CONFIDENTIAL

FERMI 2

MAIN TURBINE GENERATOR

DECEMBER 25, 1993

FORCED OUTAGE

ROOT CAUSE ANALYSIS

REPORT

JULY 1994

Prepared By Root Cause Analysis Team:

J.D. Black J D Black
R.J. Corkins R J Corkins
L.G. Fron
D.B. Smith
G.M. Trahey
J.L. Uicker James L. Uicker

Approved by L.C. Fron L. C. Fron
Chairman

B/S

EXECUTIVE SUMMARY

On December 25, 1993 the Fermi-2 Main Turbine Generator (MTG) tripped at 1315 hours. The Root Cause Analysis Team identified and evaluated more than 1600 potential causes of the event. The root cause analysis concluded that the event was initiated by the failure of a single eighth stage blade in the front flow of Low Pressure Turbine No. 3.

The Root Cause Analysis Team further concluded that the cause of the eighth stage blade failure is a combination of physical defects and other factors:

1. Physical defects in the blade which are not operationally related:
   - a. The thickness of the blade at the location of the failure was 40% less than specified by design documents.

[redacted]

2. Other factors that may have been major contributors to the failure are:
   - a. rotor ~~torsional~~ resonance,
   - b. moisture content of the steam,
   - c. oxygen content of boiling water reactor generated steam.

Confirmation requires completion of finite element analysis, torsional vibration testing to confirm analysis, and fatigue testing. Because of the decision to operate in Fuel Cycle 5 with low pressure turbine seventh and eighth stage blades removed, conditions at the time of failure cannot be duplicated to confirm root cause.

The Root Cause Analysis Team developed recommendations to address all of the above issues in the interim (Fuel Cycle 5) and for the long term (post RF05).

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1.0 INTRODUCTION

On December 25, 1993 Fermi-2 was operating at 93% of licensed reactor power generating 1107 MWe Net. Operators reported that the plant was operating 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. Hydrogen seal oil, hydrogen, and lubricating oil were released and ignited. The resultant hydrogen and oil fires triggered deluge and sprinkler systems. The severe vibration also damaged General Service Water and Turbine Building Closed Cooling Water supply piping. The resultant 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 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 conduct a Root Cause Analysis.

The purpose of this report is to communicate the results of the Root Cause Analysis effort and to provide conclusions and recommendations based on information obtained and evaluated through July 1, 1994.

2.0 CONCLUSIONS

The RCA Team concluded:

1. The MTG tripped as a result of high shaft vibration which actuated the mechanical overspeed trip mechanism. The MTG did not overspeed during the event.
2. The event was initiated by the failure of a single eighth stage blade (Blade No. 9) in the front flow of LP-3.
3. Blade No. 9 failed through the mechanism of high cycle fatigue.
4. Blade No. 9 was uniquely susceptible to failure because of preexisting conditions [redacted]

[illegible] proprietary [illegible]

5. Blade No. 9 may have been subjected to increased steady state and/or cyclic stresses because of any or all of the following: low quality steam, low condenser back pressure, rotor torsional resonance excited by electrical system disturbances and/or negative sequence current.

6. Blade No. 9 may have had a reduced fatigue life because of the oxygen content in Boiling Water Reactor generated steam.

7. Blade No. 9 caused the subsequent failure of four adjacent blades (Blade Nos. 8 thru 5).

8. Damage to other systems, structures and components, except for 7th stage blading and discs, was consequential to the failure of Blade No. 9.

9. Cracks discovered in 7th stage blade roots and disc serrations during post event examination, existed prior to the event, but were not a cause of the event.

3.0 SEQUENCE OF EVENTS

On December 25, 1993 Fermi-2 was operating at 93% of licensed reactor power, generating 1107 MWe net. Condenser back pressure was approximately 1.36 in. Hga, which is among the lowest levels in the operating history of the plant. Operators reported the plant had been operating normally.

Blade No. 9 of the eighth stage front flow (turbine end) of LP-3 of the Fermi-2 MTG failed at 13:15 hours on December 25, 1993. The blade created an approximately 2 ft. by 2 ft. hole in the west side of the exhaust hood and came to rest on a platform above the West Moisture Separator Reheater (MSR) near a reheat stop and intercept valve. Blade Nos. 8 thru 5 failed as a result of striking Blade No. 9, but remained in the condenser. A blade punctured an approximately 1 ft. by 1 ft. hole in the west side of the turbine exhaust neck.

The unbalanced condition associated with the sudden mass loss (approximately 450 lbs) resulted in shaft vibration at all MTG bearings in excess of recorder range of 37 mils p-p. The MTG overspeed trip was activated and the reactor scrammed. Recorded data indicates the rotor line was running at synchronous speed (1800 RPM) for approximately 9 seconds after the start of the event [Ref. 2]. At this time the main generator breaker opened. Recorded data further indicated that the machine coasted to 780 RPM in approximately 100 seconds, at which time the turbine vibration instrumentation signal was lost. Post event inspection of the stub shaft at the front standard, which contains the two mechanical over-speed trip rings, indicated shaft radial movement of at least 3/16 in.

This movement exceeds the 1/8 in. design clearance between the shaft mounted rings and trip levers of the mechanical overspeed trip system which accounts for the MTG trip.

The severe vibration of the shaft destroyed the No. 11 bearing and sheared the bolts in the exciter/generator coupling destroying the exciter. Hydrogen seal oil, lubricating oil and hydrogen were released and caught fire. The sprinkler systems and deluge systems triggered by the fire sprayed water into the area that mingled with the oil and the water from damaged General Service Water piping and Turbine Building Closed Cooling Water piping and flooded the Turbine and Radwaste Buildings. One of the vibratory shocks transmitted through the foundation triggered the seismic event recorder.

The Fermi-2 Sequence of Events Recorder print outs, control room log, Shift Supervisor's logs, and selected control room recorded data were reviewed, evaluated, and consolidated into the sequence of events for the period 00:00 hrs on December 23, 1993 thru 24:00 hrs on December 25, 1993. [See Appendix B] This document was refined and used along with interviews, results of the root cause analysis effort and other information to construct an Event and Causal Factor Chart. [See Appendix C]

4.0 BLADE NO. 9 FAILURE MECHANISM

Metallurgical analysis revealed that Blade No. 9 failed due to the mechanism of high cycle fatigue. The fatigue crack initiated about 1 - 1/4 in. above the blade platform on the pressure (concave) side near the trailing edge. The crack propagated to a critical size (approximately 40 - 50% of the foil cross-section) and the blade failed due to overload. The separated foil section (approximately 85 lbs) impacted trailing Blade No. 8 and caused it to fail due to tensile overload. Trailing Blade Nos. 7, 6, and 5 then failed in succession also due to tensile overload. Remaining front flow eighth stage blades and nearby structures were damaged in varying degrees due to impacts by ejected blades, diffuser fragments and pieces of blade lacing spools. [Ref. 3]

Metallurgical examination of the fracture surface of Blade No. 9 revealed that the fatigue crack progressed in a continuous manner (stable crack growth) with an estimated thirty minutes from initiation to catastrophic failure (assuming a once per revolution stress cycle). No contribution from stress corrosion cracking was detected. Blade No. 9 was found to be of the proper material heat treated to the specified strength and toughness levels. [Ref. 3]

5.0 CAUSE ANALYSES

5.1 Approach

The RCA Team utilized the quarantine period to develop its approach to identification of the Root Causes of the Turbine Generator event. In anticipation of a very complex problem with many possible scenarios, it was decided to use problem solving tools to facilitate the tracking and systematic elimination of failure modes.

Tools used included sequence of events charting, change analysis (Kepner-Tregoe), and event and cause factor charting. Integration of these tools provided a means of validation and verification of decisions and conclusions reached as the analysis progressed.

An Analysis Tree was developed to provide a relatively simple, graphic method of assuring that no failure mode was overlooked, particularly in the early, screening phases of evaluation and determination of causes. The premise is that all possible modes of failure are depicted in a validated diagram, and by addressing each, specific terminal item, the true failure mode (apparent cause of the problem) will become obvious. Team members were assigned responsibility for documenting and evaluating each terminal item. While fact-based information was preferred, expert opinion was an accepted basis for a decision.

In the case of the Fermi-2 MTG failure more than 1600 potential causes were identified that could have contributed to the event. In order to assure that these many items were addressed, a matrix was developed to track each item to resolution. Examples of the analysis tree and summary pages of the matrix are provided in Appendix D. Working copies of the analysis tree, matrix, and other key information used in the root cause analysis are stored in the Fermi-2 records repository.

In implementing the process it was important that the differences between apparent causes and root causes be understood. An <u>apparent</u> cause of a problem is best described as an identified failure mode. e.g., a shaft fails due to high cycle fatigue (the failure mechanism) due to shaft misalignment (the <u>apparent</u> cause). A <u>root</u> cause is best described as a factor that, if corrected, would have prevented the failure from happening, e.g., poor work practices and defective testing that allowed the misalignment to occur.

The approach described above narrowed the 1600 possible causes down to ten credible apparent causes:

1. Preexisting Conditions
2. Torsional Resonance
3. Moisture/Water
4. Unbalanced Steam Flow
5. Steam Flow Blockage
6. Material
7. Foreign Object
8. Flow Induced Vibration
9. Major Resonance
10. Lacing Spools

These apparent causes and their disposition are described in the following sections.

5.2 Preexisting Conditions

In the course of the investigation of the factors contributing to the failure of Blade No. 9, two categories of preexisting conditions were identified and are believed to have had a significant role in the failure. These conditions are described and discussed below.

The first category is physical defects (not operationally-related). Detailed inspection and metallurgical examinations of Blade No. 9 revealed two characteristics which would make it vulnerable to steady state and cyclic load conditions. 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. 2) A residual tool mark was found on Blade No. 9 at the point of initiation of the fatigue crack. [The mark was oriented perpendicular to the longitudinal axis of the blade foil. The mark had a sharp 45° "V- Notch" geometry and was approximately 0.003" deep.] Both of these conditions are considered undesirable from the standpoint of affect on blade life. [Ref. 3] These defects are not characteristic of operationally-caused wear. The RCA Team considers these two observations to be significant causal factors relative to the failure of Blade No. 9.

If eighth stage blade fatigue life was a generic problem, other blades with some evidence of fatigue cracking would be expected. Visual and non-destructive examination of eighth stage blades removed from the LP rotors revealed no evidence of such cracking. The trailing edges of all eighth stage blades on the LP rotors were measured. Blade No. 9 exhibited the thinnest trailing edge. This observation was statistically significant in that its measurement was more than three standard deviations from the mean of the total population. Therefore, the fatigue failure problem is not generic, rather it is believed to be limited to Blade No. 9 due to its trailing edge and surface finish.

[redacted]

- The eighth stage blade failure on Dec. 25, 1993
- Seventh stage blade root cracks observed on LPs 2 and 3.
- Seventh stage blade root crack identified in 1989 (RFO1). [Ref. 8]
- Fifth stage blade failure identified in 1989 (RFO1) resulting in redesigned blades. [Ref. 7]
- Fourth stage blade failure identified in 1990 resulting in redesigned shroud under-strapping. [Ref. 7]

not proprietary

- Turbine/Generator System torsional vibration analysis was not available until requested by Detroit Edison in February, 1994.

Ref. 10 is not proprietary

- There is no evidence suggesting the BWR operating environment was considered in the design of the prototypic Fermi-2 blading. [Ref. 10] The concern with the BWR operating environment is the effect of increased levels of oxygen in BWR steam (18 ppm) on blade material fatigue strength.

The RCA Team focused on two issues, namely that the blade design may not have adequately considered all potential blade loads expected within the envelope of operation of the plant, and the design may not have provided sufficient margin for the expected degradation of the strength of the blade material in the environment of BWR-generated steam and the local conditions of the eighth stage.

The RCA Team had neither full access to the eighth stage design calculations, nor hard data to substantiate the effects of BWR steam, nor expertise to judge the applied margins. However, based on the successful application of the eighth stage design at two other PWR locations without any failures, the RCA Team concluded that the design was not significantly deficient. However, the RCA Team did identify a different blade failure history at Fermi 2 (BWR) compared to sister MTG's at PWRs. There is also a perceived different blade failure history between BWRs and PWRs with other manufacturer's turbines Consequently, the RCA Team concluded that the presence of much higher levels of oxygen (1000 times) in BWR-generated steam may be a contributor to the failure of Blade No. 9 and it appears that this may not have been considered in the blade design.

Not proprietary see p 6 of CAL response

The RCA Team commissioned Stress Technology Inc. (STI) to conduct an independent analysis of the Fermi-2 eighth stage blades [redacted] A final report of results is expected by July 29, 1994.

5.3 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 more 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 the turbine blades.

There are several sources of negative sequence current but the most common are load distribution and system transients. There is <u>always</u> some unbalance in the system, therefore there is always some source for the torsional resonant excitation frequency. [Ref. 1]

ANSI Standards and manufacturers provide guidelines for acceptable negative sequence current for synchronous generators. There is no comparable standard for turbines. Typical operating negative sequence current, as indicated by the panel meter, is reported to be usually less than one percent for Fermi-2. This indicates that the steady state negative sequence current was well within the manufacturer's guidelines and well within the industry accepted guidelines. At Fermi-2, as well as all other Detroit Edison plants, the negative sequence current is not automatically recorded. This is consistent with industry practice.

Therefore if torsional resonance originated with the electrical system, it would have had to occur with a relatively weak 120 Hz negative sequence current, or as the result of a transient event.

There were two system transients on December 21, 1993, one at about 07:30 hrs. and another at about 11:30 hrs. These transients were due to switching of generating units at Ludington, a common event not unique to the time of failure. These could be the source of an impulse excitation for torsional resonance. There were no subsequent transients up to and including December 25, 1993.

At 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 that time. More recent analyses have utilized advanced modeling capabilities that take into account the flexibilities and interactions of rotors, shafts, discs and blades.

Successful prevention of double frequency torsional resonance requires [Ref. 5]:

- Recognition of the existence and complex behavior of blade-coupled high-frequency torsional modes through appropriate modeling techniques.
- Factory and field testing so specific designs can be verified.
- A design approach with rules that integrate the above steps, enabling the designer to tune torsional mode responses away from 120 Hz.

A Turbine Generator System analysis for Torsional Resonance of the Fermi -2 system was completed by GEC ALSTHOM in May 1994 [Ref. 6]. They concluded that results were satisfactory. The analyses were reviewed by an independent third party and additional information regarding system parameters which will aid in evaluating the potential for a resonant torsional mode have been requested. This matter has not yet been resolved.

The RCA Team recognized that the GEC ALSTHOM torsional analysis was not validated by any tests. Experience reported by other vendors indicates that computer analysis of torsional resonance without incorporation of test data is invalid, especially at the higher modes in the 120 Hertz range. Consequently, the RCA Team is unable at this time to prove or disprove torsional resonance as a root cause. 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. Later testing of the revised rotor assembly and comparison with the appropriate torsional model will provide additional useful information.

5.4 High Steam Path Moisture

The steam supplied to the Fermi-2 turbine is near-saturated, and a significant fraction condenses to moisture as it passes through the turbine steam path. Steam exiting last stage blades normally contains approximately [12%] moisture. The moisture forms as droplets which impact the rotating and stationary blades and accumulate and are shed from the trailing edges as larger droplets. The moisture is also slung radially by the centrifugal force, accumulating to some depth at the outer ring of the diaphragm. Moisture is removed between stages and piped to feedwater heaters with extraction steam.

[Thermodynamic cycle analyses, using a refined Syntha II model [Ref. 4], indicate steam path moisture content to be up to 1% higher than design heat balance levels due to high load, condenser pressure below 1.5 in Hga, poor MSR performance, operating with Nos. 1 and 2 feedwater heaters out of service, etc.] This is an increase of [10%] in the volume of moisture passed by the turbine stage and is expected to be within the capability of the stage to pass without damage.

Other observed deleterious effects of high steam path moisture are erosion of the leading edge of rotating blades and stage efficiency loss. These effects are not a cause of the failure of Blade No. 9.

A postulated mechanism to explain observed turbine blade failures is described as a "proud" blade, i.e. one that projects radially or axially to a greater extent than the majority of the blades. Due to manufacturing and installation variations, one blade will be proud on each row to some extent. The proud blade is subject to additional loads in the presence of moisture. [Unshrouded blade tips act as pumps, propelling the surface moisture through the stage. The susceptibility of a proud blade to damage is a function of many factors, such as blade strength, shroud and grouping arrangements, moisture level, and rotating blade tip clearance.] Two potential failure mechanisms are proposed.

a. As the proud blade pumps moisture, it untwists due to the retarding force. This causes further untwist of the blade to catch more moisture and increasing the retarding force. At some threshold, the blade becomes overloaded and experiences permanent deformation or breakage.

b. The depth of water that each blade pumps varies around the circumference of the circle of rotation, due to manufacturing and assembly variations, gravity, etc. The resulting retarding pumping force on the blade is a cyclic load on the blade. The total cyclic load component may exceed the fatigue strength of the proud blade and cause it to fail.

The RCA Team was neither able to confirm nor deny the presence of high moisture in the steam as a cause of the failure of Blade No. 9 for the following reasons:

a. Blade No. 9 was extensively damaged during the event, so it is not possible to determine if any deformation occurred prior to failure. No records are available to confirm if it was a proud blade.

b. The conditions that existed on December 25, 1993 can not be repeated to establish a definite cause-effect relationship.

c. Damage to other blades of the front flow of LP-3 judged to be consequential to the failure of Blade No. 9 makes it difficult to establish if any blades were damaged by the presence of excessive moisture.

d. Review of the operating history failed to reveal any abnormal event that resulted in high moisture in LP-3 that was coupled in time to the failure of Blade No. 9.

5.5 Water Induction

A source of dynamic loading of eighth stage blading is water induction involving reversal of flow in the extraction/drain lines to the Nos. 1 and 2 feedwater heaters under conditions which could cause a "slug" of water to impact eighth stage blading. The Nos. 1 and 2 heaters were specifically evaluated because they do not have "non return" valves between the LP cylinders and heater inlet nozzles. An independent review of No. 1 and 2 feedwater heater system designs for conformance with ANSI/ASME TDP-1-1985 concluded that no significant deficiencies existed in the heater designs. In addition, no significant structural damage, or evidence of a flood up condition was identified during inspection of extraction steam piping, heater internals, and LP turbine cylinder halves. Rapid load reductions can result in interstage turbine pressure becoming less than the heater shell pressure, creating a potential for reversal of fluid flow. A review of operating history indicated that no load change had occurred for ten days prior to the event. Thermodynamic analysis [Ref. 4] and fluid dynamic analysis [Ref. 12] concluded that water induction events associated with the Nos. 1 and 2 feedwater heaters are not likely. Based on the foregoing the RCA Team concluded that water induction is not a root cause of the failure.

5.6 Unbalanced Steam Flow

The following cases of unbalanced steam flow were considered:

a. Between the three LP turbines. The plant was operated for a period of time in December 1993 with one reheat stop valve closed. Thermodynamic analysis of the operating condition reveals that this condition results in unbalance between the MSR flows, but produces essentially no effect on the individual turbine section flows. Therefore, this is not a root cause for the failure.

b. Between the two ends of LP-3 turbine. The steam flow balance between the two end flows of the LP turbines is a function of the flow-passing area of each. Visual examination of the stationary and rotating blades of LP-3 subsequent to the event revealed no significant difference between the two ends. Consequently this is not a credible failure cause.

c. Between the stationary or rotating blades. Inspection of the rotating and stationary blades of LP-3, after the event revealed damage to both rotating and stationary blades of the front flow of the eighth stage. The RCA Team concluded that the damage was consequential to the failure of the eighth Blade No. 9, and did not exist prior to the event. All of the rotating and stationary blades of all stages of all the other LP turbines were essentially undamaged capable of passing normal steam flow. Therefore, unbalanced flows between the stationary and the rotating blades was ruled out as a root cause.

5.7 Steam Flow Blockage

With the exception of the eighth stage of the front flow of LP-3, no blade damage was observed during disassembly inspection. No foreign objects that could block flow through any of the LP turbine flows were found. Therefore, steam flow blockage was not a root cause.

5.8 Materials

Samples from Blade No. 9 and other blades were subjected to a number of metallurgical, chemical and physical tests. The blades were found to have been made from the specified material, a modified 12-chrome alloy and heat treated to specified strength and toughness levels. Therefore, deviation from material specification was not a root cause. [Ref. 3]

5.9 Foreign Object

Foreign objects such as tools, weld slag, valve parts, etc. are an occasional cause of steam turbine blading damage. Typically the foreign objects are carried by the inlet steam and cause damage to the admission stage and downstream stages. In such events, typically all blades are damaged to a similar degree, resulting in closing of the flow-passing area of the rotating and stationary blades. Numerous marks are noted on the blade leading edges from the impact of the foreign objects and broken blade pieces.

Examination of the eighth stage blades following the event revealed none of the characteristics of foreign object damage. No foreign objects were found in the condenser that could have been in the eighth stage. No foreign object damage and no failed blades were observed on the seventh or earlier stages that could have been a source of debris to cause failure of the eighth stage. Therefore, foreign object damage was not the cause of the failure of Blade No. 9.

5.10 Flow Induced Vibration

Stalled flutter is a potential failure mechanism of turbine blades that has been observed to occur in free standing blades at low flow, high back pressure conditions. The angle of incidence of the steam on the rotating blade at low flows is such that unsteady flow, or stall, occurs, identical to airplane wings under similar conditions. If the conditions persist, the blade is subjected to cyclic loads and may fail from fatigue. Turbine blades are generally protected from stalled flutter by providing a trip at high back pressure, typically 5 in. Hga. Fermi-2 has a high back pressure alarm and trip set point of 4.5 in. Hga. An approach to preventing stalled flutter is to provide a continuous tie of the blade tips, such as by the use of lacing spools. Discussions with industry experts indicate that no instances of stalled flutter have been reported in turbine blades with a continuous tie. Since the Fermi-2 eighth stage blade failure occurred at high load, and the eighth stage blade design utilizes a continuous tie, and there is no evidence to suggest that a lacing spool was lost prior to the event, stalled flutter is unlikely a cause.

Unstalled flutter was ruled out as a cause for the following reasons:

a. Unstalled flutter has only been observed in free-standing blades. Since the Fermi-2 eighth stage blades are continuously coupled by lacing spools, the blades cannot vibrate independently as would be required for unstalled flutter.

b. Unstalled flutter has only been observed in precision-manufactured blades. Unstalled flutter requires that adjacent blades vibrate at the exact same frequency. Only modern precision forging techniques can consistently produce blades with the required identical natural frequencies. Since the Fermi-2 eighth stage blades were produced from envelope forgings and then machined and hand-finished to final dimensions, it is unlikely that adjacent blades have identical resonant frequencies.

c. As a further check on blade vibration at high flow, [an Extended Strouhal Number was calculated for the eighth stage blade row, per techniques of Siemens. The Extended Strouhal Number was calculated to be 0.017E-3, well below the threshold of 0.29 E-3 where self-excited blade vibration was observed in free-standing blades.] This analysis confirms the conclusion that unstalled flutter is an unlikely cause of the eighth stage blade failure. [Ref. 11]

5.11 Major Resonance

Turbine manufacturers typically test assembled blade rows on a prototype wheel to determine resonant frequencies. Accumulated test data and analytical techniques allow these frequencies to be calculated with some degree of precision. Typically the last two or three stages of turbines require detailed design and test to avoid major resonance. The blades are tuned by design and tested during manufacture so that critical frequencies are avoided.

Experience indicates that blade failures due to major resonance are likely to occur after a few months of service as demonstrated by the fifth stage blade failures at Fermi-2 in 1988 and 1989. Typically many cracked or failed blades are observed as all of the blades respond similarly to the forces that are common to all of the blades.

Major resonance is not a likely cause of the eighth stage blade failure due to the extensive frequency testing performed on the prototype blades during the design phase. A Campbell Diagram of the eighth stage provided by GEC ALSTHOM indicates the first three vibration modes are well clear of possible resonance. In addition, the long service life of these blades [redacted] and the longer service life of similar blades at other plants [redacted] indicates that the blades are well tuned to avoid major resonance. The fact that only one blade (Blade No. 9) shows evidence of fatigue indicates that the blade row is well-tuned to avoid major resonance.

5.12 Lacing Spools

The eighth stage blades are linked by lacing spools with one spool between each blade. The loss of a spool or spools would allow a blade to become free-standing and possibly more susceptible to excitation. The loss of one lacing spool would produce a detectable change in turbine vibration [Ref 9]. Review of vibration data and Control Room strip chart data showed no vibration changes indicative of mass loss from the MTG occurred from the start-up from RF03 to the event on December 25, 1993. The RCA Team considered a scenario where two lacing spools could come free at one end, but remain in place on a blade foil, resulting in a free-standing blade. This condition would not change rotor balance and therefore could go undetected. The RCA Team concluded that it is extremely unlikely that lacing spools would remain in-place under a 10,000 lb. centrifugal force.

6.0 RECOMMENDATIONS

The RCA Team is 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 and to replace the low pressure turbine steam path in RF05. Therefore, no recommendations pertaining to return to service with existing seventh and eighth stage blades installed have been provided. The RCA Team recommends the following:

a. Complete a torsional vibration analysis for the Turbine Generator System that will exist in the restart following RF04.

b. Conduct a resonance test during the start-up following RF04 to verify the torsional vibration model used.

c. Repeat recommendations a and b whenever the main turbine generator system is modified in a manner that affects MTG system response to torsional resonance excitation.

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

e. Review results of any torsional resonance analyses and confirmatory testing performed on similar machines.

f. Upgrade MSR to improve moisture removal efficiency and reheat performance.

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

h. Ensure that the Boiling Water Reactor steam environment is considered in the design of replacement components.

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

APPENDIX A

REFERENCES

1. Technical and Engineering Services Report 94J70-21, "Fermi-2 Turbine Generator Assessment Team Root Cause Analysis of the Turbine/Generator Incident of December 25, 1993 - Electrical Report", June 20, 1994

2. Technical and Engineering Services Report 94R71-1, "Analysis of DVA Vibration Alarm/Coastdown Magnetic Tape for Fermi-2 MTG", Jan. 11, 1994

3. Technical and Engineering Services Report 94V70-13, "Metallurgical Analysis of Fermi-2 LP3 8th Stage Turbine Blading ", June 20, 1994

4. PEP 94-025, "Thermodynamic Modeling and Analysis of Fuel Cycle 4 (In Support of Root Cause Investigation into December, 1993 Turbine Failure)", July 11, 1994

5. Hurley, J and Welhoe[illegible], "Turbine Generator Designs and Testing for Prevention of Double-Frequency Torsional Resonance", American Power Conference, April 1989

6. GEC ALSTHOM report "Torsional Vibration of Fermi-2 Rotor/Blade System", Transmittal letter P.M. McGuire to L.G. Fron, May 6, 1994

7. DER 89-0331 "Manual Scram was initiated due to high MTG vibration" (LER 89007)

8. DER 89-1242 "Stage 7 Turbine Blade Root Crack LP-2 Generator End"

9. Memo, L.G. Fron to RCA Team, "Analysis of Fermi-2 Main Turbine-Generator Vibration from November 1992 to December 25, 1993", Mar. 22, 1994

10. Merz and McLellan, "Detroit Edison Company Enrico Fermi Atomic Power Plant - Unit 2 Turbine Generator 2 Design Review 46" Long Prototype Last Stage Blade", circa 1973

11. Memo, with attachment, D.B. Smith to G. M. Trahey, "Turbine Blade Flutter" July 6, 1994

12. TMNF 94-0047, "Evaluation of Conditions Which May Cause Reverse Flow from No. 1 Feedwater Heater to LP Turbine"

APPENDIX B
TURBINE GENERATOR FAILURE
TIME/EVENTS LINE

12/23/93 00:00:00.000 hrs to 12/25/93 24:00:00.000 hrs

(Constructed from Sequence of Events Recorder and Control Room and NSS Logs. Additional data from other sources to be incorporated in subsequent revisions.)

04D058 12/23/93

Numerous Casing H2 p Lo
0000 - 0200 Hrs
0800 - 1220 Hrs
2000 - 2338 Hrs

086N30

Condenser p HI 1846 - 1910 Hrs } Need to Ck

Resolved - Surv. 27.112.04 Performed On 2/23/94 Expected Alarms

Control Room (C/R) Log

0200 Hrs H2 Added To Gen (67 psig to 72 psig)

0210 Hrs Surveillance 27.112.08, H2 Gas Usage Failed (> 2000 SCF/Day)

1213 Hrs H2 Added To Gen (67 psig to 72 psig)

1350 Hrs XFR Oil From "New" Oil Tank To Turbine Oil Reservoir

12/24/93

Numerous Casing H2 p Lo
App. 0000 - 1330 Hrs
2100 - 2330 Hrs

C/R Log

0900 Hrs H2 Delivery XFR Identified Leak In Fill Isoln Valve

1030 Hrs H2 Cooler Alarm HI Temp (183) AndLo Temp Alarm On Opened TCV Bypass

1321 Hrs Repair Of Fill Isoln Valve Compl

1331 Hrs H2 Added To Gen (66 psig to 72 psig)

Legend

Time Frame Initiation

Significant Event

Window
Alarm Description
Point Time (hh:mm:ss.msc)

Response characteristics of SOER are such that events occurring within 50 milliseconds are considered to have occurred concurrently.

G. M. Trahey
6/28/94
Revision 1

12/25/93

Numerous Casing
H2 p Lo
Alarm/Clear
Sequences
00:02 - 01:12

C/R Log

0120 Hrs H2
Added to Gen
(68 psig to 72 psig)

4D099

Main TLO
Res. HI Cleared
@ 05:19:40.338
086N30
04:09:33.289

Expected - See
Oil Transfer
Cleared
05:19:40.338

10D070 *

SS 69 XFMR
Trouble Cleared
@ 09:09:23.229
017R12
09:09:21.697

09D006 *

SS 66 XFMR
Trouble Cleared
@ 09:11:04.899
008R12
09:11:03.265

9D005 *

SS 68 XFMR
Trouble Cleared
@ 09:50:27.511
011R12
09:50:26.151

4D051

Stator Coolant Leakage HI
Cleared @ 10:33:41.783

S.P. Makeup Flow > 1 gpm
Expected when filling
head tank or system

119N30 10:31:36.954

4D056

Casing H2 Gas p Lo
SP: HI = 77 psig
Lo = 68 psig
Numerous
App. 0812 - 1030 Hrs

086N30

C/R Log

1029 Hrs H2 Added To Gen
(67 psig to 72 psig)

*XFMR alarms - expected Oper Rounds - See Rounds Sheet

4D133 *

Main XFMR 2A Trouble
Cleared @ 10:48:22.835

002S11 10:48:21.631

4D134 *

Main XFMR 2B Trouble
Cleared @ 10:52:44.115

006S11 10:52:42.987

4D006 *

SS 64 XFMR Trouble
Cleared @ 10:56:01.213

002R12 10:55:59.840

4D129

Main XFMR 2A Oil Temp HI
Cleared @ 10:48:22.835

001S11 10:48:21.631

*XFMR alarms - expected Oper Rounds - See Rounds Sheet

EVENT INITIATION t = 0

< 13:15:47.406

4D008

Turbine Overspeed Elect
CKT Fault (de-energized)
Relay RLG-1

140N30 13:15:47.406

4D110

Thrust BRG Strainers
Delta p HI

13:15:47.413

4D013

Main Turbine Vibrn HI

BRG #9 - 13:15:47.443
BRG #8 - 13:15:47.482
BRG #4 - 13:15:47.514
BRG #11 - 13:15:47.530
BRG #5 - 13:15:47.534
BRG #7 - 13:15:47.558
BRG #10 - 13:15:47.582
BRG #3 - 13:15:47.598
BRG #1 - 13:15:47.617

NOTE: At the time of the event, select SW for vibration as follows: PED - 1, 10, & 11 SHAFT - 2-9

S.P	Shaft	PED
HI	6	3
HI-HI		
1, 10, & 11	8	4
2-8	12	6
9	10	5

Per P. Hudson, 1/10/94

NOTE: Also came in "ON LOAD TRIP" no window

SP
Shaft 10 mils
PED 5 mils

BRG #11 - 13:15:47.526
BRG # 8 - 13:15:47.536
BRG # 9 - 13:15:47.591
BRG # 5 - 13:15:47.601
BRG # 4 - 13:15:47.623
BRG # 7 - 13:15:47.624
BRG # 2 - 13:15:47.637
BRG #10 - 13:15:47.664
BRG # 3 - 13:15:47.682
BRG # 1 - 13:15:47.739

NOTE: "On Run-Up Trip Alarm"
SP Shaft - 10 mils PED - 5 mils

#11 - 13:15:47.532
8 - 13:15:47.599
9 - 13:15:47.600
5 - 13:15:47.606
7 - 13:15:47.622
4 - 13:15:47.632
2 - 13:15:47.648
3 - 13:15:47.654
#10 - 13:15:47.655
1 - 13:15:47.738

SEISMIC SYS
EVENT/TROUBLE

13:15:47.475

4D093

Detraining Tank Slip
Ring End Level HI/Lo

13:15:47.454

6D069

Seismic Sys Event/Trouble

S.P. 0.01 g Also triggers
triaxial accelerometers

13:15:47.475

4D002

UA Throttle Vlv Fault

13:15:47.529

TURBINE TRIP

13:15:47.531

No Window

Turbine O/S Mech Trip
SP-110%

062N30 13:15:47.531

No Window

Turbine Trip Relay Tripped

13:15:47.543

3D089

Turbine Control Vlv Fast
Closure (B1, B2, A2, & A1/2)

Betwn 13:15:47.544 & .550

RPS ACTUATION

13:15:47.535
thru
13:15:47.595

RPS Actuation

B2 - 13:15:47.555
B1 ↓
A2
A1 - 13:15:47.562

RPS Actuation

B2 - 13:15:47.581
B1 ↓
A2
A1 - 13:15:47.595

4D091

Electric Governor
Trouble
201N3 13:15:47.587

Note: EVCI Speed
Discrepancy Channel 1 vs
Channel 3 Speed Signal
Mod F

MAIN STEAM BYPASS
VALVES OPEN

13:15:47.697

4D085

Gen. Liquid Leak
Detector Hi

88N30 13:15:47.603

4D001

U/A HP Stop
Valve Fault

13:15:47.691

Main Steam Bypass
Valves Open

13:15:47.697

None

Main Steam Stop
Valves Close

13:15:47.790

None

Main Steam Stop-Throttle
Valve 1-2 Turbine Trip

13:15:47.791

None

Main Steam Stop-Throttle
Valve 3-4 Turbine Trip

13:15:47.801

2.790 MATERIAL
Withheld From Public Disclosure

t ≈ 0.6 Second

Approx. 13:15:47.906

#6 Feedwater Heater
ESS Check Valves Close

13:15:48.155 - 13:15:48.356

4D028

6S Feedwater Heater
ESS Check Vlv Closed

218N30 13:15:48.155

4D009

Turbine Vibm HI - HI
(See Pg. 4 for Setpoints)

BRG # 9 - 47.871
BRG #10 - 47.956
BRG # 11 - 47.975
BRG # 1 - .48.073
BRG # 8 - 48.084
BRG # 4 - 48.125
BRG # 5 - 48.156
BRG # 7 - 48.165
BRG # 2 - 48.190
BRG # 3 - 48.247

4D093

Detraining Tank Turbine
End Level Hi/Lo

221N30 13:15:48.316

4D004

Stator Water Flow Low Fault
SP: 653 GPM
128 W.G.

185N30 13:15:47.897

4D028

6N Feedwater Heater
ESS Check Vlv Closed

13:15:48.356

t = 1.0 Second

Approx. 13:15:48.406

3 & 4 Feedwater Heater
ESS Check Vlvs Close

13:15:48.432 - 13:15:48.705

None

LP Stop/IV 3-4 Turbine Trip
(C.LP)

077N30 13:15:48.416

04D026

Main Turbine 4S Fdwtr Htr
ESS Check Vlv Closed

214N30 13:15:48.432

04D026

Main Turbine 4N Fdwtr Htr
ESS Check Vlv Closed

213N30 13:15:48.447

04D006

Unitized Actuator
Intercept Vlv Fault

161N30 13:15:48.458

04D025

Main Turbine 3N Fdwtr Htr
ESS Check Vlv Closed

211N30 13:15:48.516

04D026

Main Turbine 4N Fdwtr
Htr ESS Check Vlv Closed

213N30 13:15:48.635

t = 2.0 Seconds

Approx. 13:15:49.406

Loss of H2 Seal Oil

13:15:48.989 - 13:15:49.125

04D025

Main Turbine 3S Fdwtr Htr
ESS Check Vlv Closed

212N30 13:15:48.705

04D076

Hydrogen Seal Oil
Pump Auto Start
(<12 psid Oil to Gen
Diff Pressure)

032N30 13:15:48.989

04D079

Hydrogen Seal Oil
Emergency Pump
Auto Start
(<10 psid Oil to Gen -
Normal 15 psid)

034N30 13:15:49.125

Loss of Rectifier &
Stator Cooling

13:15:49.573

04D004

Rectifier Coolant Line #4
Low Flow Fault

138N30 13:15:49.454

LP Stop/IV 1-3-5
Turbine Trip
(E. MSR Side)

025N30 13:15:49.515

04D050

Stator Coolant Pump
Auto Start

038N30 13:15:49.573

04D004

Seal Oil/Gas Diff
Press Low Fault
153N30 13:15:49.765

2/4 SW w/any SW @
10 psid x 2 = trip

H2 Pressure Low

13:15:50.167

04D083

Seal Oil Hydrogen Diff.
Pressure Low

072N30 13:15:49.770

04D027

Main Turbine 5N Fdwtr Htr
ESS Check Vlv Closed
(5S Comes In
at 13:15:59.382)

215N30 13:15:50.058

04D056

Casing Hydrogen
Gas Pressure Low

086N30 13:15:50.167

LP Exhaust Sprays On

13:15:50.991

04D040

Gland Steam Pressure
High/Low

092N30 13:15:50.311

04D031

LP Exhaust Sprays On
(87 GPM Flow)

091N30 13:15:50.991

04D035

LP Exhaust Spray
Emergency Pump Auto
Start (100 PSIG ↓)

023N30 13:15:51.185

[illegible]

t ≥ 4.0 Seconds

Approx. 13:15:51.406

Condenser Press
High & Fault
(SP = 26.5 In Hg)

13:15:52.953
thru
13:15:53.572

04D086

Seal Oil Strainer Diff.
Pressure High

074N30 13:15:51.396

04D004

Rectifier Coolant Line #4
Low Flow Fault

138N30 13:15:51.556

None

Rectifier Coolant Line #4
Lo Flow Turbine Trip

149N30 13:15:51.559

04D018

BRG #6 Shaft Diff.
Expansion Negative

179N30 13:15:52.190

04D114

Thrust BRG Oil Press
Low (SP = < 8 psig)

067N30 13:15:52.599

04D086

Seal Oil Strainer Diff.
Pressure High

074N30 13:15:52.720

04D108

Condenser P: . ısure High
(PDC 9187, Rev. C)

192N30 13:15:52.953

04D073

Generator H2/H2O Diff.
Pressure Low

080N30 13:15:53.091

04D004

Condenser Pressure
High Fault (4.5" Hg)

151N30 13:15:53.572

04D047

LP Exhaust Cooling H2O
Strainer Diff. Press. High

089N30 13:15:53.766

04D105

Thrust BRG Negative
Wear Pre-Trip
(SP = 1040" Movement)

225N30 13:15:54.099

04D077

AVR Channel B Tripped

133N30 13:15:55.212

[illegible]

t ≈ 8.0 Seconds

Approx. 13:15:56.408

Loss of Turbine Lube Oil (?)

13:15:55.311
thru
13:15:55.644

04D004

Bearing Oil Pressure
Low Fault (< 10 psig)

150N30 13:15:55.311

Pt. 2086 BRG Oil
P Lo Fault
Back In at 16:06.164

150N30 16:06.164

04D088

Turbine Oil Pump Auto
Start (10 psig↓)

005N30 13:15:55.351

04D061

AVR On Manual Control

102N30 13:15:55.658

04D092

Turbine Emergency Oil
Pump Auto Start (10 psig↓)

006N30 13:15:55.644

04D018

BRG #1 Shaft Diff.
Expansion Positive

174N30 13:15:55.992

04D018

BRG #6 Shaft Diff.
Expansion Negative

179N30 13:15:56.367

345 KV Breakers Open

13:15:57.183
thru
13:15:57.184

4D065

Gen. Diff. Rel.
String Operated

114N30 13:15:57.161

None

E. Stator Coolant
Pump Off

037N30 13:15:57.229

4D121

345 KV Breaker
Pos. CF Open

021S31 13:15:57.183

None

W. Stator Coolant
Pump Off

037N30 13:15:57.238

4D123

345 KV Breaker
Pos. CM Open

017S31 13:15:57.184

4D144

Gen Field Breaker Open

142N30 13:15:57.306

t ≥ 10 Seconds

> 13:15:57.406

1st Fire Alarm

13:15:59.599

4D132 *

Gen. Freq. Hi/Lo
(SP = 60.5 Hz)
Cleared @ 13:15:59.239

167N30 13:15:57.397

4D004

Stator Water Flow Lo Fault

185N30 13:15:58.036

21U Turbine Building
HVAC Trips

13:15:58.226
13:15:58.234

4D070

Gen. Inlet Water Temp Hi

278N30 13:15:58.530

4D027

Main Turbine 5S Fdwtr Htr
ESS Check Vlv Closed
(5N Closes at 13:15:50.058)

216N30 13:15:59.382

16D027

Fire Alarm

008P80 13:15:59.599

4D132 *

Gen. Freq. Hi/Lo

167N30 13:15:59.694

4D004

Rectifier Coolant Line #1
Lo Flow Fault

110N30 13:15:59.714

4D027

#5N Fdwtr Htr ESS
Check Vlv Closed
(Originally Closed at
13:15:50.058)

215N30 13:15:59.815

None

Rectifier Coolant Line #1
Lo Flow Turbine Trip

096N30 13:15:59.945

*Gen f increasing (SP=60.5 Hz) - Cool Down to Reset. These alarms are low f.

T+ 15 Seconds

Approx. 13:16:02.406

None

Rectifier Coolant Line #4
Lo Flow Turbine Trip

149N30 16:00:00.176

4D004

Rectifier Coolant Line #3
Lo Flow Fault

137N30 16:00:00.194

4D004

Rectifier Coolant Line #2
Lo Flow Fault

111N30 13:16:00.619

4D018

BRG #1 Shaft Diff.
Expansion Positive

174N30 13:16:00.206

None

Rectifier Coolant Line #2
Lo Flow Turbine Trip

39N30 13:16:01.186

None

Rectifier Coolant Line #3
Lo Flow Turbine Trip

106N30 13:16:01.505

4D071

Gen. CT Temp HI

274N30 13:16:01.648

4D018

BRG #1 Shaft Diff.
Expansion Positive Cleared

174N30 13:16:02.863

7D014

Gen. Service Water
HDR p Hi/Lo

008P41 13:16:01.985

16D014

Turbine Bldg
Roof Vents Open

23U41 13:16:03.474

Note: SP Heat 160 deg. F
Electrically CR 20 PSF
Manually

4D018

#6 BRG Shaft Diff.
Expansion Negative Clear

179N30 13:16:03.573

4D073

Gen. H2/H2O Delta p
Lo SP (2 PSID)

80N30 13:16:04.024

4D004

BRG Oil p Lo Fault
(<10 PSIG)

150N30 13:16:06.164

4D084

BRG Oil p Lo
(10 PSIG)

068N30 13:16:06.506

t ≥ 20 Seconds
> 13:16:07.406

4D018
BRG #6 Shaft Diff.
Expansion Negative
179N30 13:16:07.321

4D064
Gen H2 Clrs Inlet/Outlet
Gas Temp Hi/Lo
112N30 13:16:07.522

4D004
H2 Gas Temp Hi Fault
144N30 13:16:08.050

4D016
Bypass Steam Sys
Lo Vac Fault
280N30 13:16:09.600

None
Bypass Steam Sys
Lo Vac Trip
285N30 13:16:10.520

None
Bypass Sys Trip
Relay Tripped
063N30 13:16:10.525

None
LP Stop/IV 5-8 , wbine
Trip (S.LP)
076N30 13:16:10.666

None
NSSS CNDSR Low Vac Trips
Ch D 13:16:12.118
Ch A 13:16:12.119
Ch B 13:16:12.279
Ch C 13:16:12.650

5D013
TBCCW Head Tank p Lo
002P43 13:16:13.470

First Turbine BRG Metal
Temp HI Alarm
13:16:16.435

Note: Brg #11 Lost
@ 13:15:27

4D062
Rectifier/Stat Coolant Loss
Unloading Req'd
277N30 13:16:14.561

4D115
Turbine BRG Metal
Temp HI
N30R837 RCDR
Pts 1-11 - 196 deg. F ↑
Pt 12(thrust) 180 deg. F ↑
103N30 13:16:16.435

Note: Brg #11 Lost
@ 13:15:27

t ≅ 30 Seconds

> 13:16:07.406

t ≅ 60 Seconds

> 13:16:47.406

4D067

Gen. Core Monitor
Trouble

293N30 13:16:17.838

16D028

Fire Det/Prot
System Trouble

009P80 13:16:20.201

04D025

Main Turbine 3N Fdwtr Htr
ESS Check Vlv Closed

211N30 13:16:27.847

4D101

Manifold Steam
Pressure Low

002N11 13:16:28.393

04D006

Unitized Actuator
Intercept Val Fault

161N30 13:16:28.451

04D143
(Rotor)
Generator Field
Temperature High

170N30 13:16:26.763

Note: Measured Three Slip
Rings Approx. 1400 RPM

04D005

Unitized Actuator
LP Stop Val Fault

157N30 13:16:30.580

4D053

AVR Rectifier
Diode Trouble

033N30 13:16:37.720

Note: Indicator Pin In
Fuse "Popped"

4D131

LP Exhaust Temp HI
(See 13:17:25.263)
(230 deg. N20R860)

136N30 13:16:42.670

04D102

Turbine Valve
Position Abnormal

128N30 13:16:46.563

[illegible]

4D083

Seal Oil H2 Delta p Lo
(SP = 11 PSID)

072N30 13:16:48.741

4D004

Seal Oil/Gas Delta p
Lo Fault

153N30 13:16:48.627

None

LP Stop Valves Closed

155N30 13:16:49.000

None

LP Stop/IV 1-2
Turbine Trip (N.LP)

139N30 13:16:49.005

None

LP Stop/IV 2-4-6 Turbine
Trip (W. MSR Side)

043N30 13:16:49.006

4D046

Main Turbine Tripped

093N30 13:16:49.006

4D094

Elect. Turning GR
Clutch/MTR Failure

073N30 13:16:52.051

Note: Same Signal
As 4D096

4D096

Jacking Pumps All
Auto Start Failure
< 250 RPM

019N30 13:16:53.090

Note: Same Signal
As 4D094

None

Rectifier Coolant Line #3
Lo Flow Prot. Defeated

190N30 13:16:57.357

t ≅ 120 Seconds

> 13:17:47.403

4D112

Gen. Exciter
Field Ground

095N30 13:17:03.581

4D004

Seal Oil/Gas Delta p
Lo Fault

153N30 13:17:05.220

4D010

Turbine Vibration
Trip Defeated

126N30 13:17:15.650

None

Rectifier Coolant Line #1
Lo Flow Turbine Trip

96N30 13:17:15.979

4D004

LP Exhaust Hood Temp
HI Fault (See 13:18:42.870)
(> 280 deg. N30h360)

152N30 13:17:25.243

4D115

Turbine BRG Metal
Temp HI

103N30 13:17:27.352

4D071

Generator CT Temp HI

274N30 13:17:31.003

4D131

LP Exhaust Temp
HI Clear

136N30 13:17:42.699

4D070

Gen Inlet H2O Temp HI
Multiple (Approx. 21) Alarms
Clear 17:53:14 -
17:56:28

276N30

t ≥ 15 Minutes

> 13:30:47.406

4D062

Rectifier/Stat Coolant
Loss Unloading Req'd

277N30 13:18:10.576

4D004

LP Exhaust Hood Temp
HI Fault SP (> 280 deg. F)

152N30 13:18:10.696

04D004

LP Exhaust Hood Temp
HI Fault Cleared

152N30 13:18:20.122

4D027

Main Turbine 6N Fdwtr Htr
ESS Check Valve Closed

215N30 13:18:29.263

4D053

AVR Rectifier Diode
Trouble Cleared

33N30 13:18:32.033

None

H2 Temp HI Trip
(SP = 185 deg. F)

55N30 13:21:48.317

6D003

Waste L.O. Tank Level Hi

001P70 13:28:50.759

4D060

Casing H2 Gas Purity Lo
(Clears @ 13:30:06.871)

084N30 13:29:41.235

04D059

Stator Coolant Demin
Conductivity #1

120N30 13:39:08.598

4D078

Seal Oil Reservoir
Tank Level - Lo

075N30 19:30:48.048

4D143

Gen Field Temp HI In & Out
(SP = 302 deg. F)
21:15:01
170N30 21:18:28

4D143

Gen Field Temp HI
Numerous 21:42:14
Alarm & ↓
Clear
Events 21:56:06.527
(SP = 302 deg. F)

170N30

NOTE:

- Gen'l SW Header
- AVR Rect. Diode Trouble
- Fire Alarm (Reflash)
- Gen CT Temp HI
- Gen Field Temp HI
- TBCCW Hd Tank p Lo

Occasional alarms/clears
21:56 - 23:36

C/R Log

1355 Hrs Field Team
Reports Fire @ "Generator"

1400 Hrs Fire Brigade
Mustered

1556 Hrs Isolated GSW to
H2 Coolers

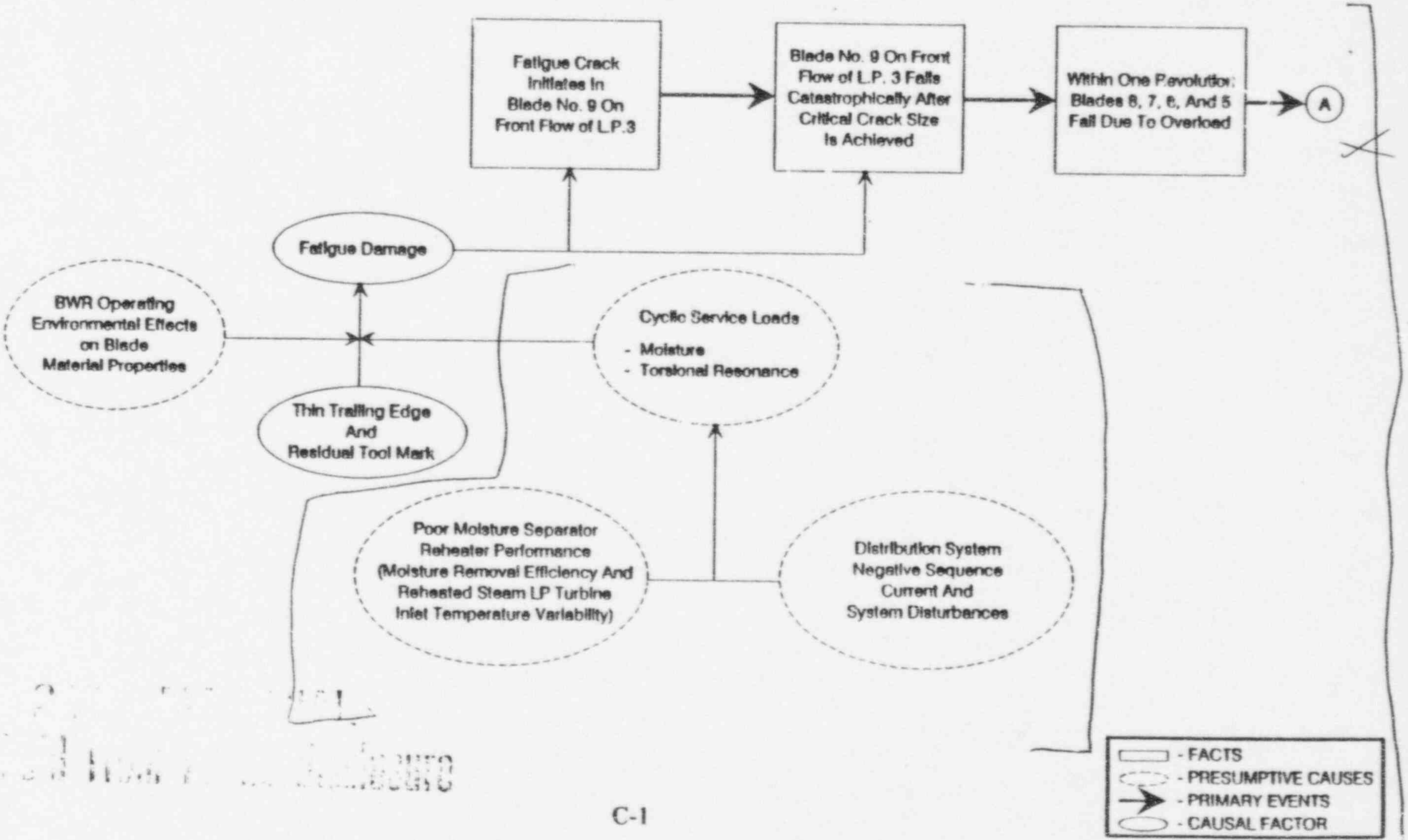
1726 Hrs Unitized
Actuators S/D

1838 TBCCW S/D

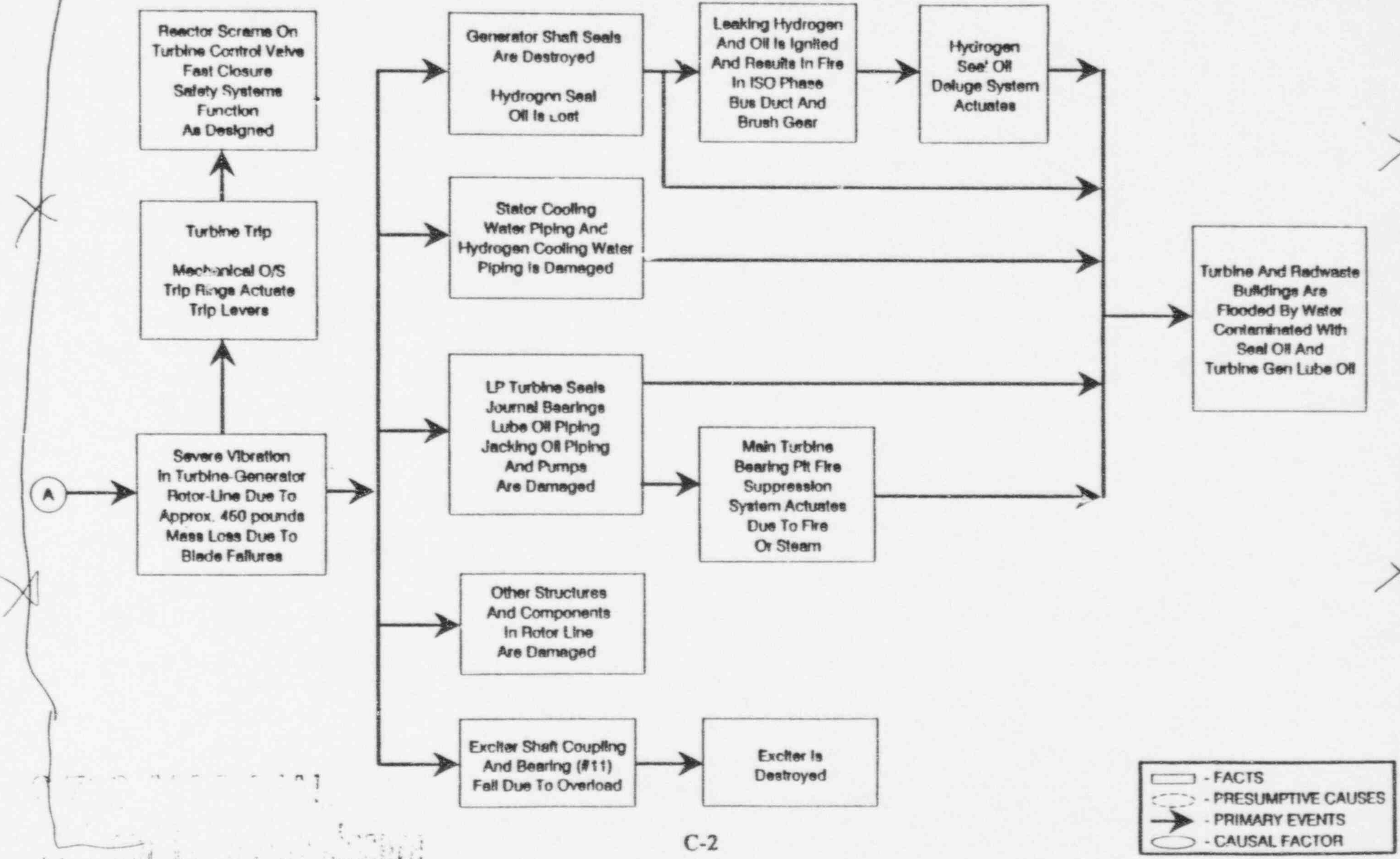
C/R Log

1952 Hrs "Air Leak"
In Generator Reported

APPENDIX C
EVENT & CAUSAL FACTOR CHART
FERMI 2
MAIN TURBINE GENERATOR EVENT

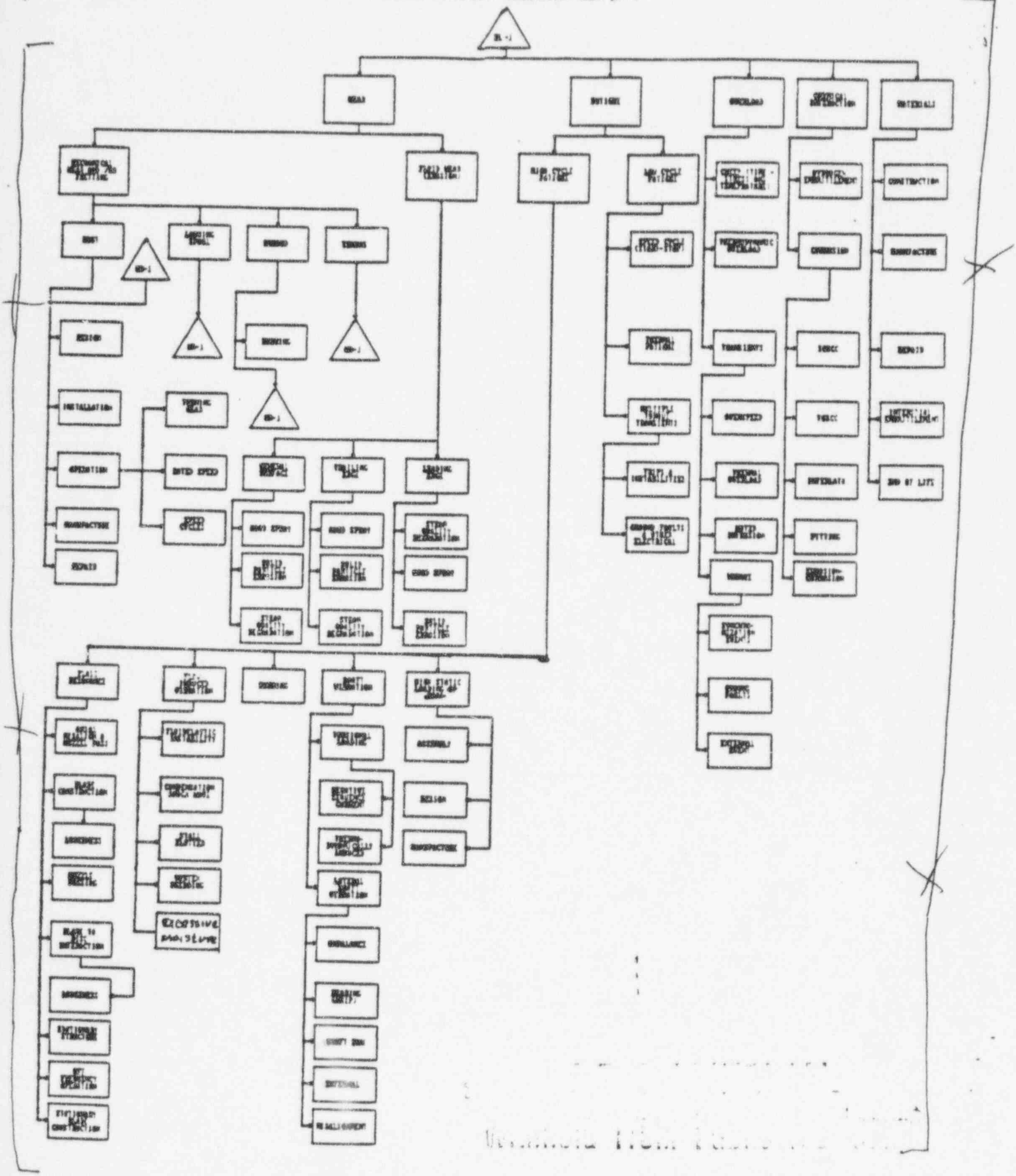


APPENDIX C
EVENT AND CAUSAL FACTOR CHART



APPENDIX D

TURBINE FAILURE
BLADE FAILURE TRANSFER REV X 5



APPENDIX D
LP-3 TURBINE FAILURE
BLADE FAILURE

CODE	TITLE	GOTO	REFERENCE	NO.	DONE	SIG
BL-1	BLADE FAILURE			92	92	17
BL-1A	MECHANICAL WEAR AND /OR FRETTING					
BL-1A1	ROOT					
BL-1A1.1	DESIGN		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A1.2	INSTALLATION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A1.3	OPERATION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A1.4	MANUFACTURE					
BL-1A1.4.1	TURNING GEAR		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A1.4.2	RATED SPEED		D. SMITH TO G TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A1.4.3	SPEED CYCLES		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A1.5	REPAIR		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A2	LASHING SPOOL					
BL-1A2.1	DESIGN		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	1
BL-1A2.2	INSTALLATION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	1
BL-1A2.3	OPERATION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	1
BL-1A2.4	MANUFACTURE					
BL-1A2.4.1	TURNING GEAR		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A2.4.2	RATED SPEED		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A2.4.3	SPEED CYCLES		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A2.5	REPAIR		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A3	SHROUD					
BL-1A3.1	DESIGN		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A3.2	INSTALLATION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A3.3	OPERATION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A3.4	MANUFACTURE					
BL-1A3.4.1	TURNING GEAR		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A3.4.2	RATED SPEED		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A3.4.3	SPEED CYCLES		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A3.5	REPAIR		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A3.6	RUBBING		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A4	TENNONS					
BL-1A4.1	DESIGN		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A4.2	INSTALLATION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A4.3	OPERATION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0

APPENDIX D
LP-3 TURBINE FAILURE
BLADE FAILURE

CODE	TITLE	GOTO	REFERENCE	NO.	DONE	SIG
BL-1A4.4	MANUFACTURE					
BL-1A4.4.1	TURNING GEAR		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A4.4.2	RATED SPEED		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A4.4.3	SPEED CYCLES		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1A4.5	REPAIR		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-2A2	FLUID WEAR (EROSION)					
BL-2A2.1	GENERAL SURFACE					
BL-2A2.1.1	HOOD SPRAY		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-2A2.1.2	SOLID PARTICLE EROSION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-2A2.1.3	STEAM QUALITY DEGRADATION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-2A2.2	TRAILING EDGE					
BL-2A2.2.1	HOOD SPRAY		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-2A2.2.2	SOLID PARTICLE EROSION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-2A2.2.3	STEAM QUALITY DEGRADATION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-2A2.3	LEADING EDGE					
BL-2A2.3.1	HOOD SPRAY		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-2A2.3.2	SOLID PARTICLE EROSION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-2A2.3.3	STEAM QUALITY DEGRADATION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1B	FATIGUE					
BL-1B1	HIGH CYCLE FATIGUE					
BL-1B1A	BLADE RESONANCE					
BL-1B1A1	AXIAL MISALIGNMENT & NOZZLE PASS		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1B1A2	BLADE CONSTRUCTION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	1
BL-1B1A2.1	LOOSENESS		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1B1A3	NOZZLE PASSING		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1B1A4	BLADE TO DISK INTERACTION					
BL-1B1A4.1	LOOSENESS		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1B1A5	STATIONARY STRUCTURE		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1B1A6	OFF FREQUENCY OPERATION		R. CORKINS ELECTRICAL REPORT	1	1	0
BL-1B1A7	STATIONARY BLADE CONSTRUCTION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1B1B	FLOW INDUCED VIBRATION					
BL-1B1B.1	UNSTALLED FLUTTER		D. SMITH TO G. TRAHEY; TURBINE BLADE FLUTTER; 7/6/94	1	1	1
BL-1B1B.2	CONDENSATION SHOCK WAVE		D. SMITH TO G. TRAHEY; TURBINE BLADE FLUTTER; 7/6/94	1	1	1
BL-1B1B.3	STALL FLUTTER		D. SMITH TO G. TRAHEY; TURBINE BLADE FLUTTER; 7/6/94	1	1	1

APPENDIX D
LP-3 TURBINE FAILURE
BLADE FAILURE

CODE	TITLE	GOTO	REFERENCE	NO.	DONE	SIG
BL-1B1B.4	VORTEX SHEDDING		D. SMITH TO G. TRAHEY; TURBINE BLADE FLUTTER; 7/6/94	1	1	1
BL-1B1B.5	EXCESSIVE MOISTURE		RCA REPORT 7/94	1	1	1
BL-1B1C	RUBBING		L. FRON LTR ON VIBRATION ANALYSIS	1	1	0
BL-1B1D	SHAFT VIBRATION		L. FRON LTR ON VIBRATION ANALYSIS	1	1	0
BL-1B1D.1	TORSIONAL LOADING		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 7/7/94	1	1	1
BL-1B1D.1.1	NEGATIVE SEQUENCE CURRENT		RCA REPORT 7/94	1	1	1
BL-1B1D.2	LATERAL SHAFT VIBRATION					
BL-1B1D.2.1	UNBALANCE		L. FRON LTR ON VIBRATION ANALYSIS	1	1	0
BL-1B1D.2.2	BEARING WHIP		L. FRON LTR ON VIBRATION ANALYSIS	1	1	0
BL-1B1D.2.3	SHAFT BOW		L. FRON LTR ON VIBRATION ANALYSIS	1	1	0
BL-1B1D.2.4	EXTERNAL		BROKENSHIRE REPORT	1	1	0
BL-1B1D.2.5	MISALIGNMENT		L. FRON LTR ON VIBRATION ANALYSIS	1	1	0
BL-1B1E	HIGH STATIC LOADING					
BL-1B1E.1	ASSEMBLY		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1B1E.2	DESIGN		RCA REPORT 7/94	1	1	0
BL-1B1E.3	MANUFACTURE		RCA REPORT 7/94	1	1	0
BL-1B2	LOW CYCLE FATIGUE					
BL-1B2.1	SPEED CYCLE (START STOP)		D. SMITH TO G. TRAHEY; SPEED CYCLES; 7/6/94	1	1	1
BL-1B2.2	THERMAL FATIGUE		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1B2.3	MULTIPLE TORQUE TRANSIENTS		RCA REPORT 7/94	1	1	1
BL-1B2.4	TRIPS AND INSTABILITIES		R. CORKINS ELECTRICAL REPORT	1	1	0
BL-1B2.5	GROUND FAULTS AND OTHER ELECTRICAL		R. CORKINS ELECTRICAL REPORT	1	1	0
BL-1C	OVERLOAD		R. CORKINS ELECTRICAL REPORT	1	1	0
BL-1C1	CREEP (TIME STRESS AND TEMP.)		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1C2	THERMODYNAMIC OVERLOAD		RCA REPORT 7/94	1	1	1
BL-1C3	TRANSIENTS		R. CORKINS ELECTRICAL REPORT	1	1	0
BL-1C3.1	OVERSPEED		L. FRON LTR ON VIBRATION ANALYSIS	1	1	0
BL-1C3.2	THERMAL OVERLOADS		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	1
BL-1C3.3	WATER INTRUSION		RCA REPORT 7/94	1	1	1
BL-1C3.4	TORQUE					
BL-1C3.4.1	SYNCHRONIZATION EVENTS		R. CORKINS ELECTRICAL REPORT	1	1	1
BL-1C3.4.2	GROUND FAULTS		R. CORKINS ELECTRICAL REPORT	1	1	0
BL-1C3.4.3	EXTERNAL EVENTS		R. CORKINS ELECTRICAL REPORT	1	1	0

APPENDIX D

LP-3 TURBINE FAILURE

BLADE FAILURE

CODE	TITLE	GOTO	REFERENCE	NO.	DONE	SIG
BL-1D	CHEMICAL INTERACTION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1D1	HYDROGEN EMBRITTLEMENT		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1D2	CORROSION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1D2.1	IGSCC		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1D2.2	TGSCC		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1D2.3	INTERLATH		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1D2.4	PITTING		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1D2.5	EROSION/CORROSION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1E	MATERIALS		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1E1	CONSTRUCTION		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1E2	MANUFACTURE		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1E3	REPAIR		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1E4	INTERSTITIAL EMBRITTLEMENT		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0
BL-1E5	END OF LIFE		D. SMITH TO G. TRAHEY; TURBINE BLADE FAILURE; 4/5/94	1	1	0

GEC ALSTHOM

ELECTROMECHANICAL

FERMI 2 TURBINE GENERATOR INCIDENT
25TH DECEMBER 1993

ROOT CAUSE INVESTIGATION CONCLUSIONS BASED ON INFORMATION AVAILABLE UP TO 30th JUNE 1994

SUMMARY

On 25th December 1993 the Fermi 2 turbine generator shed five last row blades from the front flow of the LP3 rotor. The resultant mechanical unbalance caused extensive consequential damage during run down.

GEC ALSTHOM has worked closely with the DETROIT EDISON COMPANY (DECO) to establish the root cause of the incident. Interim reports were provided in March and April 1994 and this further report has been produced at DECO's request to assist them in making submissions to NRC. It summarises GEC ALSTHOM's conclusions based on the evidence available at 30th June 1994.

The root cause has not been established with 100% certainty but there is confidence that it was due to the presence of abnormal water in the LP3 turbine. Metallurgical examination of the fracture surface supports this conclusion and there is experience of water damage to other LP stages at Fermi 2 as a result of poor drainage of bled steam spaces. The isolation of LP heaters in the LP3 cylinder during September 1993 could be a contributory factor.

A detailed torsional analysis of the complete rotor system has been carried out. This eliminates torsional excitation of the rotor system as a potential root cause mechanism.

Fatigue cracks in LP stage 7 blade roots, stress corrosion cracking of LP stage 7 disc heads, the LP3 stage 5 rear disc head and LP3 rear steam balance holes were not a factor in the incident. They are however indicative of the presence of water and questionable steam chemistry over a long period.

Stage 7 and 8 blade rows have excellent vibration characteristics. These were established, at the time of manufacture, by rotational tests on a full size test wheel and confirmed by further rotational tests on a production rotor. These tests show that the critical resonances are well clear of the operating speed range. Identical blades used on other large nuclear turbines have been trouble free for more than twice the Fermi 2 operating hours. This supports the conclusion that the failure of a single last stage blade was a consequence of abnormal circumstances at Fermi 2.

B/6

1. INTRODUCTION

On 25th December 1993 the Fermi 2 turbine generator was operating at full load under nominally steady state conditions when five adjacent last row (stage 8) blades on the LP3 front (south) flow fractured. One blade (blade 9) penetrated the exhaust hood. The resultant mechanical unbalance caused extensive consequential damage during run down. There was no prior indication from operational parameters of the impending failure.

GEC ALSTHOM have worked closely with the Detroit Edison Company (DECO) to investigate the reasons for the failure. Examination of the evidence supports the conclusion that the first major mechanical incident was the loss of a single last stage blade (blade 9) on the LP3 front flow. The fracture of the next four blades (blades 5-8) on the same row was a consequence of this single blade failure. The following are unconnected with the incident:

[redacted]

This report summarises background information regarding the Fermi turbine, gives details of relevant parts of the investigation and discusses various root cause scenarios which have been examined. These lead to the conclusion that the abnormal presence of water in the turbine was responsible for the last stage blade failure and that water provides a common link between the present stage 8 failures, cracking of stage 7 and earlier failures of LP stage 5 blading. In view of this, particular attention has been focused on the design and operation of the feedheating system.

2. BACKGROUND TO LP TURBINES

The LP turbines were designed specifically for use on large 1800 rpm wet steam nuclear turbines, seven of which were manufactured in the 1960's/1970's. Table 1 lists the turbines involved together with their operational hours upto December 1993. This shows that although Fermi 2 was the first to be ordered, it has the shortest operational life [redacted] The lead unit Kori 1 [redacted] has operated successfully for more than twice as long as Fermi 2.

Identical stage 7 and 8 blades with side entry roots were used for each contract but there are inevitably variations in steam flow rate and Fermi 2 is not the most highly loaded. There are differences in the blading for the earlier stages to accommodate different bled steam requirements and general changes in Company design philosophy, e.g. on the later turbines pinned root blade fixings replaced the earlier straddle root designs used at Fermi 2. [redacted]

Riveted cover bands are used to link the moving blades for all but the last two stages which employ a continuous interconnection between blades. This eliminates the possibility of individual blade vibrations and thereby reduces vibratory response, particularly under buffeting loading and eliminates any susceptibility to flutter. This interconnection is provided by a single row of split D type lacing wire on stage 7 and by lacing rods on stage 8. Both methods have been successfully used on a wide range of turbines.

The provision of extraction steam to LP heaters before both stage 7 and 8 is a common feature of this class of turbines, although different feedheating systems are in use. Apart from Fermi 2, which operates with a boiling water reactor (BWR), all other applications are with pressurised water reactors (PWR). The higher levels of oxygen generally present in BWR steam can lead to a reduction in material resistance to fatigue and stress corrosion.

3. FERMI 2 LP BLADING EXPERIENCE

This section provides a brief summary of damage found during previous inspections on certain stages of the Fermi 2 LP blades and outlines remedial actions taken.

3.1 LP Stage 8

Prior to the 25th December incident there had been no experience of similar blade damage on the Fermi 2 last stage blades or any of the sister turbines elsewhere.

At Fermi 2 there was a long delay between the completion of the turbine installation and the commencement of commercial operation. There were extended periods (circa 20,000 hours) of turning gear operation which resulted in significant wear of the lacing rod holes. Similar wear has been observed on the other turbines but this was generally less severe, reflecting shorter periods of turning gear operation.

This problem was overcome by the installation of ripple springs beneath the blade roots to reduce the tip rock which can occur due to the absence of centrifugal loading at turning gear speed. Ripple springs were installed on all last stage blades at Fermi 2 during RF01(1989) and a rolling programme of last stage blade replacement was instituted. A set of new last stage blades was installed on the LP1 rotor during RF01 and refurbished blades on the LP2 rotor during RF02(1991). A limited amount of remedial work was carried out on LP3 during RF01 when 6 front flow and 4 rear flow blades with excessive lacing hole wear were replaced with less worn ex LP1 blades and a number of larger lacing rods were fitted. It is of interest to note that the five fractured blades did not include any of these replacement blades but one of the replacement blades (blade 10) immediately preceded blade 9.

GEC ALSTHOM recommended that the LP3 blades should be replaced during RF03(1992) but prior to the outage DECO indicated that they intended to defer this until RF04(1994). GEC ALSTHOM's acceptance was conditional on repeat measurements of lacing rod/hole wear being carried out to confirm that there had been no significant deterioration. In the event DECO chose not to employ GEC ALSTHOM technical service support during RF03 and it only became apparent during the present investigation that practical difficulties had prevented the taking of reliable repeat measurements. For reasons discussed below the lacing hole wear itself is not considered to have been a significant factor in the failure of the five front flow blades.

[redacted]

3.3 LP Stage 5

During the RF01 inspection a number of failed stage 5 blades were discovered on the LP2 rotor and cracked blades were found on all three cylinders. In addition, a small number of stage 5 disc head cracks were found on the LP1 rear flow and LP2 front flow. Metallurgical examination confirmed that the failure mechanism was high cycle fatigue and it was concluded that this resulted from abnormal excitation of modes whose frequencies were in the range where damaging vibration is not normally encountered. Water ingress was cosidered to be the source of abnormal excitation. Further inspection revealed the presence of a large volume of water in the LP2 cylinder due to a blocked drain and it was subsequently discovered that restricted drainage in LP1 and LP3 cylinders could also cause water build up during service.

The primary remedial action was to ensure that adequate drainage of the LP cylinders and bled steam lines was maintained at all times. In addition, modified blades with increased frequency margins were installed during RF02. As a short term measure the turbine was operated for one fuel cycle with stage 5 blades removed while replacement blades were being manufactured.

The effectiveness of the actions taken is reflected in the fact that no further fatigue cracking of the stage 5 blades or disc heads has occurred.

3.4 LP Stage 4

During the period in which the turbine was operated with stage 5 removed, failures of stage 4 blades occurred on the LP3 front and rear flows and there was some associated disc head cracking. It was concluded that this was a result of the abnormal loading produced due to the absence of stage 5. Identical replacement blades with continuous shrouding were fitted during RF02 when the new stage 5 blades were installed. The absence of any subsequent failures of this stage at Fermi 2 or any of the sister turbines confirms the conclusion reached at the time.

4. REVIEW OF SALIENT INFORMATION

This section deals with significant features of inspections carried out after the 25th December incident. Four main areas are considered, namely:

a) stage 8 blades
b) stage 7 blades
c) other LP stages
d) feedheating system

4.1 Stage 8 Blades

The most significant evidence was provided by the fracture surface from blade 9 on the LP3 front flow which showed that a fatigue crack had initiated close to the trailing edge, approximately 1¼" above the root platform. It propagated for approximately [5"] before the steady centrifugal load caused ductile failure of the reduced section. Magnetic particle inspection (mpi) revealed no evidence of fatigue on any other LP3 front flow blades, including the fractured blades (5-8), even though many of these had tears or impact damage.

MPI was also carried out on the stage 8 blades from the other flows but did not reveal any cracking. The damage on these rows was limited to rubbing of the feather tip which would have occurred during the run down with high unbalance.

Metallurgical examination has confirmed that there were no material abnormalities or prior damage which may have contributed to the failure. It was observed that the trailing edge of blade 9 in the immediate vicinity of the crack initiation point was thinner than for other blades at the same position, although there is at least one other LP3 front flow blade with practically the same trailing edge thickness. Subsequent detailed measurements [carried out with a travelling microscope on the aerofoil after it had been sectioned for metallurgical examination] showed that this effect was extremely localised and the blade was not inherently weak. There was a small machining mark close to the crack initiation point on blade 9 and similar marks were observed on other blades.

During the initial examination of the fatigued portion of the fracture surface, striation counting had been used to deduce that the period from initiation to final fracture was limited to the few hours immediately prior to the incident. Subsequent more detailed analysis carried out by GEC ALSTHOM metallurgists has shown that the assumed fatigue striations were in fact secondary cracks. There is no known relationship between the spacing of secondary cracks and propagation rate and therefore the original hypothesis suggesting rapid fatigue crack growth rate is not supported.

[The detailed SEM (Scanning Electron Microscope) examination of the micro fracture surface showed that the cracking was transgranular with no signs of intergranular facetting. It also showed a beachmark at a distance of 60mm from the crack initiation site. This precedes a deviation in the fracture path direction which takes the form of a ridge adjacent to the convex surface of the blade and a smaller trough adjacent to the concave surface. This is consistent with shear stress being applied during this phase of crack growth.]

[illegible]

In order to investigate these observations further a test programme was set up using last stage blade material specimens. This work is ongoing but the main conclusions reached so far are:

(i) the lack of intergranular facetting indicates that the dynamic stress was small relative to the steady stress.

(ii) a change in steady stress due, for example, to a step change in the blade loading, a shut down or overspeed can produce beachmarks of the type observed on the fracture surface.

(iii) Periods with no significant crack growth due to reduced cyclic stress could occur without leaving significant evidence (beach marks) on the fracture surface.

The relevance of these observations is dicussed in section 5.1.

4.2 Stage 7 Blades

MPI examination of stage 7 has revealed cracking in both blade roots and disc head serrations.

[redacted]

The inspections carried out did not reveal any obvious reason for the greater concentration of cracks on the LP2 front flow or the absence of cracks on the LP1 rotor. However, there is a general correlation with the damage observed on stage 5 during RF01. It was observed that the blades were easier to remove from the LP1 than either of the other two rotors. This may indicate some difference in the steam quality between the cylinders but this has not been quantified.

In all cases the cracks are in the root top neck and appear to have initiated inboard of the root inlet face on the concave side of the blade. There are significant variations in the crack depth but the most severe have extended across the root inlet face. A number of the most severely cracked blades have been broken open to enable more detailed examination. In each case the main features of the fracture surface are the same as those observed on the blade which was replaced during RF01, i.e. high cycle fatigue, multiple initiations, clearly discernible arrest marks and significant oxidation. This indicates slow interrupted growth consistent with the cracks having propagated over a long period which could be number of years and they may even have stopped. The nature of the fracture surface is different from that observed on the LP3 front stage 8, blade 9 and it is clear that the stage 7 cracks were not a consequence of the 25th December incident.

Stage 7 disc head cracking has not been analyzed in such great detail as the blade root but extensive cracking has been found on all flows including the LP1 rotor. Initial examination suggests that the cause of the cracking is stress corrosion and although further analysis is being carried out there is little doubt that this will be confirmed. As two different mechanisms are involved (fatigue for the blade roots and stress corrosion for the disc heads) it is extremely unlikely that one is the consequence of the other but it is probable that steam environment may provide a common link.

4.3 Other LP Stages

Non destructive examination of the other stages of LP blading has revealed a disc head crack on stage 5 of the rear flow of the LP3 rotor. As with the disc head cracks on stage 7, final confirmation of the crack mechanism has yet to be obtained but after initial examination it is thought to be due to stress corrosion. It should be noted that during RF02 the GEC ALSTHOM Technical Service Engineer reported significant disc head corrosion in the LP3 cylinder and recommendations were made to minimise operation of the condensate system with the condenser at atmospheric pressure. It is extremely likely that the steam environment contributed to both the stage 5 and stage 7 disc head cracks.

[redacted]

Apart from the effects of consequential tenon and shroud rubbing which occurred during the unbalanced run down on 25th December, no other LP blading damage was observed. Early reports of crack indications on LP2 stage 4 disc heads were incorrect.

[redacted]

There was no evidence of the passage of any foreign objects through the earlier stages of the LP3 turbine which may have been responsible for damaging the front flow stage 8 blading.

4.4 Feedheating System

In RF01 when the stage 5 blade failures were discovered abnormal quantities of water were discovered in the LP2 cylinder due to blocked drains. There was also evidence of inadequate drainage of bled steam lines in the LP1 and LP3 cylinders. GEC ALSTHOM expressed concerns at that time about the operation of the extraction steam drainage and a number of recommendations for improvement were made.

The number 1 and 2 LP feedheaters which extract steam from before stage 7 and 8, are located in the condenser neck beneath each LP cylinder. The heaters unique to the LP3 cylinder were isolated on the condensate side for approximately two weeks in September 1993. This was the first time that any of these heaters had been isolated at Fermi 2 and therefore particular attention has been focused on the way in which this was done and the general mode of operation of these heaters.

Initially the situation was extremely confused because the written procedure for removing either heater from service requireded that both the normal and emergency heater shell drain valves should be closed. If this had been carried out, conditions would have existed for the heaters to flood and, since there are no non return valves in the corresponding bled steam lines, water ingress into the LP3 turbine would have been inevitable. After further investigation it was established that this approach was not used and a temporary procedure had been written which restricted isolation to the condensate side only. No changes were made to the shell drain valves which continued to operate in response to the level control system. DECO are confident that this revised procedure was used and provided that the level control system was functioning correctly, the heater drains should have dealt with the water extraction flows in the bled steam lines.

A general inspection of the system is presently being carried out and to date the following has been revealed:

- the arrangement of bled steam pipes to number 1 and 2 heaters is identical for each LP cylinder.
- there are undrained horizontal sections of pipe from the front flow but not from the rear flow.
- small negative gradients were measured in some of the LP3 front pipe runs.

- a variety of foreign objects have been retrieved from the pipe runs and heater inlets. These include part of a wooden plank, a sling, a hammer head and safety helmets. Some of these were specific to the LP3 and it is also clear that they were there before the incident.

In view of their concerns about the operation of the feedheating system GEC ALSTHOM conducted a separate review of its ability to remove water and preserve the steam path integrity. This has shown that it does not conform with their practice nor with the ANSI/ASME specification TDP-2-1985 (Recommended Practices for Preventing Water Damage to Steam Turbines Used for Electric Power Generation). One area of particular relevance is that the LP heaters operate with significant water levels in the heater shell. As this water is at saturation temperature any pressure drop, due for example to a load reduction, will result in water 'flashing off' in the heater and cause a transient flow reversal in the bled steam lines. This would interrupt the water extraction flow from the turbine and could force slugs of water from the heater into the main steam path.

Historically there have been problems with water levels in heaters at Fermi 2 which are controlled by automatic drain valves. Initially the control for these valves was provided by differential pressure transducers with water filled legs which are known to be unreliable, particularly when operating close to saturation conditions or under sub atmospheric pressures. During early operation is reported that it was necessary to override the control system to ensure that heaters remained adequately drained.

A significant improvement was made when the differential pressure transducers were replaced by conventional level detectors, although it was necessary to increase the water level in No.2 heater to obtain satisfactory performance. Nevertheless, GEC ALSTHOM still has a number of reservations about the operation of the system. These are principally related to lack of independent controls and the absence of any on line testing facilities.

For each heater two level detectors are used both of which are mounted from the same tapping points with common source manual isolation valves. One detector operates both the normal and emergency drain valves and the second provides signals for control room indications and alarms. Hence if normal drainage were lost due to a detector malfunction the emergency back up would also fail to function. Alternatively, if a leakage or blockage were to occur in the common lower leg, or one of the manual isolation valves was inadvertently closed, the heater would flood but the control room indications could appear to be normal. The checks carried out after the incident did not identify the status of the manual isolating valves.

DECO believe that other operational data indicates that the system was functioning correctly but as this is based on spot readings the possibility of transient malfunction remains. GEC ALSTHOM have recommended that tests should be carried out to confirm the satisfactory operation of the level control systems and the absence of any heater tube leaks.

GEC ALSTHOM and other manufacturers have had experience in the past of inadequate bled steam drainage resulting in water damage to blading. This led to the adoption of LP heaters situated in the condenser neck which operate with a minimum quantity of standing water within the heater shell. In such arrangements manometric loops or orifice plates in the drain lines eliminate the need for control systems and valves. This not only provides a less complicated, maintenance free system but has the additional advantage that it is fail safe. In view of the difficulties of access associated with BWR plant such systems offer significant advantages.

5 ROOT CAUSE DISCUSSION

5.1 LP Stage 8 Blades

The evidence overwhelmingly supports the conclusion that the first major mechanical event was the loss of a single last stage blade (blade 9) in the front flow of the LP3 rotor. Metallurgical examination has shown that on that blade a high cycle fatigue crack initiated at the trailing edge approximately 1¼" above the root and propagated until the reduced blade section was no longer able to withstand the steady centrifugal force. Fracture mechanics analysis carried out for the blade material confirms that the fatigue crack had extended beyond the minimum critical depth.

There is no evidence of fatigue on any other stage 8 blade in the damaged row, including the four fractured blades immediately following blade 9, or the five other identical blade rows on the turbine.

Under normal conditions, fatigue of these blades would not occur because this blade row has excellent vibration characteristics. These were established by rotational tests on a full size prototype wheel when the blade was initially developed and were later confirmed by further rotational tests on a production rotor. These tests showed that the major critical resonances of the low order wheel modes likely to cause damaging vibration are well clear of the operating speed range. Fig. 1 shows the Campbell diagram derived from the tests. The long trouble free experience on the other similar units and also at Fermi 2 [redacted] prior to the incident confirms the validity of the test results and the soundness of the blade design.

The absence of resonant conditions is supported by detailed metallurgical analysis. The lack of intergranular facetting on the fracture surface of blade 9 indicates that the dynamic stress was small relative to the steady stress, which would not be the case for a blade in resonance. Further evidence is obtained from tests on blade material specimens which showed that once a crack had been initiated it propagated with relatively low dynamic stress.

The tests also showed that the beach mark part way across the fracture surface of blade 9 could be caused by a change in the steady blade loading. If this was due to the loss of centrifugal stress it indicates that the crack initiated before the last shutdown on 17th September 1993 but after the penultimate shut down on 14th August 1993. Alternatively, there may have been an abnormal event during operation which produced a substantial transient increase in the blade load. If so, an earlier similar event could have been responsible for the crack initiation. In this case both events would have had to have occurred after the last shutdown.

The well proven vibration characteristics, absence of resonance, presence of the beach mark, and the fact that only one blade suffered fatigue damage leads to the conclusion that some abnormal event happened.

At Fermi 2 there were no signs of foreign objects having passed through the LP3 turbine prior to the incident but the recent discovery of old debris in the bled steam lines means that this cannot be discounted as a possible source of damage to blade 9. However, based on the past history of drainage problems at Fermi 2, the concerns about the heater isolation and markings on fixed and moving blades which indicate the presence of water in all three LP cylinders, it is considered most likely that blade 9 suffered water damage.

Homogeneous mixtures of steam and water in the later stages of LP turbines can increase the general level of excitation and cause erosion. They do not generally present a serious problem and there is no practical limit to the quantity of entrained water. The situation is quite different if slugs of water are present. These may be due to reversal or blockage of bled steam flow causing an interruption in the normal water extraction process, or as a result of steam boiling in the bled steam line/heater and forcing water back into the turbine.

Impact between the high velocity blading and a small consolidated mass of water can exert large impulsive forces capable of producing major deformation of blades. 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.

It is concluded that this is the mechanism which affected blade 9 of the LP3 front flow. In principle, blades in any one of the six last stage rows could have suffered in this way but the prior trouble free operation of stage 8 blading suggests that this was a consequence of an exceptional combination of circumstances coupled with special features unique to the LP3 front flow.

One such circumstance was the period in September 1993 when the LP3 cylinder number 1 and 2 LP heaters were taken out of service. Fermi 2 had never operated in this mode before and it is entirely possible that the initiating water damage occurred at that time particularly since load was reduced prior to returning the heaters to service so that the reduction in pressure could have caused water in the heater to flash off. Furthermore the last shutdown before the 25th December incident occurred after the heaters had been returned to service.[and it has been shown that the beach mark on the fracture surface could be consistent with a shut down.]*

It is possible, but not essential to the general explanation, that impact with slugs of water could have caused sufficient distortion for the lacing rod connection between blade 9 and its immediate neighbours to be lost, thereby causing that blade to become free standing with different vibration characteristics.

GEC ALSTHOM philosophy for last stage blade rows is to provide continuous blade to blade interconnection, and there was never any design intention that the Fermi 2 last stage blades should operate free standing.

[redacted]

[redacted]

Initially loss of lacing rods had been discounted as there was no supporting evidence from the rotor vibration records to indicate a balance change of sufficient magnitude. It is now believed that a mechanism for losing the lacing rod connection involves a single blade twisting so that one end of two adjacent rods comes free whilst the other ends remain in place in their respective blades. The free rods would bend outwards under the influence of centrifugal force and could remain hooked in the blade with no change of rotor unbalance. The additional rod mass close to the tip of the resulting free standing blade would cause a further small frequency reduction (approximately 0.5Hz) beyond that measured in the tests. Stress calculations indicate that it is possible for a rod to bend in this way without fracture and this was also confirmed by static tests carried out by DECO.

Lacing rods are normally trapped in position by the blades and therefore considerable thought was given to the possibility that the worn lacing holes may have been a factor, particularly since significantly greater wear had been measured on the front flow during RF02. However, blade 9 was by no means the most severely worn blade and measurements taken after the incident showed that, in general, there had been no significant increase in wear since RF02. It is therefore considered that lacing hole wear alone was not responsible for the loss of lacing rods.

Similar conclusions have been reached with regard to the locally thin trailing edge and the presence of a machining mark on blade 9. For the fundamental vibration mode of the blade, the point of highest stress coincides with the crack position and this would be the position of failure with or without these two features.

Awareness of other North American experience of failures of long blades due to shaft torsional excitation led to a detailed analysis of the Fermi 2 rotor line being carried out. The results of this analysis and the available evidence from site (e.g. only one cracked blade, lack of system frequency variations, no reported abnormal negative sequence currents) do not support this as a possible root cause in this case. Further discussion about the torsional analysis for both stage 7 and 8 blades is given below in section 5.4.

The higher oxygen levels present in BWR steam inevitably has some impact on the fatigue strength of the blading material. Under normal circumstances the design margins are such that this is not significant but the reported higher corrosion in the LP3 cylinder and the presence of stress corrosion cracking on other stages suggests that the steam chemistry at Fermi 2 may not always have been optimum and

[redacted]

could have been a contributory factor.

Summarising, as is frequently the case in such incidents, there is a lack of totally conclusive evidence but that which is available indicates the root cause to be the presence of abnormal quantities of water within the turbine.

5.2 LP Stage 7

Although both stage 7 and 8 blade cracking is associated with fatigue, there are a number of differences which indicates that one is not a consequence of the other. These include:

(i) no fractures of stage 7 blades

(ii) the fracture surfaces are quite different. Those on stage 7 are long term, with clear signs of arrest.

(iii) the distribution of cracks is more widespread on stage 7 with the greatest concentration on the LP2 rotor

(iv) there is extensive stress corrosion cracking of the stage 7 disc heads

The vibration characteristics of this stage were confirmed by full size rotational tests prior to service and the Campbell diagram (fig. 2) shows that the low order critical resonances are well clear of the operating speed range. This together with the long term nature of the crack propagation, the absence of any root fractures and the trouble free operation of this identical blade on other turbines eliminates resonance of low order wheel modes as a factor. It is more likely that there were periods of unusual operation at Fermi 2 which introduced abnormal intermittent excitation of higher order modes which are not normally considered to be of significance.

The greater number of cracks on the LP2 rotor, and the general correlation with the earlier stage 5 damage, raises the possibility that they may well have initiated at the same time as the previous stage 5 failures which were also most severe in the LP2 cylinder. There was clear evidence of water in the LP2 cylinder at that time together with bled steam drainage problems in the other two cylinders.

Subsequent water incidents may have been responsible for further intermittent crack growth but it is also possible that, once the cracks had initiated, normal levels of background excitation were sufficient to promote growth. An important factor in this case is the possibility that poor steam chemistry has contributed to reduced fatigue strength. The extensive stress corrosion cracking found on the disc head suggests that this is a high probability.

The torsional analysis carried out (see section 5.4 below) showed that the frequency of the all in phase tangential mode for this stage is well clear of both 60 and 120Hz. This eliminates torsional vibration as a possible root cause of stage 7 damage.

It had initially been suggested that lack of contact between the lacing wire and blades may have been a contributory factor but subsequent examination of the lacing holes and wire showed this not to be so.

5.3 Stress Corrosion Cracking

In addition to the stage 7 disc head cracks, it is also thought that the cracks found on the LP3 stage 5 rear flow disc head and the LP3 steam balance holes are due to stress corrosion. There are a number of factors which influence stress corrosion but the previously observed corrosion/pitting of parts of the LP3 rotor suggests that steam chemistry is the important ingredient in this case.

The degree to which a more severe steam environment could exist in the LP3 cylinder than elsewhere is open to debate but the two following factors may be significant:

(i) It was observed in RF02 that, during condensate recirculation under atmospheric conditions, the LP3 cylinder was streaming with warm condensation - ideal conditions for pitting and local yielding which can lead eventually to stress corrosion. This is almost certainly due to the recirculating connection being at the LP3 end of the condenser. Recommendations were made at that time to minimise these conditions.

(ii) Examination of MSR outlet temperature records indicated that the steam entering the LP3 cylinder is approximately 50°F cooler than the design value. This would lead to greater wetness in the LP3 cylinder.

5.4 Torsional Vibration

It is well known that there is a potential risk of exciting vibration of long turbine blades by electrically induced torsional oscillations of the rotor system, and there have been a number of failures of other manufacturers turbines which have been attributed to this. It was therefore natural to consider torsional vibration as a possible root cause for both stage 7 and 8 blades, particularly since it was only after the Fermi 2 turbine generator was designed that the possibility of exciting vibration in this way was fully recognised and appropriate calculation methods developed.

[redacted]

[redacted]

The important modes with regard to the blading are those defined in category (c) and (i) for stage 8 blades and category (e) for stage 7. This leads to the following conclusions:

- The stage 8 blade first mode frequency [redacted] is clear of 60 Hz and should present no problem under system fault conditions causing excitation at this frequency.
- The stage 8 blade second mode frequency [redacted] is well clear of 120Hz negative sequence torque variations.
- The stage 7 blade first mode frequency [redacted] well clear of 60 and 120 Hz, and the margins are sufficiently large not to require a more detailed analysis.

The mode whose frequency is closest to 120 Hz is a second LP torsional mode [redacted] for the full rotor line with some coupled stage 8 blade second mode. This is considered to be satisfactory. It is likely to be difficult to excite electrically as the generator is in its first mode shape. This will result in strong energy cancellation. It is also sufficiently removed from the blade natural frequency to result in relatively low blade torques.

6. CONCLUSIONS

(a) The 25th December 1993 incident at Fermi 2 was caused by the high cycle fatigue failure of a single last stage blade (blade 9) on the front flow of the LP3 rotor.

(b) The initiation mechanism was due to impact with a slug of water and higher excitation forces existing due to the presence of water.

(c) There is past experience of water induced blading damage at Fermi 2 resulting from inadequate drainage of the bled steam spaces.

(d) Deficiencies in the effectiveness of the heater drains system indicates a high probability that they have contributed to this problem. The initial stage 8 damage may have occurred when the LP3 heaters were isolated during September.

(e) The previous trouble free operation of this blade design at Fermi 2 and elsewhere indicated that the failure was a consequence of abnormal circumstances at Fermi 2.

(f) Cracking over an extended period of the LP stage 7 blade roots can also be attributed to the abnormal presence of water.

(g) Stress corrosion cracking of stage 7 disc heads, the LP3 rear flow stage 5 disc head and LP3 rear flow steam balance holes indicate that there may have been deficiencies in the Fermi 2 steam/water chemistry at some time. These would cause a reduction in both fatigue strength and stress corrosion resistance.

(h) Torsional excitation of the shaft system has been eliminated as a potential root cause.

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112 W. Canada • San Clemente, California 92672 • Phone: (714) 361-5474 (714) 361-5479 FAX: (714) 240-9365