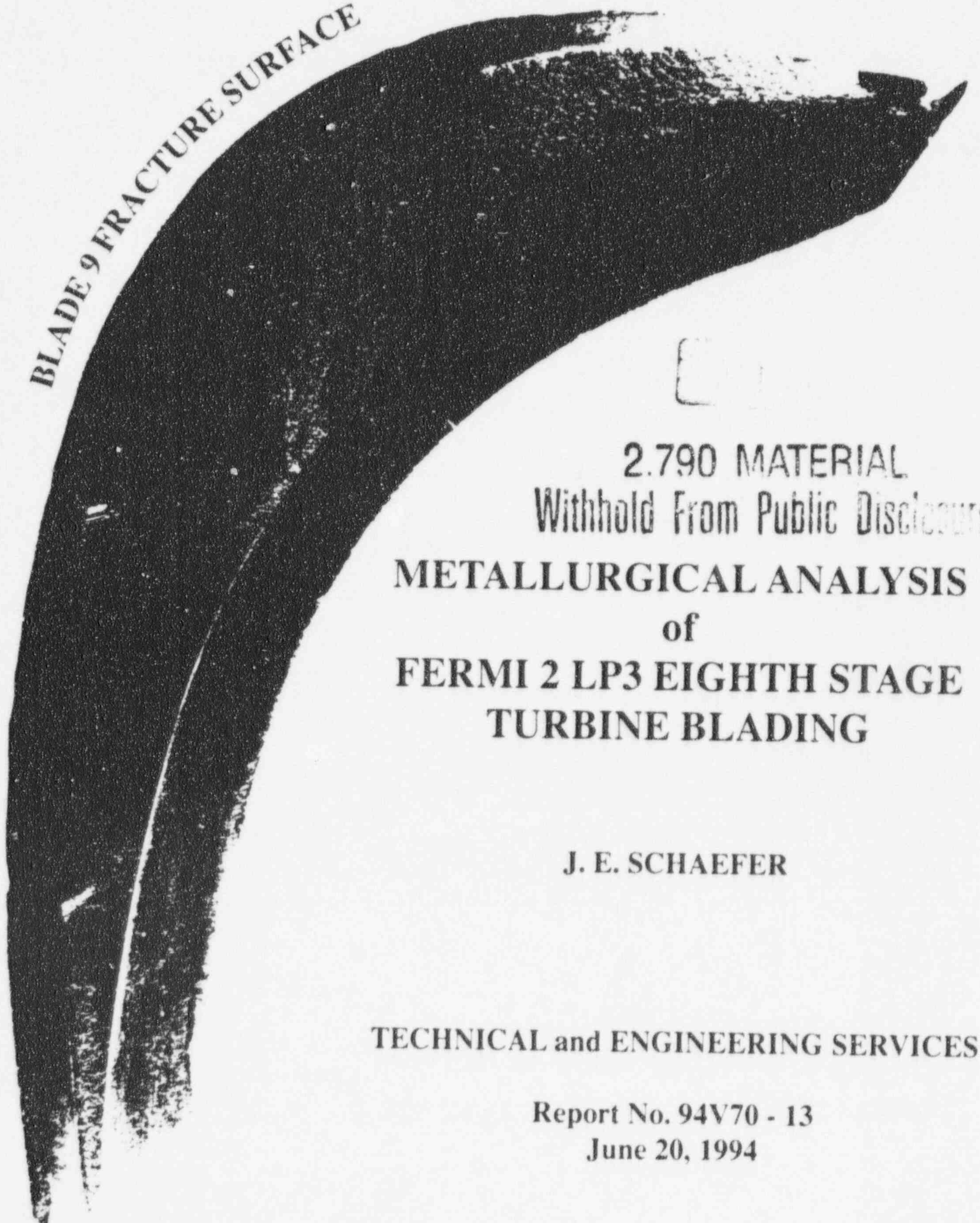

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METALLURGICAL ANALYSIS of FERMI 2 LP3 EIGHTH STAGE TURBINE BLADING

J. E. SCHAEFER

TECHNICAL and ENGINEERING SERVICES

Report No. 94V70 - 13
June 20, 1994

B/1

EXECUTIVE SUMMARY

The December 25, 1993 Fermi 2 Main Turbine Generator trip was accompanied by high vibration, the penetration of a low pressure turbine casing by a piece of turbine blade, and damage or destruction of other key components. Subsequent damage assessment revealed the loss of five eighth stage blades from the turbine end of LP3. Metallurgical analysis indicated that the failure of one blade, Blade 9, initiated the blade failures and that Blade 9 failed by fatigue with the origin near the trailing edge about one inch above the platform. The fatigue failure appears to have originated at a tool mark similar to those found at random locations on other blades. Blade 9 is distinct in that it was significantly thinner in the failure plane than other blades at the same location and that the tool mark was located in the area of reduced cross section. All blades tested were of the specified material and had been uniformly heat treated to produce the specified mechanical properties. As the information and data contained herein became available, they were transmitted to the Root Cause Analysis Team of the Turbine Generator Assessment Team.

METALLURGICAL ANALYSIS

of

FERMI 2 LP3 EIGHTH STAGE TURBINE BLADING

INTRODUCTION

On December 25, 1993, the Fermi 2 Main Turbine Generator tripped and coasted to a stop in about two and one half minutes accompanied by severe vibration. A 61-pound piece of blade penetrated the LP3 casing and came to rest on the grating above the West Moisture Separator Reheater. Upon removal of the LP3 casing it became evident that five blades were missing from the turbine end eighth stage. Nineteen lacing spools that couple the blades at running speed were also discovered to be missing. As is shown in Figure 1, Page 9, five blades, identified as Blades 5, 6, 7, 8, and 9, failed about one inch above the platform in the air foil section of the blade. Additional blades, shown in Figure 2, Page 10, exhibited impact damage at the trailing edge and the tip area. Upon removal of the blades, the root portions of the failed blades plus a number of intact blades were submitted to Technical and Engineering Services (TES) for failure analv s and laboratory testing. Submitted to TES were Blades 2, 3, 4, 5, 6, 7, 8, 9, 10, 19, 23, 44, 48, 59, 60 and 6..

Visual examination of the fracture surfaces revealed an obvious fatigue failure in Blade 9 originating from the trailing edge area. All other fractured blades (5, 6, 7 and 8) exhibited sudden overload type breaks. Indications are that these failures occurred in succession by impact from the departing fragments of Blade 9 and subsequent blades as they failed. Blades 1 and 3, with significant impact damage, also exhibited trailing edge cracks about one inch above the platform. These cracks, shown in Figures 3 and 4, Pages 11 and 12, were subsequently confirmed to be sudden overload tears related to blade impact. The 61-pound segment that penetrated the casing was confirmed as being from Blade 9.

The scope of the investigation described herein is limited to metallurgical analysis of the submitted eighth stage blades and conclusions resulting therefrom. Testing and analysis of the lacing spools are to be covered in a separate report, 94V70 - 18. The lacing spools are potentially related to the root cause and were evaluated through a parallel investigation.

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VISUAL EXAMINATION

Initial visual examination of Blade 9 indicated a thin trailing edge and a sharp "V" edge (Figure 5, Page 13) as opposed to the rounded and thicker edge on other blades (Figure 6, Page 14). A thickness survey of other blades as shown in Table 1, Page 15 shows an obvious trailing edge thickness problem in Blade 9. As a further check of the trailing edge problem, a dimensional survey was made of two blades (4 and 9) for a 3.5 inch distance from the trailing edge. A plot of the cross sections and integration of the areas revealed Blade 4 to have 28 percent more cross sectional area over the 3.5 inch distance. The reduced thickness is obviously not confined to the very edge of the blade. This reduced cross section would produce a higher stress in Blade 9 for the same blade load. In addition, a forging or machining condition at the failure elevation above the platform was also noted on nearly all blades. A pronounced gradual dip in the concave surface up to 0.040 inches deep was found to extend across the full section of the blade. However, there was no evidence of any cracking associated with this condition. A cursory review of turbine blade records noted the reference to a manufacturing problem, the accidental thinning of the trailing edge, which was designated as Deviation T52 (Merz and McClellan - Design Review - 46" Long Prototype Last Stage Blade, 22 June 1973). Further details on the problem were not readily retrievable.

Not proprietary referenced elsewhere in non proprietary documents

Many of the blades, particularly on the concave surface, exhibited grinding and/or tool marks running in an undesirable direction transverse to the blade. Surface conditions such as these act as stress raisers and may lead to the initiation of fatigue cracks. Good finishing practices include the removal of such marks.

Evidence of fatigue cycling in Blade 9 during turning gear operation was apparent from the indentations on the blade platform where contact was made with Blade 8. Reportedly the manufacturer originally used spacer pins ("packer pins") to close the gap when excessive clearance existed. Figure 7, Page 16, shows the contact surfaces of Blade 8 to Blade 9. A seven mil indentation in Blade 9 indicates a loose condition. This could be influential during turning gear operation in amplifying the trailing edge stress condition. Laboratory strain gauging and testing of a sample blade or Finite Element Analysis would assist in determining the magnitude of this stress cycle. While the installation of "ripple springs" in RF01 would minimize subsequent movement, it would not remove fatigue damage accumulated during many hours on turning gear.

METALLOGRAPHIC EXAMINATION

Metallographic examination of cross sections of blades revealed a normal martensitic microstructure, indicating a quenched and tempered heat treatment. Further, the blades were found to have been uniformly heat treated. A few fine particle non-metallic inclusions were noted. A cross section showing an example of a tool mark, many of which were found to be up to 0.003 inches deep, is shown in Figure 8, Page 17. Tool marks of this type and orientation serve as stress raisers for fatigue crack initiation as noted above.

Scanning electron microscope (SEM) examination of the fracture surface revealed characteristic fatigue striations typical of sub-critical crack growth by high cycle fatigue. The fracture was found to have initiated on the concave side of the blade, 0.136 inches in from the trailing edge, about 1.25 inches above the platform. Cracking progressed in a continuous manner across the blade and then along the blade profile for a distance of about six inches from the trailing edge. The blade then failed by sudden ductile overload. Fatigue striation measurements revealed a spacing of $1.9-3.9 \times 10^{-5}$ inches for the initial stage of the fracture (up to 0.25 inches) and 9.6×10^{-5} inches for the remainder (up to 5.8 inches). A typical example of the Blade No 9 fatigue fracture surface is shown in Figure 9, Page 18. The fracture surface did not reveal any evidence of arrest points. Indications are that the crack, once initiated, propagated to failure.

CHEMICAL AND MECHANICAL TESTING

The blade material, which is covered by GEC Specification 30/476, is a modified 12 chrome stainless steel. Chemical analyses of Blades 1 and 9 were performed and these blade analyses meet the GEC requirements. Results of these analyses are listed in Table 2, Page 19.

Hardness tests revealed values of Rockwell C 30-32 for both Blades 1 and 9. These values are acceptable and meet the specified values of Brinell 285-331 (Rockwell C30-35). The blade hardness was found to be uniform with no difference between root and foil sections. These results are satisfactory and indicate favorable toughness in the blade material.

- Tensile test values on material from Blades 1 and 9 are satisfactory and meet the GEC requirements. Results of the tensile tests are given in Table 3, Page 20.

Samples from the root section of Blade 9 were subjected to Charpy Impact tests according to the ASTM E-23 procedure. [The impact values meet the specified value of 40 ft-lbs minimum.] The results of Charpy Impact testing are listed in Table 4, Page 21.

RESIDUAL STRESS MEASUREMENTS

[Residual stress measurements on Blades 10, 48, and 60 were performed by TEC in Knoxville, TN. Their analysis shows significant residual compressive stress at the surface for locations comparable to the initiation site on Blade 9. Values of -67 to -94 ksi at the surface decaying to -2.7 ksi at 15 mils below the surface have been reported. A plot of residual stress found in Blade 48 is shown in Figure 10, Page 22. These results must be related to the Finite Element Analysis work to establish the overall significance. Reference data cannot be obtained from Blade 9 and assumptions must be made in view of the thin trailing edge. If the trailing edge condition were introduced after final heat treatment the residual stress pattern could be totally different.]

DISCUSSION

The normal sequence of a fatigue failure (high cycle) is a long time period (or equivalently, a large number of cycles) for crack initiation to occur followed by a short time period for crack propagation. A major unknown in the failure of Blade 9 is the accumulation of fatigue damage prior to crack initiation. It is not known if it occurred continuously over the life of the unit or if it occurred at discrete intervals due to some operating condition. This determination can not be made on the basis of metallurgical evidence alone but must be deduced through a formal root cause analysis process. [Also, the residual stress pattern may be significant as the residual stress measurement results indicate a favorable compressive stress condition at the blade surface. This condition may be a partial explanation of why Blade 9 did not fail earlier.]

One possible failure scenario is that the crack initiated due to conditions existing over the life of the unit and then progressed rapidly to failure. [After 43,000 hours of service] and assuming a once per revolution frequency

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(cyclic stress condition exists at running speed), a total of 4.6 x 10^9 stress cycles would have accumulated prior to crack initiation. A review of published fatigue data for a comparable turbine blade alloy (Type 403 Stainless Steel) revealed a minimum combined stress for failure of about 72.5 ksi at the endurance limit (10⁶ cycles). The data is plotted in Figure 11, Page 23. Classical fatigue theory predicts that failure will not occur at stresses below the endurance limit. However, experience has shown that some alloys do not have a true endurance limit and will fail at stresses lower than the endurance limit after more than 10^6 cycles. A high cycle fatigue crack such as developed in Blade No 9 indicates operation at a stress level close to the endurance limit. A finite element analysis will be performed by Stress Technology Incorporated to determine the stresses at the origin.

The other possibility is that the fatigue damage prior to crack initiation accumulated as the result of a series of discrete disruptions such as might occur as the result of torsional vibration or flutter (stalled or unstalled). This scenario is supported by the fact that the large number of cycles experienced at running speed far exceeds the expected number of cycles at the endurance limit. Fatigue testing is in progress at GEC Alsthom that may help resolve this issue.

It is clear that, once initiated, the fatigue crack propagated to failure in a relatively short period of time. Further, uniformly spaced striations on the fracture surface point to an orderly, uniform progression of the fatigue failure, such as would be found with a laboratory fatigue test where the loading conditions are precisely controlled. This is commensurate with the evidence that the unit was operating under stable conditions when the failure occurred. Based on the observed striation spacings over the length of the fracture surface, the time from crack initiation to failure is estimated to be about thirty minutes. For comparison, an estimation of time to failure was made using crack propagation rates for this type of alloy using reference data from the literature. A typical plot for a comparable alloy, Type 403 stainless, is shown in Figure 12, Page 24. The total range of stable crack growth of 10^{-3} to 10^{-6} inch/cycle converts to potential failure times ranging from three minutes to fifty-five hours (assuming a once per revolution stress cycle at 1800 rpm). The observed propagation rate fits well with reported data.

SUMMARY OF RESULTS AND CONCLUSIONS

Metallurgical investigation of the eighth stage blade failure on the turbine end of LP3 revealed the high cycle fatigue failure of a single blade originating on the concave surface in a thinned trailing edge. Failure initiated inboard from the edge at an estimated distance of 0.136 inches. Failure progressed in a continuous manner (stable crack growth) with an estimated propagation phase of approximately thirty minutes from initiation to catastrophic failure (assuming a once per revolution stress cycle). All blades tested conformed to the specified physical properties and were made of the specified modified 12 chrome stainless steel. Heat treatment was considered satisfactory. There was no evidence that corrosion contributed to the failure. The investigation revealed potential factors contributing to the failure include the thinned trailing edge, tool marks, residual stress condition, blade looseness and a reduced section typically found in all eighth stage blades at the failure location.

A generic fatigue problem with eighth stage blades would be reflected in additional blades having some evidence of fatigue cracking. No evidence of such cracking has been found to date. Indications are that eighth stage blades with full trailing edge thicknesses have stress levels below the endurance limit and therefore are not prone to failure. Substantiation will require Finite Element Analysis of normal and thinned profile blades. Any consideration for returning eighth stage blades to service (temporary or permanent) should include the removal of objectional tool marks and shot peening the lower airfoil section and blade root area.

All work except for residual stress measurement by TEC was performed in accordance with Traveler 2706 and the Technical and Engineering Services Quality Assurance Program.

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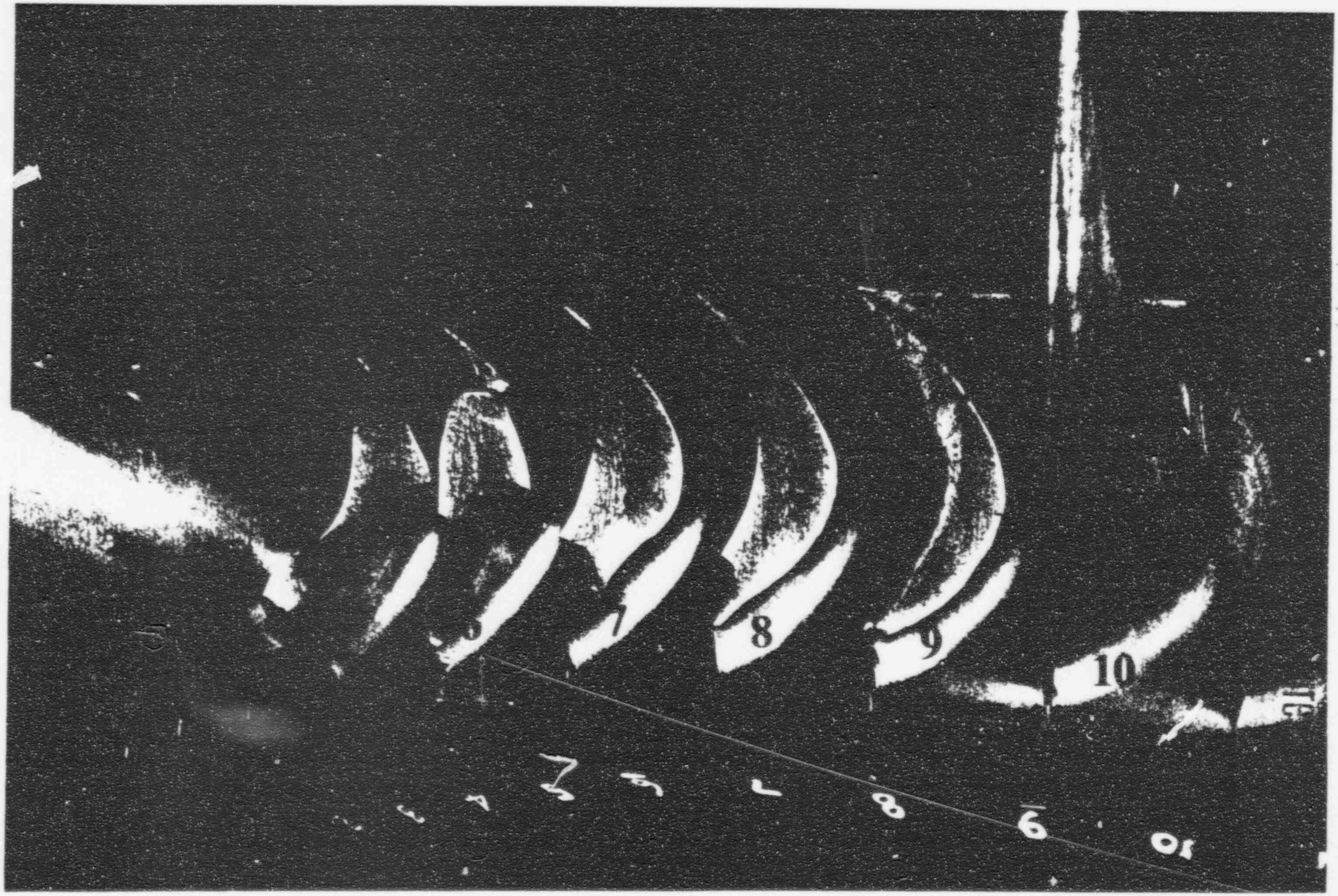

Figure 1 Stage 8 of L.P. No. 3 Turbine showing failed blade sections

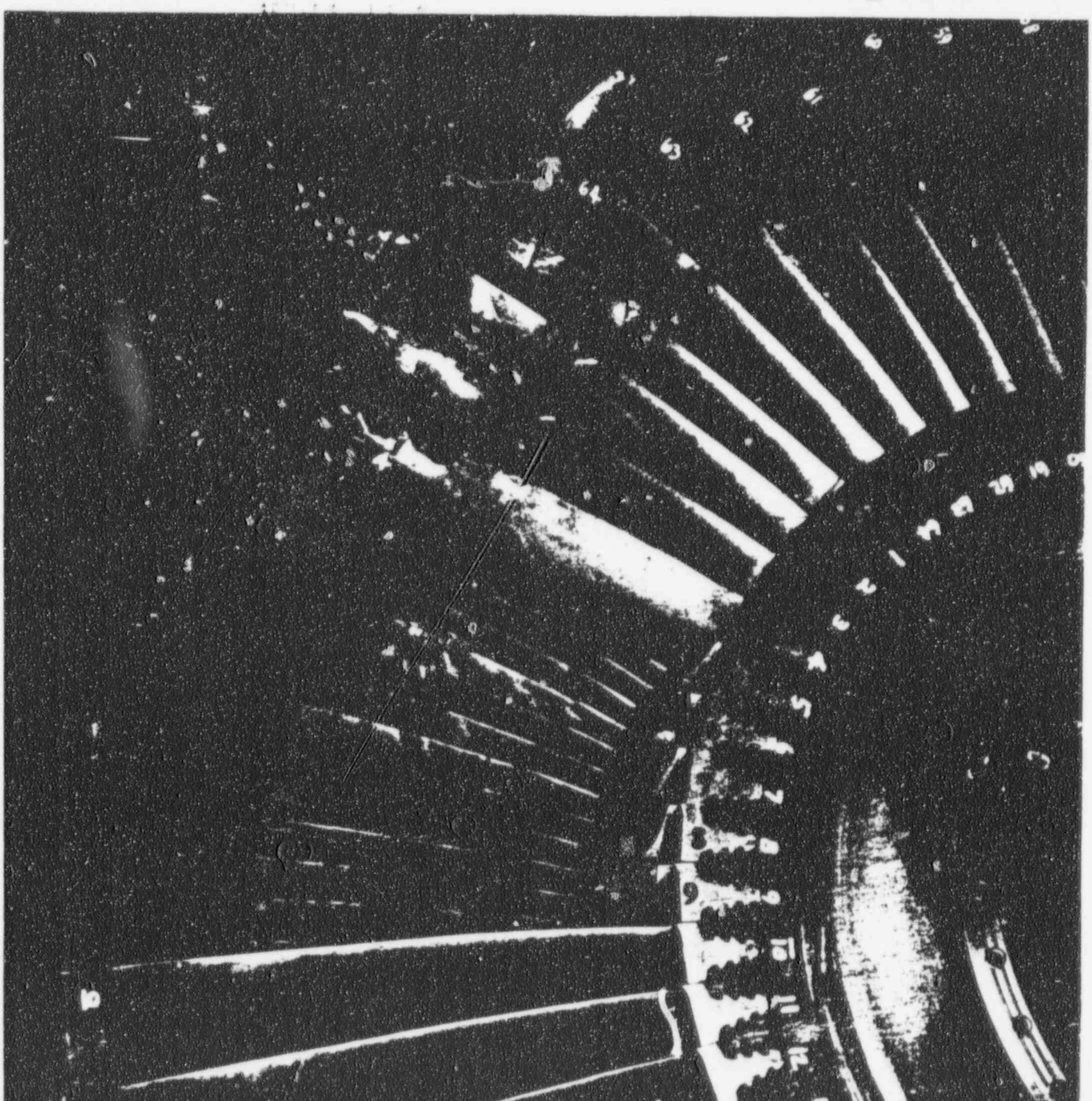

Figure 2 Failure area of L.P. No. 3 showing fractured and damaged blading.

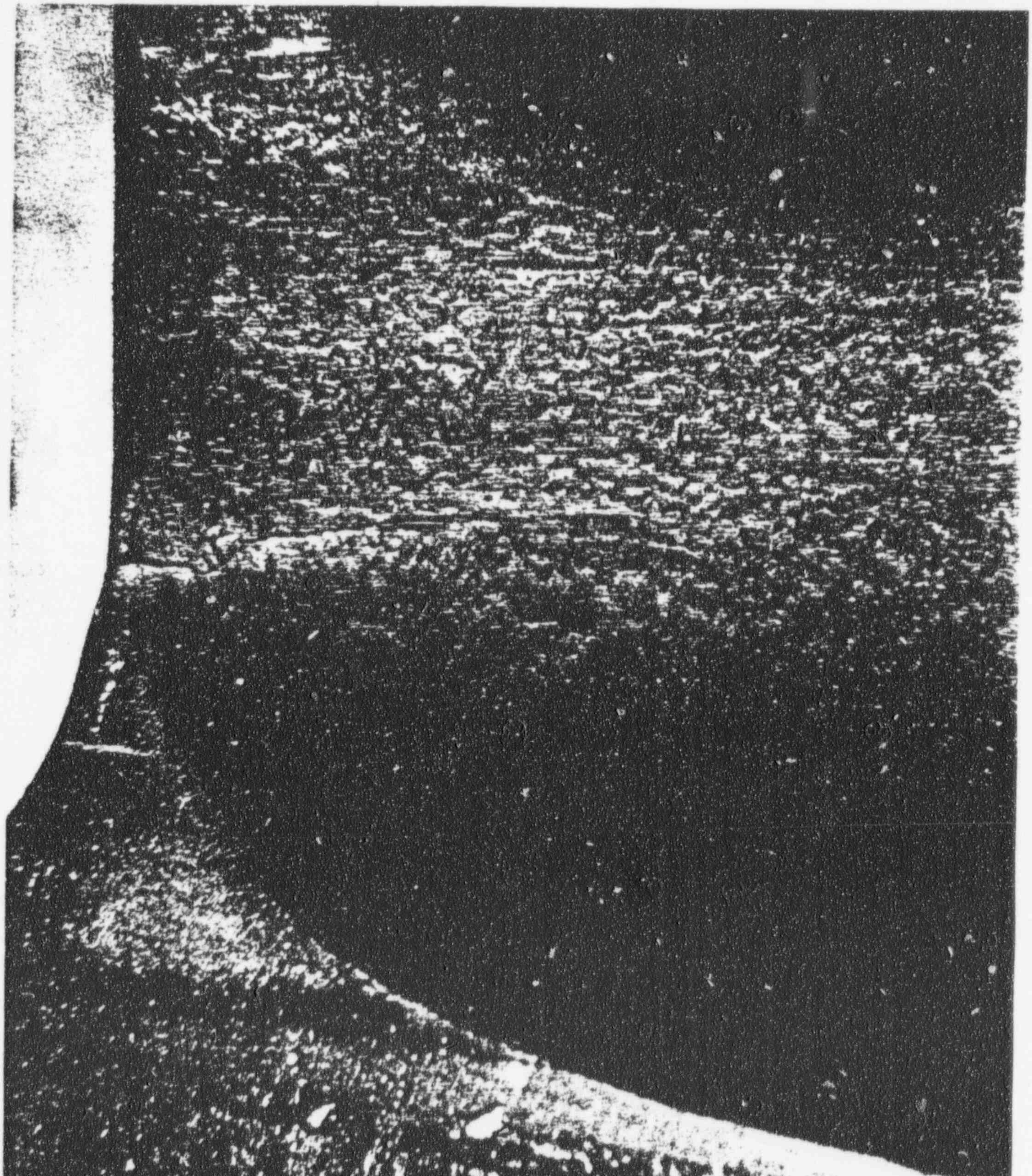

Figure 3 Trailing edge crack in Blade 3.

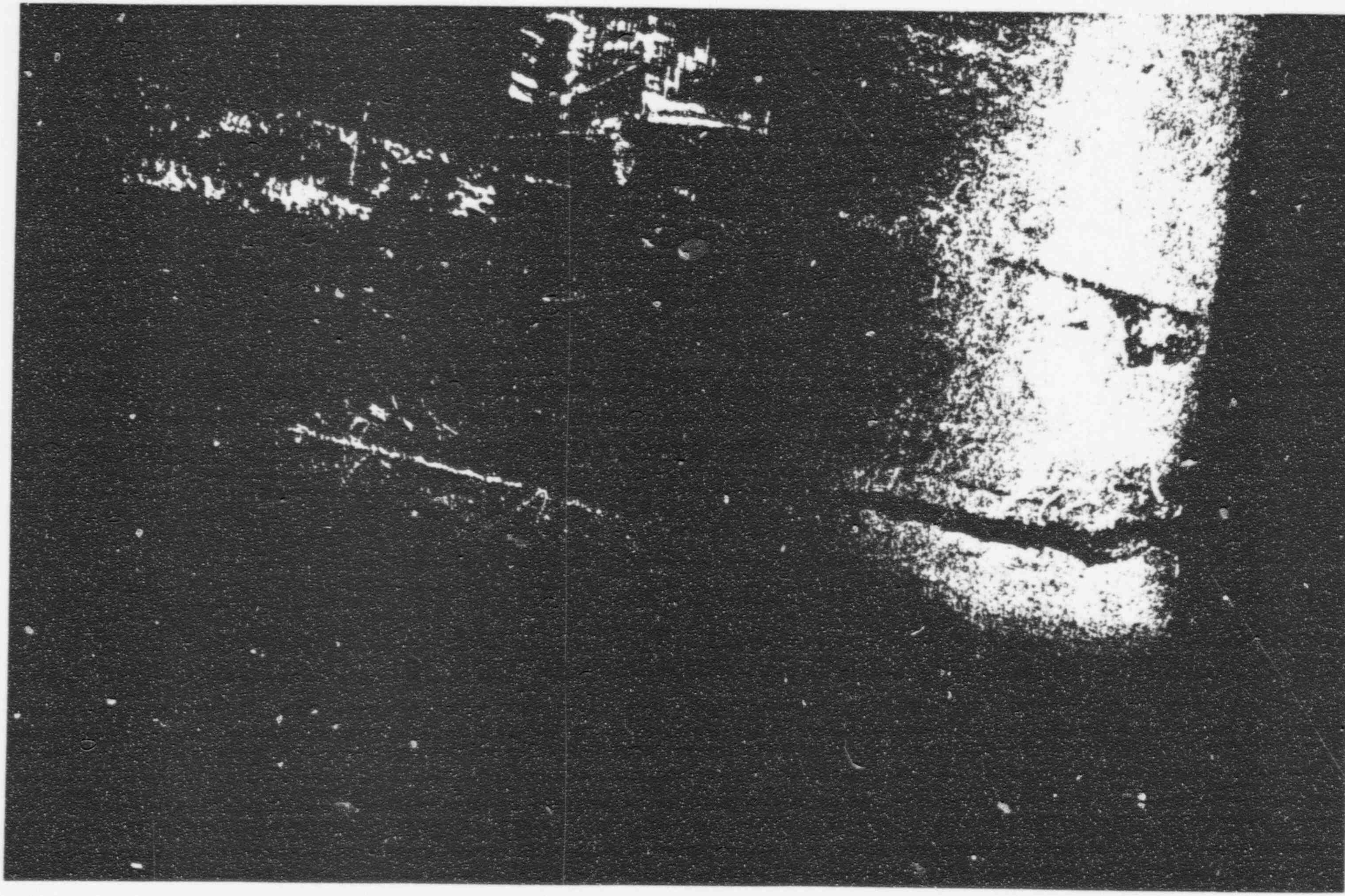

Figure 4 Trailing edge crack in Blade 1.

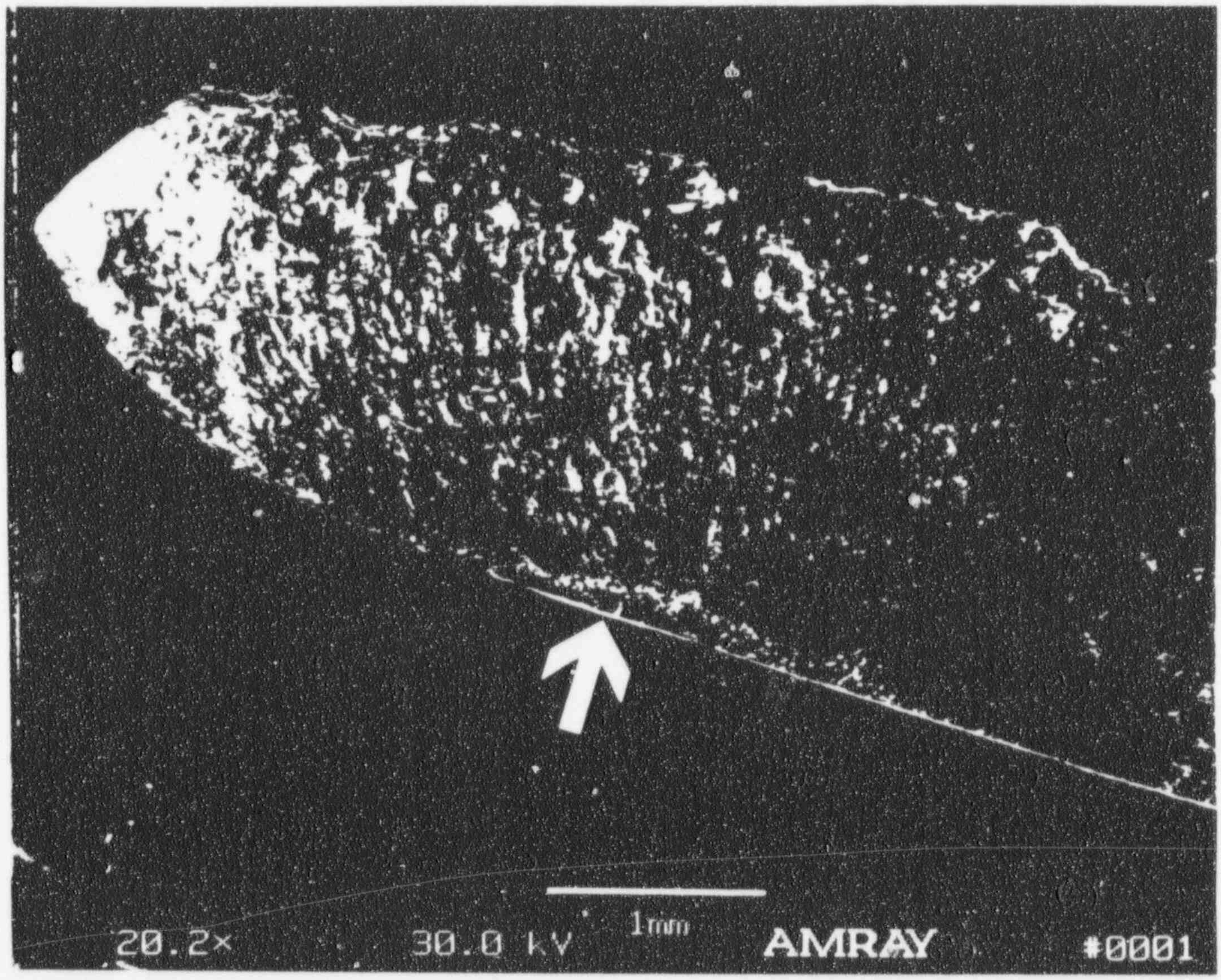

Figure 5 Thinned and pointed trailing edge, and fatigue crack initiation (arrow) in Blade 9.

Mag. 20.2 x

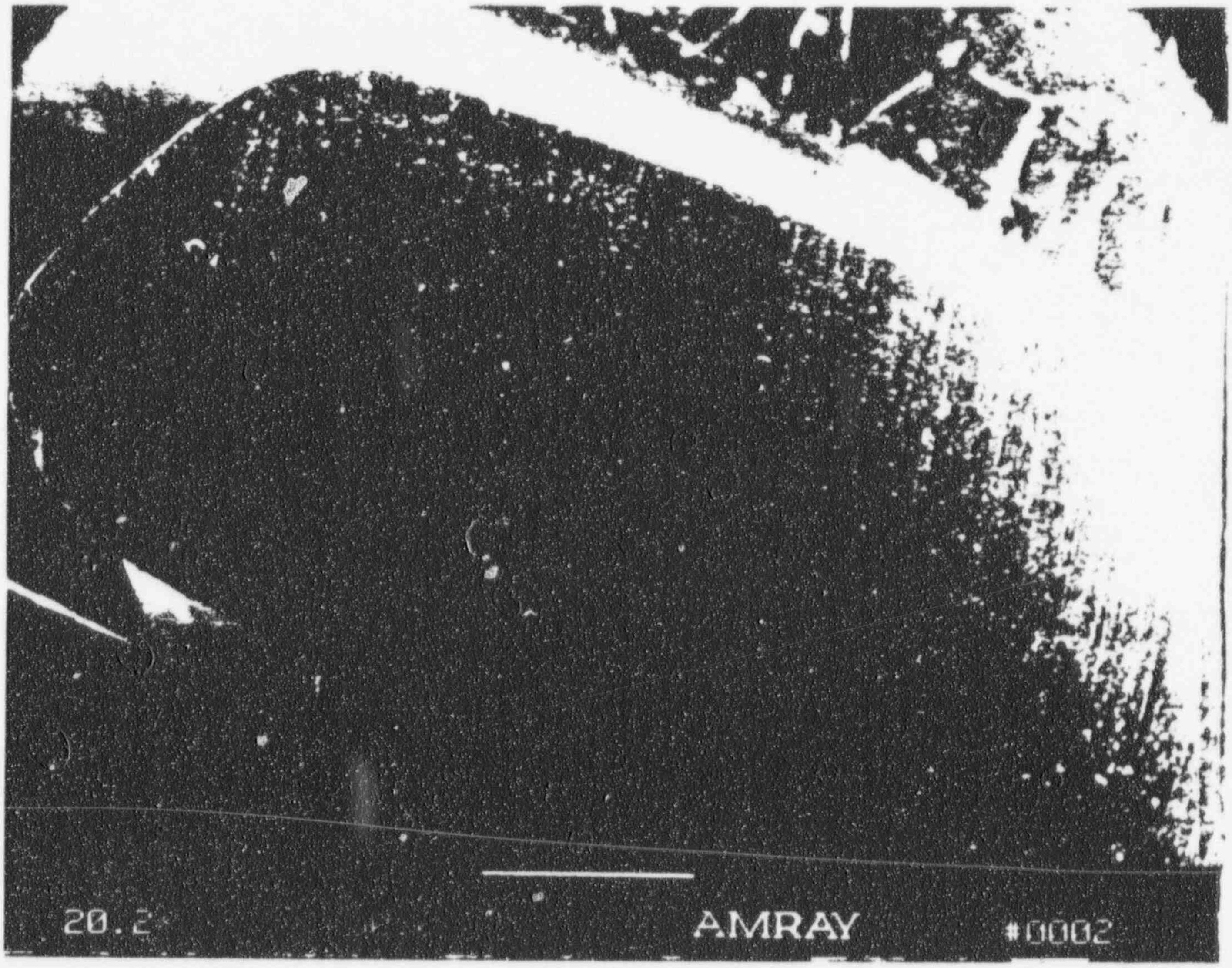

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Figure 6 Cross section of Blade 4 at failure reference location showing normal rounded edge and increased thickness.
Mag. 20.2 x

TABLE 1

LP3 8th STAGE TURBINE BLADE MEASUREMENTS

Measurements taken on trailing edge of blades approximately [0.125"] from the edge and [1.4"] from the top of the platform.

Blade	Thickness, inch
1	0.085
2	0.110
3	0.110
4	0.095
5	Damaged
6	0.080
7	0.155*
8	0.128*
9	0.073
10	0.115
19	0.085
44	Damaged
48	0.115
59	0.085
60	0.115

[* Measurement at thinnest portion of the trailing edge below the fracture.]

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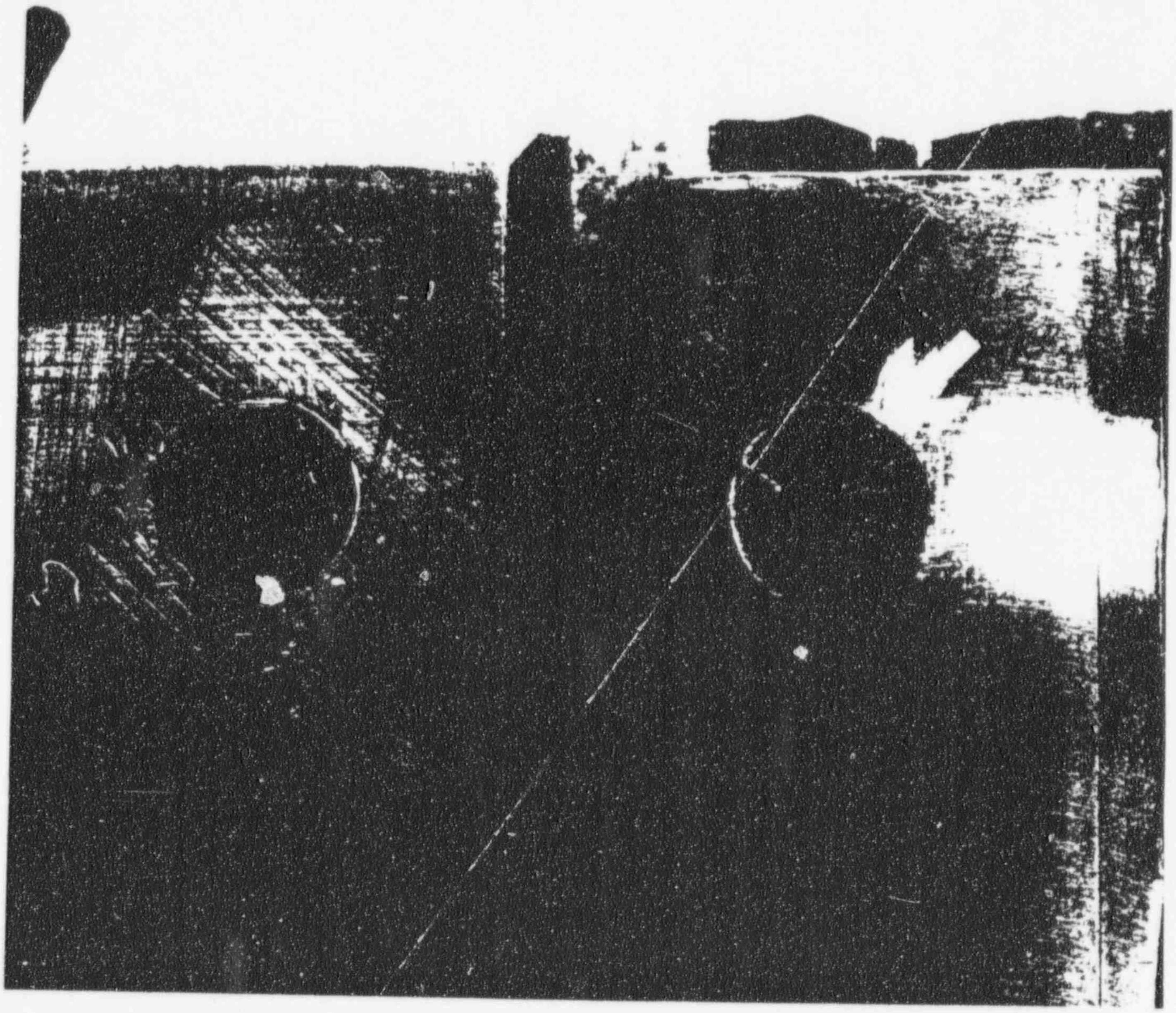

Figure 7 Platform contact between Blades 8 and 9 shows indentation in Blade 9 from "packer pin".

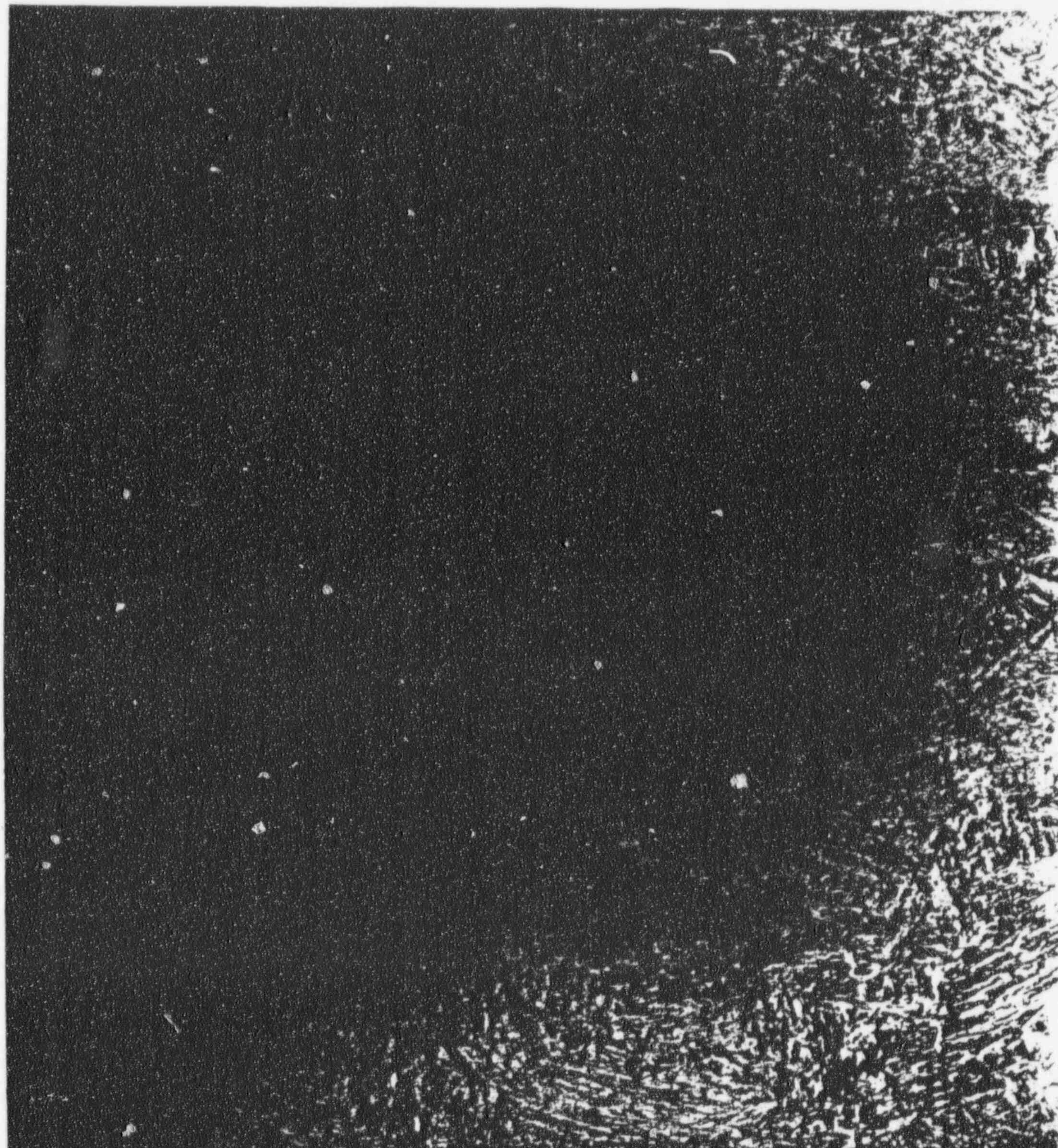

Figure 8 Concave surface of the blade exhibits tool marks up to 0.003 inches deep.
Mag. 100 x

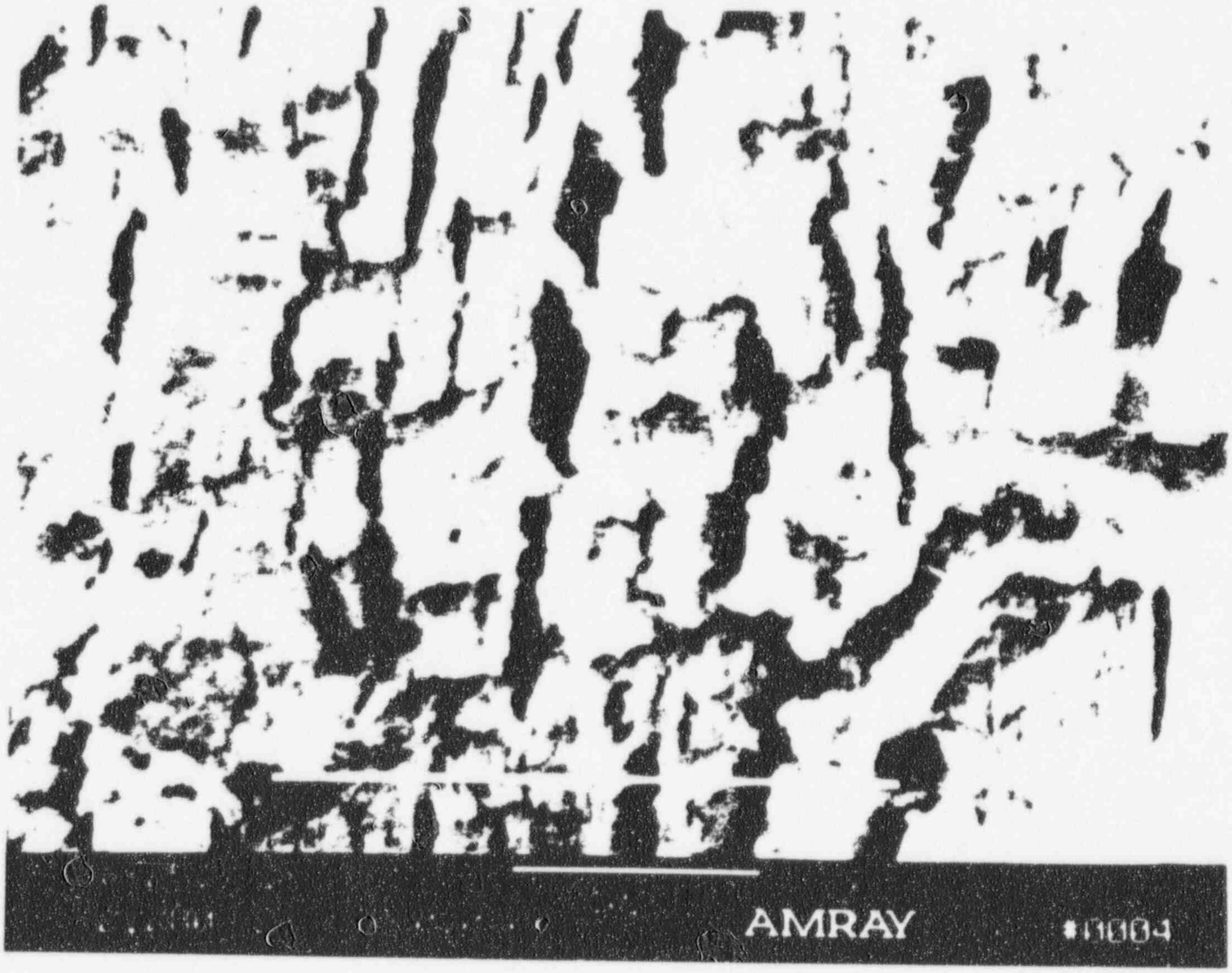

Figure 9 Typical fatigue striations observed in Blade 9.

SEM Mag. 2280 x

TABLE 2

CHEMICAL COMPOSITION of BLADE SAMPLES (Weight Percent)

SAMPLE	C	Mn	Si	P	S	Ni	Cr	Mo	V	Fe
Blade 1	0.100	0.69	0.17	0.01	0.011	2.30	12.3	1.78		Rem
Blade 9	0.105	0.71	0.12	0.02	0.014	2.57	12.5	1.41		Rem
GEC SPEC 30/476	0.08 - 0.15	0.4 - 1.0	0.6 max	0.025 max	0.015 max	2.0 - 3.0	11.0 - 13.0	1.0 - 2.0	0.05 - 0.40	Rem

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TABLE 3

TENSILE TEST RESULTS

SAMPLE	TENSILE STRENGTH KSI	YIELD STRENGTH KSI	ELONGATION %	REDUCTION of AREA %
Blade 1A	139	117	19.6	52.6
Blade 1B	140	118	19.6	52.4
Blade 9A	148	118	18.1	50.5
Blade 9B	148	118	18.3	49.3
GEC SPEC 30/476	134-157	112 min.	15.0 min.	40 min.

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TABLE 4

IMPACT TEST RESULTS (room temperature)

SAMPLE	CHARPY VALUES, ft-lb.
Blade 1 (root)	53, 44, 50, 56.5, 45, 48
Blade 9 (root)	63, 64, 65, 64.5, 69, 67
Blade 9 (air foil)	58, 56
GEC SPEC 30/476	40 min.

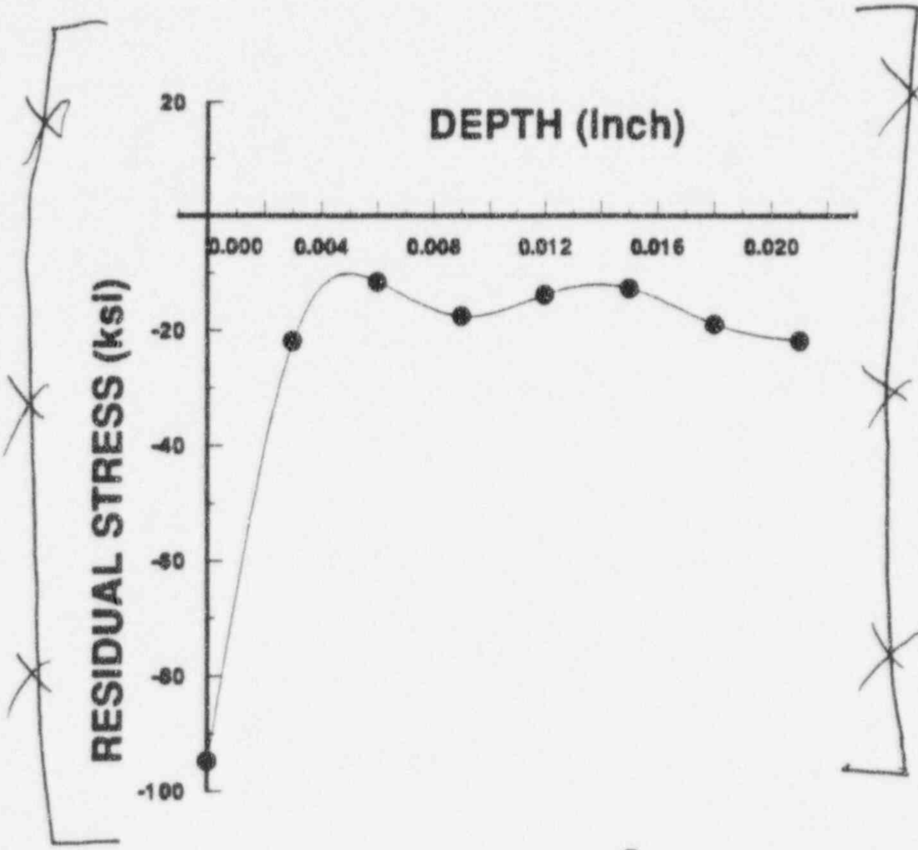

FIGURE 10 - Residual Stress Profile for Blade 48 at Failure Initiation Point.

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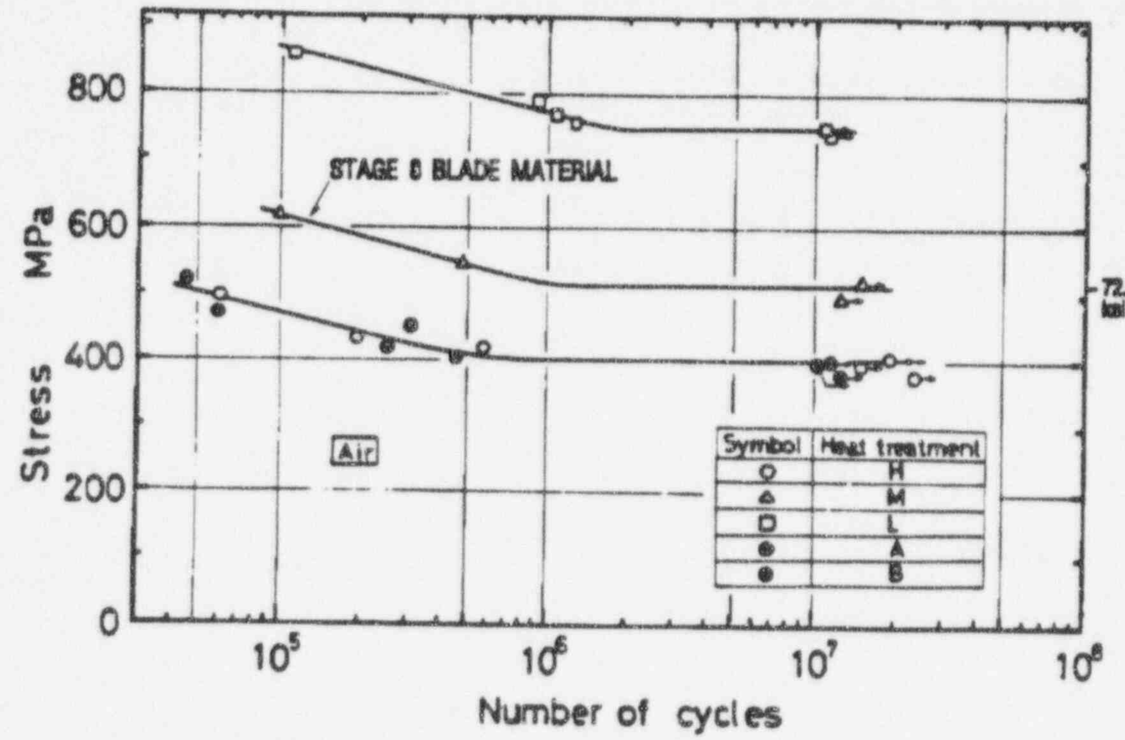

Figure 11 - Fatigue Plot for Type 403 Stainless Steel Blade Material. Plot for Heat Treatment Equivalent to Stage 8 Blades is Indicated.

Source: Hitoshi Ishii, "The Effect of Heat Treatments on the Corrosion Fatigue Properties of 13 Pct Chromium Stainless Steel in 3 Pct NaCl Aqueous Solution," in Metallurgical Transactions A, Hitoshi Ishii, Yuji Sakakibara and Ryuichiro Ebara, American Society for Metals, Metals Park OH, 1982, p 1523

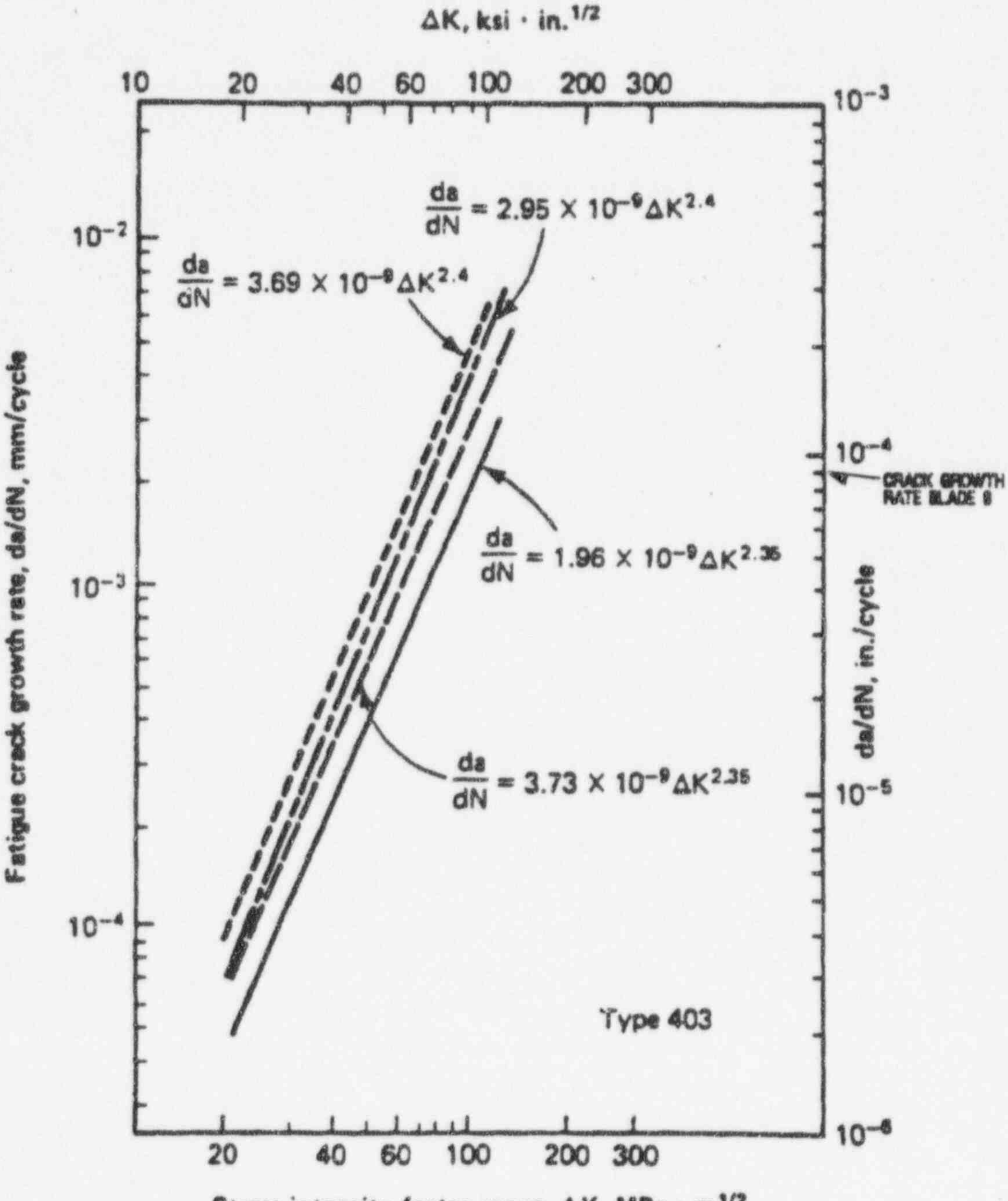

Figure 12 - Crack Growth Data for Type 403 Stainless Steel.

Source: J. E. Campbell, "Fracture Properties of Wrought Stainless Steels," in Application of Fracture Mechanics for Selection of Metallic Structural Materials, James E. Campbell, William W. Gerberich and John H. Underwood, Eds., American Society for Metals, Metals Park OH, 1982, p 145

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Detroit Edison

Date: July 21, 1994

To: L. C. Fron
Director, Turbines, Fermi 2

From: J. E. Schaefer
Metallurgical Research Engineer
Technical and Engineering Services

Subject: **Metallurgical Examination of Fermi-2 Low Pressure Seventh Stage Turbine Blading**
Technical & Engineering Services Report 94V70-22

BACKGROUND

The December 25, 1993 Fermi-2 turbine generator event was determined to have resulted from the failure of a single Low Pressure (LP) eighth stage blade.[1,2] During the damage assessment period following the failure, it was discovered that a number of LP seventh stage blades were cracked in the root. A typical example of this cracking is shown in Figure 1, Page 5. Following blade removal and grit blasting, liquid fluorescent magnetic particle (LFMT) examination revealed a total of 114 cracked blades in LP's 2 and 3 but no cracked blades in LP-1. Reportedly, blades in LP-1 were more easily removed than those in LP-'s 2 and 3. A review of turbine history revealed that, during RF01, a single cracked seventh stage blade (No. 38) of LP-2 was discovered. The initial cracking was found to have propagated by high cycle fatigue[3] and was judged to be unique.

To gain a further understanding of the seventh stage blade cracking mechanism, a random sampling of seventh stage blades was submitted to Technical and Engineering Services for metallurgical examination. A total of twenty-five blades containing visual and/or LFMT indications were submitted. Data was provided to the Root Cause Analysis Team as it became available.

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1 J. E. Schaefer: "Metallurgical Examination of Fermi-2 Eighth Stage Turbine Blading" TES Report 94V70-13, July 23, 1994.

2 Root Cause Team: "Fermi-2 Main Turbine Generator December 25, 1993 Forced Outage Root Cause Analysis Report" TMTB 0010, July, 1994.

3 J. E. Schaefer: "Metallurgical Examination of a Failed Seventh Stage Turbine Blade" TES Report 91V35-55, April 9, 1992.

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PROCEDURE

Sampled blades were notched opposite the cracks, chilled in liquid nitrogen and fractured to expose the cracked surfaces. These newly exposed surfaces were then accessible for metallurgical examination including visual, light microscopy, and scanning electron microscopy (SEM). Randomly selected samples were also subjected to chemical analysis and hardness testing.

VISUAL EXAMINATION

Visual examination revealed that crack surfaces on all samples exhibited beach marks characteristic of high cycle fatigue. Fatigue cracks (single and multiple) were found to have initiated inboard from the inlet face at the upper serration and then propagated across the blade section to an apparent arrest condition. The appearance of a heavy black oxide deposit on the fatigue crack surface, apparently magnetite (Fe_3O_4), and the presence of numerous arrest points established that the cracks had been in progress for a period of time long before the eighth stage blade failure in December 1993, perhaps even years. Crack size varied greatly with some showing little growth while other had propagated across the blade. The crack propagation direction indicates the cracking was the result of tangential blade vibration. Samples of blades exhibiting typical fatigue crack surfaces are shown in Figures 2 - 4, Pages 6 - 8.

The blade roots exhibited conditions deleterious to fatigue life including surface blemishes from machining or installation. Such surface blemishes provide a poor surface finish for a blade root and degrade fatigue properties. A shot peened or glass bead peened surface has superior fatigue properties and is normally a requirement for blade roots. The blade roots also exhibited evidence of fretting which is an indication of micro-movement between blade root and steeple. Fretting and surface imperfections degrade fatigue properties. Two other likely sources of surface damage, corrosion and pitting, were not apparent.

Measurements of blade root thickness across the root on nine blades revealed thichnesses in the range of 0.001 - 0.002 in. above specified maximum. This would help explain the field report of difficulty in removing blades. An interference fit would increase stresses in the area of cracking.

Other evidence supportive of cyclic loading that could lead to fatigue cracking in the seventh stage blades was found on the split lacing wires used to connect adjacent blades. Samples of the lacing wire exhibited extensive fretting at the contact points with the blades indicating relative movement between blade and wire.

SEM EXAMINATION

Analysis of the fatigue crack surface by SEM examination was complicated by surface degradation due to oxidation and physical damage. In spite of this damage, characteristic fatigue striations typical of high cycle fatigue were identified on a number of blades. A typical crack surface is shown in Figure 5, Page 9. The striation spacings measured on the seventh stage blades were typically an order of magnitude greater than that measured on the eighth stage blade, e.g., 2.3 X 10^{-4} in./cycle for a seventh stage blade as compared to 9.6 x 10^{-5} in./cycle for the eighth stage blade. This would indicate a somewhat higher stress level in the seventh stage blades than that found in the eighth stage blade assuming all other factors being equal.

The crack initiation sites on all submitted blades were examined for evidence of stress corrosion cracking or other environmentally related mechanisms. No crack propagation mechanism other than transgranular high cycle fatigue was found. The surfaces of some blades had been lightly polished in attempts to remove LFMT indications and crack origins may have been removed.

MATERIAL PROPERTIES

Based on chemical analysis, hardness test and metallographic examination, the seventh stage blade material met GEC ALSTHOM specifications. Exhibiting satisfactory martensitic microstructure, the blades had been heat treated to a hardness of 33 - 34 Rockwell C as compared to the GEC ALSTHOM specified range of 30 - 35 Rockwell C. The blade material was found to be a modified 12-chrome alloy which met the GEC ALSTHOM specification with a typical composition shown in Table 1, Page 10. No evidence of metallurgical defects was found.

CONCLUSIONS

The Fermi-2 LP seventh stage blades developed high cycle fatigue cracks as the result of intermittent cyclic stresses. The source(s) of the cyclic stresses could not be determined. The cracks initiated inboard from the root face and cannot be visually detected until they are well formed and have propagated to the platform face. There did not appear to be any obvious correlation in growth pattern among blades. The cracks have existed for a considerable period of time, perhaps years, and certainly were not a consequence of the eighth stage blade failure. Crack initiation may be related to surface finish, fretting and/or high stresses resulting from an interference fit. The blade material met specifications and deviation therefrom was not a contributing factor.

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G. J. McDonald
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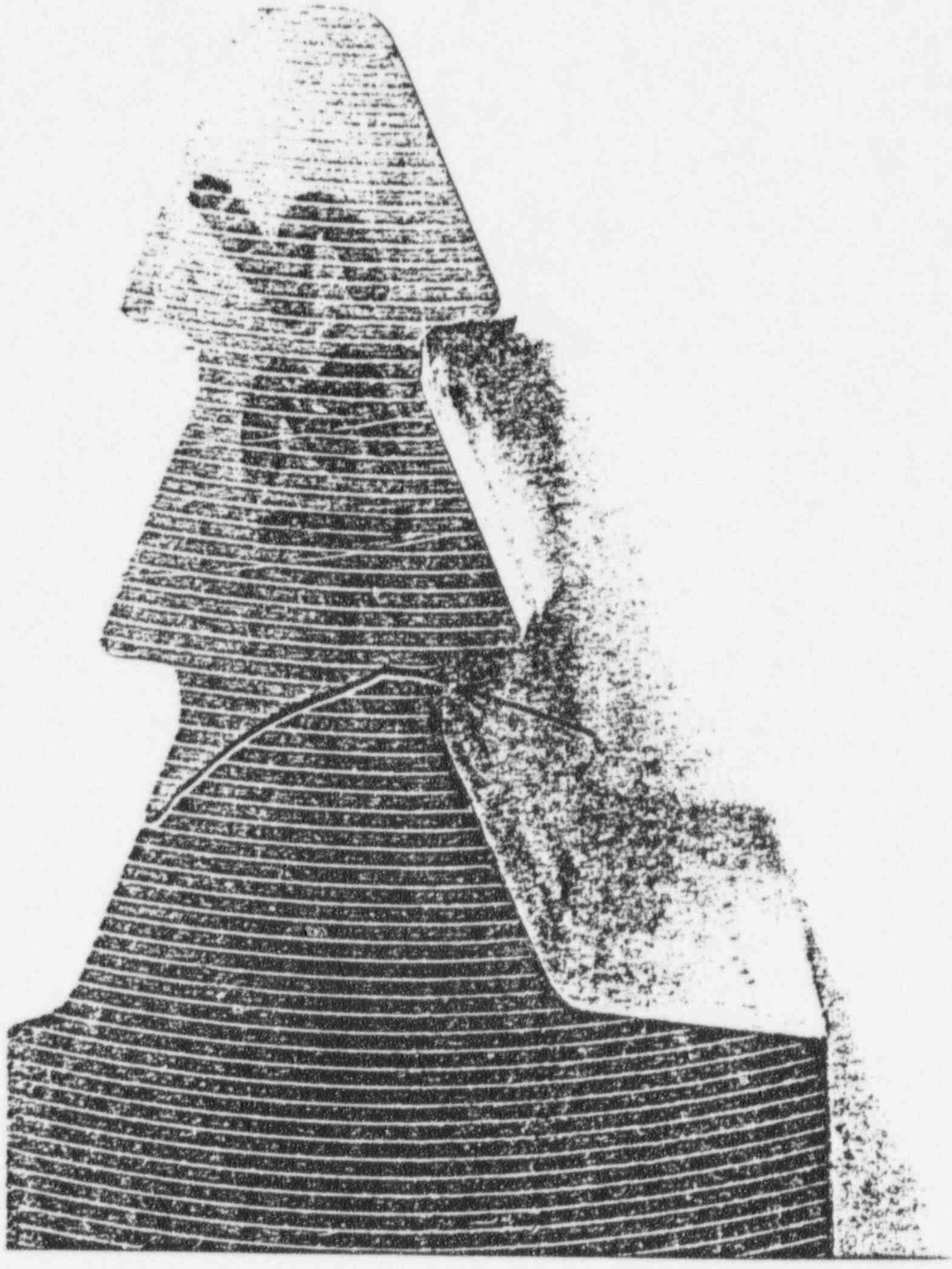

Figure 1 Typical root section of seventh stage blade showing crack initiation location (arrow).
Approx 2X

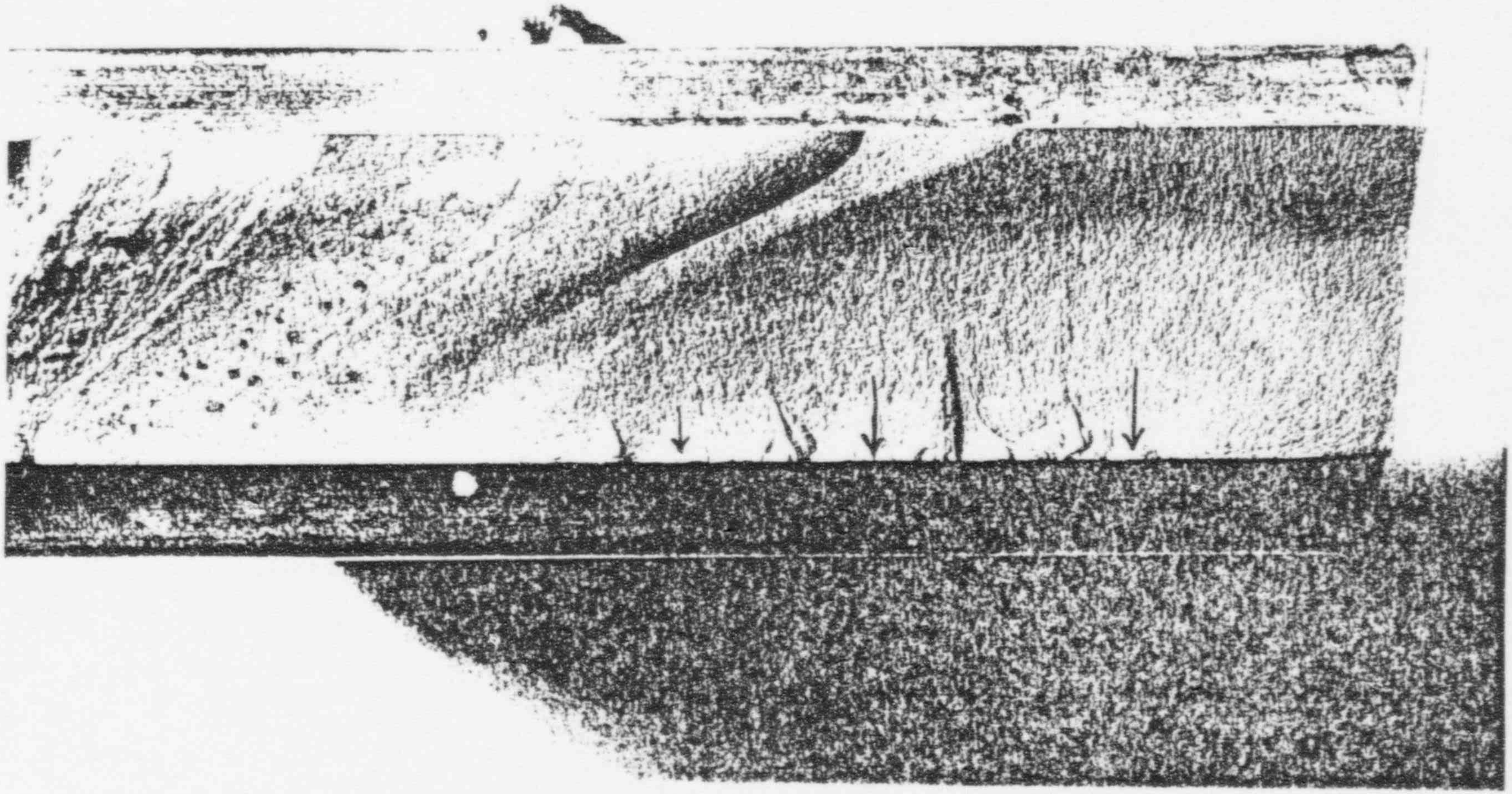

Figure 2 Crack surface of Blade No. 62 showing high cycle fatigue. Initiation sites are indicated by arrows.

Approx 3X

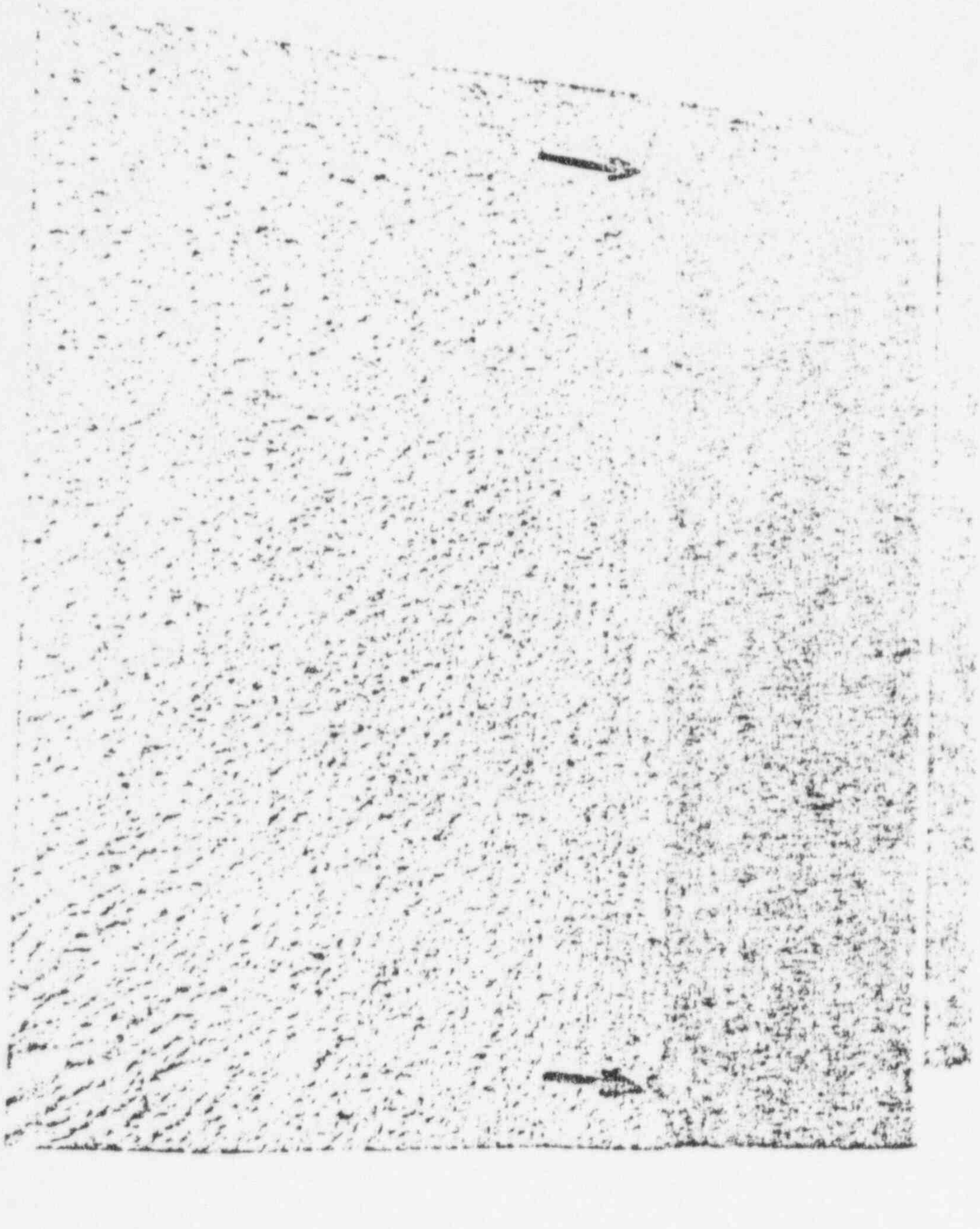

Figure 3 Crack surface of Blade No. 82 showing two minute fatigue cracks (arrows). Note black oxide on crack surface. Approx 6X

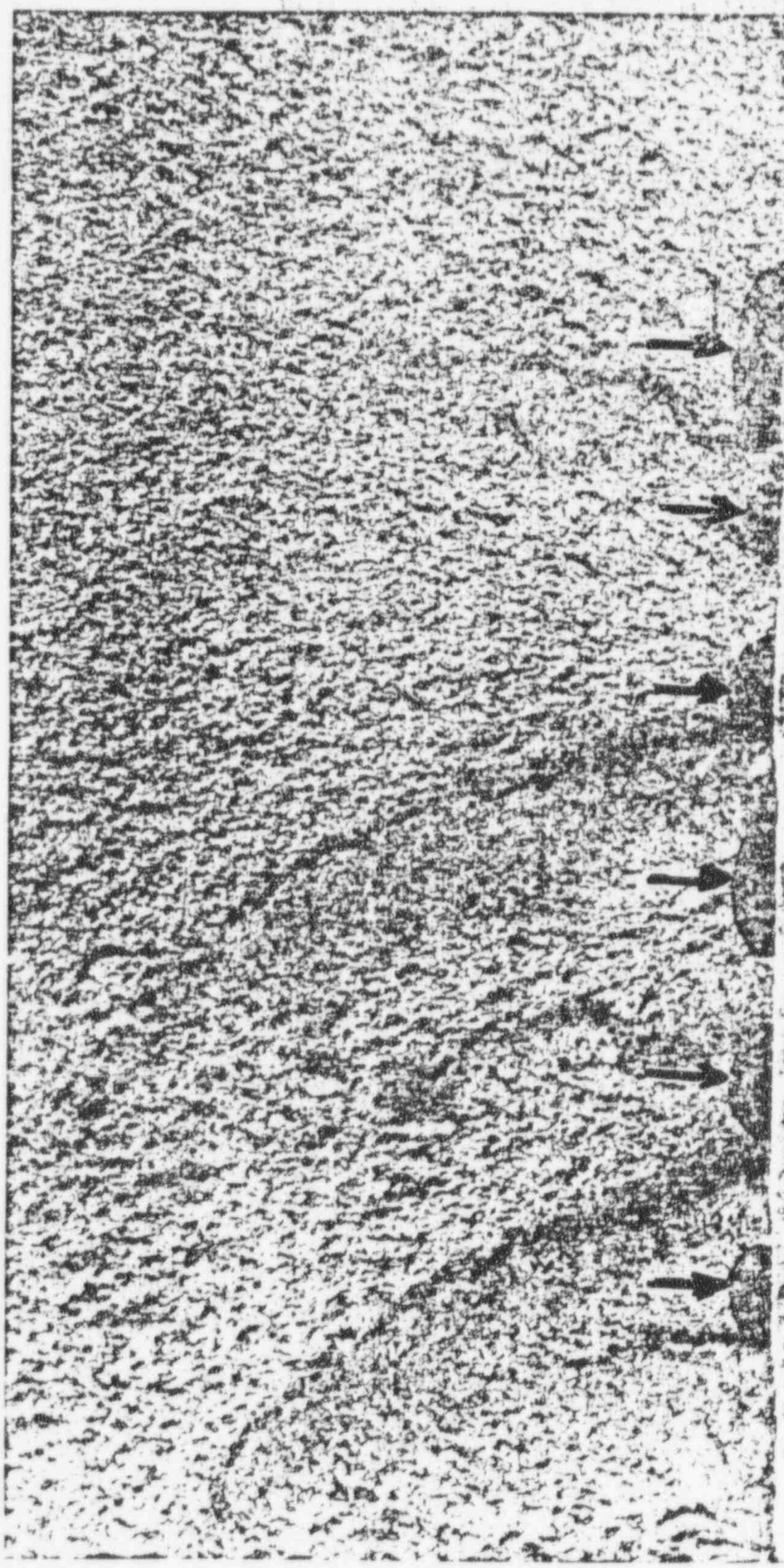

Figure 4 Crack surface of Blade No. 116 showing multiple fatigue crack initiation sites (arrows).

Approx 10X

Figure 5 Crack surface of Blade No. 62 showing fatigue striations.

TABLE 1

CHEMICAL COMPOSITION of BLADE SAMPLE (Weight Percent)

SAMPLE	C	Mn	Si	P	S	Ni	Cr	Mo	V	Fe
Blade 116	0.125	0.78	0.29	0.01	0.011	2.29	12.5	1.34	0.08	Rem
GEC SPEC 30/476	0.08 - 0.15	0.4 - 1.0	0.6 max	0.025 max	0.015 max	2.0 - 3.0	11.0 - 13.0	1.0 - 2.0	0.05 - 0.40	Rem

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Detroit Edison

Date: July 22, 1994

To: L. C. Fron
Section Head, Turbines
Fermi-2

From: J. D. Black
Supervisor
Metallurgy, NDE and Welding
Technical and Engineering Services

Subject: **Metallurgical Analysis of Fermi-2 Low Pressure Seventh and Eighth Stage Turbine Blading**
Technical & Engineering Services Report 94V70-30

INTRODUCTION

Technical and Engineering Services (TES) metallurgists have been heavily involved in the numerous activities that have ensued since the December 25, 1993 turbine generator event. They participated in the initial damage assessment and played a key role in the inspection, identification, documentation and preservation of evidence important to root cause analysis. A metallurgist was the initial chairman of the specially formed Turbine Generator Assessment Team and later participated as a member of the Root Cause Analysis Team.

In addition to the on-site activities, laboratory support was provided at the TES metallurgical analysis facility. TES metallurgists performed failure analysis of the failed eighth stage low pressure turbine blades which appeared to hold key information regarding the root cause of the event. This analysis and the analysis of cracking that was later discovered in the seventh stages are summarized below.

EIGHTH STAGE BLADES[1]

The Fermi-2 low pressure eighth stage blade failures initiated with the failure of a single eighth stage blade, Blade 9. This blade failed by the mechanism of high cycle fatigue. The failure initiated at a point about 1 inch above the platform, 1/8 inch from the trailing edge and on the concave side of the blade. The blade failed due to tensile overload after the high cycle fatigue crack propagated across about one third the width of the blade.

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The fatigue crack appeared to have originated at a surface defect that appeared to be a tool mark. Based on the absence of oxide and beach marks, it was concluded that the crack, once initiated, propagated rapidly to failure. Based on fatigue striation spacing and assuming a once per revolution stress cycle, the time from initiation to catastrophic failure was estimated to be on the order of an hour.

Comparison of Blade 9 revealed it have a thinner trailing edge and a reduced cross section for at least three inches from the trailing edge. These observations are based both on comparison with other blades and with specified values. These blades are rough forged and hand finished to final dimensions. Some variation is expected but Blade 9 was significantly thinner than most of the other eighth stage blades. The fatigue crack initiated in the area of greatest thinning which appears also to be the area of highest stress. It was concluded that the reduced cross section and tool mark produced a stress and stress concentration that exceeded the fatigue strength of the blade.

The blades were subjected to chemical, mechanical and metallographic testing. They were found to be of the proper alloy, a modified 12-chrome, which had been uniformly heat treated to a hardness of about 30 Rockwell C. All physical and chemical properties were found to be well within the manufacturer's limits.

SEVENTH STAGE BLADES[2]

The Fermi-2 low pressure seventh stage blades developed high cycle fatigue cracks as the result of intermittent cyclic stresses. The source(s) of the cyclic stresses could not be determined. The cracks initiated inboard from the root face and cannot be visually detected until they are well formed and have propagated to the platform face. There did not appear to be any obvious correlation in growth pattern among blades. The cracks have existed for a considerable period of time, perhaps years, and certainly were not a consequence of the eighth stage blade failure. Crack initiation may be related to surface finish, fretting and/or high stresses resulting from an interference fit. The blade material met specifications and deviation therefrom was not a contributing factor.

cc: G. A. Horuczi(File)
G. J. McDonald

REFERENCES

1 J. E. Schaefer: "Metallurgical Examination of Fermi-2 Eighth Stage Turbine Blading" TES Report 94V70-13, June 23, 1994.

2 J. E. Schaefer: "Metallurgical Examination of Fermi-2 Low Pressure Seventh Stage Turbine Blading" TES Report 94V70-22, July 23, 1994.

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Date: July 30, 1994

To: L. C. Fron
Director
Turbine & Special Projects

From: P. K. Hudson
Engineer
Turbine

Subject: **N.D.E. Testing of LP and HP Turbine Rotors**

2.790 Material
Withhold from Public Disclosure

HP Rotor

After removal of the HP rotor from the cylinder, complete magnetic particle examination of rotor external surfaces, blades, tenons, shroud, disc face, and blade roots was conducted using the methods outlined below:

1. End-to-end - or head shot - used to inspect shaft for axial indications and disc faces for radial indications.

2. Coil method - used to inspect rotor for circumferential indications.

3. Draping method - used to inspect blades, tenons, shroud and disc faces.

Some indications were noted on Stage 1 generator end blades and shrouding, but following rework, this area was retested and no indications found.

A rotor bore examination was carried out, which included rotor bore diameter measurements, visual and magnetic particle inspection of bore surfaces and a U.T. inspection of the near bore region. Results of this test concluded the rotor could be returned to service, with further inspections recommended after 80,000 operating hours - nominally 8 cycles.

LP Rotors

Prior to shipment of the three LP rotors to Westinghouse at Charlotte, each LP rotor had the following NDE's performed:

1. Each of the three methods described above for the HP rotor was performed, i.e. end-to-end, coil method and draping method. These tests showed indications in the steam balance holes of LP3 rear discs, Stages 2, 4 and 5 and numerous indications in blade roots of the Stage 7 blades on LP2 and LP3.

2.790 MATERIAL

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2. The Stage 8 blades, removed from each rotor, were examined and no indications apart from those as a consequence of the December 25 incident, were found.

Additional examinations were then performed on the rotors at Charlotte, as follows.

1. All Stage 7 blades were removed and tested using an AC Yoke, with the following results:

[redacted]

   These blades are not being reused - those without indications will be used as root blocks to protect the discs and prevent turbulence.

2. The Stage 7 and Stage 8 disc slots were dust-blasted and M.P.I. performed. No indications were found on any of the Stage 8 disc slots; however, all rotors exhibited stress corrosion cracking in the steeples of Stage 7 discs.

   Westinghouse performed further examination of those with the more significant indications and documented this by way of their internal-material disposition report, M.D.R. Indications on LP 1 were ground out and disappeared at .040/.050 inches and on LP2 at .008 and .005 inches, those on LP3 were not judged significant.

   In each case, the rotor was then bladed and run to 120% overspeed - root blocks and not blades will be used in this location during the next cycle.

   The indications remaining on all 3 rotors at these locations are not judged to be significant, by either Westinghouse or GECA, and as such, will be left as is.

3. The LP rotors had previously been refitted with new Stage 4 and Stage 5 blades during RFO2, in June of 1992. Testing of Stage 6 blade roots, along with Stage 4 and Stage 5 blade roots with their respective disc heads was performed in Charlotte by GECA, using UT, on all three rotors.

   The results showed indications in one location only - Stage 5 disc head on LP3 rear flow. The blades in this location were later removed and M.P.I. did indeed confirm the UT findings.

4. Disc bore and dowel hole U.T. of all three rotors was performed by Wesdyne, using an automated scan method. The discs on these rotors do not have key ways in the rotor/disc interface, but are interconnected by dowels.

   All testing produced satisfactory results. Data is being stored on computer disc for future testing comparison, if applicable.

Repairs performed at Charlotte:

a. The Stage 5 disc head cracking has been examined by GECA and Westinghouse - replicas made show the cracks to be typical stress corrosion cracking. GECA recommended grinding out and retest before reinstalling the blades; this is being done by Westinghouse.

b. The steam balance hole cracking has also been inspected by GECA and Westinghouse. It is not significant, but following the OEM and recommendation, will be dressed-out and re-inspected by Westinghouse.

All three rotors have or will be run to 120% nominal speed, i.e. 2160 RPM, and then trim-balanced at nominal speed, 1800 RPM. The remaining bow in each rotor will be offset by balancing to minimize vibration at running speed. The C.F. forces induced during these runs are greater than those that can be expected during the remaining life of these rotors. Overspeed testing during start-up is only to 110%; hence it is concluded the rotors will operate safely for the next 18 months, under normal operating conditions.

PKH/klb