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Observations and Comments on the Turbine Failure at Yankee Atomic Electric Company, Rowe, Massachusetts

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ABSTRACT

We present a preliminary analysis of the catastrophic disc failure in the low-pressure turbine at the Yankee Rowe nuclear reactor plant. The analysis is based on on-site inspection and documentation of fractured components. Heavily oxidized thumbnail cracks were observed on fractured surfaces of the first-stage generator-end disc, indicating stress corrosion cracking as the precursor to the catastrophic failure of this disc. No evidence of such cracks was seen on the corresponding fractured governor-end disc. We propose a number of alternative possible causes for the failures and for the differences observed between the two discs.

INTRODUCTION

On February 14, 1980 two discs in the low-pressure turbine at the Rowe nuclear reactor plant of the Yankee Atomic Electric Company failed catastrophically. At the request of NRR we visited the plant on February 20 to inspect this failure. We were hosted by C. David Sellers of NRR and T. Foley of IAE. Also present were John Weeks of BNL, and Leslie D. Cramer of the Steam Turbine-Generator Technical Operations Division of Westinghouse, Lester, PA, Branch.

The failure initiated during start-up as the turbine speed was being stabilized at 1800 rpm with about 2% steam. It is believed that the No. 1, generator-end disc fractured first, causing a series of chain events resulting in the fracturing of the No. 1, governor-end disc and the disintegration or damaging of a number of blades attached to the first three sets of discs. On shutdown, it normally takes about an hour for the turbine to come to rest. This time was reduced to approximately 30 minutes due to fracturing, impacting, and rubbing of the two No. 1 discs and the affected blades.

We were to examine and document the failure at the plant and then at some later date evaluate some of the fractured components in considerable detail at our laboratory. A preliminary report in the form of a letter, "Observations and Comments on the Turbine Failure at Yankee Atomic Electric Company, Rowe, Massachusetts" dated March 6, 1980, was sent to NRR. The contents of this letter were based primarily on the documentations made during the plant visit. The purpose of this document is to formally record the information presented in the March 6 letter.

Yankee Rowe is a single-unit PWR plant which has been in operation since 1960. The turbine was manufactured by Westinghouse. The turbine system consists of both a high-pressure turbine (steam from the steam generator) and a low-pressure turbine (demoisturized steam from the high-pressure unit). The low-pressure unit (in which the failure occurred) is designed symmetrically about the low-pressure steam inlet, Fig. 1. There are six discs on either side of this inlet; these are designated the governor end and generator end, respectively. The first three discs, in turn, are fitted with two rows of turbine blades or stages, whereas the outer three discs are single stage. The low-pressure turbine assembly is contained by two covers. The inner cover encloses the inner three discs on either side of the steam inlet. The complete unit--including the inner cover and low-pressure stages--is enclosed by an outer cover. Alignment between the outer and inner covers is achieved by a locating pin which is press fitted into the inside surface of the outer cover. The various turbine components are shown in the schematics of Fig. 1. The inlet steam temperature was estimated at 300°F (149°C), whereas the exit temperature is approximately 90°F (32°C). The generator nameplate states the capacity as 145 MW; however, we were also quoted a value of 185 MW. There is some question as to which is the correct value.

OBSERVATIONS

OVERVIEW OF THE FAILURE

When we arrived at the site, the fractured sections were grouped according to their original location in the two respective discs (Fig. 2). The No. 1 governor-end disc (gov. disc) is close to the camera; the No. 1 generator-end disc (gen. disc) is away from the camera. The inlet faces of both discs are facing up. All of the blades from these two discs, as well as all the blades from the No. 2 discs and about half of the blades from the No. 3 discs, were badly disintegrated (deformed and fractured). The blades that had separated from the discs were found piled together with the damaged turbine steam shroud (Fig. 3). The remaining blades were still intact; however, many showed considerable damage (Figs. 4, 5, and 6). Erosion/corrosion could be seen on the leading edge of numerous blades on the remaining discs.

None of the broken pieces had penetrated the turbine containment. However, there appeared to be considerable damage to the inner covers (Figs. 7 and 8); and further, large cracks were observed at the alignment pin hole in the outer cover (Figs. 9 and 10).

The No. 1 gen. disc had fractured into six sections. These were numbered 1 through 6, with No. 4 being a small section out of the rim (Figs. 11 and 12). The corresponding gov. disc had fractured into two large sections and six small pieces. The large sections were numbered 1 and 6 with arcs of approximately 130 and 190 degrees, respectively. The six smaller pieces are identified as Nos. 2, 3, 4, 5, 7, and 8 (Figs. 13, 14, 15, and 16). Both discs exhibited evidence of rubbing during the failure--especially on the gov. disc. The discs measure approximately 36 in. (0.91 m) i.d. by 80 in. (2.03 m) o.d., with the thickness at the rim and bore about 9 and 10 in. (0.23 and 0.25 m), respectively. The thinnest section of the web is about 4 in. (0.10 m).

We were somewhat limited in our examination as the fractured discs were in the process of being prepared for shipment to Westinghouse Electric Corporation for their evaluation. Nevertheless, we were able to document (via photographs, sketches, and notes) many of the significant features. Specific details of our observations are presented below.

NO. 1 GENERATOR-END DISC

Numerous cracks (probably several hundred) were present on the bore surface of the gen. disc, generally running parallel to the shaft axis. Several of these cracks extended almost across the entire thickness of the disc (Figs. 17, 18, and 19). However, they appeared to be somewhat more concentrated near the disc faces in contrast to the center of the bore. Each of the fractured surfaces contained some three or four heavily discolored, oxidized, thumbnail cracks originating at the bore surface. These cracks appear typical of stress corrosion cracking (SCC). Figures 20 through 25 show the gen. disc failure surfaces starting with Section 1 and following through to Section 6.

The deepest of the thumbnail cracks was located between Sections 5 and 6 (5/6) and measured about 1.9 in. (48 mm) deep by 1.5 in. (38 mm) wide (Figs. 26 through 29). This crack was distinct in that although its tip was curved, its sides were straight and parallel. It was clear from the fracture surface markings that this crack was the precursor to the 5/6 fracture. Three other thumbnail cracks were also present on the fracture surface but on slightly different planes. Crack propagation seemingly progressed along a plane originating from the deepest crack, producing a series of fine rivers or chevron markings. These markings fan out radially for about 5 in. from the tip of the 1.9 in. crack (Fig. 29) and intercept the markings originating from the three parallel cracks. The propagation then continues developing a much coarser fracture pattern to ultimate failure (Figs. 26 and 27).

We were unable to examine all of the fracture surfaces in detail, but it appears that each of the fractures initiated from a single crack on a given surface with both the precursor crack and fracture surfaces lying essentially in a radial-axial plane. The widths of all the thumbnail cracks observed on the failed surfaces fall into the range of the smaller crack lengths that appear along the bore surface, i.e., approximately less than 2 in. (51 mm). This implies that the long cracks, possibly approaching 10 in. (254 mm), were not responsible for the initiation of any of the fractures. Were the longer cracks less sharp than the shorter cracks? Are they shallower than the shorter cracks? Was the penetration of the shorter cracks associated with some microstructural defect? These questions should be investigated in a thorough laboratory analysis.

Beach marks or arrest bands were not detected on any of the thumbnail cracks. This may be due to the fact that the bore surface sees a relatively constant stress--regardless of the turbine speed. However, removal of the corrosion layer might reveal evidence of low cycle events. Also, using SEM and TEM techniques, one should be able to establish whether or not high cycle fatigue had occurred.

Normally, one expects the keyway to be a source for crack initiation; but no apparent cracking was observed in any of the keyways. The disc contained three keyways, with the keyway pins still intact (Fig. 18). It is possible that the finish of the keyways was superior to that of the bore surface. It may also be that the corrodent responsible for the SCC along the bore surface did not penetrate into the keyways. The keyways should be examined for the presence of cracks and corrosion products.

NO. 1 GOVERNOR-END DISC

We did not see any evidence of SCC on the gov. disc, either along the bore surface or on the fracture surfaces. This is rather surprising in that the disc material is reported to be identical to that of the failed generator end. It would be interesting to reexamine sections of the governor-end bore surface under more appropriate conditions in a laboratory. Some of the fractures present were initiated at balance holes (Fig. 30). A number of the surfaces were damaged either by impact or by subsequent friction rubbing; one region at a fracture-bore intersection, in fact, had melted and had been partially extruded (Fig. 31). Evidence of the severity of the impact or friction rubbing between fractured pieces was seen in the smeared surfaces on sections from the gov. disc. The concensus among those present at the site was that the fracture of this disc was most likely caused by the impact of flying pieces from the gen. disc.

DISCUSSION

Understanding the reasons for the observed differences between the two No. 1 discs is of considerable importance in the analysis and solution of the failure problem. The obvious questions are: Were the materials in the two hubs identical? Were the stresses identical? Were the shaft and bore surface finishes the same? Were there any residual contaminants at the shaft/bore interface and were these the same in both cases?

Our understanding is that both discs were forged in 1958 from the same heat (0.32 C - 0.48 Mn - 0.01 P - 0.014 S - 0.31 Si - 2.76 Ni - 0.67 Cr - 0.08 V - 0.50 Mo); and probably both were taken from the same ingot. However, was there much macrosegregation in the ingot; and, if so, was the gen. disc removed from a region that had more segregation and a higher concentration of detrimental impurities than did the corresponding region of the gov. disc? Although such macrosegregation may cause differences in the degree of susceptibility to SCC, it is very unlikely that it would result in the extreme differences apparently present on the two fractured discs.

The tensile properties are listed in Table 1.

TABLE 1. Tensile properties of No. 1 generator-end and governor-end discs.

Tensile specimen	Yield strength (ksi)	Yield strength (MPa)	Tensile strength (ksi)	Tensile strength (MPa)	Elongation in 2 in. (%)	Reduction in area (%)
Generator end:						
1	112.8	777.7	136.3	939.8	18.0	41.6
2	105.7	728.8	128.4	885.3	18.0	51.6
Governor end:						
3	106.8	736.4	130.3	898.4	18.0	47.3
4	103.2	711.5	120.8	830.1	20.5	55.9

Differences in properties are very minor; however, as a material is heat-treated to higher yield strengths, a point is reached where there is a rapid-drop off in toughness with increased yield. We may be at the start of such a drop-off. Variations in material properties could be due to either variations in composition or heat treatment. Important questions to be resolved include: Have the material properties changed with time? Are the material properties a function of orientation, i.e., circumferential, radial, and axial? Do the listed properties reflect the circumferential direction, i.e., a C-R oriented crack, the critical direction for failure? The materials in both discs should be characterized for mechanical properties and microstructure to answer these questions. Fracture-toughness properties should be included in the characterization. What are the transition temperature ($FATT_{50}$) and upper shelf energy values? Impact and fracture toughness properties are more sensitive to slight variations in the microstructure and in the concentration and distribution of impurities than are conventional tensile properties, and may therefore shed some light on the observed differences between the two fractured discs.

The discs are fitted onto the shaft with a shrinkage preload at the hub (bore) surface of approximately 65% of minimum specified yield. As the turbine comes up to speed, there is substantial drop-off in the shrinkage preload. Concurrent with this, there is a corresponding increase in the operating stresses such that the net tensile hub stresses at the bore should remain approximately constant at 65% of minimum yield. However, during start-up a transient condition may exist in which the rim is significantly hotter than the corresponding hub. Such radial gradient thermal stresses may increase the hub stresses well beyond the 65% design specification. Considering that the minimum yield is about 105 ksi (724 MPa) implies that the operating circumferential stress is about 68 ksi (469 MPa). If we model the observed thumbnail cracks as semicircular with a radius of 1.5 in. (38.1 mm), then the "predicted" fracture toughness, K_{Ic}, is about 94 ksi·in.$^{1/2}$ (103 MPa·m$^{1/2}$). The predicted fracture toughness could be as high as 145 ksi·in.$^{1/2}$ (159 MPa·m$^{1/2}$) if the transient stresses increase the design limit to yield. A cursory literature search shows that similar materials have a fracture toughness of approximately 200 ksi·in.$^{1/2}$ (220 MPa·m$^{1/2}$) at 300°F (149°C). Whether failure is due to poor material property, high-transition temperature, environment, or other effects has to be determined.

With a 36-in. (914-mm) diameter shaft, a variation of 0.001 in. (25.4 μm) on the radius would correspond to a variation of shrinkage stress of nearly 1 ksi (7 MPa). If the errors on all four radii (two locations on shaft and two disc bores) were additive, the variation in shrinkage stress may be as high as 4 ksi (28 MPa). Any stress variations between the two discs would be further accentuated by variation in surface finishes of the respective hubs and shafts.

It is our understanding that MoS_2 was used as a lubricant on the shaft. It was suggested that differences in the amounts of lubricant retained at the shaft-hub interface may have been responsible for the differences in the surface appearance (cracks) of the two hubs. Considerably more MoS_2 residue was evidently present along the shaft interfacing with the gen. disc than along that interfacing with the gov. disc. The MoS_2 is insoluble in H_2O but does dissolve in some acidic and basic solutions. We know that sulfur generally accelerates SCC; the effect of molybdenum has been the subject of numerous investigations, primarily on how it acts as an alloying element to reduce corrosion and SCC. Calhoun documented a number of examples of accelerated corrosion caused by the presence of MoS_2.[1] The chemistry of the surfaces

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[1] S. Fred Calhoun, "Wear and Corrosion Tendencies of Molybdenum Disulfide Containing Greases," Rock Island Arsenal Laboratory Technical Report No. 62-2752 (1962).

along the shaft and hub must be carefully analyzed for their elemental content and type of corrosion product with special emphases on any differences between the two disc environments. Depending upon the results, a careful literature search may be in order to aid in the evaluation of possible effects due to any detected contaminants.

Could there have been an excess (above normal) of some corrodent in this final startup? Could there have been some abnormal overload? Was the gen. disc at a critical stage for catastrophic failure due to having a critical flaw (SCC cracks) size? These are questions which must be answered to determine why the fracture occurred at this particular startup.

To perform a proper assessment of the disc failures requires adequate material for mechanical property evaluation, metallography, and surface analyses. We propose that the following sections be used in such an evaluation:

a. Sections containing fracture surfaces of both discs with those from the gen. disc having a number of undisturbed thumbnail cracks.
b. Sections containing hub bore surfaces with those from the gen. disc having a number of cracks, intact, and not disturbed by NDE.
c. Material from both hub and web sections for mechanical testing and metallurgical characterization. The purpose and extent of such characterization should be agreed upon by NRR and LLNL at an early date and prior to specifying the amount of material to be sent for this purpose.

CONCLUSIONS

Our preliminary analysis indicates that the precursor to the failure was the presence of one or more critical size cracks. Their surface appearance suggests that they resulted from SCC. A number of possible causes that could lead to the failure are suggested. However, we believe that the final analysis of the two turbine disc failures must include a clear understanding of the differences in the observed failure of the two discs. The steel manufacturing practice, the location of the disc forgings in the ingot, the composition and the elemental distribution, the microstructure, mechanical properties, net stresses, and the corrosive environment, as well as the precrack (SCC) and fracture (catastrophic) mechanisms, are all factors to be considered.

ACKNOWLEDGMENTS

We wish to thank Dave Sellors of NRR and Tom Foley of IAE for their valuable help and comments during our inspection of the Yankee Rowe turbine failure. We also wish to thank Richard R. Vandervoort of LLNL for reviewing the original draft.

JCC/jmp

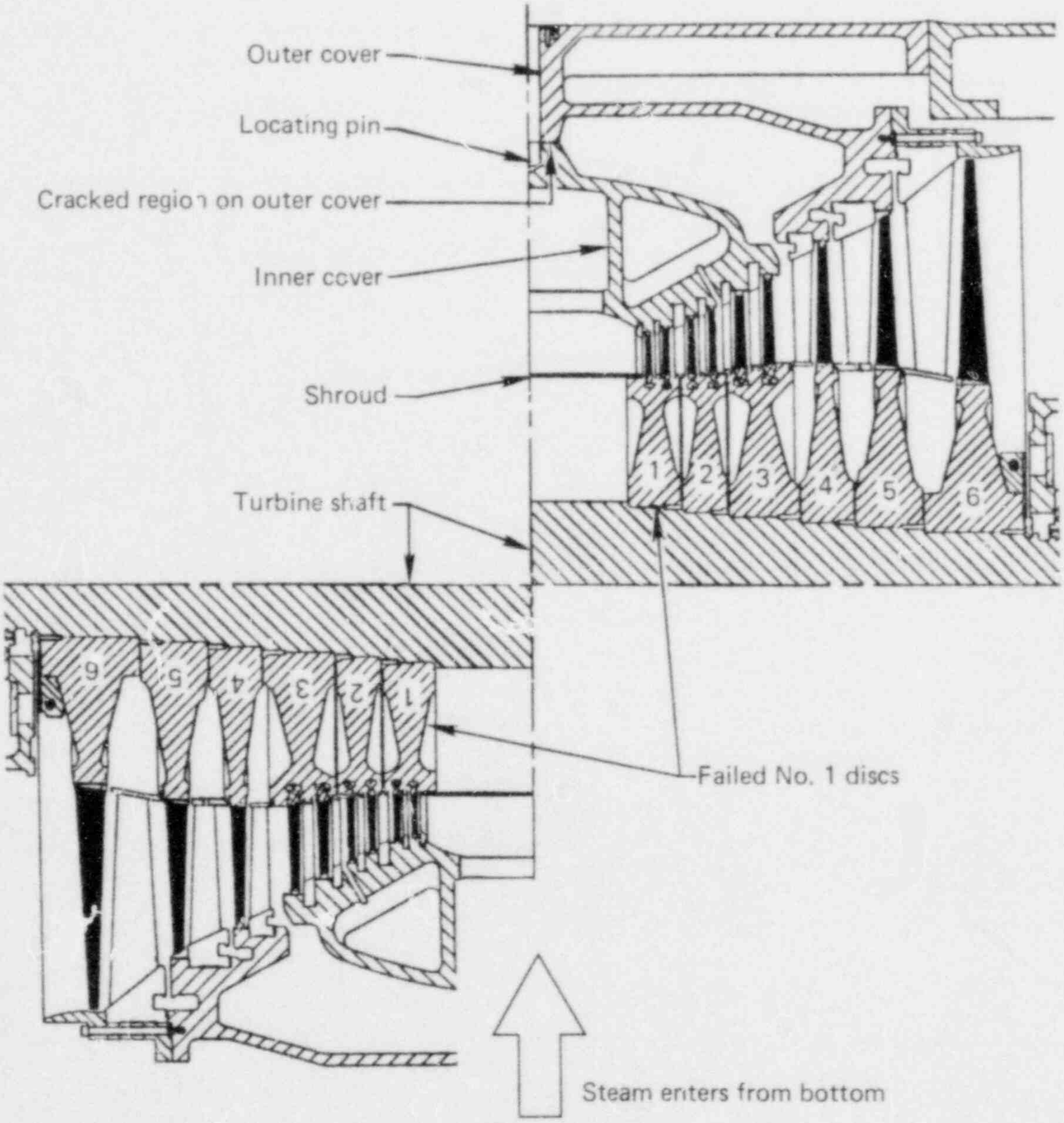

FIG. 1. Schematic of low-pressure turbine at Yankee Atomic Electric Co., Rowe, MA.

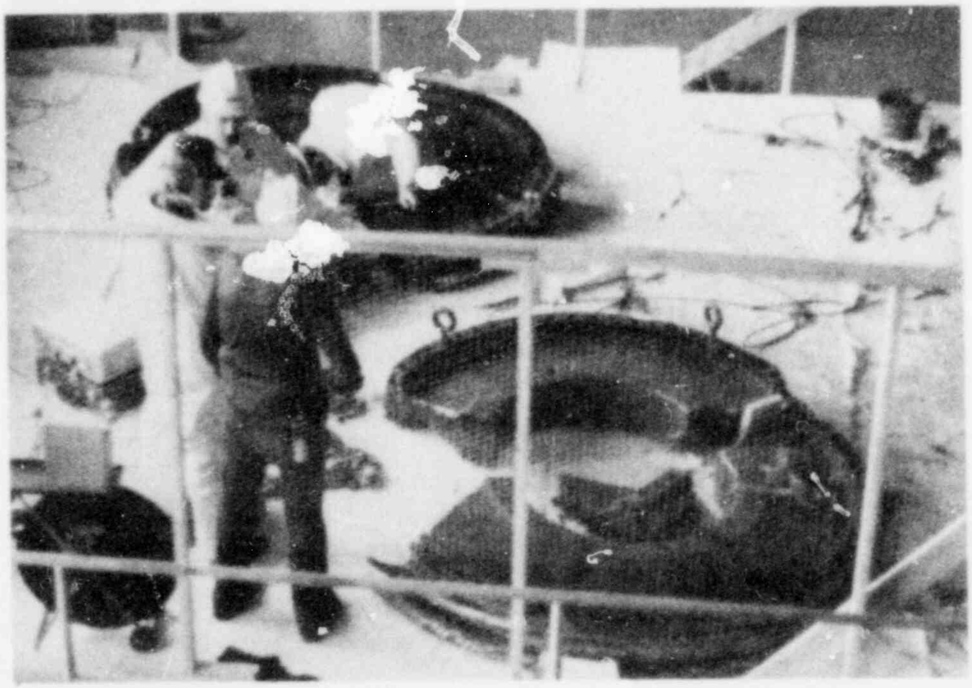

FIG. 2. Overall view of failed No. 1 turbine discs. Governor end is nearest the camera.

FIG. 3. Pile of miscellaneous parts from inside the turbine cavity; broken turbine blades and shroud.

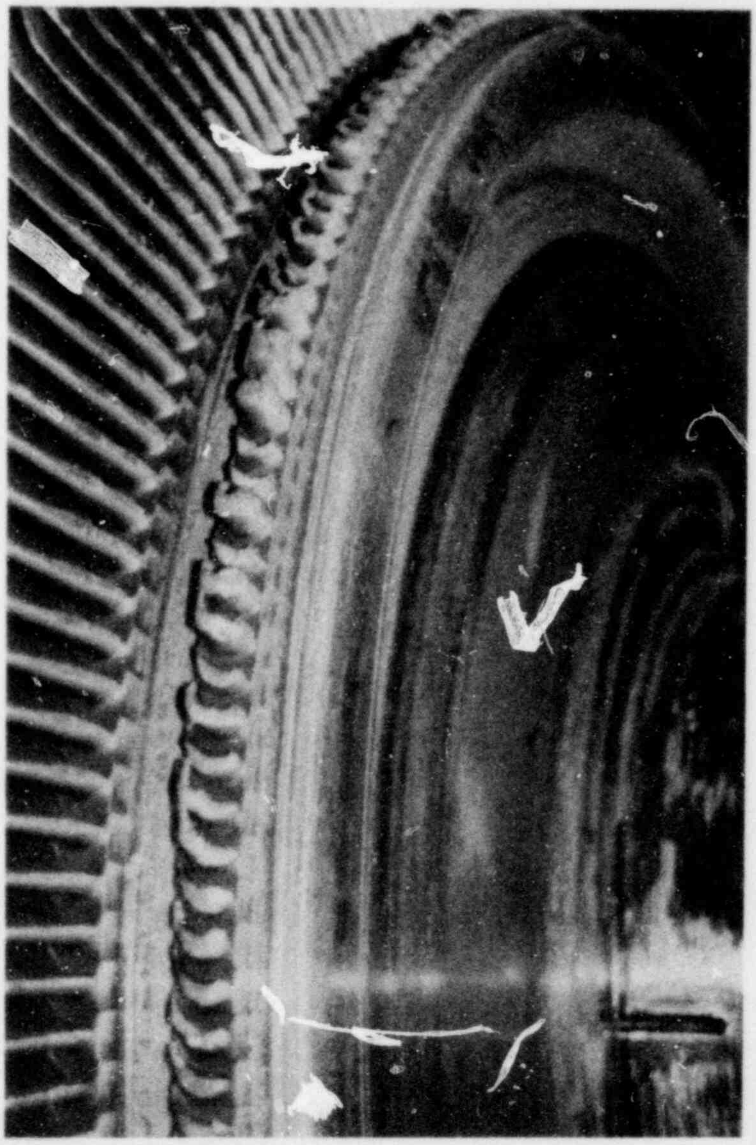

FIG. 4.

FIGS. 4-6. Views of the LP turbine assembly, showing blades, discs, and shaft after failure. The inside disc is the No. 2 disc.

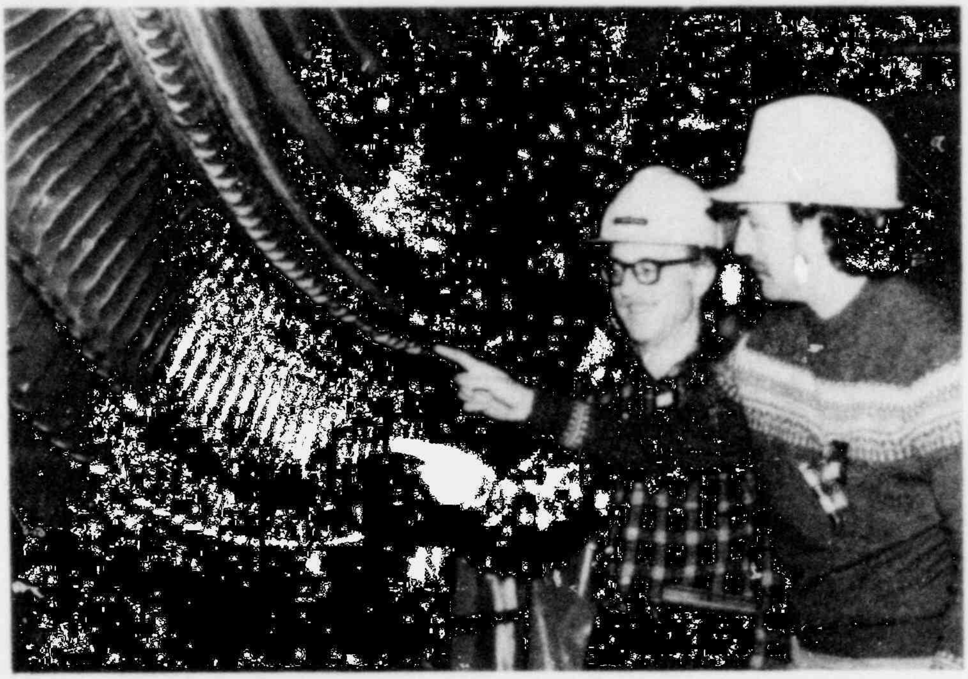

FIG. 5.

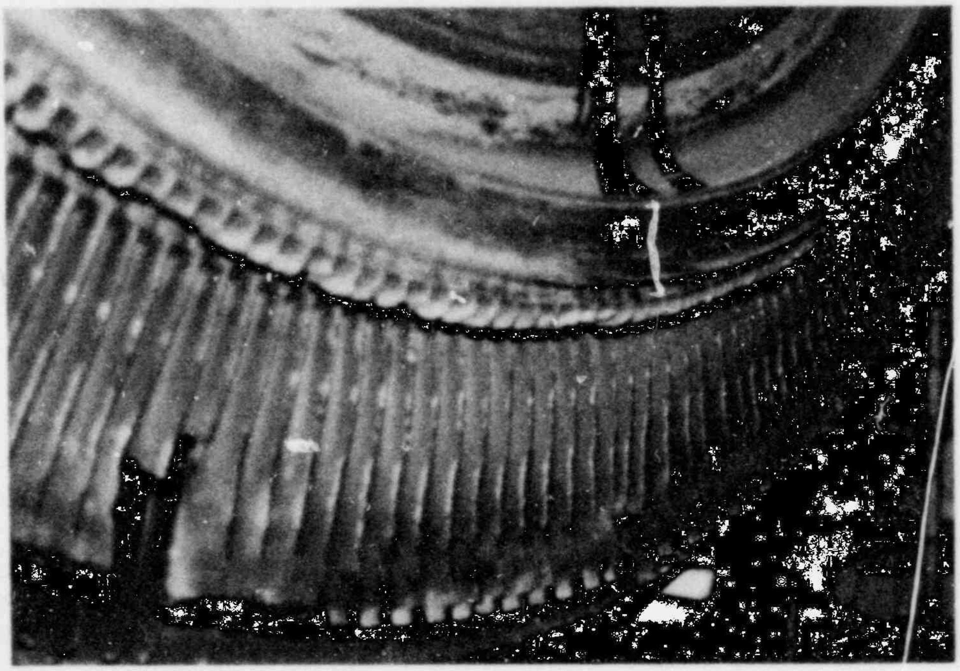

FIG. 6.

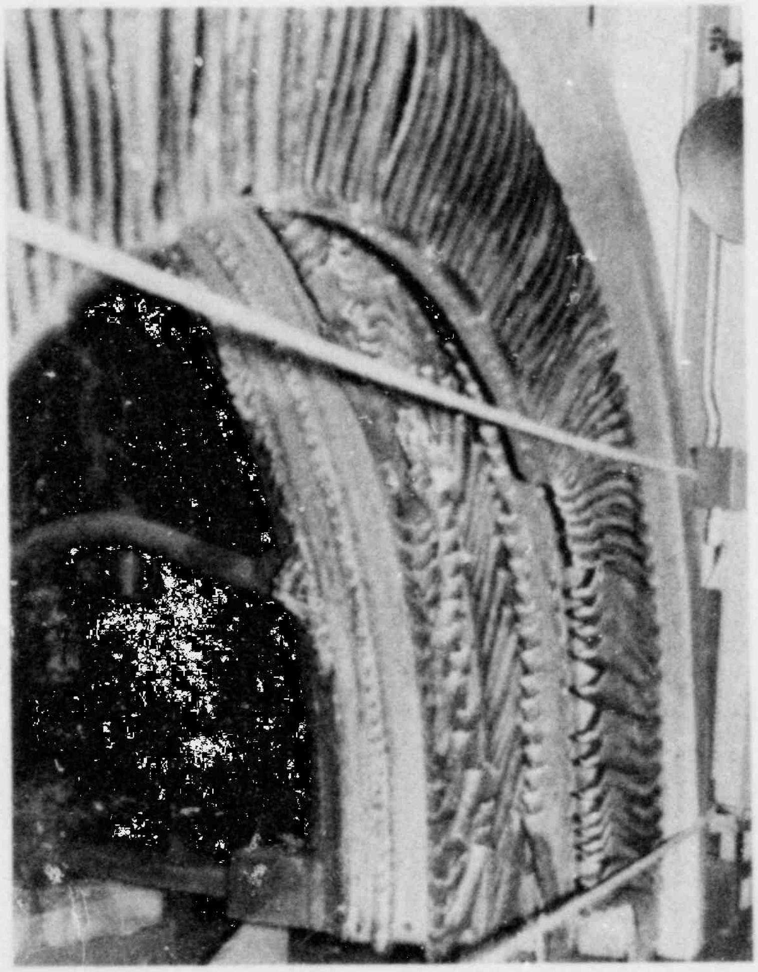

FIG. 7. Inner cover of the LP turbine. Note damage to the reinforcement bars and stator blades.

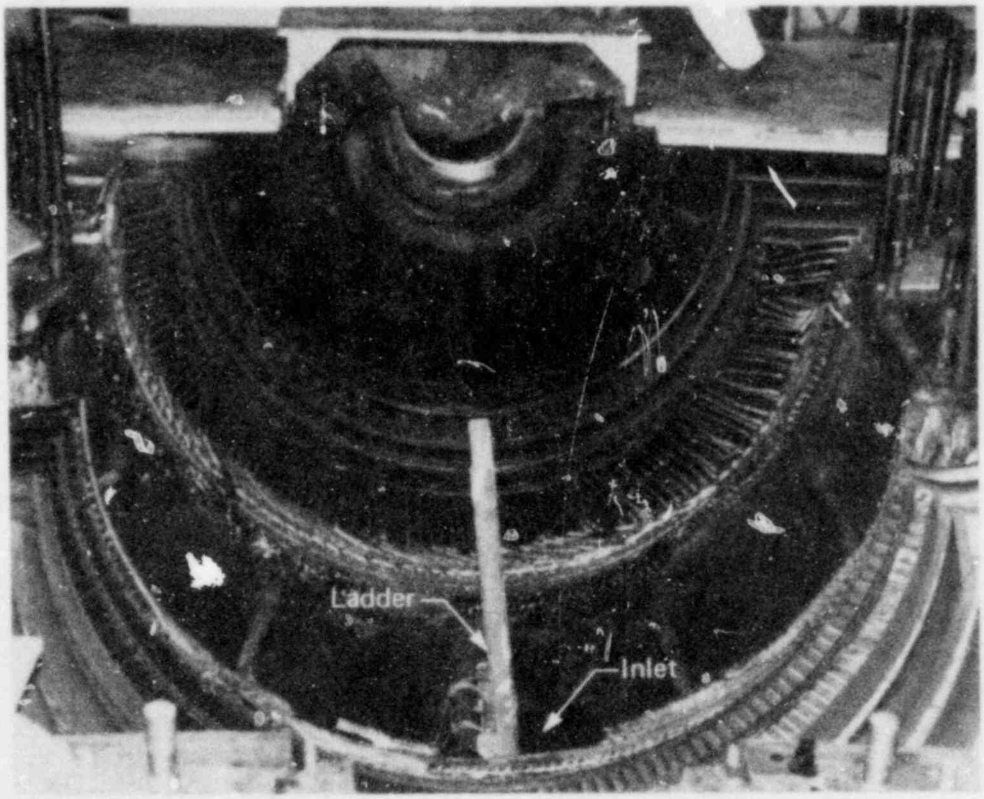

FIG. 8. Turbine cavity with steam inlet at the bottom (ladder). Note bending of reinforcement bars.

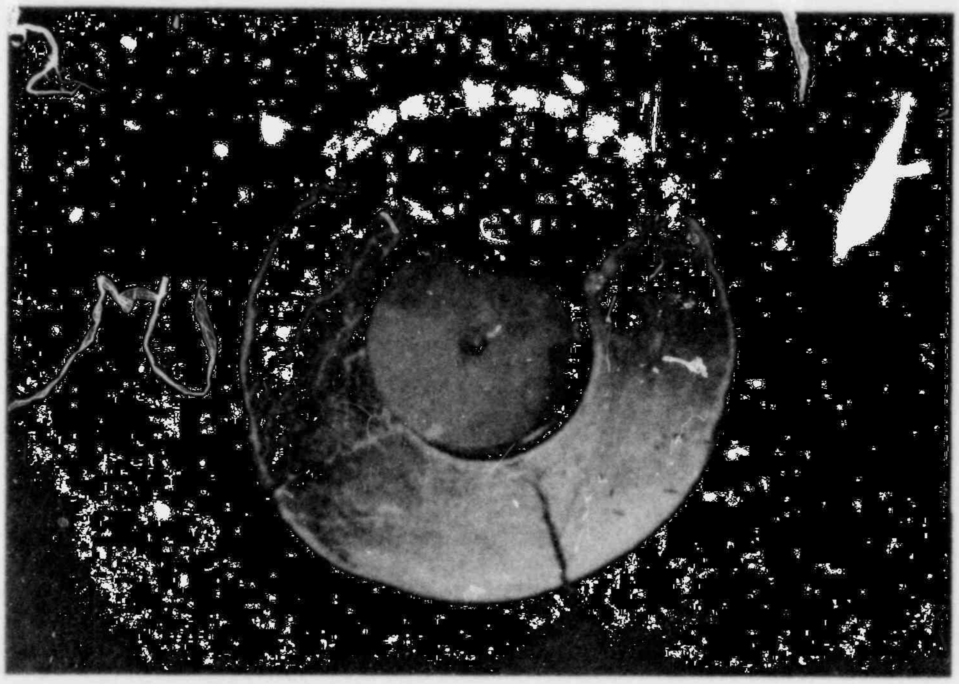

FIG. 9.

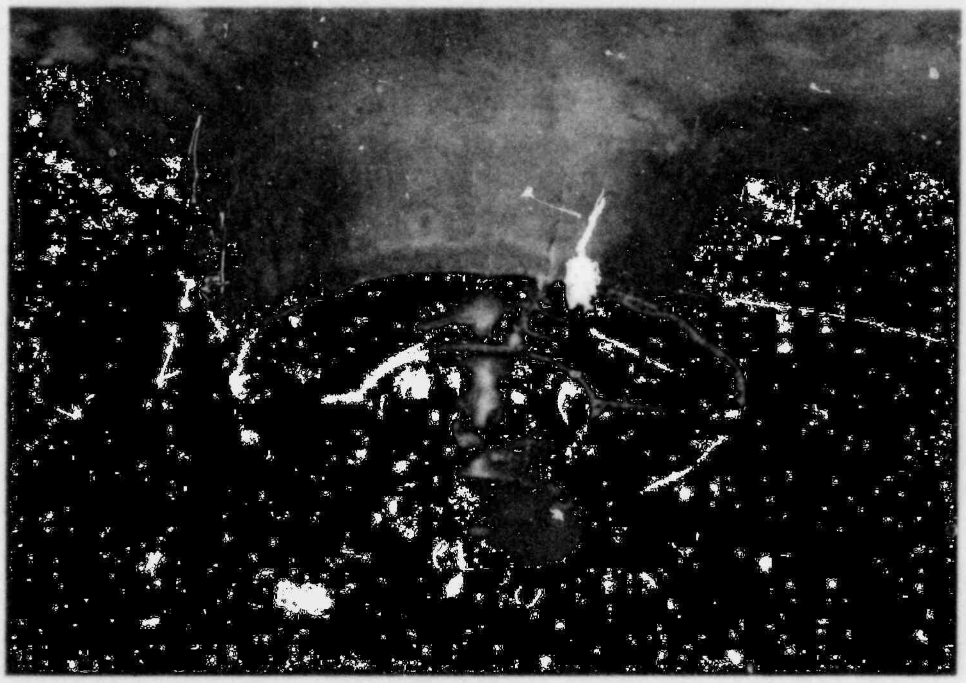

FIG. 10.

FIGS. 9-10. Locating pin on the inside of the outer cover of LP turbine.

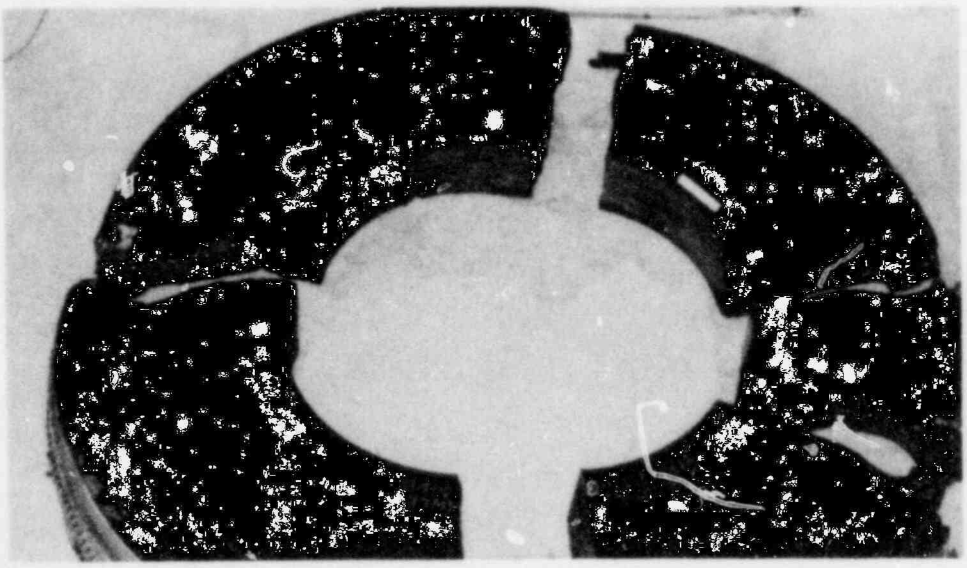

FIG. 11.

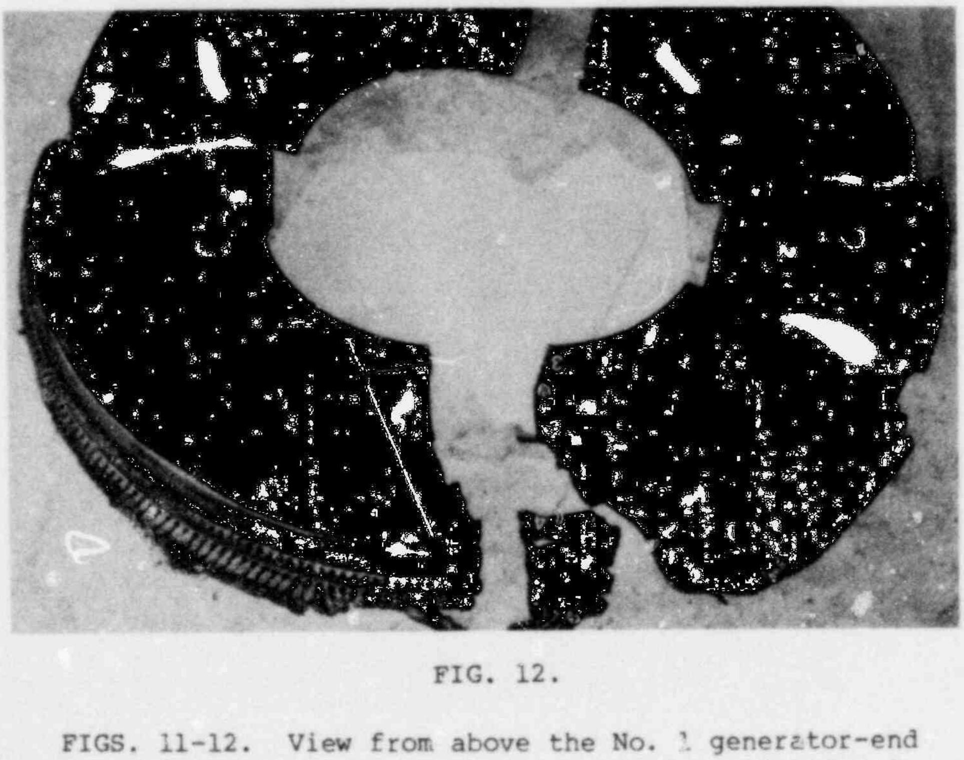

FIG. 12.

FIGS. 11-12. View from above the No. 1 generator-end disc, inlet side up. Note 6-inch scale on Section 1.

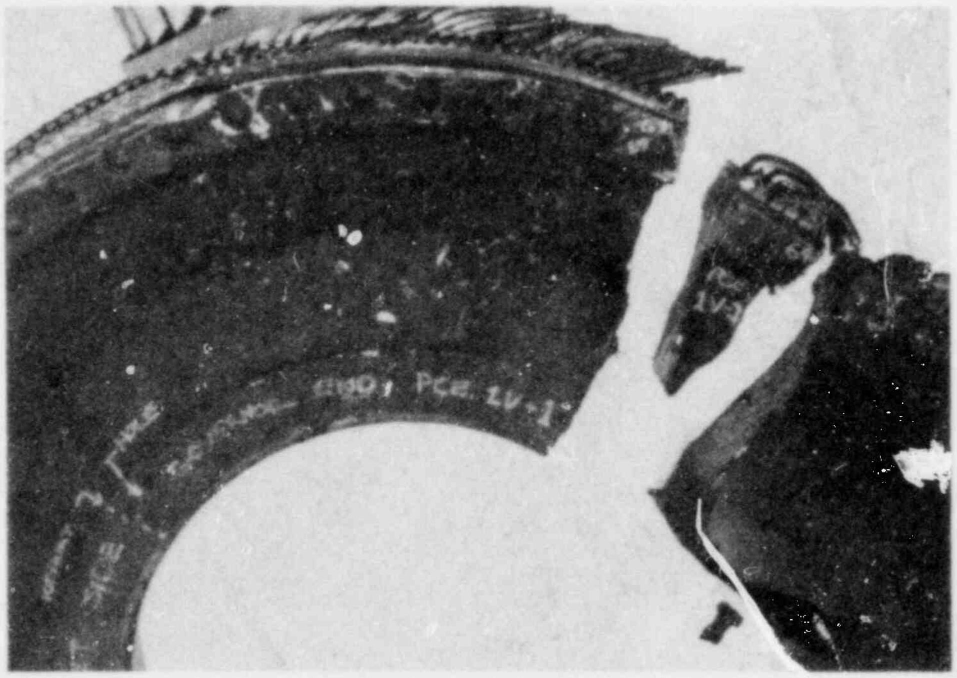

FIG. 13.

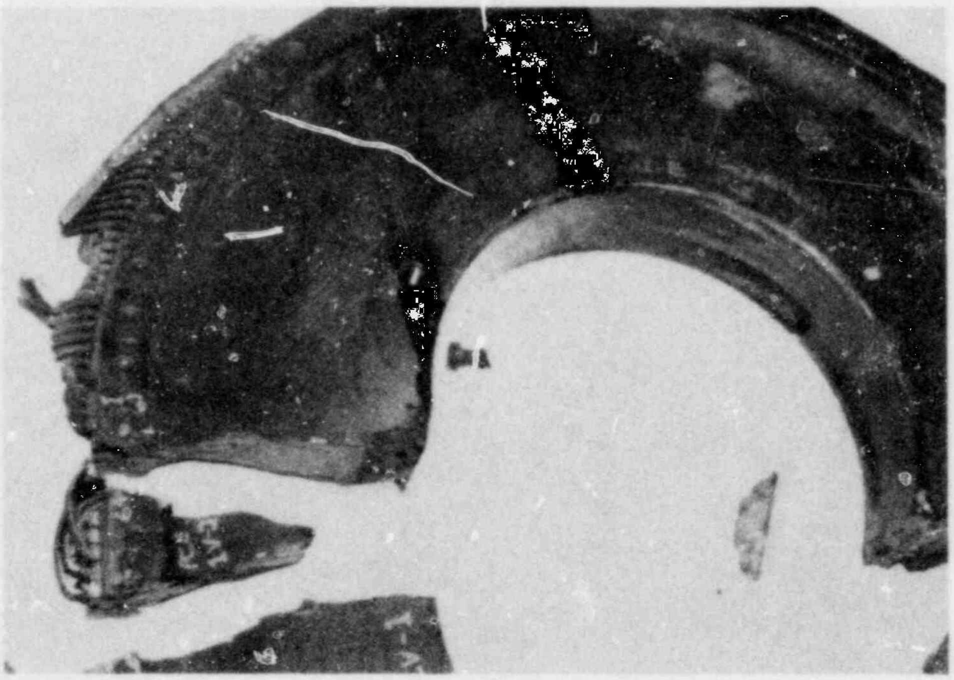

FIG. 14.

FIGS. 13-16. Views from above the No. 1 governor-end disc.

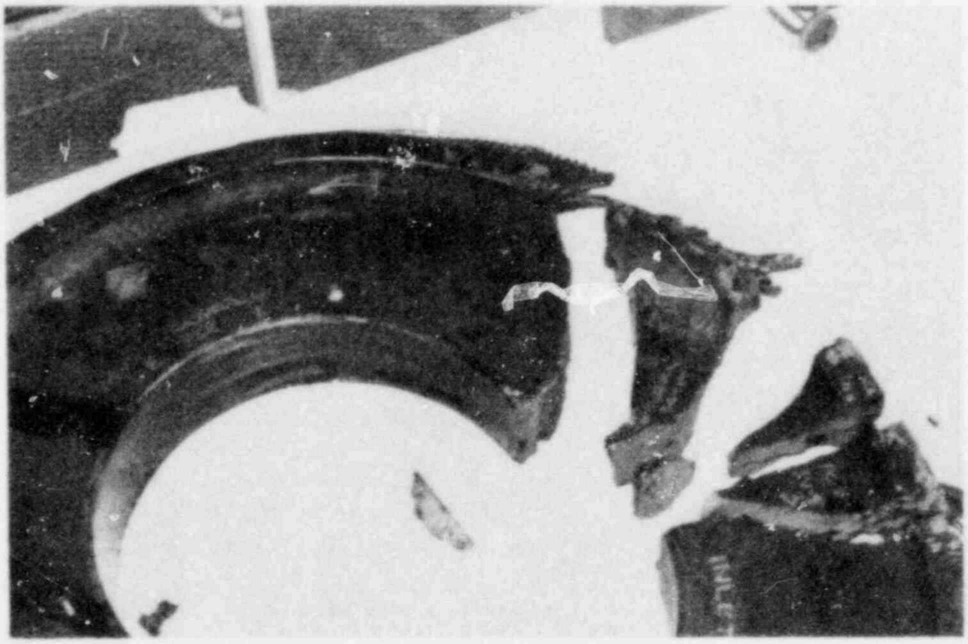

FIG. 15.

FIG. 16.

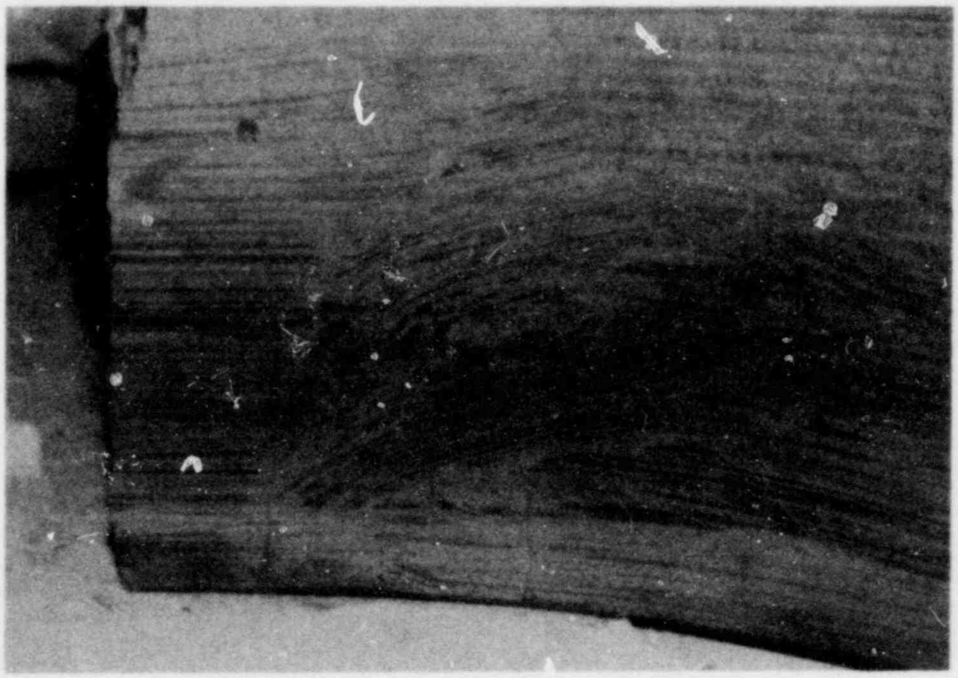

FIG. 17.

FIGS. 17-19. Surface cracking on inner bore of the generator-end disc. Note that the keyway (Fig. 18) did not fail.

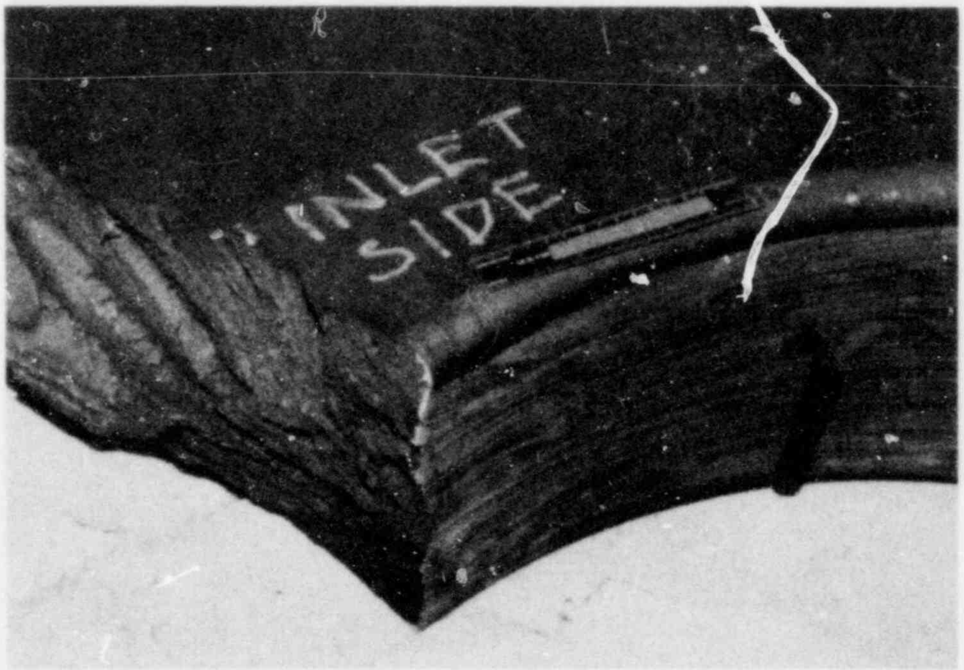

FIG. 18.

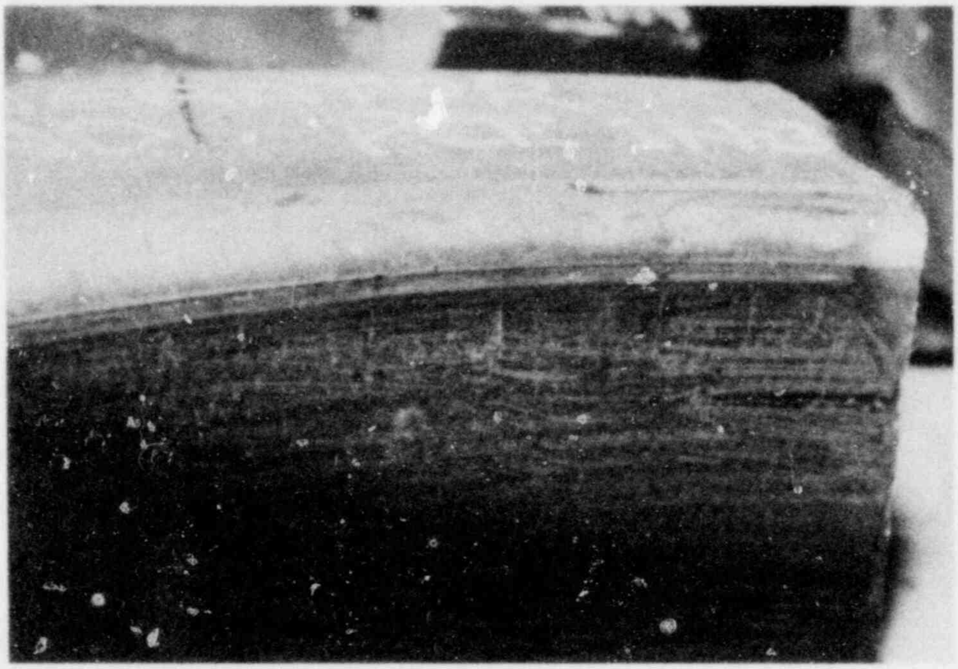

FIG. 19.

FIG. 20. Generator-end disc failure surface on Section 1, between Sections 6 and 1.

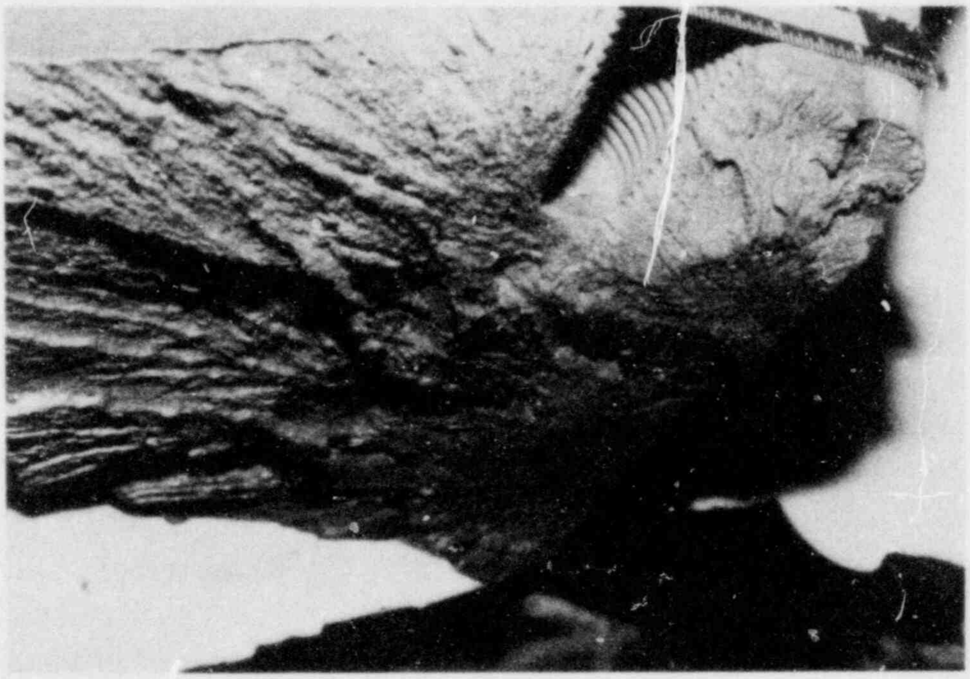

FIG. 21. Generator-end disc failure surface on Section 2, between Sections 1 and 2.

FIG. 22. Generator-end disc failure surface on Section 3, between Sections 2 and 3. Note crack growth (flaws) on different planes.

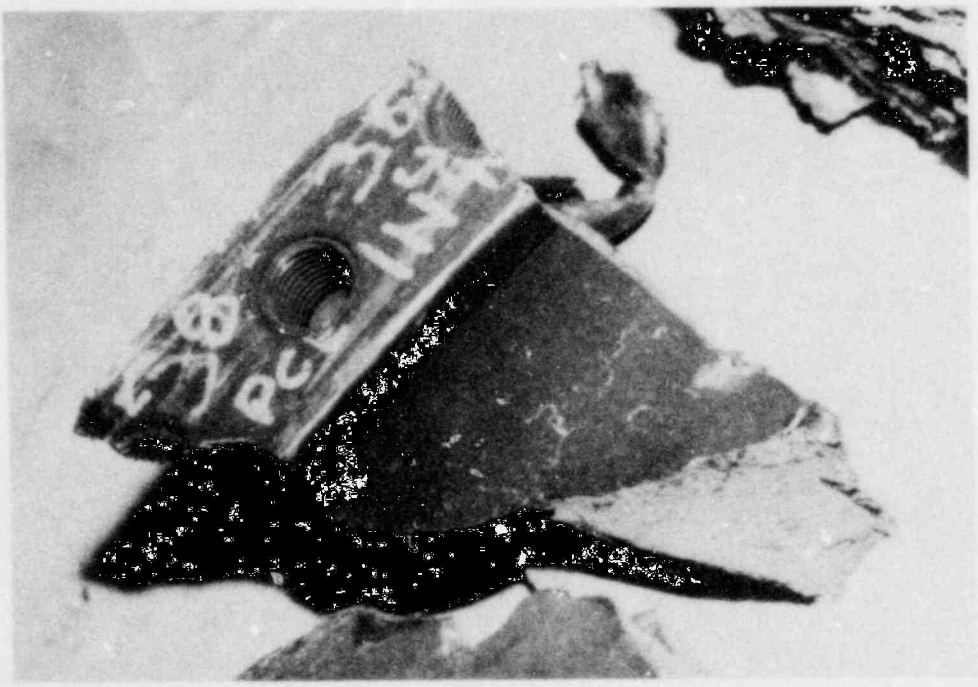

FIG. 23. Generator-end disc failure surface on Section 4, between Sections 3 and 4.

FIG. 24. Generator-end disc failure surface on Section 5, between Sections 4 and 5.

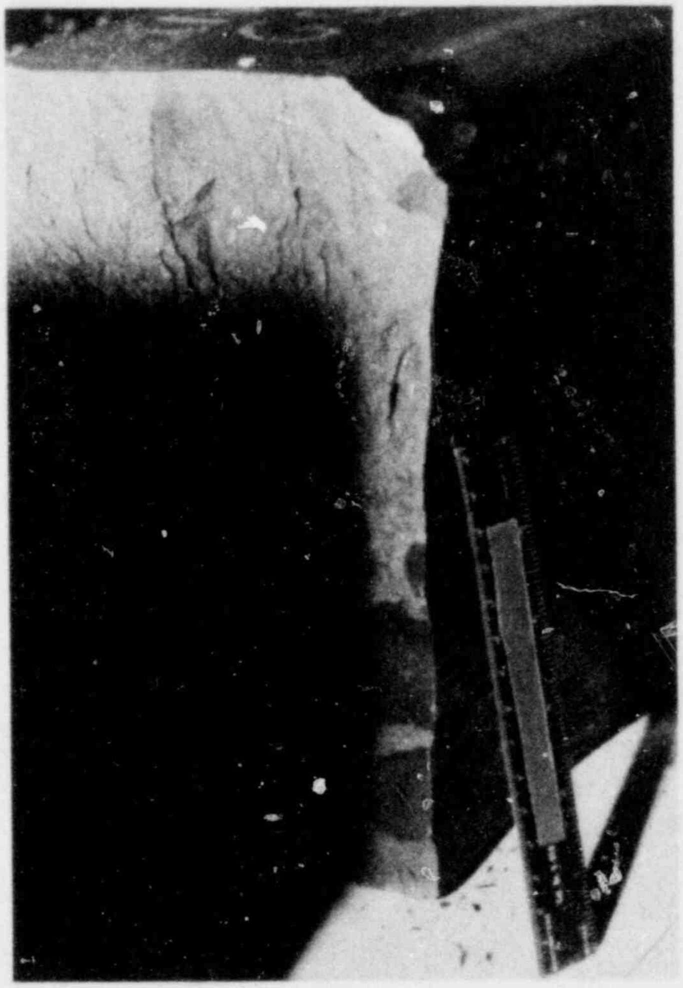

FIG. 25. Generator-end disc failure surface on Section 6, between Sections 5 and 6.

FIG. 26.

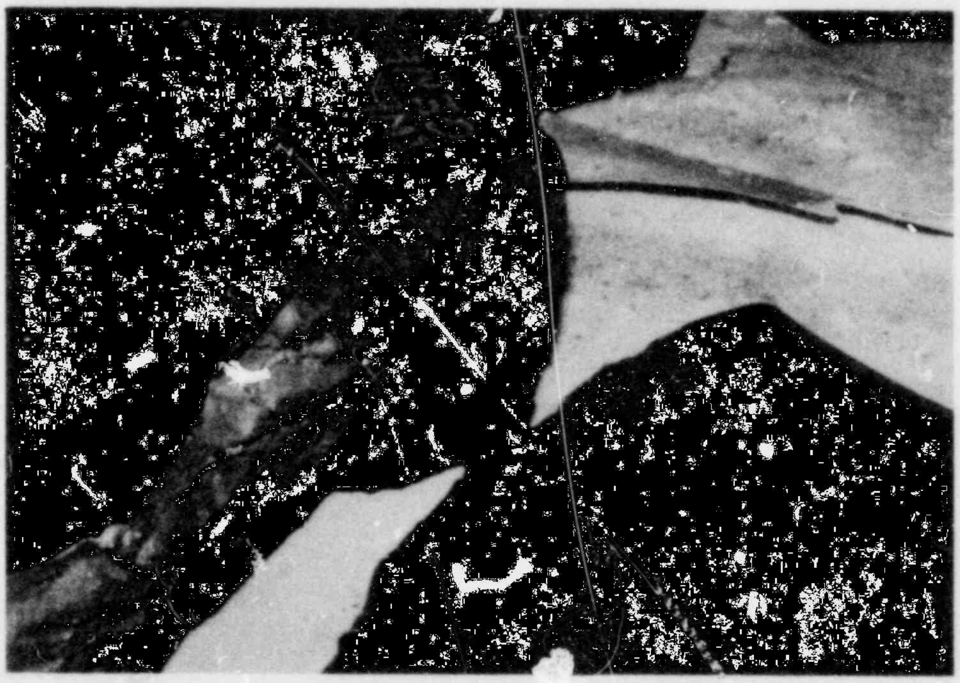

FIG. 27.

FIGS. 26-29. Views of the largest observed thumbnail flaw on a failure surface. The crack is on the generator disc, Section 6, 5/6. Note the flow pattern around the adjacent flaw.

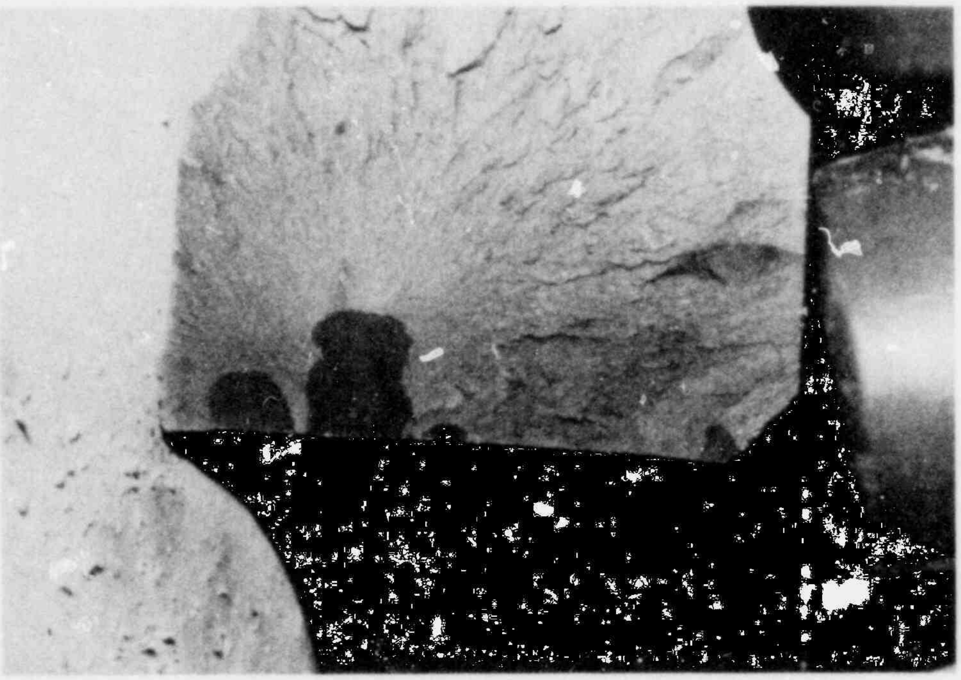

FIG. 28.

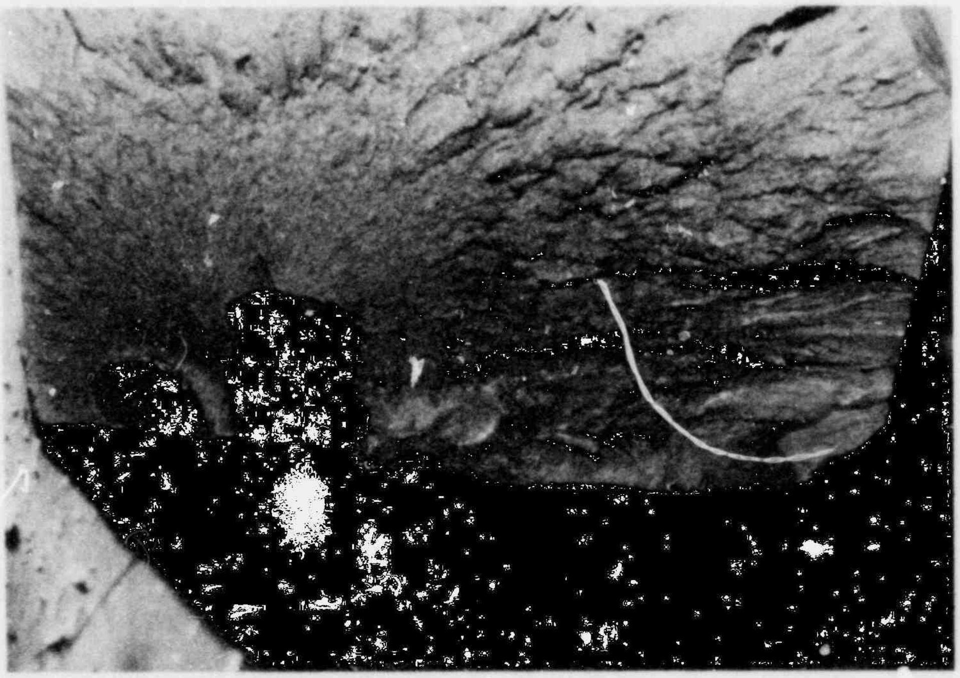

FIG. 29.

FIG. 30. Failure surface on governor-end disc showing apparent crack propagation away from the balance hole.

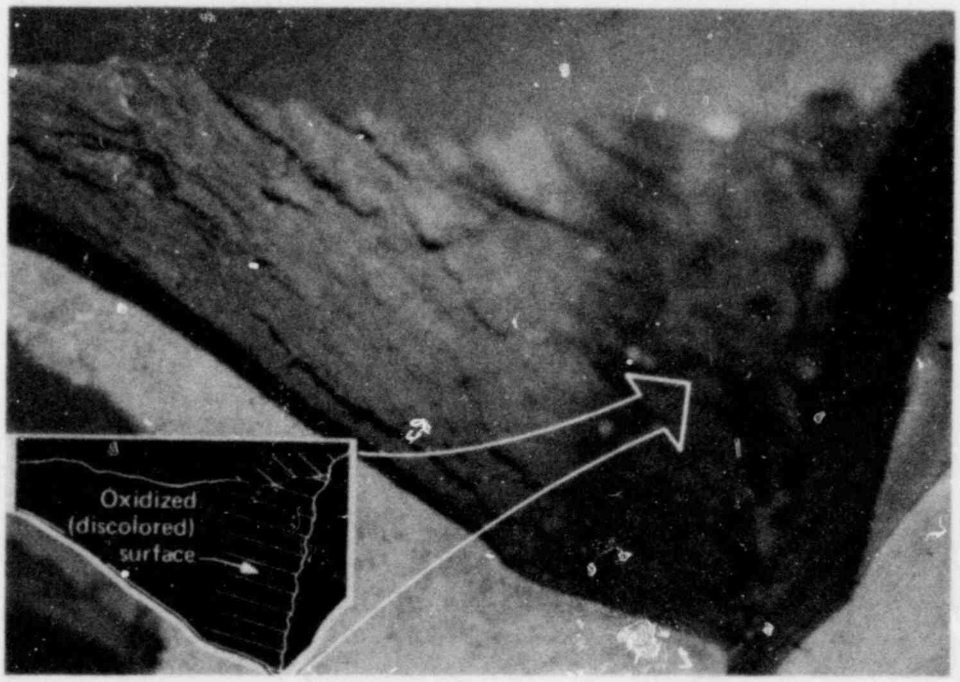

FIG. 31. No. 1 governor-end disc showing extent of rubbing and heat generation during failure.

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77)

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ABSTRACT (200 words or less)

We present a preliminary analysis of the catastrophic disc failure in the low-pressure turbine at the Yankee Rowe nuclear reactor plant. The analysis is based on on-site inspection and documentation of fractured components. Heavily oxidized thumbnail cracks were observed on fractured surfaces of the first-stage generator-end disc, indicating stress corrosion cracking as the precursor to the catastrophic failure of this disc. No evidence of such cracks was seen on the corresponding fractured governor-end disc. We propose a number of alternative possible causes for the failures and for the differences observed between the two discs.

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