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INTERIM REPORT

NRC Research and/or Technical Assistance Rept

Accession No.____________

Contract Program or Project Title: Evaluation of Material Problems & Failures

Subject of this Document: Investigation of Failed Tubes from "B" Steam Generator of the R. E. Ginna Nuclear Power Plant

Type of Document: Appendix in "Safety Evaluation Report" Docket No. 50-244 NUREG-0916

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Date of Document: 7/15/82

Responsible NRC Individual and NRC Office or Division: D. Smith

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for the
U.S. Department of Energy

Prepared for
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
Under Interagency Agreement DE-AC02-76CH00016
FIN A-3400

BNL-NUREG-31283
Ginna Restart SER
Appendix A
Limited Distribution

Investigation of Failed Tubes from "B" Steam Generator of the R. E. Ginna Nuclear Power Plant*

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May 1982

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*Research carried out under the auspices of the U. S. Nuclear Regulatory Commission

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Abstract

An investigation was performed on various steam generator tubes from the R. E. Ginna nuclear power plant (Rochester Gas and Electric). These tubes were involved in the loss of coolant accident of January, 1982. The examination of the tubes included optical metallography, scanning electron microscopy, energy dispersive spectroscopy and liquid dye penetrant examination. The report concludes that the loss of coolant accident was the result of a purely mechanical mechanism caused by an adjacent severed tube rubbing the outer surface of tube R42-C55 until its cross section was insufficient to withstand the primary to secondary side pressure differential. The initial severing of the adjacent tubes is considered to have been caused by the impacting of a carbon steel foreign object(s) on the outer periphery tubes in the "B" steam generator.

1.0 Background

On the morning of January 25, 1982 while the R. E. Ginna nuclear plant was operating at 100% power (normal operating conditions) a series of alarms indicated a steam generator tube rupture. Various procedures were instituted in order to achieve a cold shutdown condition. Cold shutdown was finally achieved early January 26, 1982.

Visual and video inspections by the utility (Rochester Gas and Electric - RGE) determined that the tube at Row 42 - Column 55 (R42-C55) had developed a "fishmouth" type crack which had resulted in the loss of primary coolant. Additional inspections by RGE personnel determined that various surrounding tubes had been severely degraded and a failure analysis program was instituted by the utility.

Several tubes and fragmented tube sections were pulled, and sent to Westinghouse Corporation for analysis. Additionally, two tubes; R45-C54 and R45-C47 were sent to Battelle Columbus Laboratory for evaluation.

On April 6, 1982 a meeting was convened with the utility, representatives of the United States Nuclear Regulatory Commission (USNRC), a representative from the Franklin Institute and two representatives from Brookhaven National Laboratory (BNL) to discuss preliminary findings of the ongoing failure analyses. The presentation of Westinghouse results suggested a purely mechanical type failure caused by an adjacent tube rubbing the outer surface of R42-C55 until the cross section of the tube (R42-C55) was worn to a thickness insufficient to withstand the pressure differential between the primary and secondary pressure boundary. This cross sectional reduction caused the tube to fail by a ductile overload mechanism and manifested itself as a "fishmouth" type fissure. This end result was postulated by the utility to have been caused by the synergistic progression of foreign objects (apparently carbon steel plates) impacting the outer periphery of previously plugged tubes severely enough to break the tube(s) at or near the tube sheet junction and that these tubes caused damage and wear to adjacent plugged tubes

through a whipping mechanism (caused by turbulent water flow) until tube R42-C55 was affected and finally burst.

Because of the potential safety ramifications of this incident, BNL was requested by the Materials Engineering Branch of the USNRC (W. S. Hazelton, Acting Chief) to conduct an independent failure analysis of affected tubes in order to confirm the RGE hypothesis of the incident's cause. This request was made under the Technical Assistance Program, "Evaluation of Material Problems and Failures," FIN A-3400.

Pursuant to this request, various tubes and tube sections were sent to BNL for evaluation.

2.0 Investigation

The tubes sent to BNL consisted of tubes previously examined by Westinghouse R44-C54, R43-C54, R44-C55, R43-C55, R43-C56 and the lower half of the "fishmouth" fissure of tube R42-C55. Additionally, RGE sent sections of R43-C59, R44-C56, R44-C57, R11-C91, R8-C92, and R10-C91 directly to BNL for examination.

All specimens received were examined visually. The following examinations were performed on selected tubes for the failure evaluation:

1) Visual Inspection/Optical Metallography/Photography
2) Scanning Electron Microscopy (SEM)
3) Energy Dispersive Spectroscopy (EDS) of severely degraded outside surfaces
4) Liquid Dye Penetrant Examination of inside surfaces of various tube sections

After determining the size and radioactivity level of the specimens received [Table 1] close up photographs were taken of all significantly sized pieces for cataloging.

2.1 Photography

Figure 1 depicts six tube sections received by BNL. The figure gives a good cross section of the types of damage encountered by the steam generator tubing in service. NOTE: the light colored dot, on the specimens, indicates that portion of the tube facing the shell of the steam generator.

2.1.1 Abraded Areas

The photographs (Figures 2-6) portray areas of the various tubes which have been worn away by a probable abrasion mechanism. These tubes are on the inner rows of the steam generator (Figure 7) and the longitudinal wear patterns (with circumferential striations) are consistent with two tubes rubbing together for an extended period of time.

2.1.2 Impacted Areas

One of the tube sections received (R44-C57), had an area of full collapse in the area of the tube sheet junction (Figure 8). This tube is in the outer periphery of the tube bundle (Figure 7) and the concave portion of the collapse faces the shell of the steam generator. The next two photographs (Figures 9-10) show an impact and wear mechanism which occurred on tubes away from the area of the leak (#4 wedge area) in the #6 wedge area.(Fig. 11) The severest damage occurred on the tube where its circumference faced the steam generator shell. The wear patterns were consistent with the rubbing of one tube by another tube of appoximately 7/8" outside diameter.

Figure 12 depicts the severe impact damage which occurred on tube R44-C54. Again, it is evident that the most severe deformation occurred on the side of this outer periphery tube facing the shell.

Figure 13 is a photograph of a severed section from tube R44-C55. This tube displayed severe impact type damage and wall thinning.

Tube R43-C59 (Figure 14) displayed a chisel-like cut and an impacted area (not shown on photo). The impacted area was approximately 1/2" diameter and hemispherical in shape. It was later determined that the cut was caused by a "miscut" of an electric discharge machining device, which was used to cut the tube section free from the steam generator, and did not occur in service.

The bottom half of the "fishmouth" fissure (R42-C55) is displayed in Figure 15. Longitudinal wear scars (with circumferential striations) are quite evident in the photograph. These wear patterns are consistent with similar areas found on other inner steam generator tubes. There were no areas of impact evident on this tube.

2.2 Liquid Dye Penetrant Examination

Dye penetrant examination was performed on the inside surface of seven sections of tube. The tubes examined and the results of the test are listed below:

Tube I.D.	Test Result
R11-C91	No relevant indications
R42-C55 (Fishmouth)	No relevant indications
R10-C91	No relevant indications
R08-C92	No relevant indications
R44-C56	No relevant indications
R43-C59	No relevant indications
R44-C57	No relevant indications

The tests were performed at room temperature and used the following Spotcheck Brand components: Cleaner/Remover SKC-NF, Developer SKD-NF and Penetrant SKL-HF/SKL-S; all Formula B.

2.3 Scanning Electron Microscopy Examination

The "fishmouth" fissure on tube R42-C55 was sectioned (Figure 16) for both SEM and optical examinations. Figures 17-24 are typical SEM photographs of the face of the "knife edge" fissure starting near the center of the "fishmouth" and moving along its length to the crotch of the crack. It is clearly seen in Figures 17 and 18, that the mode of failure was a ductile overload mechanism. The normally circular dimples (if a uniaxial tensile test were performed) are somewhat elongated, which is evidence of a pipe bulge prior to break. The elongated dimpled structure of the fracture disappeared the farther away the "fishmouth" was scanned from the center of the fissure, as seen in Figures 19-22. An impacted area was noted in specimen #3 (Figure 21), which appeared to have occurred after the tube failed. This occurrance would be consistent with the postulation that loose objects were present in the steam generator at the time of failure. Figures 23 and 24 are SEM photographs of the transition zone (end of crack) in specimen #4. It is evident by the photographs, that the end of the crack also displayed ductile overload features with no evidence of fatigue contribution.

A section of tube R44-C56 was also examined by SEM. This tube had been collapsed and broken at the tube sheet and had also been severed by the tube support plate. The section viewed was the cross section of the tube, where it was severed just below the tube support plate. The majority of the fracture face was featureless and had a tamped appearance. One interesting feature was noted on the specimen, however, shown in Figures 25-27. Chevron marks were evident (Figure 25) on the surface of the fracture, which led to a cyclically fatigued area on the specimen (Figures 26 and 27). This type of structure would be consistent with a tube breaking by the tube sheet and then "whipping" about in a turbulent flow, causing a fatigue type failure of the tube by the upper tube support plate.

An examination of the inside surface of tube R43-C59 showed one area, which initially appeared as an intergranular type crack in the tube (Figures 28 and 29). The crack-like indication found on this tube was later

determined to be associated with a prior pickling process (see EDS section).

Figure 30 is an SEM photograph of a typically abraded and impacted section of tube R11-C91. Although some wear lines are evident, the section has no predominant distinguishing features.

2.4 Energy Dispersive Spectroscopy (EDS)

Prior to EDS viewing of specimens, they were decontaminated using the following sequence of steps:

1. Ultrasonically clean in "Microclean" for 1 hour;

2. water wash;

3. ultrasonically clean in methanol for 15 minutes.

This sequence was accomplished twice prior to viewing the specimens.

This decontamination sequence had the effect of removing any loose particles from the specimens, and may have been responsible for displacing any evidence of impacting material on the majority of the scans.

Various EDS scans were performed on the outside surface of the impacted specimens of tubes, and on the inside surfaces of the impacted sections (adjacent to any breaks in the tube), in the hopes of obtaining information on the composition of the impacting object. Figures 31 and 32 are typical of the scans encountered on tube R8-C92 and are representative of the majority of scans taken.

Figure 33 is representative of the type of "etched" structure found on the inside surface of tube R8-C92. This structure was much more prevalent on this tube than the one area found on tube R43-C59. It was probably the result of pickling done on the tubes prior to their installation.

The last set of EDS scans (Figures 34, 35, and 36) display the constituents found on two smears on an impacted area on the outside surface of tube R43-C59. The scan (Figure 34a) is typical of that found on both of the smears and shows an extremely high peak of iron (Fe) relative to chromium and nickel. Since tube R43-C59 is an outer periphery tube, this finding appears to corroborate the hypothesis that the outer periphery tube damage occurred as a result of impact with a carbon steel foreign object.

2.5 Optical Microscopy

A cross sectional metallurgical mount was made of the number 1 area of the "fishmouth" fracture on tube R42-C55. It was etched with a 10% bromine + methanol etch for 20 seconds (Figure 37). There was no real evidence of cold work on this section, even though the wear patterns on the cross section are quite distinguishable. This type of wear would be consistent with a fretting corrosion mechanism, which would have reduced the tubes cross section by slow grinding over a long time period, coupled with oxidation of the freshly created surface.

Cold work was in evidence on cross sections of tubes R10-C91 and R8-C92 in small amounts and is depicted on Figures 38 and 39. The most significant areas of cold work were found on tube R44-C57 on a cross section of the collapsed area. Figures 40 and 41 give a good representation on the amount of repetitive cold work that this tube endured. Figure 42 is a full cross section of the tube displaying the amount of structural damage that the tube received prior to the plants shutdown. It is significant to note that cold work was primarily found on the outer (periphery) tubes, with the inner row tubes displaying a fretting corrosion microstructure.

Since a grain boundary "etching" was noticed during SEM examination, an optical mount was made of tube R8-C92. As can be seen on Figure 43, the extent of grain boundary etching is only a few grains deep (approximately .001") which is consistent with the suggestion that this attack was caused by

pickling prior to plant operations and deceptively appears significant only on severely degraded areas of the section.

3.0 Discussion and Conclusions

It is evident from this investigation, that all damage which occurred in the steam generator was caused by mechanical damage whether wear/abrasion or an impact mechanism resulting in ductile overload fatigue type failures or mechanical collapse. The fact that inner tubes displayed a fretting type wear with no significant areas of cold work, while outer periphery tubes displayed significant cold work, is consistent with the RGE hypothesis that damage occurred on the outer periphery tubes by impact with a foreign object(s). This theory is also substantiated by the discovery of iron smears on the outer surface of an outer periphery tube R43-C59.

The grain boundary "etching" was probably the result of an incomplete pickling operation and did not appear to have adversely affected the tubing or have contributed in any way to the "loss of primary coolant" incident.

It is, therefore, concluded that the final tube rupture (R42-C55) occurred as a result of the synergistic degradation of previously plugged steam generator tubes initially caused by impact and final severence of the outer periphery tubes by a foreign object(s).

4.0 Acknowledgement

The author acknowledges the help given him by the BNL Health Physics Group, specifically A. Lucas, R. Vogel and J. O'Connor. The invaluable help of R. Jones, K. Sutter, D. Becker, and L. Gerlach in decontamination and sectioning is gratefully appreciated. The author also wishes to thank R. Sabatini for the SEM/EDS work, P. Colsman for expediting the sample delivery, J. Langan and O. Betancourt for their typing skills, and Dr. J. R. Weeks for his continuing support and helpful discussions.

TABLE 1. Radiation Level of Individual Pieces

PC #	Date	(Contact) Reading	Approximate Size	Comments
R43C59	4/8/82	300 mR/hr.	10"	
R44C56	"	200 mR	10"	
R11C91	"	150 mR	10"	
R44C57	"	200 mR	10"	
R8C92	"	150 mR	10"	
R10C91	"	200 mR	10"	
R43C54	"	40 mR	1"	
R44C54	"	40 mR	1"	
R44C55 #3	"	40 mR	2"/1"	
R44C55 #5	"	20 mR	3/4"	
R44C54 #2A	"	10 mR	1/2"	
R43C55 #7	"	80 mR	2"	
R42C55 #5	"	80 mR	1/4"	
R42C55 #4	"	130 mR	1/2"	
R42C55 #7C	"	80 mR	1"	
R42C55 #7	"	50 mR	1/2"	
R43C56 #3	"	40 mR	1"	
R43C55 #1	"	70 mR	3"	
R43C55 #3	"	40 mR	3/4"	
R44C55 #1	"	20 mR	1/2"	
R43C55 #5	"	50 mR	1"	
R44C54 #6	"	60 mR	1 1/2"	
R4[illegible]C55 #1	"	40 mR	4" FM	
R42C55 #2	"	80 mR	1/2"	
R43C55 #2A	"	30 mR	1/2"	
R44C54 #4	"	30 mR	1"	
R43C54 #5	"	70 mR	2"	
R44C55	"	30 mR	4"	
R43C56 #1	"	90 mR	4"	
R43C54 #1	"	110 mR	4"	
R43C55 #2B	"	10 mR	1/4"	
R44C55 #2A	"	20 mR	2-1/4"	
R44C55 #2B	"	10 mR	1/4"	
R44C54 #2	"	30 mR	1 1/2"	
R43C56 #5	"	70 mR	2"	
R44C55 #7	"	30 mR	3/4"	

Reading 40 mR/hr @ 1' DISTANCE

Figure 1. Photograph of "as received" ~10" long sections of damaged tubes from Rochester Gas and Electric's (RG&E) GINNA Station

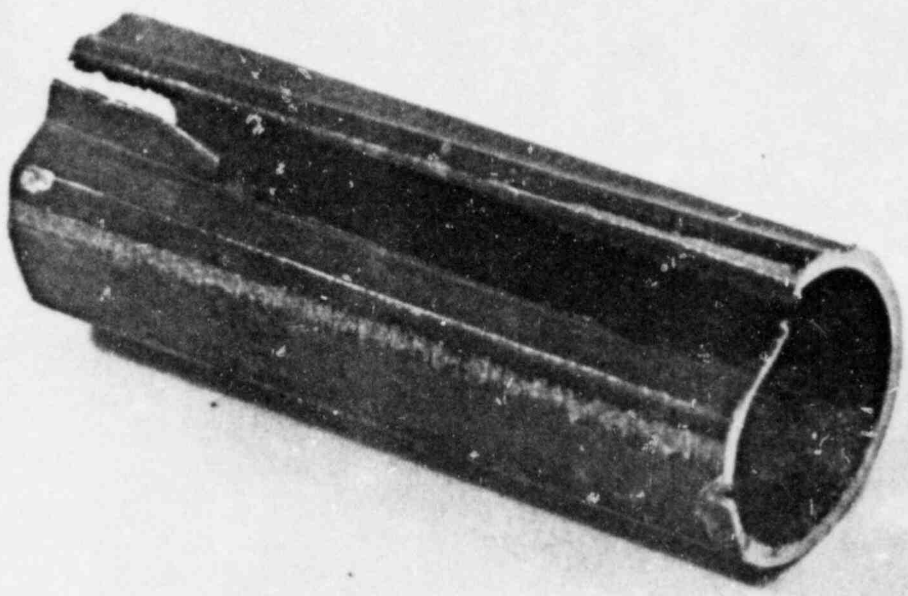

Figure 2. Photograph of specimen #7 from tube R43-C55 (GINNA) depicting through wall wear from a probable abrasion mechanism

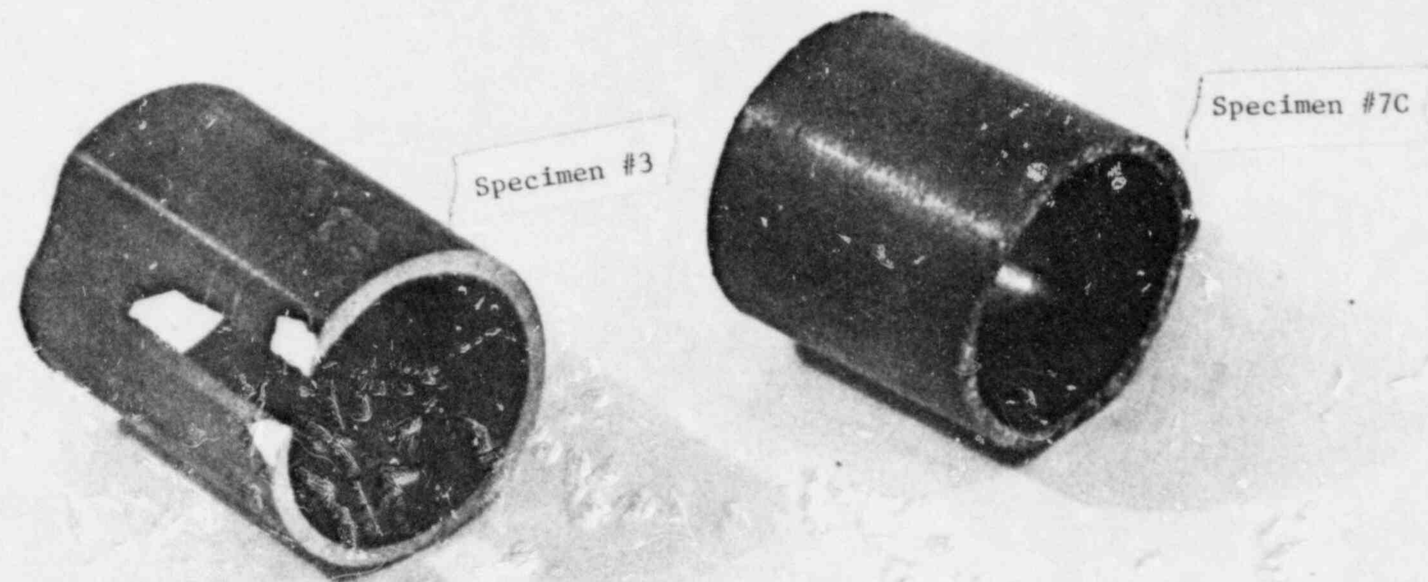

Figure 3. Photograph of specimen #3 from tube R43-C56 and #7C from tube R42-C55 (GINNA)

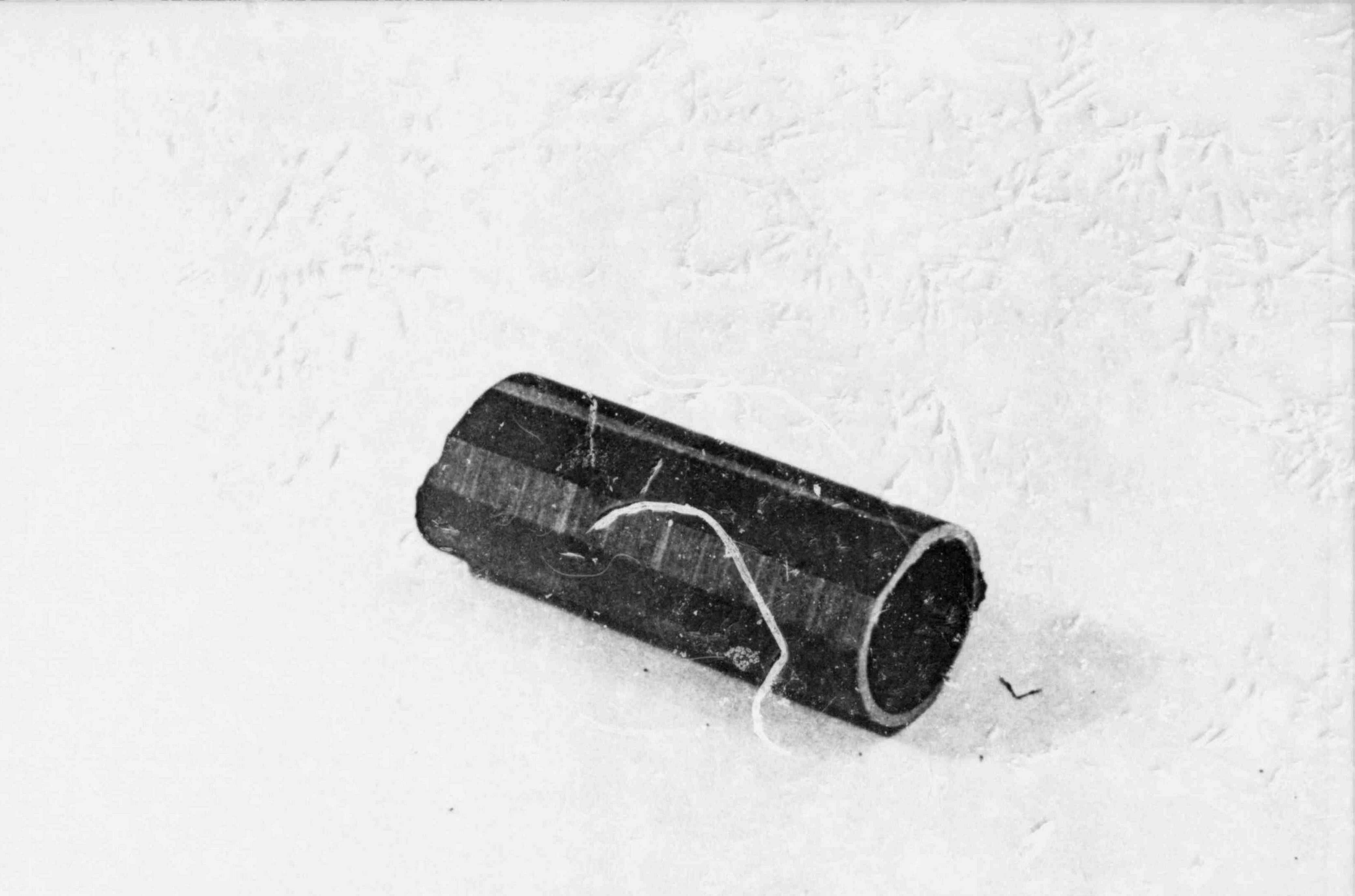

Figure 4 . Photograph depicting areas of apparent abrasion on specimen #6 of tube R44-C54 (GINNA)

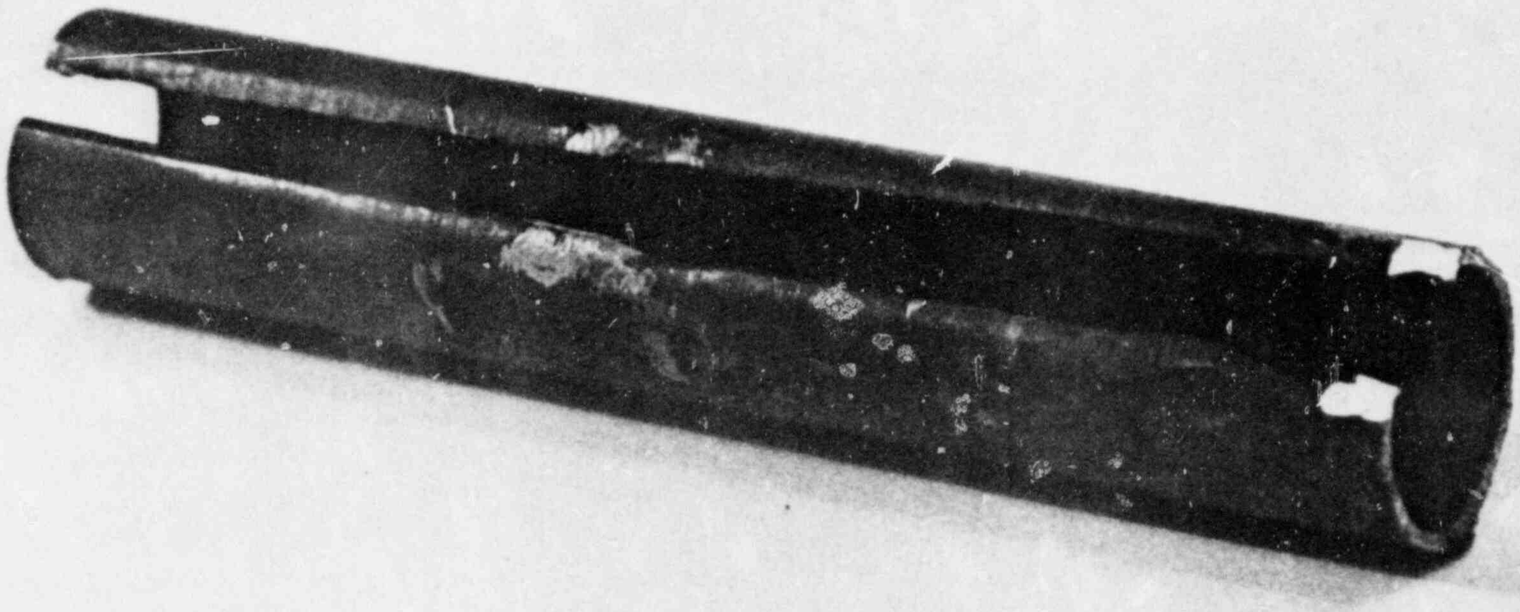

Figure 5. Photograph depicting severely abraded areas "through wall" on tube R43-C56 (GINNA)

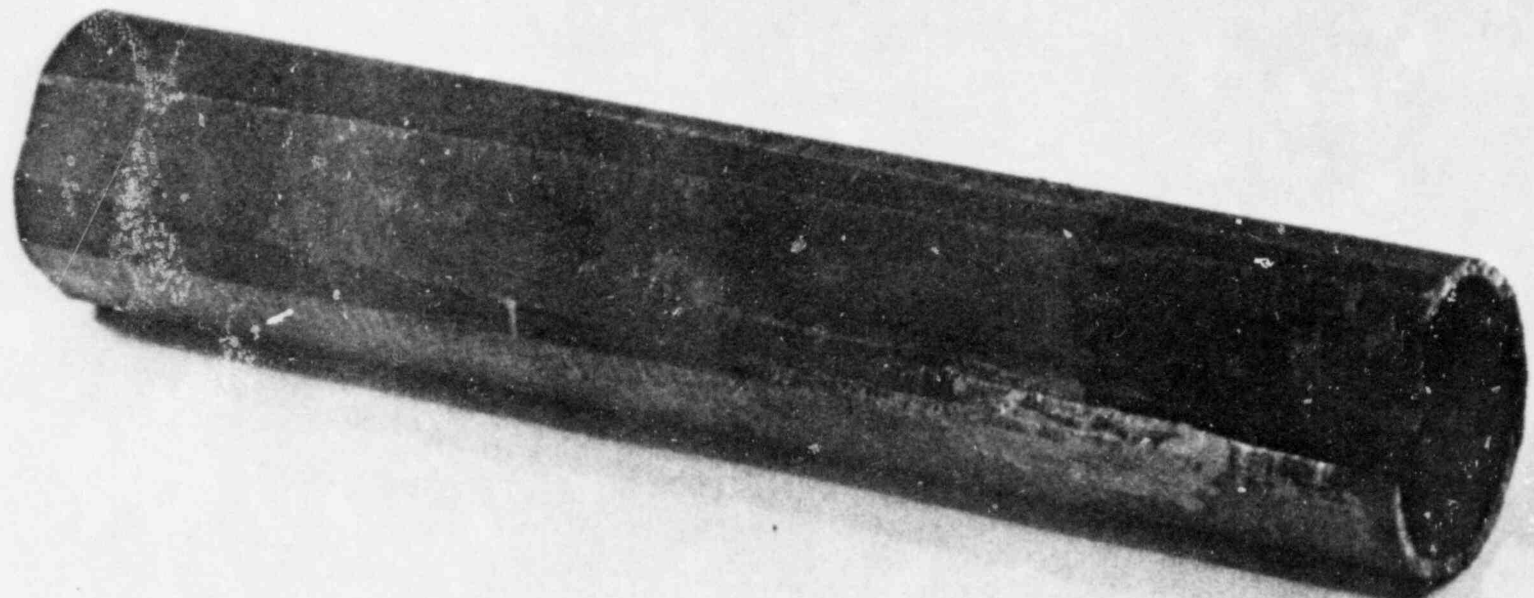

Figure 6. Photograph of severely abraded area and "through wall" thinning on specimen #1 of tube R43-C54 (GINNA)

Diagram courtesy of
Rochester Gas & Electric

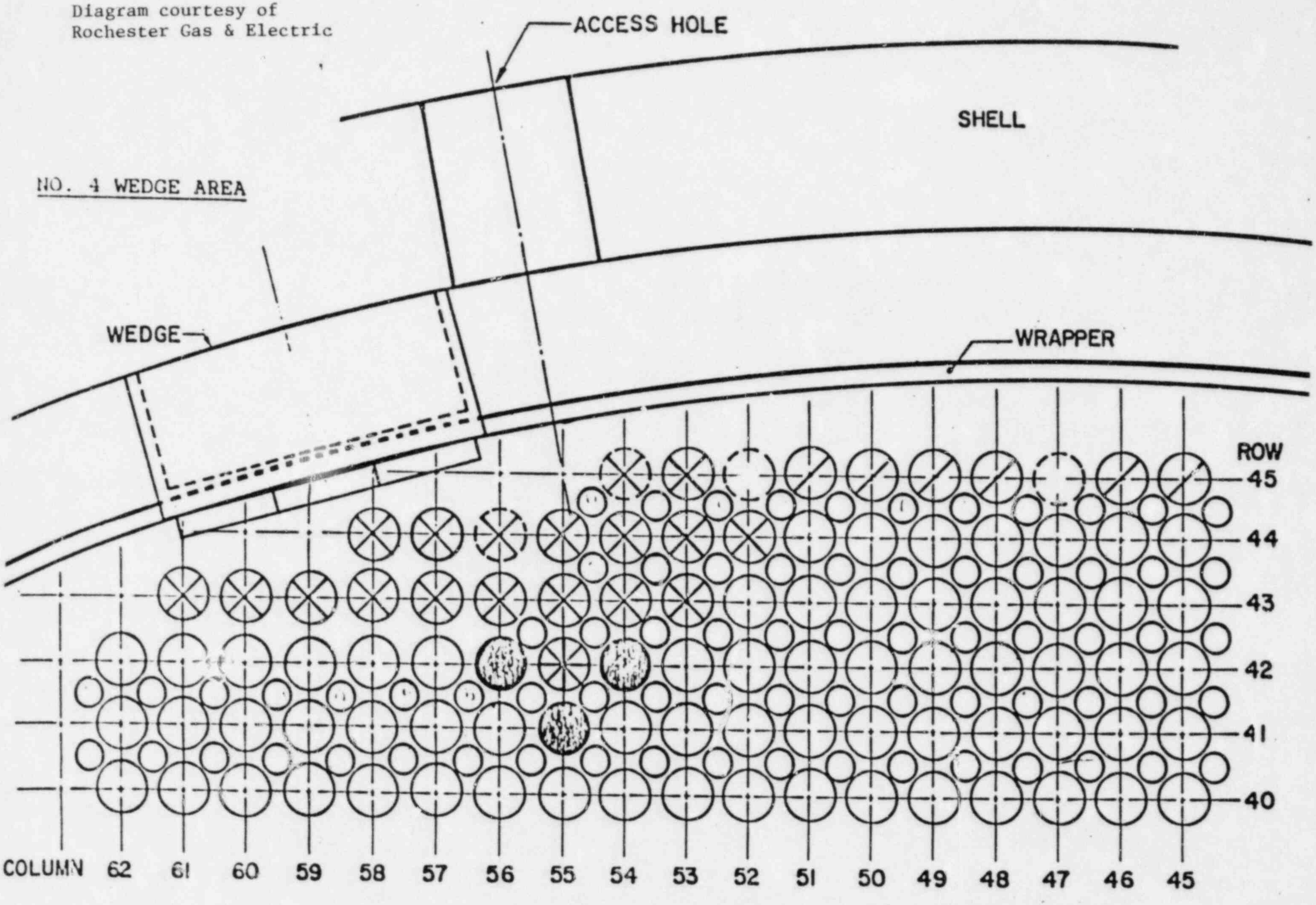

Figure 7. Diagram of Number 4 Wedge Area - Steam Generator "B" Hot Leg Side.

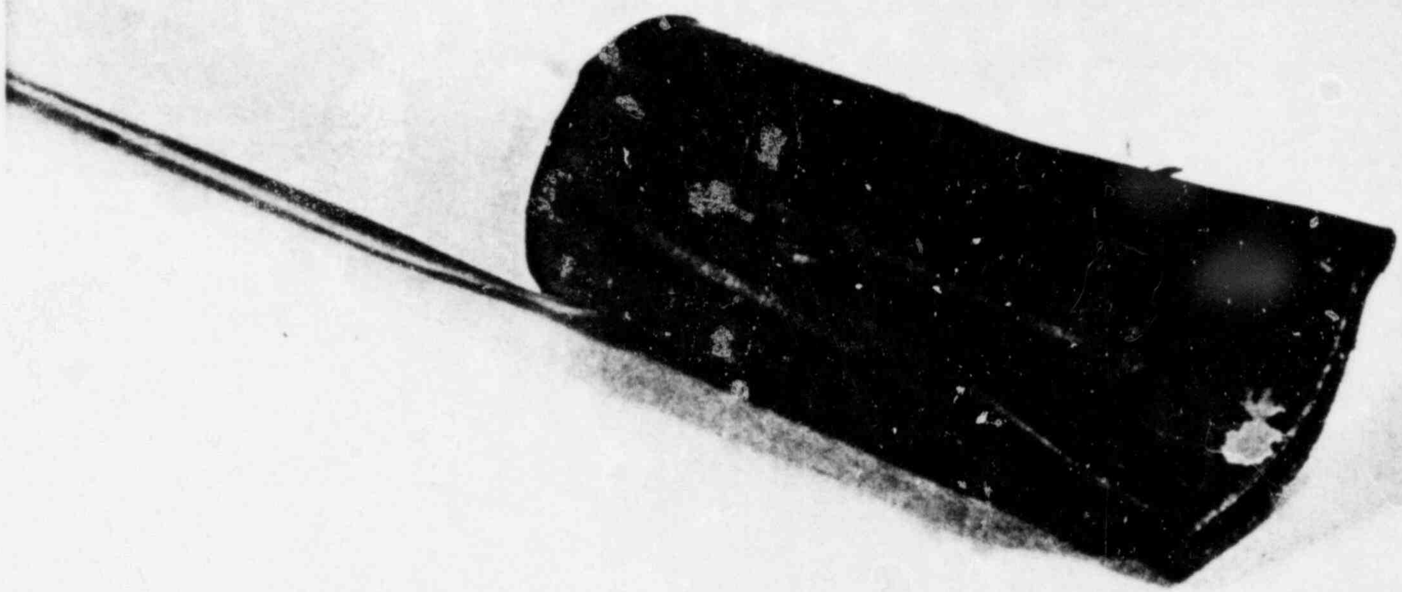

Figure 8. Photograph of collapsed area in tube R44-C57 (GINNA)

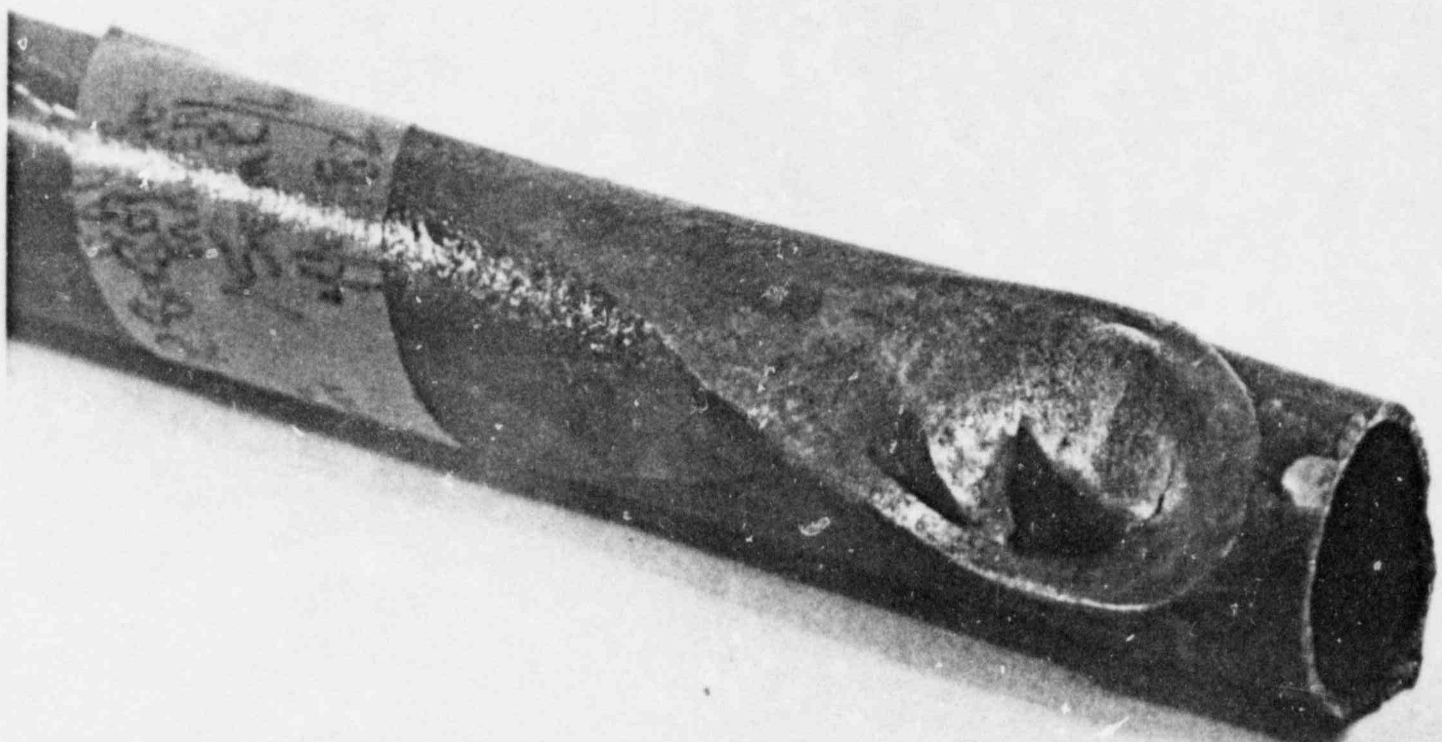

Figure 9. Photograph of apparently rubbed area in tube R8-C92 (GINNA)

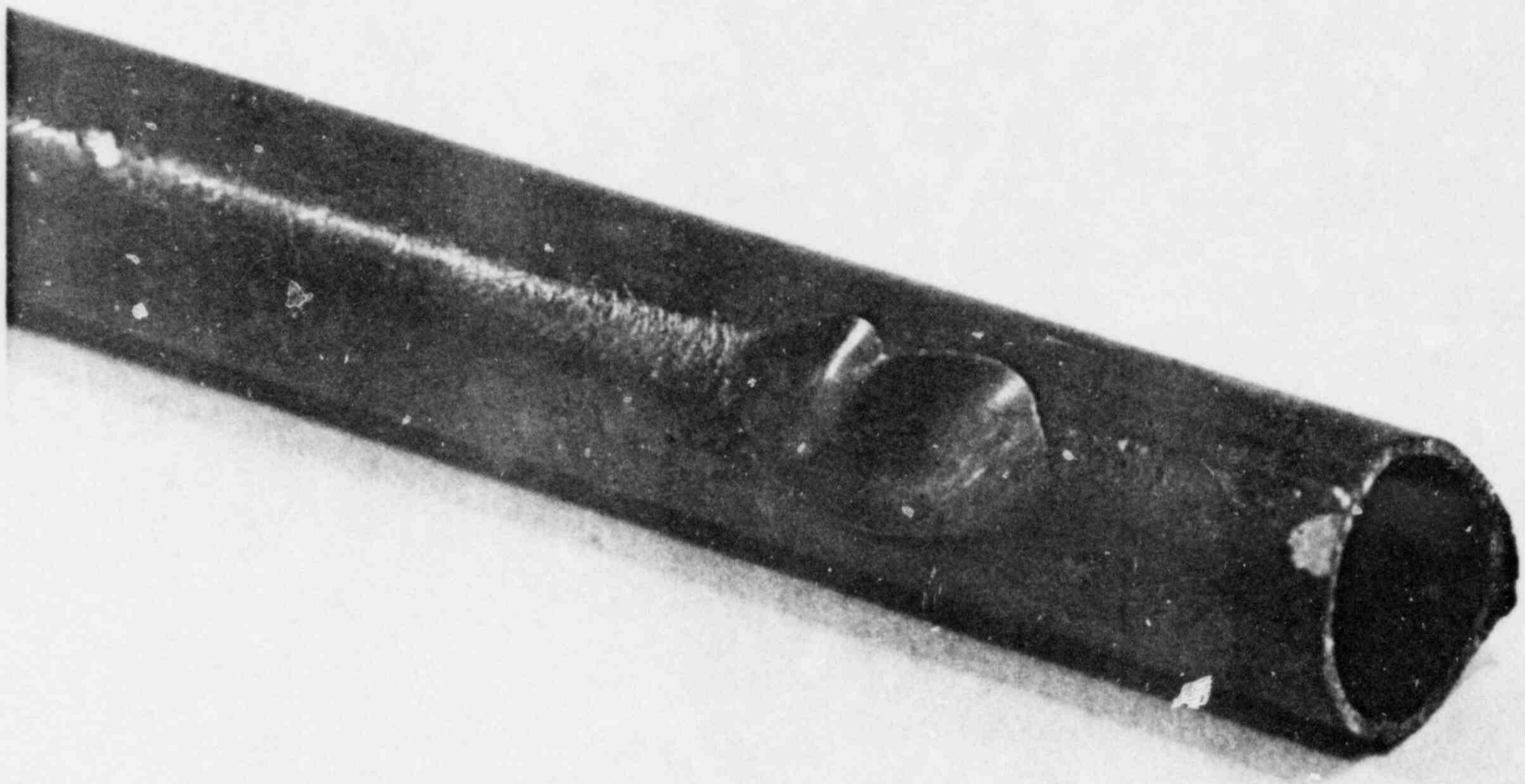

Figure 10. Photograph of abraded area in tube R10-C91 (GINNA)

Diagram courtesy of
Rochester Gas and Electric

GINNA STATION
STEAM GENERATOR
B-HOT LEG (INLET)

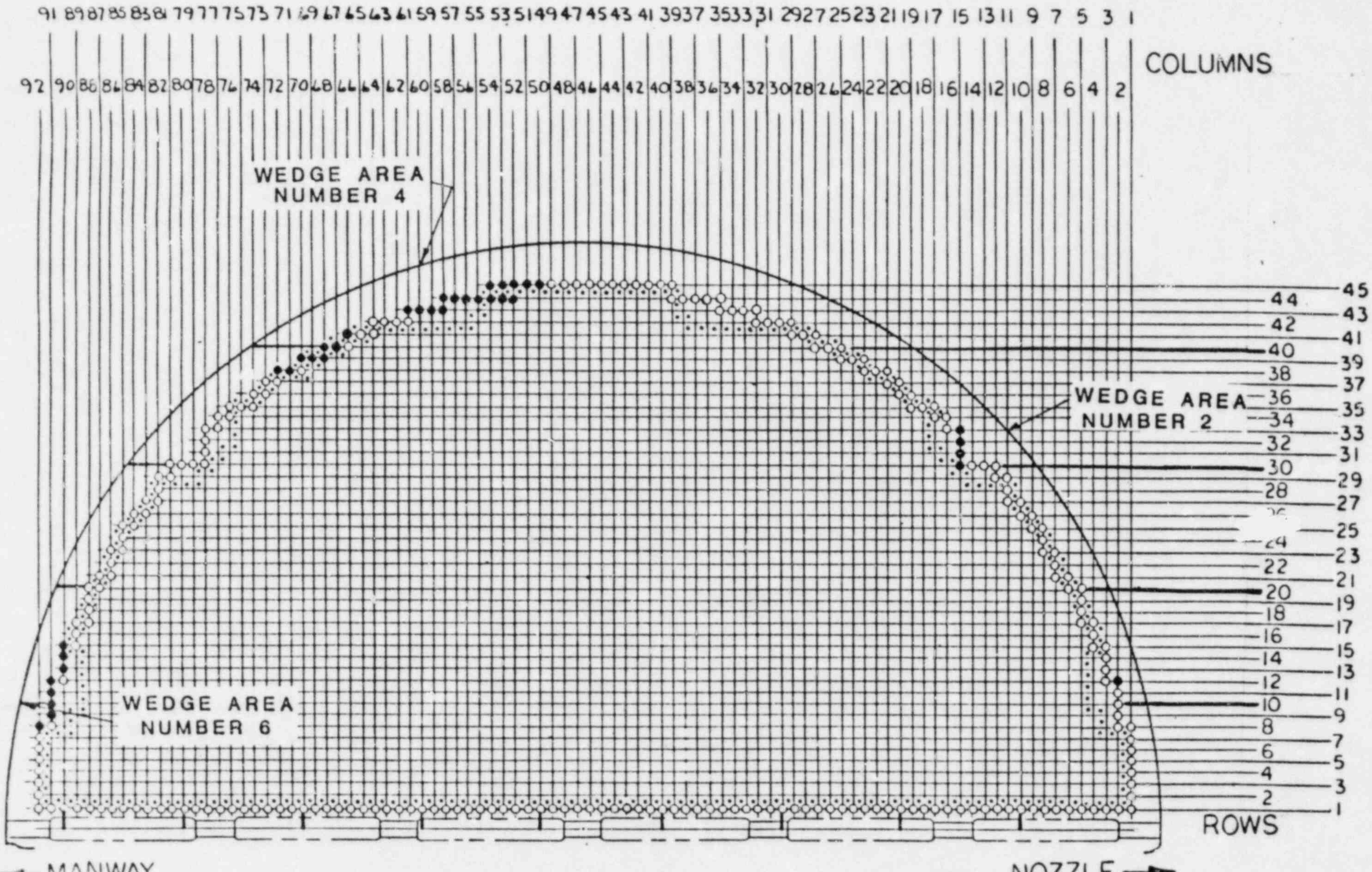

Figure 11. Layout of Hot Leg side of "B" Steam Generator depicting Wedge Areas

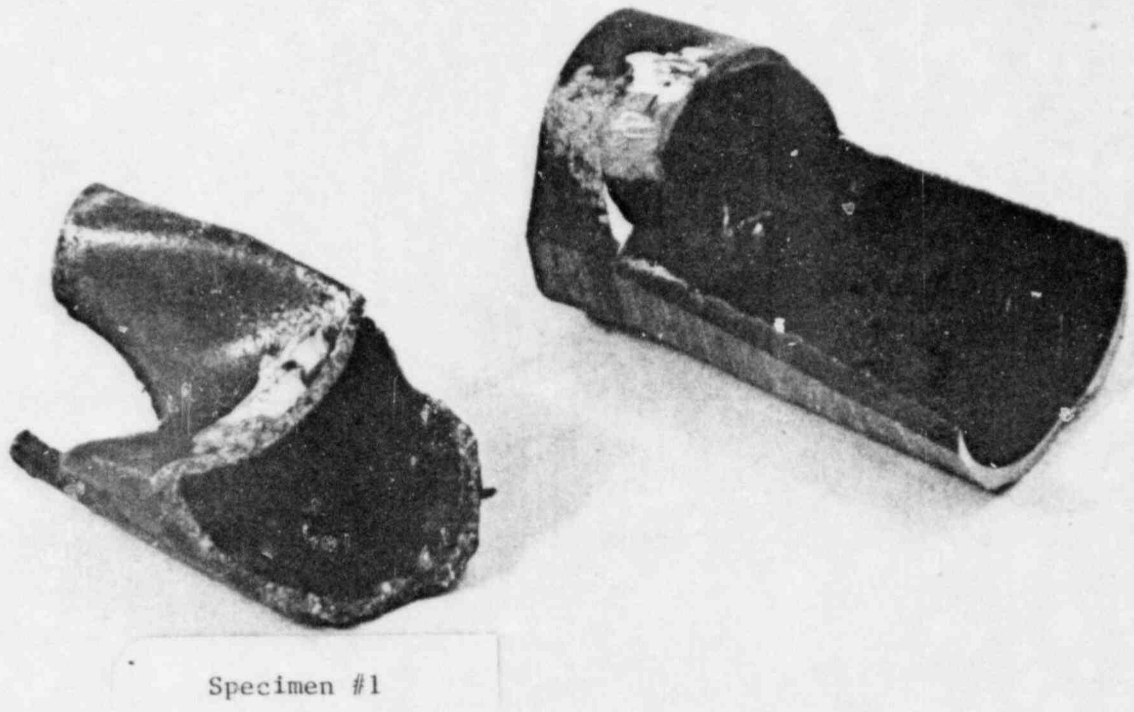

Figure 12. Photograph of two pieces of tube R44-C54 portraying considerable deformation

Figure 13. Photograph of severely deformed area in tube R44-C55 (GINNA)

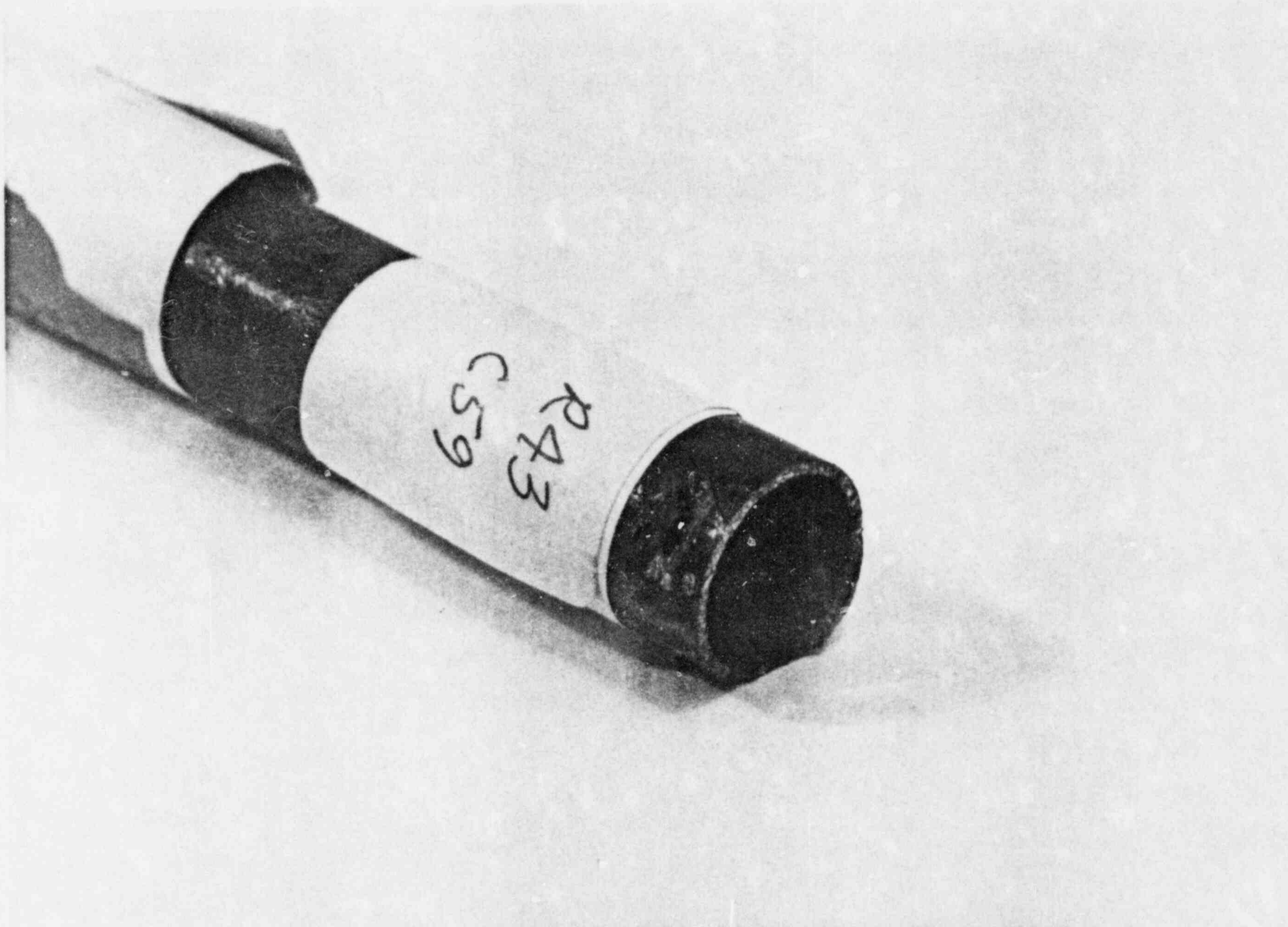

Figure 14. Photograph of probable "miscut" of Electric Discharge Machining (EDM) apparatus on tube R43-C59 (GINNA)

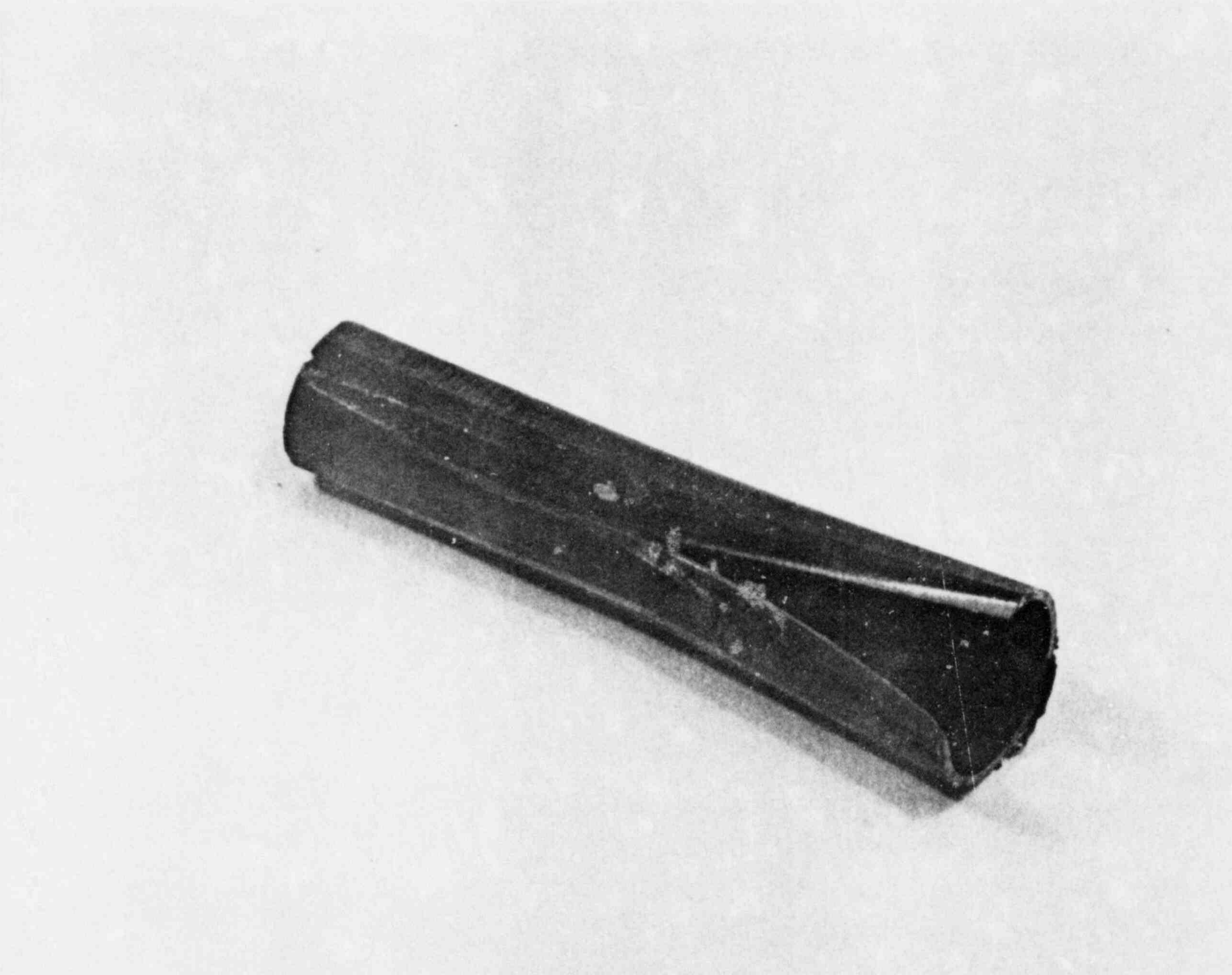

Figure 15. Photograph of "fish mouth" crack
in tube R42-C55 (GINNA)

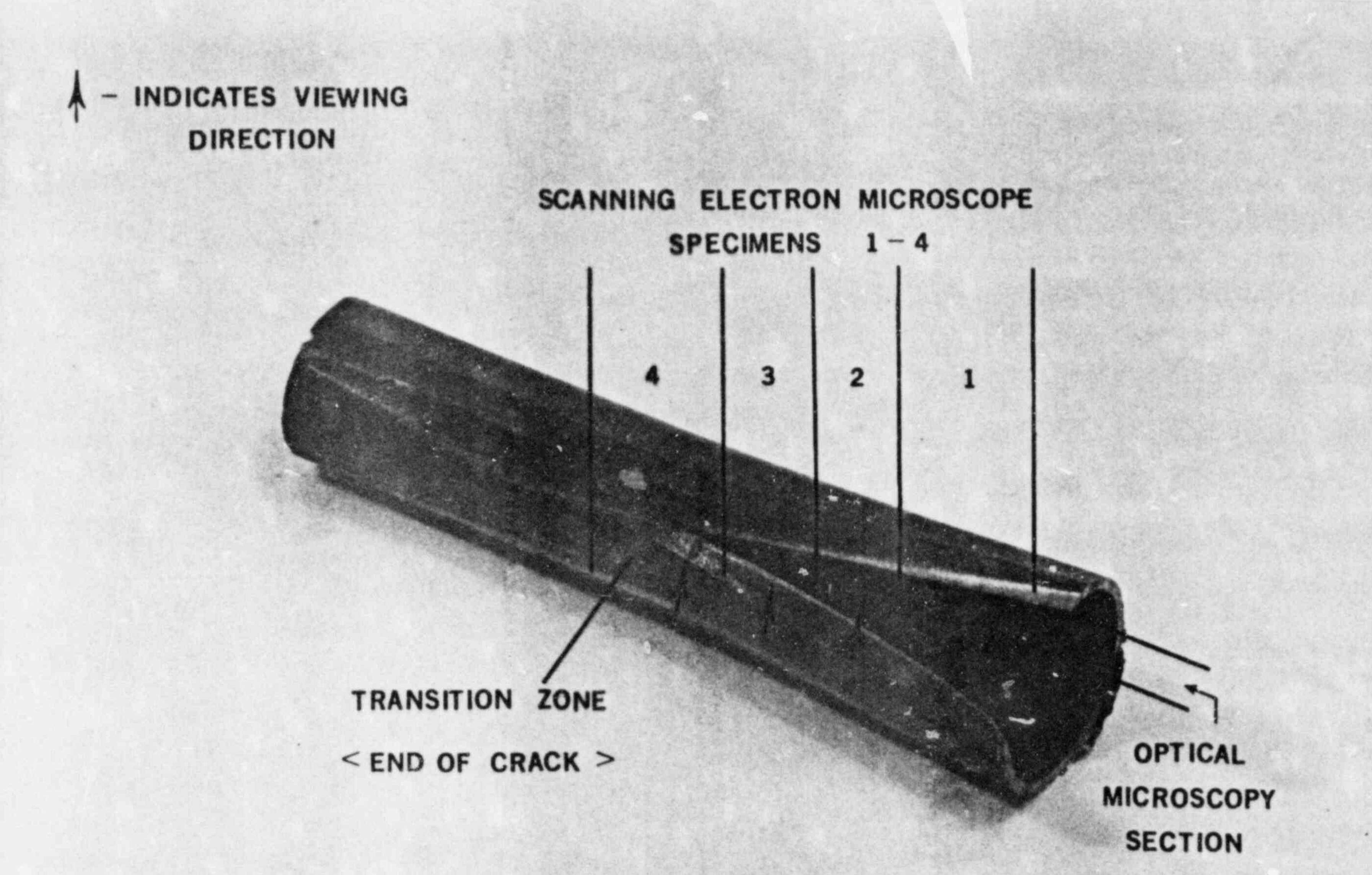

FIGURE 16. OVERLAY DEPICTING THE SECTIONING OF R42-C55 < GINNA >

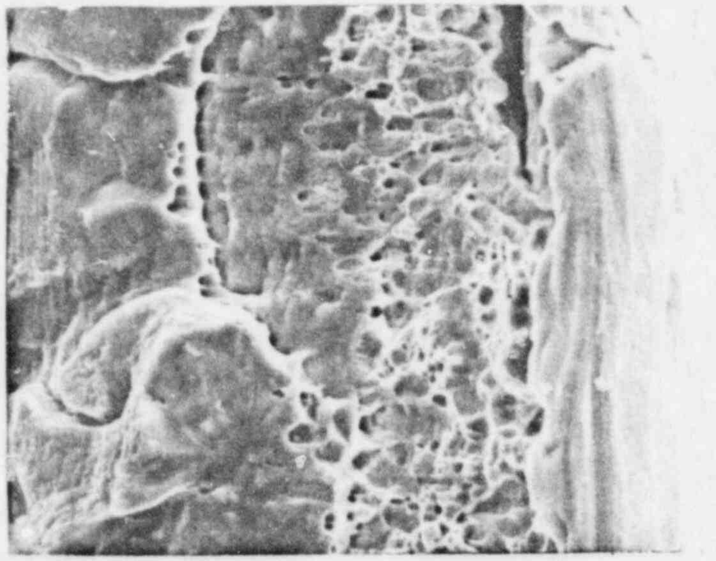

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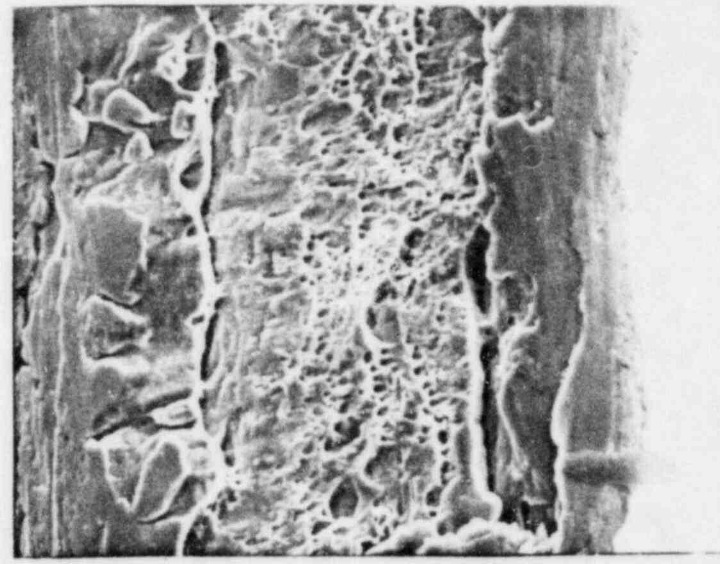
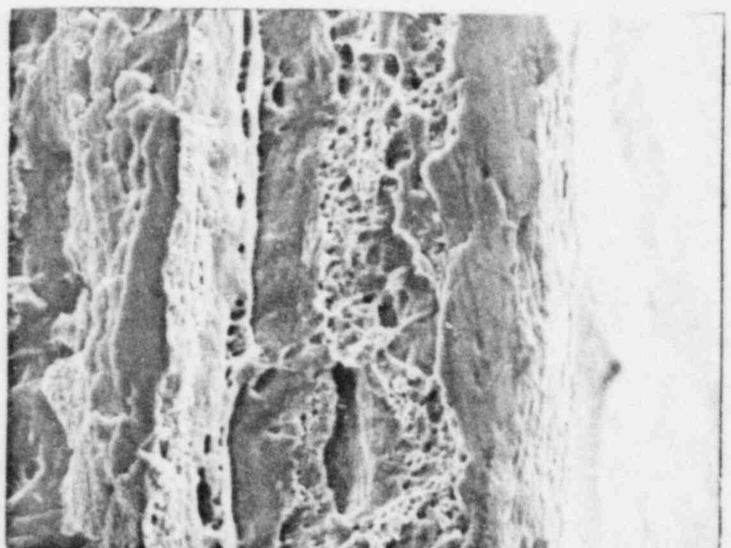
Figure 17. SEM photo of knife edge on R42-C55. Typical of "bulging" prior to ductile overload specimen #1



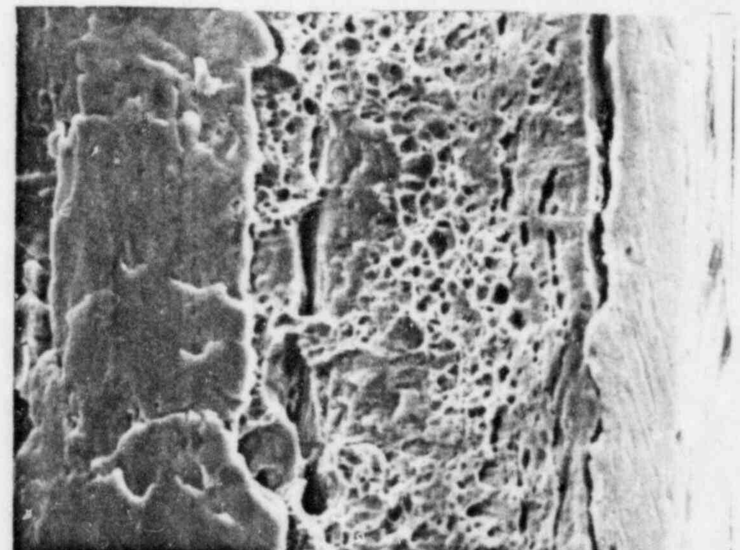
470X

Figure 18. SEM photo of knife edge on R42-C55. Elongation of dimples less pronounced. Specimen #2



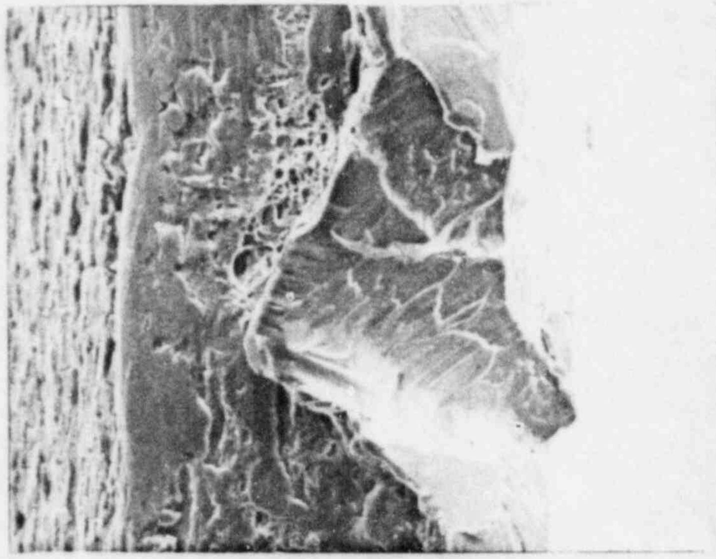
500X

Figure 19. SEM photo of knife edge on R42-C55. Higher magnification. Specimen #2.



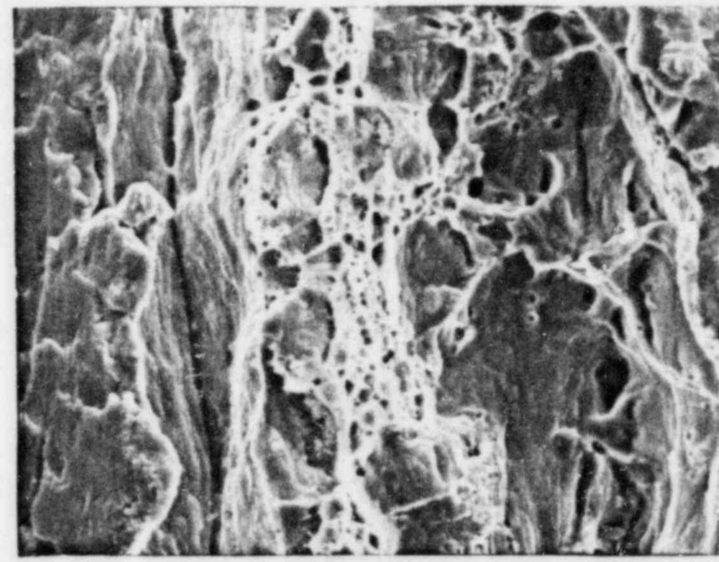
550X

Figure 20. SEM photo of knife edge on R42-C55. Specimen #3



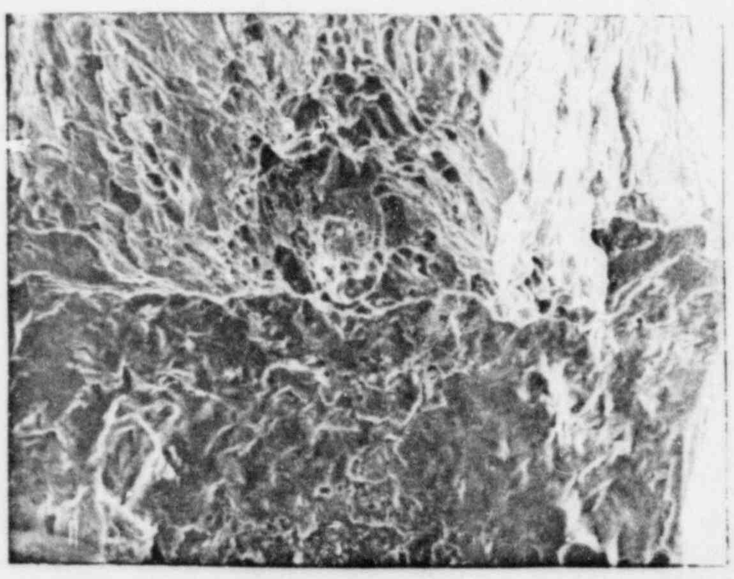
300X

Figure 21. SEM photo of knife edge on R42-C55 depicting impact after break. Specimen #3



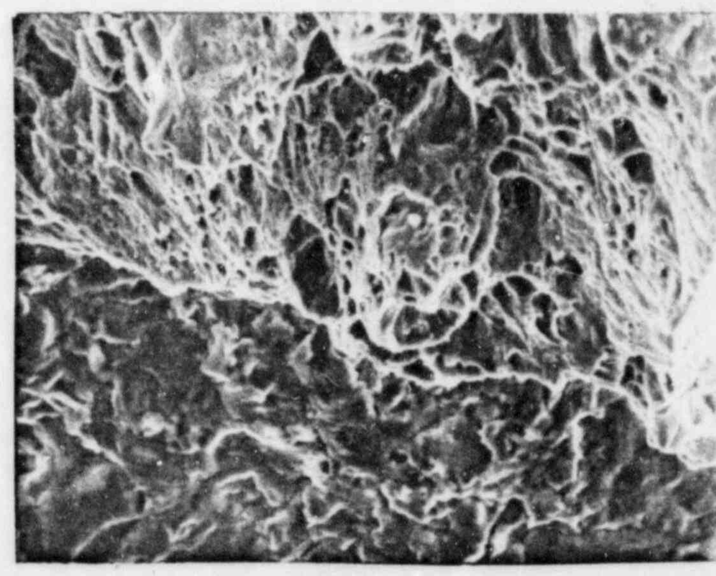
750X

Figure 22. SEM photo of knife edge on R42-C55. Specimen #4



300X

Figure 23. SEM photo of transition of knife edge on R42-C55. Specimen #4



550X

Figure 24. SEM photo of transition of knife edge on R42-C55. Specimen #4

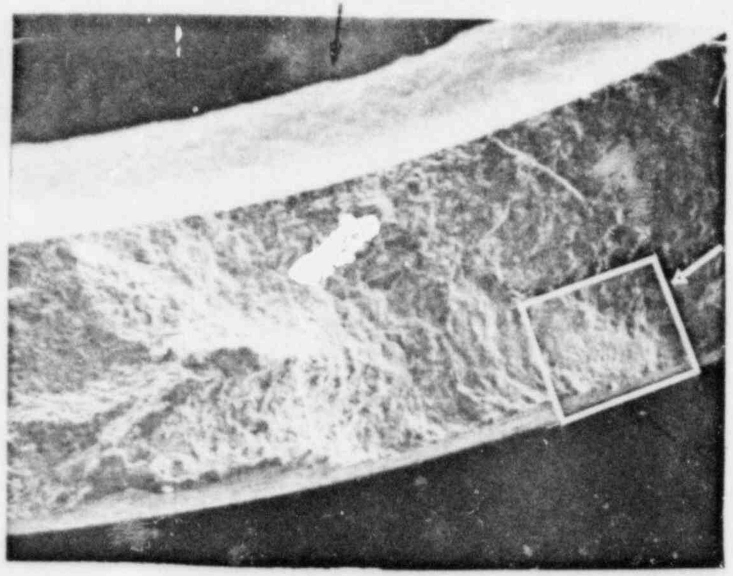


Figure 25. SEM photo of "chevron" marks (indicative of fatigue failure) on Tube R44-C56 (top) near tube support plate

Figure 26. SEM photo of probable initiation site for cyclic fatigue failure of tube R44-C56

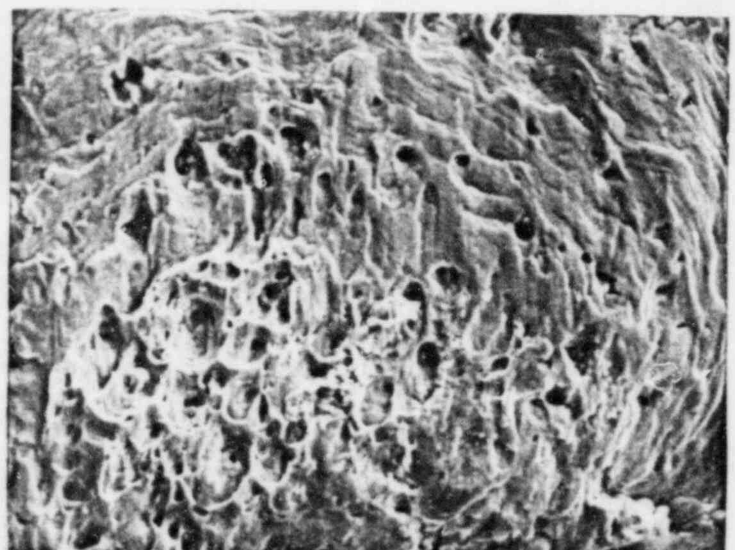


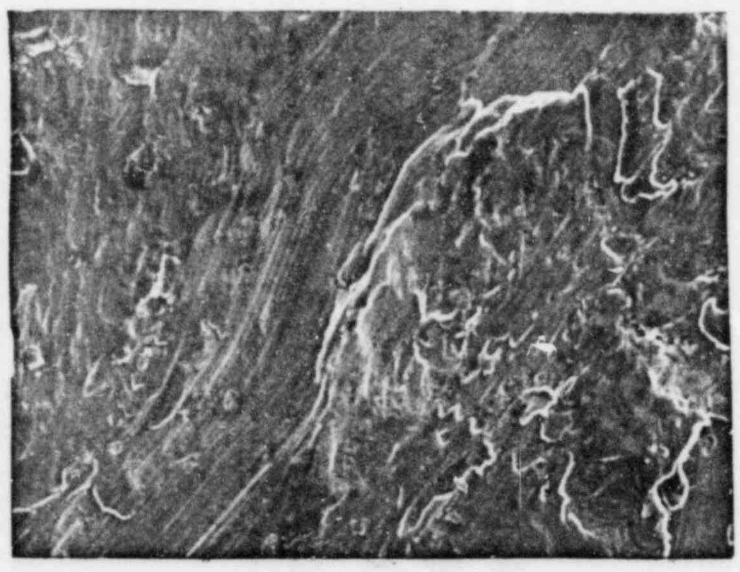
Figure 27. Higher magnification SEM photo of "initiation site" - Tube R44-C56

750X

Figure 28. SEM photo of inside surface of tube R43-C59 depicting area of possible deep etching

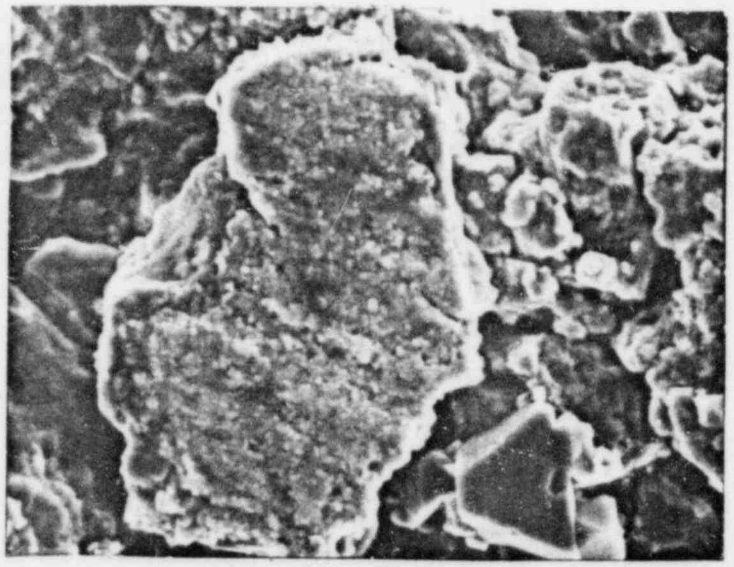
2000X

Figure 29. Higher magnification SEM photo of inside surface of tube R43-C59



390X

Figure 30. SEM photo of outside surface of abraded tube R11-C91



2000X

Figure 31. SEM photo of particle on inside surface of tube R8-C92 near rubbed area

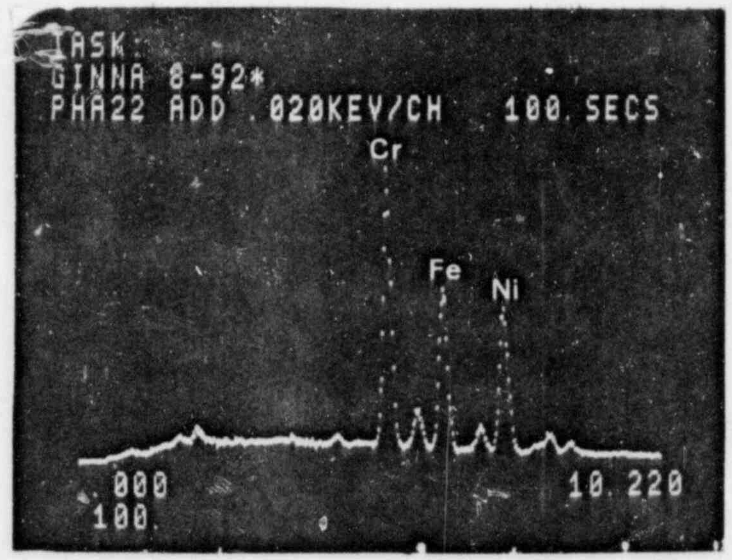
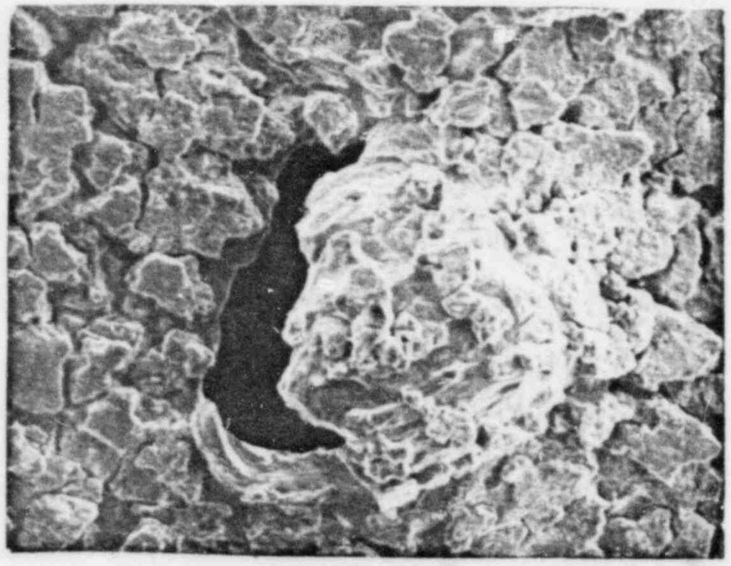


Figure31a. EDS scan of particle on inside surface of tube R8-C92 for constituents



430X

Figure 32. SEM photo of inside surface of tube R8-C92 depicting area of wall collapse

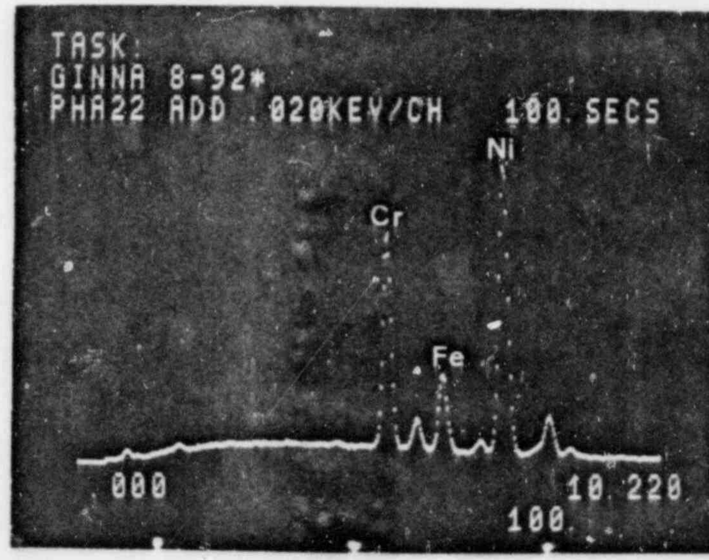
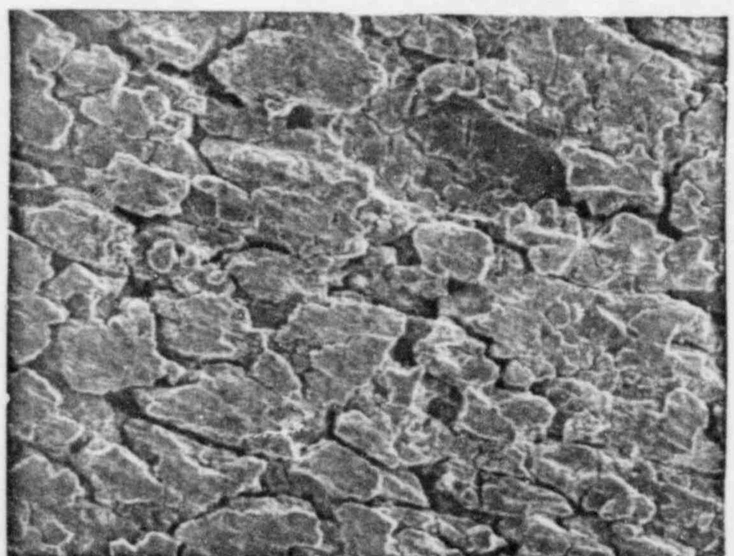
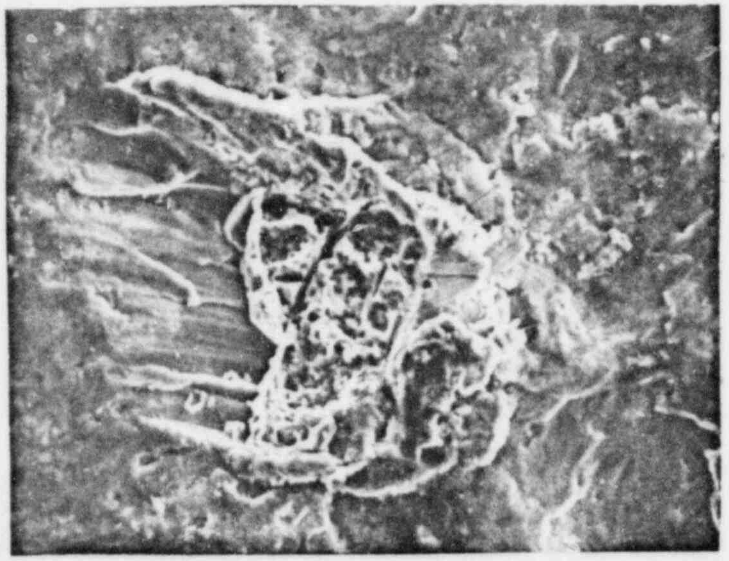


Figure 32a. EDS scan of inside surface of tube R8-C92 near collapse for constituents



240X

Figure 33. SEM photo of inside surface of tube R8-C92 depicting "etched" structure



1000X

Figure 34. Imbedded particle found on outside surface (O.D.) of R43-59

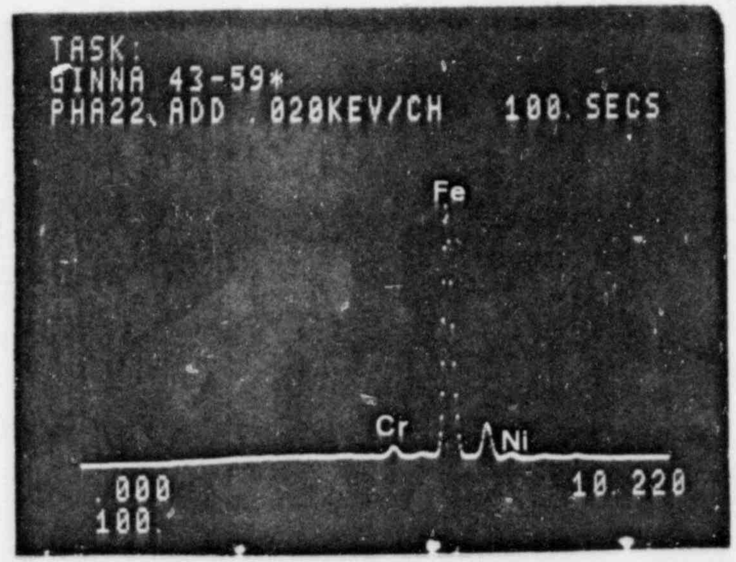
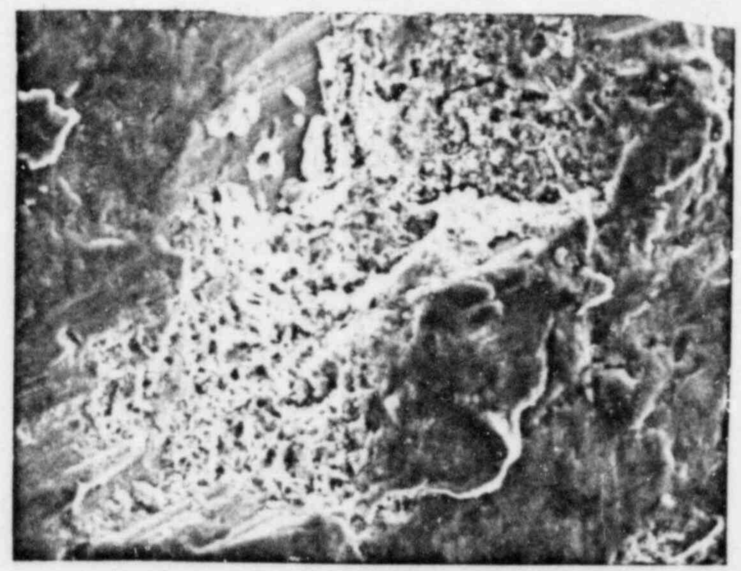


Figure 34a. EDS scan of imbedded particle found on R43-59

2200X

Figure 35. Higher magnification SEM photo of "imbedded" particle



1000X

Figure 36. SEM photo of another "smear" of iron (prior EDS scan is typical) found on outside surface of R43-59

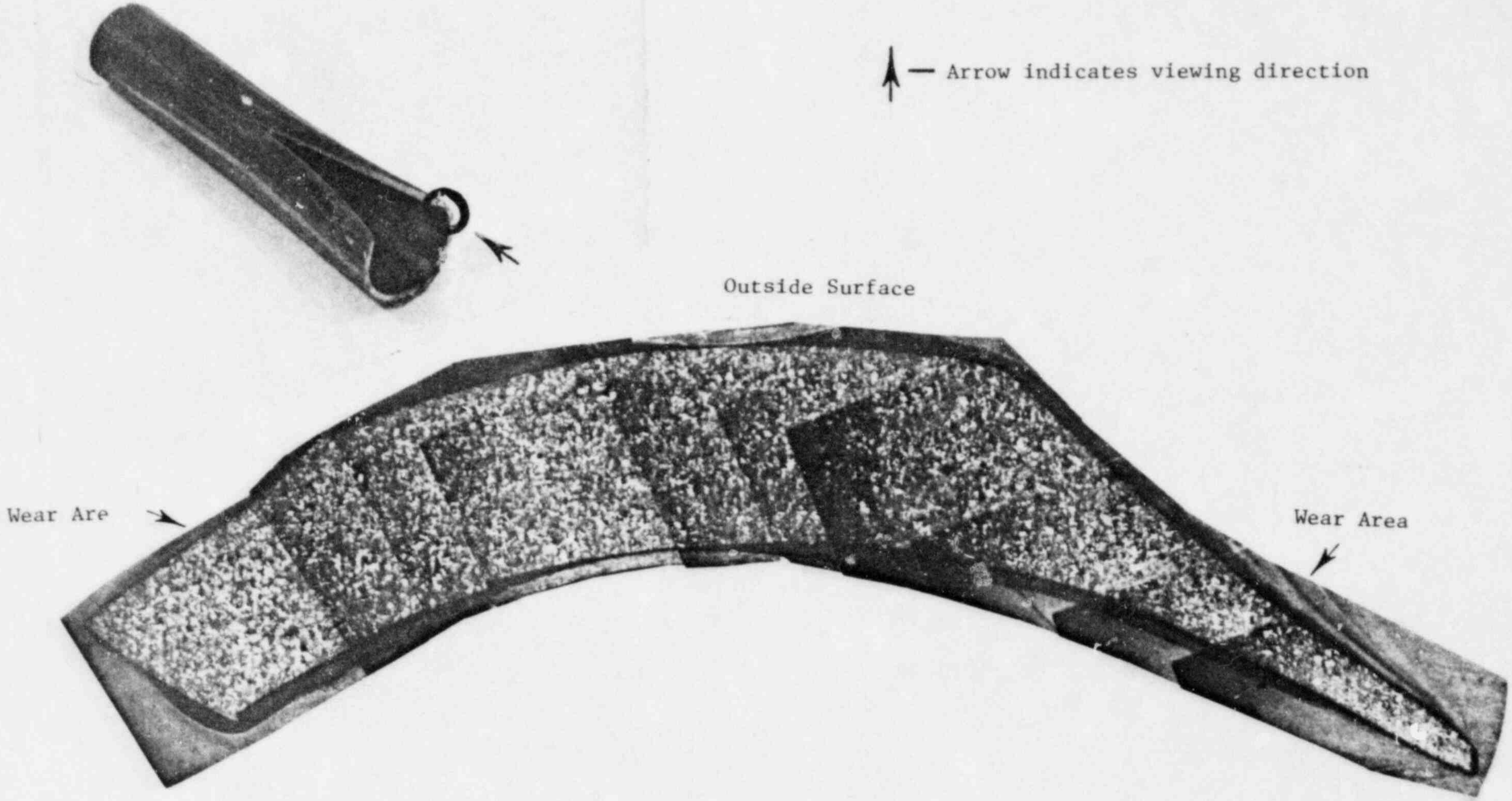
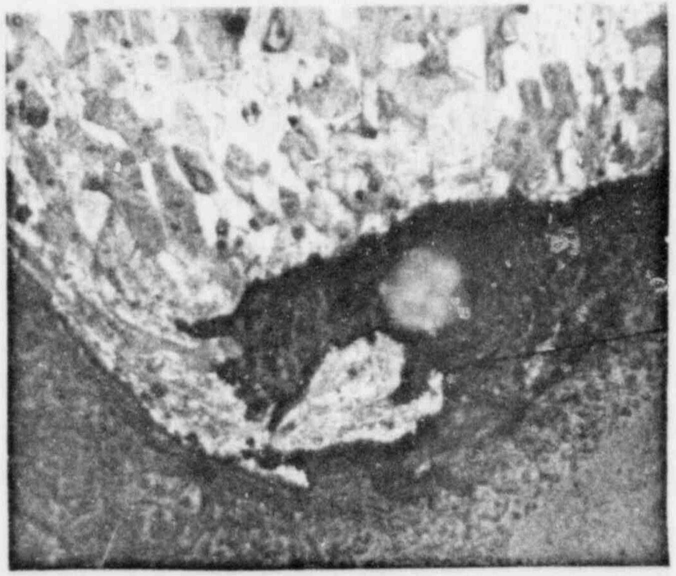
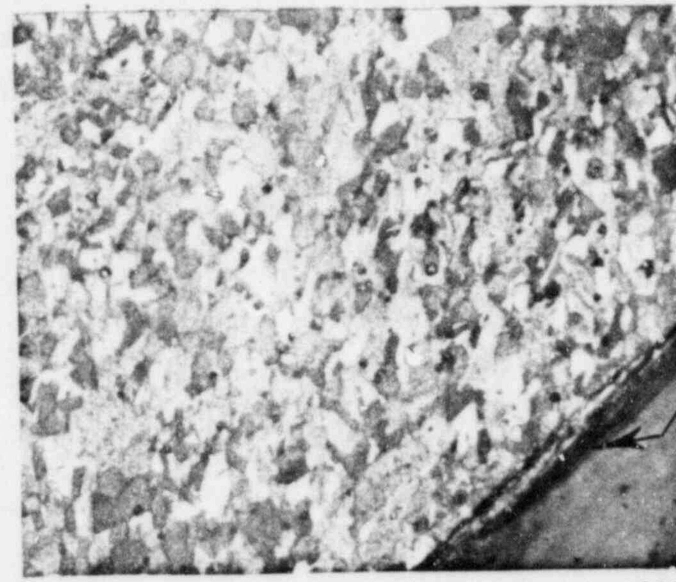


Figure 37. Optical photomicrograph of cross section of "Fishmouth" fracture (tube R42-C55) also shown is area of section relative to fracture. (Note: photomicrograph is optically reversed.



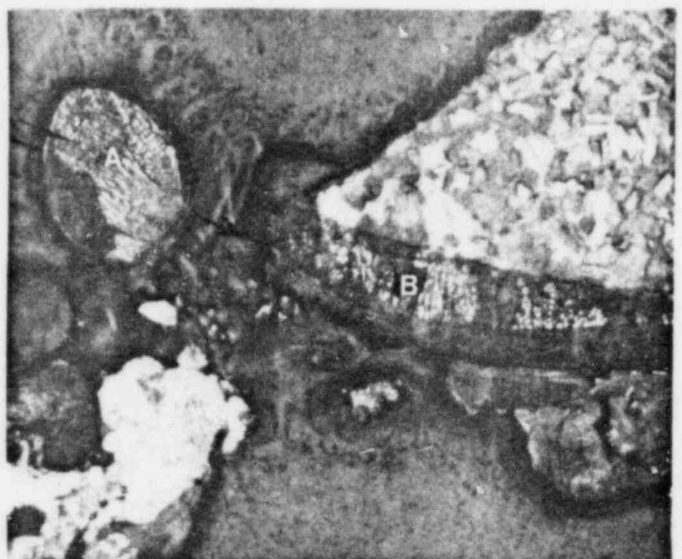
100X

Figure 38. Optical photo depicting area of cold work on tube R8-C92.



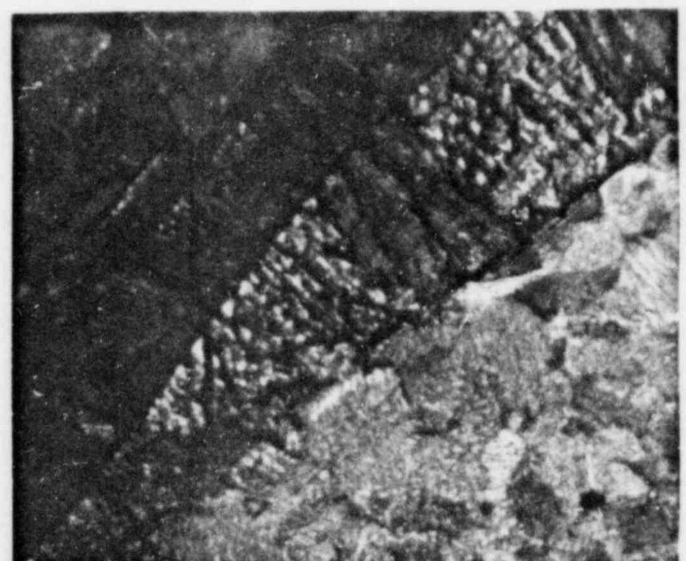
100X

Figure 39. Optical photo displaying area of cold work on tube R10-C91.



125X

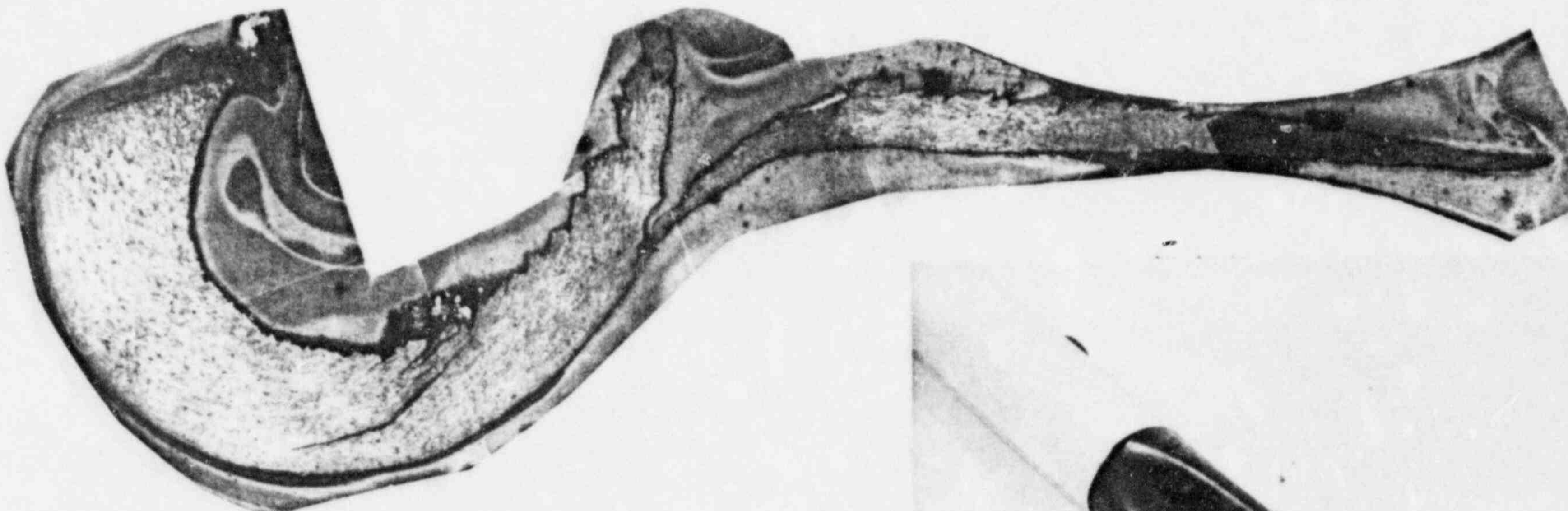
Figure 40. Low magnification photo of cold work on collapsed tube R44-C57.

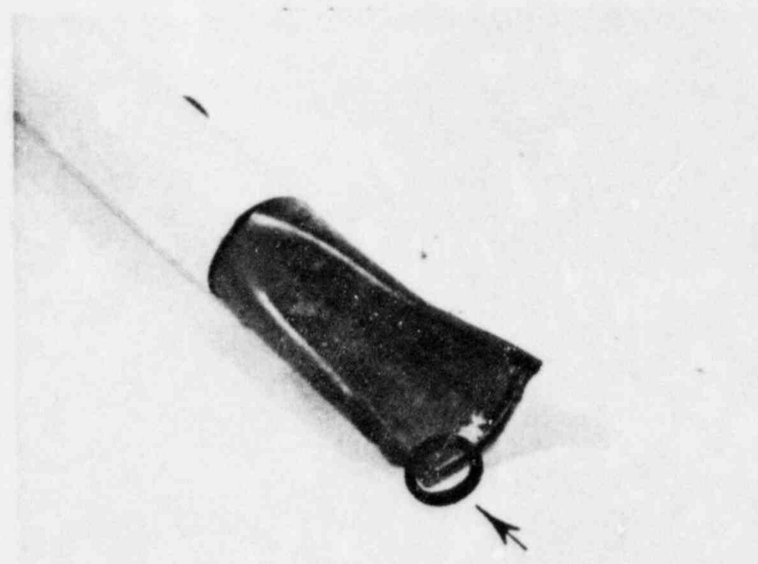


400X

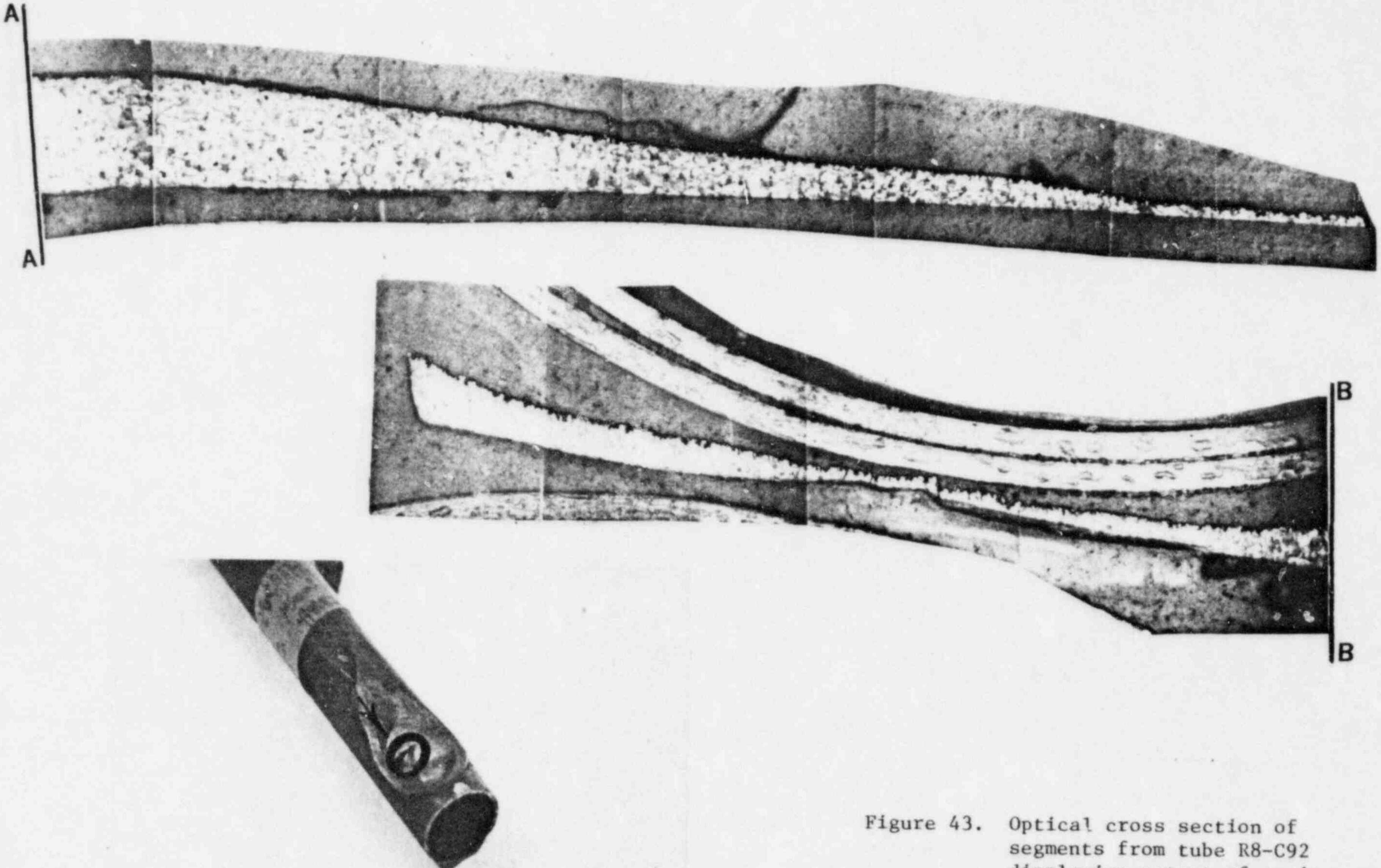
Figure 41. Higher magnification photo of cold work on tube R44-C57(Area B).

Figure 42. Cross sectional photomicrograph showing extent of damage endured by tube R44-C57. Also shown is area of section taken relative to collapse area.





Arrow indicates viewing direction



Arrow indicates viewing directi

Figure 43. Optical cross section of segments from tube R8-C92 displaying extent of grain boundary etching.