Westinghouse

A Technical Report On Steam Generator Tubesheet Cladding

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TECHNICAL REPORT ON STEAM GENERATOR CHANNEL HEAD CLADDING

INDIAN POINT UNIT NO. 3

DOCKETED USNRC
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APPENDIX A

Westinghouse Report on Evaluation
of Cladding of the Steam Generator
Channel Heads

Consolidated Edison - Indian Point Unit No. 3

Consolidated Edison Co. of N.Y., Inc.
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TD-MET-75-080

EVALUATION OF CLADDING OF THE STEAM GENERATOR CHANNEL HEADS CONSOLIDATED EDISON - INDIAN POINT #3

September 18, 1975

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WESTINGHOUSE ELECTRIC CORPORATION
TAMPA DIVISION

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SECTION 1

ABSTRACT

Inspection of the steam generator channel head bowl cladding at Indian Point #3 has revealed the presence of indications.

Further examination, excavation, and sampling of the cladding have shown these indications are interdendritic defects in the weld overlay extending to the base metal interface in some instances. Attempts to eliminate the indications by grinding and weld restoration have resulted in detection of additional indications. An appraisal of the alternative methods of repair or allowing the indications to remain in their present condition has been made. This evaluation shows that the cladding is acceptable for its intended use as is and that alternative repair techniques are infeasible. The results of metallurgical and nondestructive examinations and structural analysis are presented with a proposal for in-service monitoring of representative areas.

No defects were observed in the Inconel clad which covers the tube sheet radius and lip areas. Also, no defects are present on the nozzle knuckle areas which were clad with shielded metal arc welding.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

1. Interdendritic cracking has been detected in large areas of the stainless steel channel head cladding of all four steam generators at Indian Point Unit No. 3. Although the cause has not been clearly identified, it is suspected to be the result of accidental exposure to sea water which is known to have occurred during shipment.

2. Mechanical removal of dye penetrant indications has shown that many indications cannot be removed without extensive base metal exposure.

3. Laboratory metallographic and chemical analysis has shown the cladding in its present condition to be adequate for its intended purposes.

4. Structural analysis of indications has been performed and has shown the indications to be acceptable.

5. A method of in-service nondestructive monitoring to detect indications of critical size has been demonstrated and a schedule of inspection proposed.

6. Similar experience in other nuclear pressure vessels has shown the indications to be static and allowable in service.

7. Alternative repair procedures have been considered and none has been found to be feasible.

It is, therefore, recommended that:

1. The location of present dye penetrant indications be recorded,

2. No additional excavation be required, and

3. Representative critical areas be identified and monitored by nondestructive test methods at scheduled intervals during plant life to assure no indications reach a critical depth. Areas selected will be in high stress regions.

SECTION 3

INTRODUCTION

The four Series 44 steam generators at Consolidated Edison's Indian Point #3 Site were initially fabricated at the Lester Heat Transfer Division. The lower shell of each steam generator was completed including tubing, weld overlay of the channel heads and joining of the heads to the remainder of the lower shell. Upper shell assemblies were also completed at Lester and the mating parts were shipped by barge to the Tampa Division for the final closure weld at the cone to upper shell.

During the barge transfer, sea water leaked into mechanically-sealed nozzles and contaminated the channel head cladding. Upon arrival at Tampa, the sea water intrusion was detected and a flushing operation was performed until all residue was eliminated. The effectiveness of sea water removal was measured by absence of chloride ions detected on cleaned, washed surfaces within the primary side of the steam generator. No penetrant testing of these areas was undertaken at that time. Prior to shipping the single piece generators to the site, a cleanliness inspection of the primary side was made and the units were closed with welded shipping covers to preclude the possibility of sea water re-entering while in transit to the field site. The closure weld was performed and the steam generators shipped to Indian Point.

After placement of the steam generators into the containment, a repair of the divider plate to tube plate joint was performed. This repair was required to eliminate the explosively bonded tube plate cladding from beneath the divider plate. Removal of this original tube plate center lane cladding was followed by restoration with overlay weld cladding and the required post weld heat treatment at approximately 1100-1150°F. The repair was completed by rejoining the divider plate to the restored tube plate cladding.

Following the hot functional testing of the primary loop system, rust colored deposits were noted during visual inspection of the clad surface of the channel head in steam generator 31, outlet leg in areas near the biological shielding ledge (Figure 1). Dye penetrant inspection performed in these areas revealed linear indications oriented parallel to the automatic weld beads, (Figure 2).

The dye penetrant indications were explored on an investigative basis and in one case excavated to a depth exposing base metal. Similarly, dye penetrant indications were revealed in steam generator 32, with visual inspection revealing superficial stains in varying degrees on clad surfaces in all steam generators. Spot checks with Severn Gauge indicated 5-10% ferrite.

Metallurgical specimens (boat samples) were removed from the primary clad surfaces and forwarded to Tampa for examination and evaluation. Samples removed from unit 32 were obtained in areas having a high frequency of clad indications and in areas previously known to have been exposed to sea water.

Due to previous history of sea water exposure, it was decided to dye penetrant inspect all primary clad surfaces in each steam generator. This examination detected indications throughout the cladding of each channel head but varying in degree by location, i.e. the frequency of indications was highest at the area just above and below the biological shielding ledge (see Figure 3).

The channel heads of the steam generators are carbon steel castings, ASME SA216, WCC and the cladding is series submerged arc weld overlay using 309 stainless steel weld metal, ASME SFA 5.9, Class ER 309. The Westinghouse Specification for the weld metal modifies the chromium and nickel contents to assure proper ferrite control.

Nickel: 12.00 - 13.00
Chromium, min.: 11.00 + Ni
Chromium, max.: 25.00

The cladding is dye penetrant inspected after deposit and after post weld heat treatment. The channel head cladding will usually be exposed to two post weld heat treatments (PWHT) during fabrication; the first PWHT occurs after cladding and the second occurs after joining the channel head to the tube plate. A dye penetrant examination is performed on cladding within the PWHT affected areas subsequent to the channel head/tube plate joint PWHT.

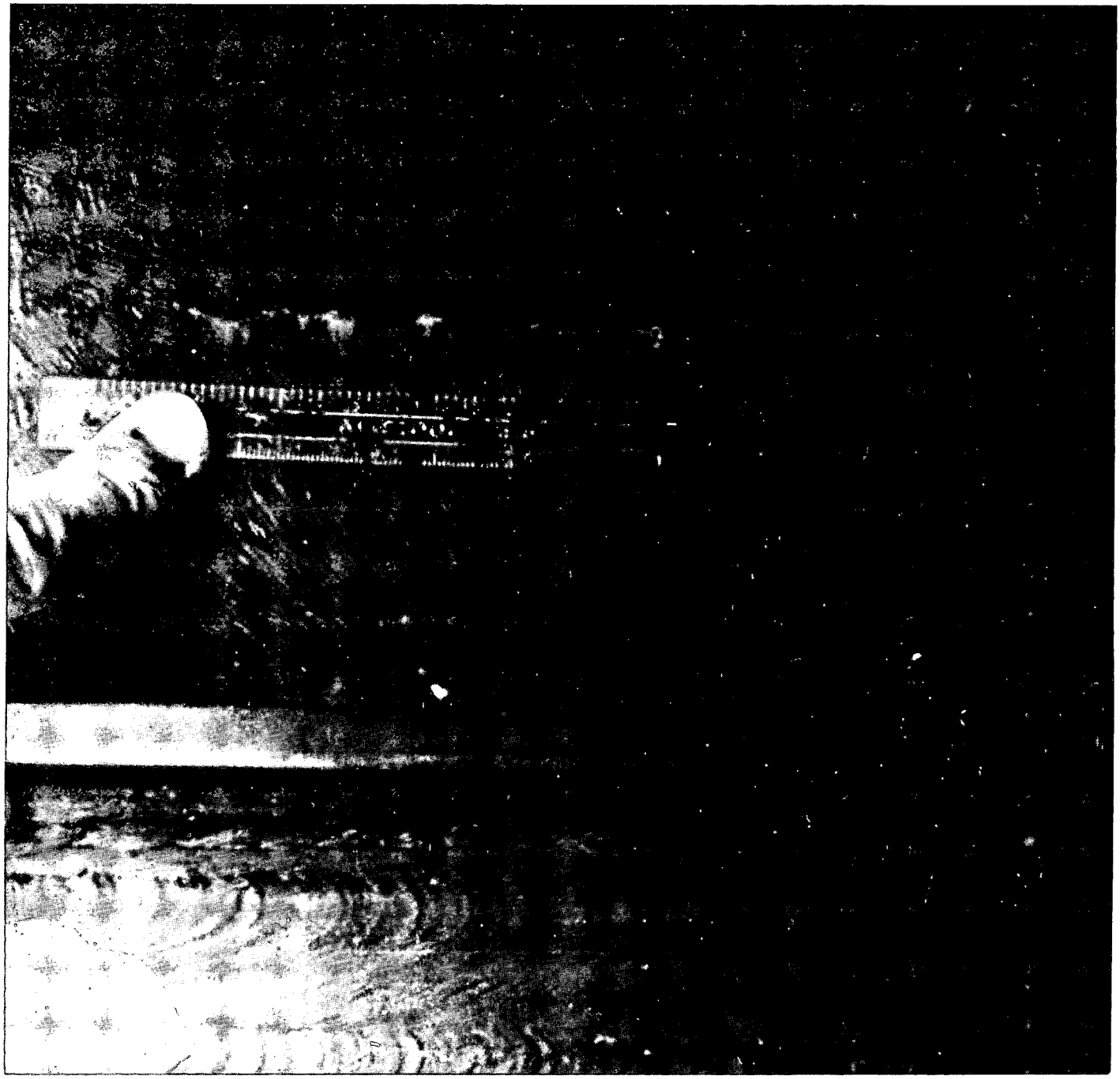


Figure 1. Photograph of superficial deposit discovered upon visual inspection in Steam Generator #32. Stain condition was prevalent in area adjacent to biological ledge located parallel and below stain deposit.

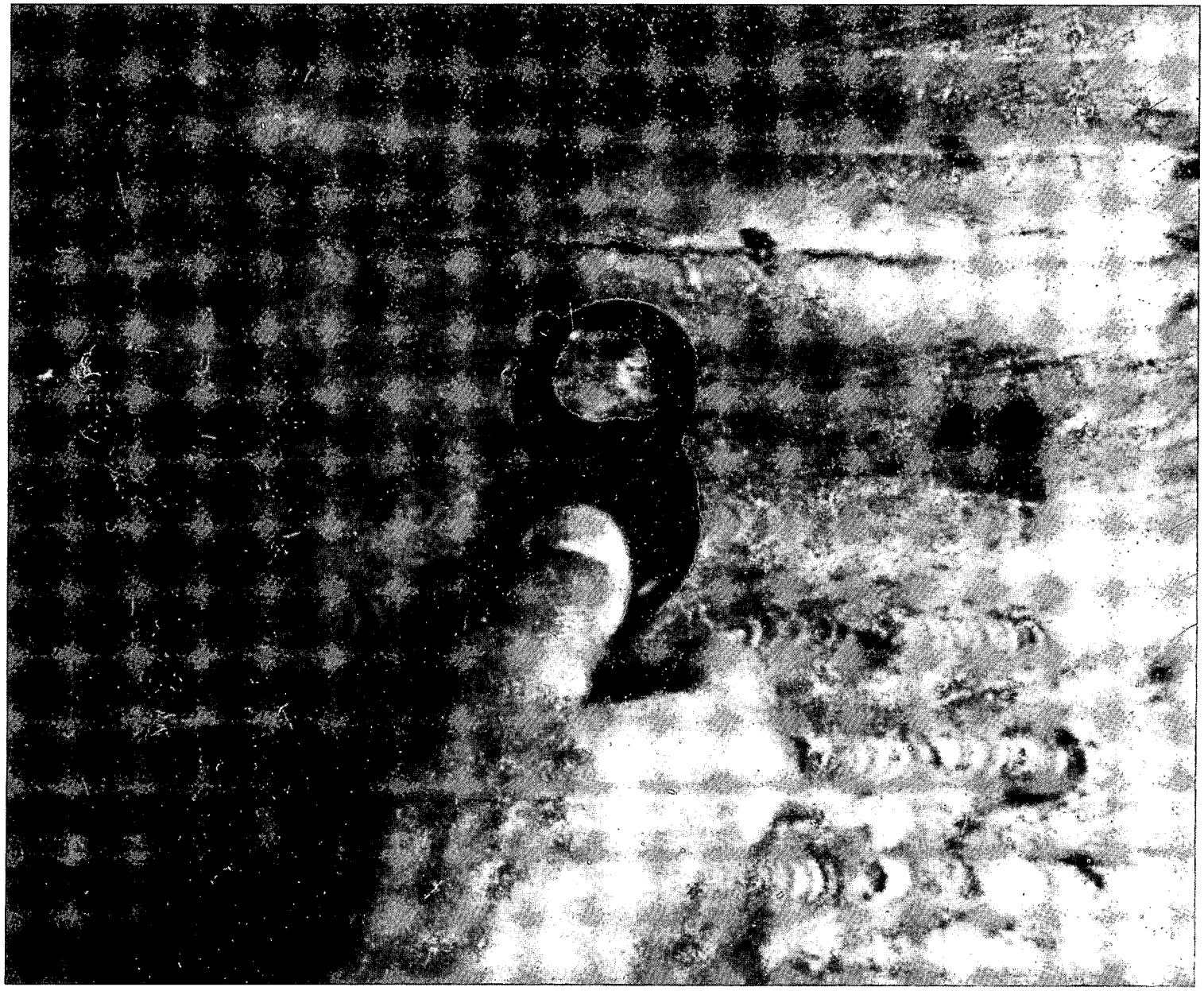


Figure 2. Dye penetrant indication on clad surface located between automatic weld beads -- Steam Generator #31.

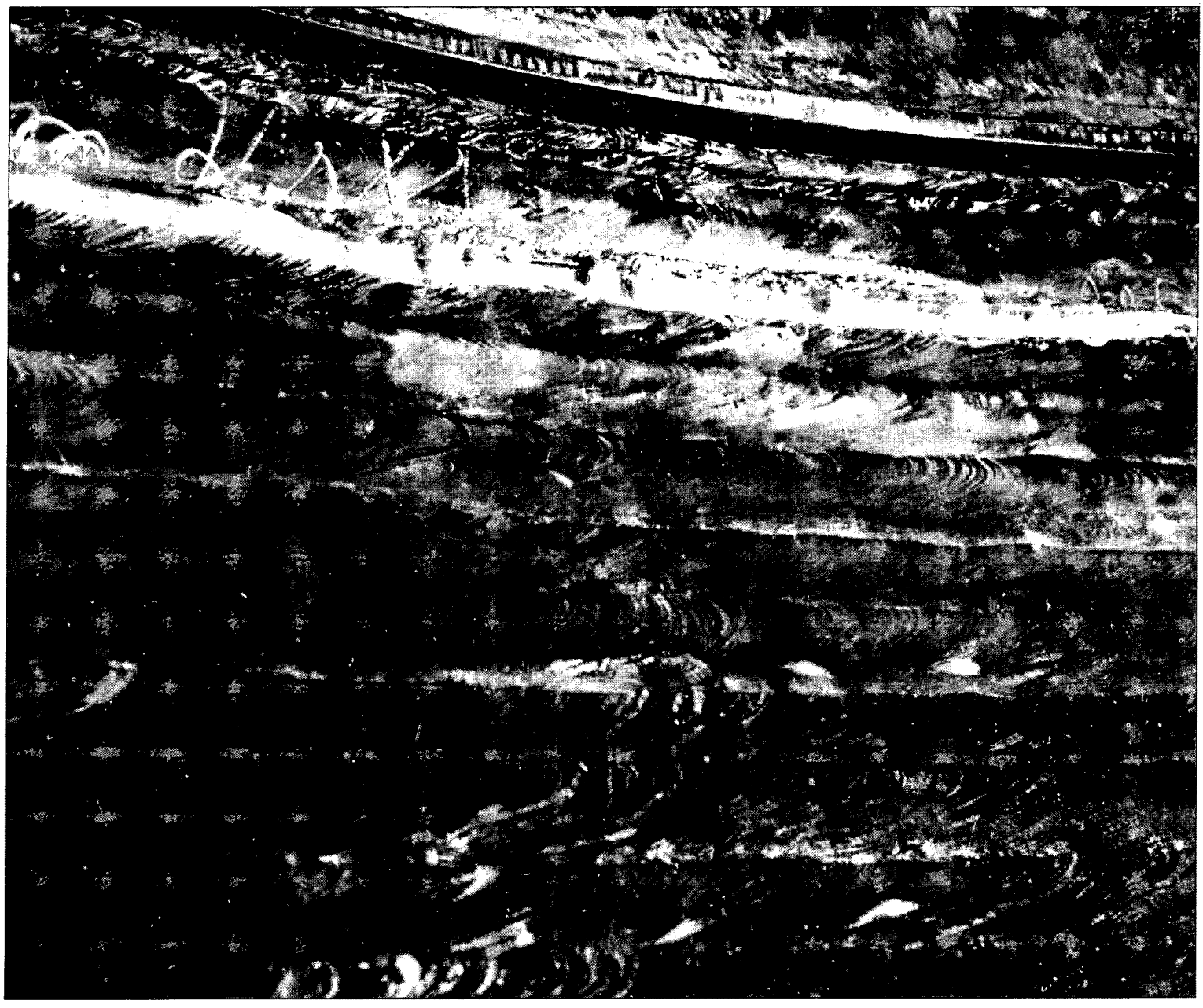


Figure 3. Excavated cladding indication between automatic weld beads in Steam Generator #33.

SECTION 4

DETECTION AND INITIAL WELD REPAIR OF CLADDING

After cladding indications were discovered in stainless steel overlay adjacent to biological ledge, all accessible primary clad surfaces (nozzle and bowl) in each of the four (4) steam generators were subjected to dye penetrant inspection. Dye penetrant indications were detected in each steam generator but only in isolated areas with only a minor portion (est. 5%) of all clad areas being affected. Systematic removal of the clad indications was carried out concurrently in all generators with progress being observed in various phases of each steam generator (i.e., Unit #33 was dye penetrant inspected with indications having been removed, subsequently repaired with this unit being closed while progress in other units had not proceeded beyond the clad indication removal stage). After grinding out the major clad indications in various portions of steam generators #31 and #34, attempted clad restoration indicated additional problems encompassing surrounding areas having previously been dye penetrant cleared. Clad repairs were performed utilizing one of two welding techniques.

1. Areas where carbon steel had been exposed were manually restored using the half bead temper repair. The unusually high preheat and postheat temperatures accompanying this type of repair limited its use and was employed only where necessary.

2. Areas where carbon steel had not been exposed but requiring restoration were repaired at ambient temperature by conventional manual weld overlay.

New clad indications were detected in the original series submerged arc overlay and were noted in varying degrees after weld repairs were made. In one instance a repair was initiated in the bottom of bowl clad of Unit #34. Subsequent dye penetrant inspection showed the deposited weld metal (repair) to be indication free with adjacent areas (previously PT clear) exhibiting dye penetrant indications. These indications were excavated and removed until

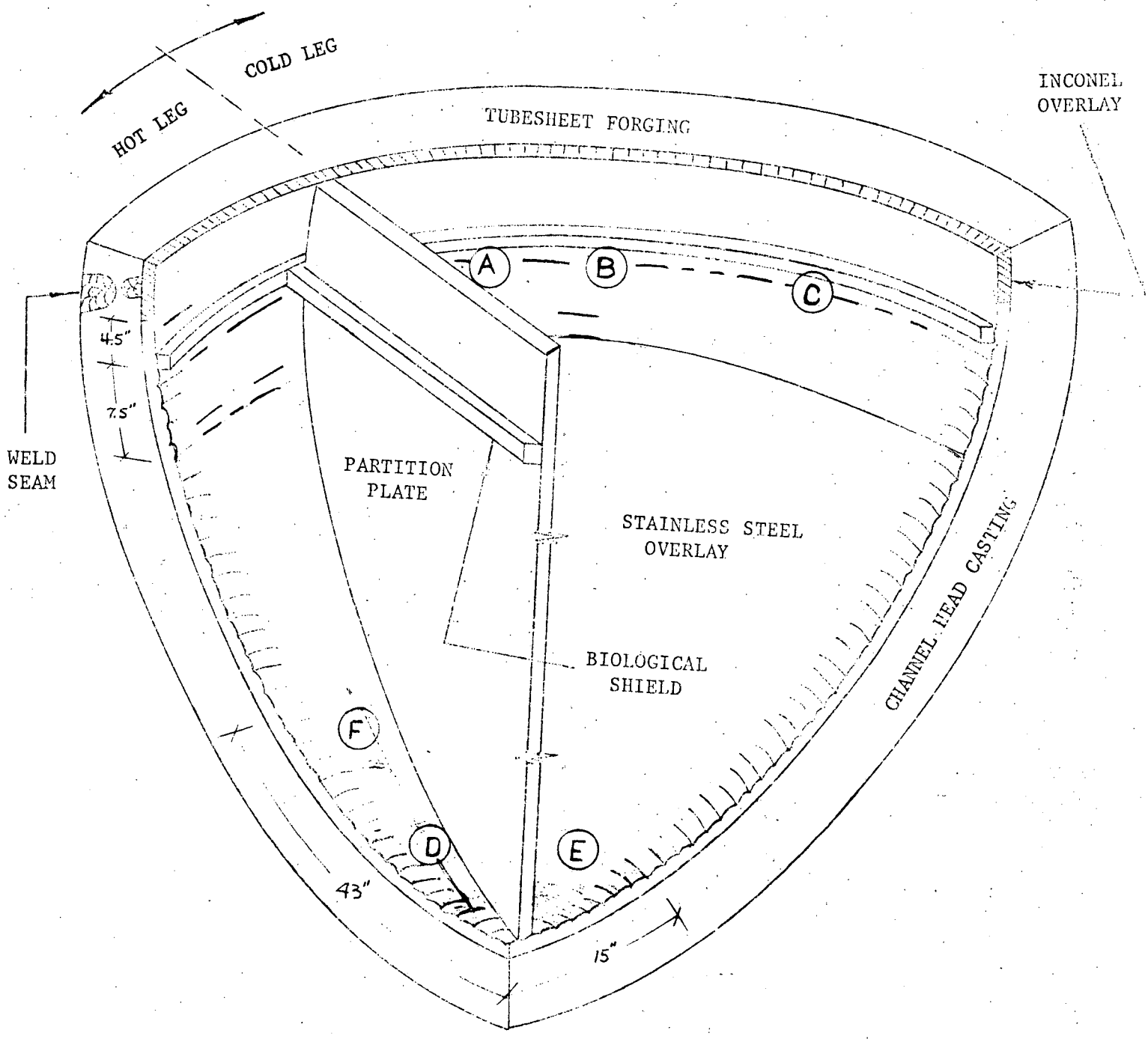
carbon steel base metal had been exposed. After totally removing dye penetrant indications a localized weld repair was made utilizing the half bead temper technique. It should be noted that it was necessary to preheat more than the area required in order to maintain the 400° temperature required for this procedure. Dye penetrant inspection subsequent to this weld repair showed new cladding indications in adjacent areas as far removed as 30 inches away. Similar patterns were detected in Unit #31 where half bead temper repairs had been utilized. Specifically areas having been locally heated to the required 400° preheat and postheat temperatures were exhibiting new clad indications.

At this point, all major cladding indications which were partially or totally removed were mapped and documented as indicated in the attached sketches and tables. A series of weldability tests was performed with samples having been removed for analysis.

Surface area now exhibiting dye penetrant indications can be conservatively estimated to be increased two-fold and is represented schematically for each steam generator in the following figures. The purpose of the selected photographs is to represent designated areas in each schematic which have newly discovered clad indications as well as showing the representative areas in various stages of repair. The photographs do not necessarily depict the final condition but are intended to show the present areas affected.

No defects were observed in the Inconel clad which covers the tube sheet radius and lip. Also, no defects are present on the nozzle knuckle areas which were clad with shielded metal arc welding.

STEAM GENERATOR #31



STEAM GENERATOR #31

Description	Vertical Reference	Curvilinear Reference	Length	Width	Depth
HL - bowl	6 beads below bio. shield	23 CW from partition plate	8	2.5	.100
HL - bowl	1 bead below bio. shield	7 CW from partition plate	7.5	3.0	.210
HL - bowl	6 beads below bio. shield	0 CW from partition plate	6.0	.38	.250
HL - bowl	1 bead below bio. shield	19.0 CW from partition plate	17.0	.38	.125
HL - bowl	1 bead tie-in below bio. shield	19.0 CW from partition plate	five areas $\frac{1}{4}, \frac{3}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}$ Ø's		BM *
HL - bowl	1 bead tie-in below bio. shield	1.0 CW from partition plate	6.0	.38	.21
HL - bowl	1 bead tie-in below bio. shield	65.0 CW from partition plate	1.125	.62	.31 *
HL - bowl	1 bead tie-in below bio. shield	63.0 CW - partition plate	51.0	.62-3.0	.25
HL - bowl	1 bead tie-in below bio. shield	0.5 CCW - partition plate	45.0	.62	.25
HL - bowl	1 bead tie-in below bio. shield	36 CCW - partition plate	1.0	.62	.31 *
HL - bowl	6-10 beads from BDC	Adjacent to partition plate CCW	7.5	.5-1.0	.25
HL - bowl	6-10 beads from BDC	Adjacent to partition plate CCW	two areas $\frac{1}{4}$ Ø, $\frac{1}{2}$ Ø		BM *
CL - nozzle	1 bead above drain	2.0 CW from drain	1/2 Ø	--	BM *
CL - nozzle	1 bead above drain	9.1 CCW from drain	1/2 Ø	--	BM *
CL - nozzle	2 beads above drain	31.5 CCW from drain	5/8 Ø	--	BM *
CL - bowl	1 bead tie-in below partition plate	12.5 CW - partition plate	2.0	.38	BM *
CL - bowl	" " " "	80.5 CW - partition plate	2.1	.38	BM *
CL - bowl	" " " "	83.75 CW - partition plate	3.25	.38	BM *
CL - bowl	" " " "	87.25 CW - partition plate	2.35	.38	BM *
CL - bowl	" " " "	94.1 CW - partition plate	4.5	.38	BM *

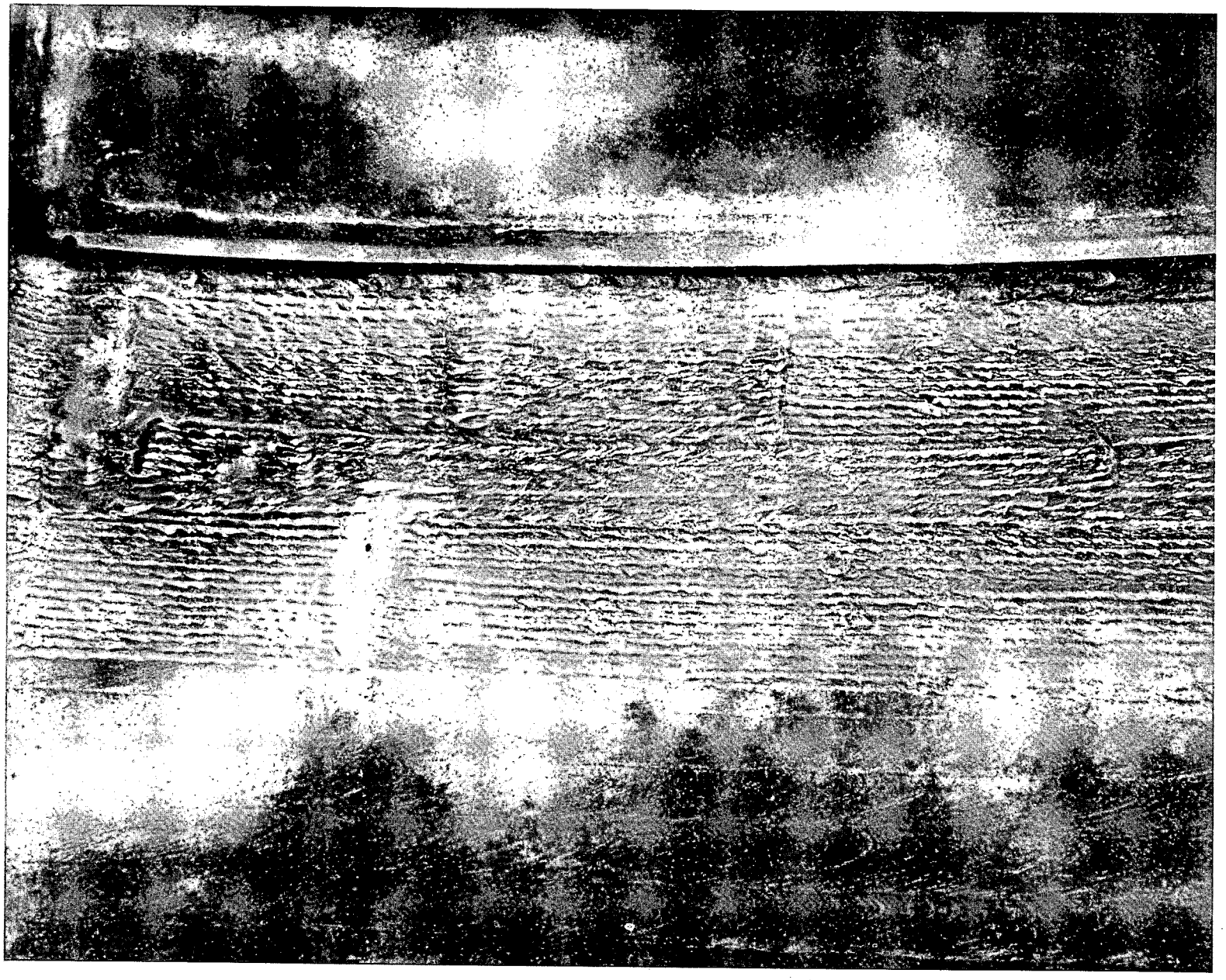
STEAM GENERATOR #31 (Contd.)

Description	Vertical Reference	Curvilinear Reference	Length	Width	Depth
CL - bowl	1 bead tie-in below partition plate	104.5 CW - partition plate	9.0	.38	BM *
CL - bowl	" " " "	117.1 CW - partition plate	8.4	.38	BM *
CL - bowl	" " " "	126 CW - partition plate	3.8	.38	BM *
CL - bowl	" " " "	132.6 CW - partition plate	11.5	.38	BM *
CL - bowl	" " " "	144.6 CW - partition plate	4.9	.38	BM *
CL - bowl	1 bead tie-in below bio. shield	150.5 CW - partition plate	9.6	.38	BM *
CL - bowl	" " " " "	161 CW - partition plate	2.0	.38	BM *
CL - bowl	" " " " "	169.5 CW - partition plate	8.5	.38	BM *
CL - bowl	" " " " "	178.5 CW - partition plate	1.5	.38	BM *
CL - bowl	6 bead tie-in below bio. shield	44.4 CW - partition plate	2.1	.38	BM *
CL - bowl	" " " " "	49.5 CW - partition plate	1.6	.38	BM *
CL - bowl	" " " " "	53.0 CW - partition plate	1/8 Ø	--	BM *
CL - bowl	1 bead tie-in below bio. shield	149.3 CW - partition plate	1.5	.38	BM *
CL - bowl	" " " " "	164.0 CW - partition plate	11.0	.50	BM *
CL - bowl	" " " " "	49.5 CW - partition plate	3.0	.31	.077
CL - bowl	" " " " "	52.5 CW - partition plate	6.75	.75	.164
CL - bowl	" " " " "	60.25 CW - partition plate	8.0	.38	.172
CL - bowl	" " " " "	68.25 CW - partition plate	10.75	1.38	.130
CL - bowl	" " " " "	80.0 CW - partition plate	4.00	1.13	.13
CL - bowl	6 bead tie-in below bio. shield	53.88 CW - partition plate	12.50	1.50	.34
CL - bowl	" " " " "	66.38 CW - partition plate	10.50	2.25	.28
CL - bowl	" " " " "	74.87 CW - partition plate	17.00	.50	.34
CL - bowl	1 bead tie-in below bio. shield	39.0 CW - partition plate	10.00	.38	.22
CL - bowl	" " " " "	51.0 CW - partition plate	3.4	.42	.30

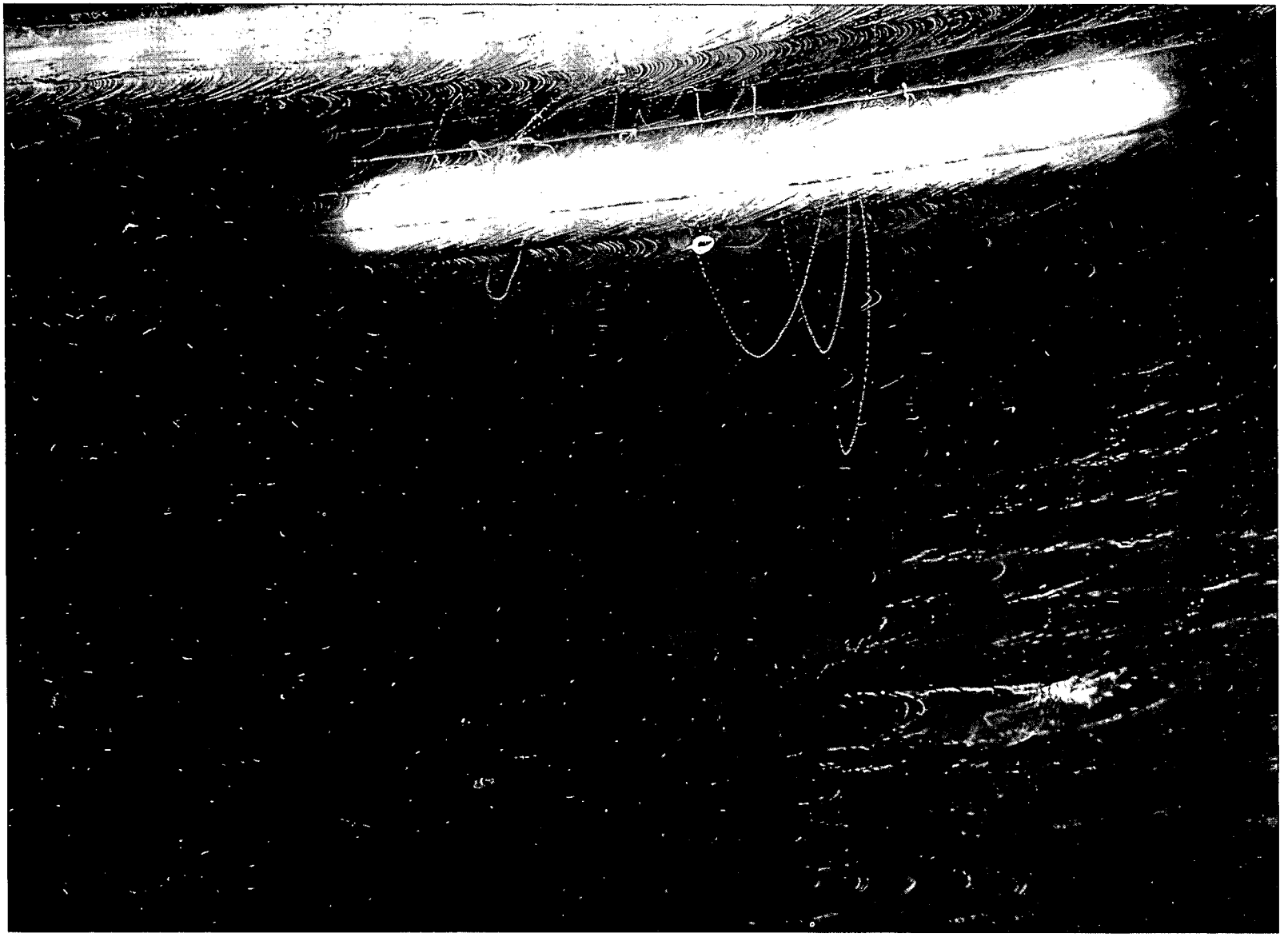
STEAM GENERATOR #31 (Contd.)

Description	Vertical Reference	Curvilinear Reference	Length	Width	Depth
CL - bowl	1 bead tie-in below bio. shield	91.25 CW - partition plate	2.75	.38	.189
CL - bowl	" " " " "	100.0 CW - partition plate	5.0	.56	.09
HL - bowl	0.75 above bio. shield	8.38 CW - partition plate	8.0	2.0	.25
HL - bowl	0.75 above bio. shield	23.50 CW - partition plate	17.5	2.0	.25
HL - bowl	0.50 above bio. shield	66.75 CW - partition plate	6.75	2.0	.25

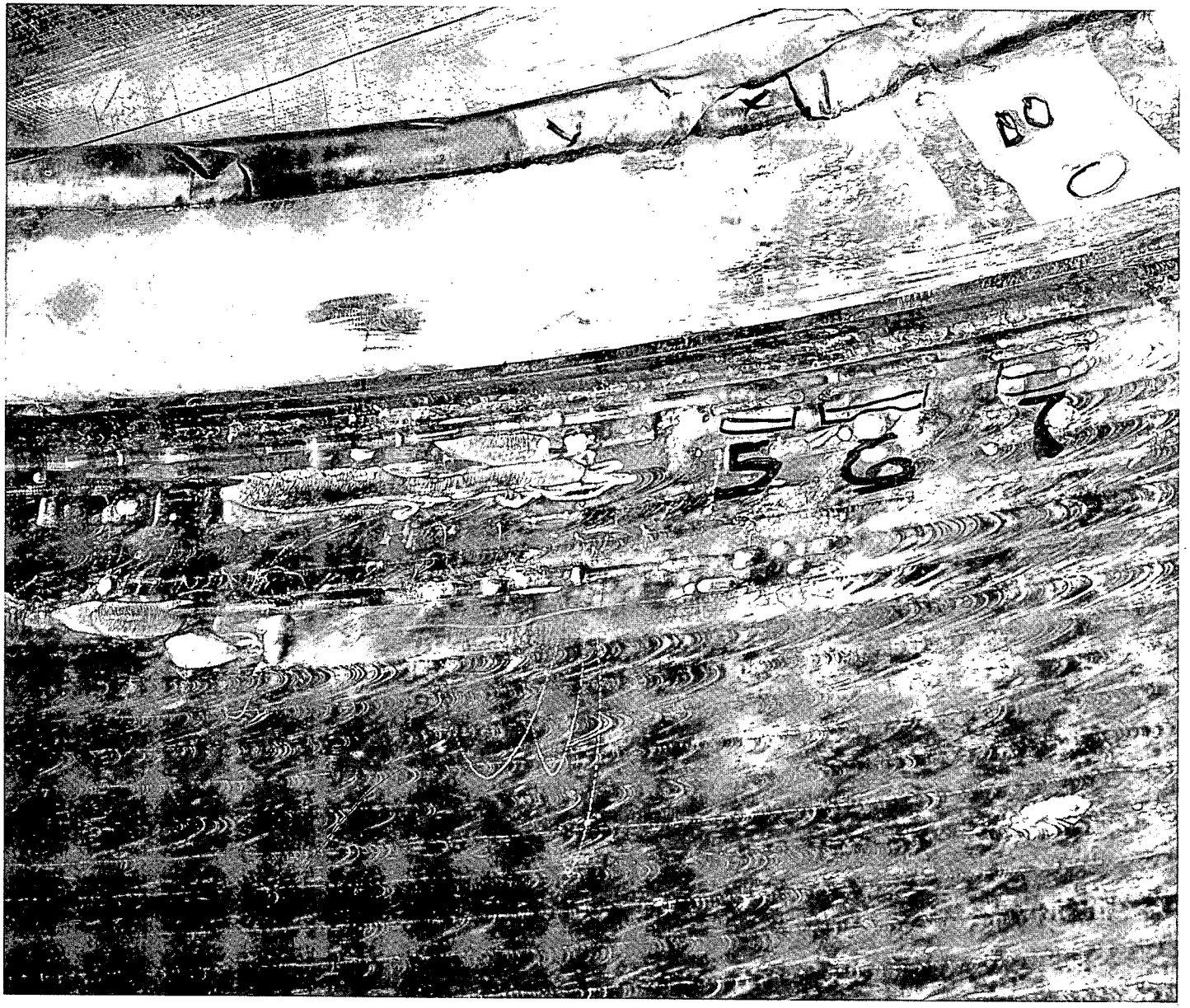
* Carbon steel base metal exposed
(No measurable depth beyond the clad/carbon steel interface)



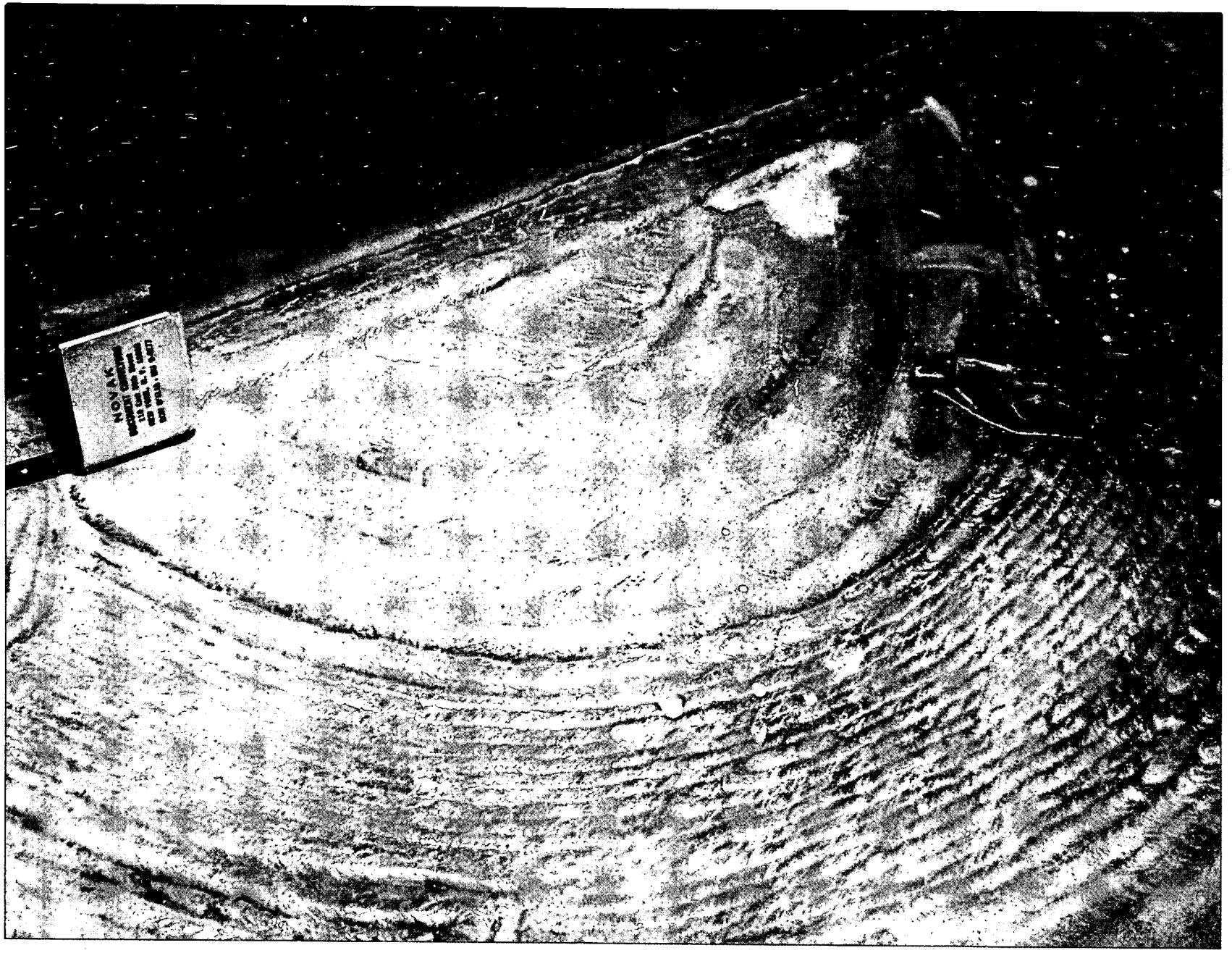
Photograph 31-A - Depicts manual weld repairs required to restore a seven inch circumferential band just below the biological ledge.



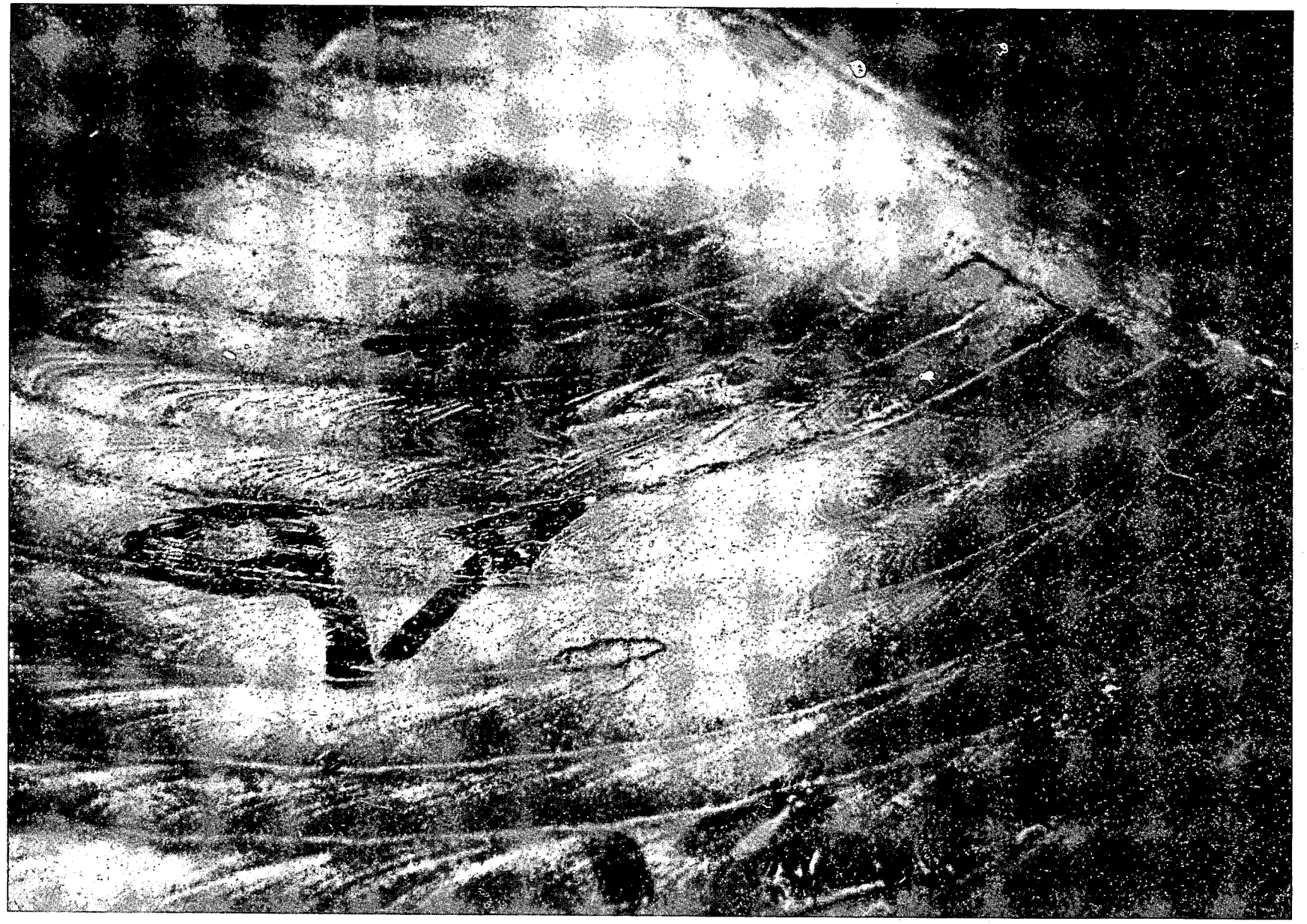
Photograph 31-B - Illustrates clad indication between beads in the early stages of grinding, excavation and removal.



Photograph 31-C - Shows excavation and clad indications being removed. Areas 5, 6 and 7 designate local conditions where all of the cladding has been removed and carbon steel has been exposed.

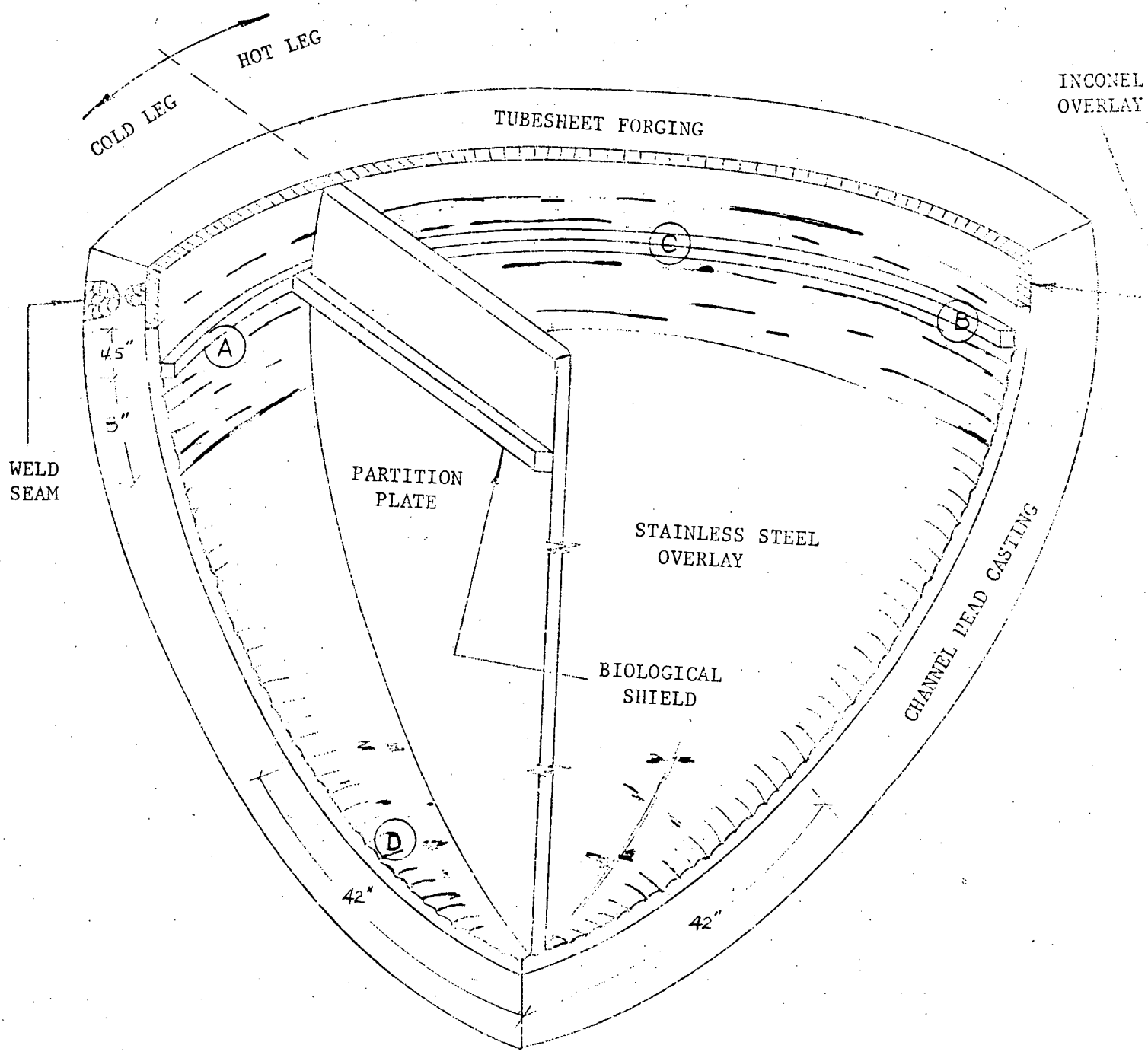


Photograph 31-D - Shows clad indications in areas adjacent to manual weld repairs. Clad indications appeared after manual weld repairs.



Photograph 31-E - Shows cold leg of steam generator near the bottom of the bowl cladding. No weld repairs were made but clad indications were noted after application of preheat/postheat temperatures required for repairs on the hot leg.

STEAM GENERATOR #32



STEAM GENERATOR #32

Description	Vertical Reference	Curvilinear Reference	Length	Width	Depth
HL - bowl	1.38 below bio. shield	130.5 CW from partition plate	0.75	0.38	BM *
HL - bowl	2.5 " " "	136.75 CW " " "	0.62	0.38	BM *
HL - bowl	2.5 " " "	139.0 CW " " "	0.25	0.25	BM *
HL - bowl	0.50 " " "	2.0 CW " " "	14.0	0.25	.080
HL - bowl	1.50 " " "	1.25 CW " " "	28.0	0.25	.090
HL - bowl	3.0 " " "	0.75 CW " " "	2.25	0.38	.180
HL - bowl	3.0 " " "	11.0 CW " " "	34.0	0.50	.160
HL - bowl	3.75 " " "	12.0 CW " " "	3.0	0.25	.080
HL - bowl	4.0 " " "	17.5 CW " " "	four indications: 3/4 Ø		.190
HL - bowl	4.75 " " "	31.0 CW " " "	one rounded: 1/2 Ø		.050
HL - bowl	3.75 " " "	35.0 CW " " "	8.0	1.25	.150
HL - bowl	1.25 " " "	39.0 CW " " "	one rounded: 1/2 Ø		.080
HL - bowl	3.75 " " "	47.0 CW " " "	five indications: 3/8 Ø		.050
HL - bowl	1.75 " " "	49.5 CW - partition plate	three indications: 1/2 Ø		.100
HL - bowl	2.5 " " "	50.0 CW " "	two indications: 1.25	.38	.120
HL - bowl	3.0 " " "	50.0 CW " "	three indications: 1.25	.25	.110
HL - bowl	2.25 " " "	52.0 CW " "	four indications: 0.75	.25	.080
HL - bowl	2.50 " " "	52.0 CW " "	2.0	0.75	.170
HL - bowl	1.25 " " "	50.0 CW " "	2.0	0.38	.105

STEAM GENERATOR #32 (Contd.)

Description	Vertical Reference	Curvilinear Reference	Length	Width	Depth
HL - bowl	1.75 below bio. shield	76.0 CW - partition plate	27.5	0.25	.050
			four indications:		
HL - bowl	3.5 " " "	89.0 CW " "	3/4 Ø		.080
HL - bowl	1.0 " " "	85.0 CW " "	1.75	.38	.080
			twelve indications:		
HL - bowl	3.75 " " "	102.0 CW " "	0.50	.38	.090
HL - bowl	3.75 " " "	107.0 CW " "	12.5	0.5	.100
			eight indications:		
HL - bowl	2.75 " " "	108.0 CW " "	3/8 Ø		.080
HL - bowl	2.75 " " "	110.5 CW " "	3.75	0.5	.120
			six indications:		
HL - bowl	0.75 " " "	116.0 CW " "	1.25	0.75	.150
HL - bowl	1.5 " " "	118.0 CW " "	43.0	0.5	.250
			eight indications:		
HL - bowl	3.75 " " "	140.0 CW " "	3/4 Ø		.180
HL - bowl	5.0 " " "	128.0 CW " "	2.25	0.75	.125
HL - bowl	3.0 " " "	140.0 CW " "	1/2 Ø		.115
HL - bowl	1.25 " " "	143.0 cW " "	4.0	1.0	.112
HL - bowl	4.25 " " "	154.0 CW " "	0.75	1.0	.113
HL - bowl	2.75 " " "	156.0 CW " "	0.75	1.0	.110
HL - bowl	4.0 " " "	158.0 CW " "	20.0	.38	.080
HL - bowl	3.5 " " "	160.0 CW " "	1-1/2 Ø		.110
HL - bowl	4.25 " " "	165.0 CW " "	1.25	0.75	.080
HL - bowl	2.0 " " "	164.0 CW " "	1.50	0.75	.150
HL - bowl	1.5 " " "	170.0 CW " "	3/4 Ø		.080
HL - bowl	2.25 " " "	166.0 CW " "	10.0	0.5	.100

STEAM GENERATOR #32 (Contd.)

Description	Vertical Reference	Curvilinear Reference	Length	Width	Depth
HL - bowl	4.75 below partition plate	170.0 CW - partition plate	5.25	0.38	.080
HL - bowl	20.0 " " "	10.0 CW " "	1.25	0.75	.040
HL - bowl	6.25 " " "	42.0 CW " "	1/2 Ø		.150
HL - bowl	22.25 " " "	70.0 CW " "	1.25	0.75	.040
HL - bowl	18.75 " " "	94.0 CW " "	1.25	0.75	.080
HL - bowl	23.0 " " "	97.0 CW " "	1.0	0.5	**
HL - bowl	0.5 above partition plate	38.0 CW - partition plate	24.0	.38	.170
HL - bowl	1.75 " " "	78.0 CW " "	26.0	.38	.070
HL - bowl	4.0 " " "	40.0 CW " "	40.0	.25	.080
HL - bowl	4.0 " " "	97.0 CW " "	14.0	.38	.105
HL - bowl	1.75 " " "	110.0 CW " "	3.0	.38	.110
HL - bowl	4.0 " " "	116.0 CW " "	27.0	.50	.110
HL - bowl	4.0 above bio. shield	132.0 CW - partition plate	8.0	.38	.110
HL - bowl	2.25 " " "	138.0 CW " "	18.0	0.5	.140
HL - bowl	4.0 " " "	156.0 CW " "	0.5	1.0	.040
HL - bowl	4.25 " " "	159.0 CW " "	1.25	1.0	.080
HL - bowl	4.25 " " "	161.0 CW " "	3.25	1.0	.060
CL - nozzle	8.06 above drain tube	10.13 CW from drain tube	2.5	0.5	.219
CL - nozzle	17.88 " " "	19.75 CW " " "	1.63	0.88	.305
CL - nozzle	6.25 " " "	31.0 CW " " "	4.0	0.50	.248
CL - nozzle	2.63 " " "	34.38 CW " " "	1.75	0.38	.146
CL - nozzle	9.88 " " "	35.63 CW " " "	1.63	0.75	.315
CL - nozzle	4.5 " " "	51.88 CW " " "	2.13	0.50	.220
CL - nozzle	17.88 " " "	57.88 CW " " "	7.0	0.63	.251

STEAM GENERATOR #32 (Contd.)

Description	Vertical Reference	Curvilinear Reference	Length	Width	Depth
CL - nozzle	9.88 above drain tube	60.88 CW from drain tube	3.0	0.38	.244
CL - nozzle	17.88 " " "	67.88 CW " " "	1.0	0.63	.301
CL - nozzle	9.88 " " "	74.13 1W " " "	1.5	0.38	.198
CL - nozzle	11.81 " " "	75.63 CW " " "	1.0	0.63	.256
CL - nozzle	9.88 " " "	75.88 CW " " "	0.88	0.63	.185
CL - bowl	3.5 above bio shield	30.0 CW from partition plate	7.0	0.75	**
CL - bowl	1.25 " " "	29.0 CW " " "	7.5	0.75	**
CL - bowl	0.75 " " "	38.0 CW " " "	10 rounded indications 1/2" Ø		**
CL - bowl	0.75 " " "	48.0 CW " " "	20 rounded indications 1/4" Ø		
CL - bowl	2.0 " " "	57.5 CW " " "	1.5	.38	**
CL - bowl	0.50 " " "	61.0 CW " " "	20 rounded indications 3/8" Ø		
CL - bowl	0.50 " " "	61.0 CW " " "	1.0	.38	**
CL - bowl	1.0 " " "	72.5 CW " " "	9.5	.50	
CL - bowl	2.5 " " "	75.5 CW " " "	8 rounded indications 3/8" Ø		**
CL - bowl	2.5 " " "	75.5 CW " " "	1.0	.38	**
CL - bowl	3.25 " " "	84.0 CW " " "	2.5	.75	**
CL - bowl	2.25 " " "	92.5 CW " " "	20	2.0	**
CL - bowl	3.0 " " "	0 CW " " "	11.0	0.25	**
CL - bowl	0.75 " " "	0.25 CW " " "	2.5	1.5	**
CL - bowl	0.75 " " "	3.5 CW " " "	5.5	1.5	**
CL - bowl	0.25 " " "	59.0 CW " " "	9.3	0.5	**
CL - bowl	0.25 " " "	73.5 CW " " "	6.5	--	**

STEAM GENERATOR #32 (Contd.)

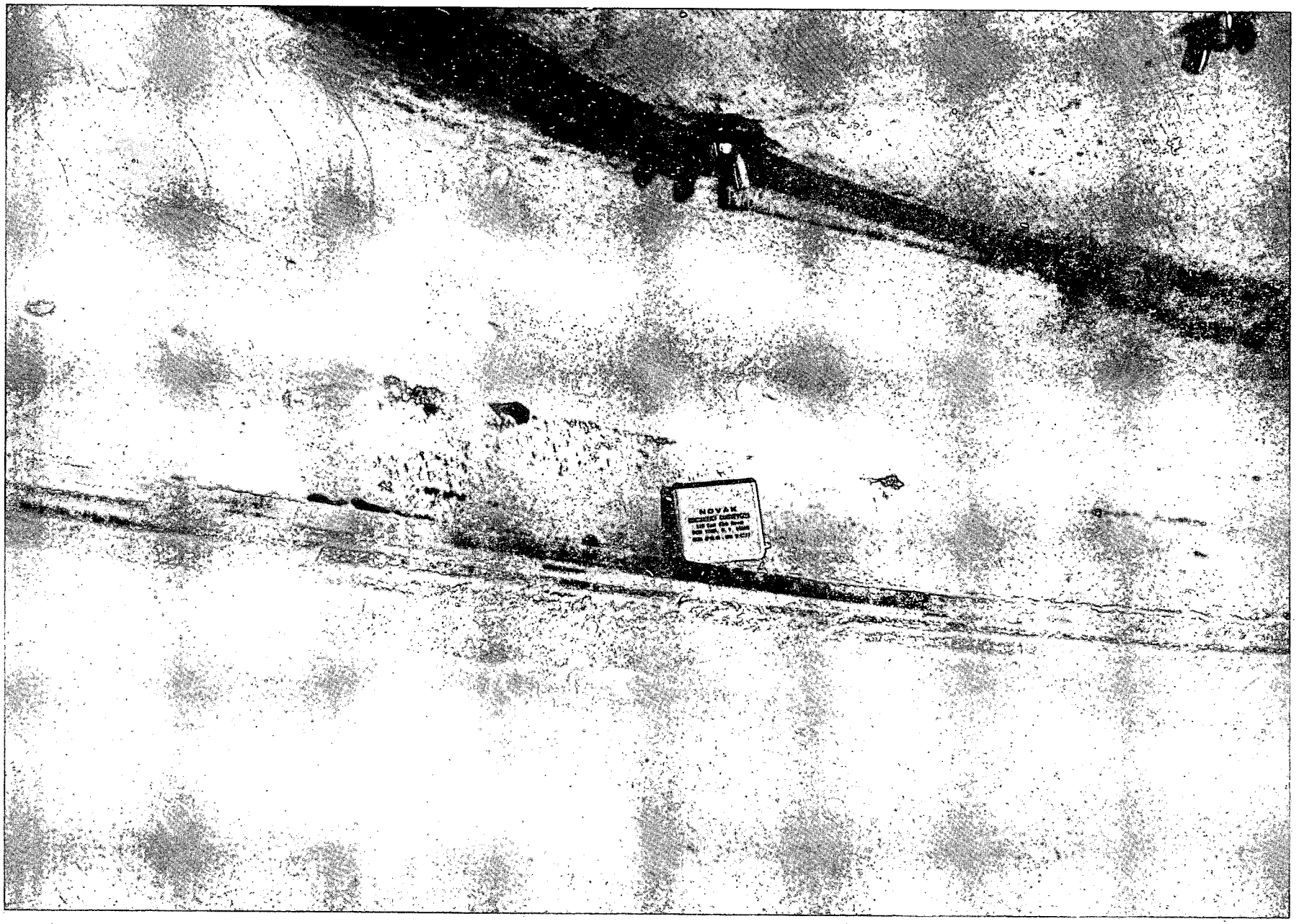
Description	Vertical Reference	Curvilinear Reference	Length	Width	Depth
CL - bowl	0.25 above bio. shield	92.5 CW from partition plate	7.5	--	**
CL - bowl	1.0 " " "	11.5 CW " " "	11.0	0.62	**
CL - bowl	1.0 " " "	24.0 CW " " "	14.5	0.62	**
CL - bowl	3.5 " " "	15.0 CW " " "	0.5	0.75	**
CL - bowl	3.5 " " "	17.0 CW " " "	1.0	0.62	**
CL - bowl	3.5 " " "	18.0 CW " " "	8.0	0.5	**
CL - bowl	2.25 " " "	49.5 CW " " "	6.25	.38	.235
CL - bowl	0.56 " " "	52.0 CW " " "	3.38	.38	.214
CL - bowl	0.88 " " "	59.0 CW " " "	23.50	.38	.254
CL - bowl	1.50 " " "	64.0 CW " " "	7.75	.38	.235
CL - bowl	2.50 " " "	64.75 CW " " "	0.75	.38	.176
CL - bowl	2.50 " " "	66.50 CW " " "	0.88	.38	.201
CL - bowl	2.88 " " "	73.63 CW " " "	0.63	.50	.164
CL - bowl	2.50 " " "	78.50 CW " " "	4.00	.50	.250
CL - bowl	2.25 " " "	94.0 CW " " "	5.50	.75	.224
CL - bowl	1.38 " " "	11.00 CW " " "	2.0	.62	.225
CL - bowl	1.25 " " "	141.00 CW " " "	10.0	.63	.175
CL - bowl	1.38 " " "	163.0 CW " " "	4.0	.50	.184
CL - bowl	4.25 " " "	37.0 CW " " "	11.0	.88	.154
CL - bowl	3.75 " " "	114 CW " " "	2.0	scattered indications	**
CL - bowl	1.75 " " "	121.5 CW " " "	55.5	scattered 1.0 band	**
CL - bowl	4.0 " " "	125.0 CW " " "	17.0	scattered indications	**

STEAM GENERATOR #32 (Contd.)

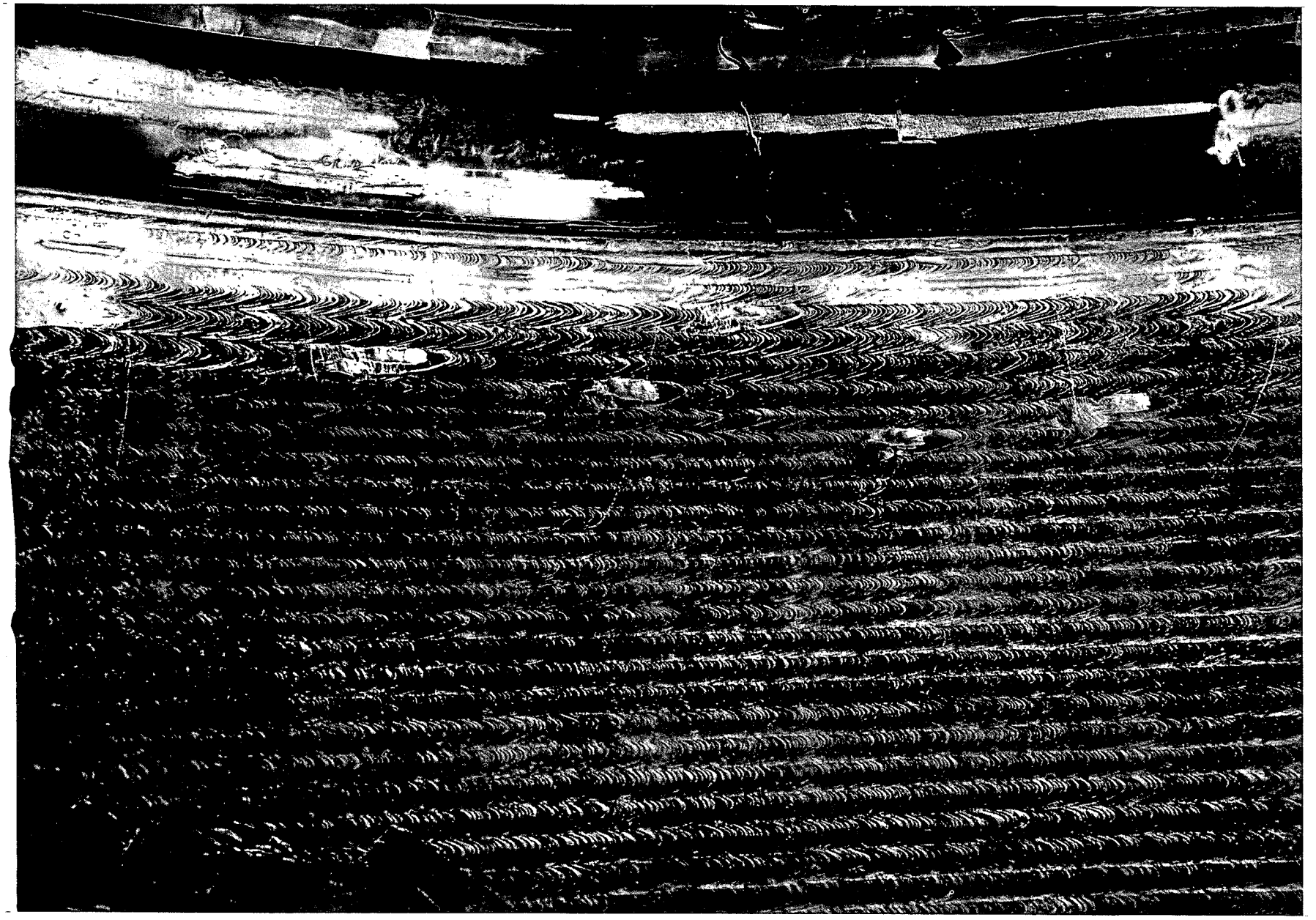
Description	Vertical Reference	Curvilinear Reference	Length	Width	Depth
CL - bowl	4.0 above bio. shield	157.0 CW from partition plate	3.5	scattered indications	**
CL - bowl	0.62 below bio. shield	7.5 CW " " "	9.75	.50	.176
CL - bowl	2.38 " " "	7.5 CW " " "	1.0	.38	.275
CL - bowl	1.5 " " "	17.75 CW " " "	1.5	.50	.200
CL - bowl	2.5 " " "	14.25 CW " " "	4.00	.50	.180
CL - bowl	4.75 " " "	15.00 CW " " "	2.50	.38	.125
CL - bowl	2.63 " " "	22.75 CW " " "	1.25	.38	.164
CL - bowl	1.38 " " "	21.0 CW " " "	7.00	.50	.208
CL - bowl	0.50 " " "	22.88 CW " " "	6.00	.38	.188
CL - bowl	1.38 " " "	28.5 CW " " "	29.63	.38	.176

* Carbon steel base metal exposed
(No measurable depth beyond the clad/carbon steel interface)

** Depth dimension is not specified when the given dye penetrant indication has not been excavated.

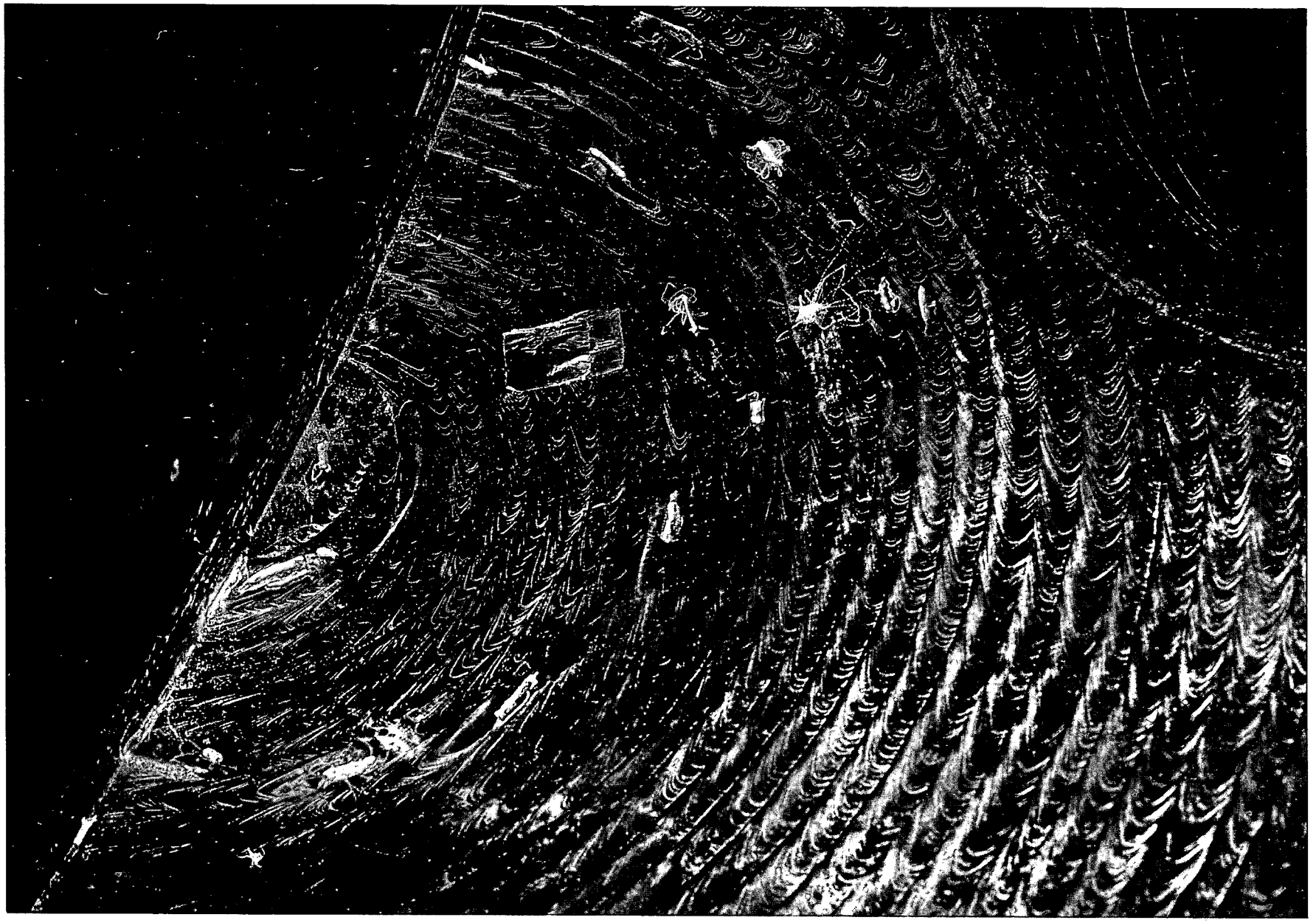


Photograph 32-A - Illustrates clad indications located above the biological ledge. Area just below biological ledge has been worked to render surface clear of clad indications.



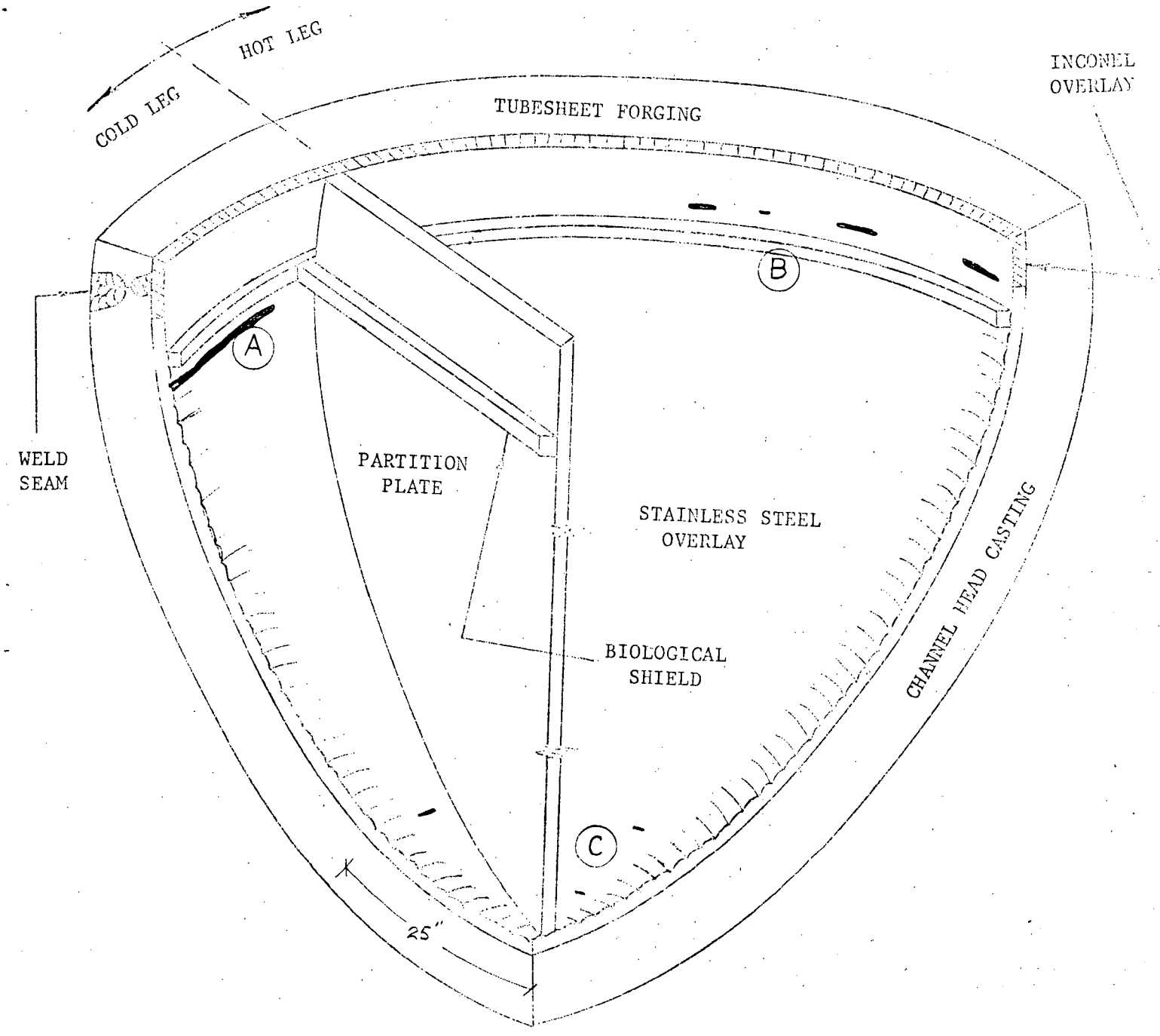
Photograph 32-B - Shows clad indications that have been partially removed in areas above and below biological ledge.

Photograph 32-C - Shows a localized area that required complete removal of the cladding to remove dye penetrant indications.



Photograph 32-D - Shows an area in the bottom of the bowl cladding that required relatively lesser amount of grinding to remove clad indications.

STEAM GENERATOR #33

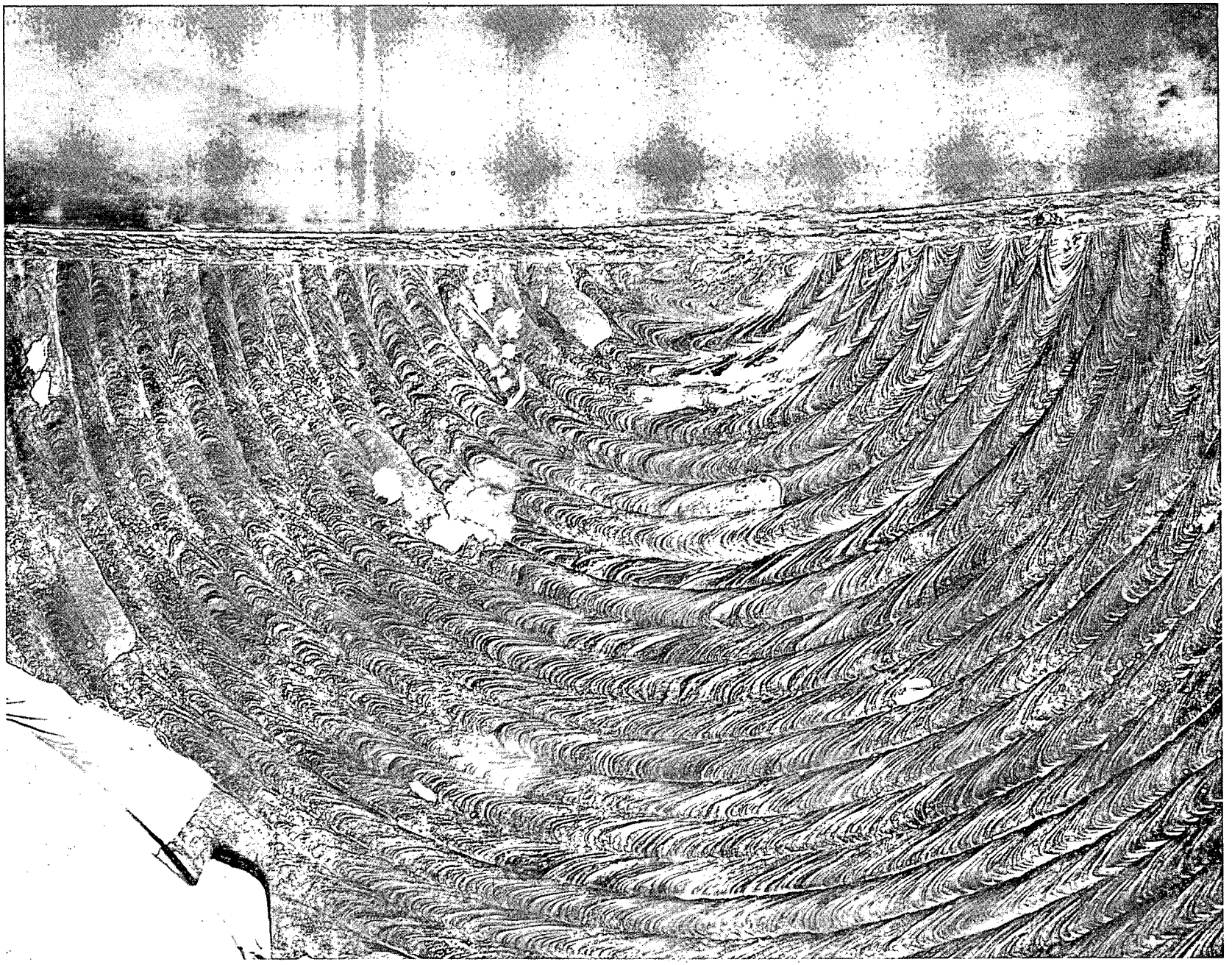


STEAM GENERATOR #33

Description	Vertical Reference	Curvilinear Reference	Length	Width	Depth
HL - bowl	4.0 above bio. shield	82.5 CCW - partition plate	4.25	0.75	0.15
HL - bowl	4.0 above bio. shield	39.0 CCW - partition plate	3.00	0.75	0.15
HL - bowl	4.0 above bio. shield	17.75 CCW - partition plate	0.43	0.43	0.25
HL - bowl	4.0 above bio. shield	14.00 CCW - partition plate	1.50	0.75	0.25
CL - bowl	0.5 below bio. shield	46.00 CW - partition plate	18.00	0.37	0.25
CL - bowl	25.0 radial - BDC	8.00 CW - partition plate	0.75	0.75	0.25
CL - bowl	radius area nozzle/bowl	23.00 CW - C_L drain	7.50	0.50	0.21

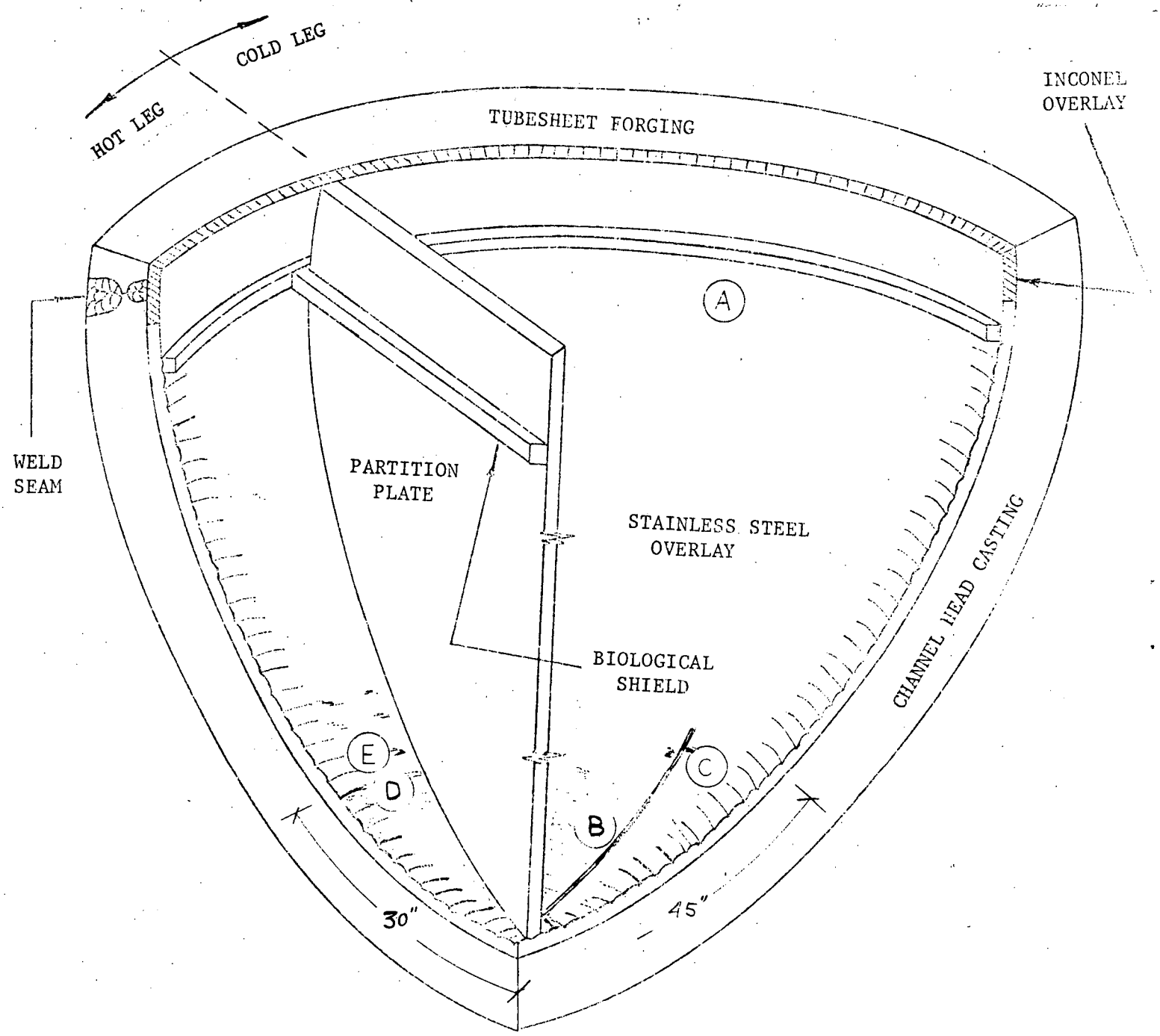
Photograph 33-A - Shows excavation required to remove clad indications, just below biological shield.

Photograph 33-B - Shows minor grinding required above biological shield.



Photograph 33-C - Shows minor grinding evident in bottom of bowl cladding.

STEAM GENERATOR #34



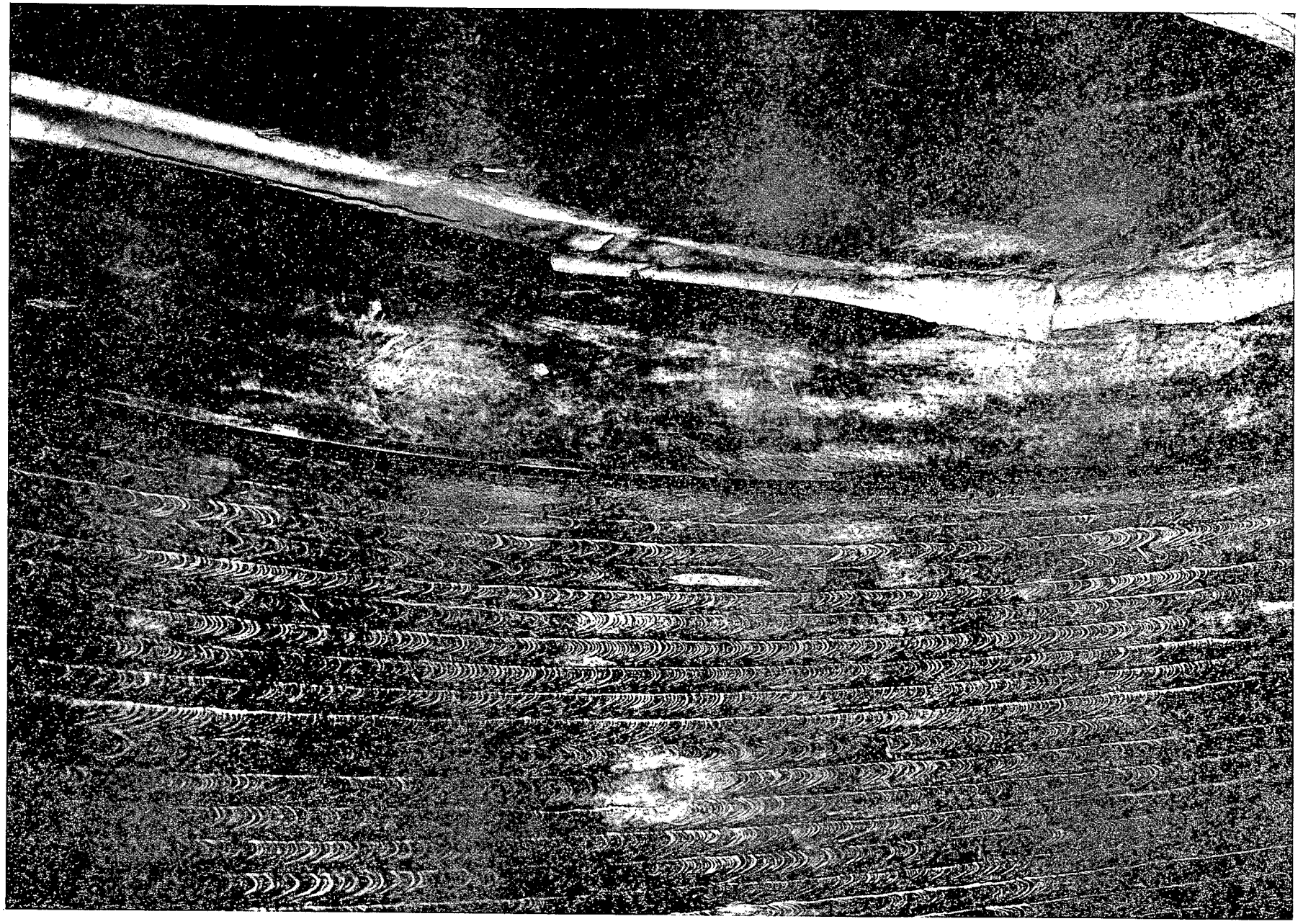
STEAM GENERATOR #34

Description	Vertical Reference	Curvilinear Reference	Length	Width	Depth
HL - bowl	24 beads radial - BDC	17.5 CCW - partition plate	.50	.38	.210
HL - bowl	24 beads radial - BDC	Adjacent to drain - CW	2.12	.50	.10
HL - bowl	24 beads radial - BDC	Adjacent to drain - CW	1.0	.43	.21
HL - bowl	24 beads radial - BDC	Adjacent to drain - CCW	0.63	.56	.20
CL - bowl	19-20 beads radial - BDC	Adjacent to partition plate - CW	2.0	.25	BM *
CL - bowl	13-14 beads radial - BDC	Adjacent to partition plate - CW	.25	.25	BM *
CL - bowl	23-24 beads radial - BDC	Adjacent to partition plate - CCW	1.50	.38	.270
CL - bowl	12 beads radial - BDC	Adjacent to partition plate - CCW	1.0	.38	.285
CL - bowl	8 radial - BDC	Adjacent to partition plate - CCW	8.50	.38	.28
CL - bowl	10.0 from partition plate	2.00 CCW - C_L partition plate	3.75	1.50	BM *
CL - bowl	13.0 from partition plate	3.75 CCW - C_L partition plate	5.00	2.0	BM *
CL - bowl	8.75 from partition plate	4.75 CCW - C_L partition plate	4.75	1.63	BM *
CL - bowl	7.25 from partition plate	8.75 CCW - C_L partition plate	4.00	1.50	BM *
HL - bowl	9.0 radial - BDC	1.75 CCW - partition plate	.25	.25	BM *
HL - bowl	9.0 radial - BDC	13.50 CCW - partition plate	.50	.25	BM *
HL - bowl	8.25-11.25 radial - BDC	4.0 CW - partition plate	2.75	.5-1.75	BM *
HL - bowl	radius area nozzle/bowl	2.50 CCW - C_L drain	2.06	.88	BM *
HL - bowl	9.00 from partition plate	4.75 CW - C_L partition plate	4.50	1.81	BM *
HL - bowl	6.25 from partition plate	9.00 CCW - C_L partition plate	4.00	1.51	BM *
HL - bowl	6.25 from partition plate	9.00 CCW - C_L partition plate	4.00	1.75	BM *
HL - bowl	9-11 beads radial - BDC	1.0 CCW - partition plate	2.0	1.25	.240
HL - bowl	11 beads radial - BDC	13.5 CCW - partition plate	4.5	1.0	.248
HL - bowl	9 beads radial - BDC	13.5 CCW - partition plate	1.5	0.75	.225

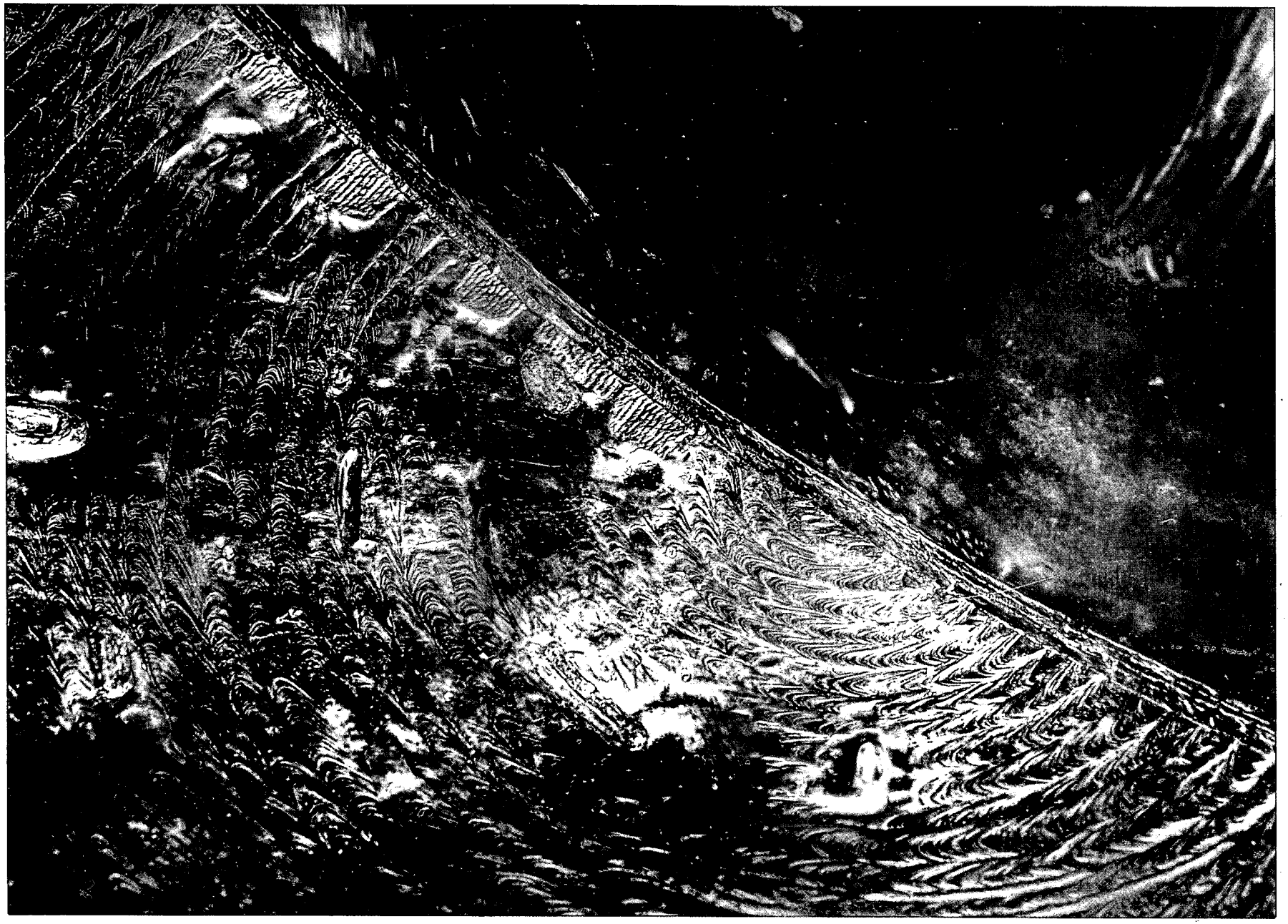
STEAM GENERATOR #34 (Contd.)

Description	Vertical Reference	Curvilinear Reference	Length	Width	Depth
HL - bowl	6 beads radial - BDC	1.75 CCW - partition plate	0.75	0.75	.190
HL - bowl	15 beads radial - BDC	9.25 CCW - partition plate	3.5	0.62	.225
HL - bowl	24 beads radial - BDC	13.25 CCW - partition plate	0.75	0.38	.232
CL - bowl	12.0 from partition plate	8.38 CCW - ℄ partition plate	4.5	1.63	BM *
CL - bowl	10.0 from partition plate	4.25 CW - ℄ partition plate	4.5	1.50	BM *

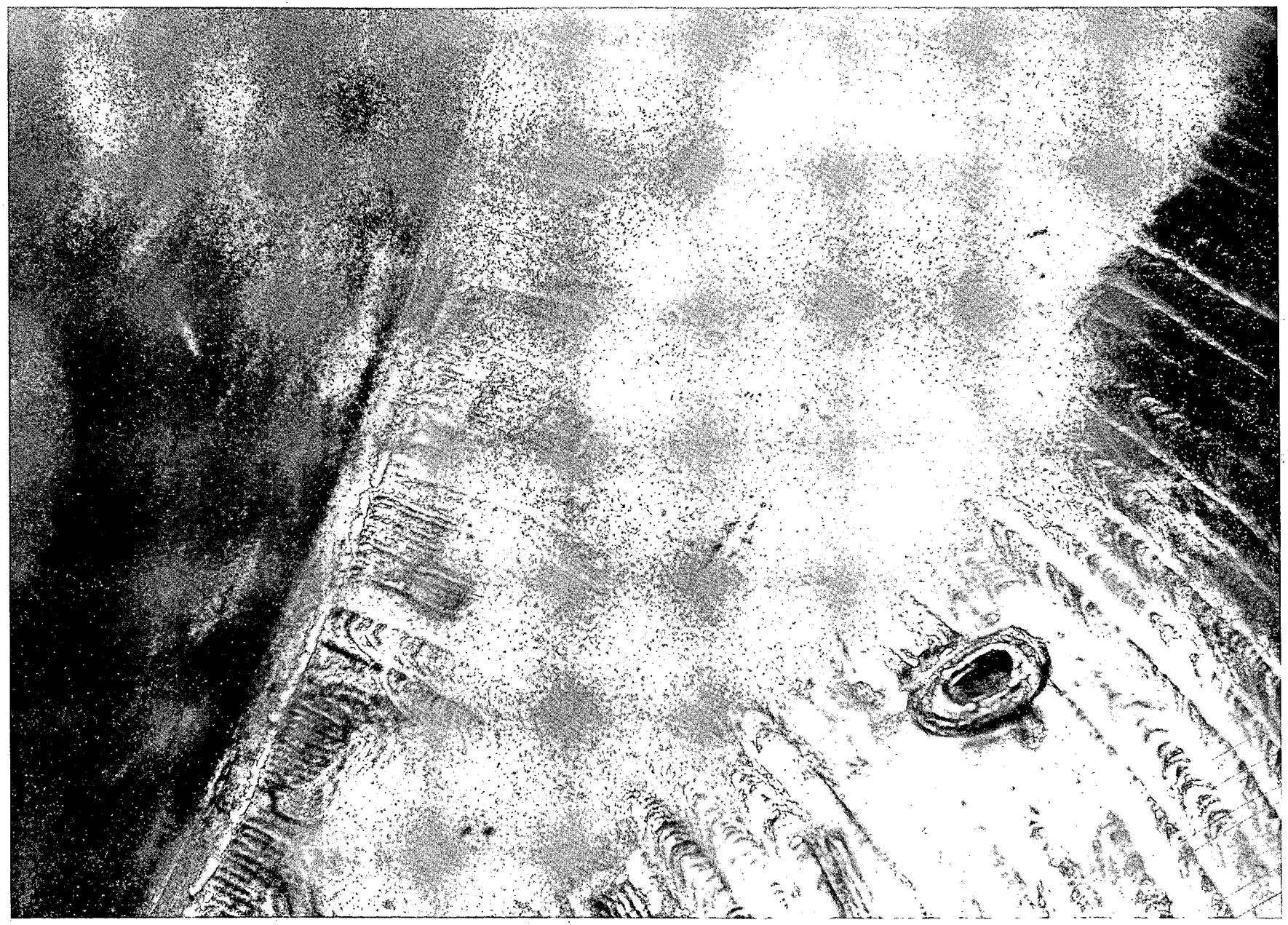
* Carbon steel base metal exposed
(No measurable depth beyond the clad/carbon steel interface)



Photograph 34-A - Shows areas that are dye penetrant clear above and below biological ledge.

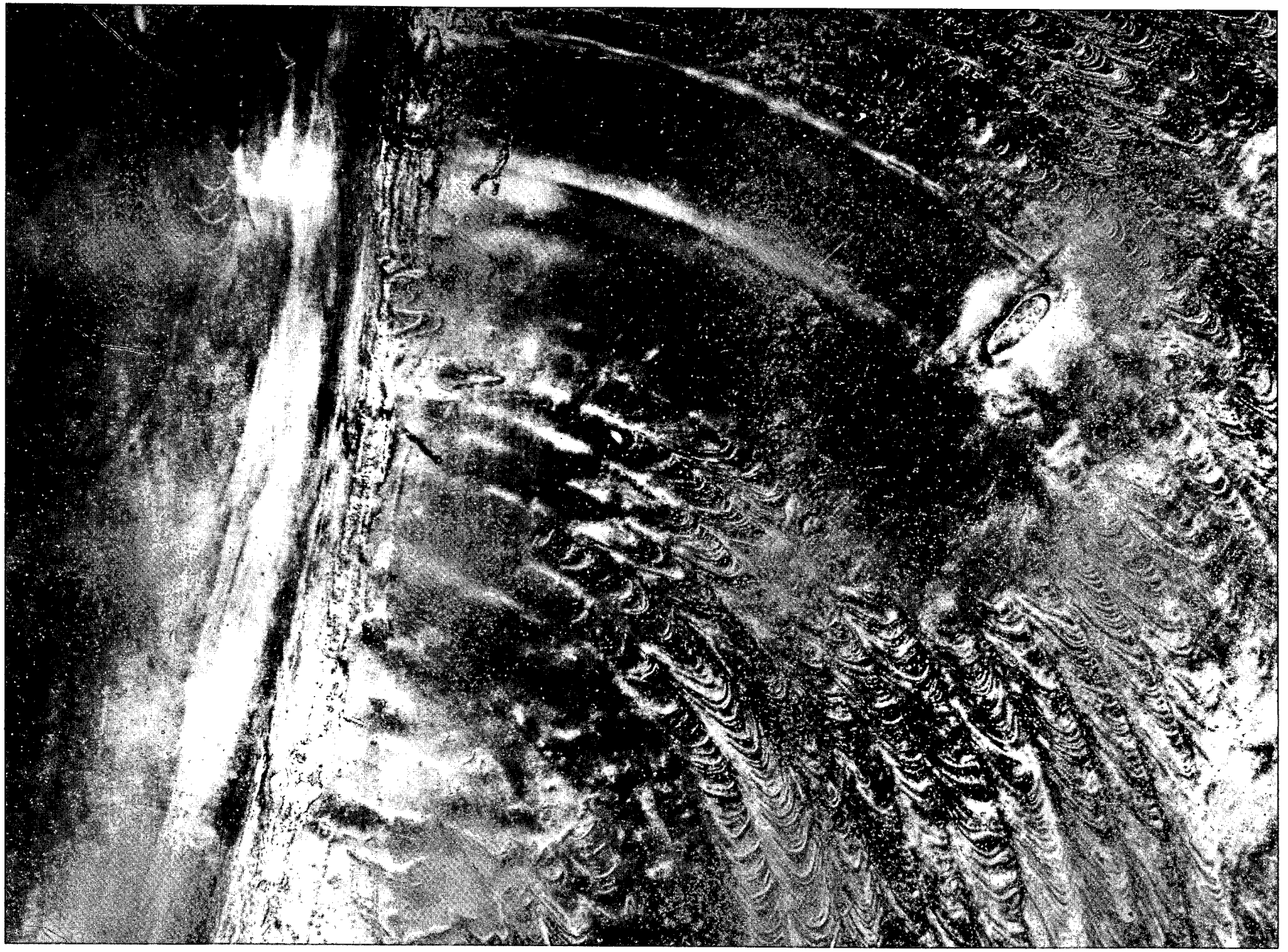


Photograph 34-B - Shows areas in bottom bowl cladding that required manual weld repairs adjacent to partition plate fillet.



Photograph 34-C - Shows clad indications accompanying a radial stringer bead extending beyond the drain tube. Note previous weld repairs and new clad indications are located at same position radially.

Photograph 34-D - Shows areas that have been worked adjacent to partition plate.



Photograph 34-E - Shows additional surface grinding extending to areas that were previously dye penetrant acceptable.

SECTION 5

METALLURGICAL ANALYSES OF CLADDING

SUMMARY

A metallographic examination of the failed cladding revealed normal austenite plus ferrite microstructure bead to bead and normal interbead heat affected zones. Electron microprobe analysis for chromium and nickel proved no elemental heterogeneities within the bead or heat affected zone. The failure was seen to be principally interdendritic with incipient transdendritic fractures. Attack was preferential, occurring to the greatest extent at the interbead heat affected zone where a portion of the ferrite has been put back in solution.

Scanning electron micrographs show inter- and transdendritic fractures. Qualitative analyses by energy dispersive techniques of particles found on the surface of fractured faces by the SEM show strong lines of sodium, potassium, chlorine, manganese, and sulfur. "Film" type indications could not be identified on the fractured surfaces.

Electron diffraction analysis shows the presence of Fe_3O_4, a corrosion product, on the fractured surface.

From the above findings and a review of literature references and past history, it was concluded that failure was probably caused by chloride stress corrosion attack as a result of having been accidentally exposed to sea water in shipment.

Elements identified on the surface of fractures which could have pinpointed the cause failure may have come from penetrant materials, flux, or as the result of sea water penetration after failure caused by another mode.

The fact that defects occurred in two distinct areas, (1) in the area of the biological shield and (2) in the bottom of the bowl in a radius of 30-40" from the center, suggests that another contaminate may have been present after the units had been placed in the vertical position.

METALLURGICAL EXAMINATION

Analyses Methods

The following metallurgical analyses methods were employed to study samples returned for evaluation.

1. Macro and light microscopy.
2. Electron microprobe analyses.
3. Scanning Electron Microscopy (SEM) incorporating energy dispersive analyses of the X-ray spectra (EDAX) generated by the SEM.
4. Transmission Electron Microscopy (TEM) incorporating electron diffraction analysis.
5. Auger Electron Spectroscopy.

Results of Macro and Micro Examination

The location of samples taken in the biological shield areas are given in Table I.

The macro examination of the fractured face of one of the samples taken from steam generator No. 32 has the appearance of an interdendritic type fracture as shown in Figure 1.

A micro of the cladding surface ("deck" of the boat) locates the defect at the "tie-in" between beads as shown in the photomacrograph of Figure 2.

Figure 3 shows a transverse microsection of the sample in the unetched condition. Note that the cracks originate in pits at the clad surface and follow a path through the thickness normal to the surface. Figures 4 and 5 show the microstructure in the etched condition at higher magnification. The microstructure reveals cracking originating in the heat affected zone of the previously deposited clad bead where the solution annealing effect of the heat of welding has put much of the original ferrite into solution. Figure 6 at higher magnification shows transdendritic as well as interdendritic cracking.

Cladding from steam generator No. 31 exhibits a similar condition, as illustrated in Figure 7. Again, cracking is seen to propagate interdendritically and for the most part is limited to areas where some ferrite had been put into solution by heat of the succeeding weld bead.

A metallographic traverse at 100X was made across the clad surface and bead tie-in areas where the major cracking existed. The microstructure exhibited (from left to right) in Figure 8 reveals: (A) Normal duplex structure of austenite plus ferrite (succeeding bead), (B) Typical heat affected zone where most of the ferrite has gone into solution from the heat of the succeeding weld bead, (C) Fracture zone oriented parallel to bead tie-in, (D) Transition from heat affected zone to typical bead structure showing intermediate ferrite formation, (E) Normal duplex microstructure approaching center location of previously deposited weld bead.

The metallographic examination indicates that presence of cracking is a function of the ferrite morphology. Specifically, the cracking is non-existent in areas containing high ferrite, is less pronounced in areas of intermediate ferrite, and is most prevalent in predominantly austenitic/low ferrite heat affected zones. This variation in crack morphology has been previously reported.[8]

Electron Microprobe Analyses

A quantitative microprobe analysis was made in order to assure that the areas in the cladding which show a predominantly austenitic heat affected zone structure resulted from normal heat effects rather than from elemental heterogenities. At locations 1 through 5, as indicated on the photomicrograph of Figure 8, quantitative analysis was made for chromium and nickel. The results of chromium and nickel analyses were as follows:

Location	Chromium*	Nickel*
1	19.51%	7.45%
2	19.12%	7.6%
3	19.75%	7.26%
4	18.95%	7.20%
5	20.01%	6.81%

*The accuracy of this method of analyses is ± 5% of actual.

Based on elemental analysis for chromium and nickel, the as-deposited cladding exhibits normal chemistry within the bead and heat affected zone. Calculated ferrite (Schaeffler Diagram from the Cr/Ni ratio would indicate a less than

± .5% variation. The variation would be even less if a reasonable assumption is made that the electron beam at location (5) was focused principally on a ferrite island.

In addition, the cracks were probed for presence of lead, tin, chlorine, mercury and sulfur, with results shown below.

Element	Quantity
Chlorine	Trace
Lead	Undetectable
Mercury	Undetectable
Sulfur	Trace
Tin	Undetectable

The above results indicate absence of minor elements which cause hot short cracking (except sulfur) and reveal chlorine and sulfur which are common to sea water.

Scanning Electron Microscopy

Scanning electron microscopic examination of several of the broken open surfaces of the boat sample showed the fracture surfaces to be a mixture of inter- and transdendritic fracture. This is illustrated in Figures 9, 10 and 11. Also illustrated in these scanning electron fractographs is the secondary cracking designated by arrows. Figure 9 shows scanning electron fractographs of the fracture surface from specimen No. 5 (from unit #32, cold leg). Figure 10 is a result of viewing specimen No. 5 after it had been rotated approximately 90 degrees and tilted to a different angle. Energy Dispersive Analysis by X-rays (EDAX) of these surfaces confirms a strong presence of chloride. Figure 11 is a scanning electron fractograph of specimen No. 6 taken from the hot leg of steam generator No. 31. The

same features and secondary cracking as shown on specimen No. 5 are evident.

The side of specimen No. 5 that represented the exposed surface of the cladding in the channel head was examined on the scanning electron microscope. Figures 12 and 13 represent the results of this investigation. Note the pits or depression with associated cracks. The horizontal markings in these scanning micrographs are the results of grinding, wire brushing or some other abrasive operation. EDAX analysis reveals a heavy concentration of chlorides in the pits and cracks but no detectable chlorides on the abraded surface.

Figure 14 shows foreign particles on the "broken open" fracture faces of specimen No. 6, i.e., indicating that these particles were present in the cracks of the specimen taken from the cladding. Particles "A" and "B" when analyzed by EDAX displayed the strong presence of Na (sodium) and Cl (chlorine). Particle "C" displayed the presence of K (potassium) and Cl (chlorine). These elements are found in strong concentrations in sea water. Figure 15 displays the foreign particle found on the "broken open" fracture face of specimen No. 5.

Transmission Electron Microscopy Including Electron Diffraction Analysis

A strip of cellulose acetate softened by acetone was placed on the "broken open" fracture faces of samples Nos. 4 and 5 (both from unit #32). This replica was allowed to dry and then stripped from the fracture surface. After normal replica processing, typical areas (Figure 16) were viewed on the transmission electron microscope. The dark particles in this electron micrograph are entrapped by the replica when it was stripped from the fracture face. Figure 17 is an electron diffraction pattern of some of the deposits shown in Figure 16. Through measurement of this pattern and

resulting calculations, a set of d spacings can be arrived at for the unknown compounds from the fracture faces. The d spacing is the spacing between layers of atoms and the value of these spacings can be used to identify the unknown compound or compounds. Table II records the unknown d spacings and those of Fe_3O_4 and Fe_2O_3 (two forms of iron oxide). It is apparent from these values that Fe_3O_4 is the main constituent on the fracture face, although the possibility of some Fe_2O_3 does exist. The d spacing values of the following oxides were compared with the unknown:

FeO	(iron oxide)
NiO	(nickel oxide)
Ni_2O_3	(nickel oxide)
CrO	(chromium oxide)
Cr_2O_3	(chromium oxide)

None of these oxides were apparent.

Weldability Tests

To assure that the cladding was sound as manufactured, it was decided to perform weldability tests on the cladding and also obtain additional wet chemistry and X-ray emmission spectrographic analyses. Three different tests were employed to determine weldability:

1. An SMAW (stick electrode) pad was deposited near the bottom of the bowl in steam generator No. 34 hot leg as shown in Sketch #1.

2. An area on the cold leg encompassing the same beads as 1. was refused by GTAW (TIG) and a circular patch without filler was fused similarly on this area to simulate a circular patch crack sensitivity test.

3. Three radial weld stringers with SMAW (stick electrodes) were made in hot and cold legs of steam generators Nos. 31, 32, and 34. These

stringers started at the bottom of the bowl and extended upward approximately 50". One was between the partition plate and the nozzle, one between the nozzle and the manway, and one between the manway and partition plate.

An additional sample of original clad was taken in the location identified as #1 located in the lower right quadrant of Sketch #2. This sample was penetrant tested and examined metallographically; no defects were found. One-half of the sample was sent to Westinghouse R&D for evaluation and was found to be susceptible to chloride stress corrosion. A GTAW pass was made on the other half; again, no defects could be detected either in the autogenous weld or the clad underneath. Samples were then submitted to Auger Electron Microscopy examination which has been successful in determining the presence of film type inclusions in weld metals. No evidence of this type defect could be detected.

A bend test was then made on this sample; no defects were found as shown in Figure 18. The boat samples from 1. above were sent to Westinghouse R&D for evaluation, except for a small section of boat #1 which was submitted for chromium and nickel analysis at WTD. The results of the examinations follow.

Boats 1 and 2 from steam generator No. 34, hot leg, bottom of bowl were cut out and preliminarily examined by Tampa. Boat 1 was longitudinal (along the original weld bead clad direction), adjacent and parallel to new beads laid over the original cladding as part of a weldability test. Boat 2 was transverse through the weldability test beads. Sketch #1 shows the location of Boats 1 and 2.

Figures 19-24 were furnished by Tampa and show macroscopic appearances, penetrant indications, and microscopy on Boat 1. No cracking was observed in the weldability test bead, but numerous cracks were present in adjacent original weld metal. Figures 25 and 26 are macroscopic pictures and penetrant indication locations on Boat 2.

Boat 2 was examined by scanning electron microscopy fractography. Figure 27 shows the sample and cracks which were present on both "edges", the edges being the saw cut faces approximately perpendicular to the original cladding surface. A montage of the cracks appears in Figure 28. A crack was next broken open by freezing the sample in liquid nitrogen and breaking the sample. Figure 29 shows the resultant fracture face and locations of points which were analyzed by SEM-EDAX. The fracture face included a small amount of carbon steel base metal which was subsequently removed by saw cutting, as shown. SEM fractographs at six locations appear in Figures 30 through 32. Fine particles on the fracture face were revealed by SEM-EDAX to be sulfur and manganese-rich, probably normal manganese sulfide, inclusions; Figure 33 shows a typical EDAX spectrum. Compositional differences between the weld metal and base metal are shown in the EDAX spectra of Figure 34; a trace of aluminum was detected in the stainless steel (weld metal) which was not clearly detected in the carbon steel. Cracks on the mating half of the laboratory fracture of Boat 2 are shown in the SEM in Figure 35. Material observed in one of the tighter cracks was analyzed by EDAX and shown to

contain chlorine (chloride) as the principal contaminant, with lesser amounts of aluminum, silicon, sulfur, potassium, and calcium; Figure 36 presents these observations.

Optical metallography on Boat 1 is shown in a series of photomicrographs in Figures 37-41. Considerable difficulty attends attempting to categorize the cracking as interdendritic with respect to the primary dendrite-dendrite boundaries, intradendritic as to exclusively intra-dendritic, or transdendritic with respect to extensions of intradendritic cracks across primary dendrite-dendrite boundaries. Cracking appears to propagate through the delta ferrite in most cases. No clear cause for the cracking is discernible from the optical metallography of these two samples.

Magne gage ferrite numbers for Boats 1 and 2 are shown on Sketches 4 thru 6, respectively. For Boat 1, classimet (metallographic) and magne gage readings are compared on Sketch #4A.

The weldability test from 2. above was devised to show that the basic weld clad chemistry was satisfactory, and that it could be remelted with a tungsten arc torch without cracking or fissuring. Remelting a circular patch would also simulate a circular crack sensitivity test. The location of these remelted areas is shown in Sketch #3. Disposition of samples shown was as follows:

1. Boat 1 Tampa for metallography
2. Boat 2 Tampa for chemistry
3. Boat 3 R&D Laboratories
4. Boat 4 Held at Tampa
5. Boat 5 Tampa for metallography and bend
6. Boat 6 R&D Laboratories

Boat 1 showed no cracking or fissuring in refused area or refused circular patch. Beneath the refusing, however, defects were observed which stopped or were "sealed" at the fusion line, indicating sound basic chemistry. See Figure 42.

Boat 4 shows the same "sealing" affect as Boat 1. See Figure 43. A bend specimen incorporating refused and unrefused clad was also made from this sample. The refused portion of the clad bent with no defects; the unfused portion cracked. See Figure 44.

All samples indicated approximately 6 - 8% ferrite metallographically except in interbead heat affected zones which were somewhat lower.

Chemical analysis on the two samples mentioned previously were as follows:

Sample	C	Mn	S	Si	Ni	Cr
1	-	-	-	-	7.7%	17.7%
2	.103	1.27	.012	.50	7.73%	16.5%
Ave	.103	1.27	.012	.50	7.72%	17.1%

When compared to the microprobe chemistry, there is good agreement on nickel content but an approximately 2% difference in chromium content. Shaeffler diagram calculations using the higher chromium content indicate ferrite in the range observed metallographically. Calculations using chromium determined by X-ray emission spectroscopy would indicate 3 - 4% lower ferrite than observed metallographically.

During the original procedure qualifications for this process it was taken into account that manufacturing deviations might possibly result in excessive dilution which would result in low ferrite contents in the weld. For this reason the weld chemistry was adjusted so that in event low ferrite was seen, the carbon/silicon ratio would be such that sound cladding would result. The carbon and silicon shown above should preclude cracking of the cladding if low ferrite were present.

The "radial bead" crack sensitivity test indicates interbead "tie-ins" are susceptible to cracking during repair welding (see photographs of PT indications).

Attempts to relate cracking to ferrite as determined by weld chemistry, magne gage, and magnetic saturation were erratic and inconsistent. For example, ferrite determined by these methods on Boat 1 and Boat 2, as shown in

Sketch #1 indicates that Boat 1 should be crack-free and Boat 2 should contain cracks. It was observed, however, that Boat 1 was more severely cracked than Boat 2. See Table III for comparison of chemistry and magnetic values.

Although both laboratories report chromium values below 17%, it is difficult to conceive this low value at the nickel contents reported (7-8%) when the wire used for these overlays have always had a requirement that the mimimum chromium content be equal to 11 plus the percent of nickel.

From the results of these weldability tests it is concluded that the cladding was sound at the time of manufacture, since refused clad was sound in spite of cracks underneath which would act as "notch extension" type crack starters.

DISCUSSION AND CONCLUSIONS

The results of various examinations, history of the units, and the literature of welding defects and corrosion processes in cast austenitic steels do not clearly permit the cracking process to be identified as exclusively related to weld metal properties, or as a corrosion process, or as some unidentified combination of both. As to the possibility of chloride-ion stress-corrosion cracking, the literature on wrought stainless steels is far too extensive to review in any detail here. Observations on cast microstructures are far more rare. A general feature seems to be that cast stainless steels are at least as resistant and probably more resistant to chloride stress-corrosion than are the wrought materials. Wrought type 304 stainless steel is not cracked by chlorides at room temperature unless hydrochloric acid is present. This has been demonstrated by Acello and Greene (1) using 10-Normal sulfuric acid, H_2SO_4, with 0.5-Normal sodium chloride NaCl (H_2SO_4 + NaCl $\rightarrow$ HCl), as

reviewed by Staehle (2), and in later work by Bianchi, Mazza, and Torchio, who worked directly in HCl solutions (3). In seawater, observations on stressed Erichsen cup specimens of 304 stainless steel showed no stress-corrosion cracking in 2-year exposure to raw seawater at temperatures of 114-125°F, although severe pitting occurred (4).

At ambient temperature, in the presence of sea water, any corrosion in weld overlays would most likely be of the pitting type (pits were detected) rather than stress corrosion. Direct comparison with expected results of cast or weld clad stainless steel is not possible.

The relative resistance of cast-to-wrought stainless steels has not been reported for exactly the same compositions at exactly the same total magnitudes of tensile stress. Hart, however, reports some observations for a cast 25Cr-20Ni-Fe alloy which resisted stress corrosion in boiling magnesium chloride for over 1000 hours at loadings corresponding to as much as 1% elongation (5). Hart notes that Copson's well-known curve for wrought Fe-Ni-Cr alloys indicates that an alloy of this composition would fail rapidly in boiling $MgCl_2$ (6). Hart was able to crack the cast alloy when it was welded, the cracking occurring transgranularly in the parent metal away from the weld. A similar increase in resistance of cast material to wrought material was reported by Flowers, Beck, and Fontana, who worked with CF-3, CF-8, and the Mo-bearing grades, compared to 304 and 316, in tests in 875 ppm NaCl at 400°F (7). Cracking was observed to propagate through the austenite and around the ferrite. Flowers, et al., attributed the increased resistance to cracking of the cast material to a "keying" action of the ferrite.

Under ordinary circumstances, no corrosion would be expected during a post weld heat treatment. The results of the metallographic examination wherein attack was seen to be related to ferrite content would indicate a stress corrosion failure following the pattern shown by Ishihara, et al.(8).

Returning to the work of Hart on cast 25Cr-20Ni-Fe, additional tests on two carbon levels (0.2 and 0.4%) on specimens loaded to either 6.4 hbars or 12.8 hbars and coated with NaCl and exposed to saturated steam produced only transgranular fractures. Hart also examined a 24Cr-24Ni-Fe-1.6Nb casting and a 18Cr-36NI-Fe casting in this NaCl coating test and reported transgranular cracking showing interdendritic branching for the 24Cr material and slight interdendritic cracking for the 18Cr-36Ni alloy. There is no way to relate Hart's observations on this high Ni alloy to the present low Ni weld clad, particularly since the lowest Ni casting that Hart studied (the 25Cr-20Ni alloy) failed in Hart's test by transgranular attack only, which attack, according to Hart, "took place so rapidly that the sample fractured before interdendritic cracking could initiate".

Hart also showed no cracking of these three cast alloys in 1000 hr. + exposures to boiling 50% NaOH solutions at 116°C, an environment of no concern here. However, interdendritic caustic stress corrosion cracking was consistently observed by Hart in KOH coated samples of all three alloys exposed to 300°C steam. Again, the pertinence of the environment is low. Hart further showed that sulfur-bearing species plus steam at as low a temperature as room temperature and also 100 and 300°C led to reproducible interdendritic stress-corrosion cracking. The sulfur solutions consisted of (SO_2 + FeS) mixtures, or (SO_2 + H_2S) "polythionic acid" mixtures, or plain SO_2 in water, all at room temperature. Additionally, Hart showed interdendritic

attack in steam at 100 and 300°C on samples of all three alloys which had been pre-sulfided by being heated at 400°C in an H_2S atmosphere.

These observations clearly show that interdendritic stress corrosion processes are possible in cast microstructures of austenitic stainless steel, but they leave open the question of the pertinence of observations to the present clad problem, both in terms of the composition of the 309 weld metal vs. the composition which have been studied and also in terms of the environments which produced such cracking. It is equally clear that controlled experiments on the stress corrosion characteristics of 309 weld metal in chloride environments are not extensive enough to be related unambiguously to the clad cracking problem.

Another possible mode of failure, a hot short condition due to films or fissures, is considered unlikely since defects of the magnitude seen here should have manifested themselves during manufacture, the PT test prior to PWHT, the PT test subsequent to PWHT, and the PT test after local PWHT of the tube plate to channel head weld. Furthermore, the examination by SEM with EDAX indicated normal rounded manganese sulfide inclusions and Auger Electron Microscopy could not confirm the presence of any film type indications.

The inconsistent chemical analysis suggests that some beads may have excessive dilution, again no evidence could be found to indicate that dilution contributed to failure.

Finally, all elements identified on the surface of fractures and in cracks which could have pinpointed cause of failure may have come from penetrant materials, flux, or as the result of sea water penetration after failure caused by another mode.

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2. R. W. Staehle, "The Theory of Stress Corrosion Cracking in Alloys," edited by J. C. Scully, NATO, pp. 267.
3. G. Binachi, F. Massa, and S. Torchio, Corrosion Science 13, 165 (1973).
4. R. T. Jones, Metals Engineering Quarterly, 7, No. 3, p. 37 (August 1967).
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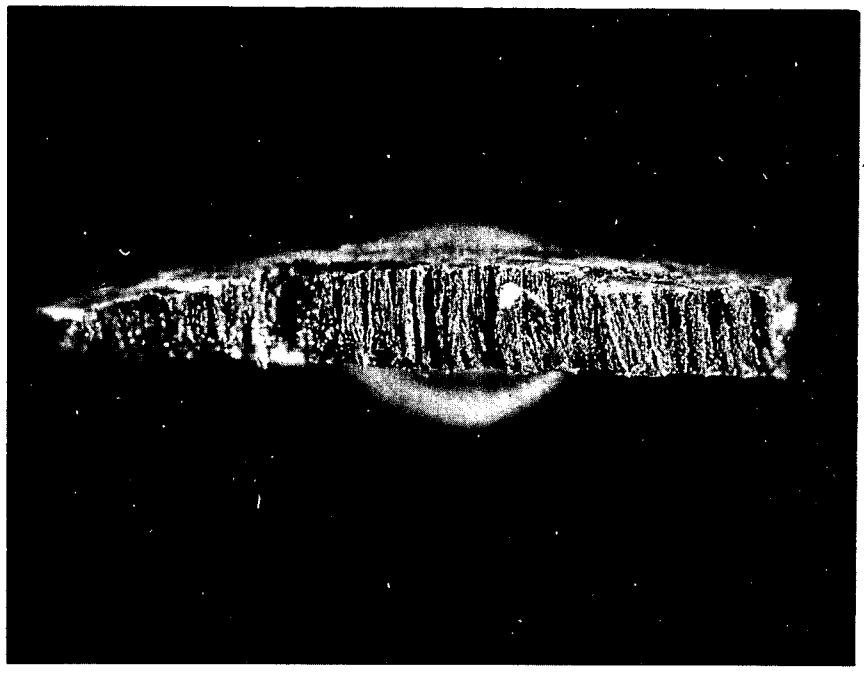
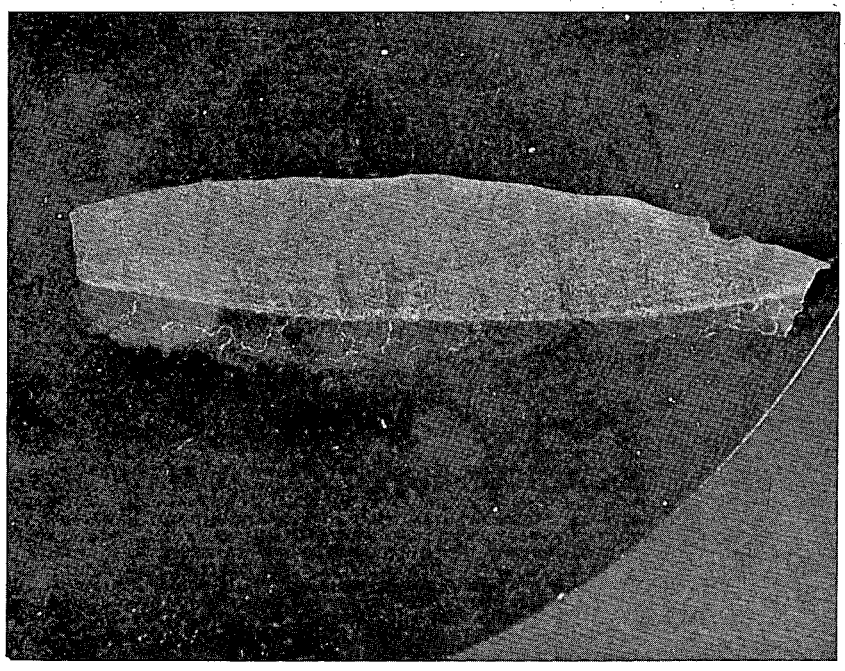
6. H. R. Copson, 1st International Congress Metallic Corrosion (London) (1961), p. 328.
7. J. W. Flowers, F. H. Beck, and M. G. Fontana, Corrosion 19, 186t (1963).
8. T. Ishihara, Y. Shimizu, and G. Ito, "Stress Corrosion Cracking of Austenitic Stainless Steel Overlays in High Temperature Water," Welding Research Abroad, Vol. XXI, 4, April 1975, pp. 11-18.



Approx. 3X

Figure 1. Depicting fractured face of boat sample.



Etchant - Kallings Reagent Approx. 3X

Figure 2. Showing "deck" of boat sample, normal weld bead (top), heat affected zone of previously deposited bead (bottom).

Unetched 240X

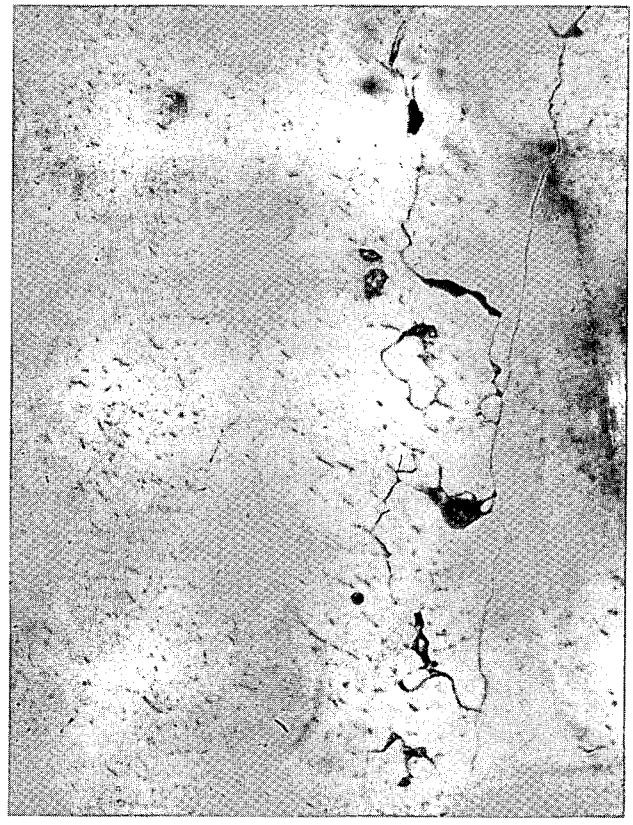
Figure 3. Showing defects started at pits and progressed through the thickness of the weld.

Etchant - Kallings Reagent 60X

Figure 4. Same as Figure 3 showing defects started in heat affected zone of succeeding bead which is seen in upper left corner.

Etchant - Kallings Reagent 120X

Figure 5. Same as Figure 4 except at higher magnification.

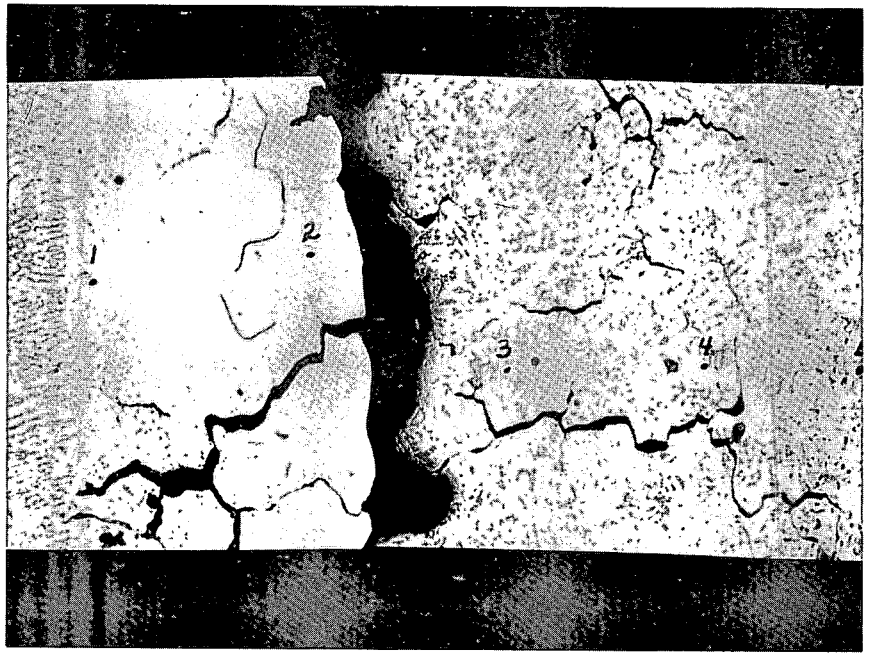


Etchant - Kallings Reagent 240X

Figure 6. Showing a portion of the fine defect seen in Figure 5. Note hint of trans-dendritic as well as interdendritic cracking.

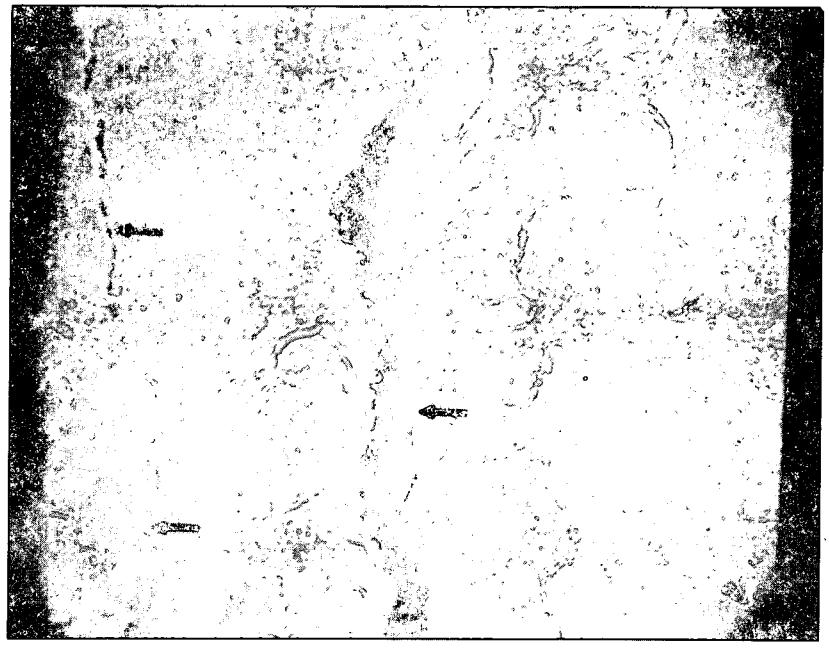
Etchant - Kallings Reagent 100X

Figure 7. Showing interdendritic cracking in low ferrite areas of steam generator #31.



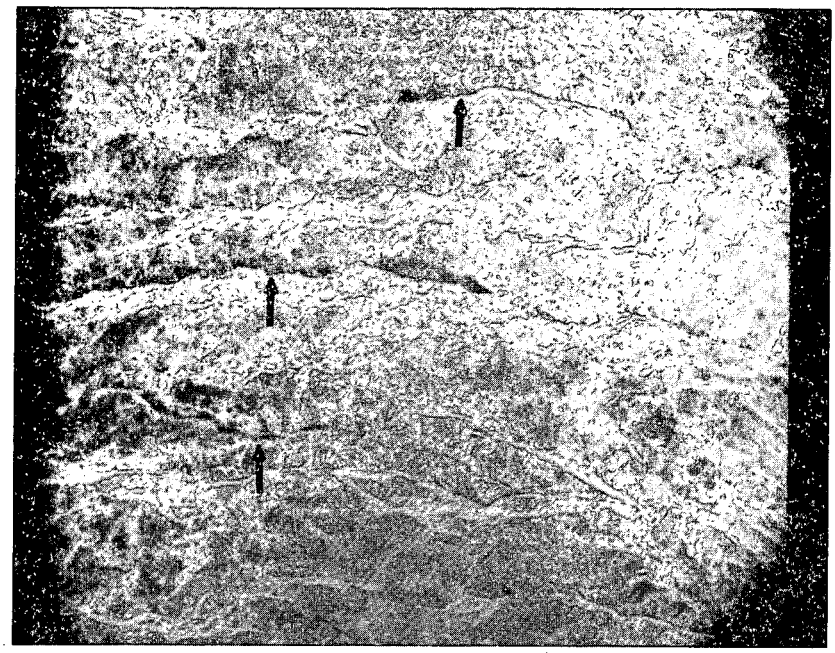
Etchant - Kallings Reagent 100X

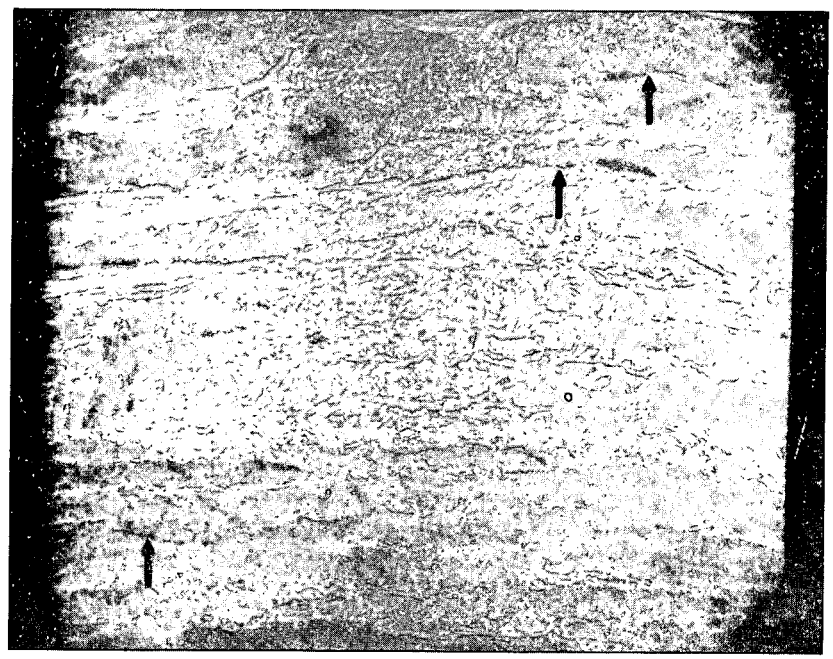
Figure 8. Showing traverse across "deck" of boat showing left to right, normal austenite plus ferrite microstructure of weld bead, heat affected zone of previous bead showing solution of much of the ferrite, fracture, then increasing ferrite as distance from heat affected zone increases. Note that the frequency of defects decreases as with increasing ferrite content.



Magnification Top - 200X
Bottom - 50X

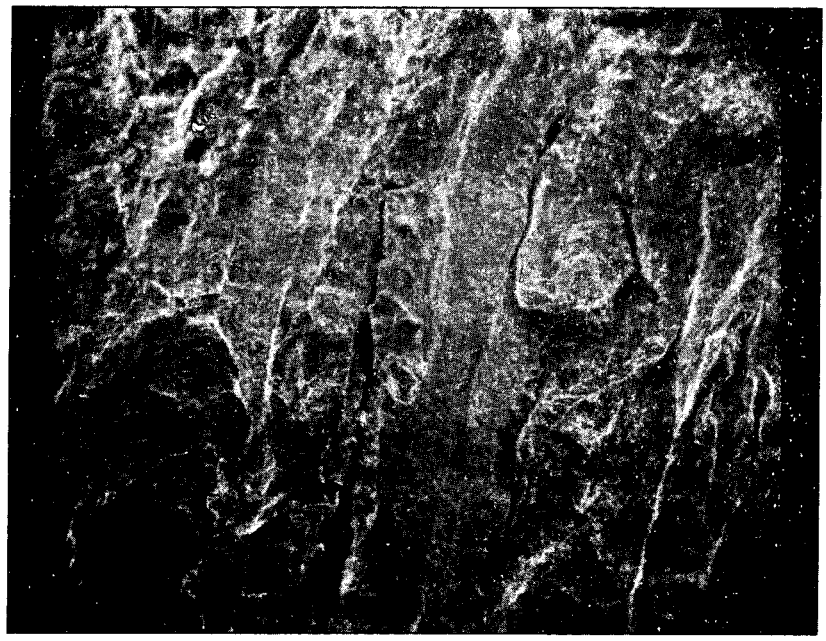
Figure 9. Scanning electron fractographs of specimen No. 5 taken from the cold leg of steam generator unit No. 32. Arrows denote some of the secondary cracks present. These multiple cracks are indicative of stress corrosion cracking. Energy Dispersive Analysis by X-rays (EDAX) of these surfaces denoted a strong chloride presence.





Magnification Top - 100X
Bottom - 50X

Figure 10. Scanning electron fractographs of same specimen as shown in Figure 9 but the specimen has been rotated 90 degrees and has a different tilt. Arrows denote some of the secondary cracks.



Magnification - 100X

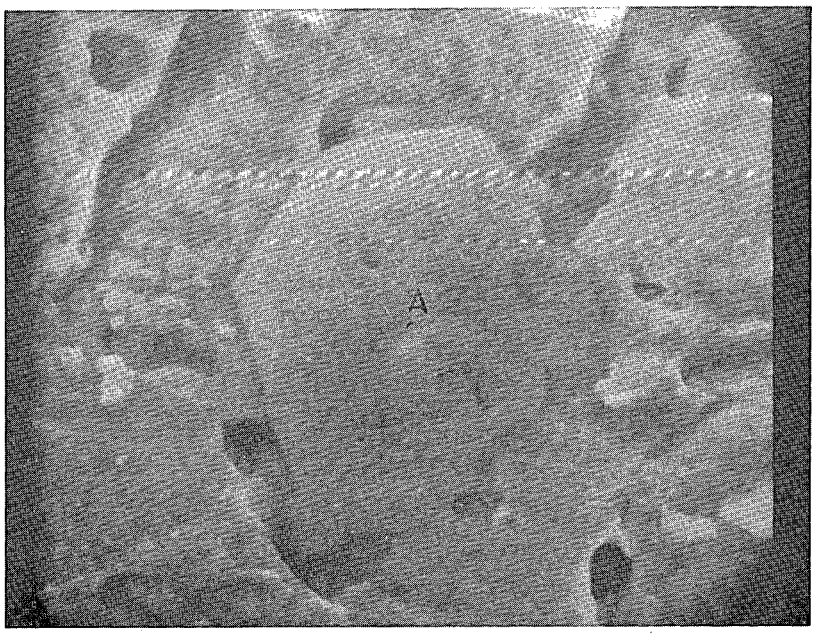
Figure 11. Scanning electron fractograph of specimen No. 6 taken from the hot leg of steam generator unit No. 31. Note the same features and secondary cracking (arrows) as shown on specimen No. 5 indicating stress corrosion cracking.

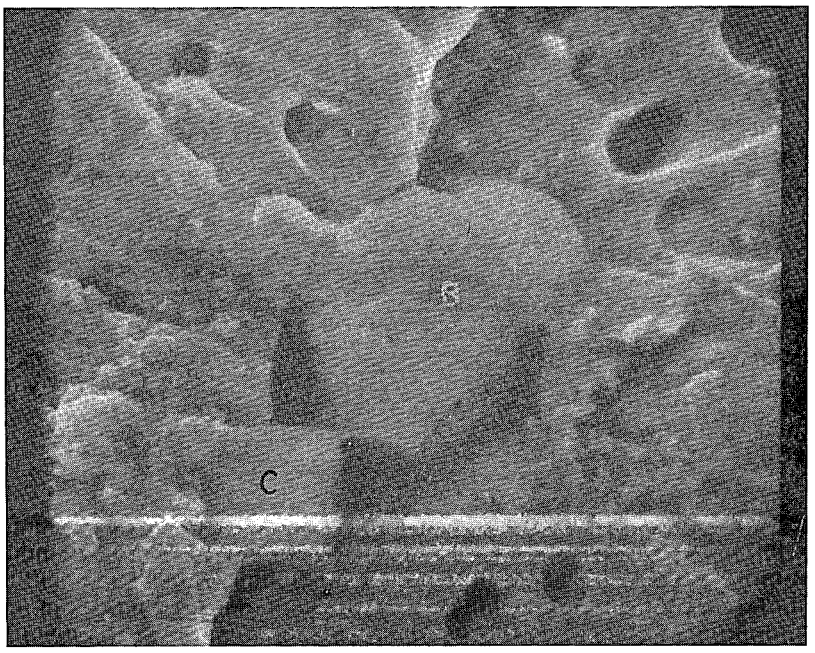
Magnification Top - 1000X
Bottom - 500X

Figure 12. The bottom scanning electron micrograph shows several surface pits (arrows) with cracks initiating from these pits. Top micrograph shows an enlarged view of one of the pits and the resultant cracking. The horizontal lines are the results of grinding wire brushing or some other abrasive operation. These micrographs represent the cladding surface of specimen No. 5.

Magnification - 200X

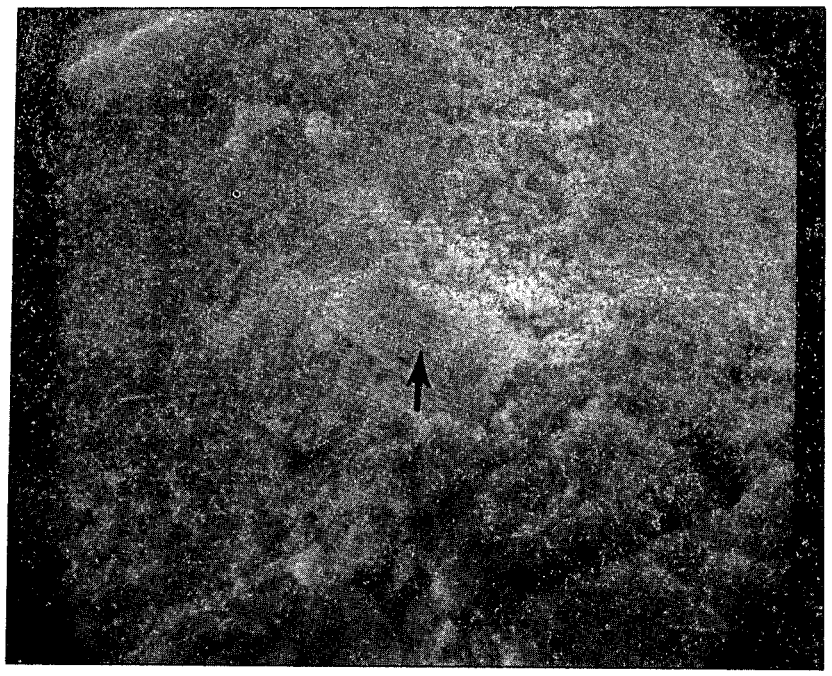
Figure 13. Scanning electron micrograph of a surface cladding area from specimen No. 5. Note the cracks in the depressed or pitted area. Arrows denote a crack initiating from this area. Horizontal lines are abrasive lines from grinding, sanding or wire brushing. EDAX analysis showed heavy chlorine concentration in the cracks and pit, but no chloride was detectable on the abraded areas.





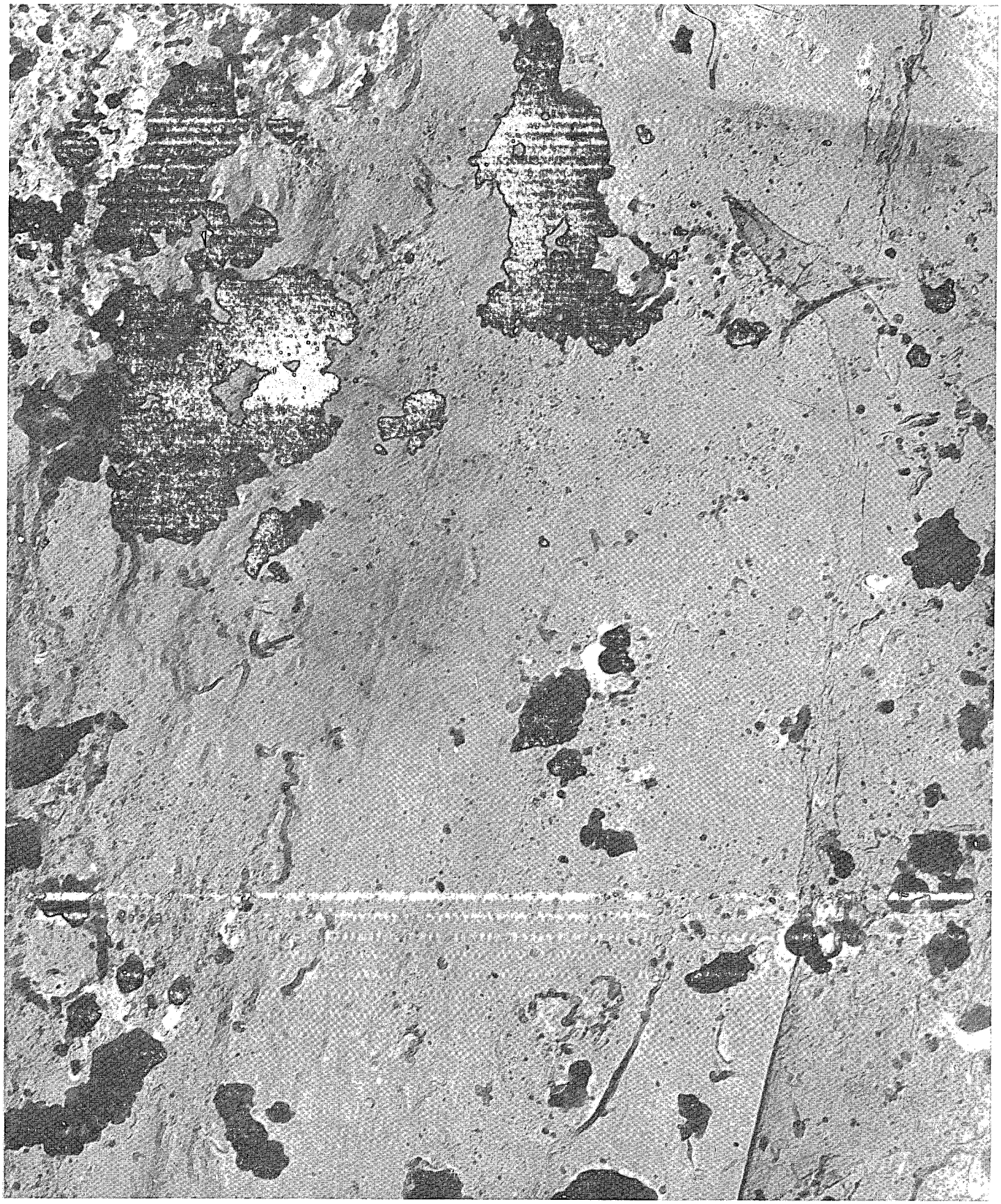
Magnification Top - 5000X
Bottom - 5000X

Figure 14. Scanning electron fractographs of specimen No. 6 (unit No. 31) indicating foreign particles on the "broken open" fracture surfaces. Particles "A" and "B" when analyzed by EDAX displayed the strong presence of Na (sodium) and Cl (chlorine). Particle "C" displayed the presence of K (potassium) and Cl (chlorine). These elements are found in strong concentrations in sea water.



Magnification - 5000X

Figure 15. Scanning electron fractograph of specimen No. 5 (unit No. 32) displaying a foreign particle (arrow). EDAX analyses display the strong presence of K (potassium) and Cl (chlorine) also indicating that sea water was present in unit No. 32 as well as in unit No. 31.



Magnification - 26,000X

Figure 16. Electron micrograph of replica from specimen No. 4 (steam generator unit No. 32) showing entrapped corrosion products from the fracture surface (dark particles).

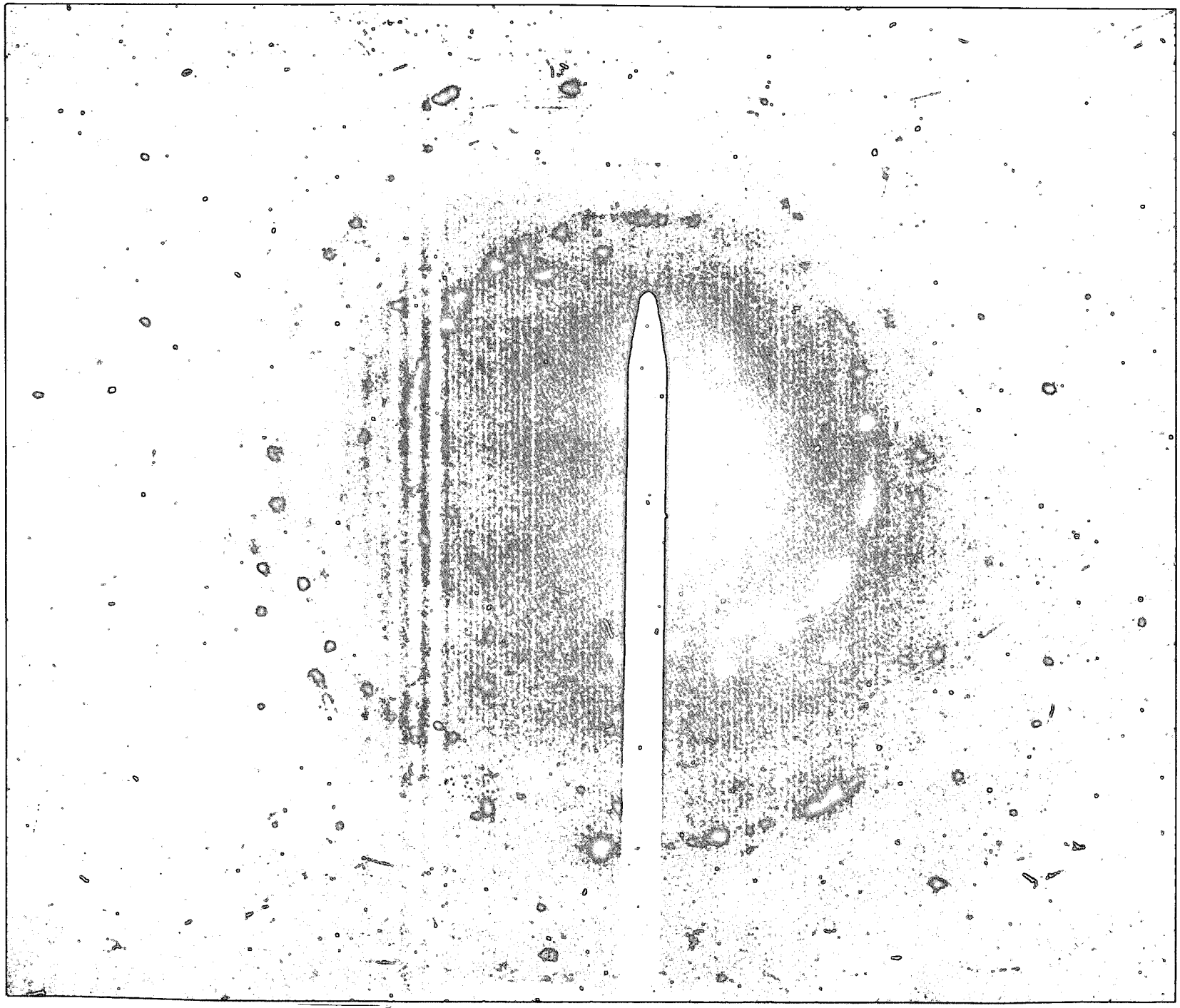


Figure 17. Electron diffraction pattern of some of the corrosion products shown in Figure 16.

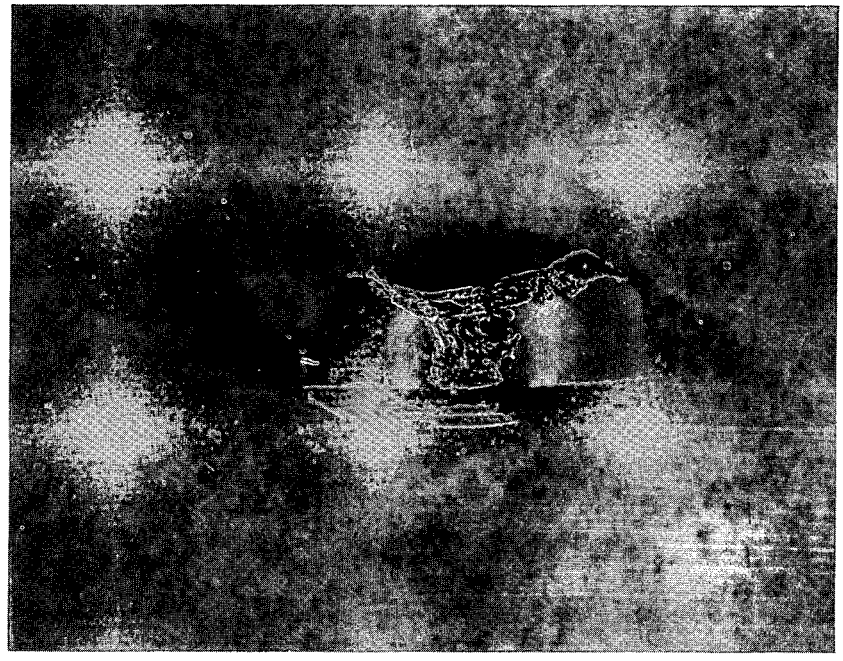


Figure 18 3X

Bend specimen from boat sample #1 Sketch #2

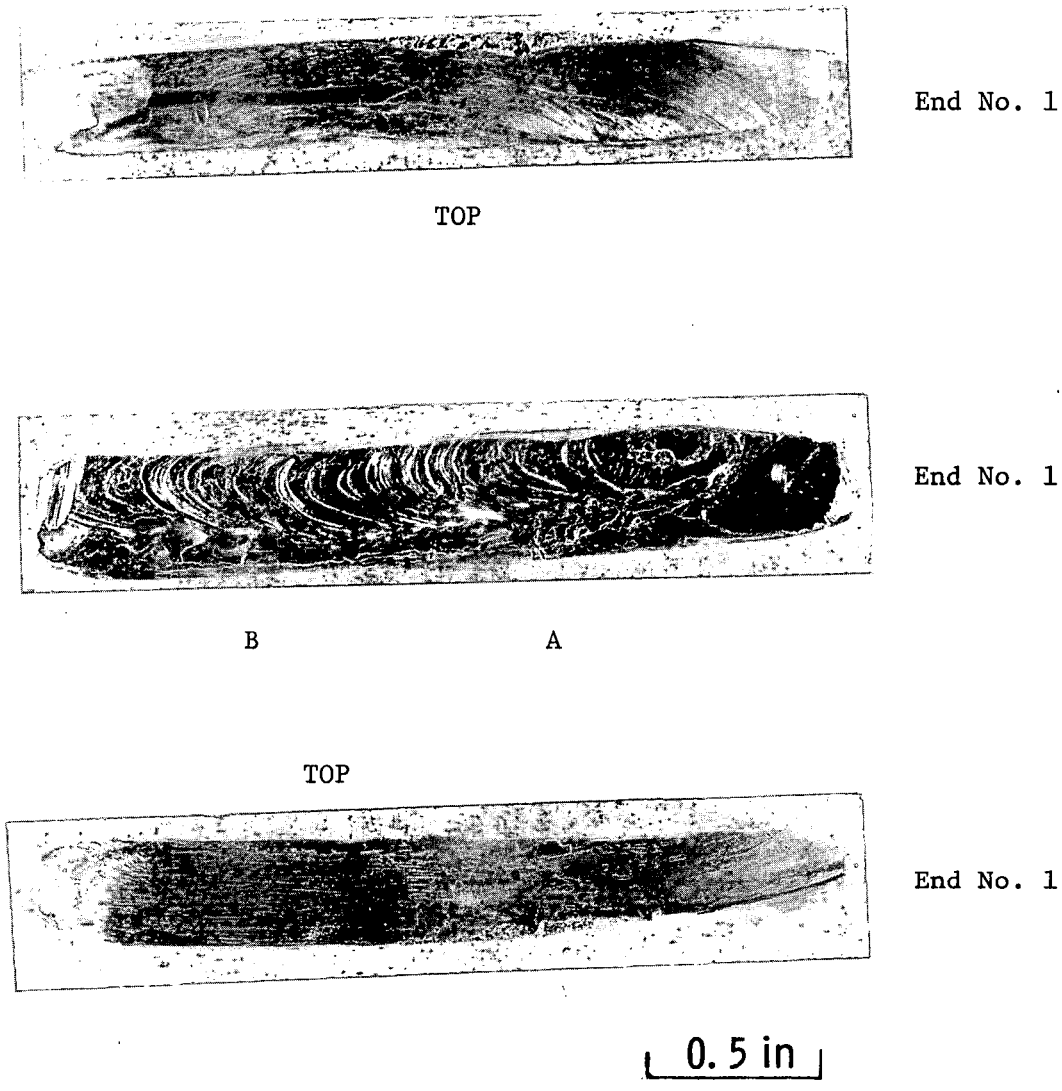
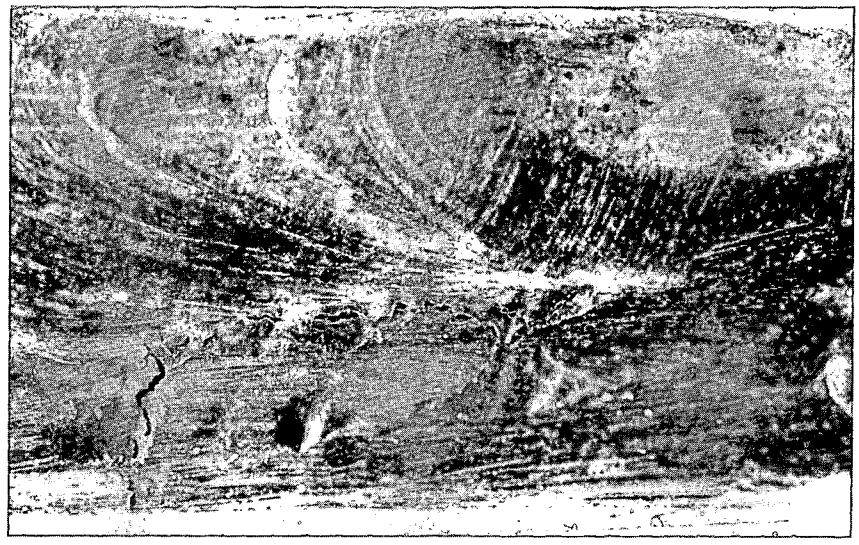
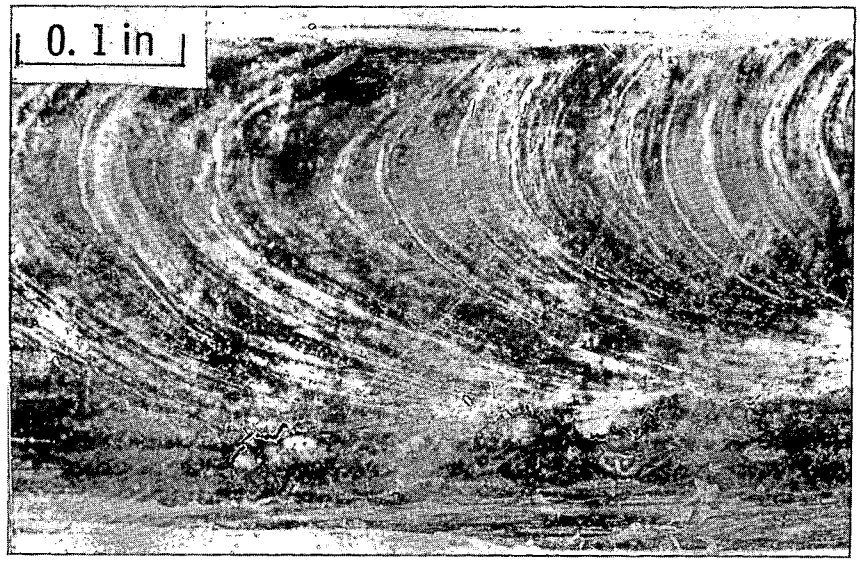


Figure 19. "Deck" view of boat No. 1 (center) and sideviews (top and bottom) of specimen taken from location shown in Sketch #1. Points "A" and "B" at higher magnification are shown in Figure 20.



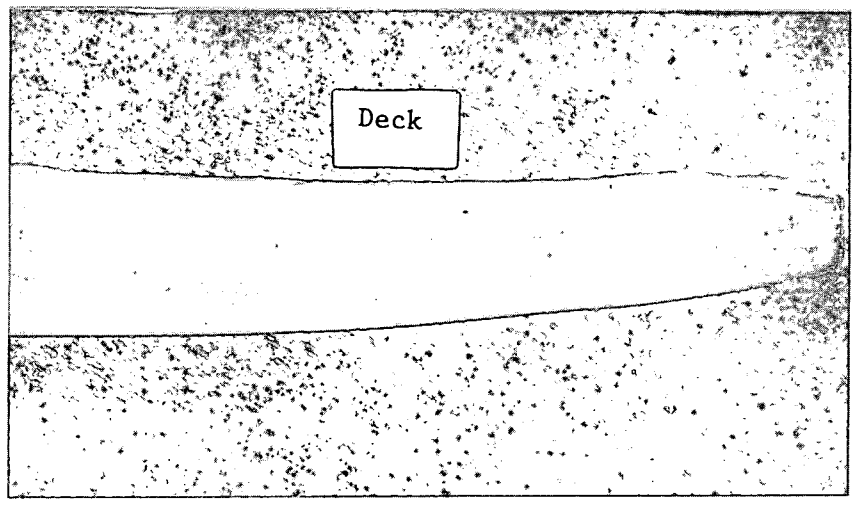
Point A



Point B

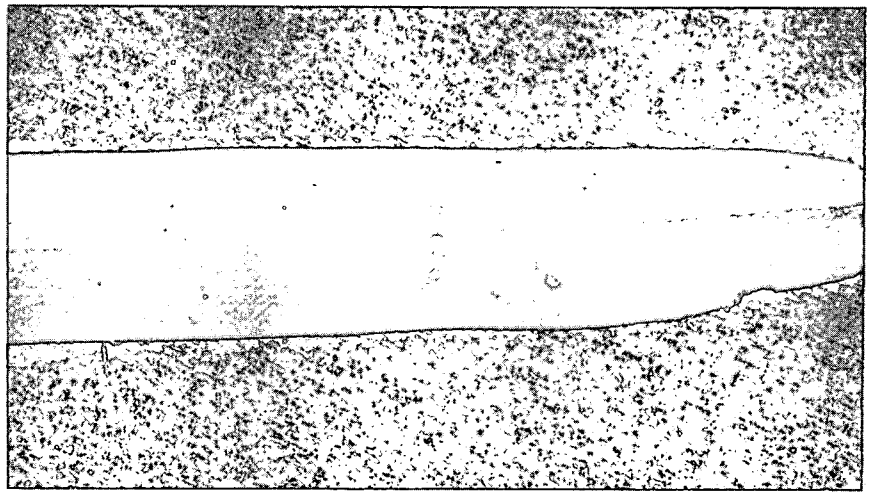
Figure 20. Points "A" and "B" from Figure 19 at higher magnification.

Side View



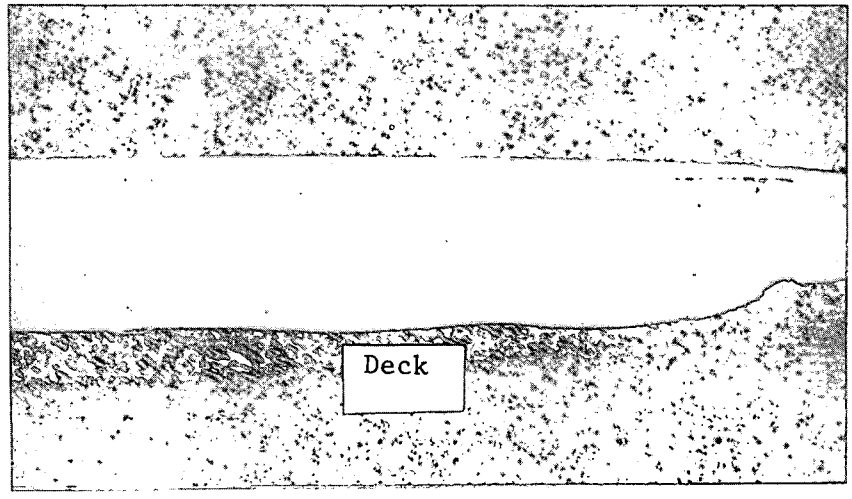
End No. 1

Bottom View



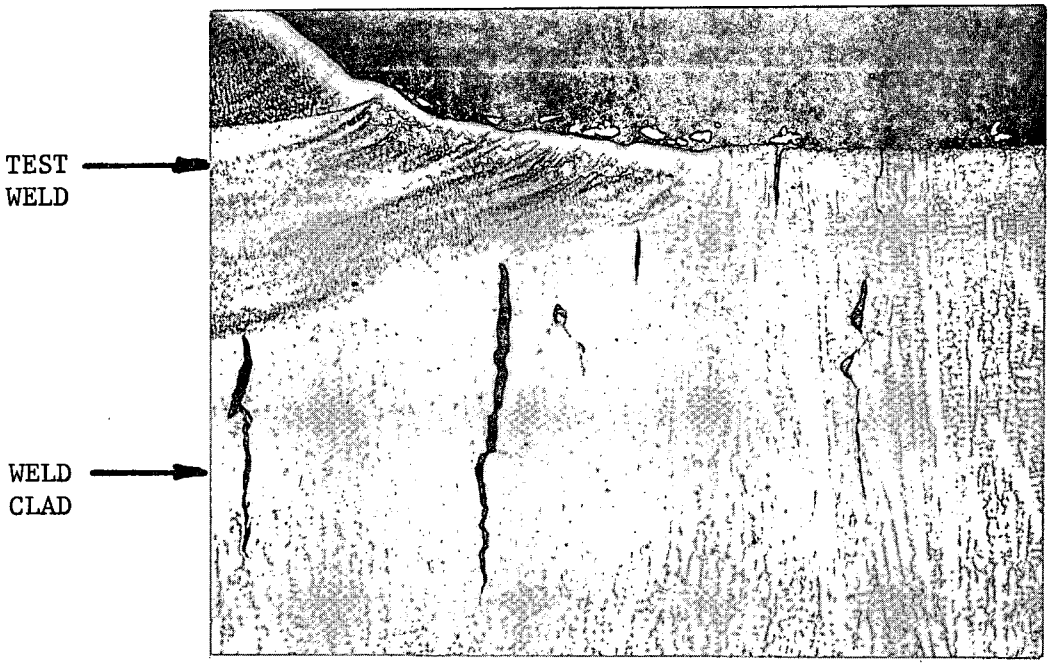
End No. 1

Side View



End No. 1

Figure 21. Dye-Penetrant Indications on Boat No. 1



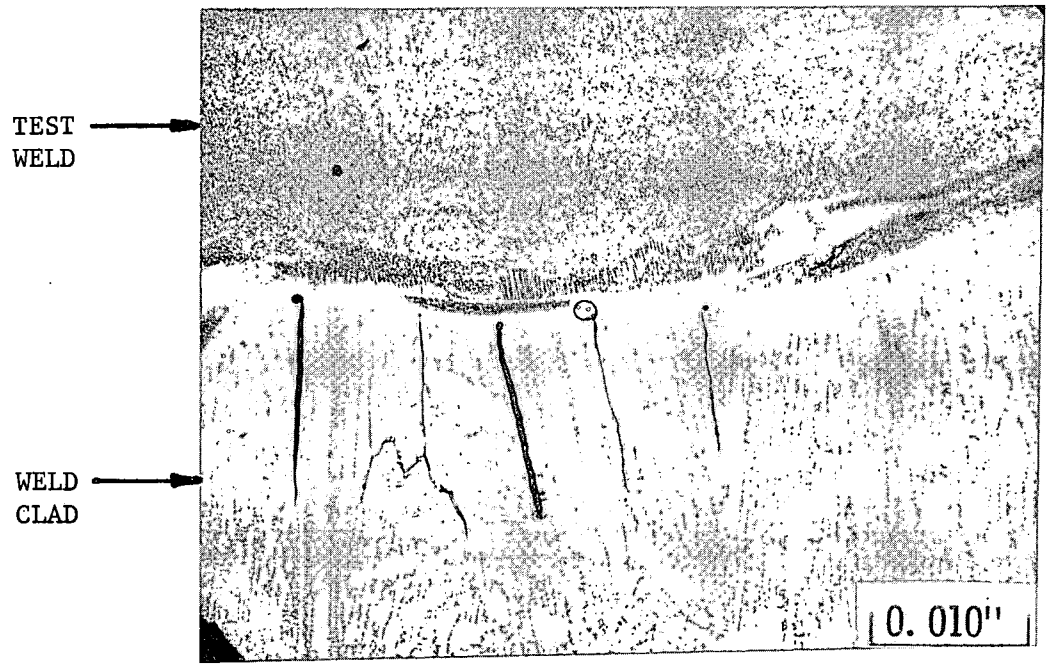


Figure 22. Transverse Section of Boat No. 1 Between Points A and B of Figure 19.

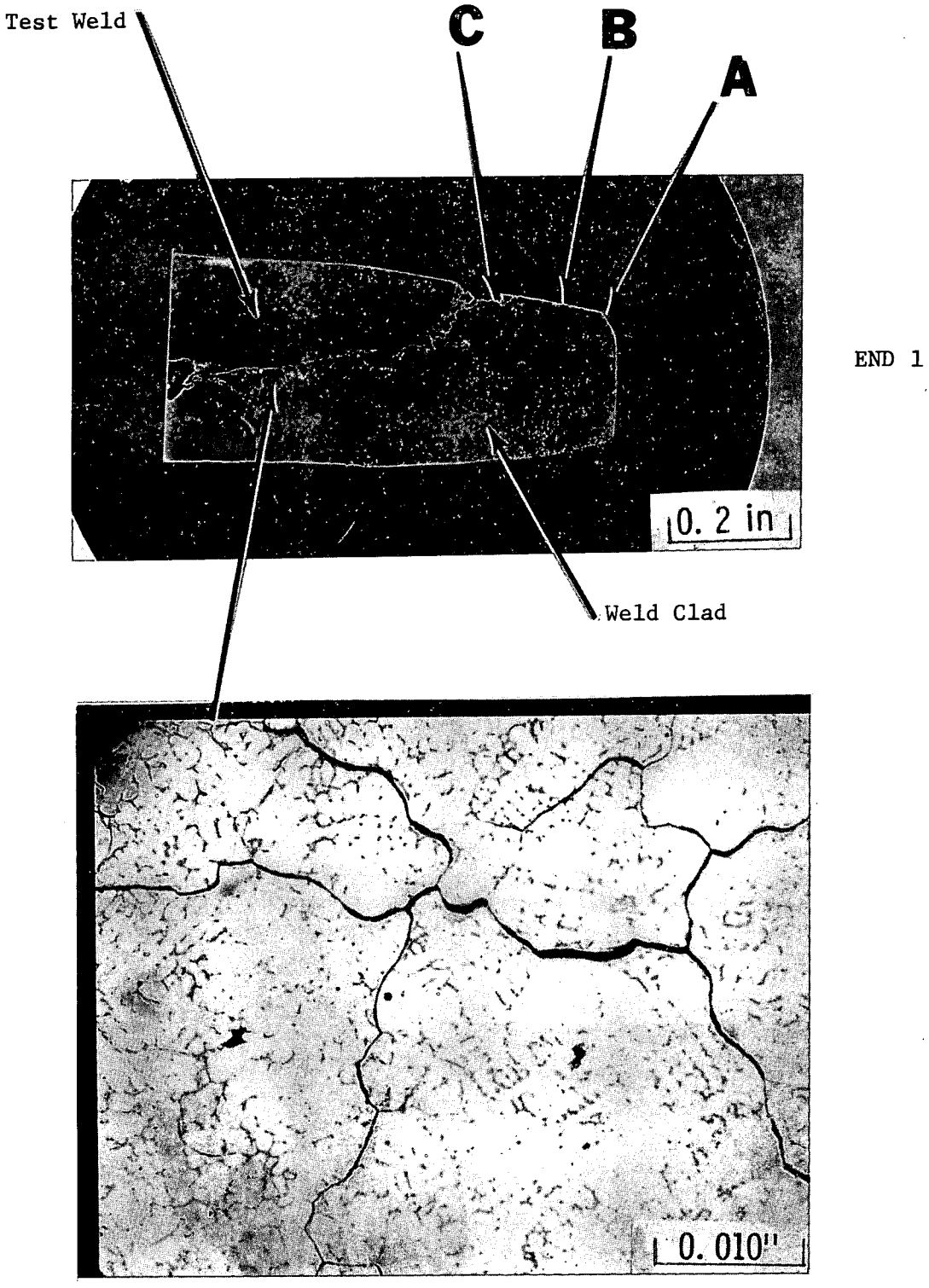


Figure 23. Photograph (top) of etched longitudinal cross section near end No. 1 of boat No. 1, Figure 19. Points "A" "B", and "C" are shown at higher magnification in Figure 24, Photomicrograph (bottom) shows cracking in weld clad below test weld.

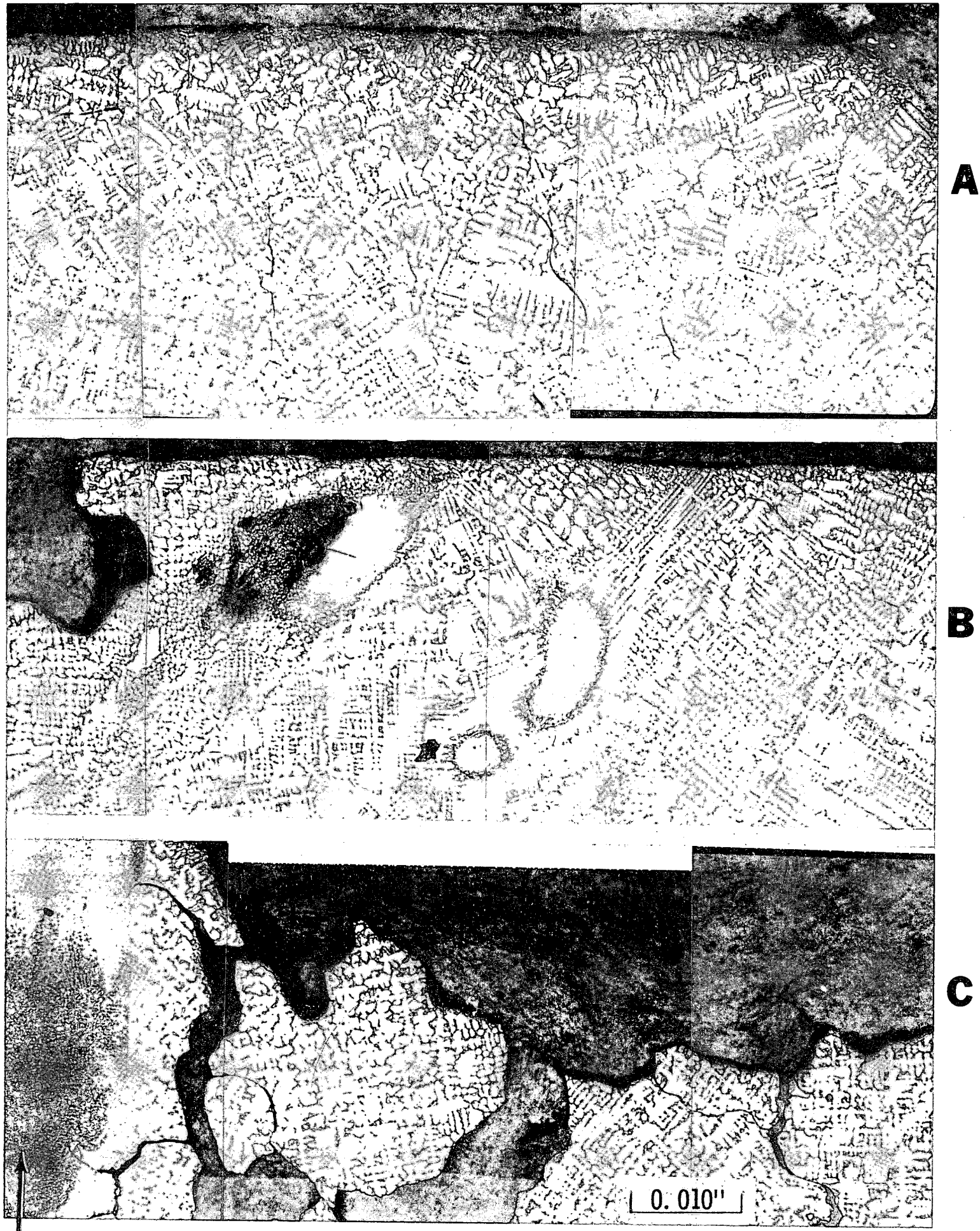


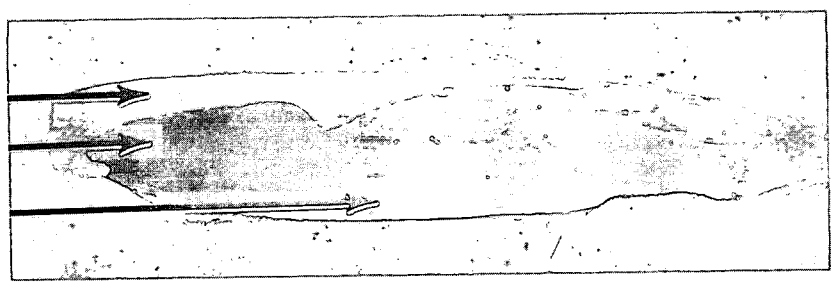
Figure 24. Points A, B and C from Figure 23 showing no cracking in Test Weld and Cracking in Weld Clad

Test Weld

Base Metal

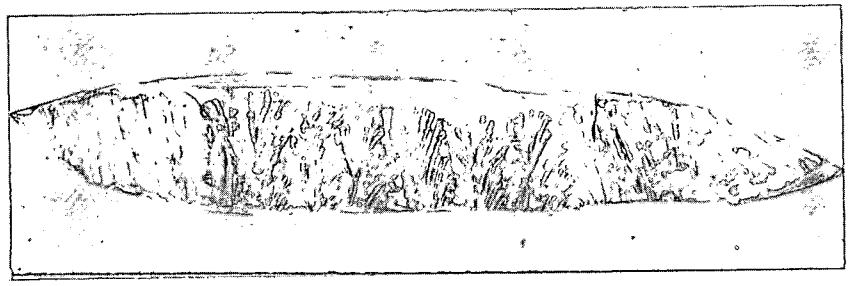
Clad

Test Weld



End No. 2

Side View



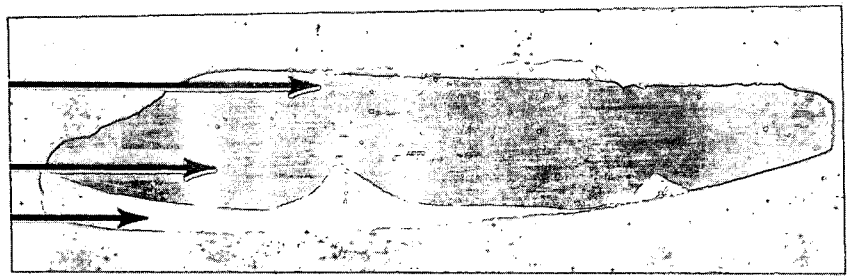
End No. 2

Deck View

Test Weld

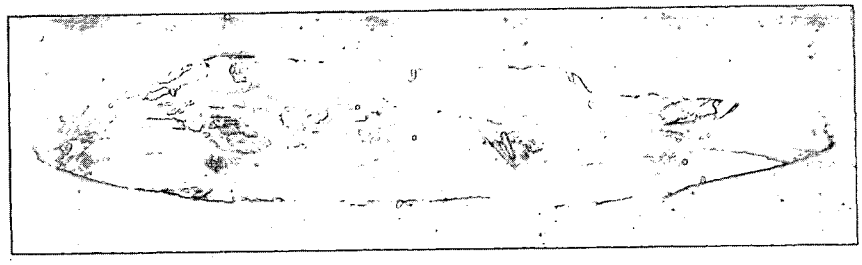
Clad

Base Metal



End No. 2

Side View



End No. 2

Bottom View

Figure 25. Transverse Boat #2 of Weldability Test Shown in Sketch #1.

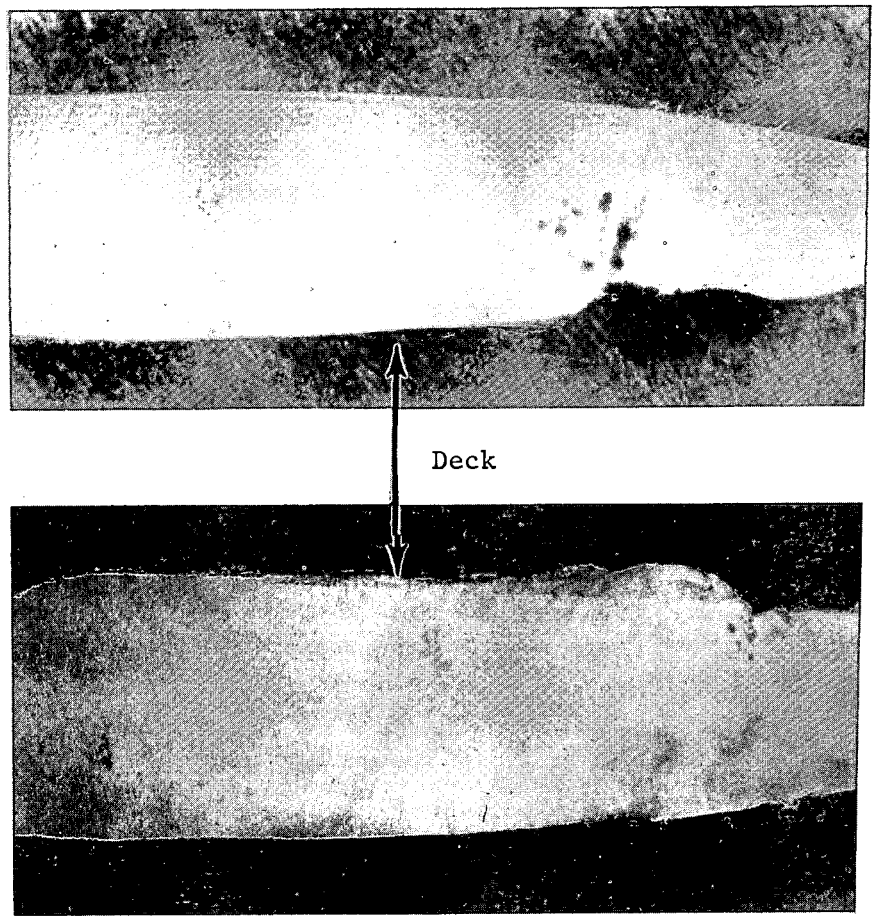


Figure 26. Dye-Penetrant Indications on Boat No.2.

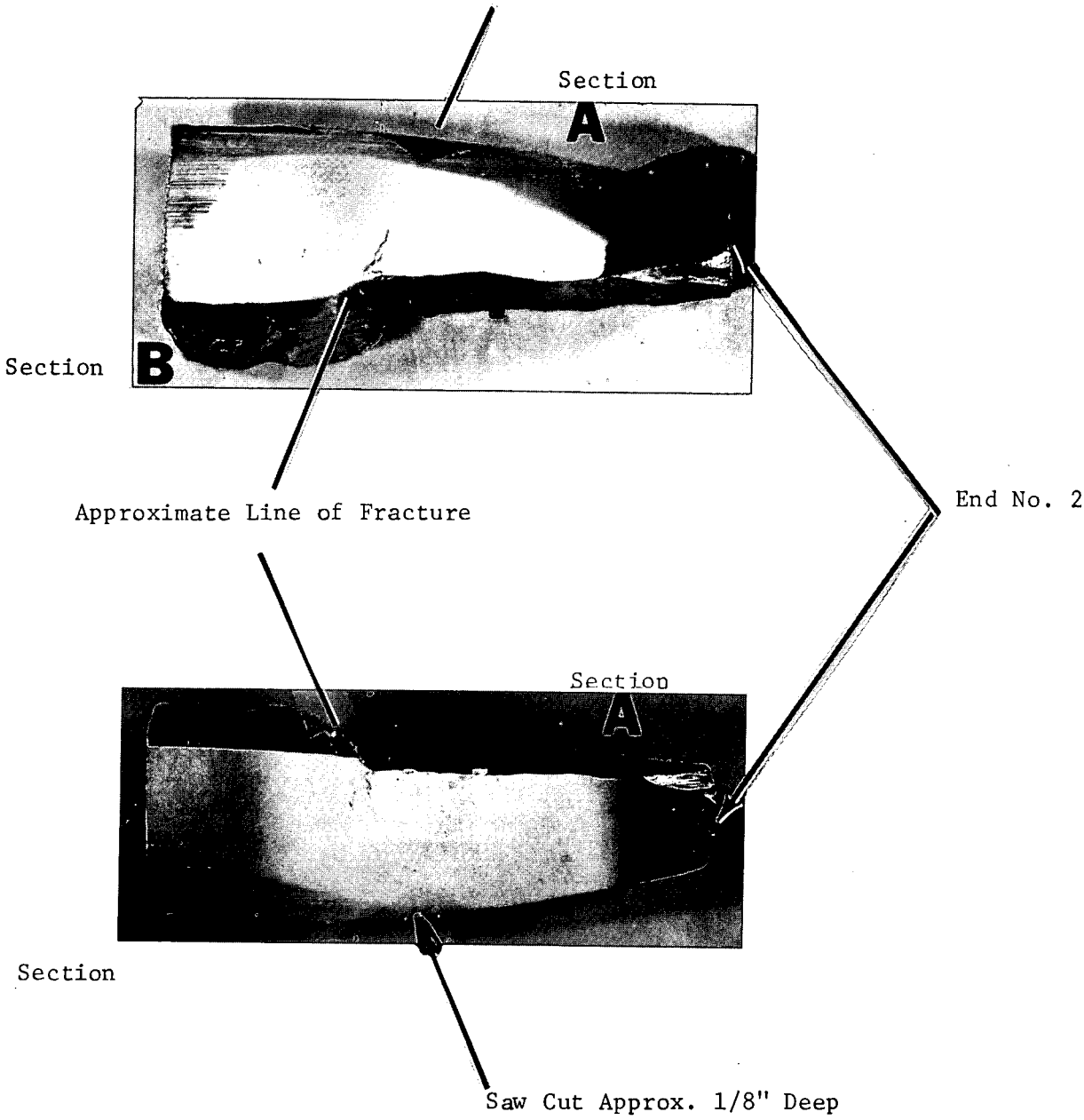


Figure 27. Boat Sample #2 for SEM Fractography Study.

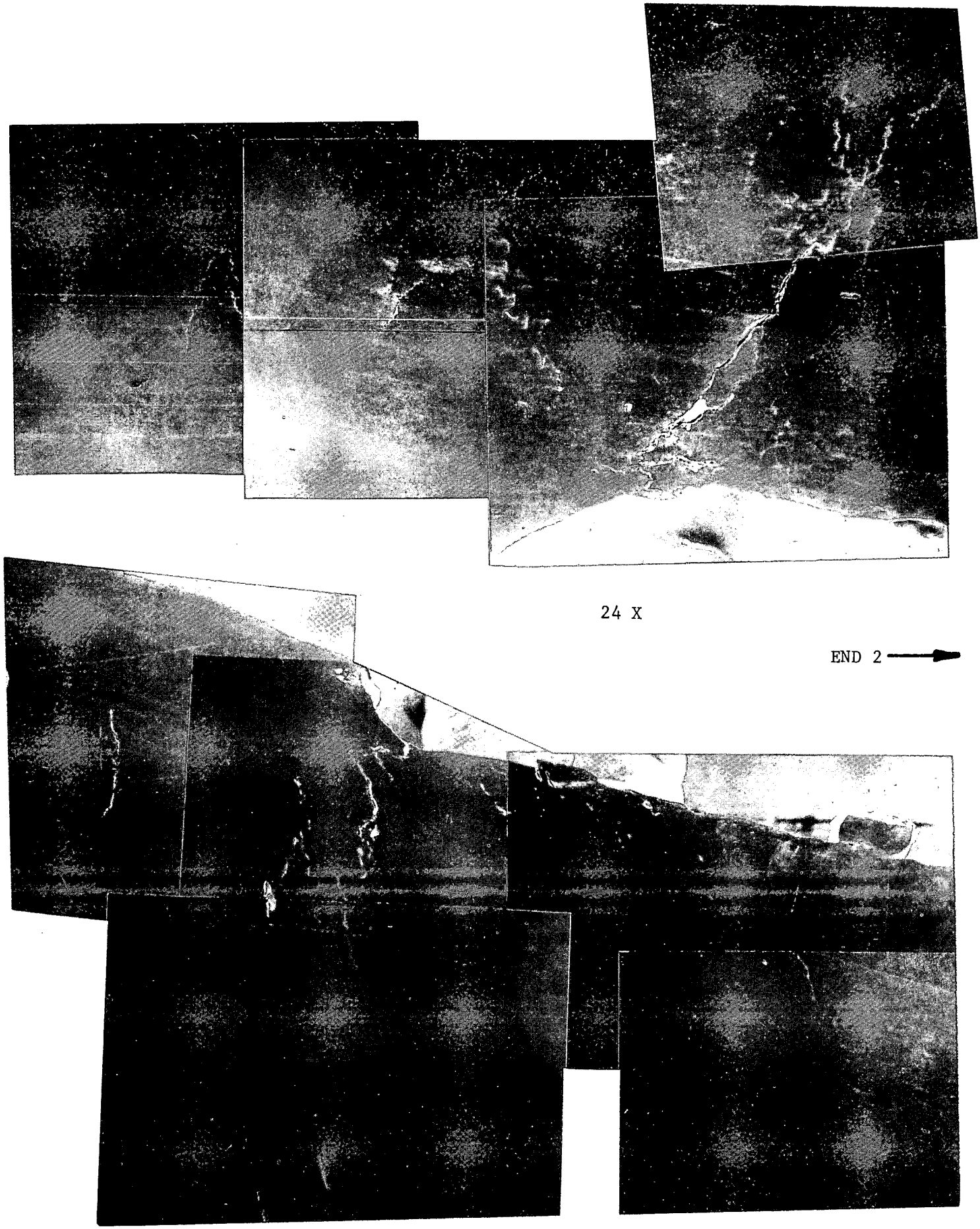


Figure 28. SEM Montage of Cracks in Boat Sample #2 Before Lab Fracture.

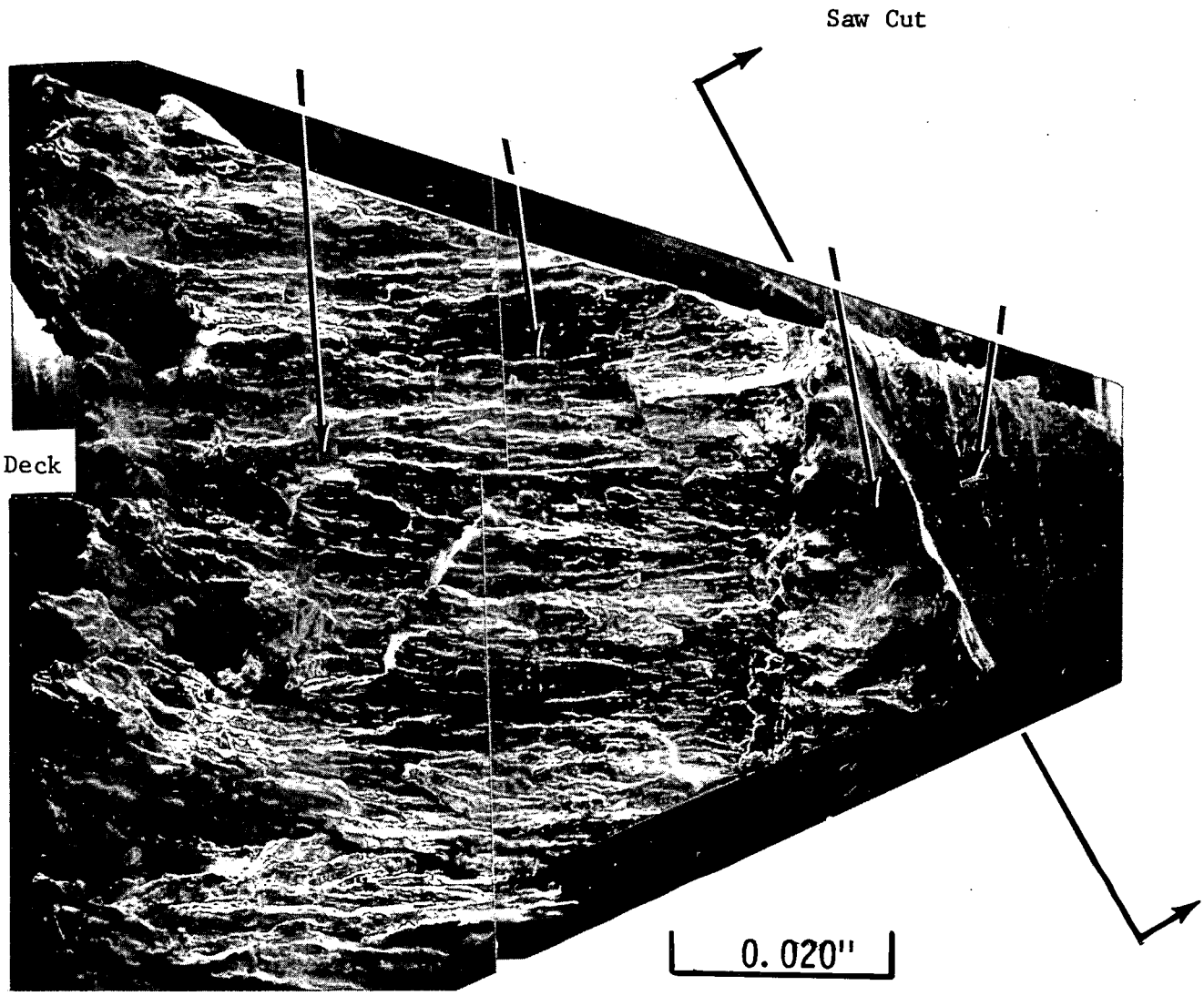
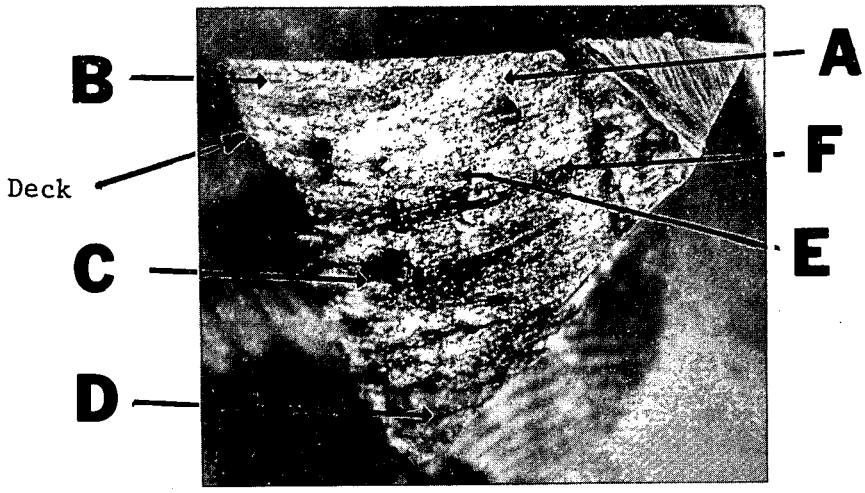
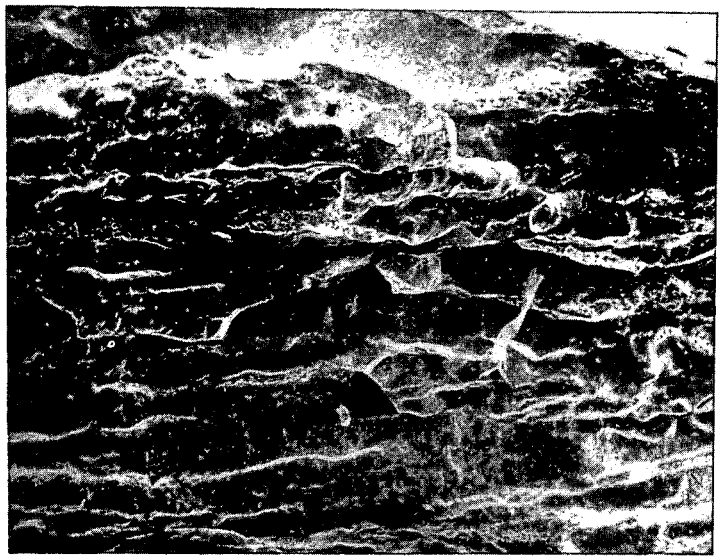
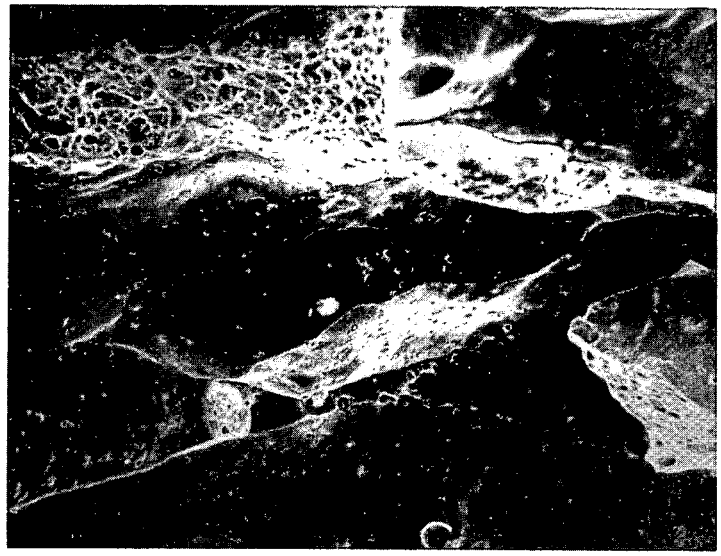


Figure 29. Fracture Face of Section A, Boat #2 SEM-EDAX Analysis Taken at Indicated Points - Analysis: Fe, Ni, Dr with trace of Al. Si also detected at saw cut face.

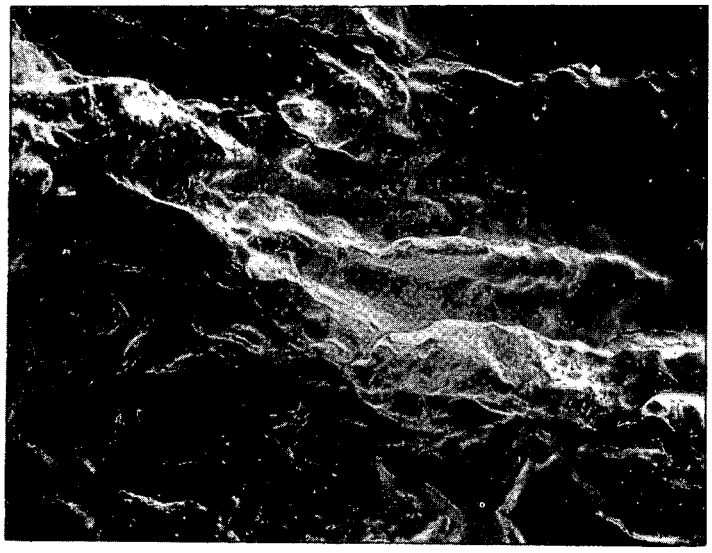




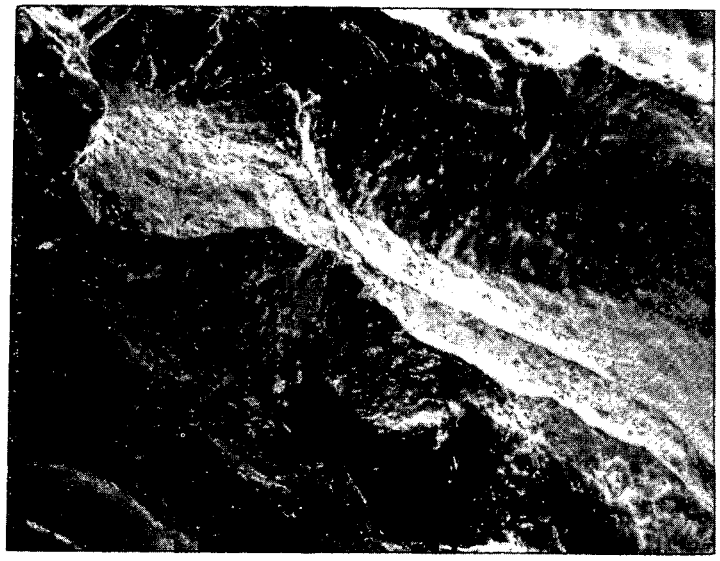
A 120 X



600 X

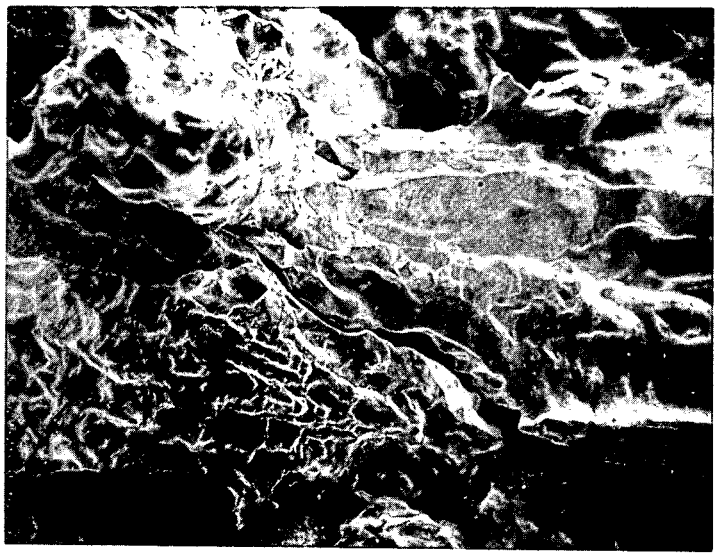


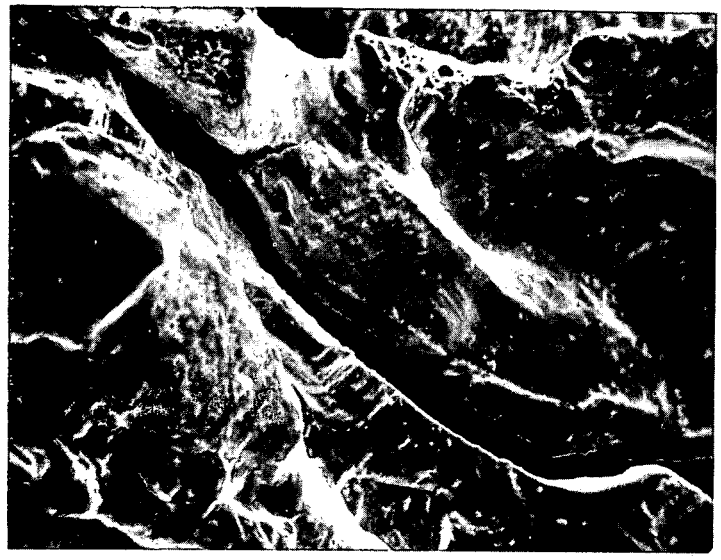
B 120 X



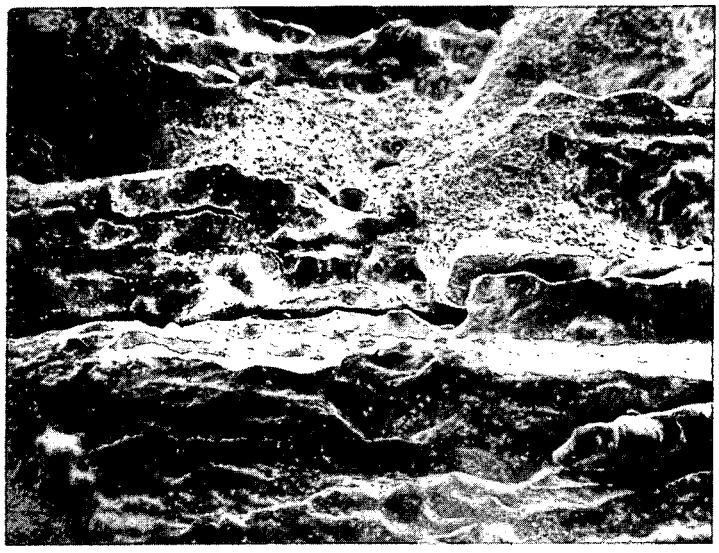
600 X

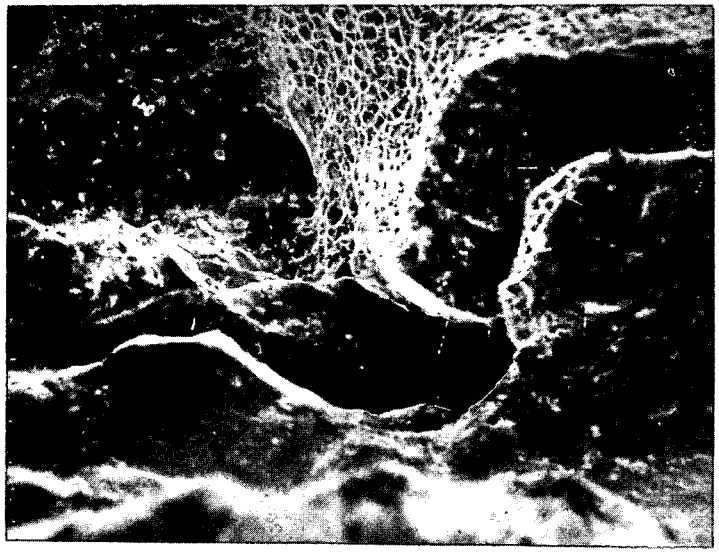
Figure 30. SEM Photographs of Lab Fracture Face of Boat Sample #2, Section A.





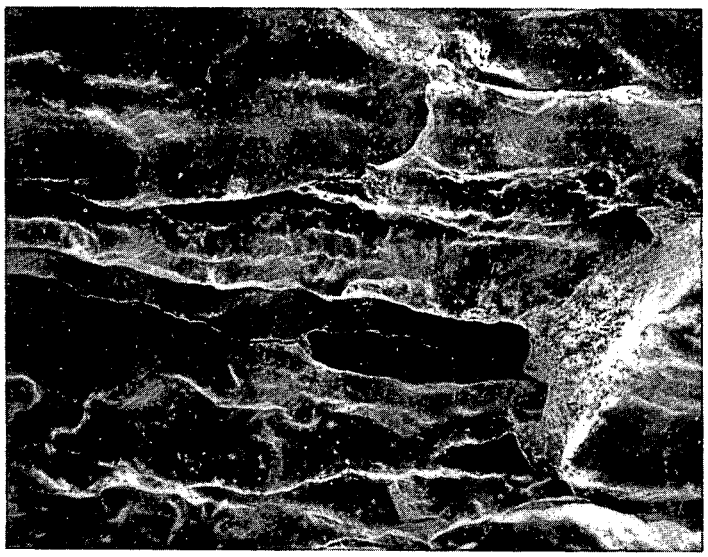
C 120 X 600 X



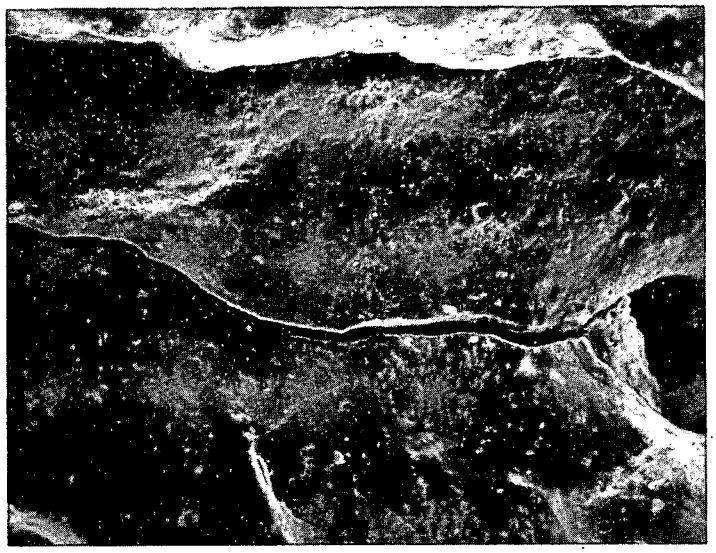


D 120 X 600 X

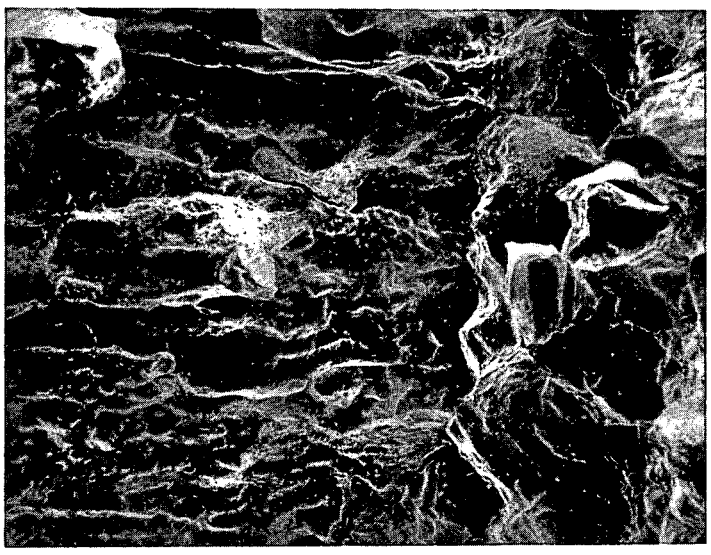
Figure 31. SEM Photographs of Lab Fracture Face of Boat Sample #2, Section A. Location Shown in Figure 30. .



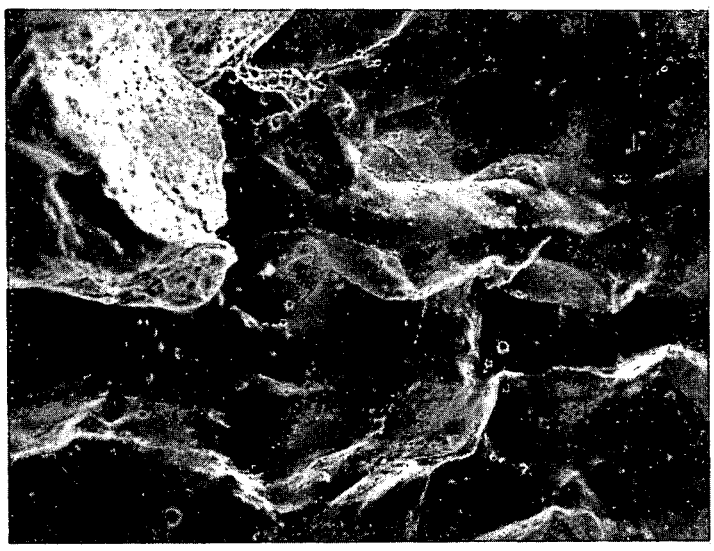
E 120 X



600 X



F 120 X



600 X

Figure 32. SEM Photographs of Lab Fracture Face of Boat Sample #2, Section A. Location Shown in Figure 30 .

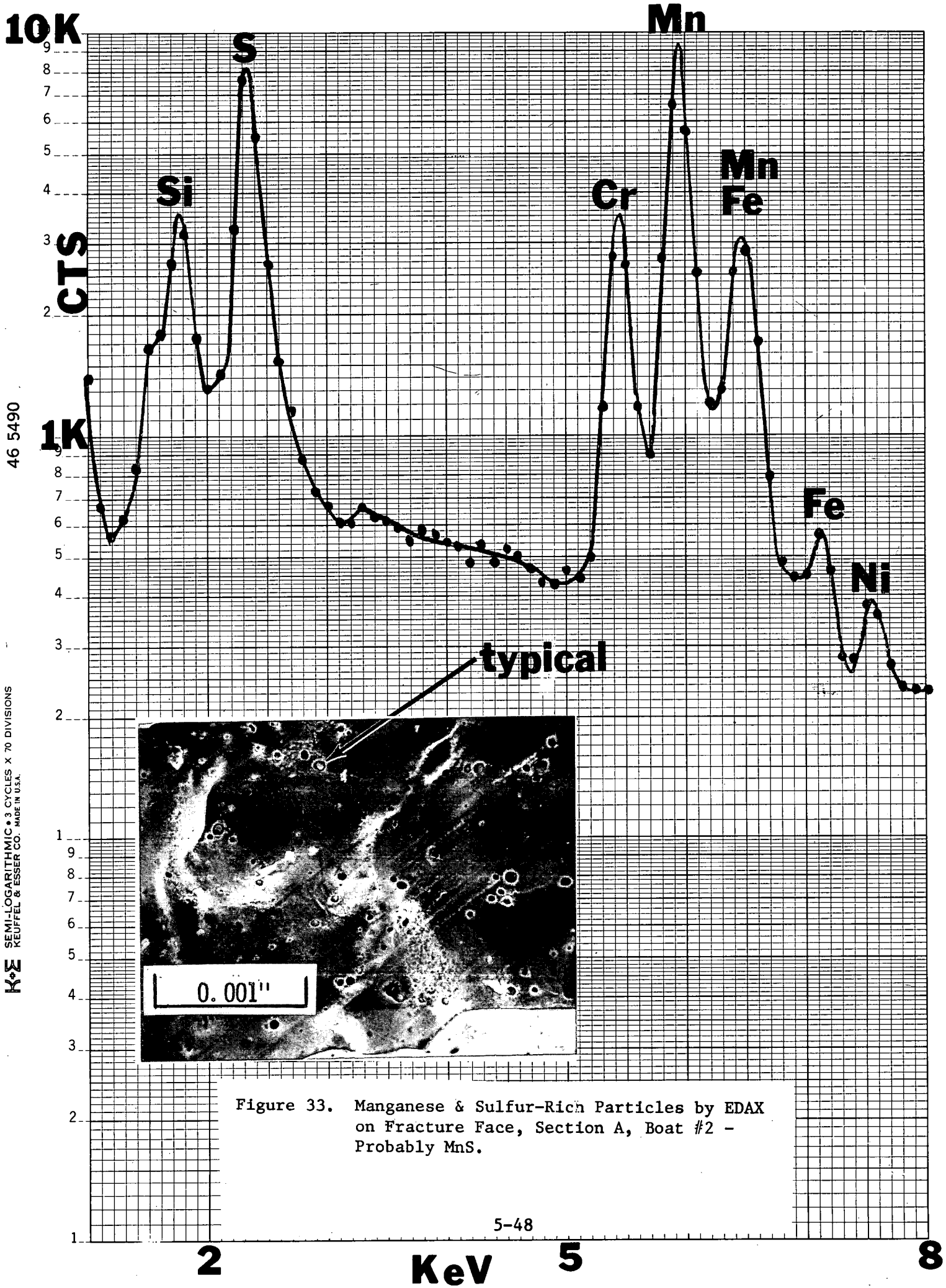


Figure 33. Manganese & Sulfur-Rich Particles by EDAX on Fracture Face, Section A, Boat #2 - Probably MnS.

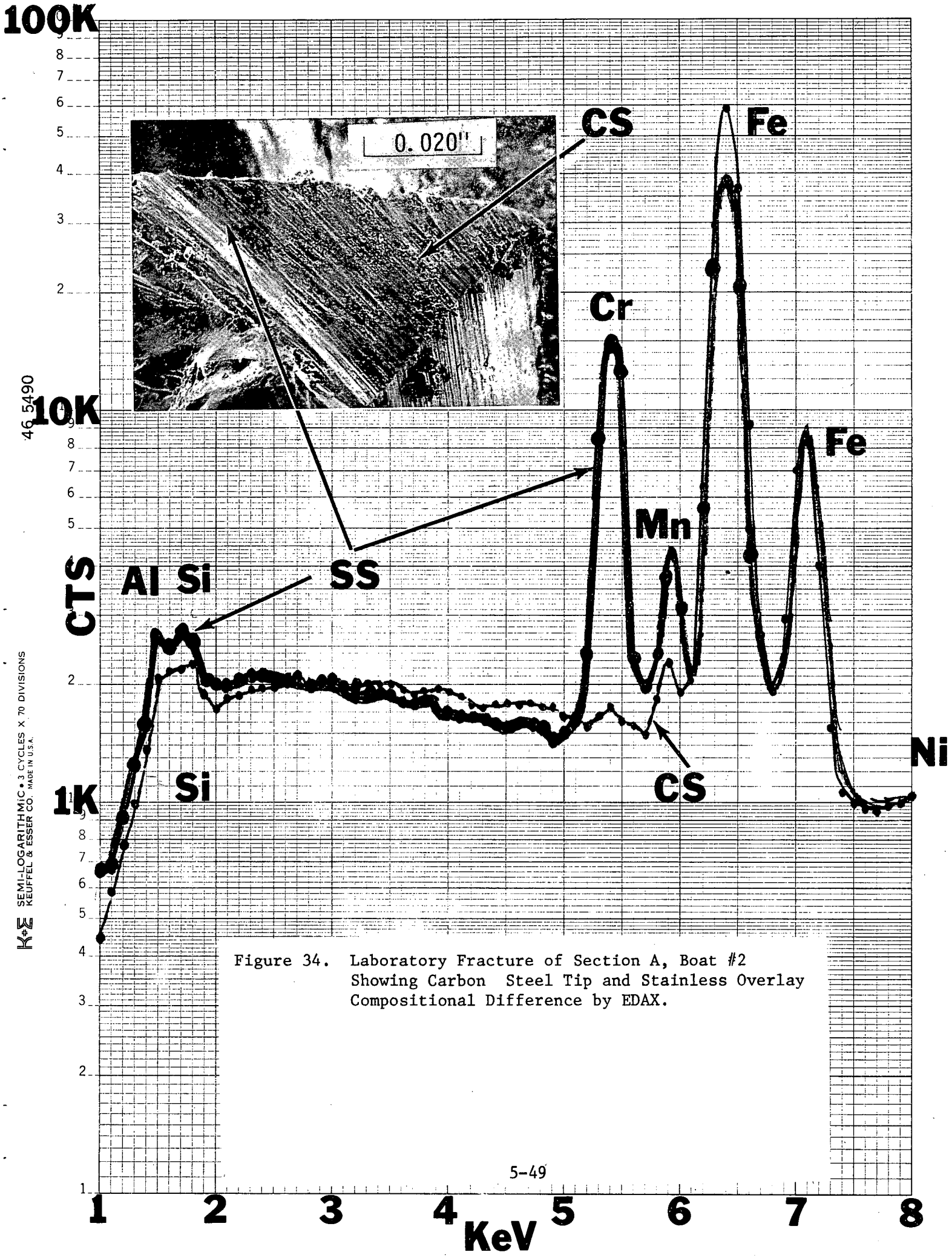


Figure 34. Laboratory Fracture of Section A, Boat #2 Showing Carbon Steel Tip and Stainless Overlay Compositional Difference by EDAX.

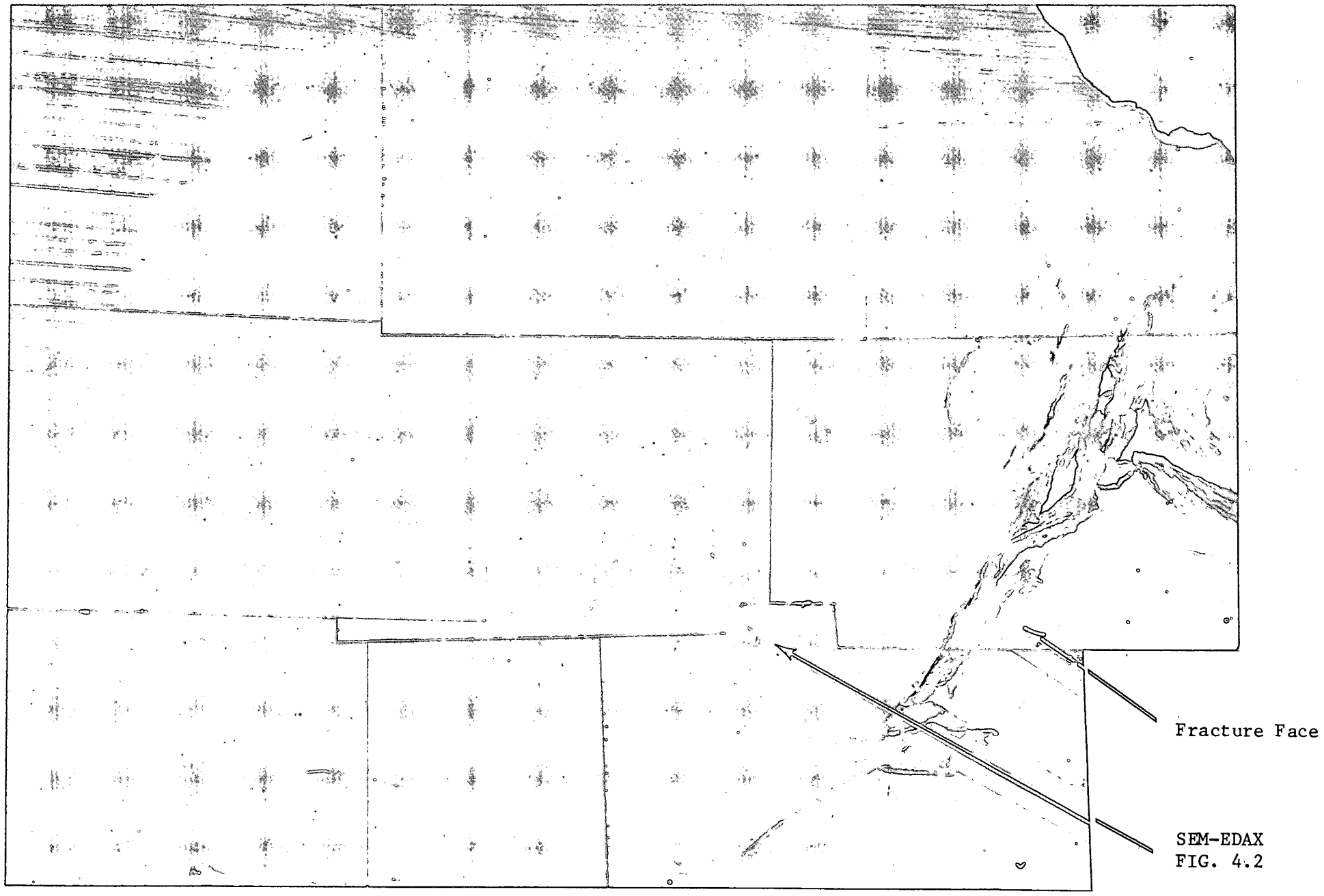


Figure 35. Boat #2, Section B after Lab Fracture

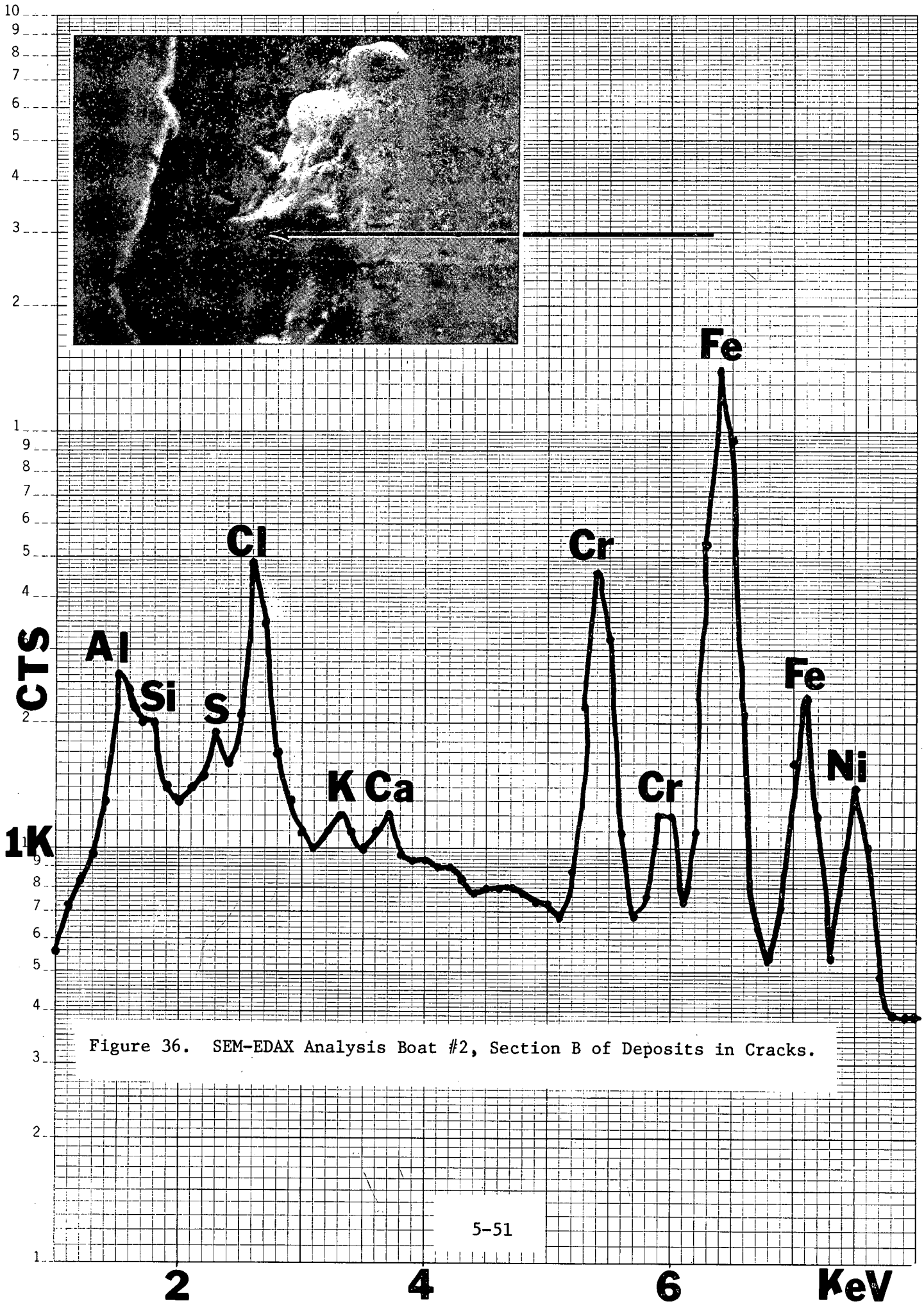
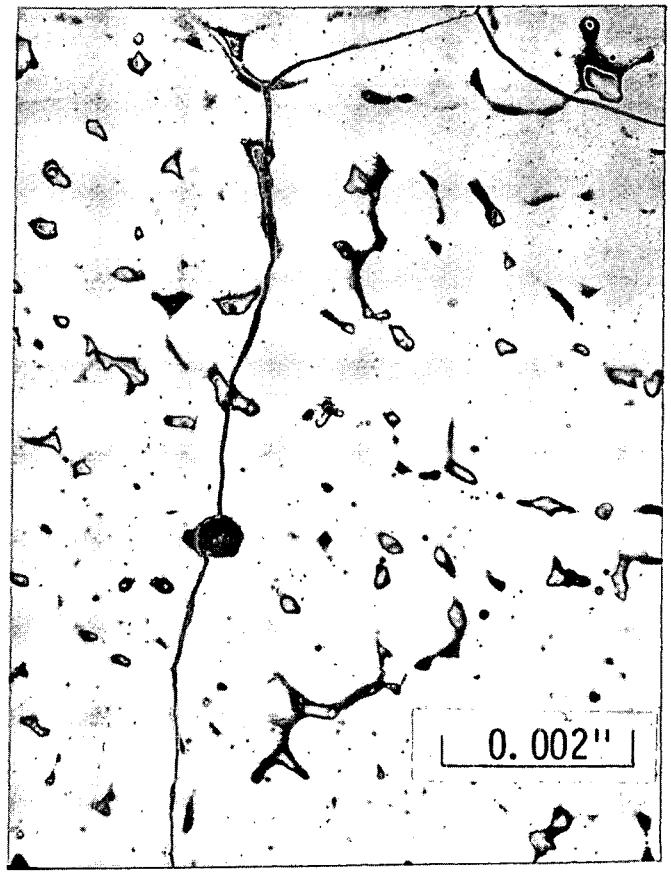


Figure 36. SEM-EDAX Analysis Boat #2, Section B of Deposits in Cracks.



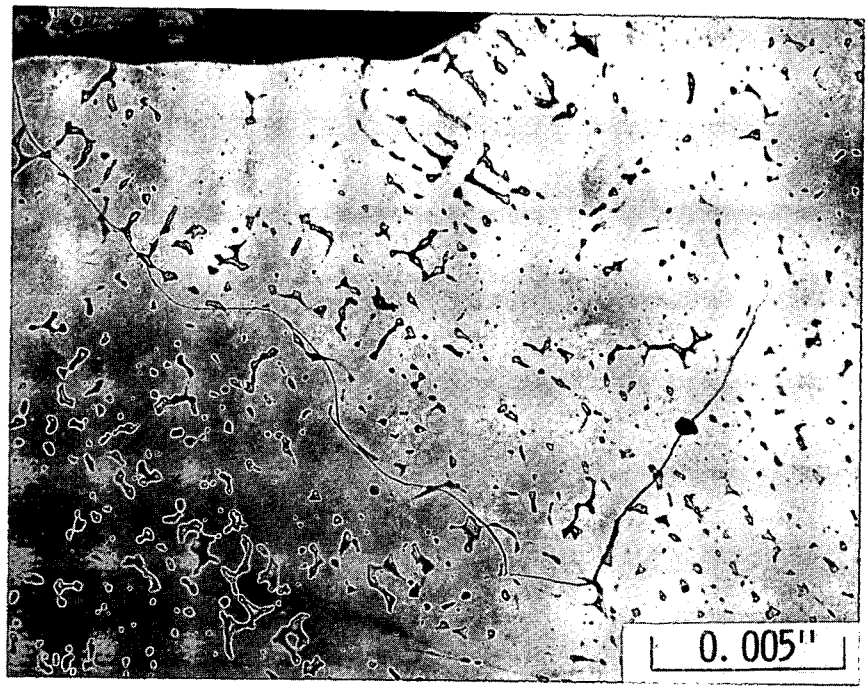
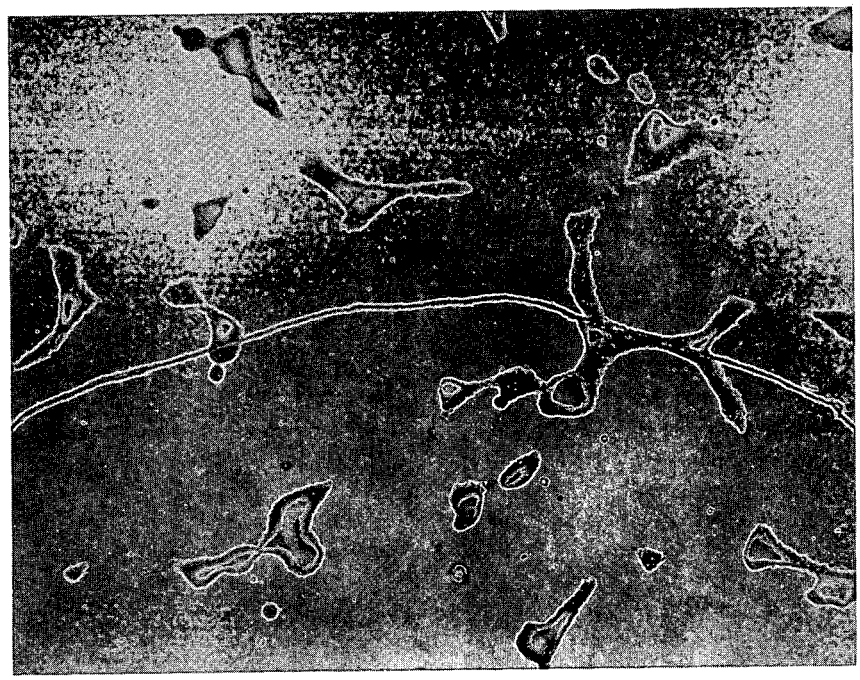
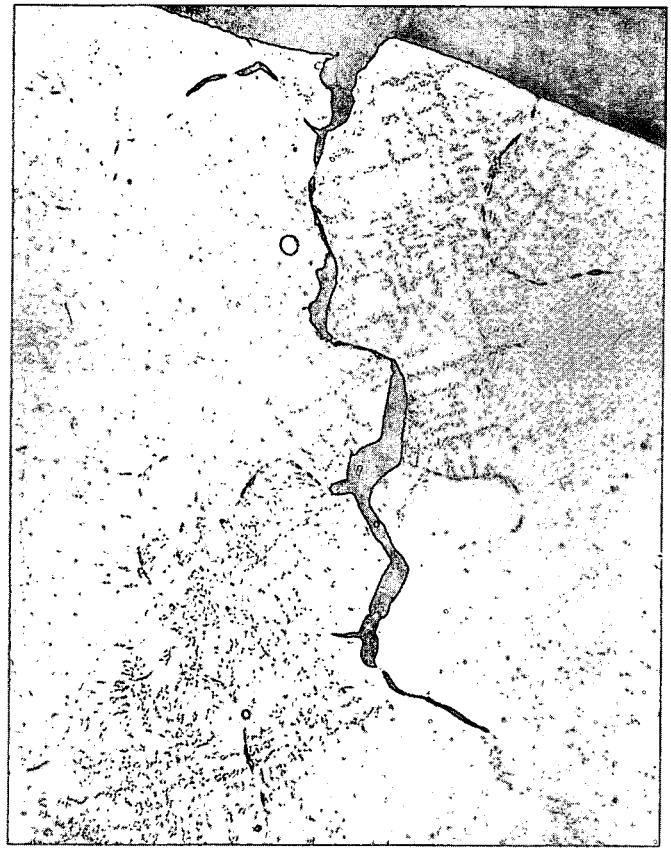


Figure 37. Etched Longitudinal Cross-Section of Weld Clad Near Test Weld at End No. 1 of Boat No. 1.

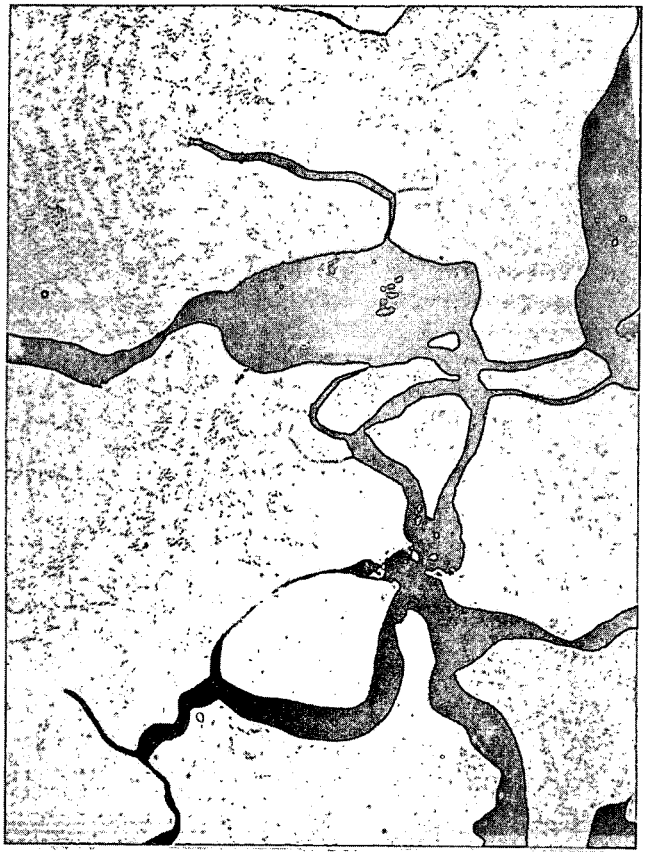


1000X

Figure 39. Crack in Weld Clad Near Test Weld Near End No. 1, Boat No. 1. Electrolytic - 10% Nital Etch. Surface examined is shown in Figure 23.

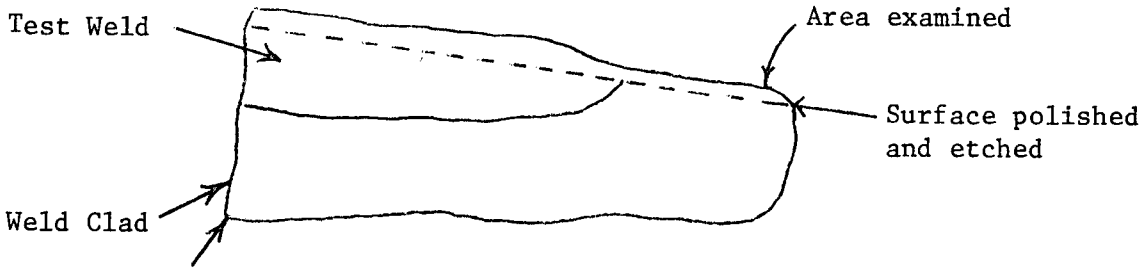


100X

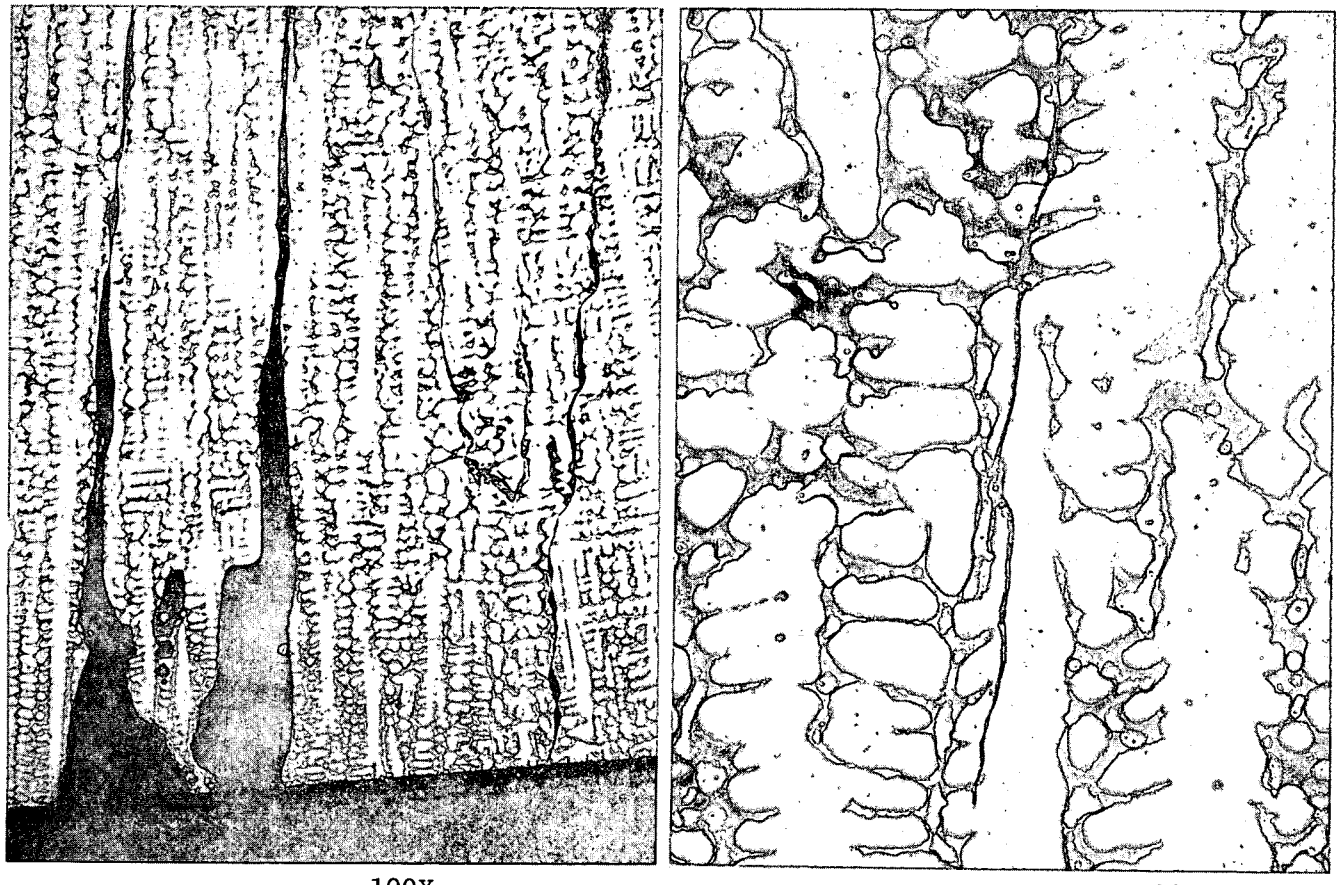


100X

Figure 40. Cracking Between Primary Dendrite Boundaries of Weld Clad Near End No. 1, Boat No. 1. Surface examined is shown in Figure 23. Areas photographed were away from HAZ of test weld. Etchant was 20 parts methyl, 20 parts nitric, 4 parts HCl. Dendrite orientations could not be brought out in HAZ.



Surface shown in Fig. 23, near end No. 1, boat No. 1.

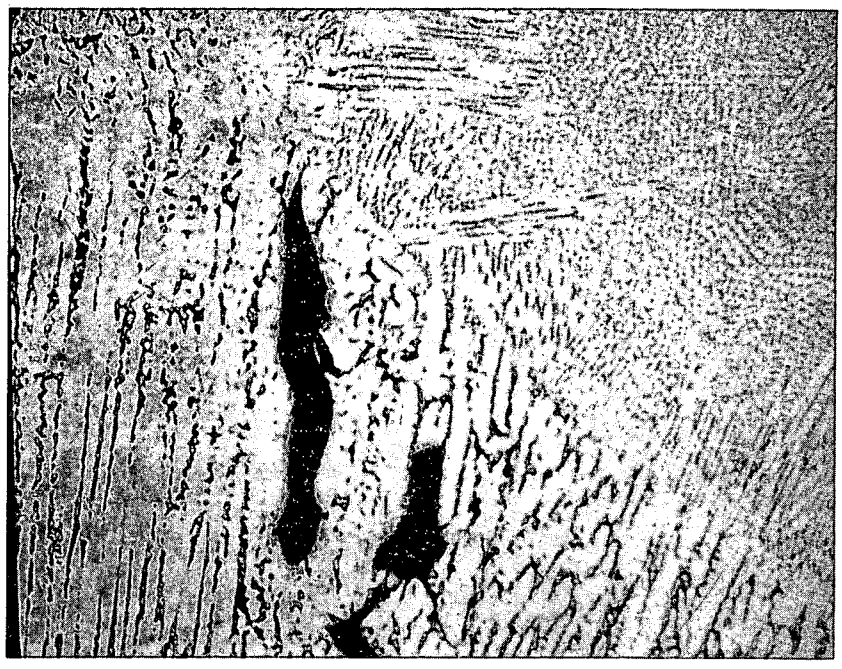


100X 500X

Figure 41. Surface Near and Parallel to Weld. Clad surface was examined in the vicinity of the boat point. Etchant = 20 parts methynol, 20 parts nitric, 4 parts hydrochloric.

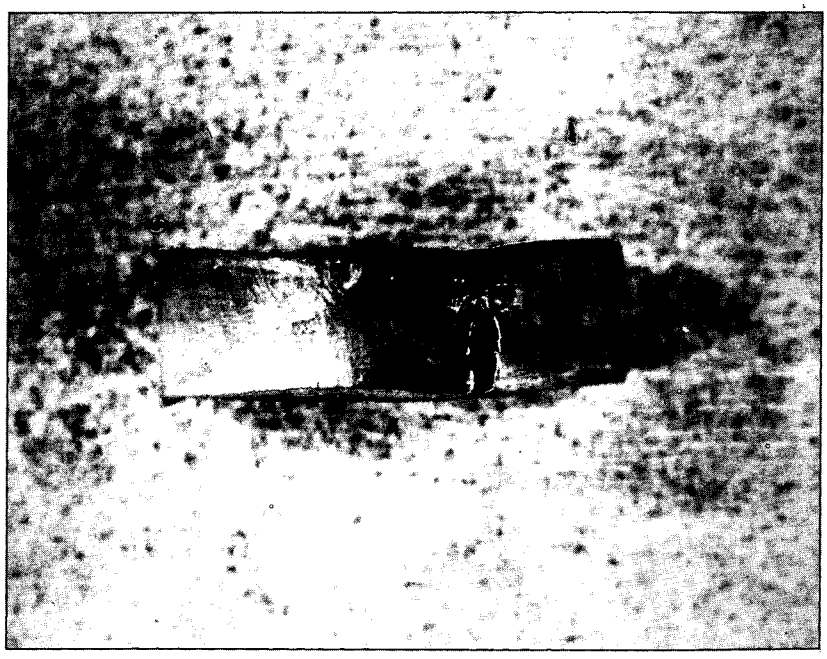
Etchant - 10% Nitric Electrolytic 40X

Figure 42. Showing defects in Clad under refused area where circular patch test was made. Cracks do not propagate into refused metal. A porosity spot is seen at the left margin.



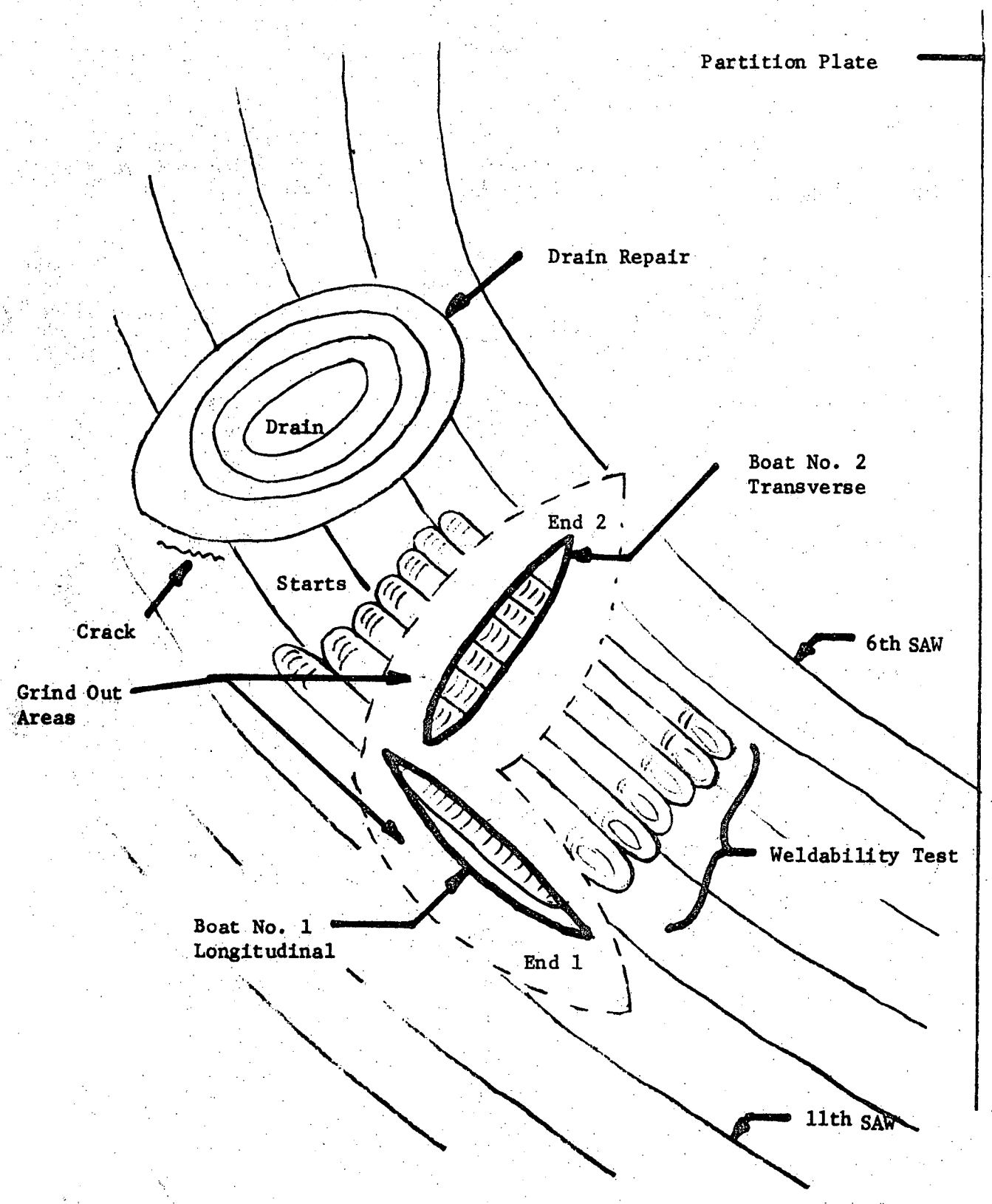
Etchant - 10% Nital Electrolytic 80X

Figure 43. Showing same "sealing" effect under refused cladding in Boat #4 as was seen in Figure 42.



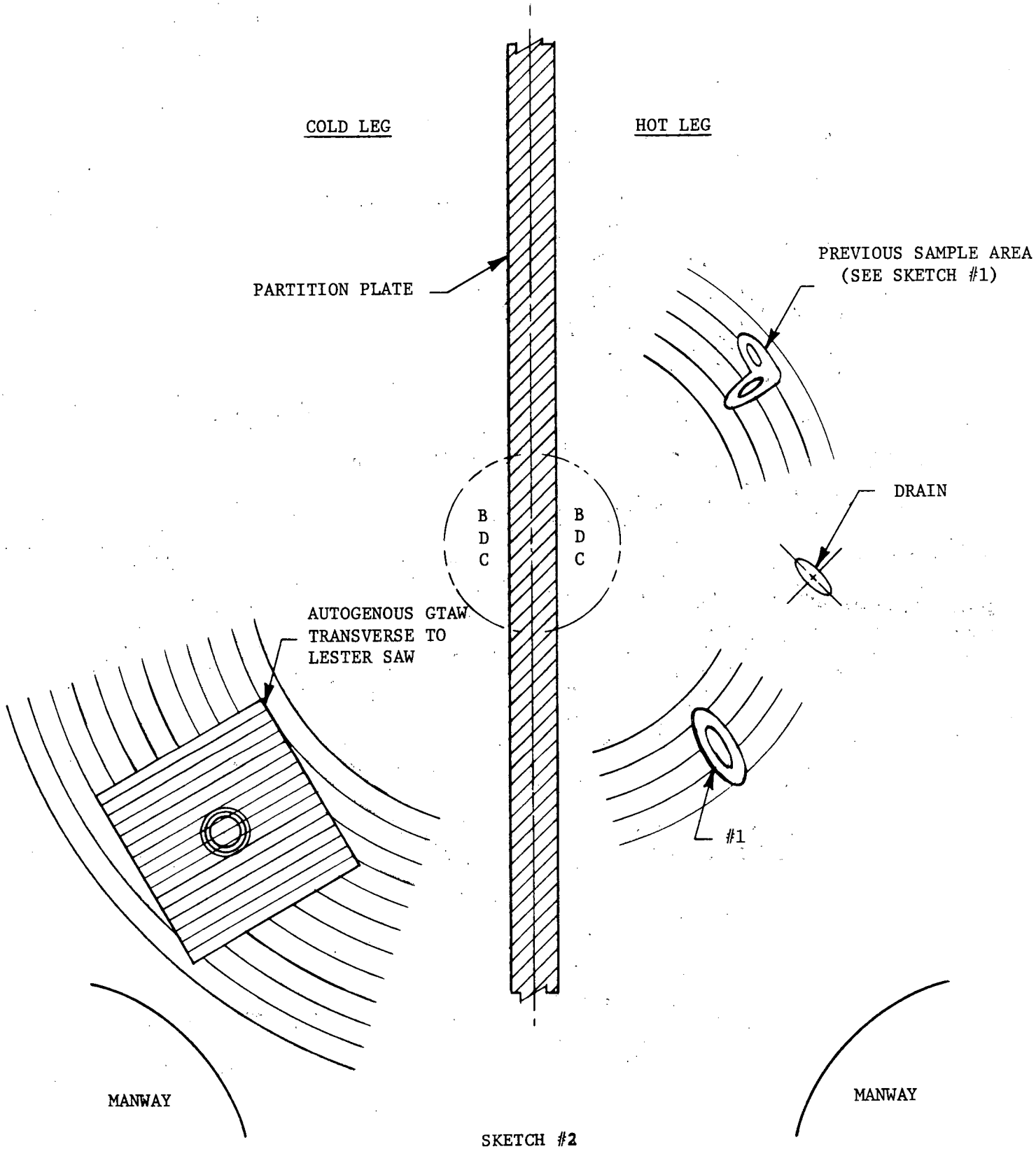
c3X

Figure 44. Showing bend specimen of sample from Boat #4. The top portion has been refused and shows no defects. The bottom portion cracks in areas below the refuse as shown in Figure 20.



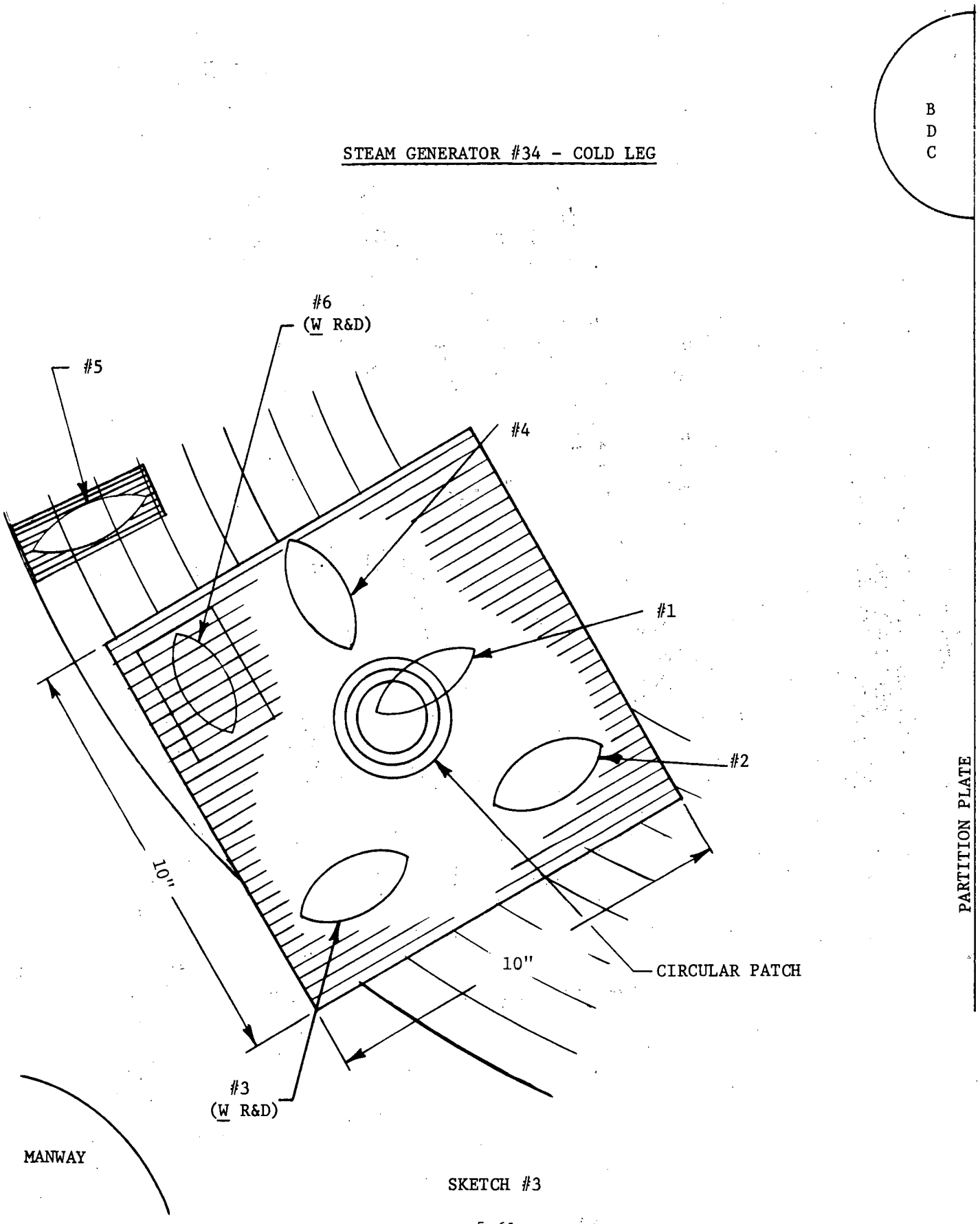
SKETCH #1
Steam Generator 34 - Hot Leg - Bottom of Bowl
Weldability Test Boat Location

STEAM GENERATOR #34



SKETCH #2

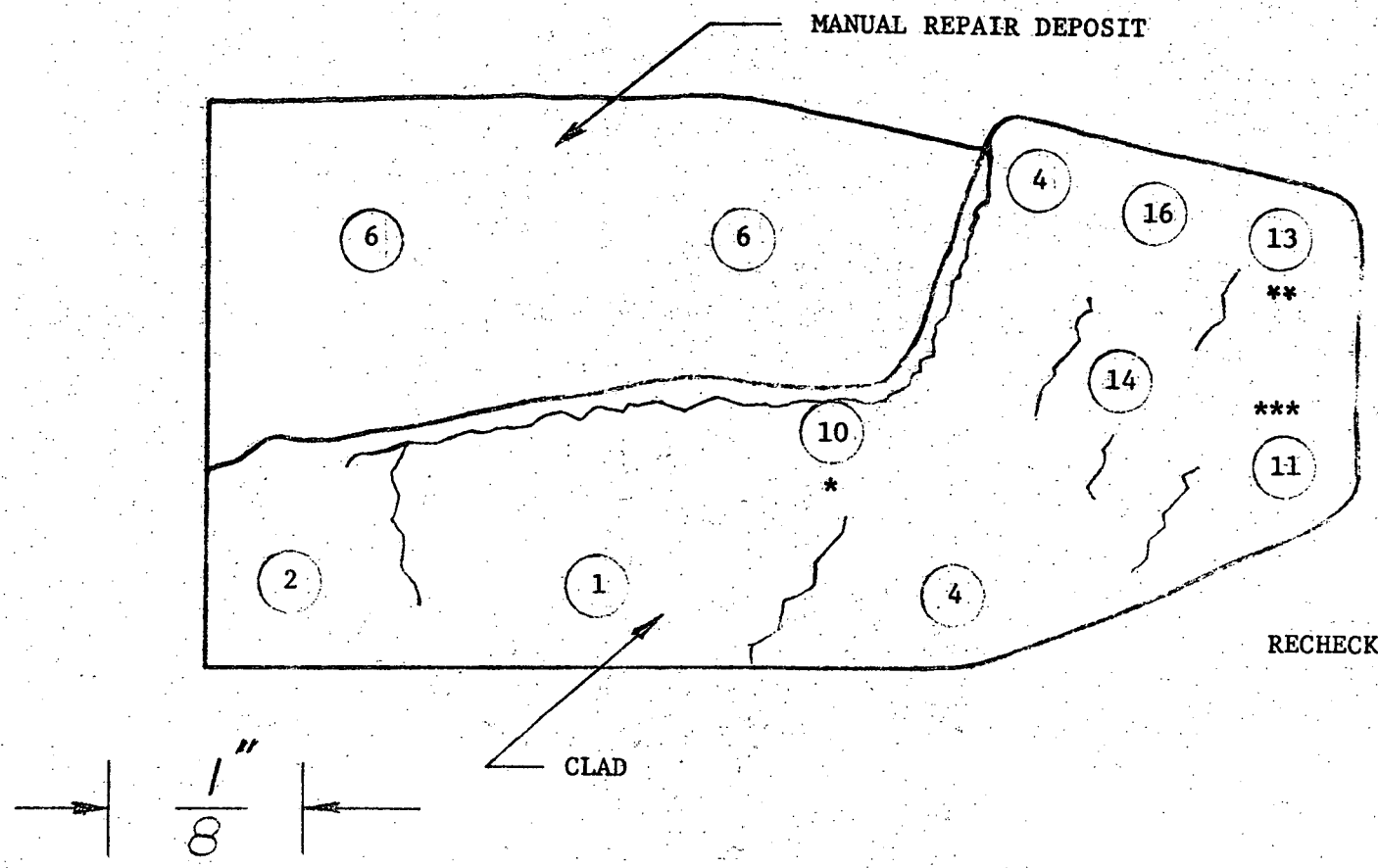
STEAM GENERATOR #34 - COLD LEG



SKETCH #3

SKETCH #4

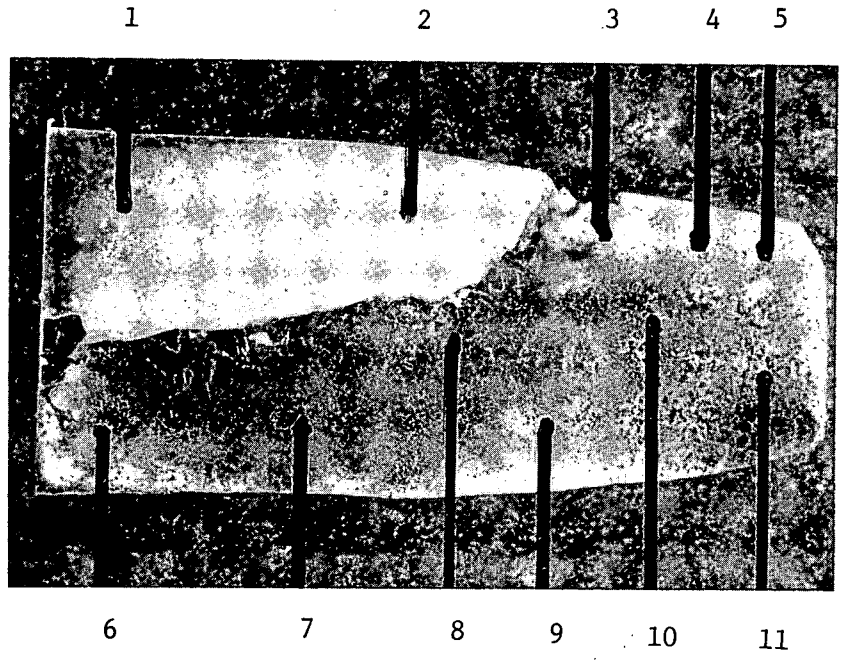
MAGNE-GAGE FERRITE NUMBERS
BOAT SAMPLE No. 1
LONGITUDINAL CENTER-LINE SECTION



RECHECK:	FN
*	4
**	14
***	10

SKETCH 4A

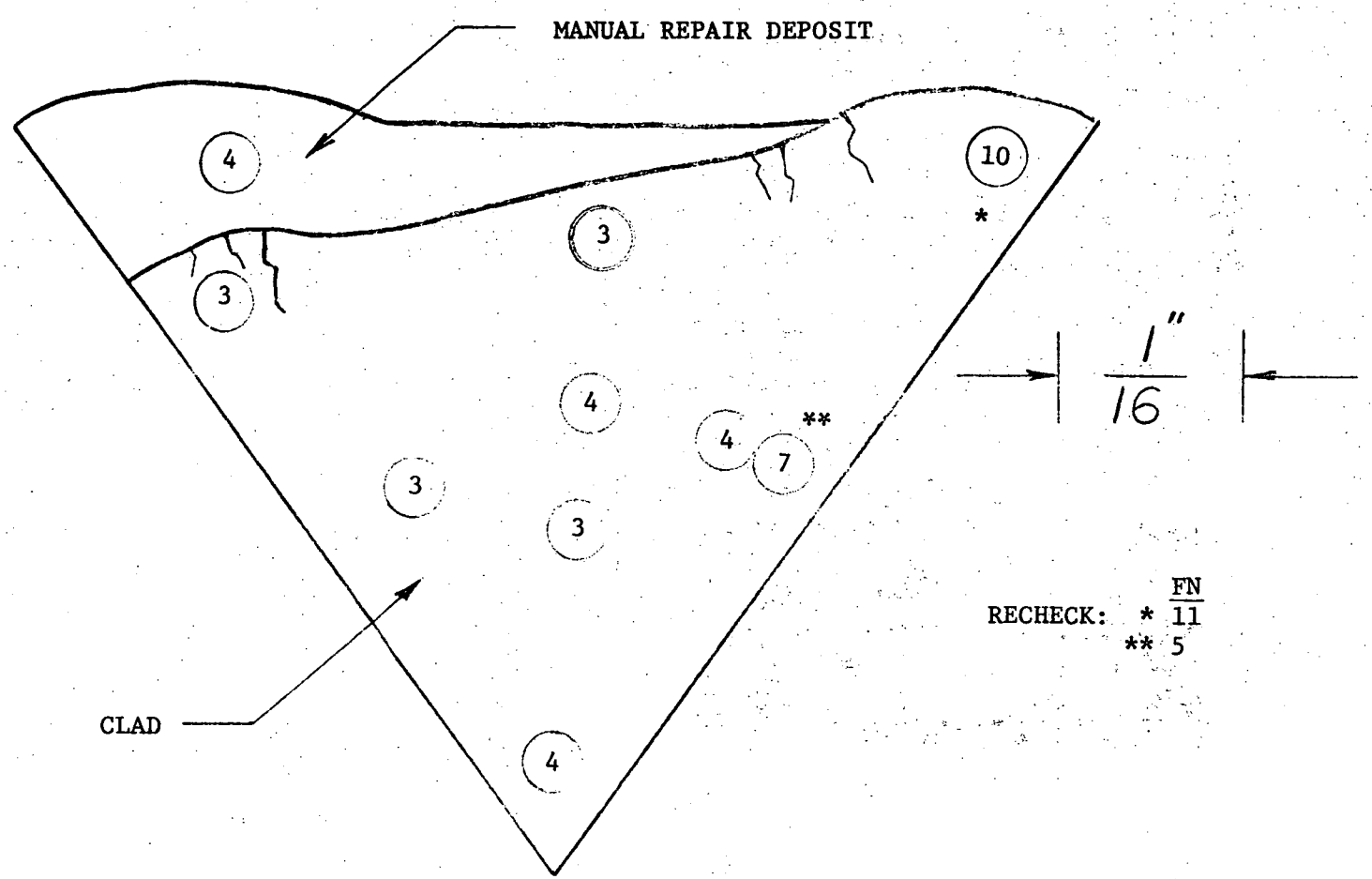
FERRITE DETERMINATIONS
BOAT SAMPLE No. 1
LONGITUDINAL CENTER-LINE SECTION



LOCATION	MAGNE GAGE FERRITE NUMBER	CLASSIMET FERRITE PERCENT
1	6	15.5
2	6	28.3
3	4	8.9
4	16	7.5
5	13, 14	7.6
6	2	11.3
7	1	11.4
8	10, 4	10.9
9	4	9.8
10	14	8.3
11	10, 11	6.3

SKETCH #5

MAGNE-GAGE FERRITE NUMBERS
BOAT SAMPLE No. 1
TRANSVERSE SECTION



RECHECK: * FN 11
** 5

SKETCH #6

MAGNE-GAGE FERRITE NUMBERS
BOAT SAMPLE No. 2
LONGITUDINAL CENTER-LINE SECTION

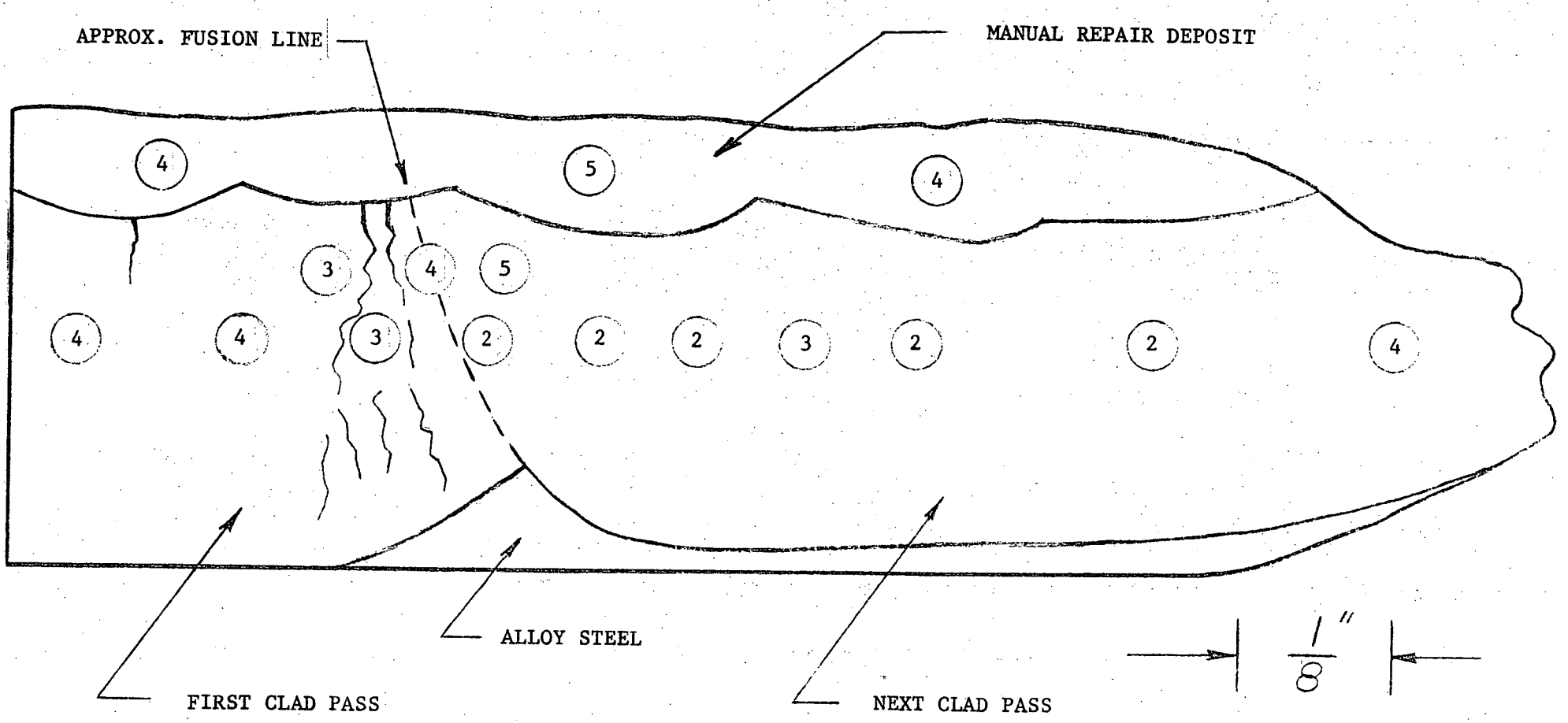


TABLE I

Location of Boat Samples

Specimen No.	Steam Generator	Leg Leg	Distance and Direction from Divider Plate	Distance from Biological Shield Above	Distance from Biological Shield Below	Report Figure No.
1	32	H.L.	C.C.W. 70"	4"		Not utilized - insufficient sample.
2	32	H.L.	C.C.W. 37"-38"	2nd Bead Tie-in		Figs. 1 thru 6 and Fig. 8
3	32	H.L.	C.W. 15"-17"		3rd Bead Tie-in	Shows similar structures as Figs. 1 - 8.
4	32	H.L.	C.C.W. 43"		2nd Bead Tie-in	Shows similar structures as Figs. 16 and 17.
5	32	C.L.	C.C.W. 67"-69"		1st Bead Tie-in	Figs. 9, 10, 12, 13, 15.
6	31	H.L.	C.C.W. 37"-38"		1st Bead Tie-in	Figs. 11, 14.
7	31	H.L.	C.C.W. 25"-26"		1st Bead Tie-in	Figure 7.

Note: C.W. - Clockwise

C.C.W. - Counterclockwise

TABLE II

Tabulation of d Spacing Values for the Unknown and for Fe_3O_4 and Fe_2O_3

Unknown	Fe_3O_4	Fe_2O_3
4.80	4.85	3.66
2.95	2.97	2.69
2.49	2.53	2.51
2.29	2.42	2.29
2.08	2.10	2.20
1.71	1.72	2.07
1.63	1.62	1.84
1.48	1.49	1.69
		1.63
		1.60
		1.48

TABLE III

COMPOSITIONS AND FERRITE CONTENTS

	Composition	Weld Overlay Ferrite Content		
		Mag. Sat.	Magne Gage	Class/Met
309 Weld Overlay Near End No. 2, Boat No. 2 (Sample was 1/16" Thick and from Top of Overlay)	15.3 Cr, 8.0 Ni, 0.13 C, 1.24 Mn, 0.022 N_2, 0.05 Mo, 0.5 Si, 0.01 S, 0.02 P, 0.0470 O_2, 0.015 Al(Sol.), 0.005 (insol.)	2.25%	Avg. 3.16 Range of 14 Readings 1.6-5.2	
309 Weld Overlay Near Center Boat #1	17.7 Cr 7.7 Ni		Avg. 10.6 Range of 9 readings 4.0-14.0	Avg. 9.1 Range of 9 readings 6.3-11.4

NOTE: Boat #1 which indicates best chemistry and highest magnetic readings has more cracking.

SECTION 6

ASME CODE COMPLIANCE AND STRUCTURAL APPRAISAL

The Boiler and Pressure Vessel Code, particularly Sections III and XI, has laterally given great attention to the discontinuities which exist in all real structures. There has been a consistent move to appraise defects such as lack of fusion, porosity, etc. in terms which are amenable to numerical evaluation and which avoid debates on semantics and definitions. Section XI of the Code is particularly advanced in this clarification and has published techniques which allow rational appraisals of defects, rather than the rules of thumb which are still common in many fabrication codes. In particular, Section XI recognizes that clad defects of the Indian Point type are common; it addresses techniques for their detection and then provides rote procedures for passing judgement upon the alternatives of repairing or not repairing the clad

Appendices I and II of this report illustrate these procedures.

Specifically:

Appendix I consists of a Flow Chart which diagrams the Code basis upon which the proposed course of action at the Indian Point Site is based.

Appendix II documents the Fracture Mechanics procedures recommended in Section XI for appraising flaw indications and lists the magnitudes of tolerable flaws.

Both Appendices illustrate compliance with the letter and spirit of Section XI and demonstrate the integrity of the proposed course of action.

APPENDIX I

COMPLIANCE FLOW CHART FOR ASME B&PV CODE, SECTION XI

ARTICLE IWB-3000
STANDARDS FOR EXAMINATION EVALUATIONS

IWB-3100 EVALUATION OF NONDESTRUCTIVE EXAMINATION RESULTS

IWB-3110 PRESERVICE EXAMINATIONS

IWB-3111 General

The preservice examinations performed to meet the requirements of IWB-2100 and conducted in accordance with the procedures of IWA-2200 shall be evaluated by comparing the examination results with the evaluation standards specified in Table IWB-3410. Acceptance of components for service shall be in accordance with IWB-3112 through IWB-3115.

IWB-3112 Acceptance

Components whose examination either confirms the absence of or reveals flaw indications that are not in excess of the standards listed in Table IWB-3410 shall be acceptable for service, provided the verified flaw indications are recorded in accordance with the requirements of IWA-6220 and I-6300 in terms of location, size, shape, orientation, and distribution within the component.

TABLE IWB-3410
EVALUATION STANDARDS

Examination Category	Component and Part Examined	Evaluation Standard
B-A	Welds in Reactor Vessel Belt-line Region	IWB-3510
B-B, B-C	Welds in Vessels, Vessel-to-Flange, Head-to-Flange	IWB-3511
B-D	Vessel Nozzles and Welds	IWB-3512
B-E-1	Welds in Vessel Penetrations	IWB-3513
B-F, B-J-1	Welds in Piping	IWB-3514
B-G-1	Bolting	IWB-3515
B-H, B-K-1	Supports—Components	IWB-3516
B-I-1, B-I-2	Interior Clad Surfaces	IWB-3517
B-L-1, B-M-1	Welds in Pumps and Valves	IWB-3518
B-L-2, B-M-2	Pump Casings and Valve Bodies	IWB-3519
B-N	Interior Surfaces and Internal Components of Reactor Vessels	IWB-3520

Revise IWB-3512.1 (d) to read:

(d) The size of allowable surface indications det ected within cladding shall be governed by the following standards:

(1) Inner surface indications not penetrati into base material are acceptable, except for noz inner corner radius indications; for any indicati at the inner corner radius, the depth "a" of dete indication shall be considered as equal to the no inal clad thickness, and compared with the standa of Table IWB-3512.1.

(2) For inner corner radius indications that penetrate into base material, the depth "a" of detected indication shall be considered equal to t sum of the nominal clad thickness and the penetration into base material.

(3) Inner surface indications at other than the inner corner radius of a nozzle, that penetrat through the cladding into the base material shall not exceed the limits of IWB-3512.1(a) except that the depth "a" of the indication shall be the total depth minus the nominal clad thickness.

Add IWB-3512.1(e):

(e) Subsurface indications in the base material o nozzle that are characterized as surface indicatio within the surface proximity limits specified in IWB-3310(b) shall not exceed the standards of IWB-3512.1(a) for subsurface indications.

TABLE IWB-3512.1
ALLOWABLE PLANAR INDICATIONS[1]

Material: SA-508 Class 2 and 3 Forgings that meet the requirements of NB-2331 and have specified minimum yield strengths of 50 ksi or less

Thickness Range, t: 3 in. and greater

Aspect Ratio, a/ℓ[3]	Surface Indications, a/t,%[2]	Subsurface Indications, a/t,%[2,3]
0.	1.9	2.3
0.05	2.0	2.4
0.10	2.2	2.6
0.15	2.4	2.9
0.20	2.7	3.3
0.25	3.1	3.7
0.30	3.5	4.1
0.35	3.5	4.6
0.40	3.5	5.2
0.45	3.5	5.9
0.50	3.5	6.5
Inside Corner Radius	2.5	[redacted]

APPENDIX II

Per proposed revisions to Section XI, Para. IWB-3512.1(d)*, cladding indications that penetrate into base metal and stay within the limits of IWB-3512.1(a) are acceptable for preservice examinations. Although this subparagraph specifically relates to nozzles in pressure vessels, application of this same criterion to the existing areas of clad cracking is logical and technically sound. It must be noted also that in no instances were cracks found to penetrate into base material. Attached herein is a plot of the allowable crack depth and length variations for base metal flaws. It can be seen that .1 inch is the acceptable depth for an infinitely long crack. Assurance that no flaws ≥ .1 in. exist in the base metal will satisfy the proposed revisions of Section XI.

For inservice examinations, flaws with dimensions which fall above the attached curve must be evaluated by analysis as described in Section XI, Para. IWB-3600, to confirm structural adequacy of the component for continued service. Until that time when component loading histories and detected flaw geometries are available, any analytical effort per Para. IWB-3600 would be meaningless.

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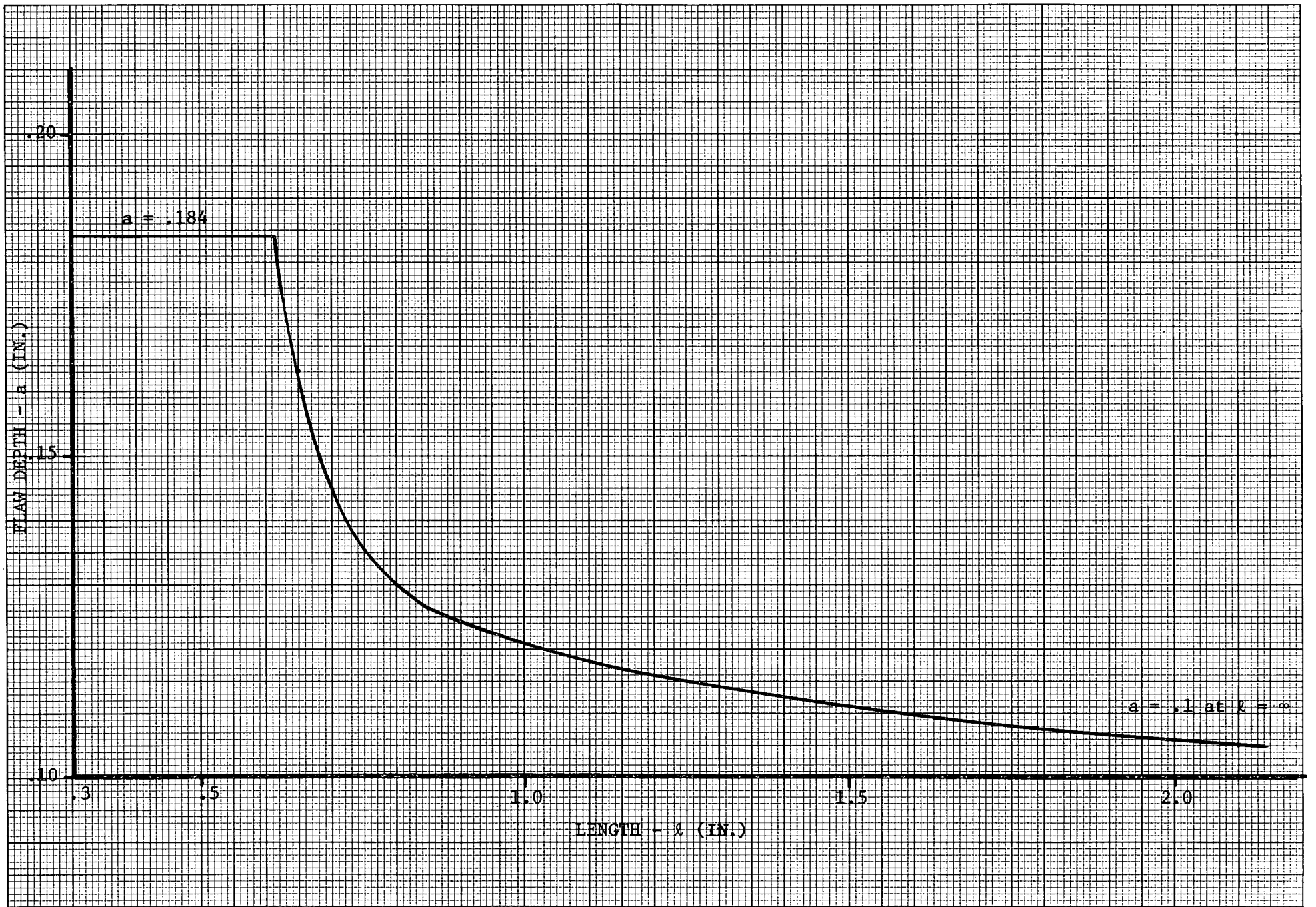
*Copy of proposed changes is included in flow chart of Appendix I.



Attachment 1 - Allowable Flaw Depth vs. Length per IWB-3512.1

SECTION 7

NONDESTRUCTIVE EXAMINATION AND EVALUATION OF IN-SERVICE MONITORING TECHNIQUES

General Discussion

The assurance of acceptability of the steam generator channel head cladding should be considered (a) in the present pre-service condition, and (b) periodically during the in-service period of power operation.

Pre-Service Condition

Based on the revised wording of paragraph IWB 3512.1 (d) recently adopted, but not yet published, by the ASME Section XI Code Committee, indications in cladding are acceptable provided they do not penetrate into the base metal. Basic assurance that the cracks do not penetrate into base metal is provided by the experience of repair grinding on 23 cracks. These cracks were excavated and the surfaces checked by the dye penetrant technique until no trace remained. The surfaces were then etched to determine whether the excavation had exposed or intruded into the underlying carbon steel base metal. None of the indications explored penetrated into base metal.

If the ultrasonic technique now under development for in-service surveillance proves capable of sufficient accuracy, surveys made with this equipment may be used to give further assurance that no indications penetrate base metal.

In-Service Surveillance

Paragraph IWB-3517 of Section XI requires periodic visual inspection of a 36 square inch area of the stainless cladding. Any indications observed must then be evaluated to determine their acceptability.

Although the Section XI Code does not specify any additional surveillance because of the presence of clad cracks, such a program is certainly logical in order to assure that the cracks now known to exist continue to be acceptable under the Code. During the in-service period cracks may be acceptable, even if they penetrate the base metal, provided they do not exceed in depth a limit of acceptability determined by fracture mechanics analyses as pre-

scribed by Appendix A of Section XI of the Code.

In order to meet the needs for this application, the ultrasonic surveillance technique and equipment under development must give a reliable indication of any clad crack which has propagated to a depth approaching the limit of acceptability.

An experimental program is being carried out to develop an ultrasonic surveillance technique and equipment suitable for in-service surveillance of the Indian Point steam generator channel head cladding cracks. In order to meet the needs for this application, the equipment must give either a reliable indication of any crack depths approaching the limit of acceptability or of any change in depth as a departure from a base line condition known to have been acceptable.

Progress on the development of the ultrasonic surveillance technique is encouraging, and a complete description of the method and equipment to be used will be given as soon as possible in a supplement to this report. If possible, the method will be used at Indian Point prior to fuel loading to establish base line data for the designated surveillance areas.

If development problems delay the availability of a reliable ultrasonic method, the surveillance base line surveys will be made at the earliest convenient plant shutdown after such a method becomes available.

A detailed In-Service-Inspection method will be issued as a supplement to this report. The method will preferably be the ultrasonic method under development. If this method proves unsatisfactory, the visual method currently given in Section XI of the Code will be used.

SECTION 8

SERVICE EXPERIENCE

It has been established by examination that the cladding flaws do not extend into the carbon steel channel head base metal. It has further been established that structurally the flaws are insignificant and are within the specifications of Section XI. Finally, a nondestructive testing method has experimentally verified that flaws of a critical depth are determinable. It remains to be shown that the cladding will satisfy its original purpose of protecting the primary system coolant from excessive corrosion products contamination.

Service experience with cladding which shows similar problems has shown no adverse effect on performance. Over the past 20 years, cracking has occurred in the corrosion resistant cladding of several nuclear steam supply system vessels. For example, cracking has been found in roll-bonded clad, resistance welded clad, arc welded clad, (Sequoia I Rotterdam KE2020 and JPDR). These examples are not a complete compilation of all cracking incidents but are meant to be illustrative of the extent of the problem. Causes for the cracking have been attributed to corrosion, hot cracking, improper welding, metallurgical conditions, or various combinations of these. Extensive metallurgical and structural investigations were made for each cracking incident. In all cases, the cracking was confined to the corrosion resistant cladding, i.e., in no cases did the cracks extend into the underlying base metal. In some instances, attempts were made to propagate the cracks into the base metal by fatigue. These were singularly unsuccessful. In at least one example, the Yankee-Rowe pressurizer, the vessel containing cracked cladding has seen extensive service -- over ten years. Periodic inspections at refueling intervals have confirmed that crack growth has not taken place. Furthermore, this plant has successfully operated even though low alloy steel has been exposed to the primary coolant. The Yankee-Rowe inspection and service has been documented in periodic reports to the AEC.

In the case of the cracked cladding in the head of JPDR, a Japanese BWR, the cracking in the weld deposited cladding was interdendritic near the surface

and transdendritic further inward. Base material, A302B, was exposed. After discovery of these cracks (∿1966), unrepaired areas were deliberately left for future observation. In 1968, a detailed metallographic examination revealed only minor pitting about 0.004" in the exposed base metal at the tip of some of the cracks. The environment was fairly aggressive since 35 ppm oxygen was present in the steam phase.[1]

This service experience indicates that the flaws in the cladding are not detrimental, and lend credability to the stability of the weld deposit. The probability of "grain dropping", i.e., granular particle falling from the clad matrix cannot be ignored but is believed to be very low. "Grain dropping" would occur only if exposure to the corrodant continued. Since the primary system operates with an extremely low oxygen and chloride content deterioration of the cladding by this method is not anticipated.

The following corrosion data indicate that should cracks propagate to base metal, the corrosion rates in service are acceptable under all conditions.

A. Environment #1	Startup	Operating	Hot Shutdown	Shutdown
Temperature, ^{o}F	100 to 630	630	630	180
Velocity, fps	14	14	14	14
Chemistry:				
Boron (as H_3BO_3), ppm	0	1200-0	2000	2000
Lithium (as LiOH), ppm	1 to 2	0.5 to 2	1 to 2	1.5 to 2
Chloride, ppm	1.0 to <0.15	<0.15	<0.15	<0.15
Fluoride, ppm	<0.15	<0.15	<0.15	<0.15
Oxygen, ppm	7 to <0.1	<0.1	<0.1	2.0
Hydrazine, ppm	21 to <0.1	<0.1	-	-
Hydrogen, cc/kg	0 to 30	30	30 to 0	0
Exposure Time, day	15	365	28	21
Material	SA-556-C2 Carbon Steel			
Corrosion Rate	105 mg/dm^2/429 days (0.6 mils/429 day)			

Reference: Westinghouse corrosion data obtained from testing in simulated reactor coolant conditions.

B. Environment #2	Aerated Solutions Coupled to S/S	Deaerated Solution Coupled to S/S
Temperature, ^{o}F	70 to 140	70 to 140
Velocity, fps	Stirred	Stirred
Chemistry:		
Boron (as H_3BO_3), ppm	2500	2500
Lithium as (LiOH), ppm	None	None
Chloride, ppm	<0.15	<0.15
Fluoride, ppm	<0.15	<0.15
Oxygen, ppm	7 to 3	<0.1
Hydrazine, ppm	None	7 to <0.1
Exposure Time, day	~120	~120
Material	SA-3028 Carbon Steel	
Corrosion Rate vs. Temp., mg/dm^2-mo/^{o}K	$\frac{-4.6 \times 10^6}{1} + 1.6 \times 10^4$	$\frac{-4.6 \times 10^4}{1} + 1.5 \times 10^2$

Reference: WCAP-7099, "Absorption of Corrosion Hydrogen by A3028 Steel at 70° to 500°F," December 1967.

C. Environment #3

Temperature, ^{o}F	650
Velocity, fps	Semistatic
Chemistry:	
Boron (as H_3BO_3), ppm	1100
Lithium (as LiOH), ppm	None
Chloride, ppm	Not given
Fluoride, ppm	Not given
Oxygen, ppm	<0.1
Hydrogen, cc/kg	100
Exposure Time, day	28
Material	Carbon Steel Plate
Corrosion Rate	105 mg/dm^2 (0.6 mils/yr)

Reference: TID-10028 Technical Progress Report, "PWR Program for Period October 7, 1954 to November 18, 1954, and WCAP-2855, "Evaluation of Yankee Vessel Cladding Penetrations," October 1965.

The corrosion data from Environment #1 should be directly applicable to the steam generator carbon steel corrosion since the test conditions represent a fuel cycle. The corrosion at low temperatures only are defined in Environment #2 while the corrosion at operating temperatures is defined in Environment #3.

Hydrogen release by corrosion reactions has been shown not to have an embrittlement effect on A302 steel and it is believed that no effect will be seen here.[2]

REFERENCES

1. T. Kondo, H. Nakajima, and R. Nagasaki, "Metallographic Investigation on the Cladding Failure in the Pressure Vessel of a BWR," Nuclear Engineering and Design, Vol. 16, No. 3, July 1971, pp. 205-222.

2. Westinghouse Report WCAP-7099, "Absorption of Corrosion Hydrogen by A302B Steel at 70° to 500°F".