EXECUTIVE SUMMARY

ROOT CAUSE ANALYSES

OF

FERMI 2 MAIN TURBINE GENERATOR EVENT

AUGUST 27, 1994

Prepared By: [signature] (for)

Detroit Edison Root Cause Analysis Team

Approved By: [signature: Leonard C. Fron]

Leonard C. Fron
Director, Turbine and Special Projects

9/15/94
Post-It™ brand fax transmittal memo 7671 | # of pages ▸ 9

To TIM COLBURN	From
Co.	Co.
Dept.	Phone #
Fax # 504-3861	Fax #

EXECUTIVE SUMMARY OF ROOT CAUSE ANALYSES OF FERMI 2 MAIN TURBINE GENERATOR EVENT

SYNOPSIS

The Fermi 2 Main Turbine Generator suffered extensive damage following a turbine blade failure event on December 25, 1993. A major investigation into the cause cf the blade failure has been carried out and this report is a summary of the conclusions reached by three independent teams - DECo, GEC ALSTHOM, and FPI. As is frequently the case with such events, there is a lack of totally conclusive evidence and it has not been possible to establish a single root cause with 100% certainty. In recognition of this, a number of corrective actions have been identified which address all the probable root causes identified by each of the teams, thereby assuring the future integrity of the turbine generator. Details of each team's findings can be found in the referenced reports.

INTRODUCTION

On December 25, 1993 Fermi-2 was operating at 93% of licens reactor power generating 1107 Mwe Net. Operators reported that the plant wa ating normally and that no abnormal indications were present. At 13:15 hours, without warning, the Main Turbine Generator (MTG) tripped and the reactor scrammed. A turbine blade penetrated Low Pressure Turbine No. 3 (LP-3) Exhaust Hood. Severe vibration caused considerable damage to the MTG, including destruction of the exciter and damage to the General Service Water and Turbine Building Closed Cooling Water supply piping. Hydrogen, seal oil, and lubricating oil were released and ignited. The resultant hydrogen and oil fires triggered deluge and sprinkler systems. The oil and water mixture ultimately flooded the Turbine and Radwaste Buildings.

Shortly after the event, site management placed the Turbine Building under quarantine to assure personnel safety and ensure that no evidence related to root cause was lost. A specially formed Turbine Generator Assessment Team developed an Action Plan that contained procedures for the identification, documentation and preservation of evidence. After initial review by turbine and generator equipment experts and a metallurgist, evidence judged to be related to root cause was uniquely identified and placed in controlled storage. A Root Cause Analysis Team (RCA Team) was then formed to determine the root cause(s) of the event. Failure Prevention International (FPI) and the manufacturer of the MTG, GEC ALSTHOM, cooperated fully with the RCA Team, and each conducted an independent root cause analysis.

The three teams independently evaluated all reasonable potential causes of the event, systematically eliminating those which did not contribute to the root cause. The analysis method ensured that all of the approximately 1600 potential causes were addressed.

From these potential causes, each independent team developed a list of probable causes, but no single root cause was identified with complete certainty. In some instances there was agreement on probable causes, but there were also differing opinions regarding the probability of other causes based on interpretation of evidence and analytical results.

Recommendations which bound the probable causes identified by the three teams are listed in this report. They are designed to prevent recurrence of the event. These recommendations were made in recognition of the decision to operate in Fuel Cycle No. 5 with low pressure turbine seventh and eighth stage blades removed and pressure plates installed, and to replace the low pressure steam path in RFO5.

CONCLUSIONS

The event started with failure of Blade No. 9 of the front flow, eighth stage of Low Pressure Turbine No. 3 (LP-3). The turbine tripped due to the effects of vibration, and did not overspeed. Damage to other LP eighth stage blades, other systems and equipment was consequential. Cracks in the seventh stage blades and discs of the low pressure turbines pre-dated the event, but did not cause the event.

Blade No. 9 failed in the airfoil section. A crack initiated about 1.25 inches above the blade platform near the trailing edge. The crack propagated by high cycle fatigue to a critical size and the remaining section failed due to overload. The eighth stage blade design has been trouble-free in thirty-two rows in nuclear pressurized water reactor service applications with up to two-and-one-half times as many operating hours as Fermi 2.

The following is a compilation and brief description of the most probable root causes identified by at least one of the three teams. These are presented in no particular order of relative importance.

Steam Path Water

This probable root cause has two categories: Accumulation of Steam Path Water and Water Induction. These causes are described and discussed individually below:

Accumulation of Steam Path Water - As steam passes through the turbine some condenses as free water. The water forms droplets which impact the rotating and stationary blades, and accumulates and is shed from a blade's trailing edge as larger droplets. The water is also slung radially outward due to centrifugal force, accumulating as an annular ring at the outlet side of the diaphragms. Moisture is removed between stages and piped to feedwater heaters with extraction steam or directed to the condenser directly from the turbine internals. Inadequate interstage water removal can lead to increased steam path water.

A postulated mechanism involving excess steam path water to explain the observed turbine blade failure involves a blade that protrudes radially or axially to a greater extent than others in a blade row. Because of manufacturing and installation variations, a blade may protrude, to some extent, and therefore, become subject to greater loading than the others. As this blade moves through the water it may twist due to resisting force. At some threshold, the blade could become overloaded resulting in permanent deformation or excited at a resonant frequency. A cyclic load could result in stresses exceeding the fatigue strength of the blade.

Water Induction - Normal moisture levels in the machine are not a source of abnormal excitation loading. They do not generally present a serious problem and there is no practical limit to the quantity of entrained water. However, the situation is quite different if slugs of water are present. These may be due to reversal or blockage of flow in extraction/drain lines causing an interruption in the normal water extraction process, or as a result of steam flashing in the extraction/drain lines or heaters and forcing water back into the turbine.

Slugs of water have been known to be capable of deforming blades foils. The water mass will break up immediately on the first impact and the effects will be restricted to only one or two blades. Observations of damage on turbines which are known to have experienced water problems confirm that often only a small number of blades can be affected.

Results of inspections of turbine and extraction steam systems, analyses of postulated events and review of historical operating data have not substantiated nor eliminated steam path water as the cause of the event.

MTG Rotor System Torsional Resonance

Negative sequence current can have an adverse effect on turbine generators if the complete rotor assembly is torsionally resonant at 120 Hertz. The negative sequence current imposes an alternating torque on the generator rotor and turbine rotors, causing the rotors to alternately twist in addition to their normal rotation. Because of the large size and complex shape of the complete Turbine Generator rotor assembly, it has many frequencies at which it is likely to twist, called torsional resonant frequencies. If the turbine generator rotors are torsionally resonant at 120 Hertz, the combination of torque due to negative sequence current and resonance can lead to high stress in turbine blades. Based on configuration of the LP rotors, the 7th and 8th Stage blades are the most susceptible to torsional resonance.

There are several sources of negative sequence current but the most common are load distribution and system transients. There is always some phase unbalance in the system, therefore, there is always some source for the torsional resonant excitation frequency.

The negative sequence current is not automatically recorded. This is consistent with industry practice since this is a relatively new phenomenon being addressed by the utilities.

At the time of the design of the Fermi 2 Turbine Generator (circa 1970) torsional vibration was considered only for rotors and couplings. Blades and discs were not addressed. This was accepted design practice at the time. More recent analyses have utilized advanced modeling capabilities that take into account the flexibilities and interactions of rotors, shafts, discs and blades.

GEC ALSTHOM was requested by Detroit Edison in March 1993, to evaluate torsional response as a result of an industry notification on this subject. GEC ALSTHOM concluded, based on tests of LP rotors of the type supplied to Fermi 2 conducted in their overspeed facilities, that "torsional response of the Enrico Fermi turbine generator is quite satisfactory and that negative sequence torque excitation will not cause any problems".

A more detailed, machine specific, turbine generator system analysis for torsional resonance of the Fermi 2 system was completed by GEC ALSTHOM in May 1994. They concluded that torsional resonance was not a factor in the failure of Blade No. 9. However, an independent third party review of GEC ALSTHOM analyses did not completely support GEC ALSTHOM conclusions and the third party recommended testing. Since the Fermi 2 MTG is being reassembled in a different configuration than existed at the time of the event, verification testing is not possible. Therefore, it is not possible to prove or disprove that torsional resonance was the root cause of the event.

GEC ALSTHOM has completed a torsional resonance stress analysis of the turbine generator system configuration (with LP Stage 7 and 8 rotating and stationary blades removed, with pressure plates installed in place of 7th and 8th Stage stationary blades, and with a static exciter) which will exist in the startup from RF-04. The analysis includes a conservative calculation of rotor stresses by considering excitation of a torsional resonance. The additional dynamic stresses are negligible and the analysis concludes that torsional vibration of the turbine generator rotor system (post RF-04) is not a concern.

The Uniqueness Of Blade No. 9

Detailed inspection and metallurgical examinations of Blade No. 9 revealed two characteristics which could make it vulnerable to fatigue failure due to steady state and cyclic service loads: 1) the trailing edge of the foil section at the point of the fracture was found to be approximately 40% thinner than blades which had not failed; and 2) a residual tool mark was found on Blade No. 9 at the point of initiation of the fatigue crack. Both characteristics are considered undesirable from the standpoint of effects on blade fatigue life. These characteristics are not typical or associated with operationally-caused wear.

In addition to the most probable root causes the following probable contributing factors were identified:

- Steam path chemistry contribution to corrosion fatigue
- Low condenser back pressure increasing eighth stage blade loading
- Inadequate interstage moisture separation and drainage
- Isolation of feedwater heaters Numbers 1 and 2 South in September, 1993
- Possible loss of lacing spool interconnection to Blade No. 9

Short term (prior to replacement of the low pressure steam path) actions addressing these contributing factors are:

A. Lacing spools and relatively low condenser back pressure are addressed by operating without seventh and eighth stage blading in all three low pressure turbines, and with pressure plates installed. Lacing spools are unique to eighth stage blades. Eighth stage blading is the most sensitive to loads associated with condenser back pressure.

B. Steam Path Chemistry - The contribution of steam path chemistry is primarily associated with the effect of ionic species such as oxygen, sulfates, chlorides, etc. on fatigue strength. This factor is of lesser concern on turbine blades and discs with significantly lower service loads than the higher loaded seventh and eighth stages of the low pressure turbines.

C. Moisture separation/drainage and isolation of feedwater heaters are bounded by the recommendations associated with steam path water and are described in the Recommendations Section.

RECOMMENDATIONS

Because a number of different root causes were identified, corrective actions to prevent recurrence for each must be implemented, and/or additional testing/monitoring must be performed.

The RCA teams are aware of the decision to operate in Fuel Cycle No. 5 with low pressure turbine seventh and eighth stage blades removed and pressure plates installed. The teams concur with this decision. The teams are also aware of the decision to replace the low pressure steam path in RFO5. The following recommendations are made to bound the probable causes and contributing factors identified by the teams, and have taken into consideration these decisions. The recommendations that follow also include actions that can be taken to provide additional information which could result in shortening the list of probable root causes.

A. Steam Path Water

Corrective Actions

1. Perform moisture carry over/moisture removal testing of the MSRs and Extraction Steam Systems upon return to service following RFO4. Review results, and implement corrective actions deemed appropriate during RFO5. (May also provide information for verification of a probable root cause.)

2. Perform moisture carryover/moisture removal testing to evaluate effects of any corrective actions implemented following RFO5.

3. Review Extraction/Heater Drain Systems for conformance with ANSI/ASME Standard TDP-2-1985, and implement appropriate changes. (May also provide information for verification of a probable root cause.)

4. Confirm that the replacement low pressure steam path has features for adequate water removal, as part of the design review, prior to RFO5.

B. MTG Rotor System Torsional Resonance

Corrective Action

1. Complete a torsional vibration analysis and conduct a torsional resonance test, if validation is determined necessary, whenever the Main Turbine Generator (MTG) is modified in a manner that affects MTG response to torsional excitation.

Actions for Additional Information

1. Review results of any torsional resonance analyses and confirmatory testing performed on similar machines, as they become available.

2. Measure and record generator negative sequence current during start-up and full load operation to characterize seasonal and holiday system tendencies.

Corrective Actions Associated With Steam Path Replacement

1. Ensure that replacement steam path component designs address all anticipated service loads and operating conditions.

2. Ensure that the steam path environment is considered in the design of replacement components.

3. Ensure that replacement steam path components are manufactured and installed to design specifications.

REFERENCES

1. GEC ALSTHOM, "Root Cause Investigation conclusions based on information available up to 30th June 1994", dated July, 1994.

2. FPI International, "Independent Root Cause Analysis Assessment", dated July 26, 1994.

3. Detroit Edison Root Cause Analysis Team, "Fermi 2 Main Turbine Generator December 25, 1993 Forced Outage Root Cause Analysis Report" (TMTB 0010-0801.21)

ATTACHMENT 11

L Goodman

Date: October 11, 1994
TMTB-94-0025

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

From: P. K. Hudson *Paul K. Hudson*
Principal Engineer
Turbine Group]

L. G. Fron *LG Fron*
Senior Engineer *LG Fron*
Technical & Engineering Services

Subject: **Summary Report - NDE Examination, Bend Reduction and Overspeed Testing of LP Rotors, Rev. 1**

1a. Magnetic Particle Inspection and Visual Examination

Prior to shipment of the three LP rotors to Westinghouse at Charlotte, each LP rotor was visually examined and MPI was performed. The visual examination documented blade and shroud damage and the material condition of rotor journal couplings, etc. The MPI was a detailed examination of rotor external surfaces, blade airfoils, tenons, shrouds, disc faces and blade roots.

1b. UT Examination:

A non-destructive examination of the 3 LP Rotors using ultrasonics was undertaken at the Westinghouse facility in Charlotte. This was performed in two phases as follows:

a. the interface between the straddle root of blades on stages 4, 5 and 6 and their respective disc head or wheel was examined, and

b. the interface between discs and the rotor, referred to as a disc bore exam, and areas surrounding dowels, which link discs together was also examined.

The UT techniques used differed in that the disc bores were examined using an auto scan method, which incorporates both sending and receiving units. This is shown in Figure 1. The data is displayed on video monitors and can be stored on magnetic tape. Results of these tests showed no significant indications on any of the three rotors.

The blade root and disc head examination was done using hand-held probes. A sectional diagram is shown in Figure 2. The angle probes are required to view up into the disc head. The areas where indications are typically seen are disc head under side radii and blade root pressure face radii.

Reference blocks are manufactured with defects built-in of known depth and location. These are then scanned and calibration traces taken, see Figures 3 and 4. The actual blade root and disc heads are then viewed for indications and, by comparison with the reference block traces, an estimate of size and position can be made.

Examination of the LP rotor stages 4, 5 and 6 blade roots and disc heads showed no significant indications, with the exception of the stage 5 rear disc on LP3. In this case, the traces indicated some crack-like indications in the disc head under approximately 42 stage 5 blades. The blades were removed and the suspect area cleaned. MPI examination did show shallow discontinuous cracks along the bottom neck radii on the exhaust side. See Figure 5. The indication shape was indicative of stress corrosion cracking, a replica of the area later substantiated this. A small grinding wheel was used to blend grind and polish out the indications and repeat MPI performed to verify clearance.

2. LP Rotor Bend Reduction:

Following the December 25 incident and dis-assembly of the LP Turbines, the LP rotors were evaluated and found to have slight bends. Each of the rotors had bends of different magnitude, but generally the bow or bend was most pronounced at the center plane, or mid-length between journals.

The amount of bend was small when compared to the rotor's span, being typically .020" over 318 inches, but the rotors have a large mass and the resulting rotation of the rotors center of gravity about the true sag line would cause large vibrations and loading of the turbine bearings and pedestals. Figure 6 shows a rotor with a normal sag line (#2) and two lines (#3), which indicate the vertical deflection of the rotor line due to the bend - the actual deflections have been greatly exaggerated for clarity.

The reduction of the induced bow was undertaken at the Westinghouse facility in Charlotte. The Fermi LP rotors are of built-up construction i.e. the rotor forging has discs or wheels shrunk onto it, which then carry the turbine blades. Couplings are then shrunk on both ends to connect the rotor line together. At 1800 rpm the disc-to-rotor interference fit is reduced by the CF forces induced by blading and disc material. Any rotor distortion at this speed can then be captured by the discs as speed is reduced due to an uneven shrinkage forces being exerted.

Normally, running the rotors to an overspeed condition will reduce shrink and allow discs to settle, on run-down even loading will be obtained. Both LP1 and LP2 were taken to 120% nominal speed i.e. 1800 x 1.2 or 2160 rpm and disc settling was seen to take place, indicated by vibration amplitude and phase angle changes, the bow in both cases was reduced.

LP3 had sustained a more significant bow, such that running to an overspeed condition presented some risk to the facility. It was therefore, decided to reduce the bow as much as possible by individual disc heating with the rotor in a vertical position. Discs 6, 5 and 2 on the front of LP3 were heated in turn, using induction heating units, so as to release their shrink fits and then allowed to cool, establishing a more uniform fit on the rotor.

This effectively reduce the bow from .036" to .018", which then made it acceptable for overspeed runs. In the overspeed facility, the bend was further reduced to .0115" by relieving the uneven fits of the remaining discs.

Below are tabulated the rotor run-out readings before and after the Charlotte work. The remaining bow is not a problem with respect to clearances with the LP cylinders, at most it decreases top and bottom clearances by only .006" on LP2 and LP3. The out-of-balance load, (which the rotor center of gravity rotating off true center induces), has been balanced out at Charlotte. Trim balance runs of each LP were undertaken with stage 7 & 8 root blocks fitted. Coupling faces and coupling rims were machined true to aid in coupling alignment and reduce site balancing requirements.

Rotor	1994 As Found	1994 After Overspeed
LP1	.016"	.010"
LP2	.018"	.012"
LP3	.033" -Disc heating .017"	.012"

3. Overspeed Testing and Balancing of LP Rotors:

The ability of the residual rotor bow to result in dynamic energy by rotation (vibration) was minimized by shop balancing each rotor and machining the coupling faces. Each LP rotor was shop balanced at full speed, 1800 rpm, in a spin box (at Westinghouse-Charlotte). Final shaft vibration at 1800 rpm for each LP rotor was less than 2 mils P-P after balancing.

The face of each coupling on each LP rotor was machined to result in a face total indicated run-out of 1 mil or less. This assures that the bow of each rotor will have negligible effect (stress due to bending, by bolting the couplings between rotors) on the adjacent rotor when coupled.

Calculations were done to verify that existing coupling bolts could be reused between couplings, after the face true-up. The resulting error between adjacent bolt holes was found to be less than 1 mil, which is well within the fit tolerance for the hydraulic coupling bolts used.

Results of Balancing LP Turbine Rotors

After each LP Turbine rotor was run to 120% overspeed and the residual bow was determined stable, the 7th & 8th stage blades were removed from the rotors, 7th & 8th stage root protection blocks were installed and the rotors were returned to the spin box for 110 % overspeed testing and final balancing.

The final balancing was performed to reduce shaft vibration amplitude at the critical speeds and at 1800 rpm to acceptable values (values which Westinghouse accepts for shipment of new rotors). The final shaft vibration amplitudes at 30 Hz after balancing at 1800 rpm for each LP rotor are as follows:

LP1	1.4 mils P-P
LP2	1.3 mils P-P
LP3	1.7 mils P-P

PKH/LGF/klb

cc: P. Fessler
R. McKeon
W. Romberg

ATTACHMENT 12

ROBERT A. NEWKIRK
SEP 28 1994

Date: September 26, 1994

To: R. A. Newkirk, Supervisor
Licensing & RA

From: K. E. Howard, Supervisor
Mechanical & Civil

K E Howard

Subject: **Response to NRC Questions**

1. "Structural Walkdown Final Report" in Page 47 states that concrete pedestals for tanks "will require" concrete repair. This statement should have read, "may require" because during the initial walkdown on February 12, 1994 (Page 46) concrete surface was not visible. However, later the tanks were jacked up for inspection of the area between the base of the tanks and the top of the pedestals. No damage was found and no repairs were required to the pedestals. This conclusion is stated on Page 3, Item #20 of "Attachment 2 - Recovery Plan Action Items" of the walkdown report.

2. After the generator stator lift, the turbine overhead cranes have continued to perform as before. At the present time, they are used to set the low pressure turbine components in place. Periodical preventive maintenance is performed on these cranes per Plant Procedure 35.716.001. However, in response to your question, a visual inspection of the hit crane girder location and column to crane girder connections at this area was performed on 9/26/94. The crane supporting structure was found to be in satisfactory condition.

Written By: H. Sahiner

HS:dsb

Post-It™ brand fax transmittal memo 7671	# of pages ▸ 1
To TIM COLBURN	From BOB NEWKIRK
Co. NRR	Co.
Dept.	Phone # 313 586-4211
Fax # (301) 504-3861	Fax #

ATTACHMENT 13