ATTACHMENT I

AEA-FRPE-282

NORTH ANNA UNIT 1
STEAM GENERATOR IMPACTED TUBE ENDS
RECOVERY EVALUATION

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NORTH ANNA UNIT 1 STEAM GENERATOR IMPACTED TUBE ENDS RECOVERY EVALUATION

1.0 INTRODUCTION

Near the end of the operating cycle completed in May 1982, evidence of impacting objects in the channel head of the North Anna Unit 1 Steam Generator "A" was obtained via the Loose Parts Monitoring System. Following plant shutdown for refueling, the three steam generators were inspected. The inlet channel heads on Steam Generators "A" and "C" were each found to have been impacted many times by one or more objects. Many of the tube ends in Steam Generator "C" were found to be heavily peened. Peening was also found in Steam Generator "A"; however, it was observed to be much lighter than in "C". In both steam generators, peening and impacting was also observed on the tubesheet, the divider plate and channel head bowl.

When the channel heads were opened and inspected, two foreign objects were found. In Steam Generator "A", a metallic object about 1 inch in diameter and about 1-1/4 inch long was found and retrieved. In Steam Generator "C", a much smaller metallic object was found and retrieved. Both objects were radioactive (30-40 R/hr.). It is judged that these objects, either alone or with other undiscovered objects, were contributers to the peening and impacting observed.

A program was established at Westinghouse which identified these objects as parts of control rod guide tube support pin nuts. The results of that program are contained in a separate report (Reference 1).

A second program was also established at Westinghouse to evaluate the effects of the impacting objects on the steam generator tube ends. The objectives of that program are:

a. To determine the extent of deformation experienced in the most heavily deformed steam generator.
b. To determine and technically justify the minimum amount of tube end deformation repair required.
c. To define a tube end repair process, if repair is needed or chosen.

This report gives the results of this evaluation, including conclusions with respect to the need for the extent of repair and a viable tube end repair process, if needed.

2.0 CONCLUSIONS AND RECOMMENDATIONS

2.1 CONCLUSIONS

A. No tube to tubesheet weld deformation in the form of cracking or missing weld material is apparent based on examination of 3X photographs.

B. Many of the more heavily peened tube ends (category b., c. and e.*) have some material missing. This material is primarily from the outer edge of the peened tube end but is also from the inner edge. The missing material does not appear to include the tube to tubesheet weld.

C. Many of the more heavily peened tube ends have small fragments attached (Categories b. and e.). These pieces could potentially become detached.

D. If eddy current examination from the steam generator inlet side is required, all tubes would have to be restored to 0.770 inside diameter or a smaller diameter probe would have to be used.

E. If a plug or sleeve is to be installed in any tube, it would have to be restored to 0.775 in I.D.

F. No tube to tubesheet weld deformation in the form of cracking is apparent based on destructive examination of prototypic mockups with intentionally deformed tube ends.

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*See Section 4.2 for definition of damage categories.

G. Restoration of impacted tube ends by hard rolling maintains the tube to tubesheet weld integrity, based on destructive examination of prototypic mockups.

H. The tube to tubesheet hard roll is adequate to maintain the joint structural integrity under all normal or upset loading conditions.

2.2 RECOMMENDATIONS

A. The inlet tubesheet in Steam Generator "C" should be decontaminated with a high pressure water jet. This will tend to remove any tube end fragments that could potentially become detached.

B. The inlet pipes to Steam Generators "A" and "C" should be examined to detect and remove any additional loose objects.

C. The bottom of the reactor vessel should be examined to detect and remove any loose objects.

3.0 RELATED EXPERIENCE

3.1 PLANT I

Relatively early in its life, some broken bolts from the reactor were transported to the steam generator. There, they were confined to the inlet channel head and impacted the tube ends.

In Plant I, the steam generator tubes project through the tubesheet a short distance and are welded to it with circumferential fillet welds (essentially like the North Anna steam generators).

The impacting broken bolts affected the tube ends minimally. The tube ends were slightly deformed and a few bolt pieces lodged in some tubes. The repair consisted of a reaming operation in which all tubes were machined to restore the inside diameter. Welds were dye penetrant inspected and no detectable cracks were found. All pieces of the broken bolts were recovered except for a few that could not be extracted from the tubes. In these few cases, the tubes were plugged.

3.2 PLANT II

In Plant II, a bolt, nut and washer were found in one of the steam generator channel heads following the cold hydro test, during which the main coolant pumps were run. A peening-type deformation of some of the tube ends was observed.

In Plant II, the steam generator tubes project below the tubesheet by a small amount and are welded to the tubesheet using fillet welds. This configuration is similar to that used in North Anna Unit 1.

Four types of tube end impact were identified. In the first, the tube end was virtually unchanged. In the second, the tube end was no longer round. In the third type, greater deformation occurred. In the fourth type, considerable tube material was missing. Detailed dye penetrant examination of five of the more severely impacted tube ends revealed no weld cracking.

The repairs undertaken at Plant II included different operations for the four types of impact. For the first type, only hand dressing to remove sharp edges was used. Light rerolling or reshaping the tube end was used for the second type. For the third type, the tube end was resurfaced by machining. For the fourth type, both resurfacing by machining and selected rewelding were used.

3.3 PLANT III

One of the steam generator inlet channel heads in Plant III was subjected to impacting by a foreign object. This object was determined to be a nozzle cover which was moved within the channel head by the reactor coolant flow. The cover, or parts of the cover, impacted areas of the channel head; however, the only area of noticeable impact was the underside of the tubesheet where the tubes project approximately 0.2 inches.

This impact did not affect the structural integrity of the steam generator or the reactor pressure boundary, nor did it keep the steam generator from performing its primary, heat transfer function. Each of the 3388 tube ends in the inlet tubesheet was repaired to a geometry sufficient to accept an eddy current inspection probe or tube plug.

The repair procedure for the Plant III steam generator tube ends included both "hands-on" operations as well as automatic operations. The principal operations included:

a. Slide hammer tube inside diameters to open sufficiently to accept camlocks (for supporting automatic equipment) and hard rollers.
b. Hard roll tube inside diameter with small hard roller to open the diameter sufficiently to accept the large hard roller.
c. Hard roll tube inside diameter with large hard roller to open the diameter sufficiently to accept an eddy current probe and, possibly, tube plug.
d. Inspect the reworked tube ends to confirm that acceptable diameters were achieved.

4.0 EVALUATION

4.1 TUBE END VISUAL EXAMINATION

To evaluate the deformation of the impacted tube ends in Steam Generators "A" and "C", a photographic technique was used for the visual examination. For each steam generator, two sets of photographs of the bottom of the inlet tubesheet were made at two magnifications. The first set consisted of two photographs which were used to orient the others. The second set of photographs, at a magnification of approximately 1X, was made to cover approximately 70% of the bottom of the tubesheet in Steam Generator "A" (which covered essentially all of the significantly damaged areas) and 100% of the bottom of the tubesheet in Steam Generator "C". A series of numbered plugs had been inserted into tubes on a regular pattern and these aided considerably in orienting the higher magnification photographs.

Figure 1 shows a typical portion of Steam Generator "A" extending to the junction of the tube sheet and channel head bowl. Note the light peening on the tube ends, the very light peening on the tube sheet surface, and considerable (but light) peening on the channel head bowl. This Figure is typical of most of Steam Generator "A".

Figure 2 shows a region adjacent to the divider plate and relatively close to the center of the tube sheet in Steam Generator "A". This is typical of only a small region that contains the maximum amount of tube end and tubesheet peening. In all cases, the peening is no more than moderate.

Figure 3 shows a typical region in Steam Generator "C" that includes the tube sheet to channel head bowl joint. Note that the tube end peening is light, the tube sheet peening is light, and the channel head bowl peening is extensive, though moderate. Note also that the tube ends have been bent more than was observed in Steam Generator "A", particularly in the region adjacent to the channel head bowl. The shape of the bending, coupled with the channel head bowl peening, suggests that the impacting object(s) ricocheted off of the channel head bowl and against the tube ends from the side.

Figure 3 also shows that many of the tube ends away from the channel head bowl sustained very minor deformation. This condition is typical of a large portion of the tube sheet in Steam Generator "C".

Figure 4 shows a portion of the tubesheet in Steam Generator "C" adjacent to the divider plate and channel head bowl. The tube ends, tube sheet, and channel head bowl are all peened lightly. (Note that the first row of tubes is completely plugged.)

Figure 5 is typical of the tube ends in the central region of Steam Generator "C" adjacent to the divider plate (first 8 to 10 rows). Note the heavy tube end peening, the missing and potentially missing tube end fragments, and the reduced tube end flow passages.

The second set of photographs was reviewed in detail by Westinghouse Nuclear Service Integration Division (NSID) personnel. The basis of this review was to determine if the impacting could have compromised the structural integrity of the tube to tubesheet weld. Each photograph was studied and tube end locations or areas that required additional review were identified. These tubes were studied further by means of photographs at a magnification of approximately 3X. Typical photographs are shown in Figures 6 and 7 for Steam Generator "A" and in Figures 8 to 11 for Steam Generator "C". All of these figures are related to Figures 1 to 5, as indicated.

Those tube ends, on the basis of the 3X photographic examination, with questionable indications on the tube to tubesheet weld were identified. Fifteen in Steam Generator "A" and nineteen in Steam Generator "C" are included in this category. Photographs at approximately 5X magnification were studied. This indicated no impairment of these welds.

Based on the visual examination, the conclusion was reached that no tube to tubesheet weld deformation exists in the form of cracking or missing weld material. However, it was recognized that many of the welds are obscured by the peened-over tube ends and more conclusive results were needed from mockup testing and analytical evaluation.

A study of photographs of the inlet tubesheet in Steam Generator "C" shows a region, predominantly adjacent to the divider plate, in which extensive peening of the Inconnel 600 tube ends has occured. This has caused the tube ends to deform both inwardly and outwardly.

In the inward direction, the material movement has caused the tube opening to decrease as the material has tended to form an orifice. (See Section 4.5)

In the outward direction the tube material has tended to mushroom over the tube to tubesheet fillet weld, covering it completely in many cases. In the outward direction, primarily, the heavily peened material has fractured in both radial and circumferential directions. This has apparently produced fragments of material that are missing from the tube ends. It has also produced fragments that are partially separated from the tube ends and are "potentially missing". (See, for example, Figures 5 and 8b.)

4.2 TUBE END TO TUBESHEET JOINT IMPACT TESTS

In order to evaluate photography as a method for inspecting the weld region, tube end impact tests to duplicate various tube end deformation types were performed. According to the visual examination, the tube end deformation type can be classified by the combination of peening, bending and cracking. The deformation observed on the 1X and 3X photographs was classified as follows:

a. bending and peening
b. peening and cracking
c. peening
d. bending, peening and cracking
e. peening on welding surface

Each of the above five cases can range from light to heavy, depending on the degree of deformation.

The inlet tubesheet in Steam Generator "A" has tube end deformation of types a. and c. and very little of type b. In all cases, the deformation is light. (See Figures 1, 2, 6 and 7)

The inlet tubesheet in Steam Generator "C" has all of the above types of tube end deformation which ranges from light to heavy. (See Figures 3 to 5, and 8 to 11)

Five impacted tube ends which are representative of each of the five deformation types were selected from 3X photos and duplicated on a test mockup which was similar to the bottom condition of the tubesheet. Before the tube ends were impacted, the conditions of the weld areas around tube ends were recorded by 3X magnification photography. After the tube ends were impacted, additional photographs were taken of the test block. Figure 12, the test block at a magnification of 1X, shows nine tube ends before impaction and nine tube ends after impaction. Figure 13 shows four of the more heavily affected tube ends at a magnification of 3X. The three worse impacted tube ends were selected for metallurgical examination. These tube ends, include heavy peening and cracking (type b.), peening (type c.) and peening on the weld area (type e.). Figure 14, 15 and 16 show representative macrographs, at 7X, of tube and tubesheet mockup axial sections.

The results of the test showed that some of the fillet welding had been flattened and covered by the deformed tube ends. However, the photographic examination of the deformed tubes showed no indication of weld degradation. Metallurgical macrographs through the weld/tube interface did not disclose any cracking. Cold work indications on the deformed area were observed.

4.3 TUBE TO TUBESHEET HARD ROLL JOINT STRENGTH TEST

The results of the photographic evaluation of the impacted steam generator tube ends indicated that the tube to tubesheet welds probably were not adversely affected. Therefore, for increased confidence, a brief program was conducted to establish experimentally the holding strength of the tube to tubesheet hard roll joint in total absence of the weld.

It was determined that the tubes in the steam generator were first tack rolled over a length of 0.5 in. above the tubesheet bottom surface and then hard rolled to a length of 2.25 in. above the tubesheet bottom surface (after welding). The tube end protrusion of 0.219 in. does not provide any holding strength so this was not included. The effective strength of the rolled joint will result from the effective 2 1/4in. long roll depth of the tube to the tubesheet. This was simulated as shown in Figure 17. The physical properties of the tube material, actual rolling torque, percent wall thinning etc. were recorded for each sample. After the samples were prepared, the strengths of the joints were established experimentally.

a.) Strength Under Tension

Six specimens were tested under tension. The steel collars were fixed and the tubes were pulled from the secondary end. The load at which the joint "slipped" was recorded.

b.) Strength Under Compression

Three specimens were tested under compression. The steel collars were fixed and the tubes were compressed from the secondary end. The load at which the joint "slipped" was recorded.

Both tests were carried out in a tensile testing machine in which load vs movement was recorded on an X-Y plotter. The results are presented in Table 1 along with the parameters of the test specimens.

From the results in Table 1 it is apparent that the tube to tubesheet hard roll joint strengths are above 3000 lbs. under either tension and compression from secondary side.

The results of this experimental program were also used in the analytical evaluation. (See Section 4.4.)

4.4 ANALYTICAL EVALUATION

4.4.1 TUBE TO TUBESHEET HARD ROLL LOAD CARRYING CAPABILITY

From the examination of the photographs taken of the inlet side of the tubesheet and from the macrographs of the impaction tube end tests, it was expected that the tube-to-tubesheet weld would still have some load carrying capability. Since the remaining load carrying capability is difficult to quantify, it was shown that the tube/tubesheet hard roll alone is sufficient to carry the Design Specification loads (Reference 2). However, in order to provide a quantitative measure of the conservatism, engineering judgement was made as to the extent of the weld remaining and calculations based on this are also shown.

Table 1 listed the results of the tube end pull and push test (See Section 4.3). Note that the push test loads are somewhat higher than the pull test loads due to poisson's effect. A statistical evaluation was performed on the six pull tests. The pull test data was plotted on normal, log normal and Weibull probability paper. The Weibull distribution represented the best fit for the given data. The median, 5% and 95% ranks were plotted (see Figure 18). The steamline break (faulted condition) has the largest primary-to-secondary pressure differential which is equal to 2485 psi. The net load to be carried by the hard roll is:

$$
\begin{aligned}
F &= \pi r_i^2 \Delta p \\
&= \pi (.3925)^2 (2485) \\
&= 1203 \text{ lbs.}
\end{aligned}
$$

It is seen from Figure 18 that with 95% confidence the probability of failure is less than 1% and, therefore, the reliability is greater than 99%. These calculations are conservative due to the following:

- o The increased interfacial pressure due to the different (tube vs. tubesheet) coefficients of thermal expansion and due to the tubesheet hole distortion from plate bending has been neglected.
- o No credit was taken for the weld.
- o The increased axial load carrying capability due to the Wes-Tex expansion process (explosive) was neglected.

For the three push tests, three standard deviations below the mean will be used as the allowable load. The mean is 5107 lbs. and the standard deviation is 854. Thus the allowable push load is 2546 lbs.

4.4.2 THERMAL TRANSIENT EVALUATION

Because the load carrying capability of the hard rolled region is dependent upon the interfacial pressure, the design specification transients must be evaluated to ensure that this pressure is sufficient to withstand the axial loads on a time dependent basis. The conditions that reduce the interfacial pressure are:

- o Rapidly decreasing primary fluid temperature, i.e., tube is cooled faster than the tubesheet.
- o A secondary pressure greater than the primary pressure which tends to enlarge the tubesheet holes on the primary side surface.

A review of the transient conditions contained in the Design Specification (Reference 2) reveals that the limiting transients are Reactor Coolant Pipe Break (LOCA) and the Loss of Flow transient.

For the LOCA transient the primary fluid temperature decreases from 614°F to 100°F with a corresponding drop in pressure from 2235 psi to 0 psig. The secondary pressure is 1005 psig. The tube to tubesheet interference diametral change due to temperature effects was calculated to be:

$$\Delta D_{ia} = -0.00142 \text{ in.}$$

The axial load due to 1005 psi differential is 604 lbs. Since the push out force is linear with respect to the interfacial fit pressure and since the interfacial pressure is linear with respect to interference fit, one can scale the allowable pull load by the reduction in interference fit. From test results it was determined that the interference fit is approximately .002 in.

$$\frac{\text{Interference Fit Reduction}}{\text{Interference Fit}} = \frac{0.002 - 0.00142}{0.002} = 0.29$$

Therefore, the required load capability $= \frac{604}{0.29} = 2083$ lbs.

Since the allowable push load is 2546 lbs., the joint should hold even though the following conservatisms are neglected:

- o No credit was taken for the weld.
- o The increased axial load carrying capability due to the Wes-Tex expansion process was neglected.

For the Loss of Flow transient the primary fluid temperature drops 120°F in approximately 40 seconds. The 100% operating pressure differential of 1400 psi is used since it is higher than the Loss of Flow Δp. Since this is a relatively longer duration transient, compared to LOCA, the tube average temperature was taken to be the fluid temperature. Similar calculations show that the change in diameter due to temperature effects is -5.34×10^{-4} inches. The axial load due to the pressure differential is 678 lbs. Therefore, the required load carrying capability is

$$678 \left[\frac{0.002}{0.002 - 0.000534}\right] = 925 \text{ lbs.}$$

From Figure 18, it is seen that with 95% confidence the probability of failure is less than 1.0% and, therefore, the probability that the joint will hold (its reliability) is greater than 99%.

4.4.3 WELD EVALUATION

From evaluation of the macrographs of the simulated impaction tube end tests, reasonable engineering judgement would indicate that the majority of weld below the primary side surface is still available to carry the load. From Figure 19 it is seen that approximately 0.037 in. of fused metal is below the primary side surface. These dimensions were determined during the initial weld qualification tests. For the Design Condition:

$$\Delta p = 1600 \text{ psi}$$

$$\tau = \frac{\pi (0.3925)^2 (1600)}{\pi (0.875)(x)} \leq 0.6 S_m$$

where $0.6\ S_m = 0.6(26{,}600) = 15{,}960$ psi-----Pure Shear Stress Limit

Solving for x (the required leg length),

$$x = \frac{(0.3925)^2(1600)}{0.875(15960)} = 0.0177 \text{ in.}$$

For the Steamline Break,

$$x = \frac{(0.3925)^2(2485)}{0.875(\text{Limit})} = 0.013 \text{ in.}$$

where Limit $= 0.6(0.7_u) = 0.42(80{,}000) = 33{,}600$ psi

For Loss of Coolant Accident

$$x = \frac{(0.3925)^2(1005)}{0.875(33600)} = 0.0053 \text{ in.}$$

It is seen that sufficient margin exists to carry the primary loads.

4.4.4 ADDITIONAL CONSIDERATIONS

It is noted that 99% of the steam generator tubes are dented at the first tube support plate. Since the combined axial stiffness of the tube bundle is much greater than the stayrods and the out-of-plane tube support plate stiffness, the tube support plate and the stayrods will displace to relieve the load due to tubesheet bending and differential thermal expansion of the tubes and stayrods. Thus, the tubes themselves would carry an insignificant portion of the load.

4.5 TUBE END FLOW RESTRICTION

An evaluation of the impacted tube ends in Steam Generators "A" and "C" was made from the viewpoint of possible flow restriction.

Based on a study of photographs of the tubesheets, it was judged that the restriction to flow in Steam Generator "C", based on tube end cross sectional flow area, increased from 2.8% (96 plugged tubes) to 19.3%. The distribution of this restriction is shown in Table 2 and Figure 20, which show the approximate location of the various damaged zones, the number of tubes affected and the approximate passage restriction for each zone. It was then calculated that this passage restriction would result in a coolant flow restriction equivalent to 8% of the the tubes being plugged.

The degree of deformed tube ends in Steam Generator "A" is much less than in Steam Generator "C" and the flow restriction is also much less. It was judged that its passage restriction increased from 2.8% (94 plugged tubes) to 7%. It was calculated that this restriction would result in a coolant flow restriction equivalent to 3.5% of the tubes being plugged. However, VEPCO indicated that no degradation in flow was noticed prior to shutdown.

The equivalent number of tubes plugged for both steam generators "A" and "C" plus the 94 tubes plugged in Steam Generator "B" are well below the NRC approved North Anna Unit 1 total steam generator plugging limit. The effect that these plugged tubes, would have on the plant performance was also determined. It was concluded that the affect on performance, compared with the plant operation prior to the tube end impaction discovered in May 1982, would be an unmeasureable reduction of steam delivery pressure of 2.6 psia at 100% plant power or a reduction in power of 0.41% at constant steam delivery pressure.

5.0 REPAIR PROCESS DEVELOPMENT

It was judged that the impacted tube ends in the steam generator could be repaired by the same process as was used in Plant III (See Section 3.3). This method was tried as described below:

5.1 MOCKUPS

Test collars, 2-1/2 in. O.D. and 6 in. long, were made from from carbon steel. Inconel tubes, 0.875 in. O.D. with 0.050 in. wall thickness, were tack rolled into the collars with 50 in-lb roll torque and then welded to the collars. The tubes were then finally hard rolled with sufficient torque to produce 4% to 6% total wall thinning. A Pedigree Test Block, that had been made by Westinghouse Tampa facilities, consisted of a carbon steel block, 4 in. thick, with an Inconel clad surface. It contained 27 tubes, hard rolled and welded, as in the case of the collars. (This is the same test block, part of which was used during the tube end damage evaluation - See Section 4.2.)

5.2 DEFORMATION SIMULATION

After tube I.D. measurements were made on both the collars and test block, the tube ends, including the welds, were subjected to rapid and sharp hits with both ends of a ball peen hammer and a metal plate about 1/8 in. thick. The direction of the impacts were such that the deformation produced closely resembled the deformation actually found in the photographs from the field. All types of defects (a, b, c, d, e: see Paragraph 4.2) were produced. Figure 21 shows a typical tube end deformation, on one of the collars.

5.3 DEFORMATION REPAIR PROCESS

After producing the deformation, some of the tubes were repaired by the same hands-on process as was used in Plant III. This involved the use of a hammered-in taper pin to make the tube mouth large enough to receive a small hard roller. Then, the tube was hard rolled consecutively with larger hard rollers, using 120 in-lbs of roll torque in each case.

The rolling process opened up the tube I.D. near the weld and 1 in. inside to approximately 0.004 in. maximum, compared to the undamaged condition. The tube mouths diameter after repair was irregular and, in some cases, the inside lip became rather sharp. Many cases of the tube end "folding" inside the tube resulted, but in all cases the resulting inside diameter was satisfactory. Figure 22 shows the Figure 21 test collar (with a damaged tube end) after repair. This repair is typical of the appearance of the hard-rolled repaired tubes for both the test collars and test block.

In those cases in which the tube material was pushed over the inside surface, the repair process produced slivers inside the tube which were confined within about 1/2 in. from the tube end. These slivers were removed by the use of a 0.7812 in. reamer. The reamer diameter was considerably smaller than the I.D. of the rolled tube (0.796 to 0.801 in.) so that the tube I.D. was not "machined" or "reamed" during sliver removal.

5.4 JOINT INTEGRITY

5.4.1 MECHANICAL

Some Hydrostatic Leak Tests and Tube Loading Tests from the secondary side (similar to simulated feedline break - FLB accident conditions) were performed on the deformed tubes before and after repair. The results are presented in Table 3 which shows that neither the deformed nor the deformed-and-repaired joint exhibited any measureable leakage. It also shows that an axial load over 6000 lbs. could be realized. This load is well above the calculated allowable push load of 2545 lbs. (See Section 4.4.1.)

5.4.2 METALLURGICAL

Optical metallography was performed on three tube ends in the test block after the deformation has been repaired by hard rolling. Figure 23, 24 and 25 show macrographs (at 7X magnification) of axial sections through the tube, test blocks and weld. These are representative of different degrees of tube end deformation. Figure 23 shows a tube end section that had not been deformed significantly out over the weld. It had, apparently, been deformed inward and, when repaired, part of the tube lip folded over and formed the imbedded sliver that is apparent. In Figure 24, the tube end had apparently been deformed both inward and outward, as evidenced by the tube wall thickening above the weld in some sections and the formation of an imbedded sliver. In Figure 25, the tube end was deformed sharply outward over the weld in one sector.

The results of the metallurgical examination indicate that:

Welds - While deformation has taken place, no cracking of the weld was observed on the test samples.

Tubes - Considerable deformation to the tube ends resulted due to impacts. Tube fractures had been noticed just above welds, at the mouth and also on the inner surface of the tube where it became exposed to the impacts from being "flared" out. Double layers of tube material had been seen inside the tube. This new layer of the tube, which was folded in during the repair process, was wedge shaped.

5.5 REPAIR CONCLUSION

From the above discussions, it was concluded that the tube end deformation in Steam Generators "A" and "C" could be repaired by basically the same process as was developed to repair the impacted Plant III steam generator. However, an additional step of deburring by the use of a suitable reamer should be added for North Anna for the tube ends in which the repair process produces visable slivers.

6.0 REFERENCES

1. AEA-FRPE-219 Revision 1, E. Paxson, S. Sinha and L. Albertin, North Anna Unit 1 Steam Generator Impacting Objects Identification, October 1982.

2. Design Specification Addendum 677307, Revision 3, March 1976, and Generic D-Specification 6-677164, Revision 1, December 1969, Westinghouse Electric Corporation, Pittsburgh, PA.

TABLE 1

TUBE TO TUBESHEET HARD ROLL JOINT STRENGTH TEST

a. Test Specimen Parameters

Tube O.D. = 0.875 in.; tube wall thickness = 0.050 in.
Tack Rolling Torque = 50 in.-lb.
Hard Rolling Torque = 80 in.-lb.

No tube to tubesheet weld
No protrusion of tube beyond collar
Tube material physical properties:
Heat = NX1019, UTS = 110,000 psi,
YS = 58,000 psi Millannealed
R.B. = 89 Inconnel 600
Elongation = 37%

b. Test Results

Sample No.	<u>% Wall Thinning @</u> 5/8"	1 1/4"	1 3/4"	Joint Slip-load lbs	Condition
9	5.7	5.9	4.4	3040	Pulled from Secondary Side
10	3.7	3.2	3.2	4220	"
11	4	4.8	3.9	3900	"
12	5	4.4	3.2	3030	"
B	7.3	6.4	6.9	4260	"
C	4.4	4.5	4	3760	"
13	4.5	4.9	4.4	5380	Pushed from Secondary Side
14	4.9	4.6	4.7	5790	"
A	5.9	6.8	6.8	4150	"

TABLE 2
FLOW PASSAGE RESTRICTION IN STEAM GENERATOR C

Tube Sheet Zone*	1	2	3	4	PLUGGED TUBES
Deformation Types	a.	None	Type c. (Light) Type d.	Type c. (Heavy) Type e	-----
No. of Tubes	200	1918	643	531	96
Passage Restriction	20%	0%	35%	55%	100%

$$\text{Initial Flow Restriction} = \frac{96 \text{ x } 100}{3388} = 2.8\%$$

$$\text{Final Flow Passage Restriction} = [200 \text{ x } 20 + 1918\text{X}0 + 643 \text{ x } 35 + 531 \text{ x } 55 + 96 \text{ x } 100] \div 3388 = 19.3\%$$

* See Figure 20

TABLE 3
JOINT INTEGRITY TEST

Tube Condition	No. of Tests	Type of Test	Results
(a) Deformed, not repaired	2	Room Temperature Hydrostatic Leak Test at 2500 psi and 3750 psi.	No leak for 10 minutes
(b) Deformed, repaired, weld machined off	2	Room Temperature Hydrostatic Leak Test at 2500 psi and 3750 psi.	No leak for 10 minutes
(c) Deformed, not repaired (from a)	2	Tube Loaded From Secondary Side - FLB Type	Tube buckled above 6000 lbs of load, without affecting joint.
(d) Deformed, repaired, weld machined off (from b)	2	Tube Loaded From Secondary Side - FLB Type	Tube buckled above 6000 lbs of load, without affecting joint.
(e) Deformed, not repaired, weld machined off	2	Tube Loaded From Secondary Side - FLB Type	Tube buckled above 6000 lbs of load, without affecting joint.
(f) Deformed, repaired, weld still in place	2	Tube Loaded From Secondary Side - FLB Type	Tube buckled above 6000 lbs of load, without affecting joint.

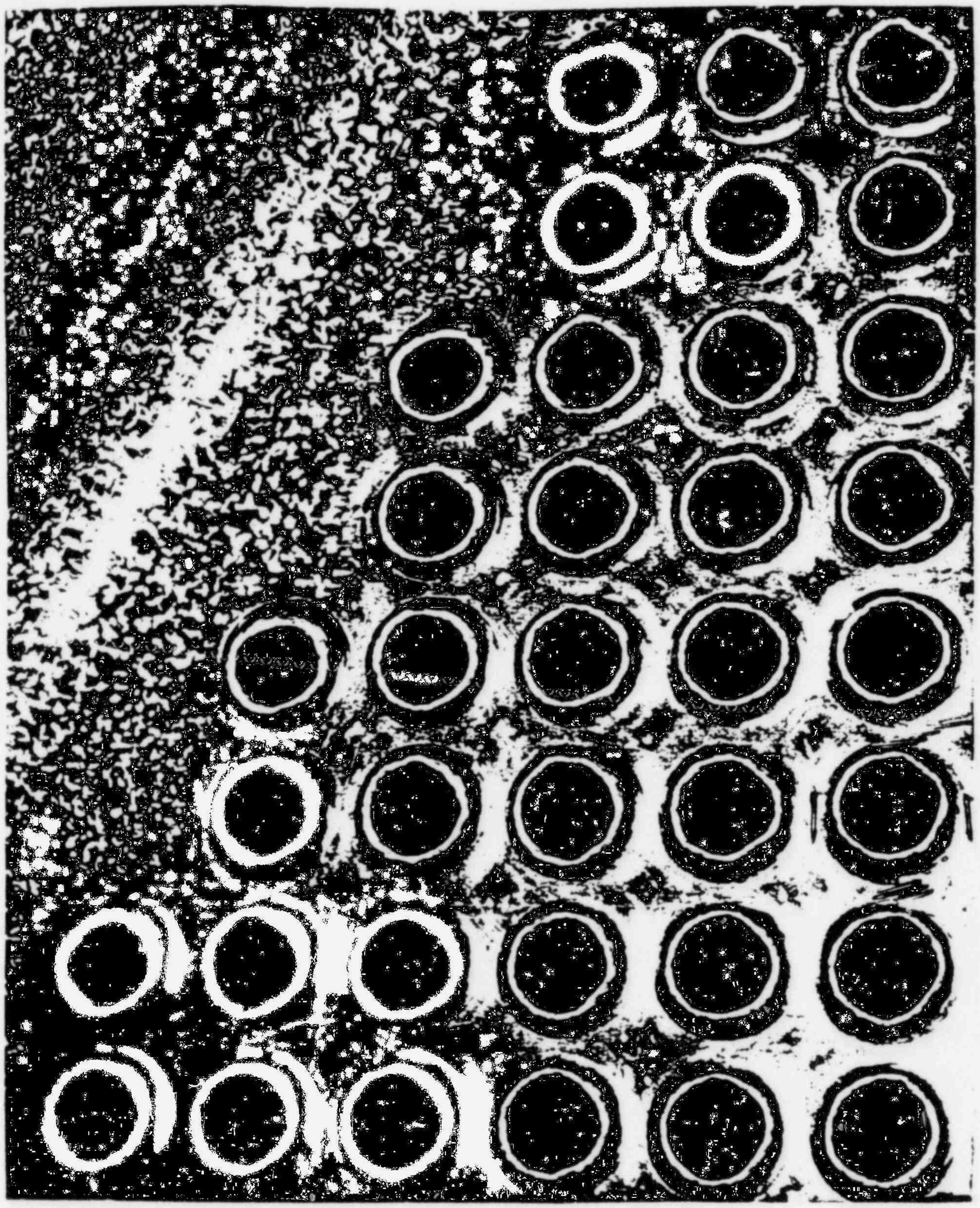


Figure 1 Steam Generator A Inlet Tubesheet, Rows 18-25, Columns 5-10, -1X

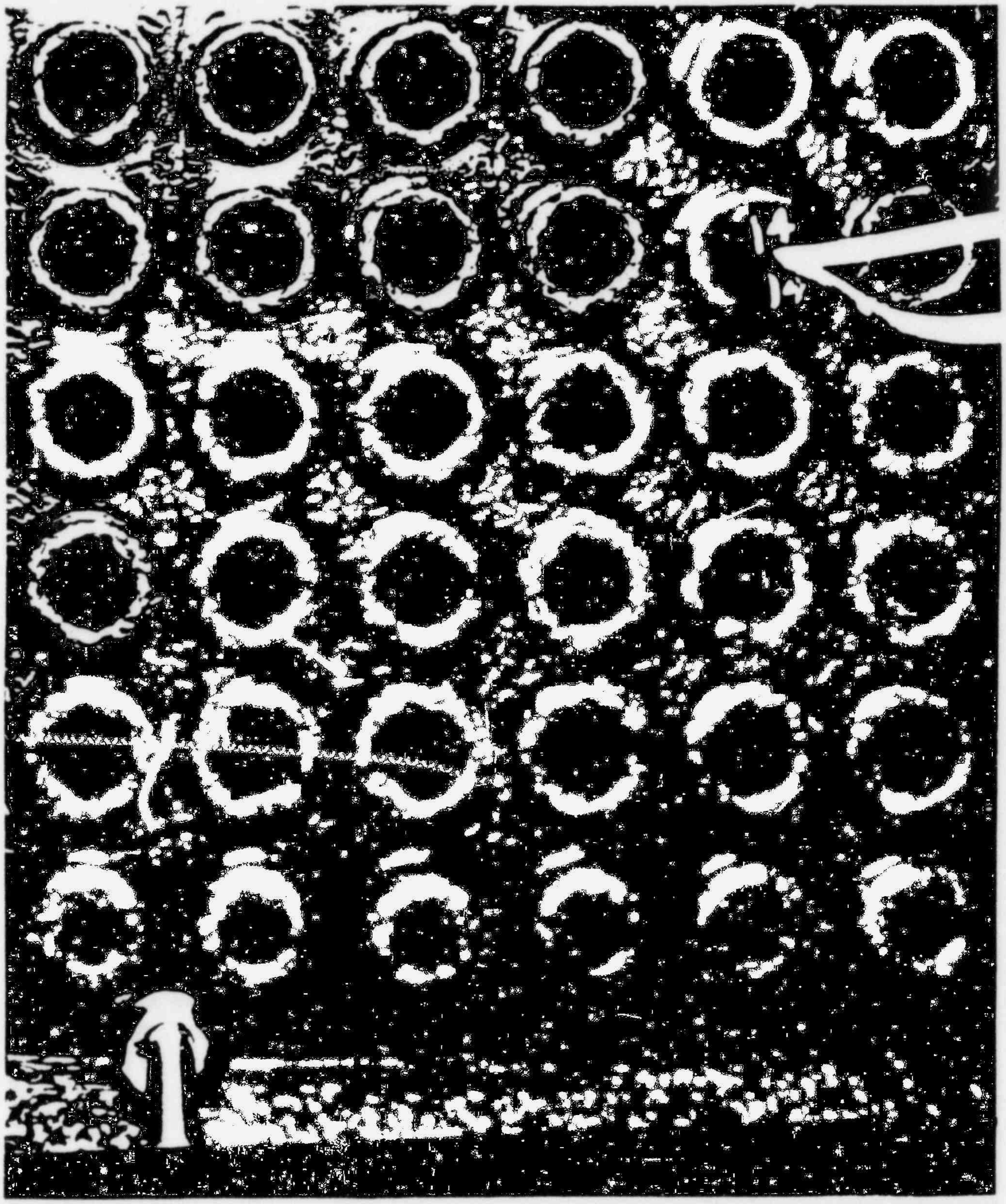


Figure 2 Steam Generator A Inlet Tubesheet, Rows 1-6, Columns 32-37, -1X.

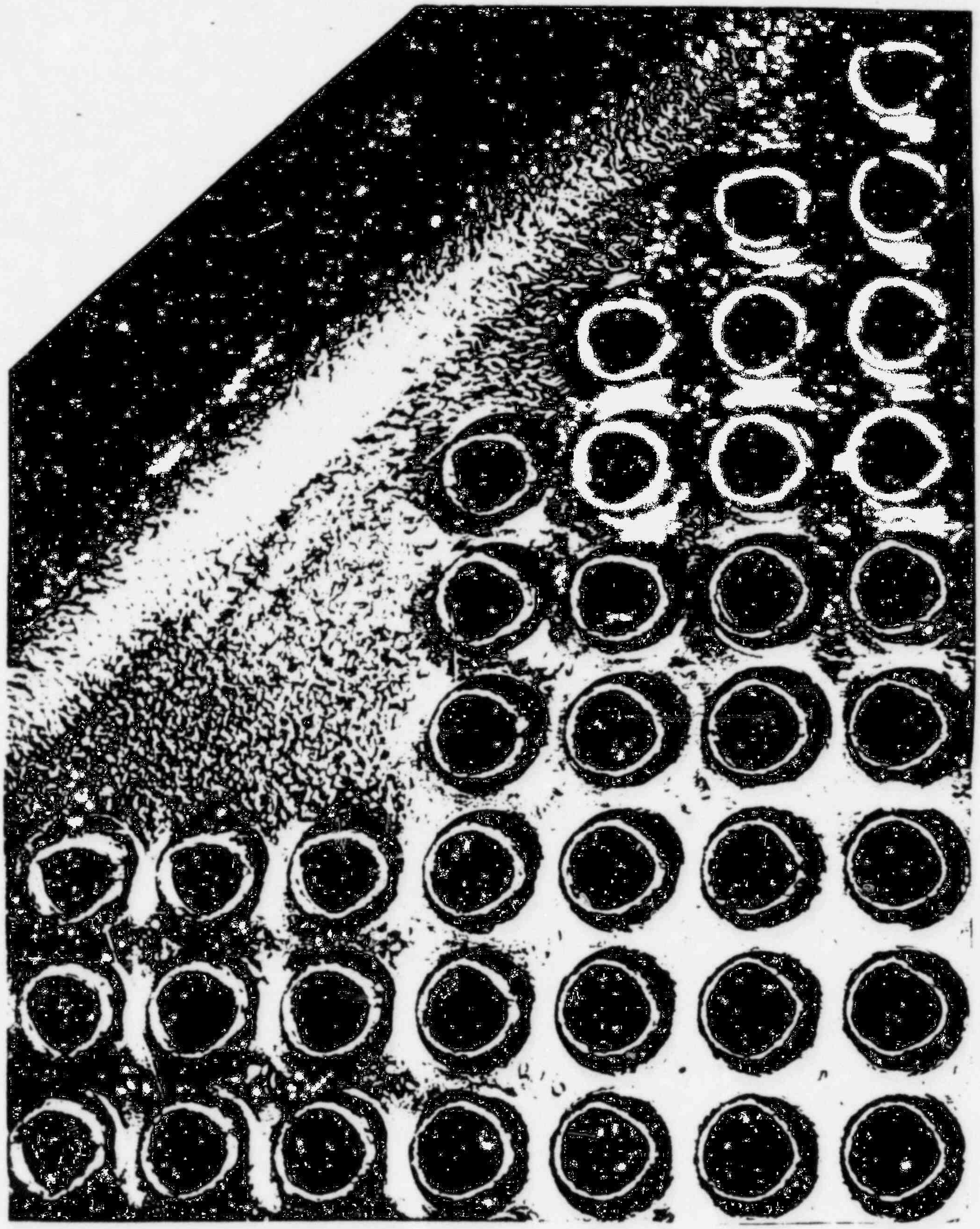


Figure 3 Steam Generator C Inlet Tubesheet, Rows 29-37, Columns 13-19, -1X

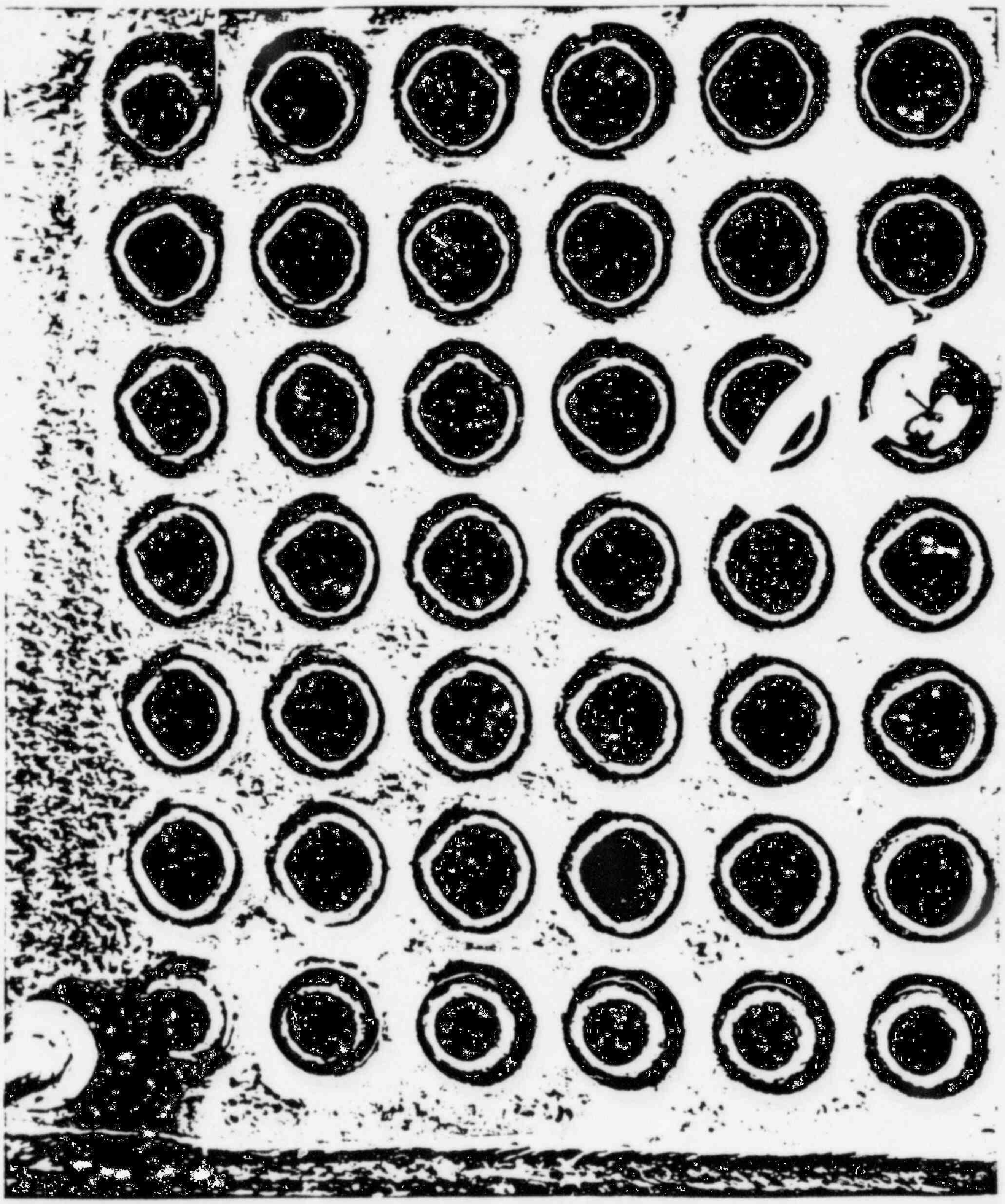


Figure 4 Steam Generator C Inlet Tubesheet, Rows 1-7, Columns 1-6, -1X

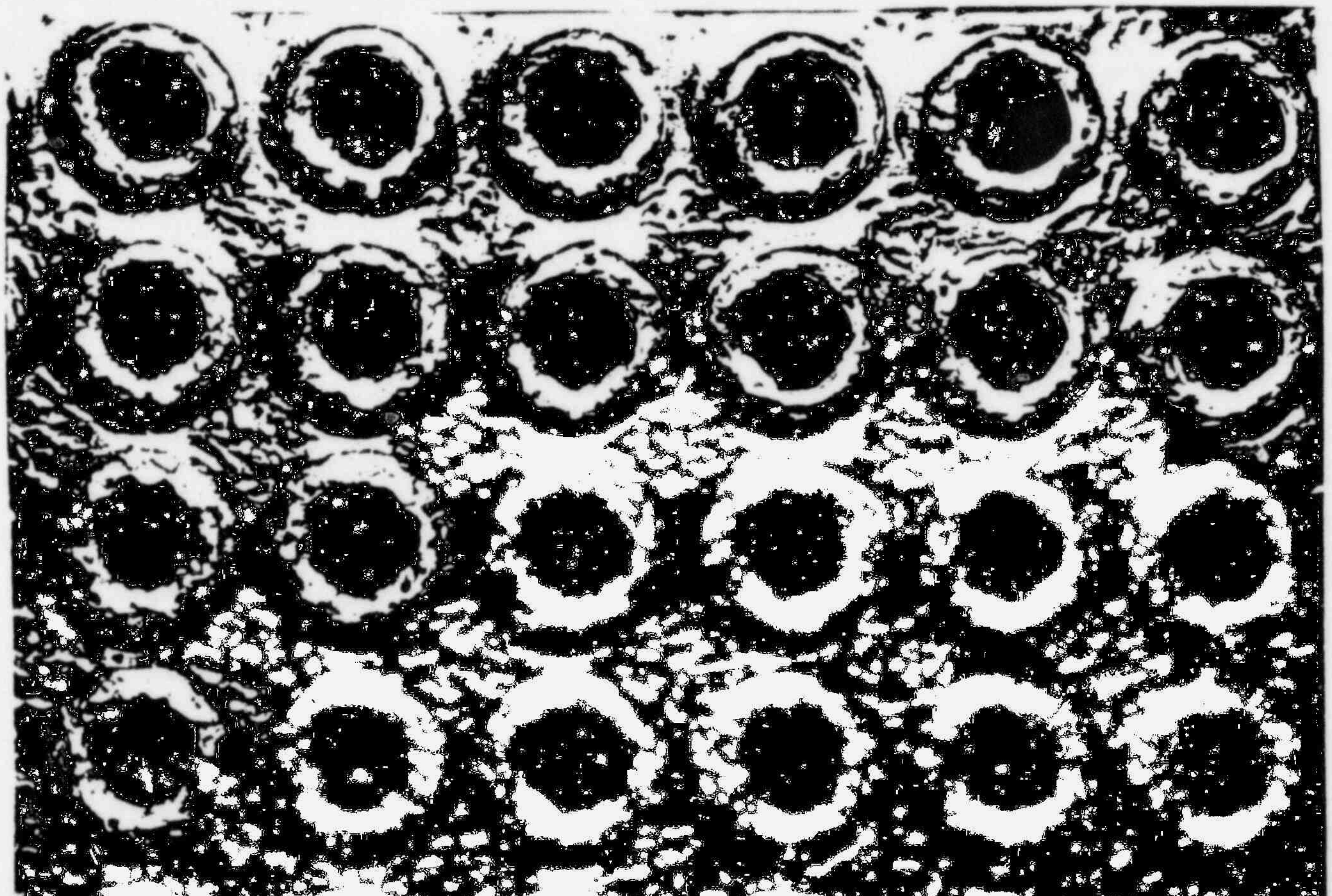


Figure 5 Steam Generator C Inlet Tubesheet, Rows 1-7, Columns 40-45, -1X

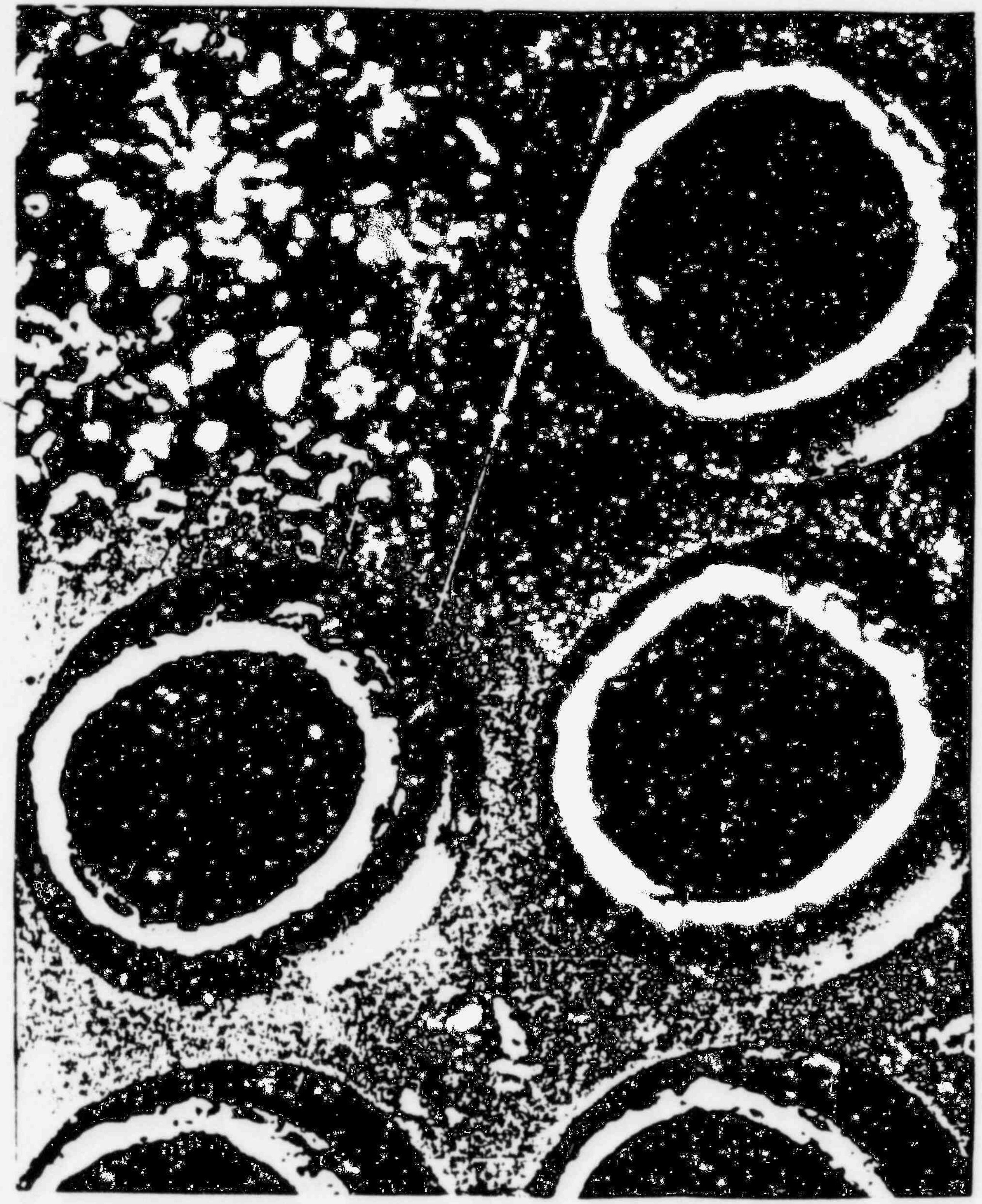


Figure 6 Steam Generator A Inlet Tubesheet, Rows 22-24, Columns 7, 8, -3X Enlargement of Fig. 1

Figure 7 Steam Generator A Inlet Tubesheet, Rows 2, 3, Columns 34, 35, -3X Enlargement of part of Fig. 2

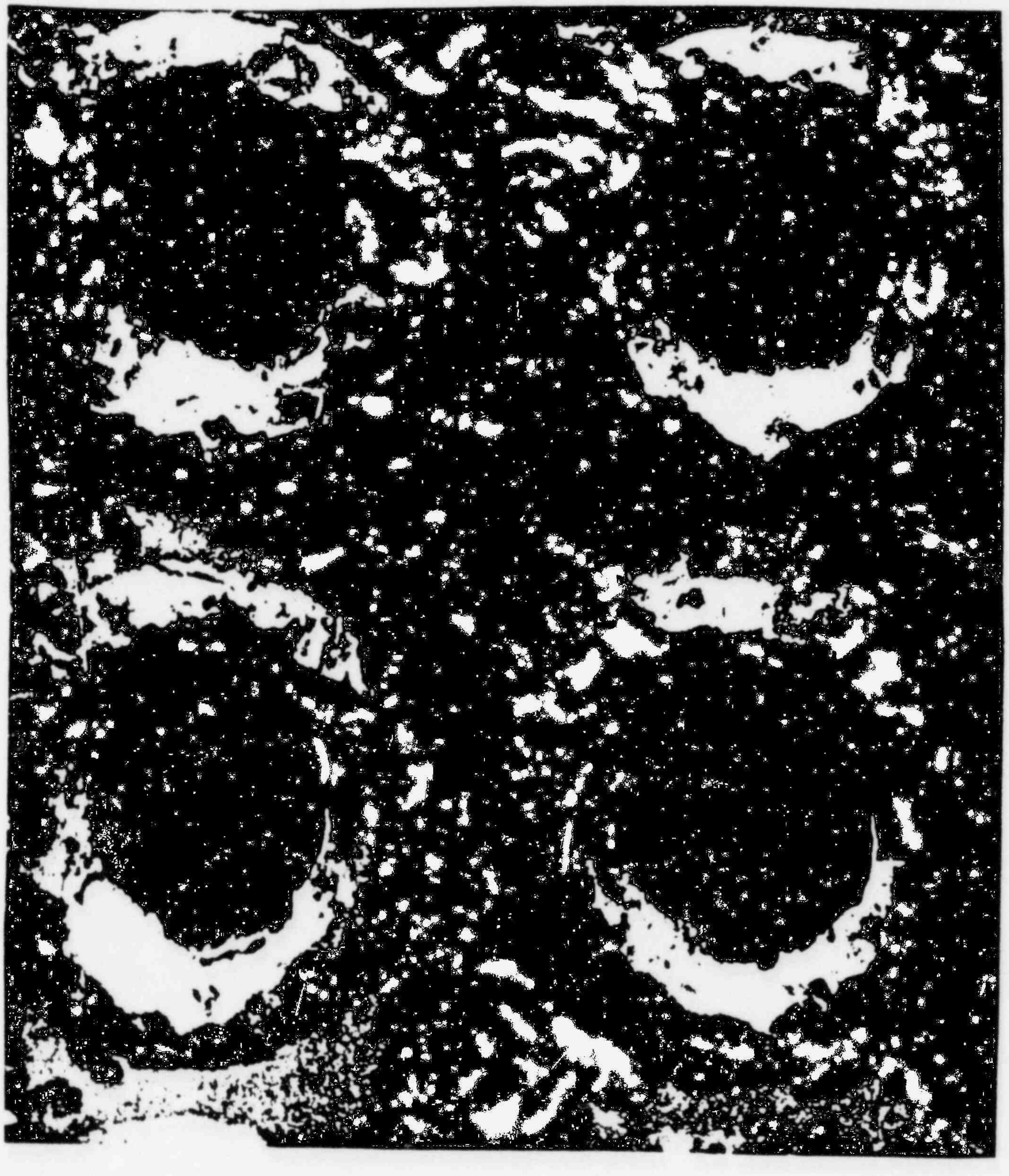


Figure 8a Steam Generator C Inlet Tubesheet, Rows 2, 3, Columns 42, 43, -3X

Enlargement of part of Fig. 5

Figure 8b Steam Generator C Inlet
Tubesheet, Rows 4, 5,
Columns 42, 43, -3X
Enlargement of part of
Fig. 5

Figure 9 Steam Generator C Inlet
Tubesheet, Rows 10, 11
Columns 38, 39,- —
3X Enlargement

Fig. 10 Steam Generator C Inlet Tubesheet, Rows 33-35, Columns 16, 17, -3X Enlargement of Part of Fig. 3

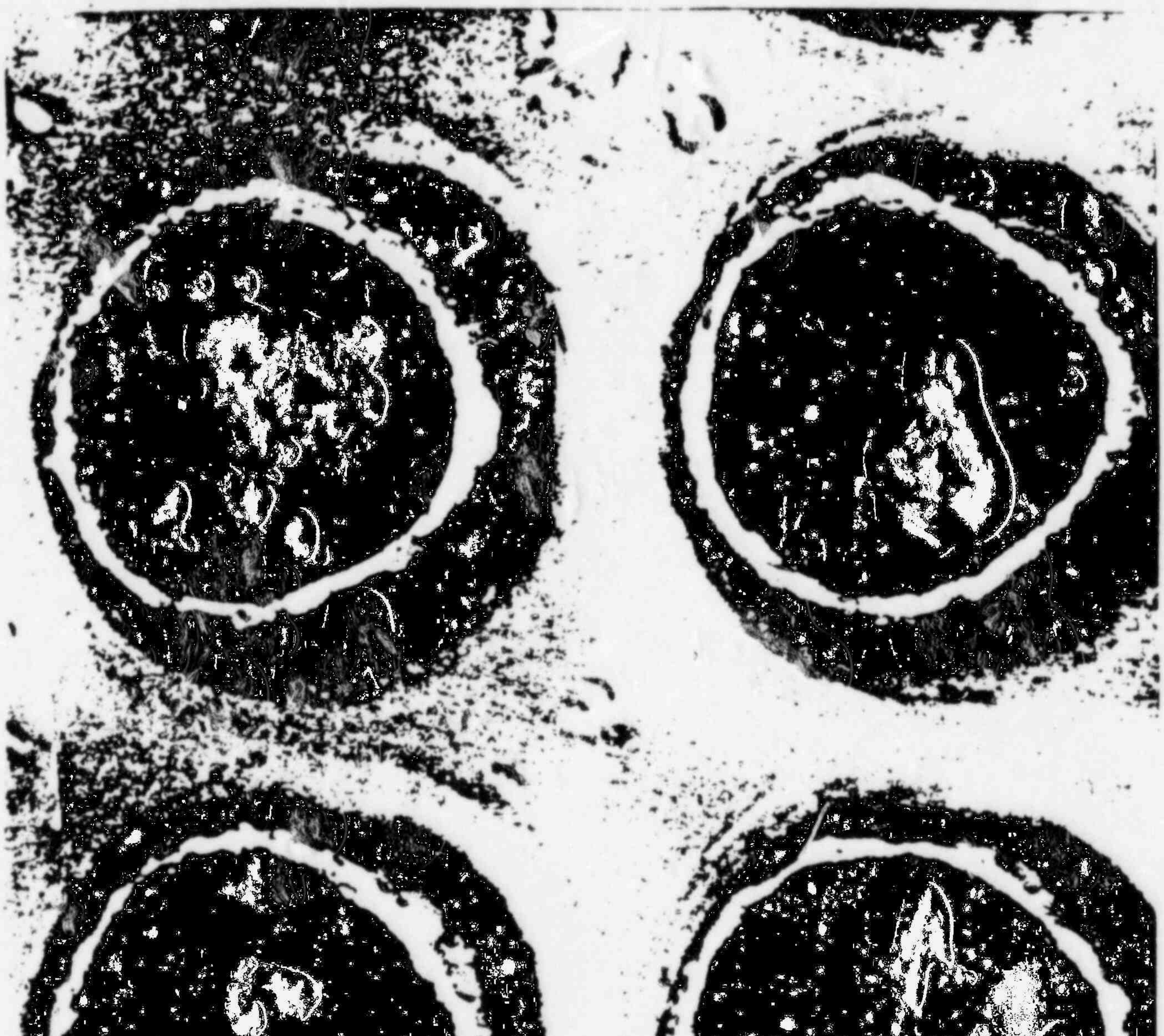


Fig. 11 Steam Generator C Inlet Tubesheet, Rows 28, 29, Columns 16, 17, -3X Enlargement of Part of Fig. 3

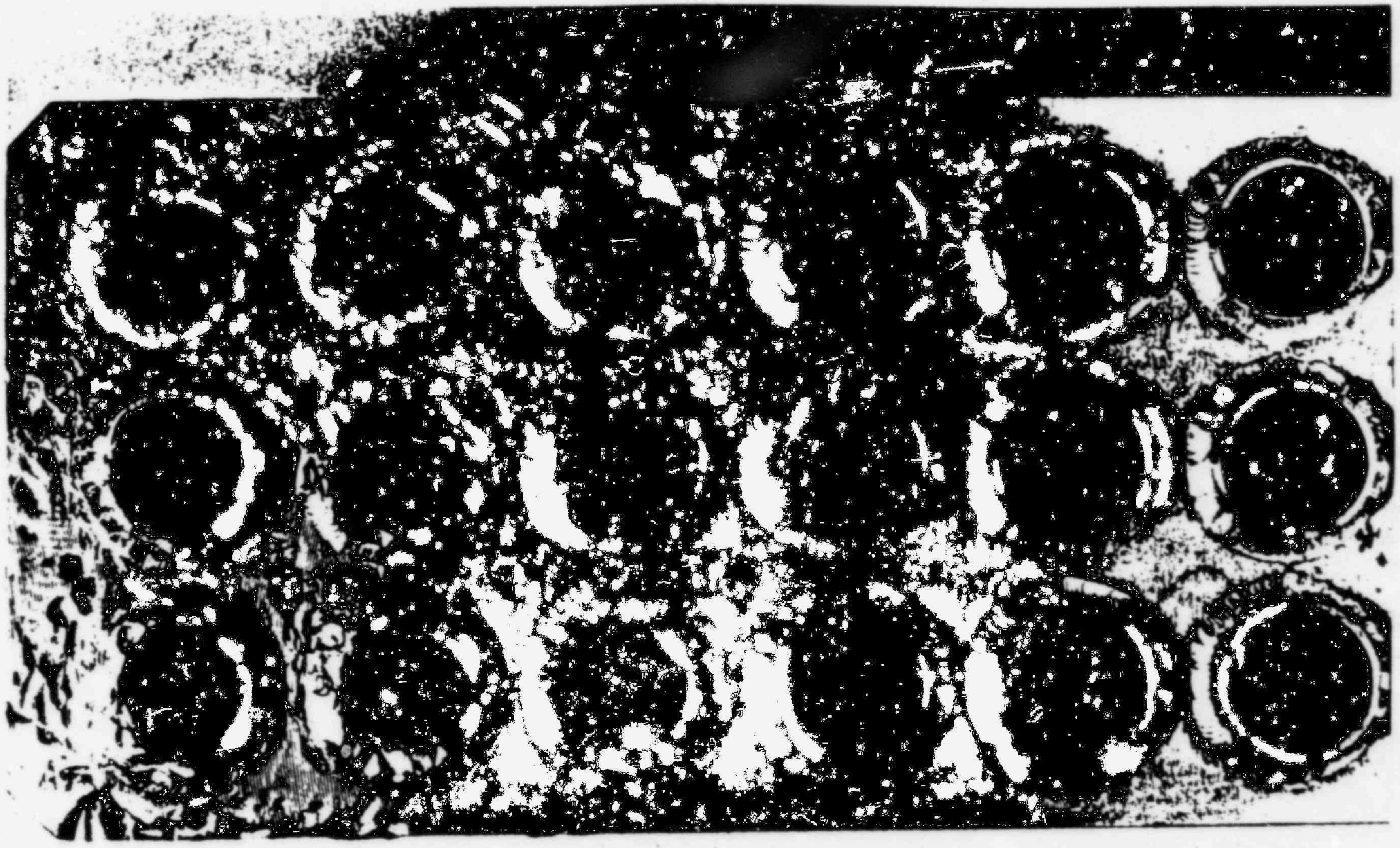


Fig. 12 Steam Generator Tubesheet Mockup Before (9 tubes) and After (9 tubes) Intentional Representative Impaction, Rows 1-3, Columns 1-6, -1X

Fig. 13 Steam Generator Tubesheet Mockup After Intentional Impaction, Rows 1, 2, Columns 1,2 -3X Enlargement of Part of Figure 12

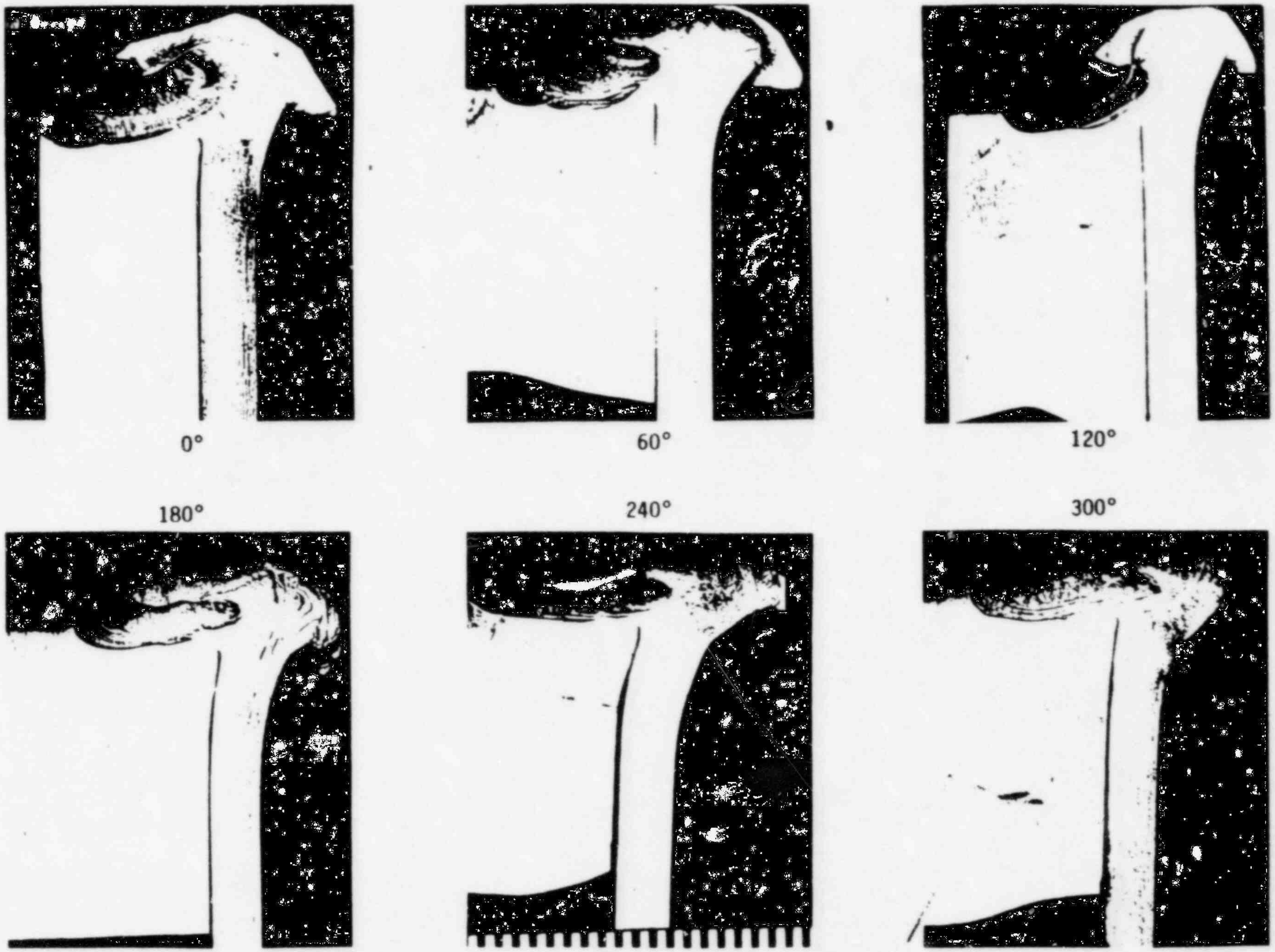
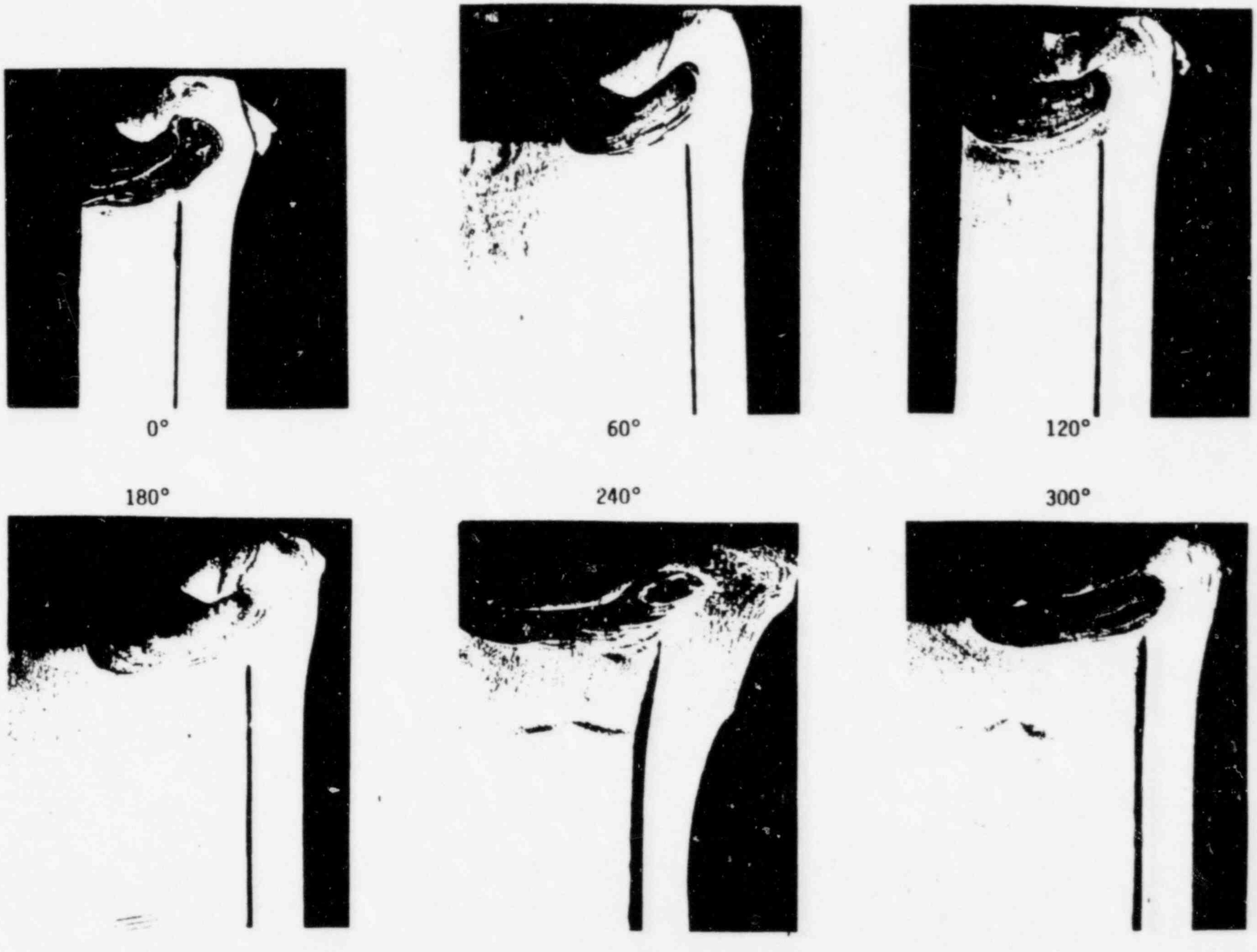


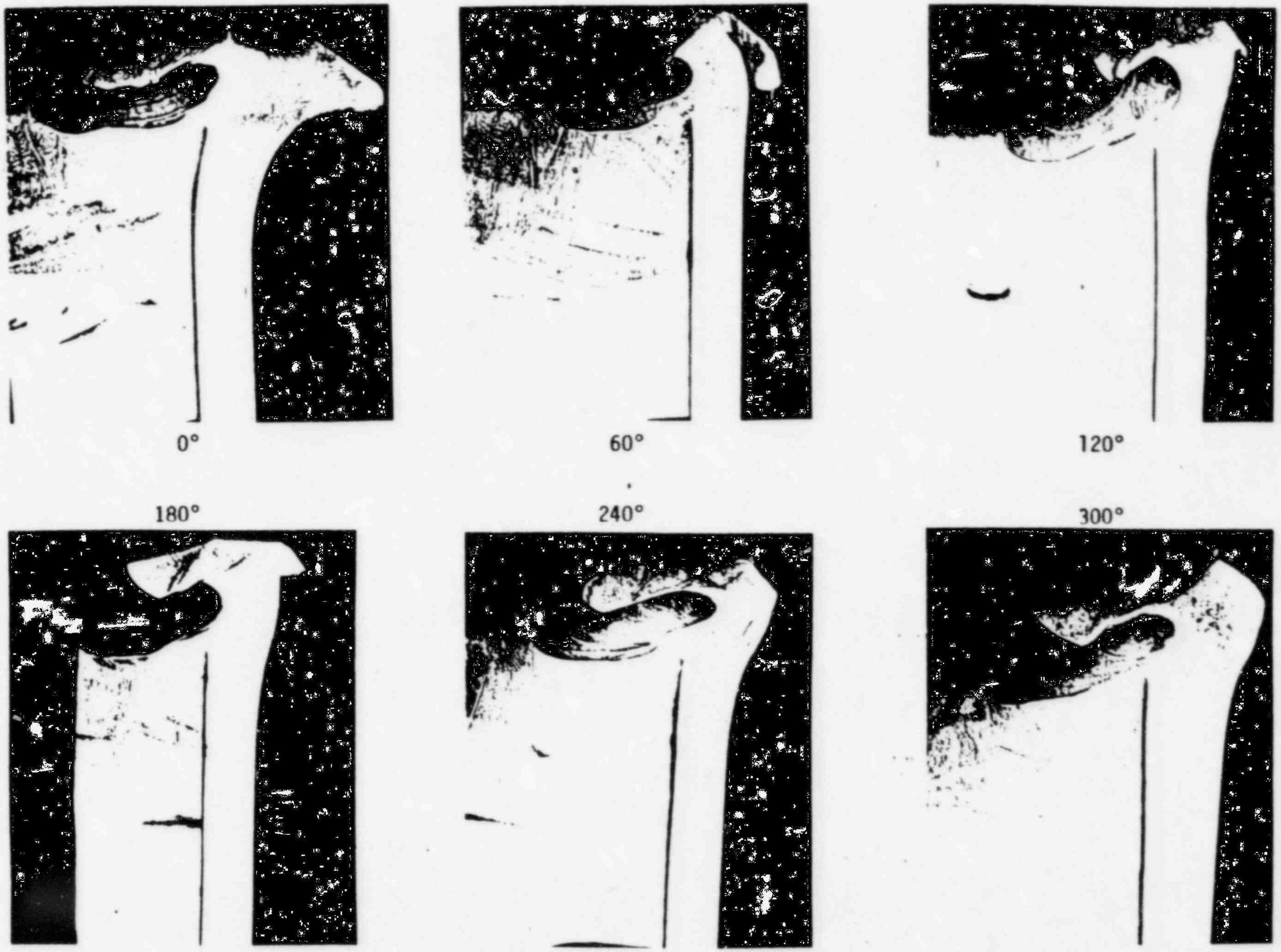
Fig. 14 Macrographs of Sections Through the Tube and Tubesheet Mockup, Row 1, Column 1 (See Figures 12, 13) -7X Magnification



0° 60° 120°

180° 240° 300°

Fig. 15 Macrographs of Sections Through the Tube and Tubesheet Mockup, Row 2, Column 1, (See Figures 12, 13) -7X Magnification



0°

60°

120°

180°

240°

300°

Fig. 16 Macrographs of Sections Through the Tube and Tubesheet Mockup, Row 2, Column 2 (See Figure 12, 13) -7X Magnification

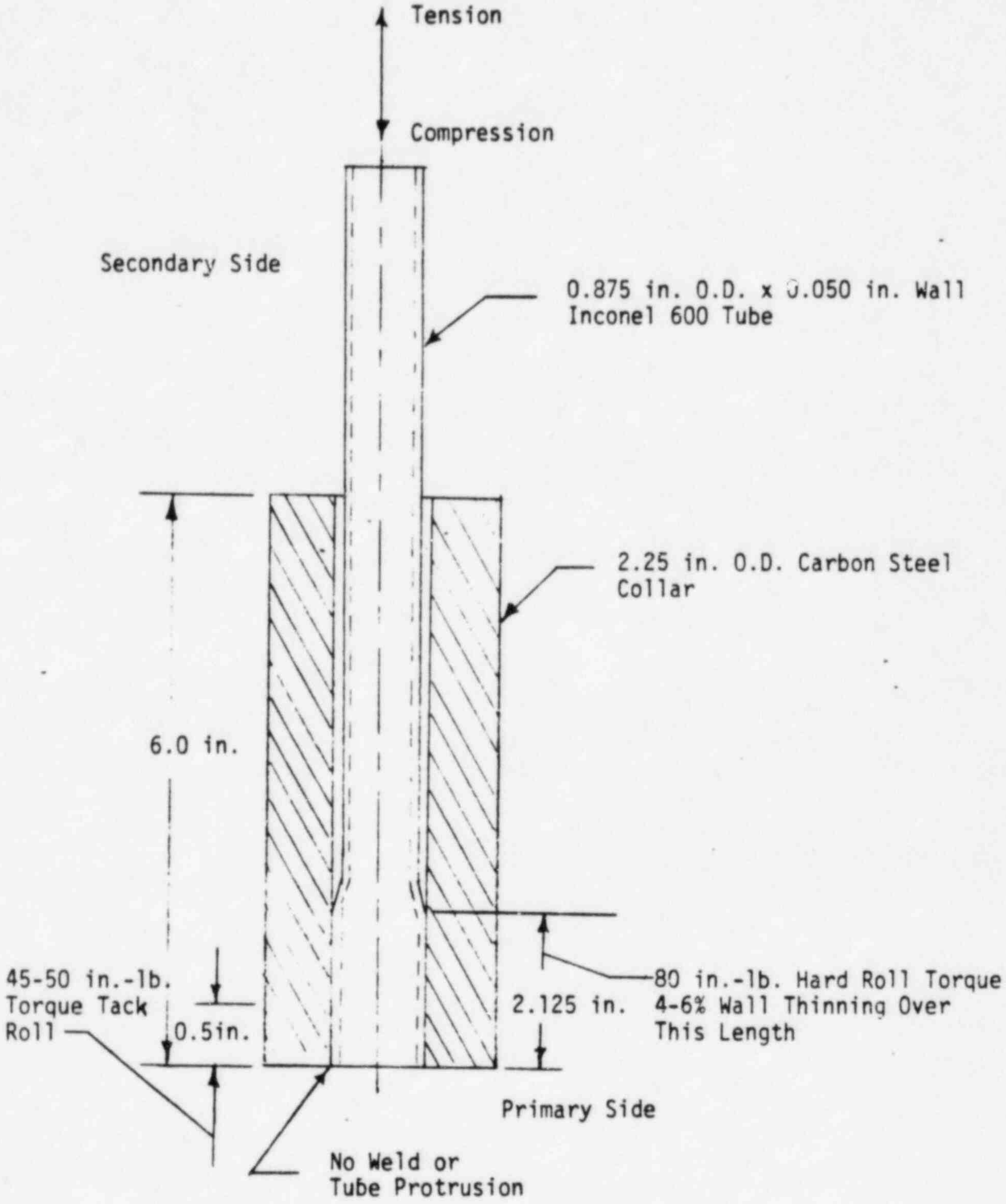


Figure 17 Specimen for Hard Roll Joint Strength Test

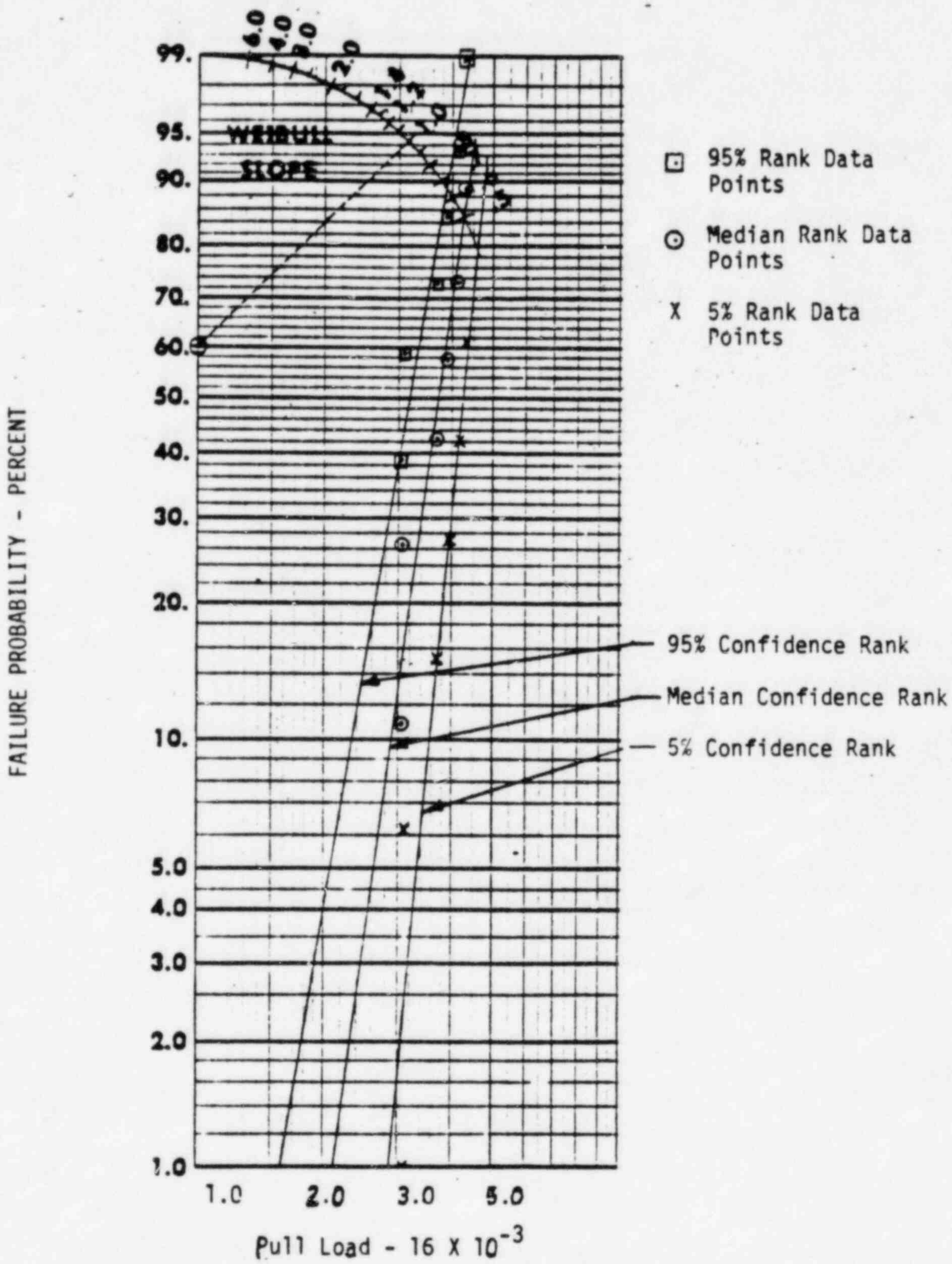


Figure 18 Weibull Distribution for Tube to Tubesheet Pull Tests

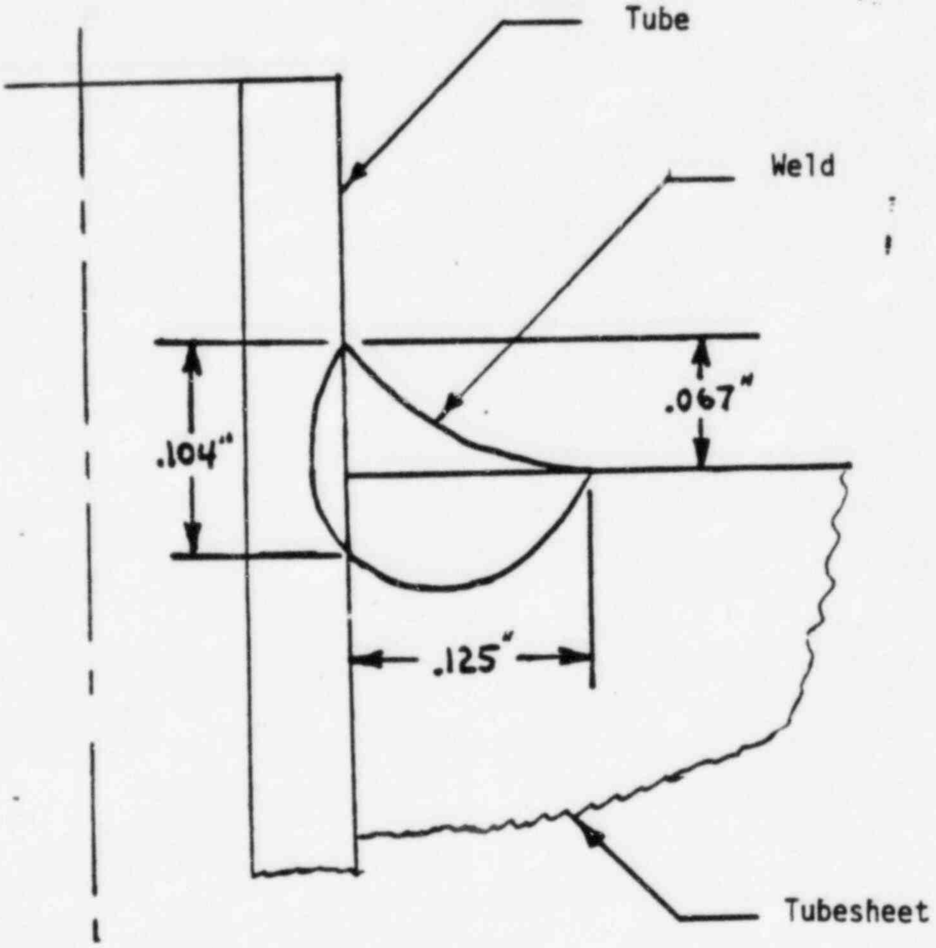


Figure 19 Tube-To-Tubesheet Weld Geometry

A	4	11/79, MECH PLUG HL&CL
B	89	12/79, TUBES PLUGGED
C	1	1/81, M/P RPLC E/P, HL ONLY
D	1	3/81, M/P RPLC E/P, HL ONLY
E	1	3/81, M/P RPLC E/P, CL ONLY

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VRA-C

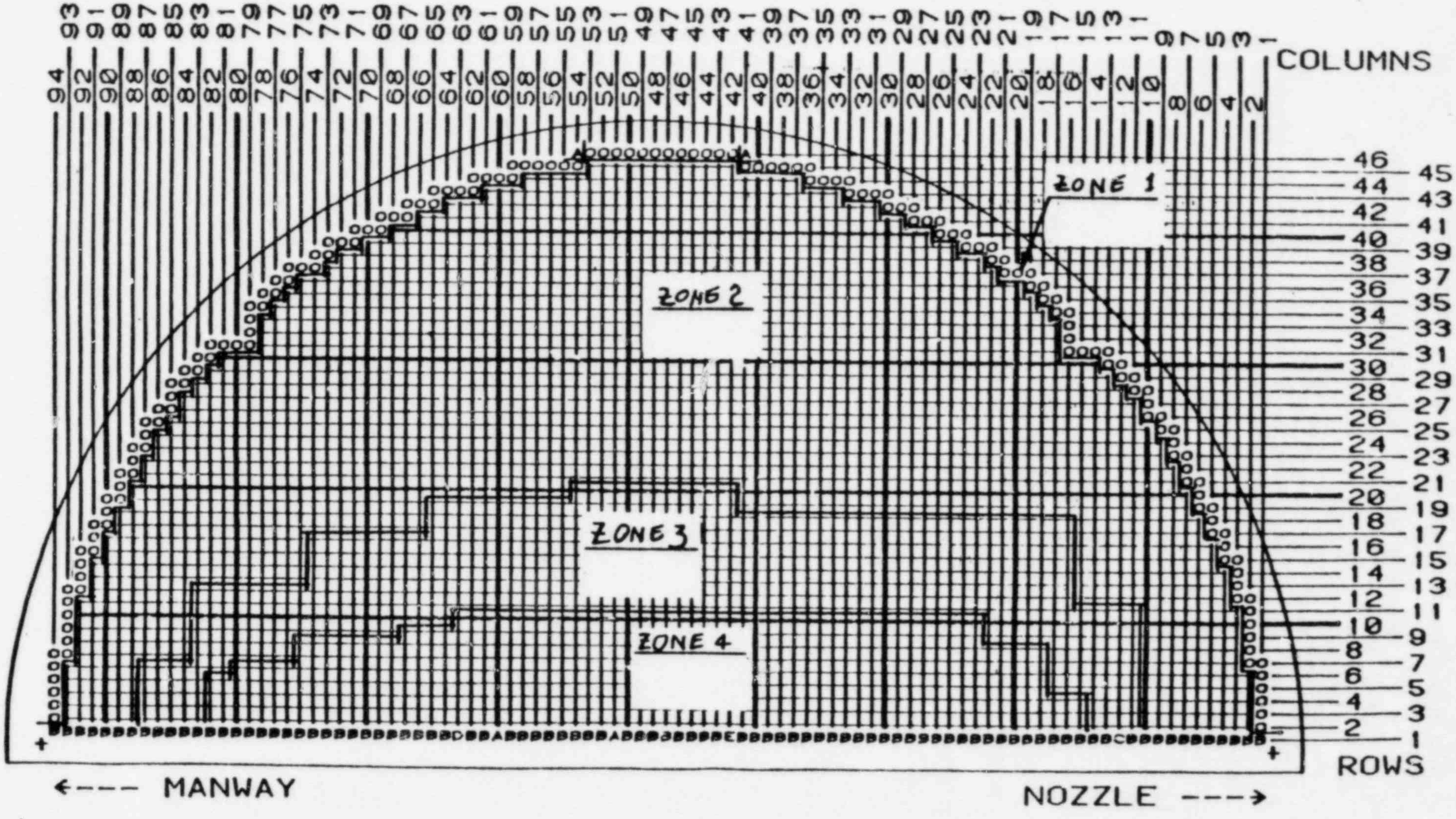


Figure 20 Steam Generator "C" Tube End Deformation Zones

FIGURE 21

INTENTIONALLY DEFORMED TUBE END
IN TEST COLLAR

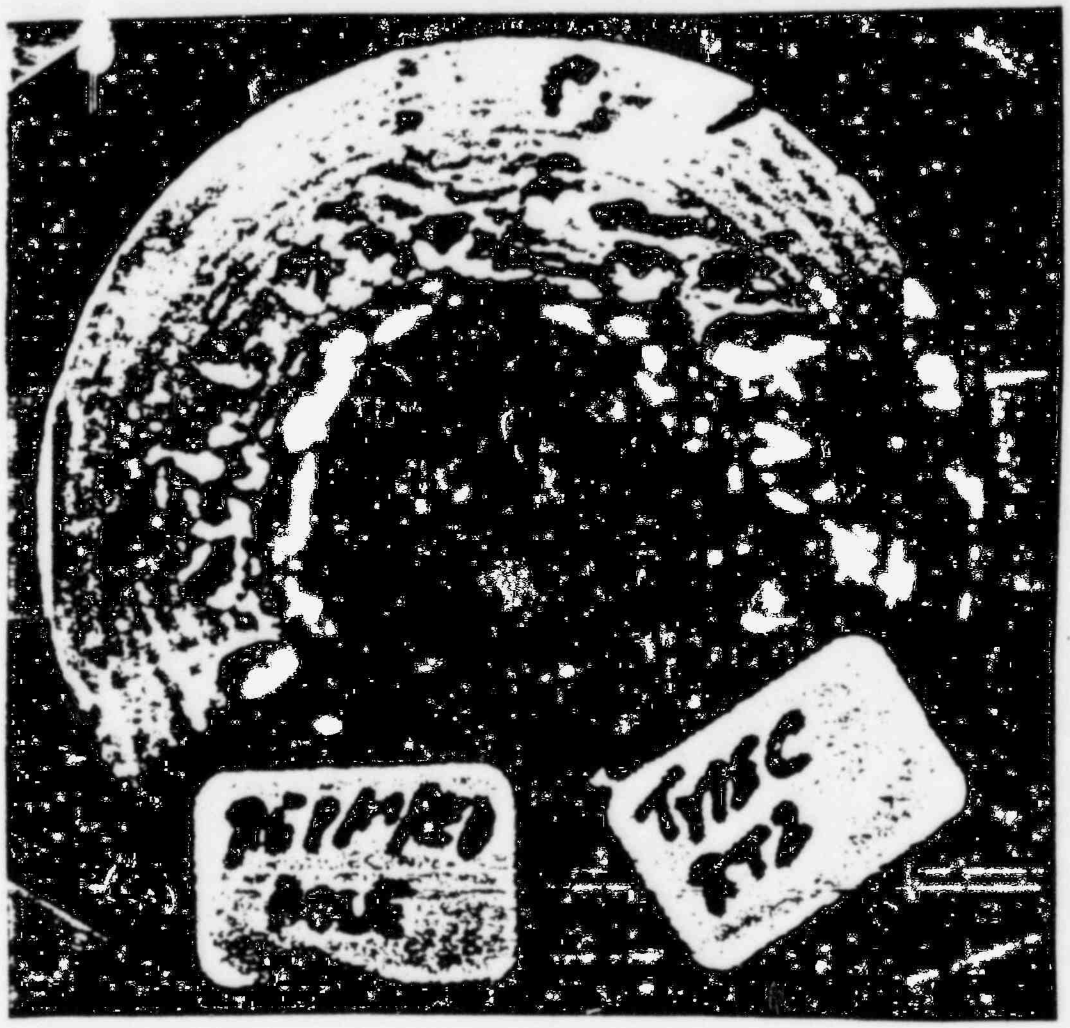
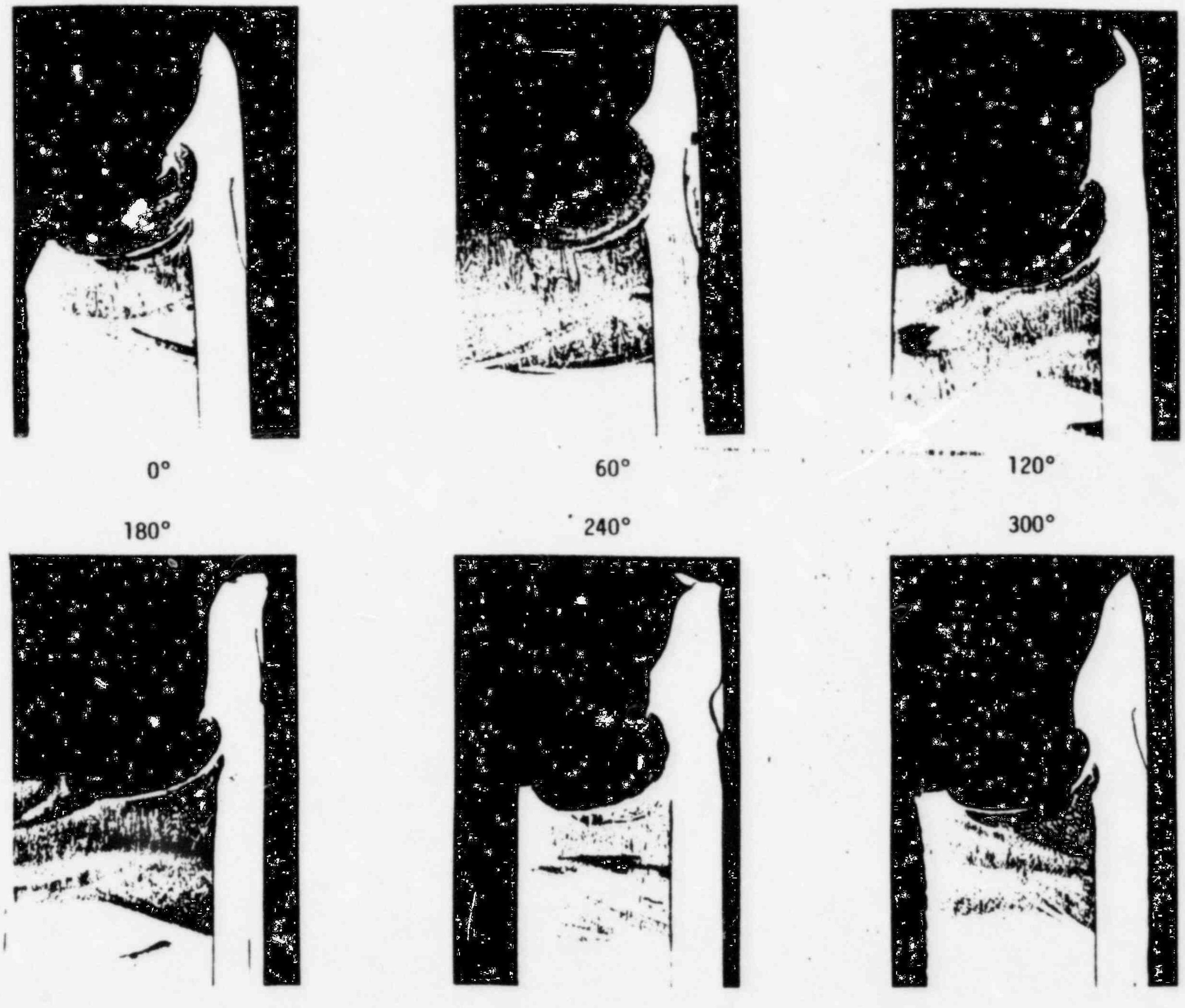


FIGURE 22

INTENTIONALLY DEFORMED AND REPAIRED
TUBE END IN TEST COLLAR
(Same Tube End and Test Collar as
in Figure 21)



0°

60°

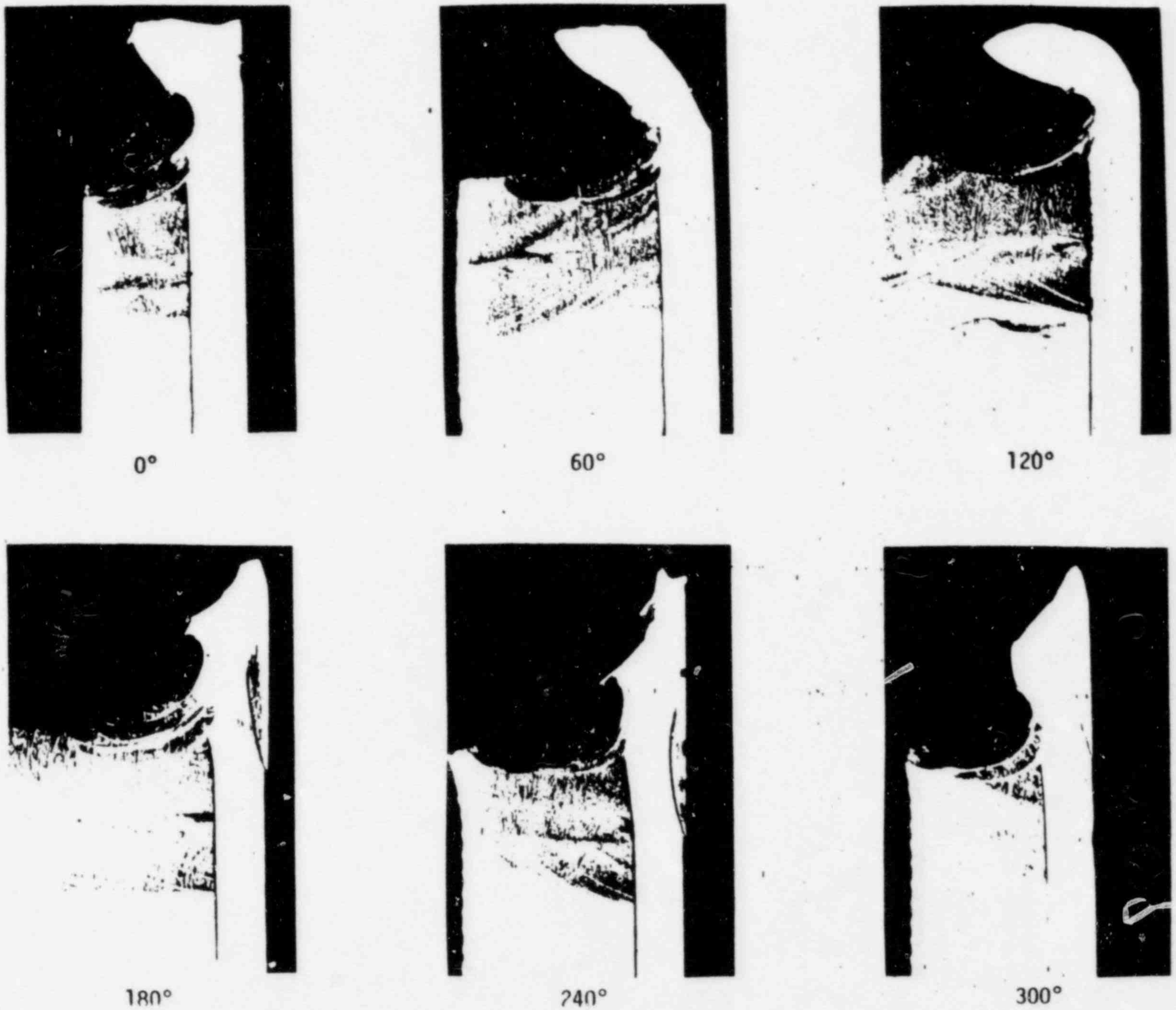
120°

180°

240°

300°

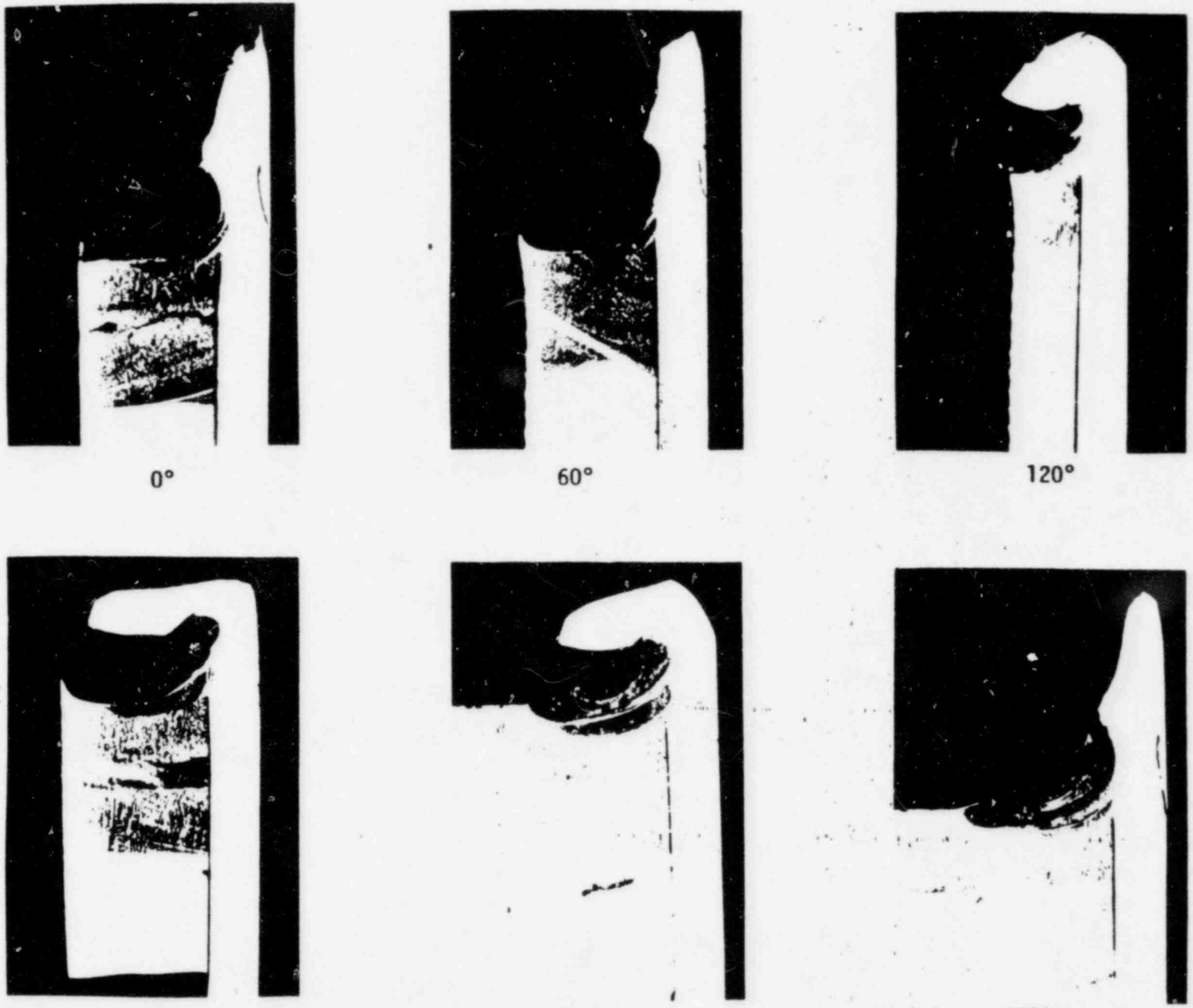
FIGURE 23 MACROGRAPHS OF SECTIONS THROUGH THE INTENTIONALLY DEFORMED AND REPAIRED TUBE AND TUBESHEET MOCK-UP, R3, C4, - 7X MAGNIFICATION



0° 60° 120°

180° 240° 300°

FIGURE 24 MACROGRAPHS OF SECTIONS THROUGH INTENTIONALLY DEFORMED AND REPAIRED TUBE AND TUBESHEET MOCK-UP, R1, C4, - 7X MAGNIFICATION



0°

60°

120°

180°

240°

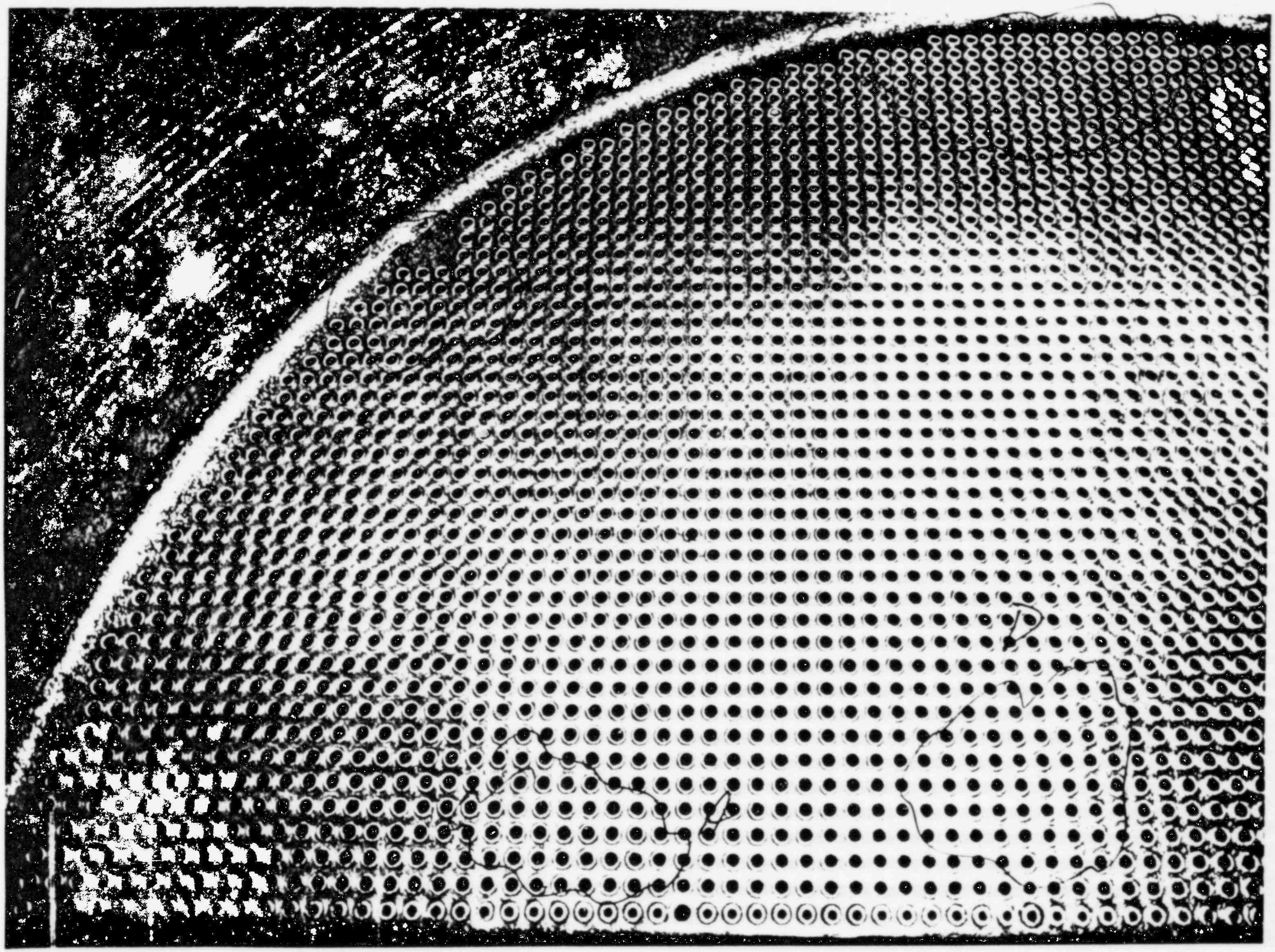
300°

FIGURE 25 MACROGRAPHS OF SECTIONS THROUGH INTENTIONALLY DEFORMED AND REPAIRED TUBE AND TUBESHEET MOCK-UP, R2, C4, - 7X MAGNIFICATION

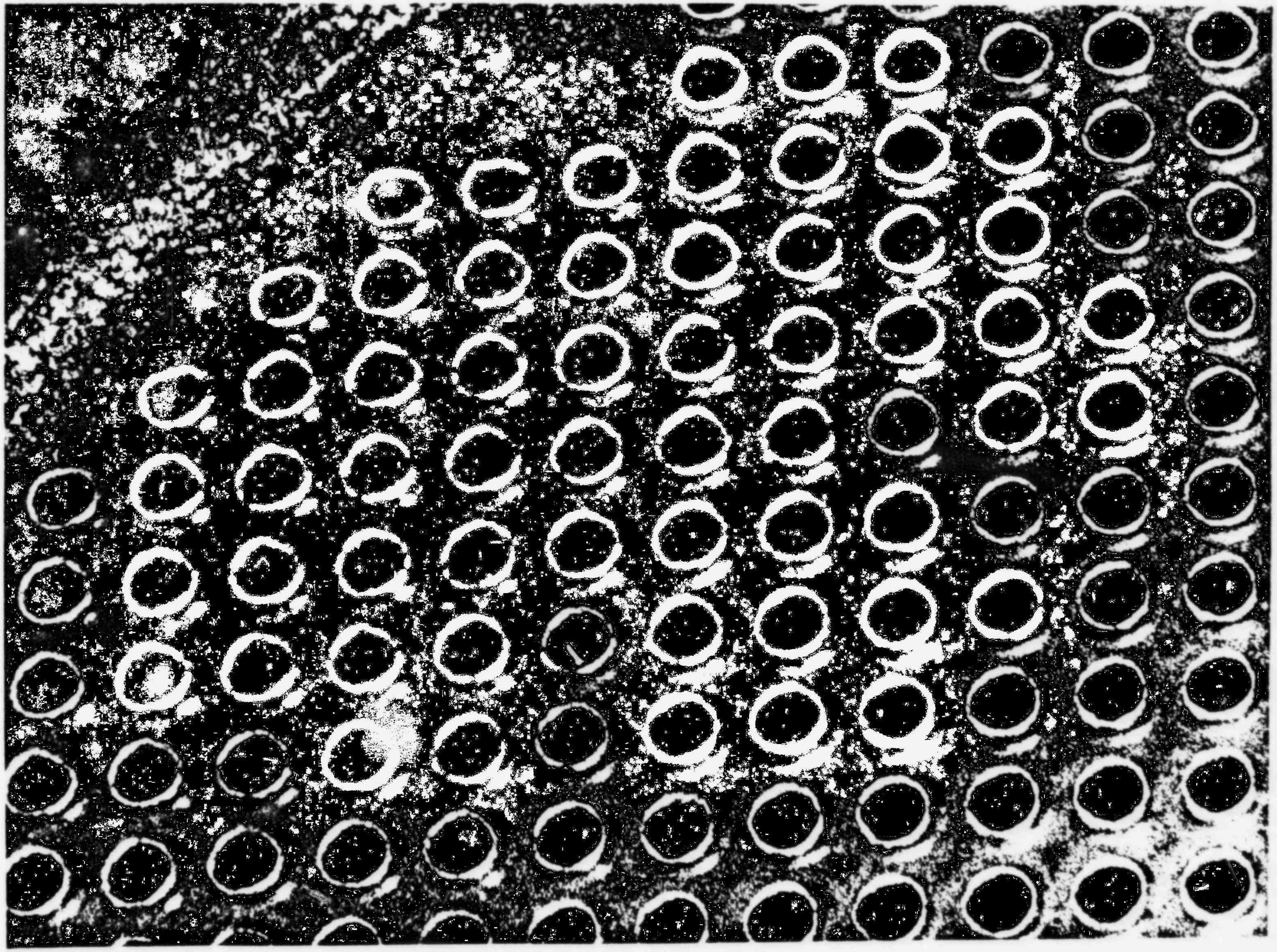
ATTACHMENT II

PHOTOGRAPHS OF STEAM GENERATOR TUBE SHEETS
BEFORE REPAIRS
NORTH ANNA UNIT 1

PHOTO NUMBER	DESCRIPTION
1	General view of tube sheet (inlet side) of steam generator "A"
2	Enlargement of area "B" as indicated in photograph #1
3	General view of tube sheet (inlet side) of steam generator "C"
4	Enlargement of area "A" as indicated in photograph #3



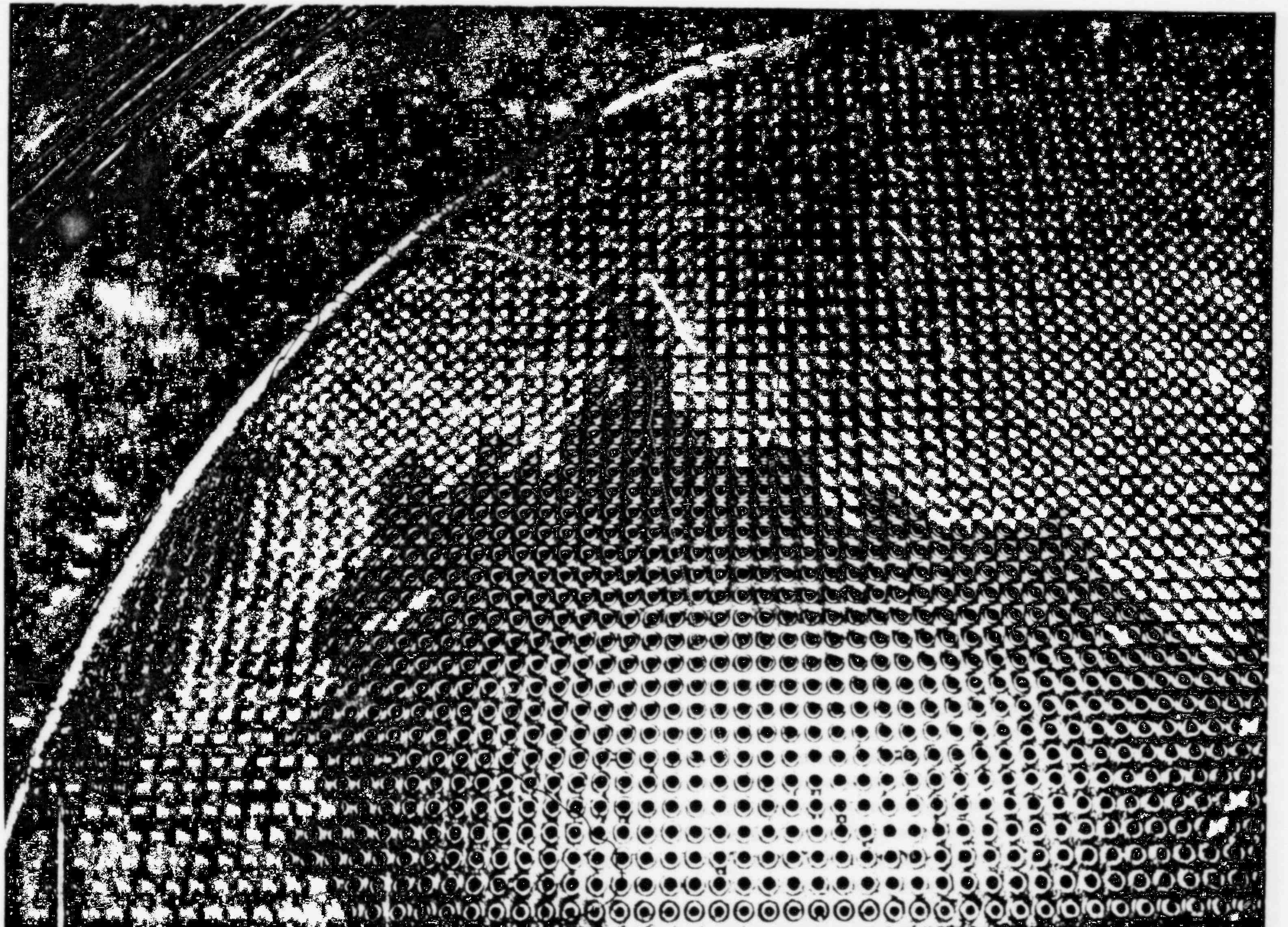
NAPS U1 S.G. A INLET BEFORE EDDY CURRENT 06-05-82 PHOTOGRAPH #1 820623 PHOTO BY THOMAS F. KELSEY



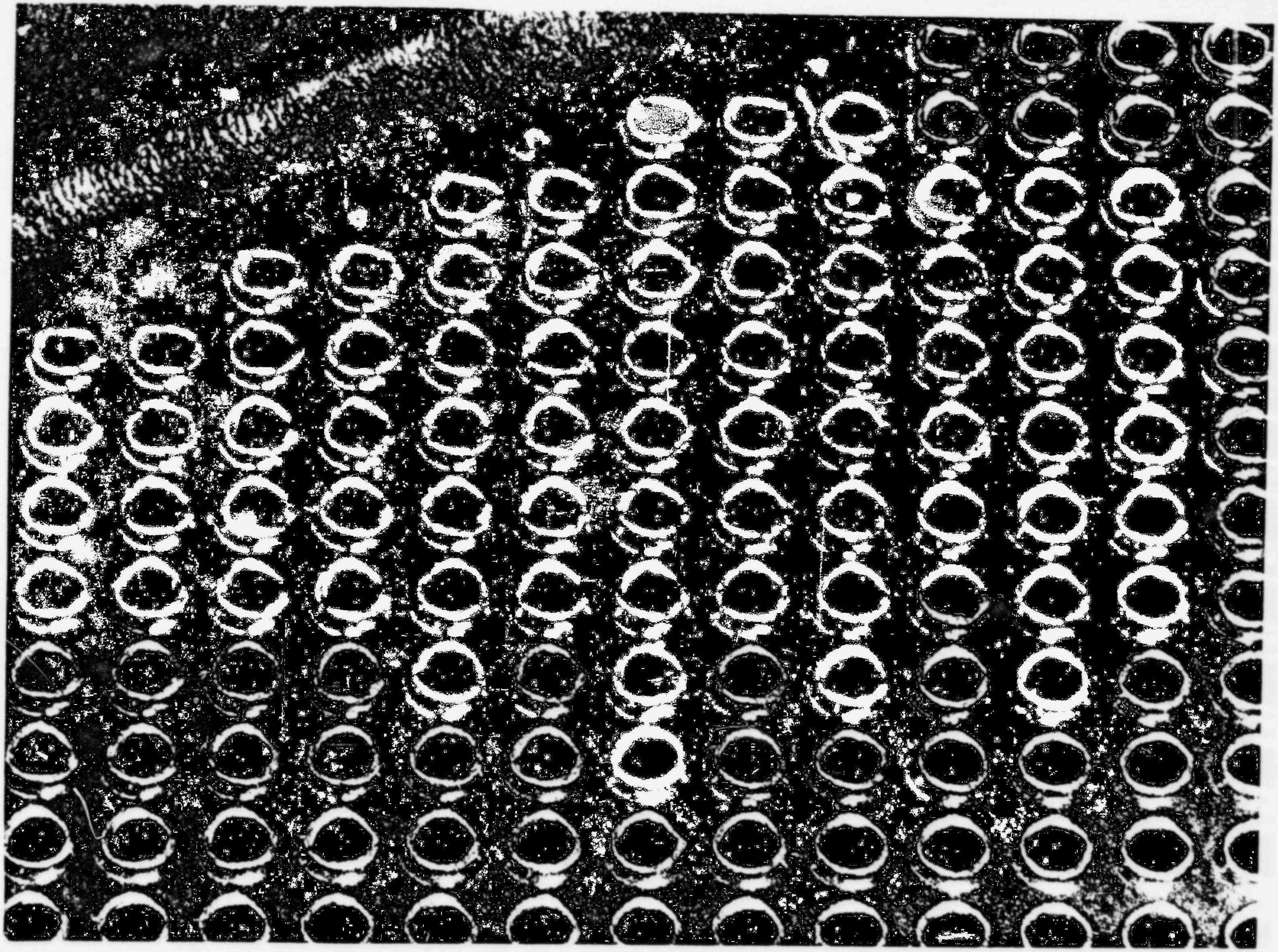
PHOTOGRAPH #2

820623-B

PHOTO BY
THOMAS F. KELSEY



NAPS U1 S.G. C INLET BEFORE EDDY CURRENT 06-03-82 PHOTOGRAPH #3 820617 THOMAS F. KELSEY



PHOTOGRAPH #4

820617-A

PHOTO BY
THOMAS F. KELSEY

ATTACHMENT III

SUMMARY OF STEAM GENERATOR TUBE END DAMAGE REPAIRS

As noted in Attachment II, Westinghouse has performed an analysis of the operation of North Anna Unit 1 with damaged steam generator tube ends and concluded that the flow restriction resulting from the tube end damage does not present a safety problem. They did recommend that the tube ends should be cleaned to remove the potential for loose pieces from the tube ends being released into the reactor coolant system. In addition, Westinghouse suggested one technique which could be used to repair tube end damage in order to increase the flow margin available and facilitate future eddy current testing and profilometry.

After an evaluation of the tube end damage in "A" and "C" steam generators at North Anna Unit 1, Vepco made the decision to repair seventy six (76) percent of the damaged tubes in each steam generator. Seventy six (76) percent represents the area that can be reached by remotely operated equipment.

The selected repair process utilizes a remotely controlled automatic two motion (R-θ) manipulator installed in the steam generator head which positions an air driven tool motor. The actual process utilizes the following steps:

1. Open the tube ID to a minimum of 730 mils using a free floating inside reamer designed to ensure that the tube minimum wall thickness will not be jeopardized.

2. Mill the tube end using an end milling tool which has a hard stop to ensure the fillet weld is not violated.

3. Clean the tube end of loose material using a rotating wire brush.

This process was presented in detail to the Westinghouse technical representatives.

We have completed the repairs in "C" steam generator and are near completion in "A". During the course of repairs in "C" steam generator, two tube ends were milled to less than .0625 inches from the tube sheet, thereby, causing removal of some of the fillet weld material. This error was caused by improper seating of the end milling tool in the tool holder. We have verified that a minimum of .017 inches of weld material remains above the tube sheet, ensuring that a sufficient corrosion boundary still exists. We also plan to perform a dye penetrant check on the welds on these two tube ends to verify the integrity of the weld material.

During the repair process in "A" steam generator, it was observed that many of the tubes near the center of the tube sheet were only slightly damaged. From this observation the decision was made to only do reaming and milling in the more severly damaged areas but to wire brush the entire seventy six (76) percent to remove potential loose parts.

In addition to the automated repairs, a manual wire brushing technique was employed on thirteen (13) tubes which could not be reached with remote equipment. These thirteen (13) tubes were selected as tubes with comparatively high tube end damage from the twenty four (24) percent of the steam generator tubes which could not be reached by remote equipment. An extensive wire brushing effort on these tubes was video taped and examined. This effort did not remove any material from these tube ends. Therefore, based on this observation and the high exposure which would be required for this manual effort, it was decided that the manual wire brushing of the remaining twenty four (24) percent of the tubes would not be necessary.

ATTACHMENT IV

**Westinghouse
Electric Corporation**

**Water Reactor
Divisions**

Nuclear Service Division

Box 2728
Pittsburgh Pennsylvania 15230

October 5, 1982

VRA-82-551

Mr. F. M. Alligood, Jr., Manager
Nuclear Technical Services
Virginia Electric and Power Company
P.O. Box 26666
Richmond, Virginia 23261

ATTENTION: Mr. M. L. Smith

VIRGINIA ELECTRIC AND POWER COMPANY
NORTH ANNA POWER STATION
RCP Diffuser Adapter Bolt Failure-North Anna Unit #1

Dear Mr. Alligood:

Enclosed for your information is a Westinghouse evaluation on the subject problem. Attachment 1 contains a brief background of the problem, a discussion of the failure mechanism and an evaluation of the new bolt material. Attachment 2 contains a safety evaluation assuming all the diffuser adapter bolts failed.

Very truly yours,

Joseph D. Cohen, Manager
Operating Plants
East Region

RRK/yt

ATTACHMENTS:

cc: M. L. Smith
W. L. Stewart
W. R. Cartwright

ATTACHMENT 1

I. BACKGROUND

During the 1982 North Anna Unit 1 refueling outage the disassembly of the "A" RCP (Model 93A) revealed seven (7) of the twelve (12) diffuser adapter bolts had failed and became trapped between the diffuser ring and the pump casing. Visual inspections and photographs were taken of the affected portions of the pump. Two the of the failed bolts and two of the intact bolts were sent to Westinghouse for analysis.

During the remainder of the outage VEPCO replaced all of the botls on the Unit 1 "A" pump with new bolts made of: SA-453 Grade 660 stainless steel. In addition, VEPCO also elected to replace all of the bolts on the "B" and "C" pumps with new material bolts. This was done even though visual inspection of these bolts showed no failures.

II. FAILURE MECHANISM

Based on an on-site inspection and the analysis to date of the "A" pump bolts sent to W, the following information has been revealed.

1. The failure did not originate from mechanical loading imposed on the adapter due to misalignment or vibration of the adapter against the casing fit. This determination was based on a detailed physical and photographic examination of the diffuser adapter.
2. The failure appeared to be due to stress corrosion cracking as evidenced by fractographic analysis on one failed bolt.
3. Chlorides were present as evidenced by a spectrographic analysis (the quantity and source is presently unknown).
4. The bolt material is 303 stainless steel, resulphurized with .32% sulfur. Sulfur stringers are evident in the material along the axis of the shank.
5. The sulfur stringers are turned in a direction nearly parallel to the head of the bolt in the area of the head/shank junction. (see Figure 1). The bolts were apparently hot-headed.
6. The cracking appears to follow the stringers orientation for short distances, jumping from one stringer to another as it moves across the head/shank interface. This "jumping" occurs for only a short distance into the bolt shank as the stringer angle steepens relative to the bolt axis.
7. The unfailed bolts from RCP "A" which were sent to W R&D are cracked under the heads.
8. Failed bolts were trapped between the diffuser ring and pump casing.

From this a probable mechanism of failure of these bolts can be proposed.

The cracking was initiated due to the presence of chlorides (source unknown), as opposed to applied mechanical oscillating loads. The bolt preload of 75 ft.-lbs. (which brings the axial stress up near the yield point at 550°F) as well as the orientation of the sulfur stringers at the head/shank junction increased the susceptiability to crack initiation under the head due to stress corrosion. As bolt cracking continued in the presence of predominant steady loading due to preload on the screws (or load applied to the adapter from the pressure field variation around the adapter once the preload is lost due to crack opening), the adapter/diffuser interface started to open. Mechanically induced loads due to rubbing of the cocked adapter against the casing fit combined with oscillating loads due to a slight shift off-center of the cocked adapter helped to continue the bolt cracking with a fatigue mechanical. Had the pump not been pulled, it is logical to anticipate that the remaining bolts would have cracked through at the same rate until the adapter broke free of the diffuser pilot fit.

III. NEW BOLT MATERIAL

Westinghouse has used the SA-453 Grade 660 stainless steel for more than 10 yrs. on RCP Turning Vane bolts, in both domestic and foreign plants. These turning vane bolts experienced higher stresses than the diffuser adapter bolts, in an otherwise similar RCS environment. To date, no inspection has revealed any abnormality attributable to either fatigue or stress corrosion. Based on this operational history, and the fact that the SA-453 Grade 660 has a higher yeild strength than the original bolt material W believes that the new material is an excellent choice for diffuser adapter bolts.

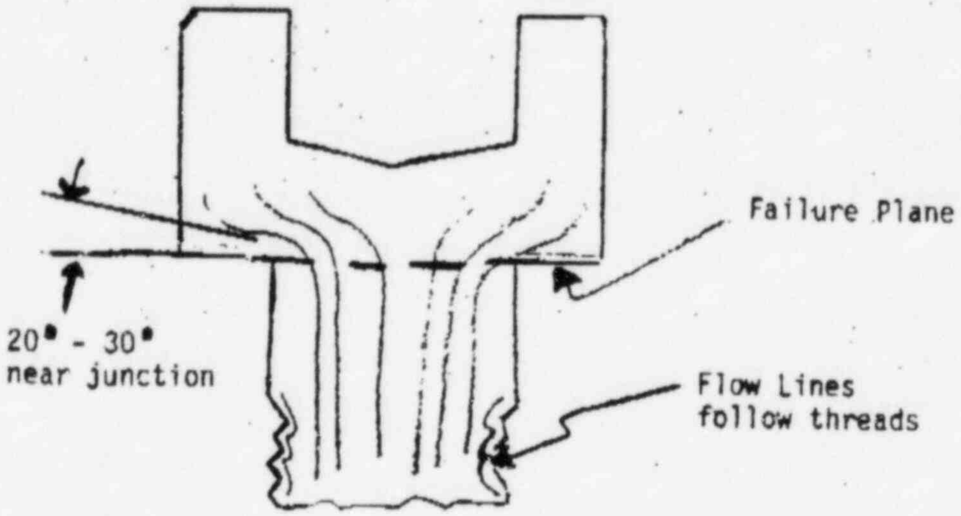


FIGURE 1

Composite of photographs and descriptions of sulpher stringers in failed socket head cap screws.

ATTACHMENT 2

SAFETY EVALUATION

Westinghouse also conducted an evaluation based on the assumption that all twelve (12) bolts failed. This evaluation revealed that:

1. Of the eight 93A RCP's (domestic) viewed after power operation (ranging from one year to ten years), none have ever exhibited distress in this joint or any failure of the bolting. RCP's of this design are also in use in Japan and have been examined after similar periods of service with no evidence of failure or distress.

2. No loose pieces would be generated as the bolt pieces would be trapped between the diffuser ring and pump casing.

3. If the adapter did drop the following would happen.

    a. Flow through the piping is expected to drop by about 0.2%. Should the adapter labyrinths now wear significantly to possible "rattling around" of the adapter in its .050 inch (on diameter) clearance, flow in the piping will drop still further. A significant amount of flow margin on the order of 5.0% is available above the thermal design flow for the core. Detection of reduced flow should be available to the plant operators.

    b. Coastdown of the RCP, as it pertains to the RCP safety function is unaffected.

    c. Friction on the impeller, although not affecting coastdown could potentially affect the usefulness of the impeller, turning vane/diffuser and adapter. This impact is purely economic.

Based on this information, reasonable assurance exists that safe operation of North Anna Unit 1 would not be affected by this type of failure.

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