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Joseph M. Farley Nuclear Plant - Unit 1
Steam Generator Tube Analysis Results

Gentlemen:

On October 8, 1992, the NRC issued Amendment 95 to the FNP technical specifications to allow the implementation of interim steam generator plugging criteria for tube support plate elevations. The NRC Safety Evaluation (SE) included a Southern Nuclear Operating Company (SNC) commitment to remove and analyze tubes and provide the results to the NRC. The purpose of this commitment was to provide supporting data for the development of an alternate plugging criteria.

Two hot leg steam generator tube segments were removed during the Unit 1 11th refueling outage and subsequently analyzed at an off-site laboratory. The analyses included eddy current (ET) and ultrasonic (UT) nondestructive examination (NDE); leak and burst testing; and metallography and scanning electron microscopy (SEM) fractography destructive examinations.

The results of the overall laboratory analysis confirmed that the dominant crack morphology at the tube support plate intersections was outside-diameter stress corrosion cracking (ODSCC). These results support the existing data for an alternate plugging criteria.

Laboratory UT results did suggest the presence of intermittent circumferential indications at one tube support plate that were not apparent in the pre-pull UT inspection. This was later confirmed to be associated with intergranular cellular corrosion (ICC) during the destructive examination. As noted in the NRC safety evaluation for the Unit 2 Interim Plugging Criteria, patches of ICC are frequently found in pulled tube examinations. The difference between the laboratory UT and field UT was not an unexpected result, as tight crack faces may have been slightly opened by the tube pulling forces.

The results of the laboratory leak and burst tests provided good supporting data for the proposed alternate plugging criteria. Neither of the two support plate crevice regions developed leaks at normal operating nor steam line break conditions even though bobbin coil signal voltages of 3.3 and 3.2 volts were present. The support plate region burst pressures (6600 psi and 8100 psi) were well above Regulatory Guide 1.121 limits even though the respective maximum flaw depths were as high as 85% and 71% respectively.

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The results of the laboratory destructive examinations, as noted earlier, confirmed the presence of significant ICC in one tube and a minor amount of ICC in the other tube. However, the metallographic examination results showed that the dominant flaw feature affecting the tube integrity as evidenced by the burst testing was axial ODSCC, as expected. It should be noted that the tube with the significant ICC and corresponding high crack densities burst at a higher pressure than the other tube, thus revealing that the ICC had negligible effects on the burst pressure. The destructive testing results also showed one instance where minor ODSCC extended up to 0.2 inch above the support plate top location. This minor cracking was typically 7% throughwall and had no effect on tube burst pressure or leakage. No surface intergranular attack (IGA) was observed. Only minor IGA components were observed in association with the SCC and ICC.

Overall, the results of the laboratory tube pull analysis support the conclusion that the Farley Unit 1 indications are consistent with the database used to develop alternate plugging criteria for ODSCC at support plate intersections. Additional details of the tube analysis are provided in the attachment. If there are any questions, please advise.

Respectfully submitted,

SOUTHERN NUCLEAR OPERATING COMPANY

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EFB:cht-tubepull.efb
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SUMMARY OF EXAMINATION CONDUCTED ON FARLEY UNIT 1 STEAM GENERATOR TUBING

Introduction

Two hot leg steam generator tube segments from Farley Unit 1 (Tubes R14-C80 from S/G B and R19-C41 from S/G A) were examined in January-February, 1993 at the Westinghouse Science and Technology Center. The examination was conducted to provide supporting data for the development of alternative plugging criteria specific to support plate crevice corrosion at Farley Unit 1. The tubes were selected to obtain two of the highest bobbin voltages (>3 volts) found in the 1992 eddy current inspection and to obtain differences in RPC response features. One indication had well defined multiple axial indications while the other had a more volumetric RPC response typical of closely spaced axial indications. The tubesheet top (TST) and support plate (SP) regions were nondestructively examined. Subsequently, elevated temperature leak testing and room temperature burst testing were conducted on SP2 of Tube R14-C80 and SP1 of Tube R19-C41, the locations with the largest voltage NDE indications. The burst tested specimens were then destructively examined using metallographic and SEM fractography techniques. The following presents a brief summary of the more significant observations.

NDE Results

Table 1 presents a summary of field and laboratory NDE results. The SP2 region of Tube R14-C80 and the SP1 region of Tube R19-C41 had 3.3 and 3.2 volt eddy current (E/C) indications, respectively, of OD origin corrosion that appeared to axially oriented. The field bobbin voltages are based on ASME standards cross-calibrated to the reference laboratory standard. Reevaluations of the field data and the field analyses are in good agreement. In the case of SP1 of Tube R19-C41, RPC volumetric characteristics were observed in the field data over approximately 180° congruently with the significant (>0.5 inch) axial indications. In the laboratory similar indications were present. An interesting observation was that the laboratory E/C voltage obtained from SP1 of Tube R19-C41 was less than in the field. This is most unusual as tube pulling operations either have no effect or increase the voltage due to tube elongation causing crack separation. At present, no satisfactory explanation exists. (The field and laboratory E/C calibrations appear to be correct.) The other regions examined had only minor indications compared to the 3.3 volt indications just discussed.

The absence of radiographic indications suggested that the cracks present were tight. Laboratory UT inspection was able to resolve more axial indications than did the E/C inspection. Laboratory UT inspection also suggested the presence of intermittent circumferential indications within the SP crevice regions that were subsequently destructively examined. These indications were more prevalent in the SP1 region of Tube R19-C41 than in the SP2 region of Tube R14-C80. In the SP1 region of Tube R19-C41 they occurred toward the top and bottom of the larger axial indications. The intermittent circumferential indications found in the post-pull inspection were not apparent in the pre-pull UT inspection. Based on prior UT inspections, the increase in these indications has been associated with intergranular cellular corrosion in which the crack faces may have been slightly opened by the tube pulling forces. As shown later, the UT intermittent circumferential indications in the SP1 region of Tube R19-C41 are associated with intergranular cellular corrosion patches near the top and bottom of the burst crack.

Leak and Burst Testing

SP2 of Tube R14-C80 and SP1 of Tube R19-C41 were leak tested at elevated temperature and pressure. This test is capable of accurately measuring very low levels of leakage. Neither developed leaks at either normal operating conditions (NOC) (1500 psi differential pressure) or steam line break conditions (SLB) (2650 psi).

Room temperature burst tests were conducted on SP2 of Tube R14-C80 and SP1 of Tube R19-C41, as well as on free span sections of each tube, at a pressurization rate of 1000 psi per second. Results of the burst tests are presented in Table 2. All burst specimens developed axial burst openings. In the cases of the two support plate crevice region specimens, they were centered within the crevice regions. The circumferential positions of the support plate crevice region specimens' burst openings were the same as the location of the deepest UT indications. (The eddy current RPC data does not provide an absolute circumferential position.) The burst pressures of the free span specimens were 12,250 psi to 12,825 psi and the burst pressures for the crevice region specimens were 6,600 psi to 8,100 psi. Table 2 also provides room temperature tensile properties obtained from free span sections of the two tubes. The tensile strengths are higher than average for Westinghouse tubing.

Destructive Examination Results

The burst fracture faces of the crevice region specimens were opened for SEM fractographic examinations. Table 3 presents a summary of the fractographic data. The burst openings occurred in axial macrocracks that were composed of numerous axially oriented intergranular microcracks of OD origin. In the case of the SP2 region of Tube R14-C80, the burst fracture microcracks were confined to a narrow axial band. In the case of the SP1 region of Tube R19-C41, the burst fracture microcracks occurred in a large patch of microcracks within the crevice region.

Most of the burst fracture microcracks had interconnected during plant operation since the vast majority of the ligaments or ledges between microcracks had only intergranular features. However, the burst macrocracks each had one to two ledges with dimple rupture features, indicating that the metal between some microcracks tore during burst testing. The thickness of these torn ledges ranged from 0.009 to 0.013 inch. The macrocrack in the SP2 region of Tube R14-C80 was confined to the crevice region. In the case of the SP1 region of Tube R19-C41, the main portion of the macrocrack was also confined to the crevice region; however, minor intergranular corrosion extended up to 0.2 inch above the SP top location. This minor cracking was typically 7% throughwall. The maximum crack depths ranged from 71 to 85% throughwall while the corresponding average macrocrack depths ranged from 50% (over a length of 0.76 inch) to 54% throughwall (over a length of 0.68 inch).

Figures 1 and 2 present sketches of the crack distributions found by visual (30X stereoscope) examinations of the post-burst tested specimens and by subsequent destructive examinations. The sketches show the locations where cracks were found and their overall appearance, not the exact number of cracks or their detailed morphology. Due to the complexities of the crack networks observed in the SP1 region of Tube R19-C41, radial metallography was utilized to provide an overall understanding of the intergranular corrosion morphology. In radial metallography, small sections of the tube (typically 0.5 by 0.5 inch) are flattened, mounted with the OD surface facing upwards and then progressively ground, polished, etched and viewed from the OD surface towards the ID surface.

From the metallographic examinations, it was concluded that the dominant corrosion morphology was axial intergranular stress corrosion cracking (IGSCC). In the case of the SP1 region of Tube R19-C41, there was significant intergranular cellular corrosion (ICC) found in association with the axial IGSCC. With an ICC morphology, a complex mixture of short axial, circumferential and oblique angled cracks interact to form cell-like structures. Only a very minor amount of ICC was found in association with the axial IGSCC in the case of the SP2 region of Tube R14-C80. The ICC in SP1 of Tube R19-C41 occurred in one large patch (approximately 0.6 inch wide by 0.4 inch high) with two much smaller patches just above this large patch. Figure 3 presents a photographic montage of a portion of a radial metallographic section at a depth of approximately 10% that shows some of the ICC found in the SP1 region of Tube R19-C41. With progressive radial grinding, it was shown that the axial IGSCC was deeper than the associated ICC. The ICC disappeared at a depth of 30 to 50% throughwall. The remaining crevice region of SP1 of Tube R19-C41, i.e., that without ICC, had axial IGSCC similar to that found in the SP2 region of Tube R14-C80.

The axial intergranular corrosion observed in both crevice regions was similar in crack densities and in crack morphologies, as measured by D/W ratios (the ratio of crack depth divided by the width of the crack at a mid-crack depth). The density of axial IGSCC ranged from 27 cracks in 320° for the SP2 region of Tube R14-C80 (which extrapolates to 30 cracks in 360°) to 37 cracks in 240° for the SP1 region of Tube R19-C41 (which would extrapolate to 55 cracks in 360° if the extrapolation ignored the presence of ICC). These are considered moderate crack densities. However, the crack densities are much higher in the regions where ICC patches were observed. (Nineteen cracks in 42° were counted in the main ICC patch in SP1 of Tube R19-C41, which would extrapolate to 163 cracks in 360° if the ICC were present throughout the crevice region.) The measured D/W ratios ranged from 14 to 60 in the SP2 region of Tube R14-C80 to 24 to 60 in the SP1 region of Tube R19-C41. The individual microcracks within the ICC appeared indistinguishable from the individual microcracks within the axial IGSCC with respect to crack morphology. No surface intergranular attack (IGA) was observed at any location in either specimen.

Conclusions

The examined two support plate crevice regions (the SP2 region of Tube R14-C80 and the SP1 region of Tube R19-C41) had combinations of axially oriented IGSCC and ICC with the ICC involvement being greater in the SP1 region of Tube R19-C41. The corrosion was of OD origin and all significant corrosion was confined to the crevice regions. Overall crack densities were moderate for the axial IGSCC but were significantly higher where patches of ICC occurred. Only minor IGA components (moderate to high D/W ratios) were found in association with the IGSCC and ICC and no surface IGA was observed.

Field and laboratory eddy current inspections accurately described the presence of axial cracking. They also suggested the presence of ICC in the SP1 region of Tube R19-C41 as RPC volumetric characteristics were noted. The volumetric RPC response of the SP1 region of Tube R19-C41 was likely due to closely spaced axial indications as well as ICC. (Only SP1 of Tube R19-C41 had significant ICC.) Laboratory UT inspection appeared to provide a more detailed resolution of the cracking, including intermittent circumferential indications where ICC was found by destructive examination.

Neither crevice region leaked during leak testing even though large bobbin signal voltages (3.3 volts) were present in the field data. The support plate burst pressures were well above the safety limitations. The crevice region burst pressures ranged from 6,600 psi to 8,100 psi. The corresponding corrosion macrocracks for the burst openings were 54% deep on average (85% maximum depth) over a length of 0.68 inch and 50% deep on average (71% maximum depth) over a length of 0.76 inch.

The examination results support the conclusion that the Farley Unit 1 indications are consistent with the database used to develop alternative plugging criteria (APC) for ODSCC at SP intersections. The two burst pressures show one burst pressure above the mean of the voltage/burst correlation and second burst pressure above the lower 95% prediction interval. The regression analysis results for the correlation are essentially the same with or without the Farley Unit 1 data included in the correlation. The lack of SLB leakage for these indications continues to support a low probability of leakage at these voltage levels. The crack morphology of IGSCC with small patches of ICC is typical of the pulled tube data in the APC database. The ICC has negligible influence on the burst pressure, as supported by the result that the SP1 region of Tube R19-C41, with a larger ICC patch than the SP2 region of Tube R14-C80, has a higher burst pressure than the SP2 region of Tube R14-C80, although the depths and lengths of the two burst location macrocracks are similar.

Table 1

Comparison of NDE Indications Observed on Farley Unit 1
S/G Tube Tubesheet Top and Support Plate Crevice Regions

Location	Field E/C Call	Review of Field Bobbin E/C	Lab Bobbin E/C	Review of Field RPC E/C	Lab RPC E/C	Lab UT	Lab X-Ray
R14-C80 TST	NDD, bobbin & RPC	Distorted roll transition signal (possible DI)	No data (deformed tube)	NDD to possible DI	No data (deformed tube)	No data (deformed tube)	No Ind
R14-C80 SP1	NDD, bobbin & RPC	0.6V DI; no dent	0.6V DI	NDD	SAI	MAI (3+C), deepest 20% near 185°, max length = 0.2"	No Ind
R14-C80 SP2	3.3V Ind, bobbin; MAI (3C), 1.2-1.4 V, RPC	3.3V Ind, 73% deep; <6 V dent	3.3V Ind, 50-60% deep; no dent	MAI (3C), 1.5V, 0.5" long	MAI (2C), 1.5V, 0.5" long	MAI (12+C), 65% max depth near 330°, 0.5"long; possible Circ Inds in center of crevice near 250°	No Ind
R19-C41 TST	NDD, bobbin; SAI with volumetric characteristics, 0.7" above TST, 0.4V, RPC	0.8V DI, 0.7" above TST	0.6V Ind, 48% deep	MAI, noisy data, 0.7" above TST	MAI (2C), 0.6" long, 0.3V	MAI (3C), deepest 20%, max length = 0.15", occur from 0.25" above to 1.0" below TST	No Ind
R19-C41 SP1	3.3V Ind, bobbin; MAI (2C), with volumetric characteristics, 0.2-0.4" long, 0.5-0.9V, RPC	3.2V Ind, 76% deep	2.4V Ind, 74% deep + 0.3 V Ind, 84% deep	MAI (2C), 0.5V, 0.5" long, with volumetric characteristics	MAI (6+C), 0.5V, 0.5" long, with volumetric characteristics	MAI (6C), deepest 80%, near 280°, length = 0.5"; possible Circ Inds at bottom and top of crevice, strongest near bottom near 300°	No Ind

Legend of Abbreviations:
NDD = No Detectable Degradation
TST = Tubesheet Top
V = Voltage
(#C) = number of cracks
RPC = Rotating Pancake Coil
Ind = Indication
SP = Support Plate
Circ = circumferential
DI = Disotorted Indication
SAI = Single Axial Indication
MAI = Mulitiple Axial Indications
max = maximum

Table 2

Leak Test and Room Temperature Burst and Tensile Test Results
for Farley Unit 1 S/G Tubing

Location*	Leak Rate** (l/hr)	Burst Pressure (psig)	Ductility (% Dia.)	Burst Length (inches)	Burst Width (inches)	Tensile 0.2% YS (psi)	Tensile UTS (psi)	Tensile Elong. (%)
R14-C80 SP2	NOC, no leak; SLB, no leak	6,600	9.4	1.019	0.215			
R14-C80 FS+		12,250+	22.2+	1.552+	0.300+	60,800	110,400	32.2
R19-C41 SP1	NOC, no leak; SLB, no leak	8,100	13.3	1.175	0.267			
R19-C41 FS		12,825	29.0	1.929	0.437	62,600	110,400	36.4

* SP = support plate location; FS = free span location
** NOC = leak rate at normal operating conditions; SLB = leak rate at steam line break conditions
+ = The free span specimen used for burst testing was observed (post-burst test) to have narrow axial bands of shallow cracking. The maximum depth of the cracking was 24% throughwall.

Table 3

SEM Fractography Data on Corrosion Present on Farley Unit 1 Steam Generator Tubes

Location	Max Depth (% depth)	Ave Depth (% depth)	Macrocrack Length* (in.)	Ductile Ligaments (#/width, in.)
R14-C80 SP2	85	54	0.68 (0.48 for main portion of macrocrack)	1/ 0.013
R19-C41 SP1	71	50	0.76 (0.61 for main portion of macrocrack); in addition, minor (7% deep) cracking exists up to 0.2 inch above SP top	2/ 0.013 & 0.009

* Intergranular crack length has been corrected for burst elongation. The correction factor was 0.86 for SP2 of Tube R14-C80 and 0.84 for SP1 of Tube R19-C41.

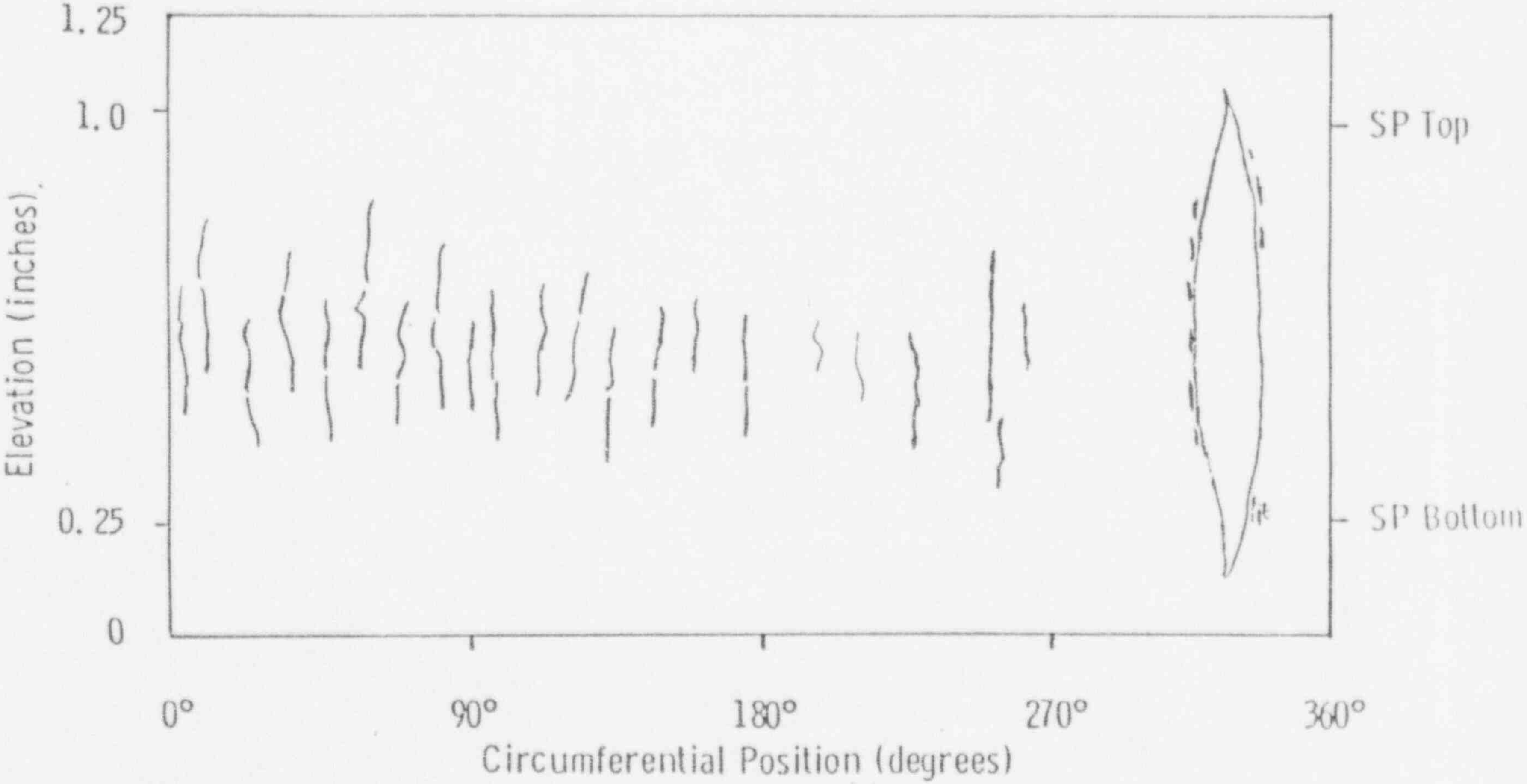

Figure 1 Sketch of the crack distribution found at the second support plate crevice region of Tube R14-C80. Included is the location of the burst test fracture face opening. The OD origin intergranular corrosion was confined to the crevice region, including that found on the burst fracture face.

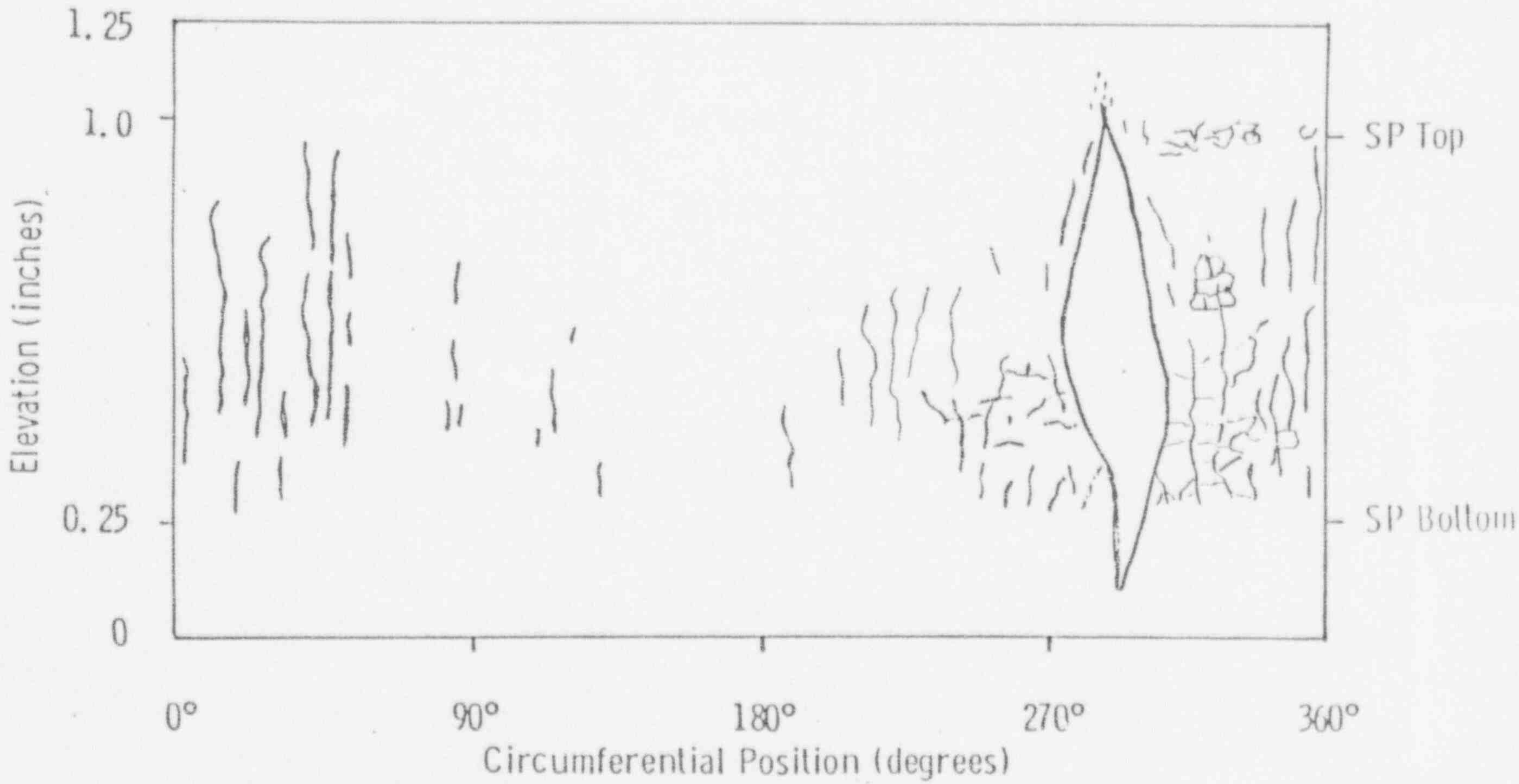

Figure 2 Sketch of the crack distribution found at the first support plate crevice region of Tube R19-C41. Included is the location of the burst test fracture face opening. All deep OD origin intergranular corrosion was confined to the crevice region, including that found on the burst fracture face. Some minor intergranular corrosion was observed up to 0.2 inch above the crevice top.

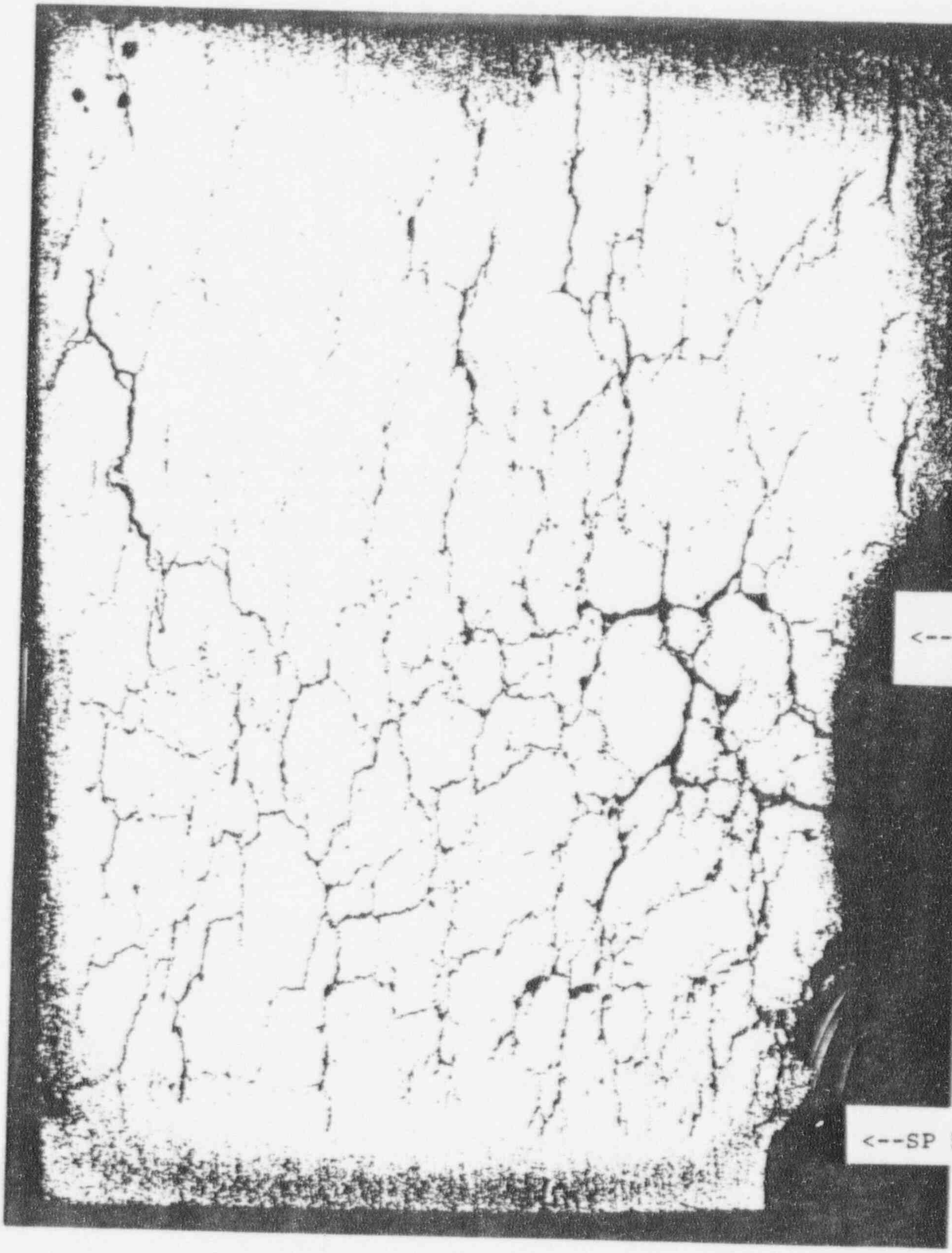

Figure 3 Radial metallography of the SP1 region of Tube R19-C41 showing intergranular cellular corrosion (ICC).