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ARGONNE NATIONAL LABORATORY
P. O. Box 299
Lemont, Illinois

EBWR TURBINE BLADE FAILURE - SUMMARY REPORT

by

J. M. Harrer and E. A. Wimunc

Reactor Engineering Division

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EBWR TURBINE BLADE FAILURE - SUMMARY REPORT

J. M. Harrer and E. A. Wimunc

ABSTRACT

This is a summary report on the failure of the EBWR turbine blade. It includes a description of the turbine shut-down sequence, the investigation into the cause of vibration, the disassembly of turbine, and observations and conclusions concerning the cause of the blade failure. The cause of failure was traced to a fault in the holding fixture used during the machining operation. There was no indication that any adverse effect on the turbine blades resulted from the fact that the steam came from a direct-cycle boiling water nuclear reactor power source.

SUMMARY

The 5000-kw turbine generator was tripped off the line by an operator at approximately 10:45 PM on May 1, 1958, when he observed excessive turbine vibration. The turbine generator had a normal vibration of about 0.6 mil and an alarm setting of 1.75 mils; a sudden vibration greater than 10 mils gave the alarm.

Prior to the start of excessive vibration, all operating parameters were normal. As the turbine went through its 2600-rpm resonant point, approximately five minutes later, the vibration could be felt in both the containment building and the control room located in the service building. Fearing possible piping damage, the reactor was shut down and isolated from the turbine. The turbine generator rolled or coasted about forty minutes before coming to a complete stop.

On the following day, an Allis-Chalmers service engineer inspected the turbine by entering the condenser manhole. He concluded that a blade had broken.

The upper turbine casing was removed on May 5, 1958 to confirm this observation. The turbine was then completely dismantled. The rotor and stationary blading diaphragms were removed. The maximum detectable radioactivity was 2 milliroentgens per hour at 2 inches. Blade No. 94 and an outer shroud had been torn free from the adjacent four blades. They were found lying between the last two rows of diaphragms on the low

pressure end of the turbine. Figure 2 is a view of the blade, along with the broken root; the root was removed from the turbine wheel after the rotor was removed from the casing.

Initial inspection indicated that the blade fracture probably resulted from fatigue of the root metal. The failure was progressive and occurred in stages across the root to the leading edge of the blade.

Following a microscopic examination of ten blades which had been attached to shrouds 31 and 32 (see Figure 15), Allis-Chalmers decided to remove and replace all the blades (a total of 158) and two spacer blocks in the next-to-the-last stage of the rotor. The reason for replacing the entire ring of blades was that each of the ten blade roots inspected contained an unexplained groove or scratch in the fillet between the neck and outlet hook of the root. These blades were removed from the wheel at Argonne. The rotor was then shipped to Allis-Chalmers for reblading and balancing.

At the time the failure occurred, the blades had been in service approximately $1\frac{1}{2}$ years with a total of 4000 operating hours.

After a detailed metallurgical investigation, the Allis-Chalmers Laboratory reported that the groove in the root metal was responsible for creating a stress concentration at that point. This stress would be in excess of the endurance limit of the material and could cause the root of the blade to fail.

The groove was made in each root fillet by a holding fixture used during the manufacture of these blades. The fixture is shown in Figure 1.

Before replacing the blades, Allis-Chalmers deepened the blade-root groove in the wheel so that a soft iron caulking piece could be driven under the blade root to maintain a tight fit. Vibration would be minimized or eliminated by this expedient. All replacement blades were shot peened at the roots to improve fatigue strength.

After vibration-frequency checks were made and the rotor was balanced, the unit was shipped back to Argonne. The turbine was in operation again on June 4, 1958. Total outage time was 35 days.

Figures 1 through 12 were submitted by Allis-Chalmers, along with their reports. Figures 13 and 14 are included to indicate the pattern of the fracture on each side of the blade. Figure 15 indicates the location of each blade, shroud, space block and key block in the wheel.

The Allis-Chalmers Manufacturing Company Laboratory Investigation Reports are included in Appendices A and B.

DISCUSSION OF ALLIS-CHALMERS REPORTS

The Magnaglo inspection referred to in B-4 of the Summary of Investigation, Appendix A, is defined from Magnaflux Corporation literature as follows:

"An intense magnetic field is set up in the proper direction within the part by means of Magnaflux equipment. Sudden interruptions in this magnetic field, caused by cracks or discontinuities in the part, crowd some of the magnetic flux (i.e., lines of force) outside the surface of the part. These 'leakage' fields act as local magnets, and attract and hold finely divided ferro-magnetic particles applied to the surface of the part. This builds up a line of particles right on the defect itself, showing the exact size and shape of the crack or discontinuity on the part.

"With Magnaflux, the magnetic particles are applied by hand or automatically, either as dry powder or by the wet method, in suspension in a thin oil or water carrier.

"The application of Magnaglo is the same as the Magnaflux wet method, but uses fluorescent magnetic particles that glow under black (near ultra-violet) light."

It is interesting to note that Argonne representatives observed the method in which these blades were "Magnaglo" inspected, and the consensus was that the cold-worked areas were apparent only when the magnetic field was in an axis perpendicular to that normally used for inspection. Observations of defects were not reproducible.

It is stated in Section B-2 of Appendix A that the blade that failed showed the fracture to be a characteristic "axial" fatigue failure. This is unusual because blades that fail at the root usually have a "tangential" failure.

In B-4 of Appendix A, no apparent reason is given for the locator corners not being rounded off to match the fillet of the blade roots. Discussion revealed that the design assumes there should be no horizontal forces applied to the blade root by the locators. If this idea prevails in design, it is evident that other blade holders could also have the potential of cold working the fillets of blade roots.

Both the Summary of Investigation (Appendix A) and the Allis-Chalmers Laboratory Investigation (Appendix B) emphasize that the EBWR turbine-blade failure was an isolated case. If one assumes that normal manufacturing and inspection methods were followed for the fabrication of the EBWR turbine blades, an obvious question comes to mind that has not been answered in the above reports. The question is; "Where did the

inspection system break down?" The inspection method, which is designed to locate surface abnormalities, allowed 149 blades with dangerous "stress risers" to be installed in one turbine. Furthermore, if this locator was used for all the blades for this particular stage, one would expect to find some faulty blade-root fillets in the duplicate blades held in stock. There still exists the possibility that this groove is not apparent until after the blade has been installed and has accumulated some history of operating cycles, i.e., a certain number of heating and cooling cycles and running time.

No satisfactory conclusions may be drawn here, but it is evident that the inspection method used at the factory was not adequate. This was certainly true as it applied to this particular stage of blades for the EBWR turbine.

The method of investigation used after the failure is apparently the same as that used during the first inspection and should have disclosed the faults prior to installation. Further development and application of inspection methods may be required.

The Argonne National Laboratory concurs with the Allis-Chalmers conclusion that a fatigue failure occurred. All indications are that the failure was in no way connected with anything peculiar to a nuclear power plant or the direct steam cycle used at EBWR.

APPENDIX A

SUMMARY OF INVESTIGATION

(Submitted by Allis-Chalmers, June 23, 1958)

A. INTRODUCTION

As a result of a root failure of a single blade in the second last spindle row of Turbine No. 10648 located at the Argonne National Laboratory, a complete metallurgical, dimensional and vibration study was conducted to determine the cause of the failure.

B. INVESTIGATION PROCEDURE AND DISCUSSION

1. Preliminary Inspection Survey

All blades from this row were vapor blasted and "Magnaglo" inspected for cracks. Two blades were found to have slight indications. Blade 91 had an indication in the root fillet on the outlet side and blade 130 in the root fillet on the inlet side. It was subsequently found by the Laboratory that the indication in blade 130 was a file mark resulting from breaking the sharp corners of the root.

2. Metallurgical Survey

Examination of a blade (No. 130) from the same heat of material (Code KEJ) as the blade that failed showed that the chemical analysis and the physical properties of this material were in accordance with Allis-Chalmers blade material specification ACM-1418. Detailed microscopic examination of the surface of the blades showed no evidence of stress corrosion, general corrosion, intergranular attack or other types of surface attack, and the general surface condition was found to be similar to other blades returned from service after operation under standard steam conditions. There is no evidence that Boiling Water Reactor steam has had any adverse effect on the blade material.

Microscopic examination of blade 91 (having a "Magnaglo" indication) showed the indication to be a mechanical lap, as evidenced by the cold working of the material. The lap was directly below the depression in the fillet.

Examination of the failed blade showed the fracture to be a characteristic axial fatigue failure. The fatigue failure originated in the outlet root fillet at the same location as the depressions in the other blades. The blade that failed shows a small plateau adjacent to the fatigue fracture, indicating the existence of a lap similar to the one found in blade 91.

3. Blade-Vibration Study

The blade and disk vibrations were reviewed both analytically and by test. In order to facilitate vibration tests, the disk groove was modified to permit caulking the blade to provide a root fixity comparable to that in operation. At the low operating stress involved the natural frequencies of the blade are not a contributing factor to the failure.

The addition, however, of a severe stress concentration, such as a lap or sharp depression, could produce a stress beyond the endurance limit of the material and cause a fatigue failure.

4. Inspection Survey

A visual inspection of all blade roots disclosed that all but nine blades in the row had a slight depression in the root fillet on the outlet side. A dimensional inspection of a typical blade root (92) and the blade groove was made. From a comparison of groove and blade root dimensions it was determined that the depression in the outlet root fillet was in no way the result of the assembly of the blade in the groove.

A review of the processing and fixturing used for the manufacture of this blade was made and disclosed that a fixture used for holding the blade while machining the outlet edge introduced the lap in the root fillet. Figure 1 shows this fixture with a finished blade inserted, although the normal conditions of a blade at this time would only have the root finished and the concave side of the form finished. The depression in the root fillet on the outlet side was formed by the sharp corner of locator "A" as shown in enlarged view. The clearance between the Allen screws and the holes in the locators permitted operator maladjustment of the locators in the direction indicated such that the corner of locator "A" rested in the root fillet. Dimension "D" was then about 0.030 whereas dimension "E" was 0.060. A number of blade roots were "blued" and inserted in this fixture confirming the cause of the depressions in the outlet root fillet. This fixture was used in the processing of this one row of blades only for the Argonne turbine.

C. CONCLUSIONS

From analysis of the investigations made, it has been concluded that the failed blade had a mechanical lap, similar to that found in blade 91. It is believed that these laps were caused by a secondary adjustment by the machine operator in the aforementioned fixture which in effect rolled over a burr formed by the initial insertion in the fixture. The increased stress resulting from the stress concentration due to the lap was of sufficient magnitude to exceed the endurance limit of the material, and initiate the fatigue failure.

It is further concluded that the lap present in these blades was an isolated case in view of the absence of similar failures on duplicate blading. All duplicate blades in stock were again inspected and none have been found with fixture marks in the fillets. Shot peening the roots of the replacement blades is considered an additional precaution in improving the fatigue strength.

APPENDIX B

ALLIS-CHALMERS LABORATORY INVESTIGATION NO. 2644

A. INTRODUCTION

A blade from the second last spindle row of the 5000/6250-kw steam turbine for the Experimental Boiling Water Reactor at the Argonne National Laboratory failed through the root of the blade. The blades in this row had a standard one-inch single "T" root. Two other blades (No. 91 and 130) from the same row had Magnaflux indications in the fillet of the root. A large number of the blades also had a groove or scratch in the fillet between the neck and the outlet hook of the root. These blades had been in service for approximately $1\frac{1}{2}$ years with a total of 4000 operating hours. The turbine was supplied with steam at a temperature of 486°F from a boiling water reactor and the operating temperature of the second last blade row was approximately room temperature.

The failed blade and twenty-one additional blades having Magnaflux indications or grooves in the roots were submitted to the Research Laboratories for examination. The material specified for the blades was ACM-1418.

B. INVESTIGATION

1. Visual Examination

The surfaces of the blades were covered with a thin brown-colored deposit. A green deposit was also observed on the surface of the blades just under the shroud.

The failed blade is shown in Figure 2. The fractured surface, Figure 2, had the typical appearance of a fatigue failure. The failure began at the edge of a small flat in the root fillet between the neck and hook on the outlet side of the blade (see Figure 4).

A Magnaflux indication was observed in the root fillet at the hook on the inlet side of blade No. 130 (see Figure 5). A typical example of the scratches or grooves observed in the blade roots is shown in Figure 6. These grooves were in the same location as the flat observed in the fillet of the failed blade. The Magnaflux indication observed in Blade No. 91 was also located in the same general location.

Although the turbine had operated on steam from a boiling water reactor, radioactivity of the blades was very low. The beta plus gamma count did not exceed that of double background, as measured with a Geiger counter survey meter.

2. Chemical Analysis

The chemical composition of the blades was as follows:

	<u>Failed Blade No. 94</u> <u>Heat Code KEJ</u>	<u>Blade No. 130</u> <u>Heat Code KEJ</u>	<u>Specified</u> <u>ACM-1418</u>
Carbon	0.107%	0.112%	0.06 - 0.13%
Manganese	0.45	0.50	0.25 - 0.80
Phosphorus	0.022	0.022	0.03 Max.
Sulfur	0.027	0.024	0.03 Max.
Silicon	0.30	0.30	0.50 Max.
Nickel	0.33	0.37	0.50 Max.
Chromium	11.95	11.95	11.5 - 13.0
Molybdenum	0.49	0.54	0.60 Max.

The material used for the blades was ACM-1418 as specified.

3. Mechanical Properties

The mechanical properties of the blade material (obtained from 0.250-inch diameter tensile bar from Blade No. 130 Code KEJ) and the original properties of the material from which these blades had been machined are tabulated in the following table:

	<u>Blade No. 130</u> <u>Code KEJ</u>	<u>Original</u> <u>Properties</u>	<u>Specified</u> <u>ACM-1418</u>
Tensile Strength - psi	110,000	112,500	111,000
Yield Strength - psi at 0.01%	75,300	81,875	77,500
Elongation - %	24.0	23.0	25.0
Reduction of Area - %	69.5	66.0	69.0
Izod-Impact - ft. lbs.	-*	86.0	89.0
Brinell Hardness	228	228	241
			200 - 240

*Blade size too small to obtain Izod impact test bar.

There were no significant differences in the mechanical properties of the blade material before and after service. The mechanical properties of the failed blade could not be determined because of mechanical damage to the blade. However, based on the hardness of 228 Brinell, the failed blade probably also met the specified tensile requirements.

4. X-Ray Diffraction and Fluorescence Analysis

The brown deposit on the blades was a soft, non-magnetic amorphous solid consisting of major amounts of iron and nickel and very small amounts of chromium, copper, lead, and zinc. The green deposit

was also soft and non-magnetic. X-ray diffraction patterns of the green deposit were similar, but not identical, to the nickel hydroxides. Small amounts of iron and copper were also present in the green deposit.

5. Microscopic Examination

The microstructure of the failed blade consisted of scattered ferrite stringers and a uniform distribution of carbides in a matrix of tempered martensite which is normal for ACM-1418 material. The fractured surface was typical of a fatigue failure which had started at the edge of the cold-worked flat in the fillet (shown in Figure 3), as indicated in Figure 7.

Longitudinal sections were prepared through the Magnaflux indications in Blades No. 91 and 130 and through the grooves in the fillets at the outlet hooks of Blades No. 34 and 35. The Magnaflux indication noted in the fillet at the inlet hook of Blade 130 was identified as a tool mark, probably caused by a file. The Magnaflux indication observed in the fillet on the outlet hook of Blade No. 91 was caused by a lap (see Figures 8 and 9). The microstructure adjacent to the lap had been cold worked and was similar to the microstructure adjacent to the flat of the failed blade. A longitudinal section through the groove of Blade 34 is shown in Figure 10. Deformation and displacement of the metal in the blade root had occurred.

Detailed microscopic examinations were made of the surface of the turbine blades. There was no evidence of stress corrosion, general corrosion, intergranular attack, or other types of surface attack. The general condition of the surface is shown in Figures 11 and 12. The microstructure adjacent to the surface and general surface condition of these blades were similar to other blades which had been returned from service after operation under standard steam conditions.

C. SUMMARY AND CONCLUSIONS

This investigation had indicated that the blade from the second last row of the steam turbine failed by fatigue. Chemical analysis and microscopic examinations indicated the blade had been made from the specified ACM-1418 material and that the material was free from abnormal inclusions and other defects. Tensile and hardness tests indicated the material met the specified mechanical properties. There was no evidence of stress corrosion or other forms of surface attack. The fatigue failure began at the edge of a cold-worked flat in the fillet at the outlet hook of the root of the blade. Similar cold-worked areas and deformation were observed in the fillets at the outlet hooks of other blades from the same row.

It is believed that the stress concentration of the cold-worked and deformed areas (laps) contributed to the fatigue failure. It is further believed that operation in steam from a boiling water reactor was not a significant factor for the failure.

FIGURE 1

TOOLING FIXTURE USED FOR HOLDING TURBINE BLADE WHILE THE OUTLET SIDE WAS MACHINED. A FINISHED BLADE IS SHOWN IN PLACE, BUT NORMALLY THE ROOT AND THE CONCAVE SIDE OF THE BLADE ARE FINISHED BEFORE PLACING IN THE FIXTURE. NOTE THE EN-CIRCLED AREA INDICATING THE METHOD THE BLADE ROOT FILLET WAS COLD WORKED.

FIGURE 2

FAILED BLADE SHOWING THE LOCATION OF FAILURE THROUGH THE NECK OF THE SINGLE "T" ROOT. THE FATIGUE FAILURE BEGAN IN THE FILLET BETWEEN THE HOOK AND THE NECK ON THE OUTLET SIDE OF THE BLADE AND HAD PROGRESSED ALMOST ENTIRELY ACROSS THE NECK BEFORE THE BLADE ROOT FAILED IN TENSION.

MAGNIFICATION: APPROXIMATELY 3/4 X.

FIGURE 3

FRACTURED SURFACE OF FAILED BLADE SHOWING CHARACTERISTIC FATIGUE FAILURE. THE FAILURE BEGAN APPROXIMATELY IN THE CENTER OF THE OUTLET HOOK AT A SMALL FLAT IN THE FILLET.

MAGNIFICATION: 2 X.

FIGURE 4.

SAME AS FIGURE 3 BUT IN GREATER DETAIL TO SHOW FLAT IN FILLET BETWEEN THE NECK AND HOOK OF THE BLADE ROOT.

MAGNIFICATION: APPROXIMATELY 6 X.

FIGURE 5

MAGNAFLUX INDICATION OBSERVED IN THE FILLET
AT THE INLET HOOK OF BLADE NO. 130.

MAGNIFICATION: APPROXIMATELY 2 X.

FIGURE 6

BLADE NO. 35 SHOWING LOCATION OF THE
SCRATCHES OR GROOVES OBSERVED IN THE
FILLETS BETWEEN THE NECK AND OUTLET
HOOK OF THE BLADES. MAGNAFLUX INDICA-
TION IN BLADE NO. 91 WAS OBSERVED IN
THE SAME LOCATION.

MAGNIFICATION: APPROXIMATELY 2 X.

FIGURE 7

CROSS SECTION THROUGH FRACTURE OF FAILED BLADE SHOWING THE START OF THE FATIGUE FAILURE AT THE EDGE OF THE FLAT. THE SURFACE OF THE FLAT HAD BEEN COLD WORKED. FRACTURED SURFACE WAS TYPICAL OF A FATIGUE FAILURE.

MAGNIFICATION: APPROXIMATELY 100 X.

ETCH: FERRIC CHLORIDE

FIGURE 8

CROSS SECTION THROUGH MAGNAFLUX INDICATION
OBSERVED IN FILLET OF BLADE NO. 91, SHOWING LAP.
THE GROOVE WAS LOCATED IN THE SAME AREA AS
THE FLAT OBSERVED IN THE FILLET AREA OF THE
FAILED BLADE.

MAGNIFICATION: 100 X.

ETCH: FERRIC CHLORIDE

FIGURE 9

SAME AS FIGURE 8 , BUT IN GREATER DETAIL
TO SHOW EXTENT OF COLD WORK AND LAP.

MAGNIFICATION: 500 X.

ETCH: FERRIC CHLORIDE

FIGURE 10

CROSS SECTION THROUGH THE SCRATCH OR
GROOVE IN THE FILLET AT THE OUTLET
HOOK OF BLADE NO. 34 SHOWING COLD WORK
AND DISPLACED METAL.

MAGNIFICATION: 500 X.

ETCH: FERRIC CHLORIDE

FIGURE 11.
CROSS SECTION THROUGH AIRFOIL OF THE
FAILED BLADE SHOWING SURFACE CONDI-
TION.
MAGNIFICATION: 500 X.
ETCH: FERRIC CHLORIDE

FIGURE 12
SAME AS FIGURE 11, BUT IN GREATER DE-
TAIL TO SHOW GENERAL SURFACE CONDITION
OF THE FAILED BLADE.
MAGNIFICATION: 1000 X.
ETCH: FERRIC CHLORIDE

FIGURE 13
CONCAVE SIDE OF FAILED BLADE (#94).

FIGURE 14.
CONVEX SIDE OF FAILED BLADE (#94).

FIG. 15
BLADE & SHROUD NUMBERS OF SECOND
FROM LAST STAGE OF EBWR TURBINE ROTOR