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EXAMINATION OF TURBINE DISCS FROM NUCLEAR POWER PLANTS

CARL J. CZAJKOWSKI
JOHN R. WEEKS

Department of Nuclear Energy
Brookhaven National Laboratory
Upton, New York 11973

ABSTRACT

Investigations were performed on a cracked turbine disc from the Cooper Nuclear Power Station, and on two failed turbine discs (governor and generator ends) from the Yankee-Rowe Nuclear Power Station. Cooper is a boiling water reactor (BWR) which went into commercial operation in July 1974, and Yankee-Rowe is a pressurized water reactor (PWR) which went into commercial operation in June 1961. Cracks were identified in the bore of the Cooper disc after 41,913 hours of operation, and the disc removed for repair. At Yankee-Rowe two discs failed after 100,000 hours of operation. Samples of the Cooper disc and both Yankee-Rowe discs (one from the governor and one from the generator end of the LP turbine) were sent to Brookhaven National Laboratory (BNL) for failure analysis.

The fracture face on the Cooper disc was observed to have both intergranular and transgranular cracks. The governor end disc at Yankee-Rowe showed no indication of intergranular attack, and failed as a result of fast fracture, probably following impact by one or more of the fragments produced by failure of the generator disc. The generator end disc had numerous intergranular axial cracks in the bore area. MoS_2 was observed on the bore of all three discs. The Yankee-Rowe discs were subjected to SEM/EDAX, uniaxial tension tests, hardness testing, Charpy "V" notch testing, and environmental notched tensile tests. The notched tensile tests of the generator discs performed with MoS_2 had the effect of reducing the notch tensile strength of the disc by a factor of 3.5. This result was consistent with a similar test conducted with H_2S at ambient temperature and pressure. On the governor disc, the H_2S reduced the notched tensile strength by only a

factor of 2.1, suggesting a reason for the absence of intergranular cracks on this disc. Laboratory data indicate that MoS_2 can hydrolyze in a steam environment to form H_2S, causing stress corrosion cracks to initiate. The results of this investigation support a model that the cracks initiated at startup of the turbine, probably from H_2S produced by hydrolysis of MoS_2, and grew at a rate consistent with the published British data for propagation of cracks in pure steam.

INTRODUCTION

The possibility of inservice failures of steam turbines, especially at nuclear power stations, has become the object of increasing concern in the past few years. This concern arises out of not only the non-profits derived by plant shutdowns which can amount to hundreds of thousands of dollars a day, but also of the possibility of significant damage to safety systems in the event of a catastrophic-type failure.

The most notable instance of this type of failure occurred in 1969 at the British Hinckley Point Nuclear Power Station.(1) The principal cause of the failure was determined to be intergranular stress corrosion cracking of a low pressure disc in the areas of the keyways, attributed to a concentration of NaOH in the keyways combined with a low fracture toughness of the steel caused by temper embrittling during manufacture.

As a result of this incident, investigations were initiated to determine if any U.S. turbines had similar flaws. Weeks,(2) in a review of stress corrosion cracking in various nuclear turbines, e.g., Rancho Seco, Arkansas Nuclear-1, Hinckley Point-A, and Shippingport, determined that caustic was present in all instances and that sufficient evidence was available to conclude stress corrosion cracking as the primary mode of cracking. (Weeks considered that any portion of the fracture face which exhibited an intergranular surface evidenced the fact that the environment played a part in the propagation of the fracture by either stress corrosion cracking or corrosion fatigue.) Since stress corrosion cracks normally occur at stresses substantially less than those required to cause a failure in a benign environment and can produce critical size flaws, the type of failures which result can be quite cataclysmic in nature, e.g., Hinckley Point-A. However, the growth rate of these stress corrosion cracks is relatively small (10^{-7} to 10^{-9} mm sec^{-1}), and their presence can usually be detected before catastrophic failure occurs. The United States Nuclear Regulatory Commission (USNRC) has been conducting ongoing investigations into these phenomena for some time.

At the request of the NRC, a section of a turbine disc from the Nebraska Public Power's Cooper Nuclear Station, which was found to be cracked by inservice inspections, was sent to Brookhaven National Laboratory for examination.

On February 14, 1980, the low pressure turbine at the Yankee-Rowe Nuclear Power Station failed catastrophically. The USNRC requested BNL personnel to visit the Yankee-Rowe site to examine the failed fragments, and, subsequently, pieces of both the failed governor and generator end discs were sent to BNL for analysis. In this paper are presented the results of the BNL examinations of the turbine disc fragments submitted for examination, and the results of experiments performed to suggest the cause of the cracking.

EXAMINATIONS

A. Cooper Disc Fragment

The following information regarding the unit's operating chracteristics and material history was obtained from discussions with representatives of both Nebraska Public Power and the USNRC:

a) The disc was manufactured of ASTM A471 steel, Class unknown.

b) The disc was the #1 disc (generator end) and contained two cracks.

c) The Station is a General Electric Boiling Water Reactor and the turbine was manufactured by Westinghouse Corporation.

d) The low pressure turbine did not have a prior reheating of the steam.

e) The station went into commercial operation July 1, 1974.

f) The disc received 41,913 hours of operation (on line).

g) The keyway temperature during operation was approximately 350°F (177°C).

h) Prior to shipment to BNL the disc had undergone both ultrasonic testing and liquid penetrant examination and had been cleaned with acetone before crating for shipment.

The disc section weighed approximately 110 pounds and its dimensions were recorded. Initial examination detected a crack in the keyway traversing its length measuring approximately 5 inches (12.5 cm) long. There was a second crack which seemed to initiate at the toe of the keyway and ran almost parallel to the main crack.

Further examination of the section disclosed some evidence of pitting in the keyway. There was also a coating of a greyish graphite-like substance covering the hub/keyway surfaces of the disc. Figure 1 shows the cracked area after a liquid penetrant examination to delineate the cracks. The crack extends into the hub surface from the tip of the keyway and a second crack branches into the keyway, also seeming to initiate at the keyway tip. The depth of the crack on the outer surface was estimated to be 2".

A section was cut from the turbine disc to facilitate opening the fracture face. The section was then immersed in liquid nitrogen for almost one hour and the crack opened by applying force on the notch in a compression tester. The resulting fracture face is shown in Figure 2. The remainder of the turbine disc was then liquid penetrant tested again to determine if the entire crack had been removed. This examination showed that some of the cracks still remained. The disc was then cut approximately one inch further along the crack direction, and the above steps repeated. The fracture faces were then reassembled and measurements taken of the crack dimensions (Figure 3). The crack's length measured 13.45 cm (approximately 5.3") at its longest dimension, and 5.564 cm (approximately 2.1") at its greatest depth.

The crack was characterized by a black adherent film covering the fracture face and appeared to be mixed intergranular and transgranular in nature as viewed through a stereo microscope. Visual examination disclosed no arrest lines or beach marks, suggesting that once the crack initiated, it progressed with no apparent cyclic frequency.

Various chips of the fracture face were broken off for SEM/EDS examination. These were taken near the crack tip in hopes of determining if any corrodent species were present and to pick areas where the prior liquid penetrant examinations had not contaminated the fracture face. The cracking appeared to be of a mixed mode, both intergranular and transgranular in nature, with the intergranular appearance more predominant in the chips taken from areas closer to the keyway (probable area of initiation). (See Figs. 4 and 5.)

Various particulates were investigated by EDS on the varying chips. All showed peaks of Cl and evidence of both Si and K in varying degrees from traces to peaks; one scan showed a trace of S and V with an abnormally high Mn peak with the Cl and K present. These particulates were widely dispersed among the chips.

Several partially opened cracks were scanned, showing peaks of Na, Mg, Si, Mo, Cl, K and Ca, with a trace of Ti in one case, only Al and Ti in one case, and Cl, Si, S and Al in three others.

An EDS scan of the graphite-like substance found on the hub surface of the disc was also performed, and identified peaks of S and Mo with a background peak of Fe (possibly from the tool used to remove substance from the disc surface). This is indicative that MoS_2 was used as a lubricant during assembly of the turbine rotor.

B. Yankee-Rowe Fragments

During the site visit it was observed that only the generator disc fragments showed evidence of stress corrosion cracking on the fractured surfaces; the governor disc appeared to have failed upon impact from fragments of the generator disc. The turbine housing and stator were not breached, so that fragment ricochet is quite possible. On neither turbine disc was there any visual evidence that the cracks initiated from the keyways.

This investigation was two-fold in objective: 1) to determine, if possible, the cause of the intergranular attack on the bore surface of the generator end disc, and 2) to ascertain if the generator end disc differed in any way from its uncracked (no intergranular attack) sister disc on the governor end.

The following information regarding the unit's operation was obtained from the Nuclear Regulatory Commission:

1) The first commercial operation for the Yankee-Rowe unit was in June 1961.

2) The failure occurred during startup after the turbine had reached operating speed, but before the generator was placed in line; conditions were 1800 rpm and 2% steam.

3) The disc material was forged in 1958.

4) The inlet steam temperature to the LP turbine was approximately 300°F (149°C).

5) The turbine had operated more than 100,000 hours on line.

6) The power plant was a Westinghouse Pressurized Water Reactor (PWR) with a Westinghouse Steam Turbine.

Visual Inspection/Photography/Optical Metallography

The crated weight of the two disc sections received at BNL was approximately 700 pounds. The two sections are shown in Figs. 6 and 7.

After being photographed, the two sections were cut to allow the bore surfaces to be examined more readily. The section of the generator disc was characterized as having numerous axial cracks running perpendicular to the circumferential direction of the hub. The fracture faces contained thumbnail corroded areas, which appeared to be mostly intergranular as viewed through a stereo microscope. (Prior to photographing this section, the visible thumbnail cracks were outlined with chalk.) The fracture faces were also characterized as having a tight black adherent oxide film on them in the thumbnail areas, similar to the film observed on the Cooper turbine disc. The balance of the fracture surface was clean and appears to have failed by cleavage after the stress corrosion crack reached a critical size. There was evidence of a grayish graphite-like substance on the hub which appeared to have been applied by brushing, as evidenced by the marked brush strokes in the photograph. These brush strokes were applied in the circumferential direction of the hub and were generally perpendicular to the cracks. There was also evidence of secondary cracking not necessarily associated with the intergranular cracks shown in Fig. 8, which is assumed to be a result of the fast fracture mode of the failure.

The governor end disc had a large rubbed area (Fig. 7) near the bore which was probably the result of its location during rundown after the failure. The area of rubbed metal which extended into the bore area was removed and the bore surface inspected by liquid penetrant examination. The bore surface of this disc was also coated with a gray substance. There was no evidence of bore cracking on this disc, nor were there any "thumbnail" cracks on any of the fracture surfaces of the governor disc, as observed at the Yankee-Rowe site and in the BNL examination.

Two cracks from the generator end disc were sectioned and mounted, with the polished face perpendicular to the growth direction of the cracks. In the photomicrographs (Figs. 9 and 10), the cracks appear to be generally intergranular in nature with very little crack branching. The metal matrix appeared to be tempered martensite (bainite) with areas of proeutectoid ferrite. This structure would be consistent with that expected by quenching and tempering a low alloy high strength steel. There was no significant difference in the microstructures of the two discs.

Various axial cracks from the generator disc were broken open after cooling the cut sections in liquid nitrogen. The fracture faces appeared to be generally intergranular in nature (Fig. 11) and had traces of Si, S, Cl, Mn with the Fe, Cr and Ni, as shown in a representative EDS scan (Fig. 12).

Samples from each of the discs were sent to an outside laboratory for chemical analysis. Table 1 depicts the results of the analysis. There are two items worth noting: 1) the carbon analysis reported exceeds the limits of the two specifications listed in the table, and 2) there appears to be some segregation in the heavier elements analyzed (e.g., Mo, V, Cr). This segregation may be the result of the relative locations of both discs in their original ingot. There is, however, no significant difference in the chemistry of the two discs.

To determine if there were any detectable differences in the mechanical properties of the two discs that might explain the differences in their properties, tensile tests, hardness tests and Charpy "V" notch tests were performed on specimens cut from each disc. No significant differences were observed.

DISCUSSION

Although previous investigators, cited in Ref. 2, had suggested that caustic deposition in the LP turbines was responsible for much of the cracking, there was no concrete evidence that caustic played a role in the cracking at either unit investigated. Indeed, Cooper is a BWR, in which no attempts are made to raise the pH of the coolant, so that caustic deposition would be less likely to occur than in a PWR turbine, where steam generator pH is usually greater than 9.0. Consequently, the common factor that might have led to crack initiation appeared to be the MoS_2 lubricant identified from this investigation as having been used in assembling both turbines. To this end, notch tensile tests were performed on specimens cut from both Yankee-Rowe discs, both in air and in clean steam. Since, when MoS_2 was sprayed on the specimens, a distinct odor of H_2S was observed during exposure to steam, comparative tests were also performed in an H_2S environment. The results are shown in Fig. 13.

Whereas steam appears to have little effect on the notched tensile strength of the material, the presence of steam plus MoS_2 and the presence of H_2S caused a 3.5-fold reduction in this property on the generator disc. The governor disc specimens appeared to be less sensitive to H_2S attack, since the reduction in notched tensile strength was only 2.1-fold for this disc.

High strength low alloy steels have been known to be sensitive to many varied environments. Since the notched tensile tests had suggested that there was probably some interaction between the MoS_2, the turbine disc steel and the steam, a further review of the effects of this lubricant was made.

Clauss[3] has recorded that MoS_2 is resistant to most acids and will begin to oxidize in dry air at approximately 750°F with MoO_3 and SO_2 as the products of oxidation. He also recorded, however, that MoS_2 will perceptibly oxidize in moist air at room temperature. This oxidation in moist air at room temperature is quite probably the characteristic most applicable to turbine discs. Haltner and Oliver,[4] in their studies on the frictional behavior of MoS_2 in flowing nitrogen/water mixtures when in contact with a rotating disc, determined in part that 1) increasing the water content increased the friction, and 2) this increase in friction was associated with the subsequent release of H_2S. This reaction is apparently reversible, as Rowe[5] was able to regenerate an oxidized MoS_2 film by heating it to a temperature of 850°C in a low pressure of H_2S gas.

Whether the MoS_2 itself or some subsequent species produced during formation of H_2S interacts with the metal surface is currently not known. The formation of metallic sulfides on the metal/MoS_2 interface have been observed, and H_2S-initiated cracking of high strength steels is well known.[6]

Other investigations have determined that there is an effect of the MoS_2 with either moisture or steam on various metals. Calhoun[7] determined that MoS_2 in greases increased the corrosive tendency of all greases tested. He postulates in part that this is caused by the formation of corrosive products, through hydrolysis. Perna[8] concluded that MoS_2 accelerates galvanic corrosion of various metals when in a steam environment. Coating turbine disc steels with MoS_2 and subjecting them to a steam environment has also been observed[9] to reduce the crack initiation time by a factor of three.

It can be argued that hydrogen attack cannot occur in the temperature range of turbine operation (over 100°C). This would be true if the turbine operation was isothermal; this is not the case, as turbines are periodically shut down for fuel loads, etc. Even so, the 100°C temperature limit is for H_2 gas embrittlement, not H_2S attack. Clark has shown[6] that H_2S embrittlement is relatively insensitive to temperature up to 100°C.

Since H_2S can be liberated by MoS_2 in a steam environment, it is necessary to see how this reaction could cause disc cracking in either the keyways or the bore.

Bore Cracking

Turbine discs are normally shrunk fit onto the shaft during the usual manufacturing sequence of turbine assembly. This shrunk on pre-load can be as high as 60% of the design yield strength. Various investigators have shown a correlation between applied stress and its proportional increase of hydrogen assisted cracking. If the hub of a turbine had been coated with MoS_2 prior to the disc being shrunk fit on it, then this initial pre-load may be significantly increased due to the tremendous load carrying ability of MoS_2. Clauss[3] has recorded a load bearing capacity for MoS_2 of over 400,000 psi.

It can be safely stated, therefore, that the original pre-load can be significantly increased if MoS_2 is applied to the hub of a turbine disc, at least in areas of heavier deposits of brushed-on MoS_2. This increase in pre-load might cause one disc to fail in a given turbine with an adjacent disc (with less MoS_2) showing no evidence of attack. The mode of intergranular attack is assumed to be caused by a hydrogen or H_2S assisted mechanism arising from the MoS_2/water/metal interaction.

Keyway Cracking

Keyway cracking may result from a slightly different mechanism due to the manufacturing processes involved. The keyways are normally drilled after the disc has been shrunk fit on the shaft, and unless MoS_2 has been used to insert the key, very little if any MoS_2 would normally be present in the keyway. Since the tip of the keyway, however, would be at the disc/shaft/MoS_2 interface, there is a possible explanation. As previously discussed, MoS_2 can hydrolyze to H_2S in steam. The interaction of H_2S with the clean metal of the keyway accelerates corrosion by a hydrogen assisted mechanism. This is probably the result of FeS formation on the clean surface of the metal, allowing H_2 entry at a faster rate. This layer of FeS is considered by Sieradzki (10) to be only a few monolayers thick, which would not be in the detectable range of EDS analysis. The amount of H_2S needed would also not have to be great because Hudgins et al.[11] observed failures in a quenched and tempered alloy steel with as little as 0.10 ppm H_2S in solution.

Postulated Cracking Mechanism

Any effect of the H_2S generated by hydrolysis of the MoS_2 would be likely to be of short duration compared to the thousands of hours the turbines have operated. However, cracks, once initiated, are known to grow in this material in a clean steam environment at a rate that is relatively insensitive to the stress intensity factor above a threshold value of approximately 20 MN $m^{-3/2}$. If we assume, therefore, that on the affected discs, hydrolysis of the MoS_2 produced an environment that led to crack initiation early in the operating life of the turbine disc, then these cracks would be expected to propagate in the steam environment throughout the life of the unit.

To test this hypothesis, the crack propagation rates were estimated from the maximum size of the "thumbnail" marks at Yankee-Rowe and the deepest penetration measured at Cooper, divided by the operating times of the two units. These were 3.7×10^{-7} mm/sec for the Cooper disc and 1.04×10^{-7} mm/sec for the Yankee-Rowe disc. These values are compared with the data of Ford[12] and McIntyre[13] in Fig. 14. Clearly, the measured crack depths are consistent with this hypothesis. Further, this figure and hypothesis are consistent with the work of Thornton et al.,[9] which showed that MoS_2 has little effect on the crack growth rate.

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TABLE 1

CHEMICAL ANALYSIS

Generator End Disc

	Results, % by wt.			ASTM A294 Class C	ASTM A471 Class 5
	B	D	F		
Carbon	0.52	0.54	0.53	0.35 max	0.35 max
Manganese	0.42	0.41	0.41	0.60 - 0.90	0.70 max
Phosphorus	0.002	0.001	0.002	0.035 max	0.015 max
Sulfur	0.017	0.016	0.018	0.035 max	0.015 max
Nickel	2.08	2.15	2.08	1.50 - 3.50	2.00 - 4.00
Chromium	0.65	0.68	0.60	0.70 max	0.75 - 2.00
Molybdenum	0.31	0.48	0.41	0.20 min	0.20 - 0.70
Vanadium	0.03	0.07	0.02	0.03 - 0.12	0.05 min
Antimony	< 0.01	< 0.01	< 0.01	-	-
Silicon	0.21	0.21	0.20	0.15 - 0.35	-

< None detected, Less than

Governor End Disc

	Results, % by wt.				
	A	C	E		
Carbon	0.53	0.53	0.54	.035 max	0.35 max
Manganese	0.41	0.41	0.42	0.60 - 0.90	0.70 max
Phosphorus	0.001	0.001	0.001	0.035	0.015 max
Sulfur	0.018	0.018	0.019	0.035	0.015 max
Nickel	2.17	2.16	2.15	1.50 - 3.50	2.00 - 4.00
Chromium	0.64	0.60	0.64	0.70 max	0.075 - 2.00
Molybdenum	0.52	0.48	0.45	0.20 min	0.20 - 0.70
Vanadium	0.07	0.03	0.07	0.03 - 0.12	0.05 min
Antimony	< 0.01	< 0.01	< 0.01	-	-
Silicon	0.20	0.20	0.20	0.15 - 0.35	-

< None detected, Less than

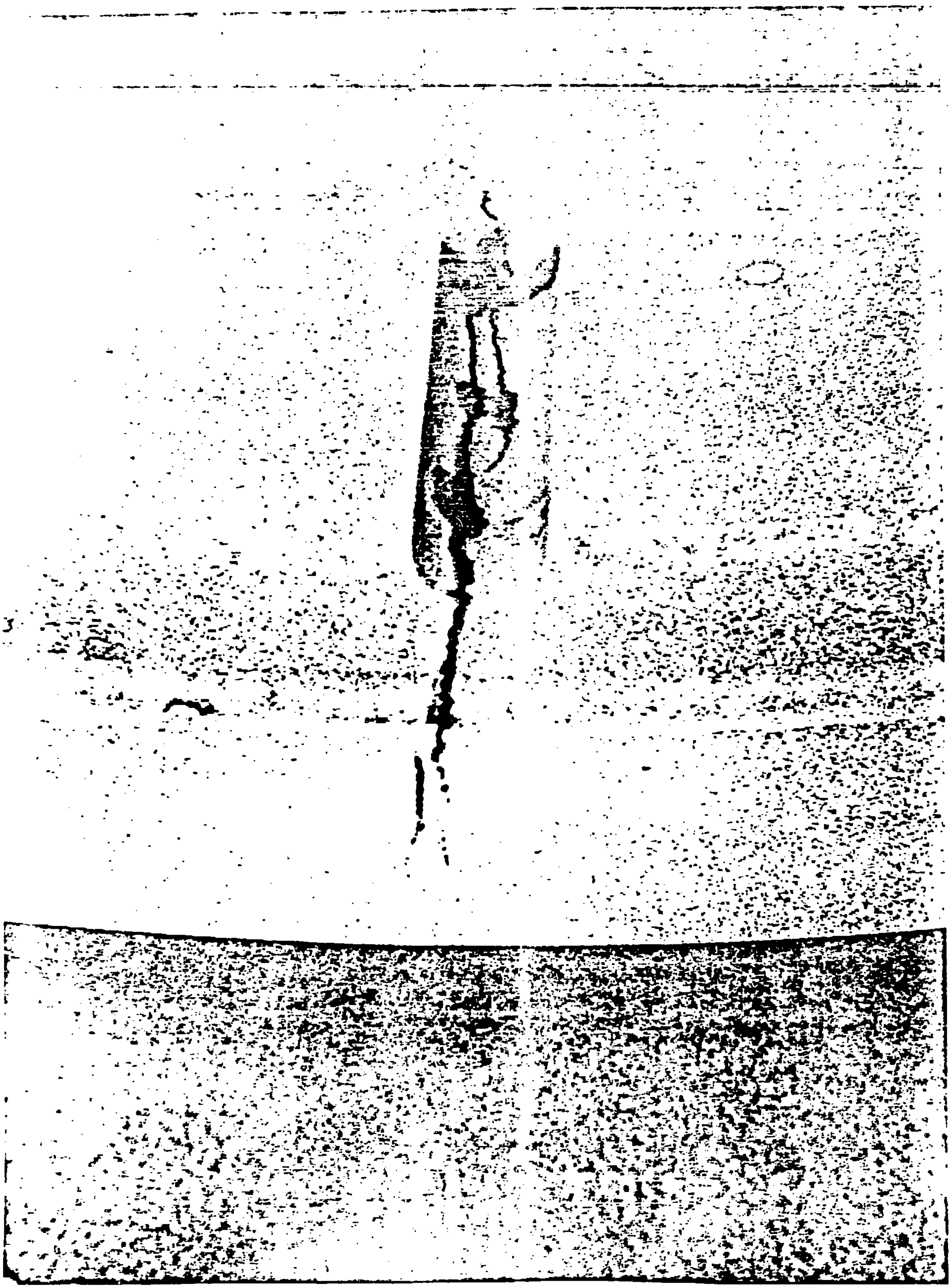


Figure 1 Photograph of keyway crack after liquid penetrant examination (front view). Cooper Turbine Disc

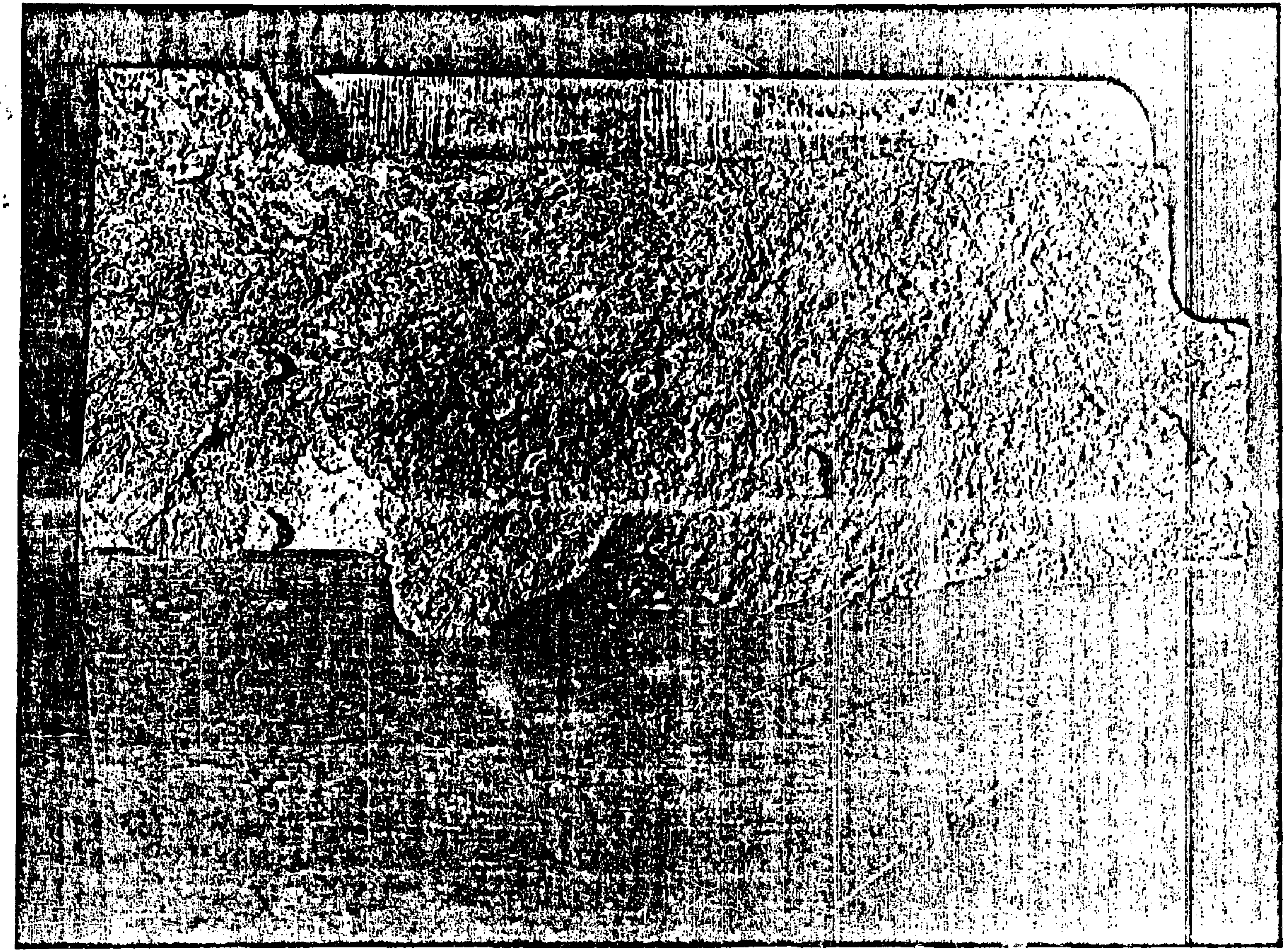
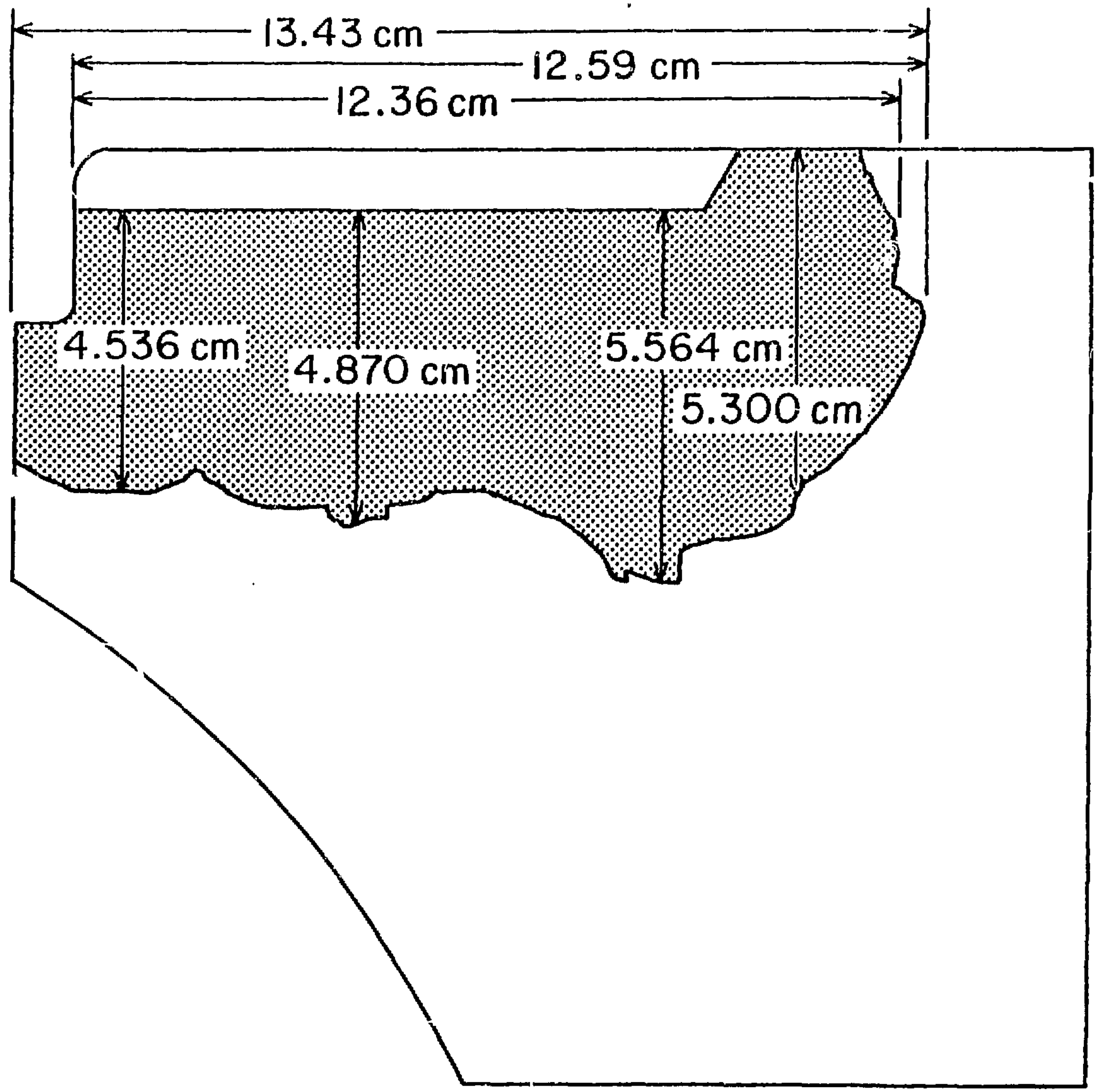


Figure 2 Fracture face of turbine disc after opening of crack with compression tester. Cooper Turbine



DIMENSIONS OF ONE HALF OF CRACK FACE
(NOT TO SCALE)

Figure 3
(Cooper Turbine Disc)

Figure 4 500X
SEM photo of intergranular nature of fracture face. (Cooper Turbine)

Figure 5 500X
SEM photo of fracture face depicting a transgranular area. (Cooper Turbine)

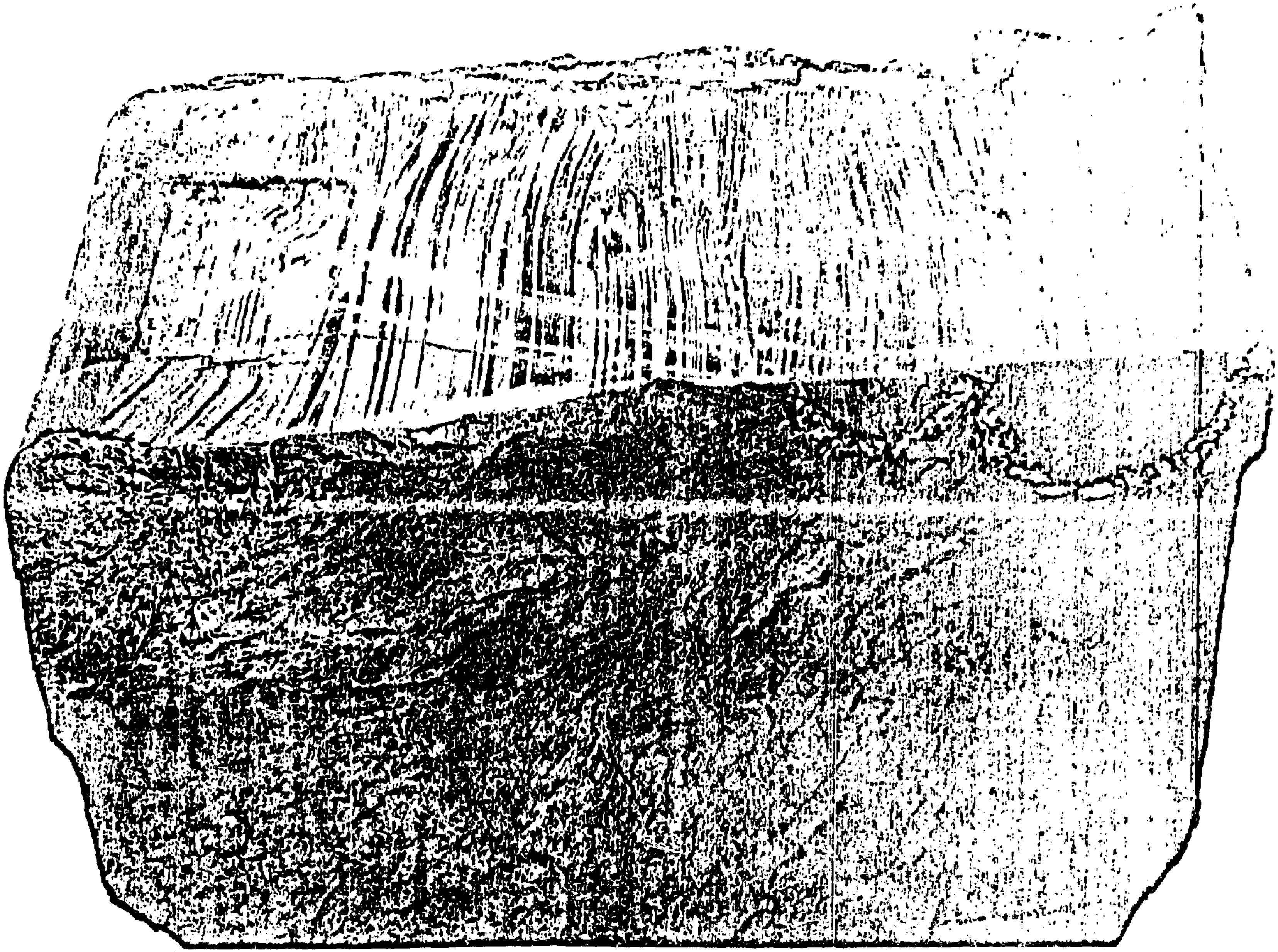


Figure 6 Section of Generator End Disc after cutting showing "thumbnail" cracks outlined in chalk and wide brush strokes on hub (Yankee-Rowe Turbine).

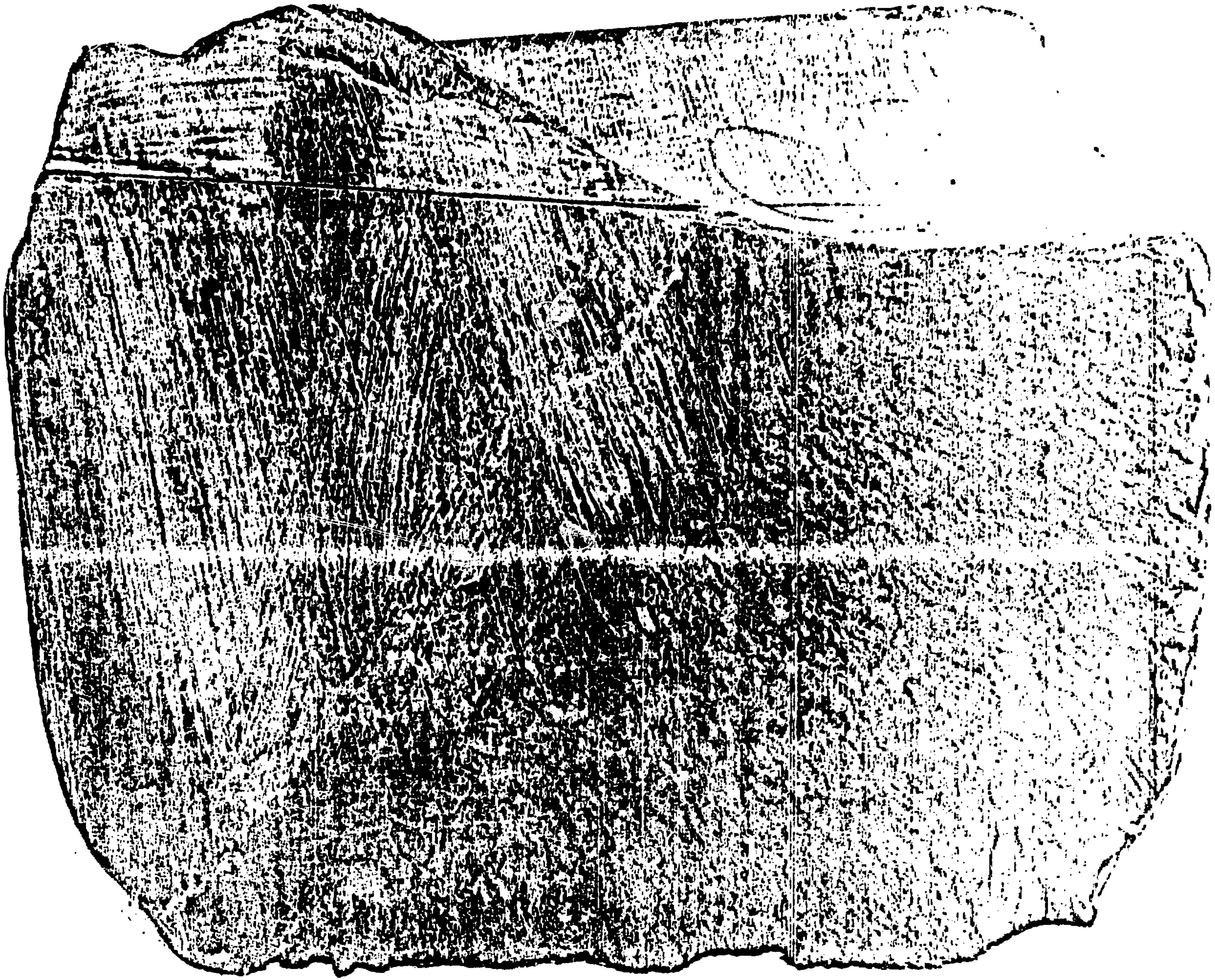


Figure 7 Governor End Disc after cutting depicting large rubbed metal area at hub surface (Yankee-Rowe Turbine)

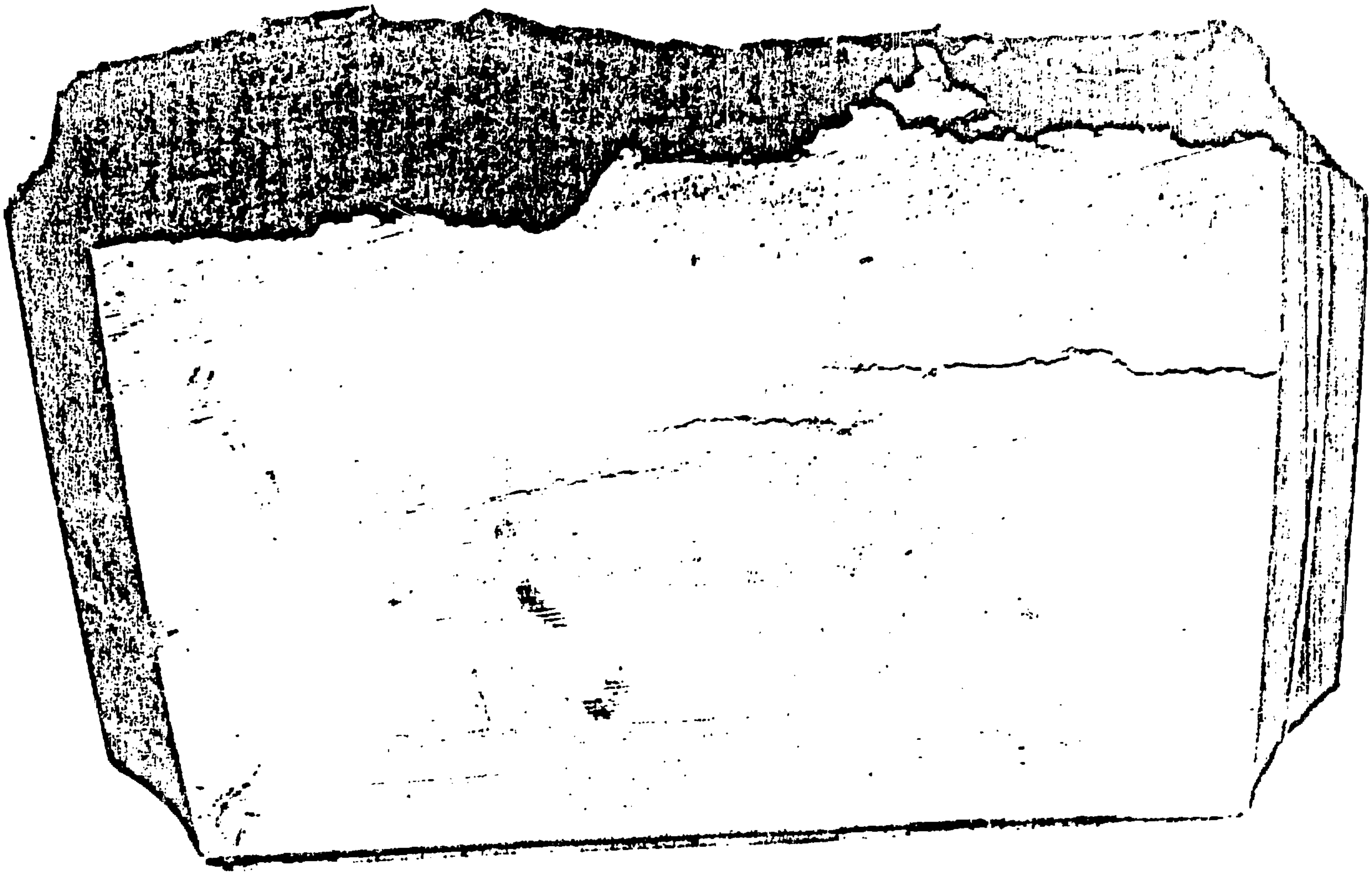
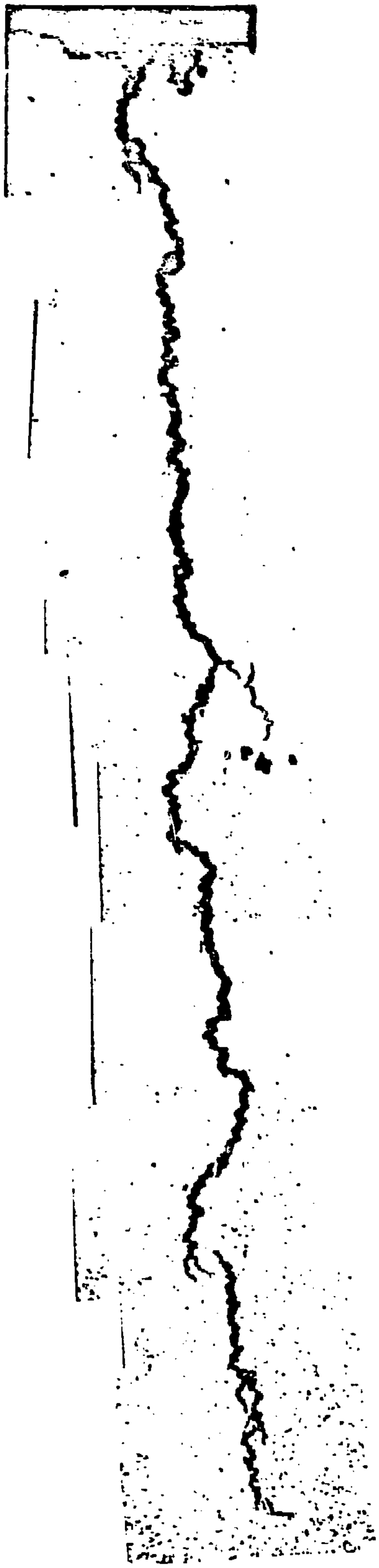
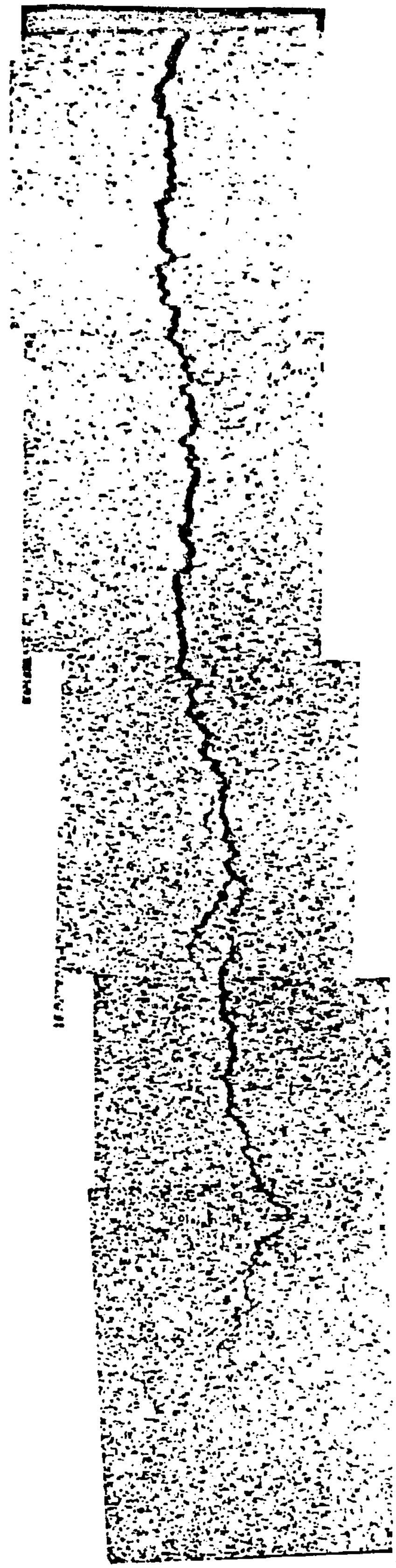


Figure 8 Cut portion of Generator End Disc showing amount of secondary cracking after failure (Yankee-Rowe Turbine)



100 X

Fig. 9 Photomicrograph of axial crack (typical) Generator End Disc, 6.7 mm in length (Yankee-Rowe Turbine)



100 X

Fig. 10 Photomicrograph of second axial crack (typical) Generator End Disc, 4.1 mm in length (Yankee-Rowe Turbine)

Figure 11 200X
SEM photo depicting cracks, predominately intergranular (Yankee-Rowe)

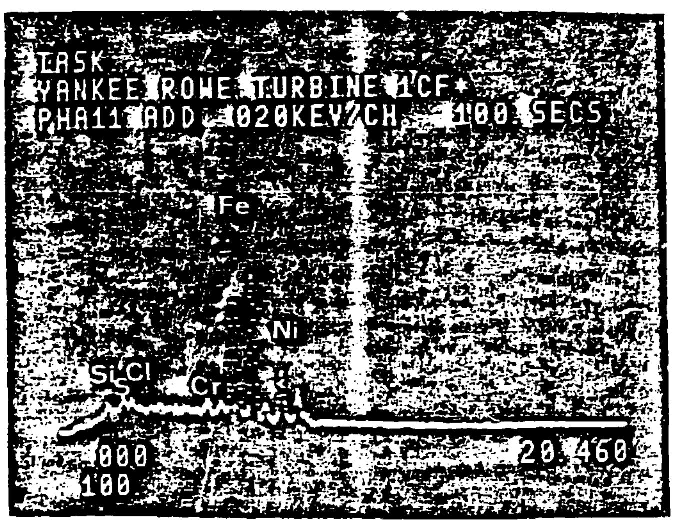
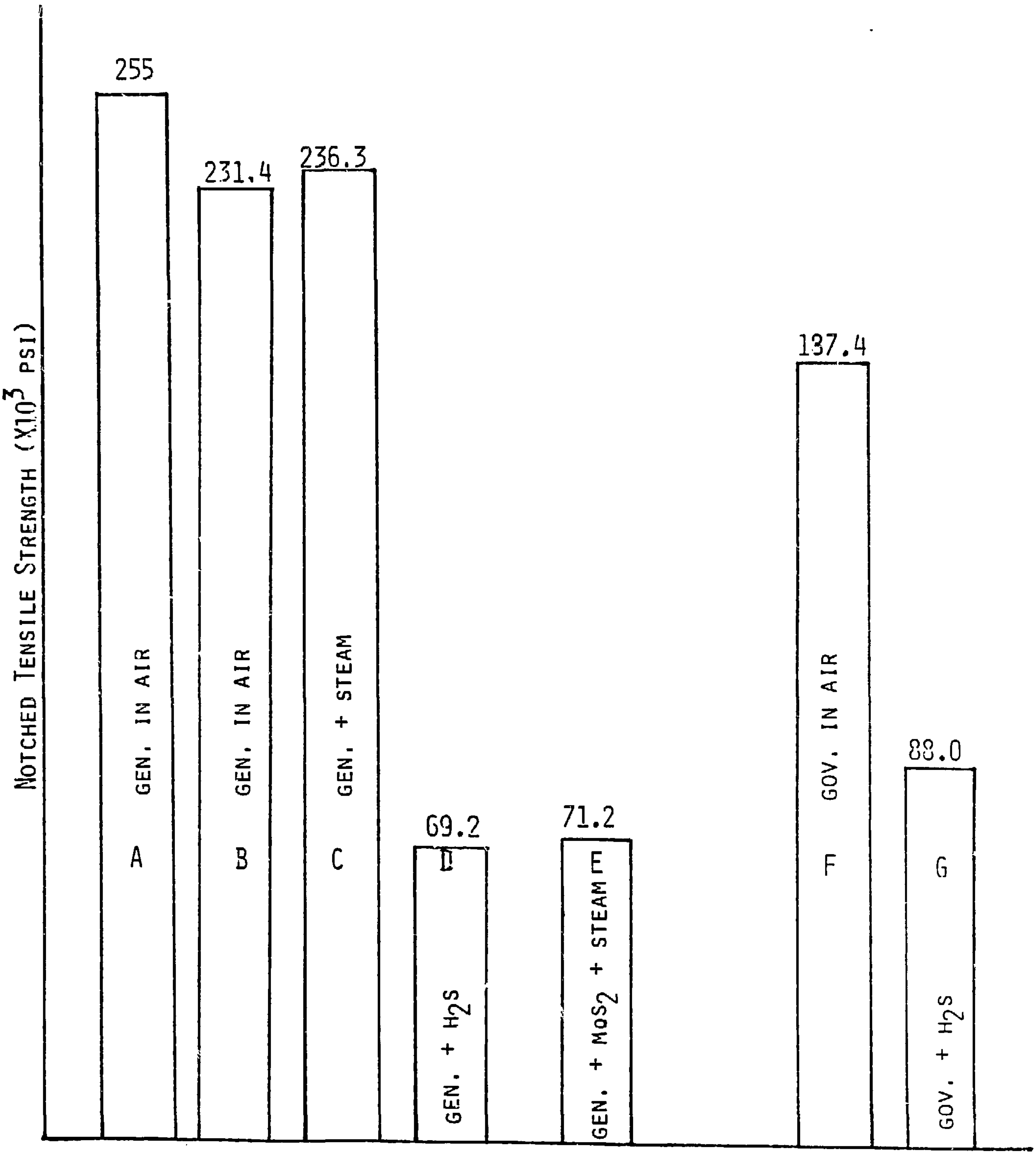
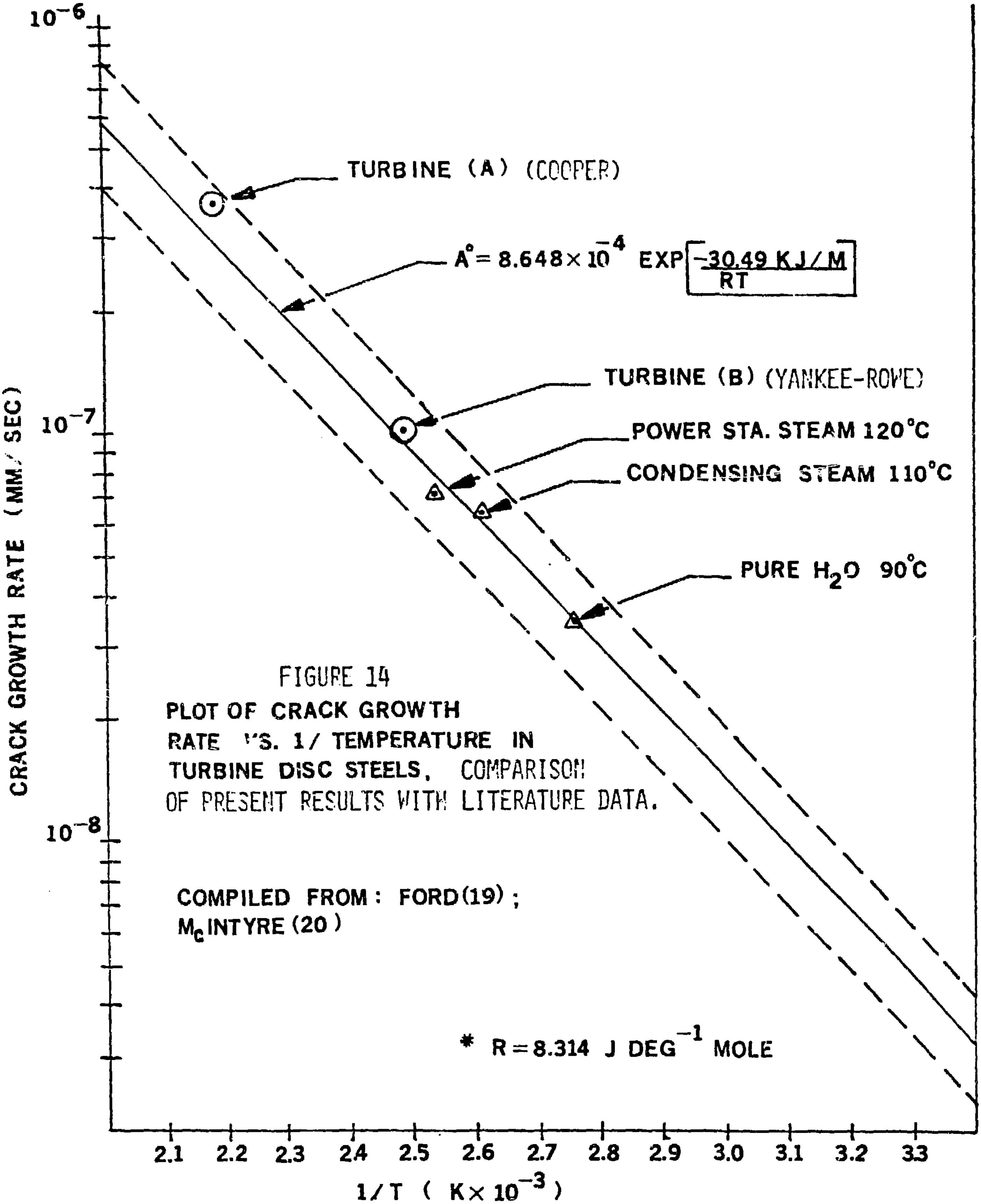


Figure 12
EDS scan showing representative elements present in fracture faces

FIGURE 13

RESULTS OF NOTCHED TENSILE TESTS
YANKEE-ROWE TURBINE DISCS





TURBINE (A) (COOPER)
A° = 8.648 × 10^-4 EXP [-30.49 KJ/M / RT]
TURBINE (B) (YANKEE-ROWE)
POWER STA. STEAM 120°C
CONDENSING STEAM 110°C
PURE H_2O 90°C
FIGURE 14
PLOT OF CRACK GROWTH RATE VS. 1/ TEMPERATURE IN TURBINE DISC STEELS, COMPARISON OF PRESENT RESULTS WITH LITERATURE DATA.
COMPILED FROM: FORD(19); McINTYRE (20)
* R = 8.314 J DEG^-1 MOLE
CRACK GROWTH RATE (MM/SEC)
10^-6
10^-7
10^-8
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
3.1
3.2
3.3
1/T (K × 10^-3)

FIG. 43

ION:

Materials Engineering Branch, ONRR

c/o S. S. Pawlicki

Materials Engineering Branch, ONRR

c/o C. D. Sellers (10)

W. Y. Kato, Deputy Chairman

Corrosion Science Group Files (50)

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A. Goldberg (5)

owe Power Plant

Plant Manager (2)