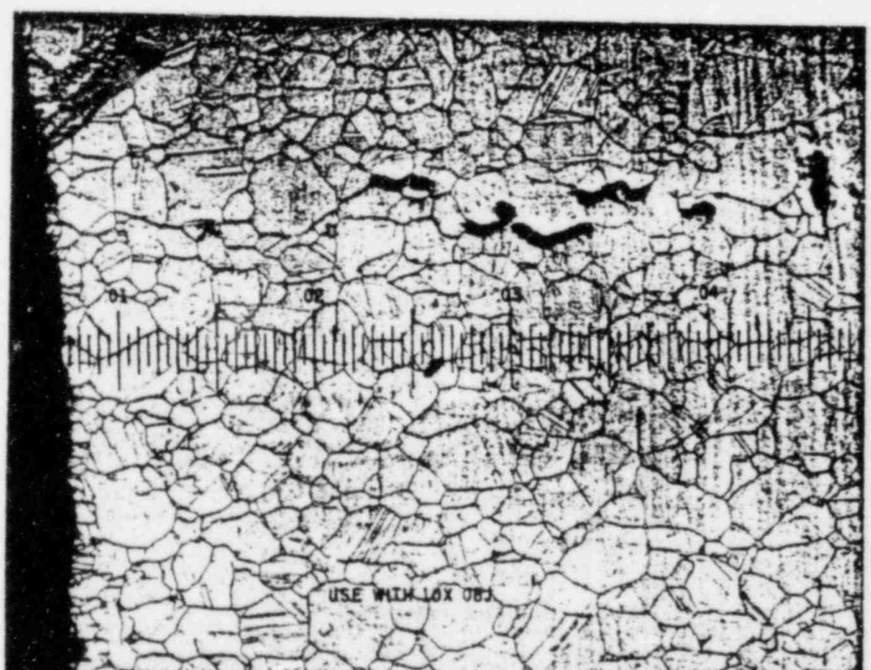
FIGURE 23

3 I 1

Joint geometry and UT screen presentation for crack on pipe side ≈.043" deep.



Mag. 100X



Mag. 100X

FIGURE 24

3 I 1

Intergranular crack .043" deep on pipe side.

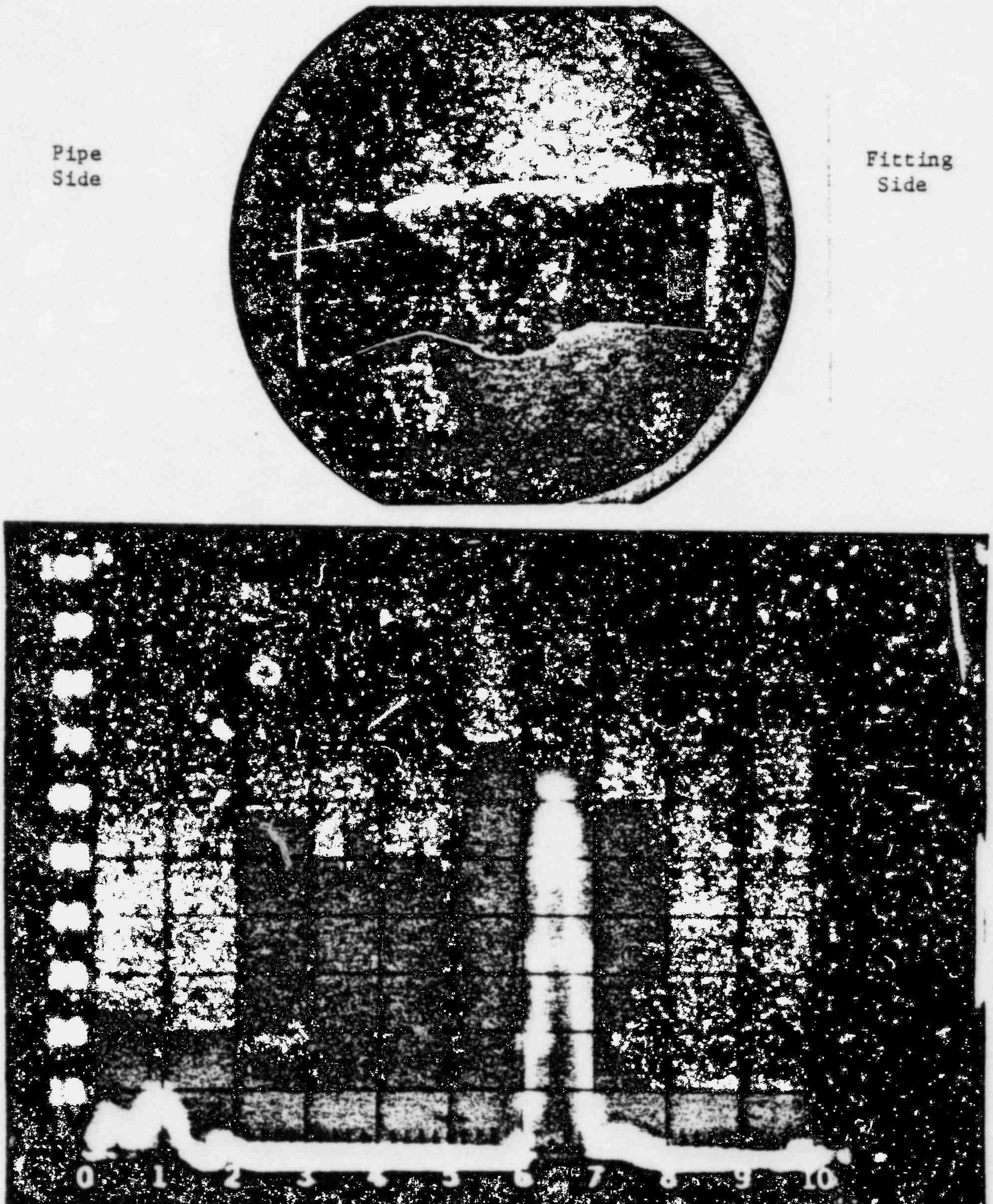
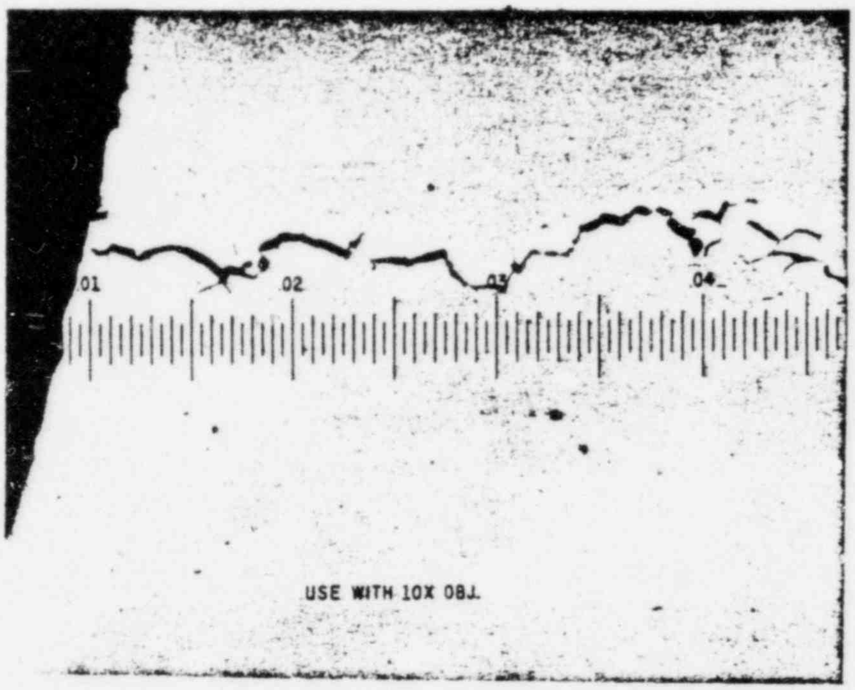


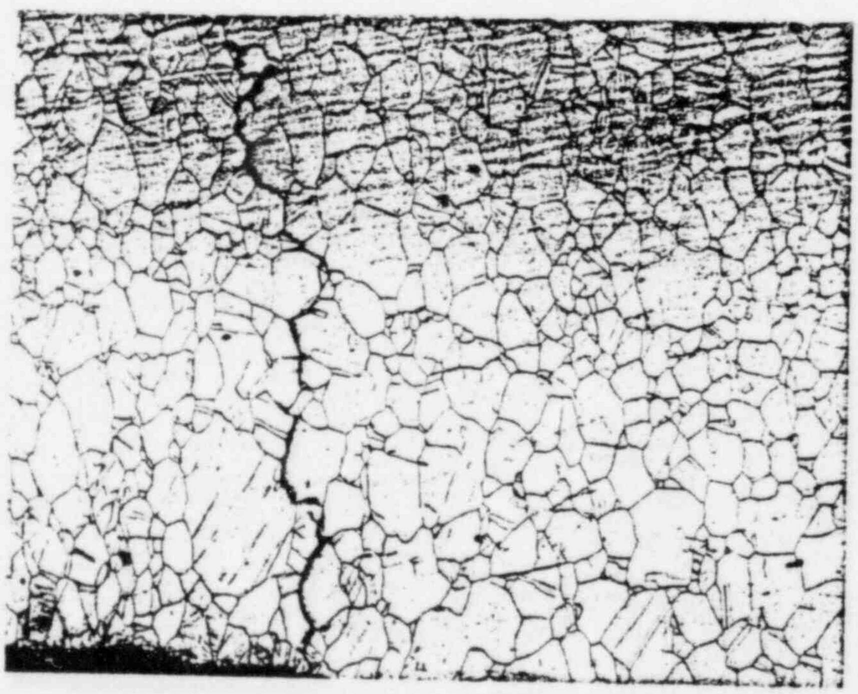
FIGURE 25

3 I 2

Joint geometry and UT screen presentation for .062" deep crack on pipe side. Note sharp angle on pipe side counterbore.



Mag. 100X



Mag. 100X

FIGURE 26

3 I 2

Photomicrographs showing intergranular crack on pipe side approximately .062" deep.

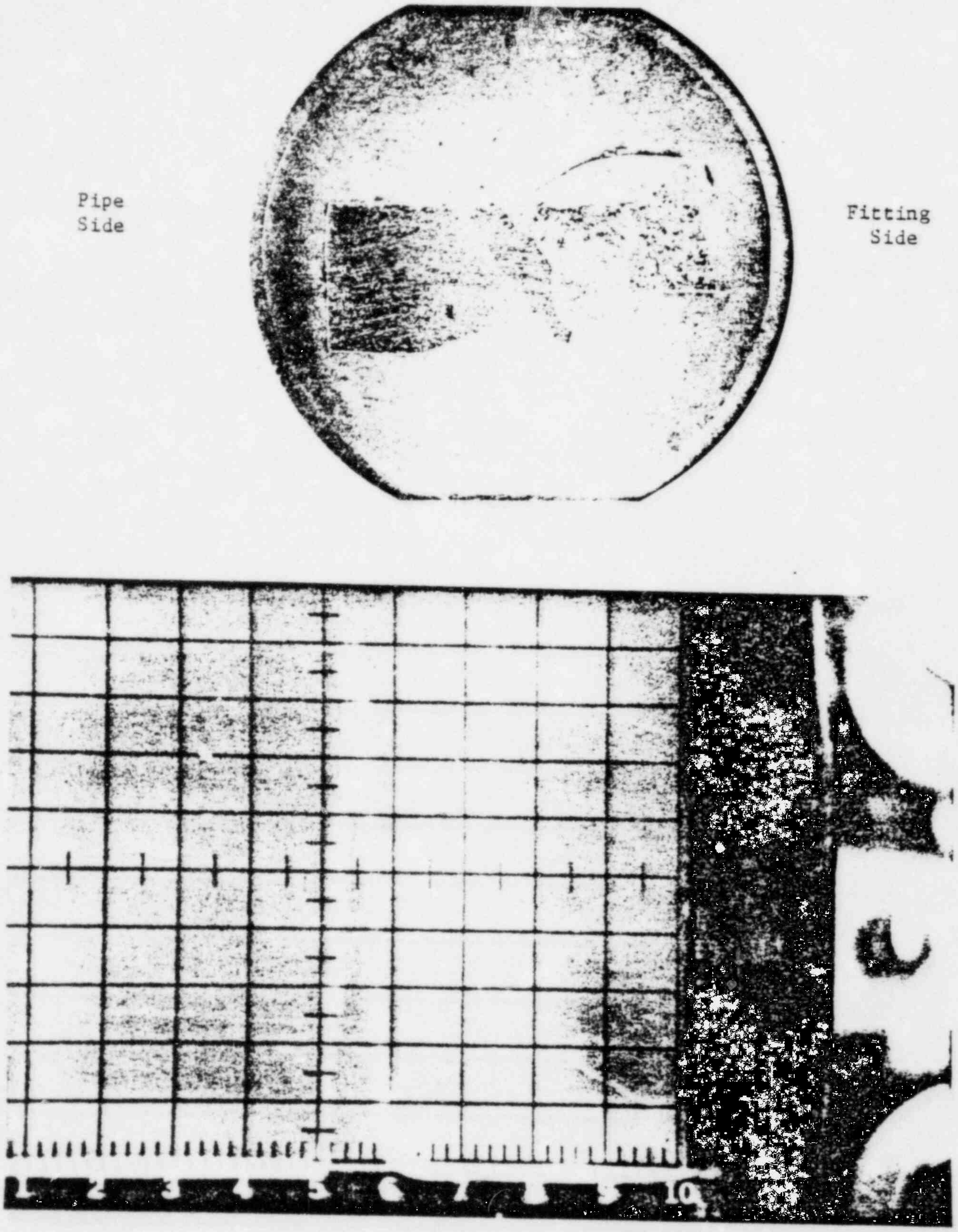
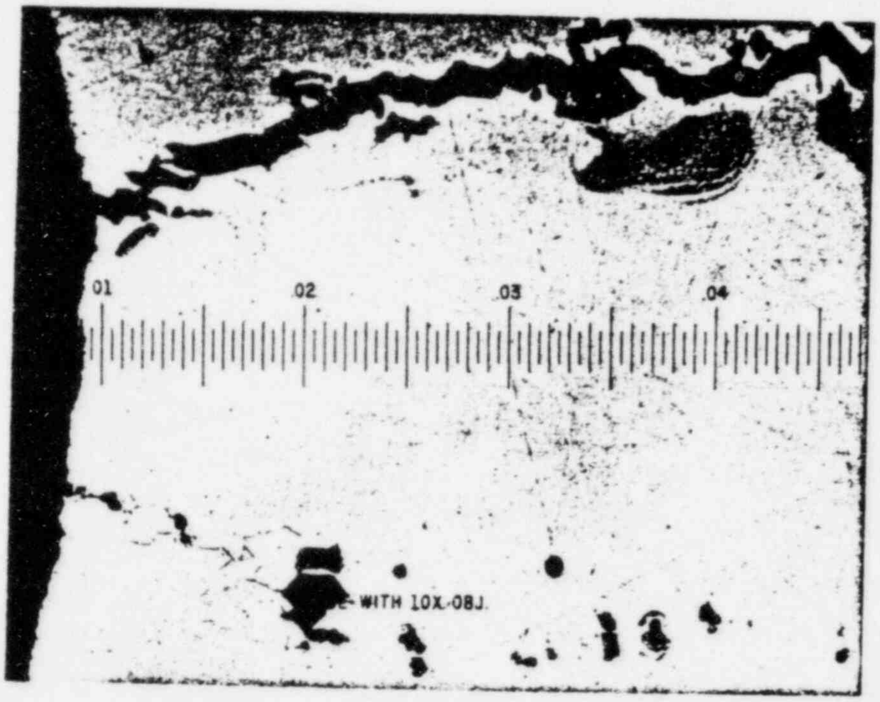


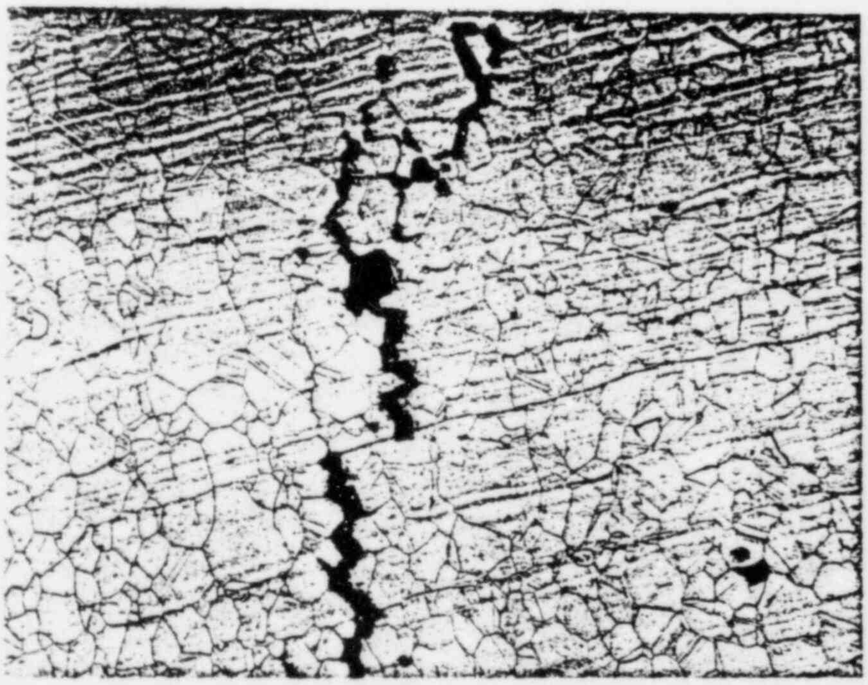
FIGURE 27

3 I 3

Joint geometry and UT screen presentation for deep crack on pipe side.



Mag. 100X



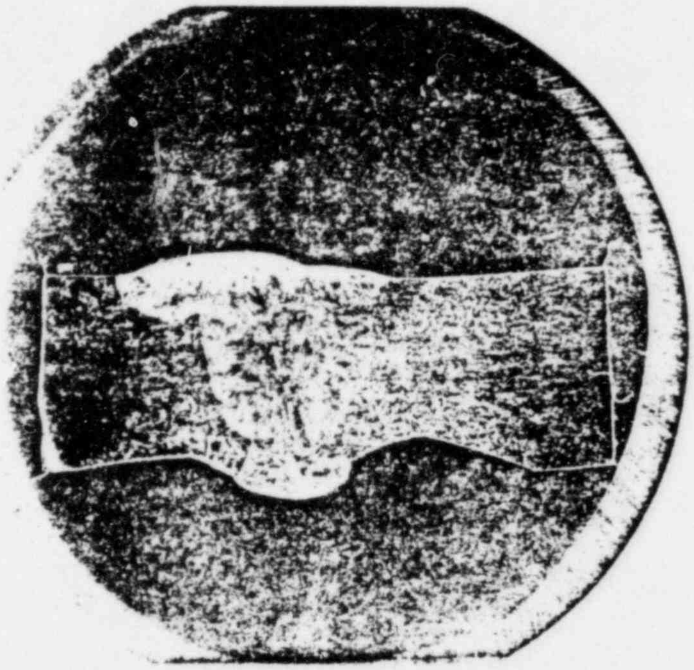
Mag. 100X

FIGURE 28

3 I 3

Photomicrographs showing intergranular crack on pipe side approximately .110" deep.

Fitting Side



Pipe Side

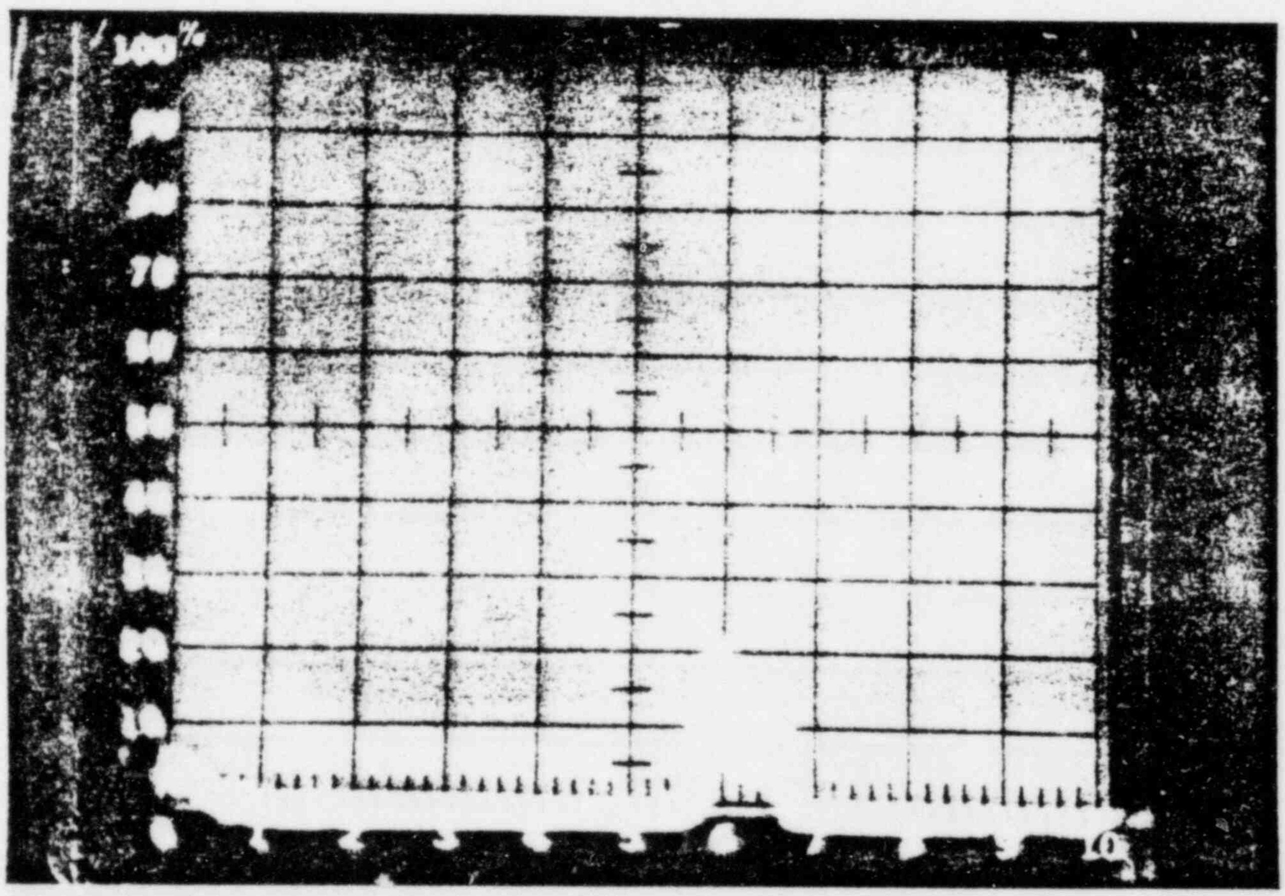
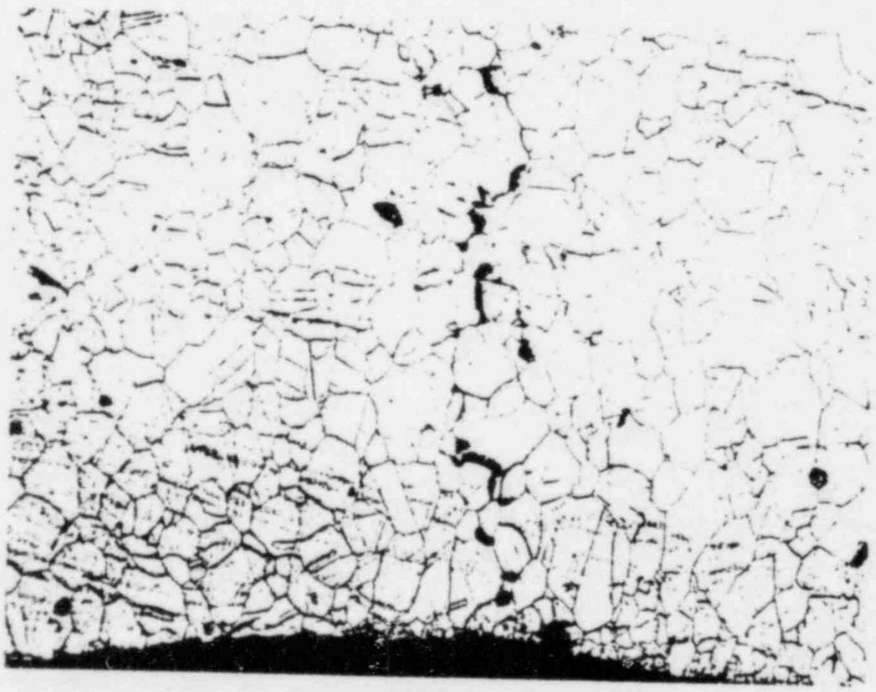


FIGURE 29

3 I 4

Joint geometry and UT screen presentation from .047" deep crack on pipe side. Double blip on screen is because two small cracks were adjacent to each other.

Mag. 100X



Mag. 100X

FIGURE 30

3 I 4

Photomicrographs of intergranular crack $\approx$.047" deep on pipe side.

PIPE SECTION 4 (SF 42B)

Heat Numbers

Pipe Side: Ht. 33416[illegible]
Fitting Side: Ht. 16462

Type of Weld:

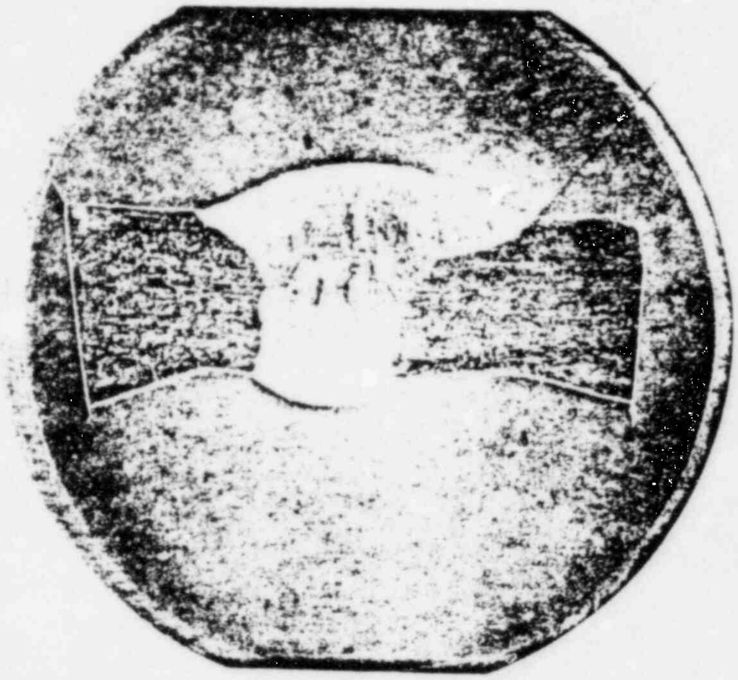
Field

Description:

This sample contained a single small linear indication on the pipe side. When the sample was liquid penetrant inspected on the I.D. it took 30 minutes to get a visual indication. This indication was identified by metallography as an intergranular crack approximately .010" deep.

Location of Indication:

	Length	Depth
4 I 1 - pipe side	3/32"	.010"



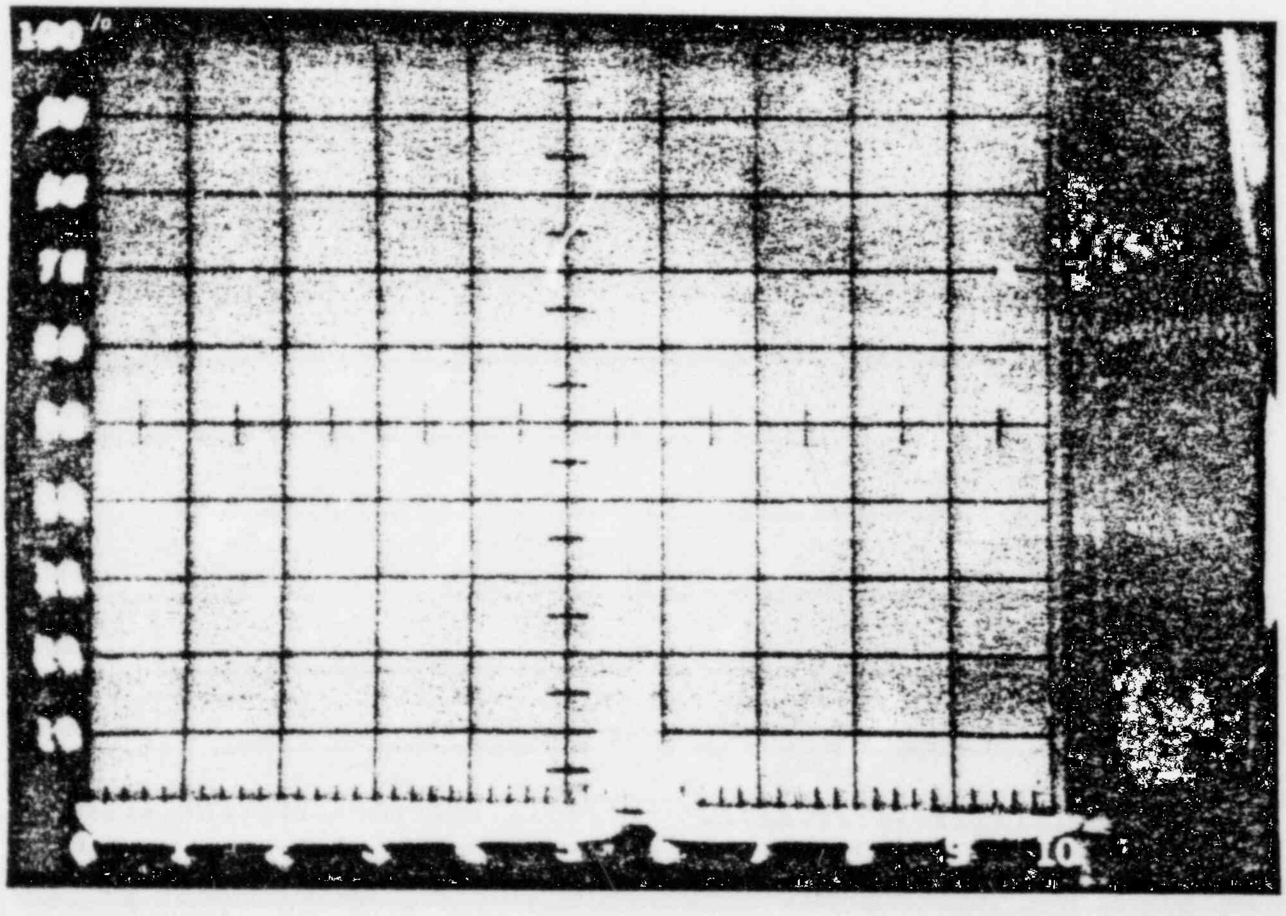
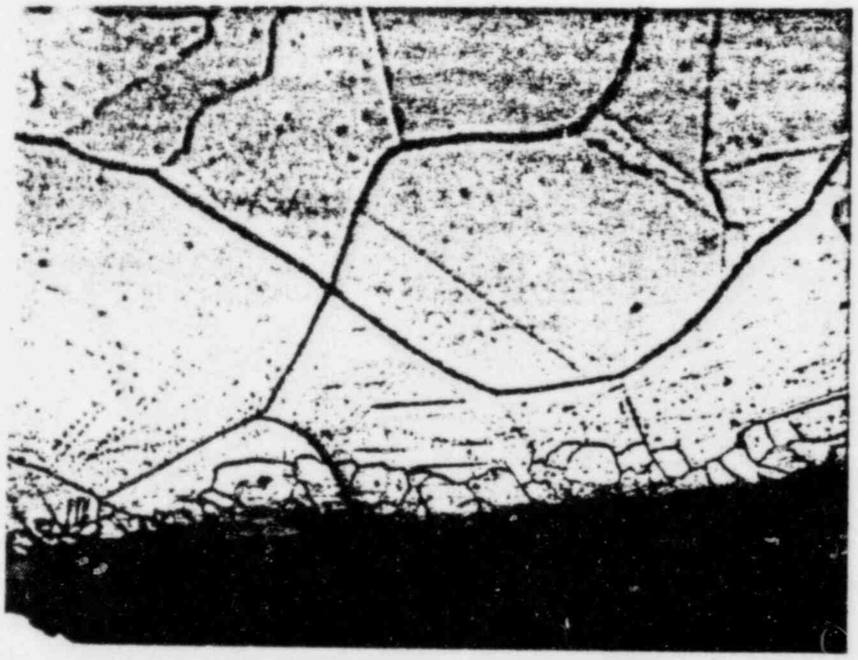


FIGURE 32

4 I 1

Joint geometry and UT screen presentation from ~.010" crack on pipe side.

Mag. 400X



Mag. 400X

FIGURE 33

4 I 1

Crack on pipe side having a depth of $\approx$.010".

Section 3: SUMMARY OF DATA

3.1 INTRODUCTION

Since the IGSCC of 304 stainless steel involves a complex interaction of environmental, stress and metallurgical parameters, any effort to evaluate the contribution of various parameters affecting IGSCC in borated water systems would be useful in understanding the overall problem and provide a basis for a surveillance program. Therefore, an analysis of the material and system parameters was undertaken to meet these objectives. The data analysis only serves to identify significant trends as they relate to the IGSCC problem and not to define the IGSCC mechanism. However, the data analysis coupled with the laboratory studies should provide a fairly comprehensive understanding of IGSCC in borated water systems at TMI-1 and provide direction as to what remedial measures should be undertaken to minimize or alleviate this problem.

The data generated by the UT inspection and screening of heat-affected zones in the TMI-1 Spent Fuel, Decay Heat, Building Spray, Make-up, Core Flood, and Pressurizer Spray/Surge Systems is analyzed for the following parameters:

1) Heat number and chemistry
2) Shop vs. field weld
3) Welder
4) System environmental conditions

This data is summarized and the analysis is presented in the applicable sections that follow. The analysis centers on indications that have been verified by UT screening and on through-wall leakers confirmed to be IGSCC. Statistical techniques are employed to determine if any

particular heat number, welder, type of weld, etc. occurs in the group of confirmed indications and leakers at a significantly more frequent rate than it does in the overall general population of heat-affected zones examined. It must be emphasized, however, that since most of the indications verified by UT screening might prove to be weld defects or geometry effects and not IGSCC, the data base and consequently the following analyses are subject to change. Therefore, the following analyses can only be considered as preliminary, pending complete verification of all indications as IGSCC by radiographic and/or metallographic examination.

3.2 DATA ANALYSIS

3.2.1 Results of UT Inspection

Results of the UT inspection are summarized in Table 3-1. UT indications are indications found using the 5 MHz transducer with a 50° angle, while the screened indications are indications found using the 2.25 MHz transducer with a 60° angle. Procedures and evaluation criteria for these two techniques have been presented in a previous section (Section One), and hence no further discussion is required. In the makeup system, 354 2-1/2" diameter pipe welds were not inspected due to high radiation and because results of a statistical analysis of previously inspected 2-1/2" makeup welds indicated no further inspection was required (Appendix). The data clearly shows the screened indications appear almost exclusively in the spent fuel, decay heat and building spray systems at similar frequencies.

The pertinent parameters associatd with each of the screened indications are depicted in Table 3.2. There are seven weld joints with through

The results of this analysis as reflected by the Column G probabilities show three heat numbers with significantly low probabilities, less than 1%. This means that these three heat numbers - 334165, 48428, and 334469 - occur in the group of indications and leakers at a much greater frequency than would be expected. Two of the heat numbers, 334165 and 334469, are Allegheny-Ludlum heats, pipe-fabricated and heat-treated at Youngstown Welding & Engineering, with carbon contents of .079 and .064 respectively as reported on the mill certifications. The third heat number, 48428, was supplied by Pipeco with a carbon content of .065%. This heat number, 48428, shows indications in the only two welds in which it was used. These welds are adjacent welds made by the same welder, so it is conceivable that factors other than heat number are in effect. Future surveillance should concentrate on welds involving the heat numbers 334165 and 334469. Heat number 48428 will require no further surveillance because only two welds in which it occurs show indications and will be handled within the repair program.

Other heat numbers with relatively low probabilities, less than 10%, as reflected by Table 3-3, Column G are: 18921, 31860, 32561, 18918, 19984, 48958 and 2P1910. All of these heat numbers show only one indication but have low Poisson probabilities for indications because they occur infrequently in the overall system population of heat-affected zones as shown in Column C. Again, other factors may be at work here, but future surveillance should include welds with these heat numbers. Carbon contents for these heat numbers, which include both fittings and pipe, range from .051% to .062%.

While heat number 334164 does not have the low Poisson probability cited for the heats described above, one must be cognizant of the fact it is the only other heat, besides 334165, that has experienced a thru-wall leak. It also has a carbon level above .07%. Therefore, the heat should be monitored in some fashion.

The remaining heat numbers do not occur in the group of indications/leaks at a significantly more frequent rate than in the overall system population of heat-affected zones.

An analysis of the carbon content of heats exhibiting screened indications/leaks was made. Carbon contents were categorized into ranges of .040-.049%, .050-.059%, .060-.069% and .070-.079% and the frequency of screened indications/leaks in pipe in spent fuel, decay heat and building spray systems was computed for each carbon range. These computations are summarized and depicted graphically in Figure 3-1. While there is not a strong functional relationship between frequency and carbon content, the histogram (Figure 3-1) clearly illustrates that the frequency of screened indications/leaks undergoes a marked increase as the carbon content exceeds .06%.

The Poisson probability analysis for the various levels of carbon is summarized in Table 3-4. It also indicates that higher carbon heats, namely .06%C, have screened indications/leaks occurring at a greater frequency than would be expected in comparison to heats with carbon levels below .06%. However, the analysis also shows that carbon content <u>alone</u> is not as significant a parameter as other factors under examination such as heat number. This is easily understood by the fact

wall penetrations, six in spent fuel and one in the decay heat system. Of the forty-two (42) screened indications/leaks, thirty-five (35) are field welds. Furthermore, of the thirty-five (35) field welds showing indications/leaks, thirteen (13) are repairs. All but four weld joints have the screened indication/leak in the HAZ of the pipe. Indications/leaks are present in pipe having a nominal size of 4, 6, 8, 10, 14 and 24 inches. All pipe is schedule 40, except the 24" pipe which is schedule 20. The detailed data analysis and the significance of various system and material parameters are presented in the following sections.

3.2.2 Analysis of UT Screened Indications and Leakers for Heat Number Trends

Initially, it must be noted that the analysis of the heat number data is limited by the relatively small number (42) of UT screened indications and leakers when compared to the overall number of heat-affected zones examined (approximately 4000). The method employed in this analysis is one of determining whether any one heat number occurs in the group of indications and leakers at a significantly more frequent rate than it does in the overall general population of heat-affected zones examined. As an example, a heat number occurs with a certain frequency, 10%, in the overall population of heat-affected zones. Therefore, one would expect that heat number to occur at nearly the same frequency, 10%, in the group of indications and leakers if random chance were the only factor. If that heat number occurs with a much greater frequency than 10% in the group of indications and leakers, then one could assume that factors other than random chance are in operation, and further investigation and surveillance are required.

Table 3-3 summarizes the heat number data connected with this analysis. Column A lists those heat numbers of the heat-affected zones with UT indications or leakers. Column B shows those systems in which the heat numbers occur. The Decay Heat and Building Spray systems are combined for this analysis because of overlap and extensive common piping. Column C tabulates the number of times each heat number occurs in the respective overall piping system. Column D represents the frequency with which each heat number occurs in the overall system population (e.g. heat number 2P1906 occurs in 6.9% of all the heat-affected zones in Spent Fuel). Postulating random chance as the only factor involved, Column E represents by system the expected number of indications or leakers for each heat number. To arrive at the numbers in Column E, one multiplies the frequency in Column D by the total number of indications or leakers actually found in each system, 23 in Spent Fuel and 21 in Decay Heat/Building Spray (e.g. again for 2P1906, 6.9% x 22 = 1.5 expected indications). Column F tabulates the actual number of indications or leakers by heat number. The Poisson probability model is used to compare Column E and Column F to arrive at the appropriate probability. Column G shows this Poisson probability, which is the probability of having the actual number of indications shown in Column F, when one expects the number of indications shown in Column E.

The Poisson model is commonly used to compare actual number of defects to expected number of defects for discrete, random variables. The application of the Poisson model to this analysis stretches the definition of random variable, in that each weld is not strictly an independent event. However, for purposes of general trending, the Poisson model is the most suitable probability model available.

that the propensity for IGSCC is directly related to degree of sensitization which incorporates carbon content, welding parameters and manufacturing variables. Therefore, the heat number, which would include all these factors, should exhibit a much greater degree of significance than one parameter such as a carbon content.

A list of welds with confirmed IGSCC is presented in Table 3-5. Significant emphasis must be placed on this information since it represents the only concrete evidence of IGSCC in the borated water systems at TMI. The data clearly substantiates the data analysis of surveying heat number 334165. Furthermore, it supports the fact that the high carbon heats are the most susceptible to IGSCC primarily due to the high degree of sensitization and must be carefully monitored.

3.2.3 Analysis of UT Screened Indications and Leakers for Shop vs. Field Weld Trends

The 42 UT screened indications and confirmed leakers were analyzed for disparities in the number of shop welds vs. the number of field welds. Table 3-6 summarizes the data associated with this analysis, which deals only with the three systems - Spent Fuel, Building Spray, and Decay Heat - with confirmed indications and leakers. Based on the overall percentage of welds in the above three systems that are shop welds, one would expect that of the 42 indications and leakers, 25 would be shop welds (42 x 59% = 25). Similarly, one would expect that of the 42 indications and leakers, 17 would be field welds. It can be seen from Table 3-6 that the number of actual indications and leakers that are field welds is twice the number expected. Using the Poisson model to estimate the probability of this occurring, one arrives at a 0.0% probability. It is therefore totally unlikely that when only 17

indications are expected to be field welds, random chance would be the only factor in 34 actual indications being field welds. Furthermore, of the 35 field welds showing screened indications or leakers, 13 are repairs, for a ratio of 35%. This is greater than the proportion of repaired field welds to overall field welds in the general population. In summary, field welds and particularly repaired field welds show a significantly greater propensity to yield a screened UT indication or leaker that cannot be attributed to random chance. This propensity can be viewed as a function of inadequate heat input control during the field welding process, resulting in a greater degree of sensitization of the pipe or fitting in the heat-affected zone. Further surveillance should concentrate on field welds, especially repaired field welds.

3.2.4 Analysis of UT Screened Indications and Leakers for Welder Trends

The group of UT screened indications and confirmed leakers was analyzed for trends involving welders. Only field weld data was analyzed because of the results in Section 2.3 above which show an extremely low number of shop welds with indications or leakers, prohibiting meaningful data analysis of the shop welders involved. Again, only Spent Fuel, Building Spray, and Decay Heat systems are involved, with Building Spray and Decay Heat combined because of extensive common piping.

Table 3-7 summarizes the analysis associated with field welders showing indications or leakers in the affected systems. The same method and Poisson probability model are used as in previous sections.

The resulting Poisson probabilities show one welder with a significantly low probability. Welder 9R shows an expected number of 4.4

indications and an actual number of 11 indications. The probability of this occurring by random chance is 0.6%. Future surveillance should concentrate on welds done by welder 9R.

Other welders with relatively low probabilities are 21U, 14B, 2S, 6K and 20K. Welds done by these welders also warrant future surveillance.

3.2.5 Environmental Factors

Figures 3-2 to 3-5 depict the location of each UT indication/leak in each of the borated water systems. An assessment of flow conditions was made for each indication/leak to establish its relationship to cracking propensity. While some indications occur in continuous flowing lines during normal operation, a review of the history of operating procedures indicates these lines were exposed to stagnant borated water for an extended period of time. UT indications/leaks occur in lines having varying degrees of stagnation which include monthly flow to virtually completely stagnant conditions. There are no UT indications/leaks in continuous flowing lines which does indicate some stagnation is required. However, the time to initiate cracking is dependent upon local chemistry, residual stress patterns, surface conditions and degree of sensitization. Therefore, it is conceivable that varying degrees of stagnation are consistent with the cracking mechanism considering all the factors affecting crack initiation.

In an effort to better define the aqueous environment causing IGSCC, samples of borated water were collected for analysis. Sample points were selected so bulk solution samples representative of the environment in the vicinity of each UT indication/leak were secured. Results of the chemical analyses of these samples are summarized in Table 3-8.

The data shows that the UT indications/leaks have occurred in borated water with relatively high oxygen levels (>200 ppb). Furthermore, there is no particular contaminants present such as chlorides or fluorides, which seems to be required for IGSCC to occur in borated water. The level of sulfur in two samples was also found to be below 1 ppm. However, one must remember that the bulk solution chemistry does not necessarily represent local chemistry conditions, so one must not view this solution chemistry as the IGSCC environment. More work is needed to determine local chemistry conditions thus defining the environment causing IGSCC.

3.3 CONCLUSIONS

1. An analysis of heat numbers conclusively indicates that certain heats show a greater frequency of UT indications/leaks than other heats. These heats are 334165, 334469 and 48428. Consideration of all pertinent data indicates future surveillance should concentrate on heats 334165, 334469 and 334164.
2. Analysis of heat chemistries shows there is greater tendency to exhibit IGSCC with increasing carbon content, particularly at levels above .06%C. In fact, if one examines only welds with confirmed cracks, it is evident that susceptible material is severely sensitized and carbon contents are greater than .07%.
3. The data clearly shows that field welds are highly suspect, particularly, field welds that have been repaired. Again, this is consistent with the degree of sensitization of the pipe HAZ and its relationship to the increased susceptibility to IGSCC.

Therefore, further surveillance should concentrate on field welds, especially repaired field welds.

4. Analysis of welder trends concludes that welds done by welder 9R should be monitored while welds made by welders 21U, 14B, 2S, 6K and 20K also warrant some sort of future surveillance.

5. Most UT indications/leaks have occurred in the pipe HAZ rather than the fitting HAZ. Efforts should be made to determine whether any cracking has occurred in fittings since this would impact future surveillance of welds. Intuitively, almost all emphasis should be placed on the pipe HAZ.

6. Examination of the flow conditions and chemistry of the borated water systems associated with the IGSCC problem did not produce conclusive evidence about the environment. Generally, UT indications/leaks were found in aerated (2.75-6.00 ppm O_2) borated water having varying degrees of stagnation. Sampling and chemical analysis of the bulk solution did not reveal the presence of any contaminants, which, at the present time are required to be consistent with laboratory work. More work is required to define local chemistry conditions in an effort to determine the IGSCC environment.

TABLE 3-1: RESULTS OF UT INSPECTION

System	Total Welds	Welds Inspected	UT Indications	Screened Indications Leaks	% Screened Indications
Spent Fuel	566	566	149	22	3.7
Decay Heat	408	408	104	11	2.7
Building Spray	241	241	64	8	3.3
Make-Up	1051	697	96	1	.14
Core Flood	31	31	0	0	0
Reactor Coolant Surge	11	11	0	0	0
Reactor Coolant Spray	28	28	1	0	0

TABLE 3-2: SUMMARY OF INDICATIONS

UT No.	Spool No.	Weld No.	Welder	Shop/Field	Location	Pipe Size, in.	Heat Number	%C
SF13	SF75/77	SF75	2L	Field	Pipeside Leaker	8 Sch. 40	334165(P) 16462	.079 .040
SF14	SF76/77	SF76	2L	Field	Pipeside Leaker	8	334165(P) 16462	.079 .040
SF22	SF29	SFV18Q	3C	Field	Pipeside Leaker	8	334165(P) SF-V-18	.079 -
SF35	SF29	SF29	3C	Field	Pipeside Leaker	8	334165(P) SF-V-17	.079 -
SF95	SF60/63	SF63Q	2L	Field	Pipeside	8	334165(P) 17617	.079 .062
SF100	SF60	SF60B	W145/W262	Shop	Fitting side	8	16462 334165(P)	.040 .079
SF103	SF67	SF67B	9R	Field	Pipeside-Both	8	48428(P) 334165(P)	.065 .079
SF104	SF62/67	SF67Q	9R	Field	Pipeside	8	48428(P) 17617	.065 .062
SF132	SF89	SF89AR	9R	Field-Repair	Pipeside	8	334165(P) Flange	.079 -
SF156	SF91/92	SF91	2L	Field	Pipeside	8	334165(P) 16462	.079 .040
SF176	SF86	SF86A	2L	Field	Fitting side	8	17617 48958(P)	.062 .062
SF182	SF92	SF92AR1	9R	Field-Repair	Pipeside	8	334165(P) 17616	.079 .062

TABLE 3-2: SUMMARY OF INDICATIONS - (Cont'd)

UT No.	Spool No.	Weld No.	Welder	Shop/Field	Location	Pipe Size, in.	Heat Number	%C
SF189	SF82	SFV9	9R	Field	Pipeside	8	334165(P) SF-V9	.079 -
SF195	SF80	SF80	9R	Field	Pipeside	8	334165(P) 17616	.079 .062
SF198	SF79	SF79	9R	Field	Pipeside	8	334165(P) 17616	.079 .062
SF210	SF26	SF26A	20K	Field	Pipeside Leaker	8	334165(P) 17616	.079 .062
SF214	SF24	SF24	9R	Field	Pipeside	8	334165(P) 17616	.079 .062
SF300	SF111/112	SF111R1	9R	Field-Repair	Fitting side Tee	8 Sch. 40	16164(T) 16711	.047 .050
SF331	SF144	SF144C	W81	Shop	Pipeside	4 Sch. 40	2P1906(P) 17688	.054
SF501	SF101/102	SF101R1	9R	Field-Repair	Pipeside	8	334165(P) 17616	.079 .062
SF265	SF29	SF30R2	3C	Field-Repair	Pipeside Leaker	8 Sch. 40	334165(P) 334165(P)	.079 .079
SF503	SF102	SF102AR1	6K	Field-Repair	Pipeside	8	334165(P) 334165(P)	.079 .079
BS-23	BS26	BS26B	2S	Field	Pipeside	8 Sch. 40	48958(P) 334353(P)	.062 .062
BS44	BS24	BS25R1	6N	Field-Repair	Pipeside	10 Sch. 40	334469(P) 18084	.064 .056
BS57	BS5	BS5A	[illegible]	Shop	Pipeside	8 Sch. 40	334353(P) 14458	.062 .068

TABLE [illegible]2: SUMMARY OF INDICATIONS - (Cont'd)

UT No.	Spool No.	Weld No.	Welder	Shop/Field	Location	Pipe Size, in.	Heat Number	%C
BS92	BS11	BS11	6K	Field	Pipeside	10 Sch. 40	334164(P) BS-V-3B	.074
BS94	BS15	BS-V-25BR1	24F	Field-Repair	Pipeside	10 Sch. 40	334469(P) BS-V-25B	.064 -
BS100	BS10	BS-V21BQR1	9R/24F	Field-Repair	Pipeside	4 Sch. 40	2P1910(P) BS-V-21B	.054 -
BS127	BS35	BS-V60B	21U	Field	Pipeside	6 Sch. 40	M4674(P) BS-V60B	.046 -
BS138	BS238	BS238B	C50	Shop	Pipeside	4 Sch. 40	2P4501(P) SRVT	.065 -
DH116	DH62	DH62AR1	4C/8A	Field-Repair	Fitting side	14 Sch. 40	18918 334166(P)	.060 .070
DH131	DH51	DH51	21U	Field	Pipeside	10 Sch. 40	334164(P) 16468	.074 .065
DH178	BS12	BS12AR1	6K	Field-Repair	Pipeside	10 Sch. 40	334469(P) 18084	.064 .056
DH180	BS12	BS12C	C119	Shop	Pipeside	14 Sch. 40	334166(P) 19986	.070 .054
DH182	BS12/13	BS12	2S	Field-Repair	Pipeside Fitting side	14 Sch. 40	334469(P) 19984	.064 .059
DH184	BS13	BS13	C77	Shop	Pipeside	14 Sch. 40	334469(P) 19984	.064 .059
DH315	DH19/20	DH20	24F	Field	Pipeside	8 Sch. 40	334165(P) 17617	.079 .062

TABLE 3-2: SUMMARY OF INDICATIONS - (Cont'd)

UT No.	Spool No.	Weld No.	Welder	Shop/Field	Location	Pipe Size, in.	Heat Number	%C
DH335	DH30	DH30A	2S	Field	Pipeside	10 Sch. 40	334164(P) 32126	.074 -
M-1	DH13	DH13R1	7G	Field-Repair	Pipeside Leaker	10 Sch. 40	334164(P) 18085	.074 .056
M-40	DH6/7	DH7	14B/14G	Field	Fitting side	24 Sch. 20	18921 332535(P)	.06 .052
M-47	DH3	DH3A	W145/W262	Shop	Pipeside	24 Sch. 20	31860(P) 334032(P)	.051 .064
MU170	DH72	DH72AR1	7G	Field-Repair	Pipeside	6 Sch. 40	32561(P) 18918	.056 .06

TABLE 3-3: HEAT NUMBERS EXHIBITING UT SCREENED INDICATIONS/LEAKS

A Heat No.	B System	C # HAZ Overall	D % of HAZ Overall	E Exp. No. of Indications	F Actual No. of Indications	G Poisson Probability
334165	SF	259	22.8	5.2	17	0.0%
334165	DH/BS	29	2.2	.5	1	39.3%
334164	DH/BS	118	9.1	1.9	4	12.5%
48428	SF	2	.2	.05	2	0.1%
16462	SF	27	2.3	.5	1	39.3%
17617	SF	52	4.6	1.0	1	63.2%
16164	SF	20	1.8	.4	1	33.0%
2P1906	SF	78	6.9	1.6	1	79.8%
18921	DH/BS	2	.2	.03	1	3.0%
31860	DH/BS	4	.3	.06	1	5.8%
32561	DH/BS	5	.4	.08	1	7.7%
18918	DH/BS	4	.3	.06	1	5.8%
334469	DH/BS	61	4.7	1.0	5	.4%
334166	DH/BS	59	4.5	.9	1	59.3%
19984	DH/BS	6	.5	.1	1	9.5%
[illegible]674	DH/BS	18	1.4	.3	1	25.9%
2P4501	DH/BS	18	1.4	.3	1	25.9%
334353	DH/BS	36	2.8	.6	1	45.1%
48958	DH/BS	2	.2	.03	1	3.0%
2P1910	DH/BS	4	.3	.06	1	5.8%
Overall	SF DH/BS	1132 1298			23 21	

TABLE 3-4: HEAT CHEMISTRY ANALYSIS

% Carbon	Overall No.	% Overall	Exp. No. Ind.	Actual No.	Poisson Prob.
.04-.049	171	16.5	6.1	1	99.8%
.05-.059	178	17.2	6.4	4	88.1%
.06-.069	179	17.3	6.4	10	11.4%
.07-.079	508	49.0	18.1	23	20.1%
	1036				

TABLE 3-5: CONFIRMED IGSCC

UT IND.	Confirmation	Heat No.
SF12	Metallography	334165
SF13	Leak	334165
SF14	Leak	334165
SF22	Leak	334165
SF35	Leak	334165
SF42B	Metallography	334165
SF103	Radiography	334165
SF210	Leak	334165
SF214	Radiography	334165
SF265	Leak	334165
M-1	Leak	334164

TABLE 3-6: SHOP VS. FIELD WELDS
(SF, BS and DH Systems Only)

	SHOP	FIELD
Overall % of Welds	59%	41%
Expected no. of indications/leaks	24	17
Actual no. of indications/leaks	7	35 (13 repair)
Poisson Probability	100.0%	0.0%

TABLE 3-7: WELDERS
(SF, BS and DH Field Welds Only)

Welder	System	Overall # of Welds	# of Overall Welds	Expected # of Indications	Actual # of Indications	Poisson Probability
3C	SF	66	20.4%	3.9	3	73.1%
2L	SF	65	20.1%	3.8	5	33.2%
9R	SF	74	22.9%	4.4	11	0.6%
6K	SF	3	.9%	.17	1	13.9%
6K	DH/BS	13	3.7%	.56	2	10.6%
20K	SF	3	.9%	.17	1	13.9%
7G	DH/BS	20	5.7%	.86	2	20.9%
14B	DH/BS	1	.3%	.05	1	4.9%
14G	DH/BS	35	10.0%	1.5	1	77.7%
4C	DH/BS	12	3.4%	.51	1	39.3%
8A	DH/BS	6	1.7%	.26	1	22.1%
2S	DH/BS	24	6.8%	1.0	3	8.0%
24F	DH/BS	36	10.3%	1.5	3	19.1%
21U	DH/BS	6	1.7%	.26	2	2.6%
6N	DH/BS	6	1.7%	.26	1	22.1%

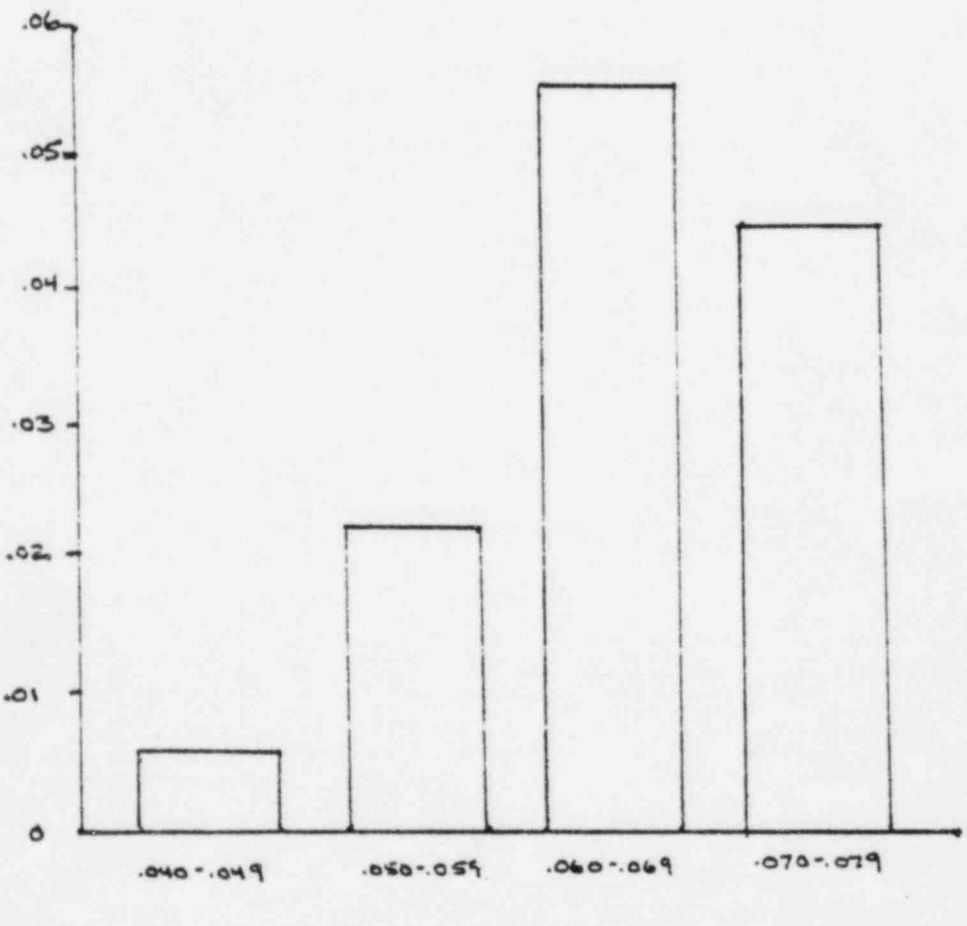
TABLE 3-8: WATER CHEMISTRY RESULTS

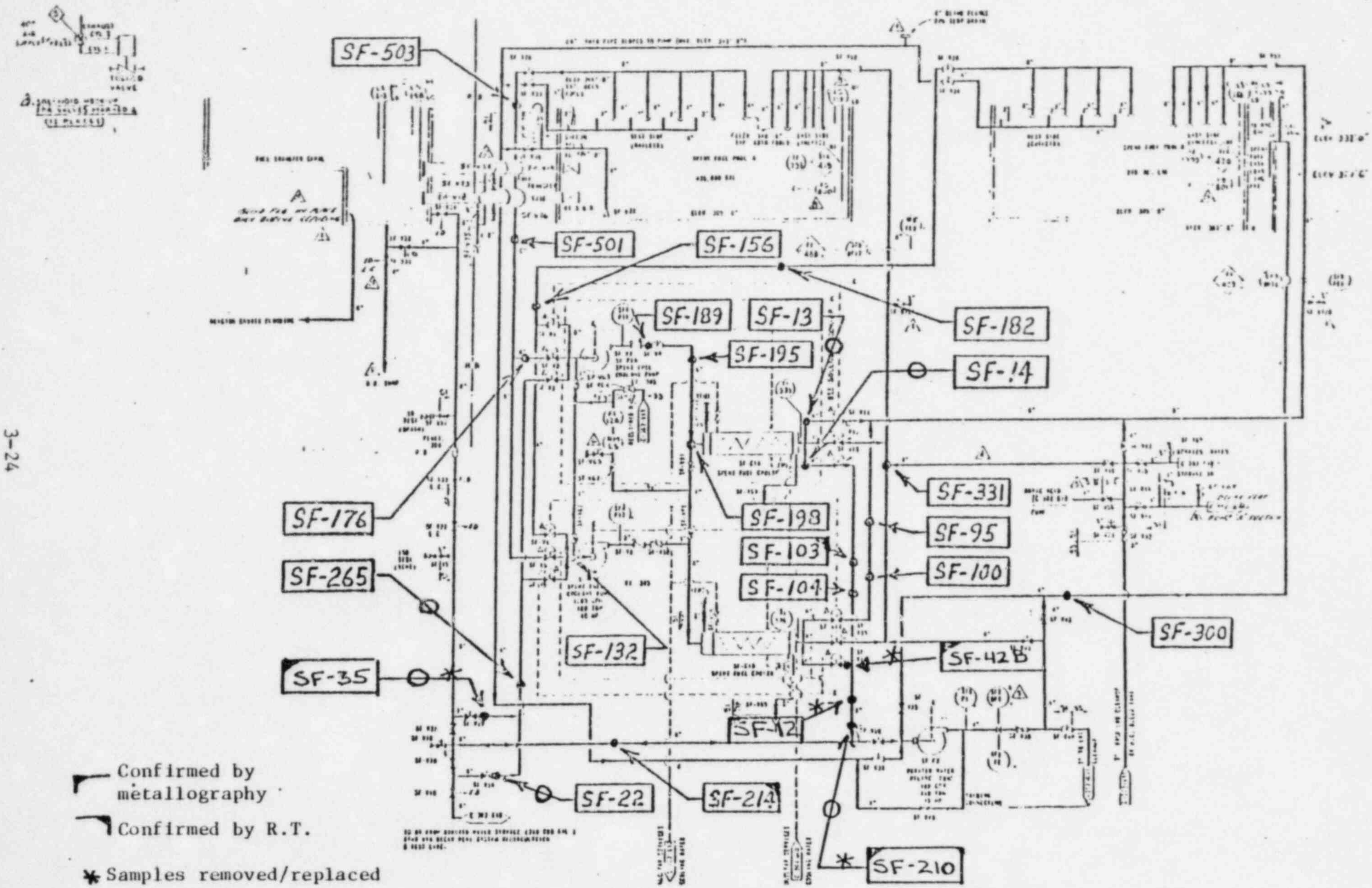
Sample	pH	mho COND.	mg/l Cl^-	mg/l F^-	mg/l Na^+	mg/l Li^+	mg/l B	mg/l O_2
DH-V-44	5.18	10.4	0.03	<.02	1.14	0.13	2433	6.20
DH-V-31	5.47	16	0.11	<.02	0.88	0.09	2393	4.20
DH-V-47B	5.37	14	0.04	<.02	0.84	0.09	2395	5.00
BS-V-47B	5.5C	42.5	0.11	<.02	3.20	0.10	2479	4.60
BS-V-48B	5.55	62.5	1.50	<.02	1.09	0.17	2283	2.75
SF-V-65	5.39	21.0	0.10	<.02	1.82	0.12	2539	6.20
SF-P-2	5.23	10.5	0.04	<.02	0.90	0.10	2402	5.60
BS-V-50A	Could not get this sample							

Sample	Indications
DH-V-44	M-1, M-40, M-47, MU-170
DH-V-31	D-315
DH-V-47B	D-335
BS-V-47B	B-57, B-127, B-23
BS-V-48B	D-116, D-178, D-180, D-182, D-184 B-44, B-92, B-94, B-100
SF-V-65	SF-182, SF-156, SF-501, SF-503, SF-176 SF-265, SF-132, SF-35, SF-22
SF-P-2	SF-198, SF-13, SF-14, SF-103, SF-104, SF-95 SF-100, SF-210, SF-214, SF-300, SF-331
BS-V-50A	B-138

FIGURE 3-1: CARBON CONTENT EFFECT ON UT SCREENED INDICATIONS - PIPE HEATS
(SF, DH and BS Systems)

Per Cent Carbon	.040-.049	.050-.059	.060-.069	.070-.079
Total Welds	171	178	179	508
Screened Indications	1	4	10	23
IND./Welds	.006	.022	.056	.045





Confirmed by metallography

Confirmed by R.T.

* Samples removed/replaced

Through wall cracks

Figure 3-2

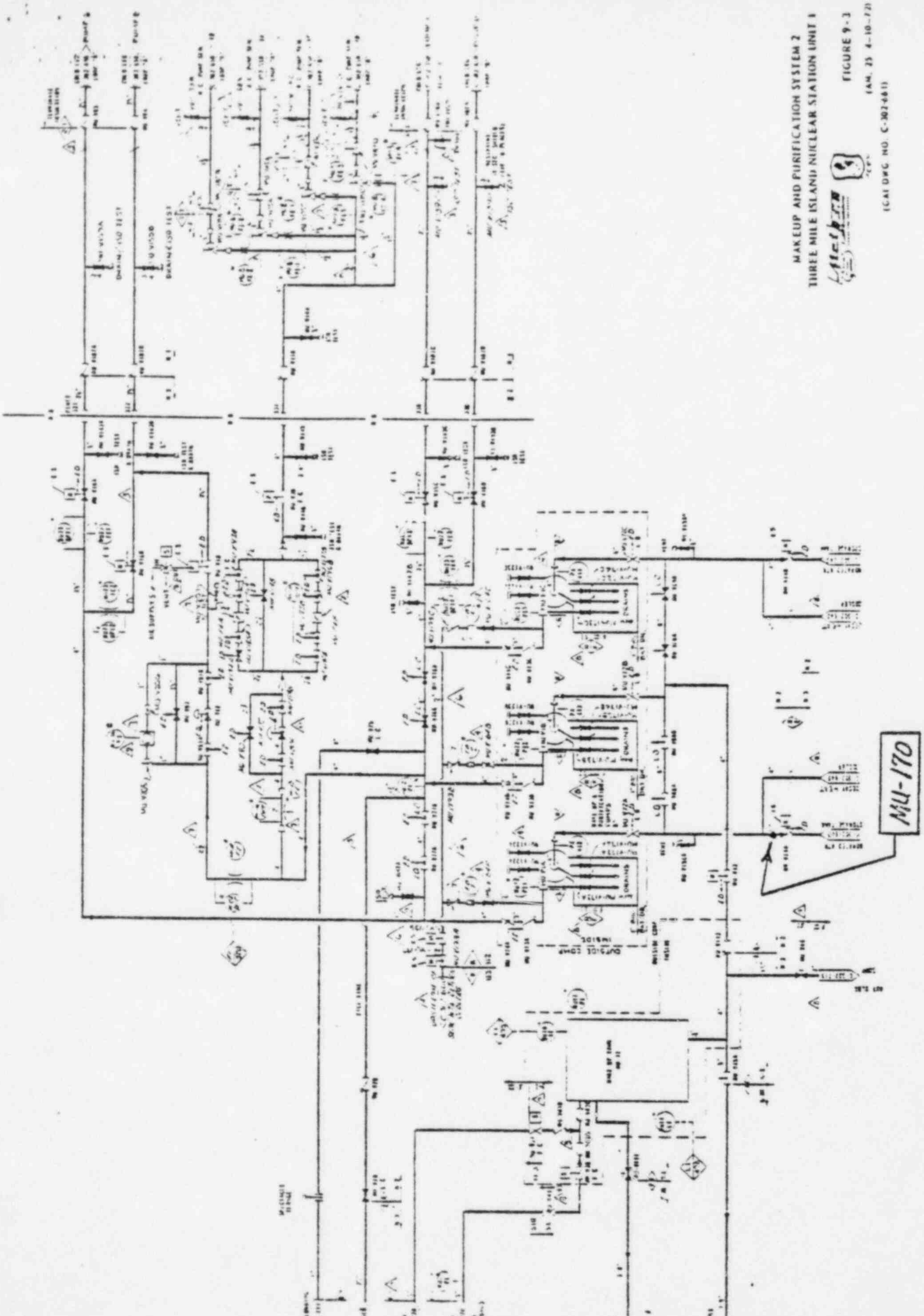
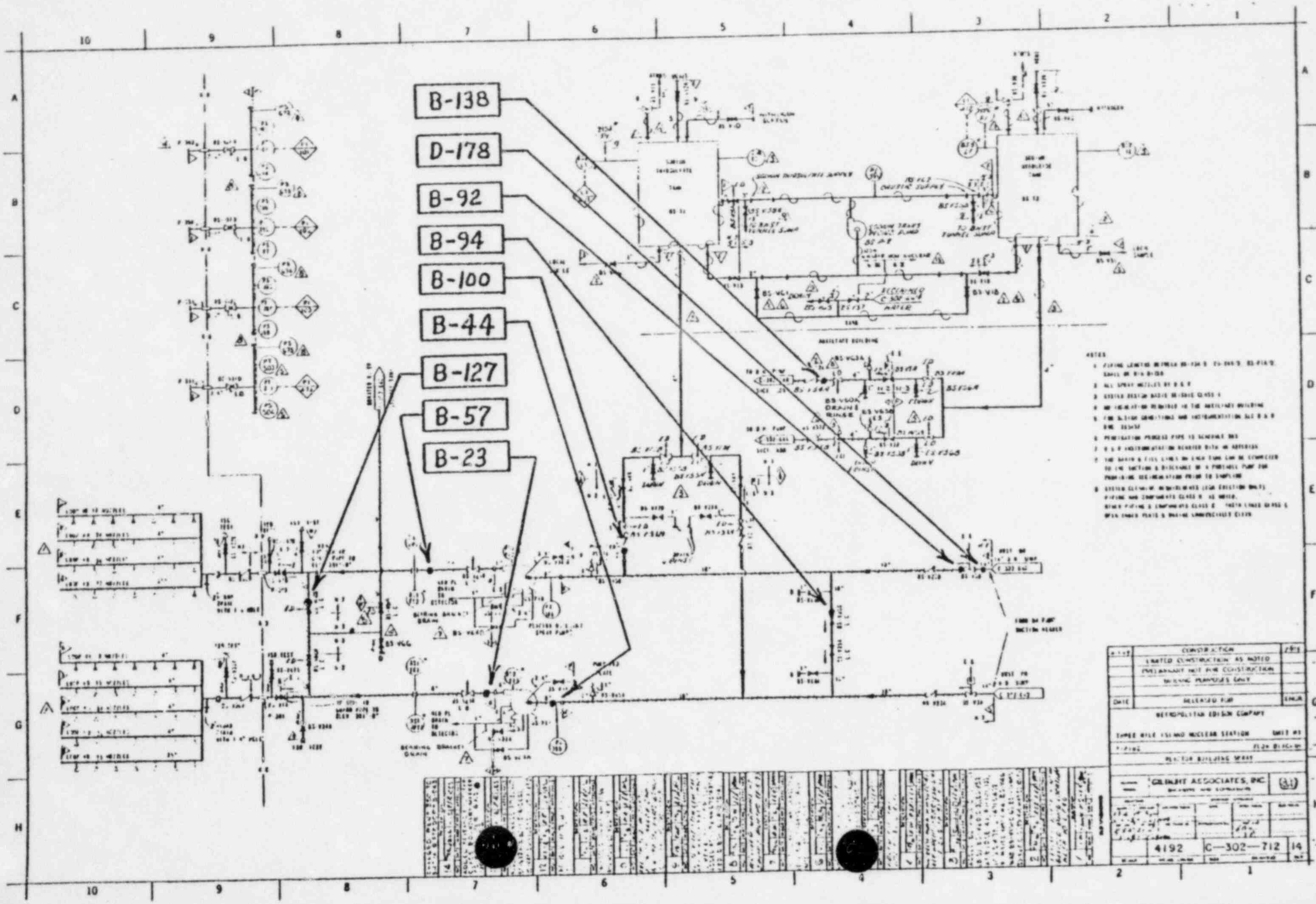

MAKEUP AND PURIFICATION SYSTEM 2
THREE MILE ISLAND NUCLEAR STATION UNIT 1
FIGURE 9-3
MU-170

Figure 3-3


B-138
D-178
B-92
B-94
B-100
B-44
B-127
B-57
B-23
METROPOLITAN EDISON COMPANY
THREE MILE ISLAND NUCLEAR STATION
GILBERT ASSOCIATES, INC.
4192
C-302-712
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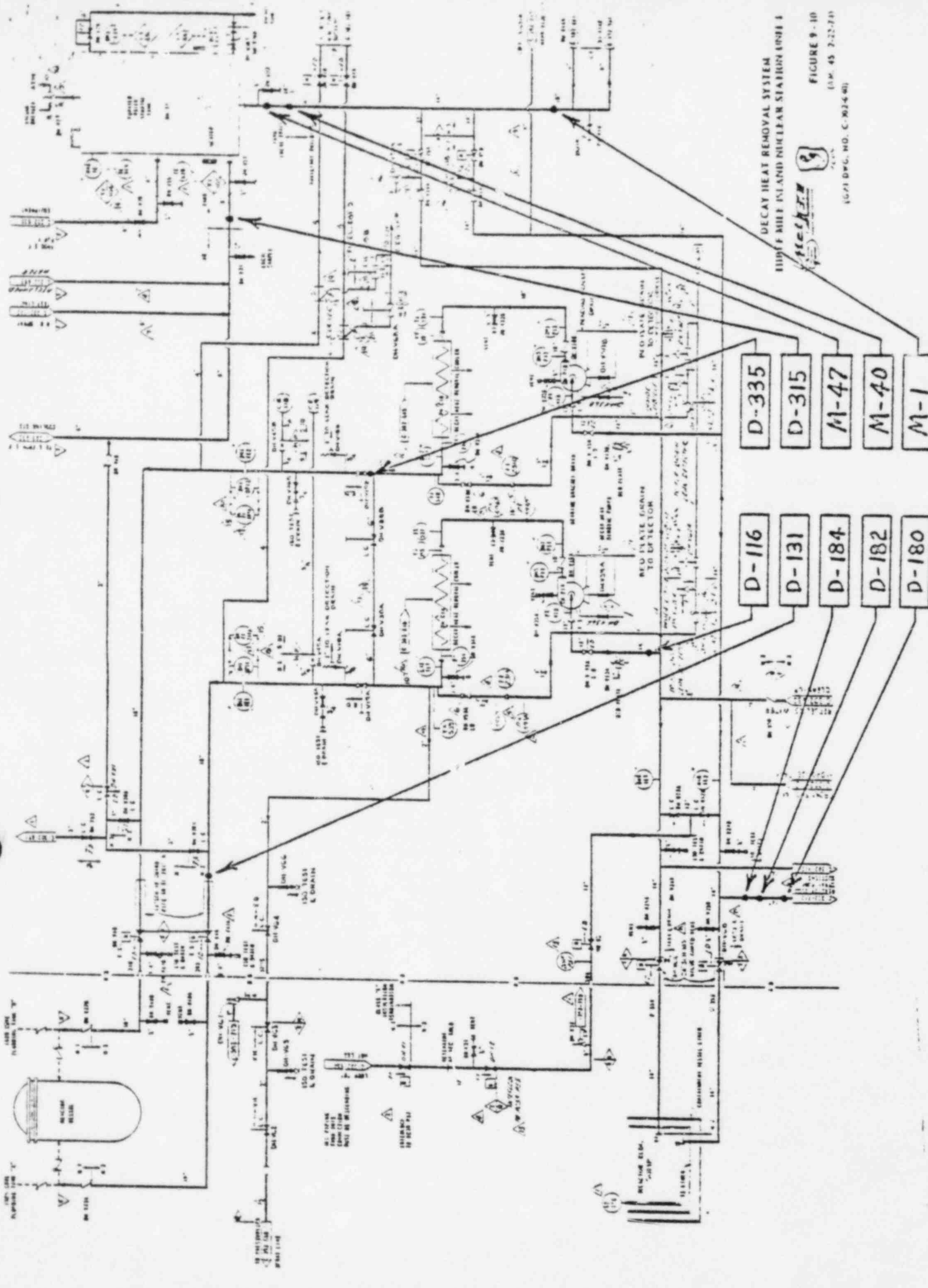

DECAY HEAT REMOVAL SYSTEM
THREE MILE ISLAND NUCLEAR STATION UNIT 1
FIGURE 9-10
D-335
D-315
M-47
M-40
M-1
D-116
D-131
D-184
D-182
D-180

Figure 3-5

METROPOLITAN EDISON COMPANY Subsidiary of General Public Utilities Corporation

Subject: WELDS REMAINING TO INSPECT IN MAKE-UP SYSTEM-TMI UNIT 1 PIPE CRACKING PROBLEM

Location: TMI Nuclear Station Middletown, PA

Date: August 16, 1979

To: N.C. Kazanas

There are approximately 395 welds in the Make-Up System that have not been inspected by UT. This number represents 38 welds in 4" pipe and 357 welds in 2½" pipe. Since all the welds in the 4" diameter pipe are readily accessible, it is recommended that these welds be inspected. In an effort to determine what level of inspection is required of the welds in the 2½" diameter pipe, an analysis of the 656 welds already inspected was made with the following results:

Welds in 2½" Pipe Remaining - 357
Welds Examined Previously in 2½" Pipe with Identical Flow Conditions - 253
Number of Indications Found - 0
Total Population - 610
Per Cent Population Sampled - 41.5
Number of Heats in Population - 11
Number of Heats Sampled - 9

There are two heats (Table I) in the population that are not included in the sample lot. However, since the heats have similar compositions and are fabricated by the same pipe manufactures as the heats already inspected, it is expected for these two heats to behave in a similar fashion as the other nine heats. Therefore, considering both system and material parameters, the 253 welds inspected in the Make Up System are a representative sample of the entire population.

If Mil-Std.-105D is used as a guideline to project the overall percent rejection rate in the 2½" Make-Up welds, the following results. The total 610 2½" Make-Up welds can be accepted based on a "sample" of 253 welds having no rejects if one applies an AQL of .065. An AQL of .065 is equivalent to .65 rejects per 1000 or approximately .4 rejects per 610. Since the number of rejects can obviously only be a whole number, the most likely number of rejects in the total 610 welds is 0, although there is a minimal possibility that there is one reject. This possibility is minimized further by favorable flow and metallurgical conditions examined previously. Therefore, no further inspection of these welds is recommended.

David M. Smith
David M. Smith
Joseph Godleski
Joseph Godleski

DMS/JG/gme

cc: F.S. Giacobbe
T.A. Mackey, Jr.
D. McConnell/C. Rowe
J.J. Potter
R. Skibinski
G.J. Troffer

INTER-OFFICE MEMORANDUM

TABLE I

Heats in Population	%C	Mfg.	Heats in Sample
2P3898	.050	USS	2P3898
2P3278	.050	USS	2P3278
M5253	.045	B&W	M5253
M5364	.050	B&W	-
2P3333	.055	USS	2P3333
2P1370	.047	USS	2P1370
M5585	.050	B&W	M5585
96599	.062	AL	96599
M4944	.060	B&W	M4944
M5677	.053	B&W	M5677
2P1906	.054	USS	-

Section 4: SUMMARY OF PROPOSED AND FINAL REPAIR PROCEDURES

4.1 INTRODUCTION

It is well known that stress corrosion cracking is a corrosion phenomenon which requires three interrelated parameters; 1) a susceptible material, 2) a corrosive environment, and 3) an applied or residual tensile stress. Eliminating any one of the three parameters will prevent stress corrosion cracking from occurring. The following sections present a variety of approaches considered to mitigate the SCC problem at TMI. Each technique is evaluated from a materials and/or stress analysis viewpoint to determine its usefulness as a potential fix to the SCC problem at TMI.

4.2 MATERIALS CONSIDERATION

In regard to the intergranular stress corrosion cracking observed at Three Mile Island Unit #1, the susceptible material was sensitized 304 SS. Sensitization refers to the depletion of chromium at the grain boundaries as a result of the formation of chromium carbides ($Cr_{23} C_6$) in the temperature range of 900-1600°F. These depleted areas then become susceptible to accelerated attack under the action of a corrosive environment. The primary driving force for inducing sensitization in the TMI piping was the heat input during welding; i.e., during butt welding of two piping components together the heat produced by the welding operation was sufficient to cause chromium carbide formation in the grain boundaries and the resulting chromium depletion in the surrounding area. Knowing that sensitization was a critical parameter in producing IGSCC, repair procedures and material selections would be made which address the minimization of this condition.

It is a well documented fact that the degree to which sensitization occurs is related to chemistry and, most specifically, carbon content. The more carbon in the alloy, the more there is available for combination with chromium as the chromium carbide. Therefore, lowering the carbon level in the alloy can be effectively used to minimize the amount of chromium carbide formation. These low carbon alloys, designated as "L" grades, will be used in the repairs at TMI. Currently, commercially available low carbon stainless steels such as 304L SS and 316L SS have a .035% C max which affords adequate protection against weld induced sensitization. Also available commercially are "stabilized" grades of stainless steels such as 321 SS and 347 SS. These alloys were designed to react the carbon with elements other than chromium thus preventing chromium depletion. These alloys would be adequate for addressing the sensitization problem, however, they bring additional problems of poor weldability, lower availability, and higher cost, thus making the low carbon grades more suitable as repair materials. In conjunction with these low carbon base materials, welding will be performed using low carbon filler metals with a minimum of 5% ferrite as defined in ASME Section III, Subsection NB-2433. This ferrite level has been determined experimentally to provide a microstructure which is highly resistant to IGSCC.

The proposed material change of affected and repaired piping sections from the existing Type 304 to 304L stainless steel was evaluated considering technical requirements of the applicable code (USAS B31.1, B31.7-1967). This was motivated by the fact that the replacement material (304L) has lower code allowable stresses than the original material (304).

The evaluation consisted of reviewing the piping stresses that are generated by the following loads:

1) Thermal expansion
2) Internal pressure
3) Dead weight
4) Safe Shutdown Earthquake (SSE)

Stress requirements of USAS B31.1-1967 were then checked against the allowable stresses of Type 304L.

Results of the evaluation are summarized below:

1) In the spent fuel cooling system, no problem results due to the material replacement. The allowable stresses for Type 304L are higher than the maximum stresses that are generated by the combined effects of the above mentioned loads.
2) Of the systems comprising Core Flooding, Decay Heat Removal, Make-up and Purification and Reactor Building Spray, six(6) subsystems were found to have problems with 304L replacement. The difficulty is that there are one or more points or nodes in thse subsystems that have combined stresses due to effects of internal pressure, deadweight, SSE and/or thermal expansion stresses which are higher than the code allowable limits for 304L. These subsystems are depicted in Table 4-1.
3) The overstressed conditions occur only at a few nodes in the piping subsystems as indicated in Table 4.1. The other nodes are acceptable and consequently permit material replacement to Type 304L.

The above results were subsequently utilized as guidelines for material replacements of the affected piping.

4.3 WELDING CONSIDERATIONS

As a further precaution taken to minimize sensitization all welding involving 304 SS will be performed using controlled heat input, as recommended by Regulatory Guide 1.31. To define an acceptable heat input, test specimens were prepared from actual pipe samples removed from the spent fuel system from the heat of material which has shown the highest incidence of cracking (HT.334165). These samples were prepared to duplicate the exact configuration to be utilized in the field when joining a new 304L SS spool piece to an existing 304 SS piping component. The 304 SS pipe had the I.D. weld clad at the joint end which in turn was welded to a 304L SS spool piece using a single bevel 75° included angle joint, with either an open butt or a consumable insert. During all welding operations on the test coupon the parameters of voltage, current and travel speed were recorded. These same parameters later provided the guidelines for performing the actual field welds, after laboratory testing had found them to produce an acceptable weld and HAZ structure. The procedure and laboratory report are included in Appendix 4.1.

Serious consideration had also been given to the application of heat sink welding (HSW). HSW is another of the repair techniques developed for the BWR Pipe Cracking program. This procedure involves making butt welds with flowing water on the inside of the pipe after the root pass has been completed. There is also a similar procedure known as last pass heat sink welding which only requires water on the I.D. during the final weld pass. The purpose of HSW is to cool the I.D. surface during welding so that upon completion of the weld the I.D. surface in

the vicinity of the weld is in compression. This compressive layer then provides resistance to IGSCC. The decision, however, was not to utilize HSW at this time. First, there is little industry experience utilizing this technique and, second, only a limited amount of empirical data exists supporting its use. Thirdly, if the technique was utilized it would have been necessary to use borated water as the cooling medium. This could expose sensitized material at elevated temperatures (300°F) to potentially corrosive conditions. With so little known about the corrosion phenomenon at this time the potential risk of doing damage was not warranted.

4.4 I.D. WELD CLAD (BUTTERING)

Taking advantage of weld metals' inherent resistance to IGSCC, it has been decided to utilize an I.D. weld overlay procedure. This repair technique is incorporated when butt welds are made to regular carbon 304 SS. Because 304 SS is susceptible to sensitization it is advantageous to provide a corrosion resistant weld metal barrier on the I.D. surface where the HAZ would exist from the butt weld. This is accomplished by weld cladding the I.D. of the pipe for a width of approximately 3/8" at the joint end. The HAZ which exists from the cladding is generally less sensitized than that associated with the butt weld due to the lower heat input involved in depositing the cladding. The cladding HAZ is also beyond the detrimental residual stress pattern produced by the butt weld.

4.5 REPAIRS UTILIZING STRONG BACK HARDWARE

Various repair schemes utilizing pipe sleeves wrapped around the affected area were proposed and subsequently evaluated considering

code requirements on design, structural integrity, fabrication and nondestructive examination. Different means of attaching the sleeves were also considered, foremost among these are:

1) Clamps

2) Fillet welds

Results of the Evaluation are summarized as follows:

1) The repair, although very simple to make, can result in further complications or problems when the crack becomes through wall and borated water collects inside the sleeve and remains stagnant. Crevice corrosion may result which further necessitates additional surveillance and potential repairs in the future.
2) The repair creates discontinuities in the piping which consequently increases the local state of stress through higher stress intensification factors. This will affect the existing piping stress analyses which consider loads generated by thermal expansion, internal pressure, dead load and SSE.
3) The pipe sleeve increases the local stiffness of the affected piping system and can consequently change the piping response to seismic excitations, change load distribution of the pipe deadweight and change thermal expansion distribution during high temperature exposure. This will necessitate reanalysis of the affected line if a number of sleeves are installed in that line.

Based on the above findings, the use of strong back in the final repair of affected was not generally encouraged.

4.6 COLD SPRINGING

Since cracking occurred in the heat affected zone (HAZ) of the pipe welds, one of the proposed repair procedures was to cut those sections which contain the cracked HAZ and then reweld the ends by pulling the pipe together. In effect, a certain amount of cold spring is applied to the affected pipe layout. This practice is being permitted by USAS B31.7, ANSI B31.1 and ASME Section III Codes provided a careful analyses of its effects are made and a judicious method of control is applied to the cold spring procedure.

The following are extracts of the above mentioned codes:

1) USAS B31.7 "Nuclear Power Piping" 1969

   1-719.9 Cold Springing

   Cold springing provides a beneficial effect in assisting a system to attain its most favorable position sooner. The effect of cold springing must be analyzed as any other movement in the system is analyzed. The maximum stress allowed due to cold springing is $2.0S_m$ at the cold spring temperature. Since the usual erection procedures may not permit accurate determination of cold spring in a piping system, the allowable reduction of forces and moments at anchors or equipment caused by cold springing shall be limited to no more than two-thirds of the calculated reduction.

2) ANSI B31.1 "Power Piping" 1977

   119.9 Cold Spring

   The beneficial effect of judicious cold springing in assisting a system to attain its most favorable position sooner is

recognized. Inasmuch as the life of a system under cyclic conditions depends on the stress range rather than the stress level at any one time, no crdit for cold spring is allowed with regard to stresses. In calculating end thrusts and moments acting on equipment, the actual reactions at any one time, rather than their range, are significant. Credit for cold springing is accordingly allowed in the calculation of thrusts and moments, provided an effective method of obtaining the designed cold spring is specified and used.

3) ASME Section III Subsection NB 3672.8 has the same requirements as USAS B31.7.

4) ASME Section III Subsections NC 3673.3 and ND 3673.3 have the same requirements as ANSI B31.1.

This approach has not been applied to any of the TMI-1 modifications since it does not allow weld buttering of the pipe. inside diameter. However, it is an acceptable fix provided the pipe can be spring/offset for weld buttering and the stress analysis is acceptable.

4.7 O.D. WELD CLAD OVERLAY

Consideration was also given to weld clad overlay on the O.D. surface in the area of the weld and HAZ. Weld metal would be deposited to a thickness equal to the original pipe wall and at a width sufficient to cover the butt weld and both adjacent HAZ's. This weld metal would then act as barrier to crack propagation at the O.D. surface plus provide the necessary wall thickness to withstand design loads. Unfortunately, this technique suffers from the same problems as HSW. In order to perform the welding without seriously collapsing the pipe wall from

weld shrinkage stresses, it is necessary to have water on the I.D. and the only source of water is the borated water. In addition it is necessary to exercise careful control on heat input, interpass temperature and bead sequence to minimize sensitization and to control distortion.

An evaluation of this repair scheme revealed the following facts:

1) The weld overlay method of repair does not require piping sections to be removed. Furthermore, the USAS B31.7, ANSI 31.1 and ASME Section III Codes do not explicitly prohibit the resulting geometry of the pressure boundary after the weld metal is added.
2) Depending upon pipe sizes, the amount of weld metal required for overlay is large. Furthermore, flow through the pipe is required during welding.
3) Since the scheme does not eliminate the existing cracks from the ID of the pipe, the resulting stress intensification factor due to this discontinuity must be considered in the evaluation of the stresses generated by thermal, dead weight, internal pressure and SSE. This will require a special detailed evaluation of the weld overlay-crack geometry since no formulation is readily available in the above mentioned codes.
4) The resulting geometry with the weld overlay will preclude any UT of the weld.
5) There is a strong possibility that during welding, the inside region of the pipe may be permanently deformed thereby reducing flow areas and will complicate the geometry for stress evaluation.

Based on the above findings, the weld overlay scheme is not presently considered as one of the final repair fix.

<u>TABLE 4-1</u>

PIPING SUB-SYSTEMS THAT HAVE PROBLEMS WITH 304L SS

GAI Identification Packet	GAI Isometric Dwg. No.	Design Temp. °F	Line Spec. No.	Node Pt. w/max. Stress	Pipe Size & Sch. No.	Problem Condition	Description of Piping Sub-System
ME 34	C 302551	300,650	2500-2 2500-3	39	10" sch.140 14" sch.140	SSE+press.+DW greater than code allowable value. 14,489 psi> 14,280 psi	Core Flooding Tank, CFTIA-penetration 303-penetration at El.316'-0"
ME 73	SS 312589	300	2500-2 300-2	22	10" sch.140 10" sch.140	same as above 15,974 psi> 14,280 psi	Decay Heat Cooler (DH-C __) to penetration 310
ME 78	C 312622	300	300-2	10	8" sch. 40 4" sch. 40	max.thermal stress greater than code allowable value. 26,837>22,475 psi	Reactor Bldg. Spray Piping, Spray Ring #4
ME 85	B 312-613	300	300-2	32	8" sch. 40	same as above 25,572>22,475 psi	Reactor Bldg. Spray Water Piping from pen. 301 to Heater at elev. 417'-6"
ME 96	C 312-654	300	300-2	102	24" sch. 20 14" sch. 40 12" sch. 40 10" sch. 40 6" sch. 40	same as ME 34 17,777>14,280	Decay Heat Removal Pump DH-P1B to various pipe anchors
ME 118	C 312-642	300	2500-2	16	2-1/2" Sch.160	same as ME 34 16,231>14,280	2-1/2" High Injection Piping from pen. 338 to RC Piping

Appendix 4-1

Field Welding Procedure

GAS TUNGSTEN ARC - SHIELDED
METAL ARC WELDING OF STAINLESS STEEL
IN BORATED WATER PIPING SYSTEMS

1. Scope

This welding procedure shall be utilized when making welds and weld repairs on the 304 SS and 304L SS piping in the following systems:

A. Spent Fuel

B. Decay Heat

C. Building Spray

D. Make-Up

E. Core Flood

Included in this procedure are the requirements specifically related to producing a corrosion resistant I.D. weld overlay (I.D. Buttering) on the ends of existing 304 SS pipes as recommended in NUREG-0313. Also, as recommended in this document, wherever possible, replacement stainless steel piping material will contain .035% Carbon max.

2. Welding Procedure Specification (WPS)

The basic WPS defining the essential variables to be utilized for this repair are contained in Catalytic WPS No. SP-4200-SS(N)-102A. Non-essential variables specifically tailored for this repair are defined herein. The basic weld procedure specification shall have been qualified in accordance with the requirements of ASME:Section IX and Regulatory Guide 1.31.

3. I.D. Weld Clad (Buttering)

When butt weld joints are to be made between replacement 304L SS piping and the original 304 SS piping in the system, the 304SS pipe ends shall be prepared in the following manner:

3. I.D. Weld Clad (Buttering) (Continued)

A. If the pipe end has been thermally cut, a minimum of 1/8" of metal must be removed from the cut and to eliminate the heat-affected-zone (HAZ) from the cutting operation.

B. Clean the pipe and per WPS 4200-SS(N)-102A.

C. Weld clad the I.D. surface of the pipe end to a width of 3/8" + 1/8" - 0 with a single layer of SFA-5.9 Class ER 308L filler metal with 5 FN minimum ferrite, using the GTAW process. (See sketch I).

D. Maximum joulian heat input as established during the I.D. weld clad qualification (GPU Lab No. 56052 rev. 1) shall be 17,100 joules/inch utilizing the following electrical characteristics:

Arc Voltage - 8 - 12 volts

Current - 80 - 95 amps

Travel Speed - 4 in./min.

E. Maximum interpass temperature shall be 100° F.

F. After the I.D. weld cladding is complete the pipe end shall be ground back ≈1/8" to assure the weld clad becomes integral with the weld root. The butt weld joint geometry shall then be prepared by maching or grinding. Joint geometry shall be a 37-1/2° ± 2-1/2° single bevel with a 3/32" ± 1/32" land.

NOTE: Grinding shall not be performed on the weld clad or pipe internal surfaces except in the immediate vicinity of the weld root to facilitate joint fit up and then only light grinding is permitted to remove high spots. Maximum I.D. mismatch on fit up shall be 1/16".

4. Butt Weld Procedure

A. Butt welding shall be in accordance with Catalytic WPS 4200-SS(N)-102A.

4. Butt Weld Procedure (Continued)

B. The root and first pass shall be deposited by the GTAW process utilizing SFA-5.9 Class ER 308L filler metal with a minimum of 5 FN ferrite. Argon gas backing shall be utilized during the first two passes.

C. The weld shall be completed utilizing the SMAW process with SFA-5.4 Class E308L-16 electrodes with a minimum of 5 FN ferrite.

D. Maximum heat input during the welding shall be 35,000 joules/in. with a 300°F max. interpass temperature.

E. Electrical characteristics shall be as follows:

	GTAW	SMAW
Voltage	10 - 12 volts	20 - 23 volts
Current	75 - 95 amps	80 - 100 amps
Travel Speed	2 - 4 in./min.	4 - 6 in./min.

5. Quality Control

A. The quality control inspector shall verify the following:

1) Correct materials, including filler metals, are being utilized.

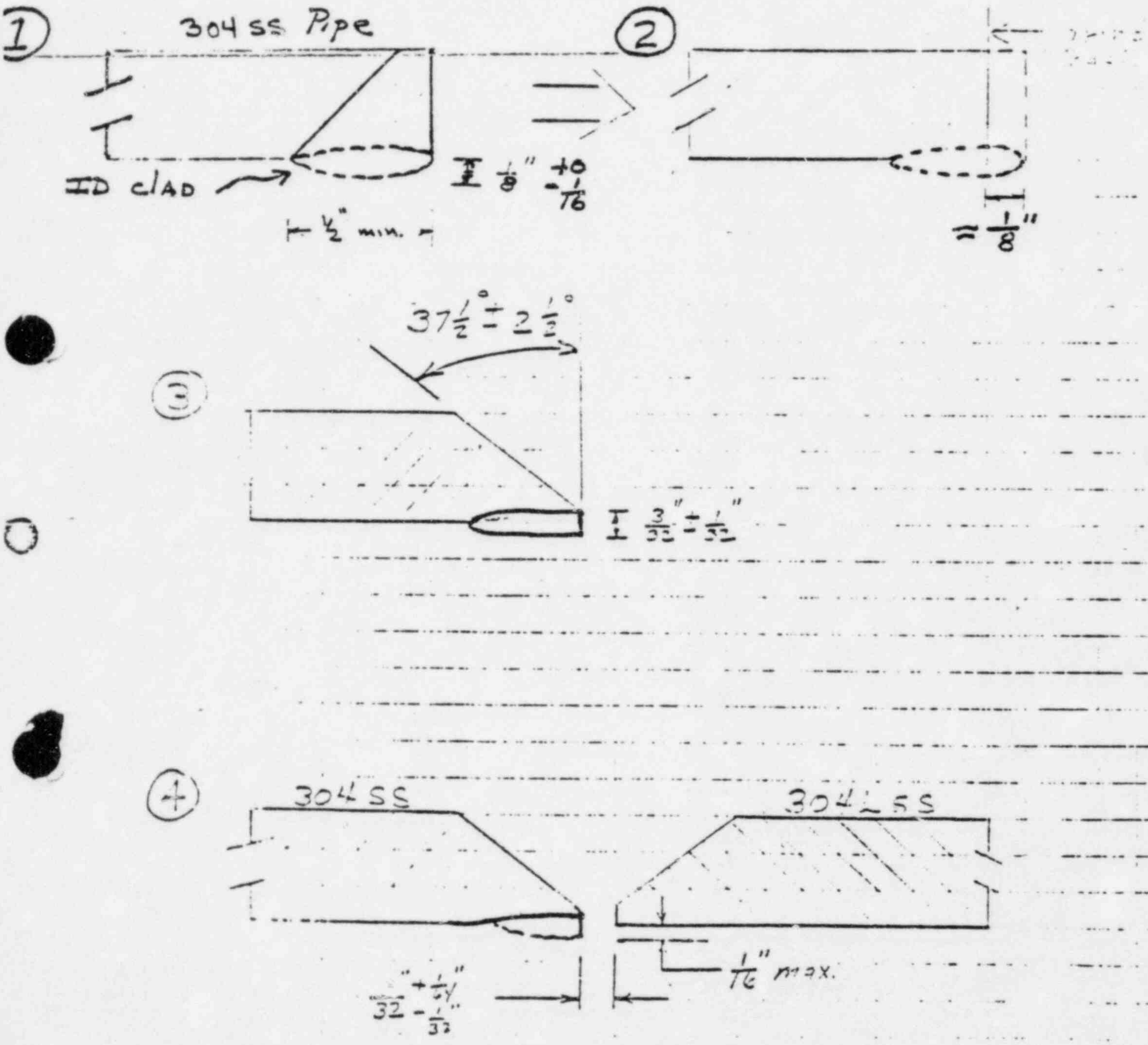
2) I.D. weld clad and joint geometry dimensions are correct.

3) Joint fit up has correct dimensions and aligmment.

B. Quality Control shall also perform spot checks to assure proper electrical characteristics and interpass temperatures are being utilized during welding.

C. Quality Control shall perform final visual inspection per the applicable quality control procedures.

Sketch I


1
304 SS Pipe
ID clad
1/8" +0 −1/16
1/2" min.
2
≈ 1/8"
3
37 1/2° ± 2 1/2°
3/32" ± 1/32"
4
304 SS
304L SS
1/16" max.
32" +1/64" −1/32"

Inter-Office Memorandum

GPU Service

Date: September 27, 1979

Subject: Evaluation of I.D. Buttering Technique to Minimize Weld HAZ Cracking, Lab No. 56052 (REVISION #1)

To: N. C. KAZANAS Location: Reading

In order to qualify a field welding procedure for joining 304L SS to 304 SS which would minimize the potential for intergranular stress corrosion cracking (IGSCC) in the 304 SS weld heat-affected-zone (HAZ), a sample was prepared for evaluation utilizing a proposed I.D. buttering technique. This sample consisted of two sections of 8" schedule 40 piping; one section 304 SS (HT.334165), the other section 304L SS (HT.83602000).

To one-half of the I.D. circumference of the 304 SS pipe a layer of ER308L SS (HT.760133) approximately 1/8" thick was deposited by the GTAW process to a width of approximately 1/2" (Figures 1 & 2). This deposit was applied at 8-10 volts, 80-95 amps. After this weld deposit had been applied, the joint geometry was then machined at this clad end. This section of pipe was then butt welded to the 304L SS pipe. The root pass was made by the GTAW process at 90 amps with argon gas backing. This pass was allowed to cool to ambient temperature at which time a second pass was made at 95 amps. When the interpass temperature had reached 120°F (this was the actual reading -- the spec required 300°F max. interpass temp.) a final cover pass was made by the SMAW process at 85-90 amps. Half this circumferential weld deposit was made with a weave bead and half with stringer beads (see sketch). This was done to assess the cover pass weld technique's effect on sensitization.

Metallurgical Evaluation

To evaluate the suitability of this welding procedure to minimize the propensity for IGSCC it was decided that the HAZ structures would be evaluated by the oxalic acid etch test (A262 prac. A) for the degree of sensitization. Metallographic specimens were prepared transverse to the butt weld from the four quadrants of the pipe. These specimens included the weld and both HAZ's. After the specimens were etched, the HAZ areas showing the highest degree of sensitization on the I.D. were photomicrographed.

Conclusion

The degree of sensitization in the HAZ adjacent to the I.D. weld clad is significantly less than that which has been observed to be associated with the current pipe cracking. Based on this observation, it appears that I.D. weld clad, deposited with good control on heat input, will be beneficial in minimizing the potential for IGSCC and therefore should be utilized when joining new spools of 304L SS to existing 304 SS pipe ends.

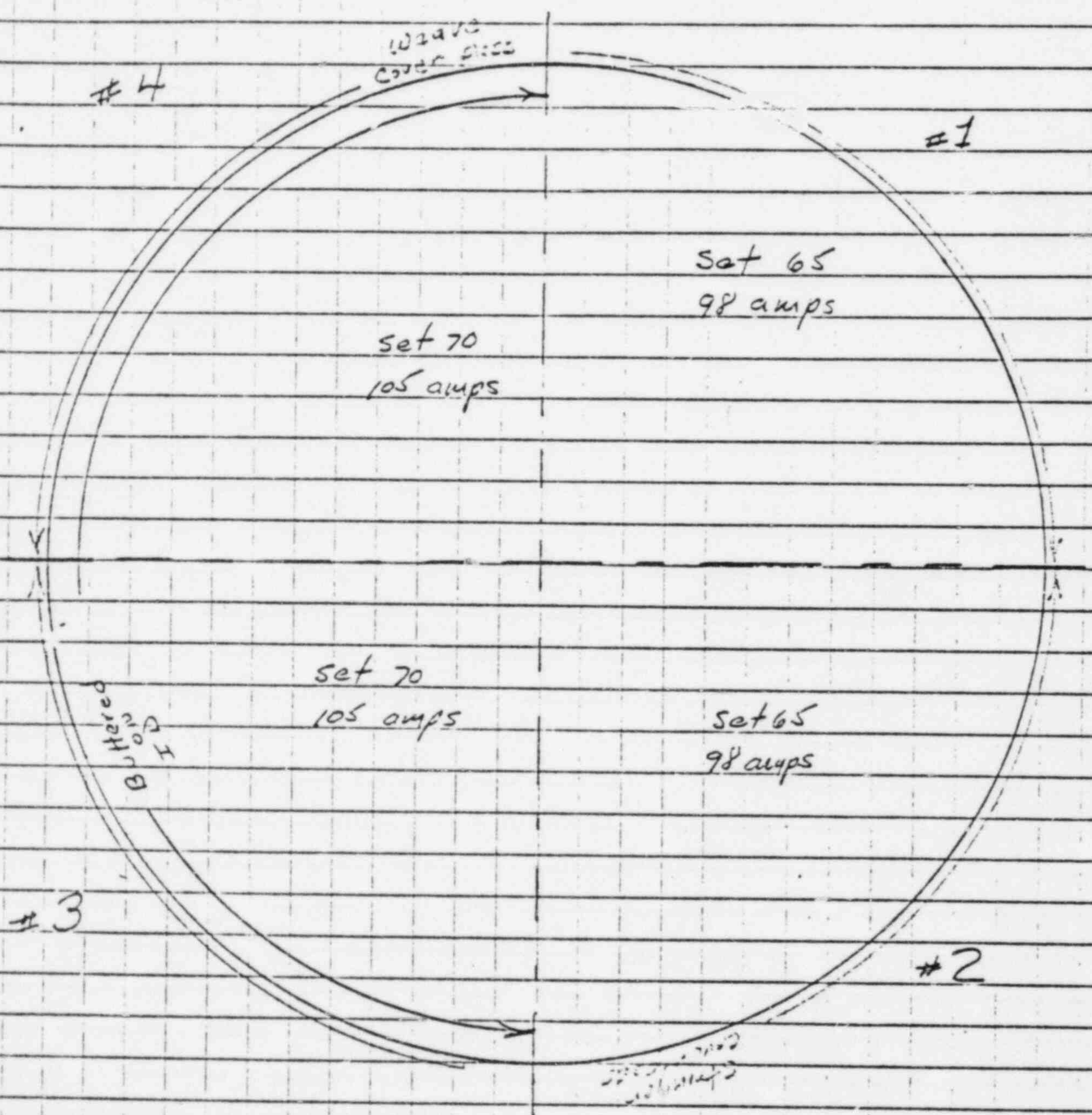
No difference in degree of sensitization at the I.D. was observed between the weave or stringer bead cover pass.

As would be expected, the 304L SS (.016% C) heat-affected-zones showed no evidence of sensitization, further supporting this material's use in the borated water environment.

F. SCOTT GIACOBBE

FSG:brk

cc: T. Corrie
R. D. Hopkins
S. Levin
T. Mackey
J. Pearce
D. M. Smith
R. L. Wayne



304 SS - 304L SS Butt Weld
GTAW Root SMAW Fill

CHEMISTRY

	HT. No. 334165	HT. No. 83602000
C	.080	.016
Mn	1.72	1.87
P	.028	.025
S	.014	.005
Si	.52	.45
Cr	18.46	18.45
Ni	8.60	10.10

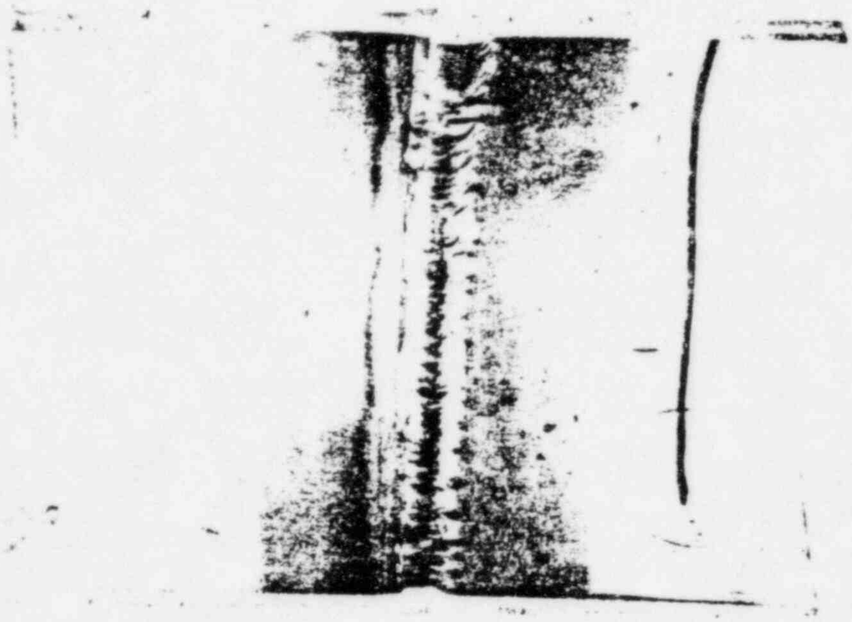


FIGURE I

Weld clad on ID surface on the 304 SS pipe end

FIGURE 2

Photo showing butt weld plus I.D. weld clad

FIGURE 3

Sample #3
Mag 500X
Etch: Oxalic Acid
HAZ adjacent to
I.D. weld clad.
Step structure,
no ditching

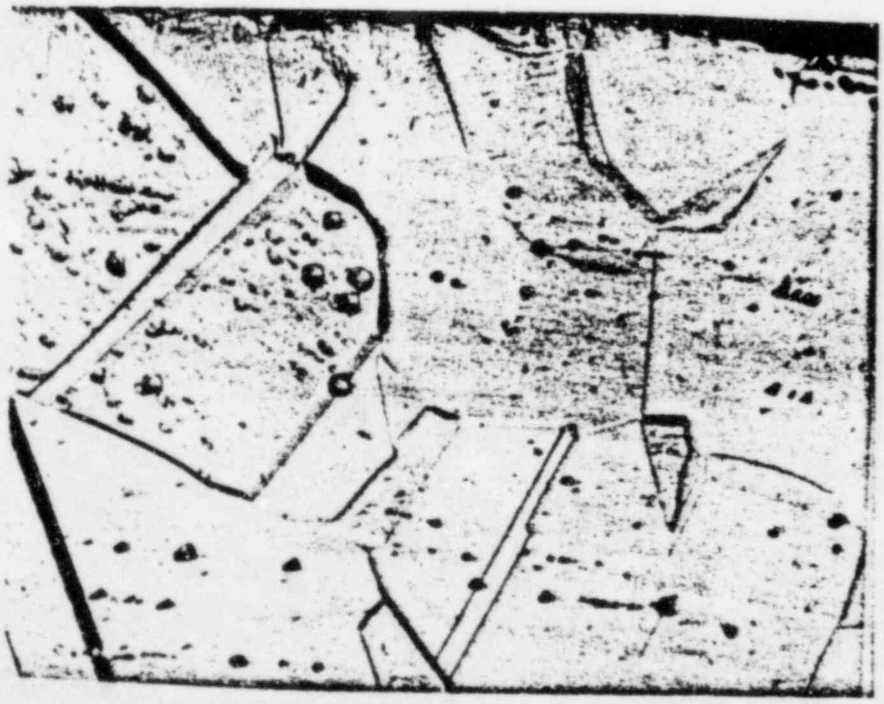


FIGURE 4

Sample #3
Mag 500X
Etch: Oxalic Acid
304 L SS HAZ on
I.D. surface.
Step structure,
no ditching

FIGURE 5

Sample #4
Mag 500X
Etch: Oxalic Acid
HAZ adjacent to
I.D. Weld clad.
Step structure,
no ditching

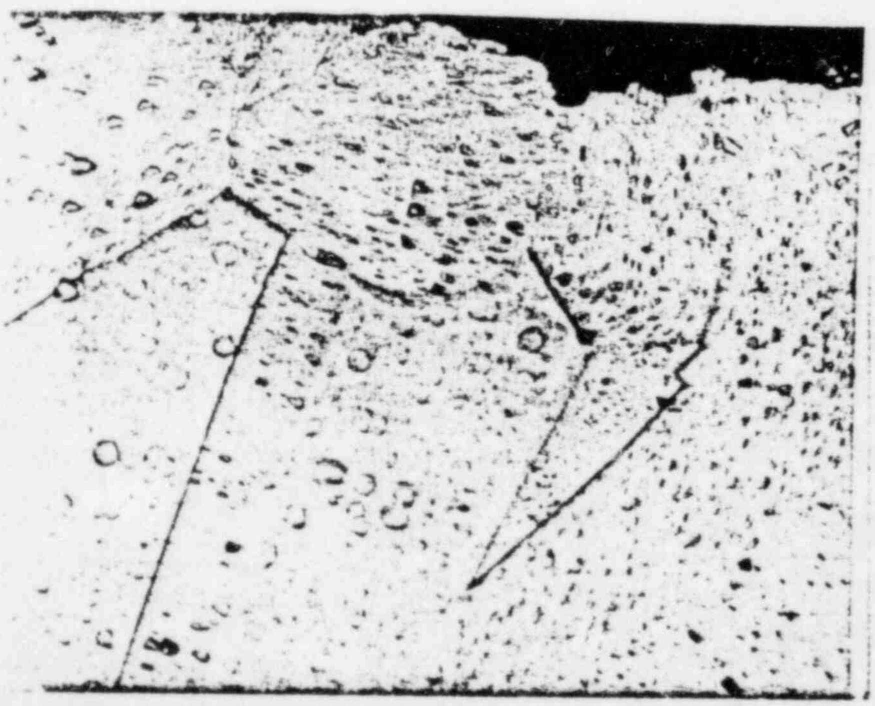


FIGURE 6

Sample #4
Mag 500X
Etch: Oxalic Acid
304 L SS HAZ on
I.D. surface.
Step structure,
no ditching

FIGURE 7

Sample #1
Mag 500X
Etch: Oxalic Acid
304 SS HAZ at I.D. surface. Step structure plus some ditching

FIGURE 8

Sample #1
Mag 500X
Etch: Oxalic Acid
304 L SS HAZ at I.D. surface. Step structure, no ditching

FIGURE 9

Sample #2
Mag 500X
Etch: Oxalic Acid
304 SS HAZ at I.D. surface. Step structure plus some ditching

FIGURE 10

Sample #2
Mag 500X
Etch: Oxalic Acid
304 L SS HAZ at I.D. surface. Step structure, no ditching

Section 5: DISCUSSION OF DESIGN CONSIDERATIONS

5.1 INTRODUCTION

The impact of the metallurgical analysis, stress analysis and environmental or operational parameters on the design consideration of the various borated water systems is addressed in this particular section. Since the metallurgical and materials analyses have been thoroughly presented in Sections 2, 3 and 4.2, it will not be further discussed in this section.

5.2 STRESS ANALYSIS

Piping that has exhibited intergranular stress corrosion cracking (IGSCC) are parts of TMI-1's auxiliary and emergency systems. Some of these systems support the reactor during normal operation and servicing of the station, while others are part of the station's engineered safeguards which are designed to function under accident conditions to prevent or minimize the severity of an accident or to mitigate the consequences of an accident. In evaluating the cracks and the proposed repair procedures, the requirements of applicable codes for the piping were always the basis for acceptance. The applicable piping codes per TMI-1 FSAR are as follows:

1. USAS B31.7 (for nuclear Class 1 piping systems).
2. USAS B31.1.0--1967 (for nuclear Case 2 and 3 pipines. Also applied for non-nuclear piping).

Structural integrity of the piping system is assured by consideration of dynamic and static loads and limiting the maximum stresses to code allowable values. The expected loadings for the affected piping systems are given below:

1. Internal pressure
2. Deadweight of pipes, valves and pipe contents

3. Thermal expansion

4. Safe shutdown earthquake

5. Thermal shock, if any

6. Anchor movements

The above loadings have been considered in the original design of the affected piping and present efforts in qualifying these piping include review of the original stress report to make sure that code requirements are satisfied.

The type of loadings that have adverse effect on crack propagation, initiation and the critical crack size are those that are cyclic in nature. These loads impose stresses that open up the cracks which are initiated in the sensitized heat affected zones of the pipe welds. These loadings will now be discussed in detail.

5.2.1 Seismic Effects

Borated water piping that have been inspected for IGSCC and found containing positive indications are seismic Class 1 types. These piping were designed such that even during an occurrence of a safe shut-down earthquake (SSE) the systems can still function. Review of the stress report reveals that for nuclear class piping, the primary stresses generated by combined effects of internal pressure, deadload and SSE are always less than the code allowable values which are:

a) For Nuclear Class 1 piping:

   Allowable Stress=1.5 Sm, where Sm is the allowable stress intensity value for the material at the operating temperature.

b) For Nuclear Class 2 & 3 piping:

   Allowable Stress=1.2 S_h, where S_h is the allowable normal stress at the operating temperature.

It is noted that the above criteria prohibits the primary stress field from reaching the yield strength of the material at the pressure boundary thereby ensuring that catastrophic failures of the piping are prevented.

It is in this context that the effects of the cracks and the proposed repairs were evaluated in the affected piping systems. The decision to replace or repair welds that exhibit IGSCC requires preliminary evaluation of acceptable crack depths, allowable stress of the replacement material, and the state of stress generated by combined effects of SSE, deadweight and internal pressure at the crack location.

In the evaluation of acceptable crack depth, linear elastic fracture mechanics techniques have been and will be utilized to study crack-stress field interactions to assure structural integrity of the system even after the occurence of these cyclic loads. This concept will be discussed in a later section.

5.2.2 Thermal Effects

After the cracks were observed in the Spent Fuel Piping System, the initial belief was that thermal loads on the piping which are cyclic in nature may have initiated the cracks. This belief was reinforced by the fact that the Spent Fuel Piping IGSCC is a unique phenomenom because it has never been observed before at service temperatures below 140°F. Furthermore, since TMI-1 came into commercial operation, the affected piping did not experience any cyclic loads except those that are due to thermal effects.

Review was then made of the original analyses of the affected piping. For those whose operating temperature was below 140°F and hence was not originally analyzed for thermal effects, new computer thermal analyses were made to ascertain thermal stress levels at the locations where cracks were observed. Major findings of this evaluation are summarized below:

1) Original thermal analysis showed that code requirements were satisfied. Thermal stresses in the affected piping system during the worst operating condition of the system are always lower than the allowable values specified in the applicable codes.
2) Thermal stresses at locations where cracks are observed for piping systems with operating temperatures that are below 140°F are low such that these cannot be primarily responsible for generating the observed cracks. The same thing can be said for piping systems whose operating temperatures are above 140°F.
3) At some points where trunnions are welded to the pipes carrying borated water, high local stresses were calculated. These stresses are primarily secondary in nature and are due to stress intensification effects at the discontinuities. No cracks were found in these areas.

The above findings support the theory that cyclic piping loads due to thermal effects is not the primary cause of the IGSCC cracks that were found in piping systems handling borated water at TMI-1. The thermal loads may have contributed to the crack propagation and opening mechanisms after it has initiated.

5.2.3 Fracture Mechanics Evaluation of IGSCC Cracks

One of the present capabilities at GPUSC is the ability to evaluate stress field-crack interaction using the principles of linear fracture mechanics and the toughness properties of the affected material. Effects of cyclic loads on the propagation of observed cracks can be studied and the results can be utilized to arrive at recommendations regarding such factors as acceptable flaw sizes, frequency of inspection, and other important IGSCC related parameters. Data on fatigue crack propagation rate in the sensitized heat affected zone of a stainless steel pipe welds in a stress corrosion environment is not readily available, but a conservative estimate can be utilized in this evaluation. This estimated rate can be compared to actual growth rate data which could be generated in laboratory studies.

5.2.4 Weld Residual Stresses

No effort has been made or planned to quantitatively determine these stresses at the locations where cracks were found in various piping systems handling borated water. However, welding procedures and techniques were reviewed to minimize these stresses during the installation of replacement sections.

A literature search revealed that the influence of residual stresses on the IGSCC process in Type 304 Stainless Steel Piping have been studied in detail by GE and EPRI (see report no. EPRI NP-944, "Studies on AISI Type-304 Stainless Steel Piping Weldments for Use in BWR Application, December, 1978). Pertinent findings on the nature and effects of residual stresses are summarized below.

1. The welding process itself produces a strain-hardened heat affected zone which remains elastic at stress levels in which

remains elastic at stress levels in which the nominal pipe becomes plastic. This higher yield strength in the heat affected zone tends to prevent mechanical shakedown of the residual stresses present.

2. Significant longitudinal tensile residual stresses occur on the inside surface of the heat-affected zone as a result of butt welding of pipe sections.
3. Severe grinding of the welds can introduce high tensile residual stresses and consequently produce a brittle "skin" which can crack under modest loadings, and produce metallurgical changes to the surface structure which include recrystallization and the formation of martensite.

The GE-EPRI IGSCC study has consequently established the possibility that cracks can be initiated by the high residual stresses that may develop in the sensitized heat affected zone of the welds. Propagation characteristics of the cracks will be affected by toughness properties of the HAZ, the crack environment and the mechanical loadings that are seen by the affected piping.

5.3 ENVIRONMENTAL ANALYSIS

An evaluation of the water chemistry of systems believed to be affected by intergranular stress corrosion cracking was performed using TMI-1 Chemistry Laboratory Log Book data from January 1975 to July 19[illegible].

Graphs were developed to assist in understanding the chemical behavior of borated water in the following systems:

1. Reactor Coolant System
2. Spent Fuel Cooling System

3. Decay Heat Removal System

4. Core Flooding System

5. Borated Water Storage Tank

The Reactor Building Spray System was never sampled as there was no means of obtaining samples and the Makeup and Purification samples were the same as the Reactor Coolant letdown samples.

Of importance to the evaluation were the operating conditions and B&W water chemistry requirements.

The Borated Water Storage Tank (BWST) is sampled twice a week.

The Decay Heat Removal System takes suction from the hot leg outlet line and delivers the water back to the reactor through the core flooding injection nozzles after passing it through the decay heat removal pumps and coolers. The system is sampled and analyzed only during shutdown and refueling.

The Spent Fuel Cooling System removes decay heat from spent fuel and circulates the pool water, the fuel transfer canal water and BWST water through the Liquid Waste Disposal System. The system is sampled once a week in the cleanup loop.

A high reactor building pressure signal of 4 psig from Engineered Safeguard Actuation System opens the Reactor Building Spray isolation valve and a building pressure of 30 psig signal starts the pump and starts operation after a LOCA. This system is stagnant. However, once a month during normal operation, the system is in the recirculation mode for pump functional test and valve lineup for about 60 seconds. There is no sampling in the system.

The Core Flooding System is normally stagnant. There is flow in the system once a year, during refueling and cold shutdown for valve operability test. The inservice inspection (ISI) is performed during reactor coolant system depressurization and cooldown. Reactor coolant pressure is at 530 ± 20 psi and temperature is within the heatup/cooldown curve.

The Makeup and Purification System is normally running during plant operation. Flow is through the normal letdown lines from the reactor coolant system loop B to letdown coolers, to makeup and purification demineralizers, to makeup and purification filters and to the makeup tank (MU-T1). Pump testing is run once a month and comes off the makeup tank. The high pressure injection lines are always full but stagnant. Flow is sent to the core once a year for flow testing.

Since the shutdown of the plant on February 18, 1979, the Decay Heat Removal System has been running from a temperature of about 200°F down to 90°F. In April 1979, an ISI was performed taking suction from BWST, recirculating the flow to the reactor core back to the BWST. Samples were taken and chloride values were reported to be 0.22 ppm on April 5 and April 23 in loop A and 0.35 and 0.19 ppm on May 11 and May 14 respectively in loop B.

The water chemistry to be maintained in the Reactor Coolant System as recommended by Babcock & Wilcox during normal operation is as follows:

Boric acid, ppm - Varies according to time in core life (13,000 ppm or 2270 ppm B)

Lithium as ^{7}Li, ppm - 0.2 - 2.0

pH at 77°F - 4.6 - 8.5 expected range with all variations of Li & B

at 600°F - 6.4 - 7.8

Max. dissolved oxygen as O_2, ppm - 0.1

Max. chlorides as Cl^-, ppm - 0.1

Max. fluorides as F^-, ppm - 0.1

Hydrogen as H_2, std cc/kG H_2O - 15-40

Max total gas, std cc/Kg H_2O - 100

The water chemistry to be maintained during cold shutdown condition or refueling (RC system below 200°F) is as follows:

Boric acid, ppm - 13,000 pp, boric acid or 2270 ppm boron

Lithium as ^7Li, ppm - 0.2 - 2.0

pH - no attempt is made to control the pH during refueling operations

Max. dissolved oxygen as O_2, ppm - no specific attempt is made to control oxygen during refueling, since the reactor vessel is open to the reactor building atmosphere via the transfer canal

Max. chlorides as Cl^-, ppm - 0.1

Max fluorides as F^-, ppm - 0.1

Hydrogen as H_2, std cc/Kg H_2O - no specific limits, once the reactor is depressurized, it is also degassed, H_2 is removed from the reactor coolant.

Hydrazine, ppm - 0.1 - 1.0, added only when dissolved O_2, Cl^- and F^- are each >0.1 ppm.

Technical specifications require that the boric acid analysis of the reactor coolant should be performed twice a week or before and after the boric acid concentration is purposely changed. Analysis for ^7Li in the reactor coolant should be necessary only once a week; however, when large quantities of fresh makeup are addded, an analysis should be performed. When a purification demineralizer with unsaturated cation resin is used, the concentration should be checked once or twice each day.

Technical specifications for the BWST require that samples should be taken and analyzed for boron concentrations twice a week.

Technical specifications for the Spent Fuel Cooling System require that sampling should be weekly only when spent fuel is stored in the pool or when plans are being made to store fuel in the pool. Samples for analysis are obtained upstream of the clean-up loop.

The TMI-1 chemistry laboratory personnel performed daily analyses for pH, conductivity, chloride, boron, fluoride, lithium and dissolved oxygen in the Reactor Coolant System during normal operations. The same analyses were performed in the Spent Fuel Cooling and Decay Heat Removal Systems during shutdown and refueling.

The Core Flooding System and the BWST were only sampled and analyzed for boron concentrations. Occasionally, the BWST samples were analyzed for pH, conductivity, chloride and fluoride.

Lithium-7 hydroxide was used in the reactor coolant as a pH control additive during critical conditions and power operations and during

subcritical or cold shutdown conditions. Lithium-7 was maintained between 0.2 - 2.0 ppm.

pH was generally in the range of 5.29 - 7.51 in the Reactor Coolant System, 4.65 - 6.29 in BWST, 4.74 - 7.66 in Decay Heat Removal System, 4.85 - 5.85 in Core Flooding System, and 4.4 - - 7.00 in Spent Fuel Cooling System.

Chloride levels in the Reactor Coolant System were in the range of 0.0 - 0.1 ppm with values reported as 0.195 and 0.155 ppm on June 21 and June 22, 1976 respectively. No attempts were made to check the values obtained during these two days, as the next analysis was performed on July 7, 1976 with a reported chloride level of 0.06 ppm. Chloride levels in the BWST were in the range of 0.0 - 0.07 ppm with reported high levels of 0.45 and 0.185 ppm on June 13 and June 20, 1976. During the months of April, May, and June 1975, chloride levels were in the range of 0.11 - 0.215 ppm in the Decay Heat Removal System. Again on April 27 and 28, 1976, chloride values were reported as 0.84 and 0.25 ppm respectively. Apparently, the system was contaminated with chlorides and it took a while to get the chlorides flushed out of the system. Chlorides in the Spent Fuel Cooling System were in the range of 0.0 - 0.1 with one reported value of 0.17 ppm on April 28, 1979. Chlorides in the Core Flooding System were in the range of 0.0 - 0.26 ppm. In February, July and August 1976 chlorides were reported as 0.125 to 0.26 ppm for Core Flood tank A and 0.12 - 0.175 ppm for Core Flood tank B. Possible sources of chlordies would be the Makeup and Purification demineralizers, the demineralized water used for mixing the boric acid solution and the chemicals added to the systems, i.e., boric acid, sodium thiosulfate and sodium hydroxide.

Oxygen has been maintained within the limits in the RCS during operation. However, during plant shutdown or refueling, oxygen removal processes cease, since the reactor vessel is open to the reactor building atmosphere via the transfer canal. Oxygen levels could increase to saturation point from aerated water, radiolysis and absorption of air. Hydrogen peroxide could be generated in the oxygenated, borated refueling water in the presence of core gamma flux.

In an attempt to further determine possible contaminants which could contribute to IGSCC of 304 SS, samples were taken from the suction of the Building Spray pumps (BS-P1A and 1B), Makeup pumps (DH-V44) and Decay Heat pumps. The following are the results of the analyses:

Sample	Date	pH	Cond mho	Cl^- ppm	B ppm	F^- ppm	Na^+ ppm
DH-V35A	7/3/79	5.01	10.5	0.12	2531	0.019	-
BS-P1A	7/3/79	5.13	31.5	7.63	2503	<0.019	-
BS-P1B	7/3/79	5.12	62.3	20.63	2503	<0.019	-
BS-P1A	7/5/79	5.35	39.5	11.63	2519	<0.02	6.9
BS-P1B	7/5/79	5.4	54.5	18.88	2491	<0.02	8.35
DH-V44	7/5/79	5.3	9.7	0.12	2487	<0.02	1.21
BS-P1A	7/10/79	5.4	36.0	10.75	2488	<0.019	2.35
BS-P1B	7/10/79	5.37	52	16.50	2485	<0.019	13.74

Additional samples were taken from the following locations:

Makeup and Purification System (dwg. no. C-302-661)

DH-V44	- pump suction
MU-V16A or B MU-V16C or D	drain valves in HPI lines

Makeup and Purification System (dwg. no. C-302-660)

DPT 429 - bypass line to Makeup and Purification demineralizers (stagnant line)

Decay Heat Removal System (dwg. no. C-302-640)

DH-V66 - line to pressurizer

DH-V68A or B - stagnant line to MU pump suction

Spent Fuel Cooling System (dwg. no. C-302-630)

SF-V59 - stagnant line used only refueling

SF-P2 - discharge of SF pump

Building Spray System (dwg. no. C-302-712)

BS-V55A or B - Sodium Thiosulfate line

BS-V56A or B - Sodium Hydroxide line

BS-V48A or B - downstream of NaOH tank

Chemical Addition (dwg. no. C-302-670)

PI 581 - 4% BAMT

Liquid Waste Dispoal (C-302-693)

WDL-V193 - local sample point in Reclaimed Boric Acid Tank

The following are the results of the analyses:

Sample	Date	pH	Cond mho	Cl ppm	F- ppm	Na+ ppm	Li+ ppm	B ppm	DO ppm
DH-V66	7/31/79	5.66	18.7	0.045	<0.02	0.81	0.13	2177	2.30
MU-V143B	7/31/79	5.51	12.8	0.070	<0.02	0.92	0.14	2262	0.190
MU-V143B	7/31/79	5.75	19.7	0.055	<0.02	0.73	0.14	2152	-
SF-P2	7/31/79	5.23	10.5	0.040	<0.02	0.90	0.10	2402	5.60
BS-V48B	8/2/79	5.55	62.5	1.50	<0.02	1.09	0.17	2283	2.75
DH-V44	8/2/79	5.18	10.4	0.030	<0.02	1.14	0.13	2433	6.20
WDL-V193	8/3/79	-	40.0	3.75	0.21	13.0	2.80	24114	-
7% BAMT	8/3/79	-	43.0	1.4	<0.02	<0.10	<0.10	15680	-
DPT 429	8/3/79	5.51	17.5	0.12	<0.02	0.71	0.20	2609	-
BS-V55B	8/3/79	9.3	13,500	59,000	<0.05	31,000	-	615	-
BS-V56B	8/3/79	11.8	>14,000	1,300	<0.05	90,000	-	1017	-
SF-V59	-	No sample flow							
DH-V68	-	No means of obtaining sample							
4% BAMT	-	No water in tank							

It appears that the two tanks, sodium hydroxide and sodium thiosulfate, can provide a source for the chloride contamination observed in samples BS-V55B and BS-V56B. Whether or not this is a source of contamination for the entire borated water system will need to be explored.

The following operational changes could be implemented if the technical specifications permit:

1) A maximum limit of 0.1 ppm chloride could be maintained by frequent recirculation of the Decay Heat Removal System during normal plant operation. This could be done by interconnecting the Decay Heat Removal System and Spent Fuel Cooling System during purification. Subsequently, sampling and analysis should be performed for chloride and fluoride to maintain the recommended level.

2) During refueling, both the Decay Heat Removal and Spent Fuel Cooling Systems take suction from the BWST and they could operate in conjunction to provide purification and recirculation of the water in the fuel transfer canal. The borated water recirculation pump takes suction from the bottom of the canal, pumps the water through a precoat filter and possibly through a cation demineralizer, then discharges into the suction header of the decay heat removal pumps which in turn inject the purified water into the reactor. Flow from the reactor to the refueling canal through the top of the opened reactor provides for canal circulation and purification.

3) Analyses for pH, conductivity, chloride, boron, fluoride and dis solved oxygen should be performed for samples taken from the BWST and Core Flood tanks. Analyses indicating in-specification chlorides require no further action. When an analysis of a sample indicates a chloride concentration beyond 0.1 ppm, the sampling frequency should be increased to determine whether or not the concentration is general.

4) pH control in the Spent Fuel Cooling and Decay Heat Removal Systems could be maintained by alkali addition.

Chemicals such as boric acid, sodium hydroxide and sodium thiosulfate are purchased to Met-Ed Generation specifications. Consideration was given to obtaining the lowest concentration of impurities available. "Rayon grade" caustic contains approximately 0.1% chloride (as NaCl). However, current technologies such as the use of a "chloride trap" to remove chlorides from caustic solutions should be given a consideration. Rohm and Haas just obtained a patent for this process.

While there is no positive evidence to associate the sodium thiosulfate tank to any of the cracking problems, efforts to discontinue use of sodium thiosulfate in the Building Spray System should be considered. (A long term modification is being carried out for upgrading the Building Spray System using hydrazine for iodine removal.)

To minimize corrosion-product formation and other deleterious effects of oxygen to BWST and related piping several alternatives were considered:

1. Vacuum deaeration
2. Nitrogen blanketing
3. Floating objects, i.e., plastic floating spheres
4. Chemical scavenging with hydrazine

A detailed evaluation of the above is required for justification of operational factors and economic feasibility.

5.4 RECOMMENDATIONS

Recommendations for dealing with the problem at hand will be divided into two subgroups: (a) Short Term and (b) Long Term.

5.4.1 Short Term

1. Replace all through-wall leaks in inspected systems containing borated water.
2. Replace all U.T. indications in the Decay Heat, Reactor Building Spray and Make-up and Purification Systems.
3. Evaluate samples removed by 1 and 2 above, and determine a positive correlation between U.T. indications and actual crack depth, if any.
4. All piping replacement will be made using low carbon stainless steel (i.e. 304L or 316L) that will meet the requirements of Regulatory Guides 1.31 and 1.44. Additionally all welding will be done using low heat input and filler metals containing a minimum of 5% ferrite.
5. Since existing pipe in systems containing borated water is 304SS with potentially high carbon content, I.D. buttering will be used to provide a more resistant material to IGSCC.
6. Should the findings of 3 above show a positive correlation between U.T. indication (full screen height) and IGSCC (crack depth), a decision will be made concerning the balance of indications in the Spent Fuel Cooling System. If no correlation can be obtained, and actual cra ks are found, all indications in one loop will be replaced immediately, and the remaining indications in the redundant loop replaced by the end of next outage.

7. Develop administrative proceedings to eliminate to the extent possible stagnant lines. This will be done by cycling from one redundant loop to another, when redundant loops are available.

Where lines are stagnant and the system or loop is inactive, periodic circulation should be initiated. If this is not possible, periodic system/loop flushing should be investigated.

5.4.2 Long Term

1. Develop an In-Service Inspection Program that will focus primarily on indications that may be left in, welds in heats with known high carbon content (e.g. 334165), field welds and in particular field welds followed by field weld repairs and welds made by welders which showed a high probability of indications (e.g. welder 9R). Additionally, other welds in systems that contain borated water will also be monitored but at less frequent intervals. The inspection program will be divided into two categories:

   a) Visual inspection for through-wall leaks, which will be done at frequent intervals, and b) U.T. inspection which will be scheduled such that the safety of the public or personnel as well as the plant operation will not be jeopardized. The details of the In-Service Inspection Program will be available at a later date, since the results of the laboratory data correlation between U.T. indications and actual cracks will have a major impact on the program.

2. Existing and future reserach in the field will be closely followed and similar occurences at other plants will be evaluated.

3. Better U.T. techniques will be used as they become available.

4. Additional repair techniques, if needed, will be investigated as more data becomes available.