Topics:
Combined-cycle power plants
Gas turbines
Reliability
Availability
Maintenance
Outages

EPRI AP-3495
Project 990-7
Final Report
May 1984

Hi SERV FACTOR

Reliability, Availability, and Maintainability Audit of the T. H. Wharton Plant, Units 3 and 4, Houston Lighting and Power

Prepared by
ARINC Research Corporation
Annapolis, Maryland

Reliability, Availability, and Maintainability Audit of the T. H. Wharton Plant, Units 3 and 4, Houston Lighting and Power

---

AP-3495
Research Project 990-7

Final Report, May 1984

Prepared by

ARINC RESEARCH CORPORATION
A Subsidiary of ARINC Incorporated
2551 Riva Road
Annapolis, Maryland 21401

Principal Investigator
R. C. Young

Prepared for

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

EPRI Project Manager
R. Duncan

Power Generation Program
Advanced Power Systems Division

ORDERING INFORMATION

Requests for copies of this report should be directed to Research Reports Center (RRC), Box 50490, Palo Alto, CA 94303, (415) 965-4081. There is no charge for reports requested by EPRI member utilities and affiliates, U.S. utility associations, U.S. government agencies (federal, state, and local), media, and foreign organizations with which EPRI has an information exchange agreement. On request, RRC will send a catalog of EPRI reports.

Research Categories: Combustion turbine and combined cycle
Plant systems and performance assessment

NOTICE

Prepared by
ARINC Research Corporation
Annapolis, Maryland

ABSTRACT

This report presents the results of an on-site reliability, availability, and maintainability (RAM) audit of the Houston Lighting and Power T. H. Wharton Plant, Units 3 and 4. Outage reports from January 1978 through October 1982 were analyzed. Overhaul activities on three combustion turbines were observed, and plant personnel were informally interviewed. The objectives of the audit were as follows:

- Observe overhaul activities to identify RAM characteristics of plant equipments, including service lives
- Review plant records to determine root causes of unavailability
- Investigate relationships between operation/maintenance practices and RAM characteristics

The project established a framework for performance of RAM audits.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This report documents ARINC Research Corporation's on-site investigation of the reliability, availability, and maintainability (RAM) characteristics of the Houston Lighting and Power T. H. Wharton Plant, Units 3 and 4. The study was conducted for the Electric Power Research Institute under EPRI project RP990-7. This represents a first-time effort by EPRI to perform an overhaul audit on a combined-cycle power plant, as recommended by the EEI Combustion Turbine Task Force, to supplement, through further research and development, other root-cause analysis efforts leading toward elimination of gas turbine problems. The investigative efforts included observation of maintenance activities, review of plant historical records, and technical discussions with site personnel concerning plant outages and problems observed during combustion turbine overhauls.

Wharton Plant Units 3 and 4 are identical General Electric STAG 400 combined-cycle power plants, each rated at 297 MW with a heat rate of 8710 Btu/kWh. The units burn natural gas but have a provision for distillate oil operation. Each STAG unit consists of four combustion turbines with electric generators, four heat-recovery steam generators (HRSGs), and one steam turbine generator. Superheated steam at approximately 850°F and 900 psig is routed via common header to the steam turbine generator rated at 110 MW. Steam turbine inlet pressure is variable as a function of the number of combustion turbines and HRSGs on-line. Each steam turbine is a straight condensing double-flow exhaust design, coupled to a hydrogen-cooled generator. Condensate is returned to the HRSGs through the condensate pump, gland exhaust condenser, and boiler feedpump. Each unit relies on a deaerating hotwell for noncondensable gas removal; there are no extraction feedwater heaters or deaerators.

An on-site audit was determined to be the appropriate vehicle for encompassing all RAM analyses. The relationships among equipment reliabilities make it necessary to review all aspects of plant operation to permit proper analysis of equipment RAM characteristics. Therefore, RAM characteristics of key plant equipment were analyzed with an understanding of maintenance policies, plant operation, and administrative policies. The analysis addressed plant operational experience from

January 1978 through October 1982, during which period 243,735 hours of combustion turbine operation were logged. The RAM analysis included all outage-causing events; equipment failures not causing an outage were not included in the data analyses.

The audit was performed between September 1982 and February 1983. During this period three combustion turbines were removed from service for major overhauls. Plant outage records were compiled and analyzed to establish priorities for technical investigations, which consisted of observations of plant activities and discussions with plant personnel.

PROJECT OBJECTIVES

The purpose of the audit was to identify the frequency, magnitude, and root causes of outage-causing failures. This report was prepared to document one plant's history so that guidance would be provided for future equipment and improvement efforts. Another objective of the study was to correlate operations and maintenance practices with equipment part lives or failure frequency. Direct quantitative correlation was not within the scope of the project; established or suspected relationships are included in the technical discussion of the plant systems. The objectives of the audit were as follows:

- Observe overhaul activities to identify RAM characteristics of plant equipment, including service lives
- Review plant records to determine root causes of unavailability
- Investigate relationships between operation and maintenance practices and RAM characteristics.

PROJECT RESULTS

The following general results were obtained from the audit:

- Reporting detail is adequate to provide sufficient data for detailed RAM analyses.
- Analysis results can be used for cost-benefit studies on RAM improvement efforts.
- RAM analyses showed that turbine availability is improving, but generator and HRSG availability are deterioriting.
- Second- and third-order RAM effects are present and may be significant. (Example: false protection trips causing low-cycle fatigue.)
- RAM improvements are incorporated into the plant design at small incremental cost because existing equipment service lives are expanded.

- Insight into root causes of failure can be obtained through interviews with plant personnel.

RAM analyses provide useful data for utility personnel who are requesting or justifying additional budgets for RAM improvement efforts. Site personnel are aware of the problems and have identified solutions; the RAM analyses provide usable numerical values for quantification of the benefit. This is a major purpose of RAM analyses of existing equipment. Simple analyses performed in this project can be easily duplicated by plant personnel for cost-benefit evaluations.

Specific results concerning the plant equipment are as follows:

- Scheduled maintenance of the turbine and combustion systems accounts for 65.1% of turbine/generator unavailability.
- The control, protection, and monitoring system is responsible for 50.8% of the unreliability and results in second-order effects on availability (trip-initiated low-cycle fatigue).
- Environmental considerations (atomizing air, water injection) have an impact on equipment reliability.
- Steam system reliability is not much better than combustion turbine reliability (steam system MTBO = 780.8 hours).
- Steam system availability is significantly better than combustion turbine availability (steam system availability = 0.89153).
- Critical systems (lube oil, cooling and sealing air, fuel system) demonstrate good reliability and availability.

The compilation and analyses of outage report data were performed on site without major expenditure of time, and yet they produced data that were compatible with cost-benefit studies of RAM improvements. Though simple in comparison with sophisticated RAM analysis, the methodology appears to be accurate and appropriate for utility use. This approach, combined with on-site technical expertise, may facilitate justification of RAM improvement expenditures.

Richard L. Duncan, Project Manager
Advanced Power Systems Division

ACKNOWLEDGMENT

ARINC Research Corporation gratefully acknowledges the advice and assistance of Mr. T. E. Gish, Houston Lighting and Power; Mr. Edward Guillory, General Electric Company; and Dr. Richard Duncan, Electric Power Research Institute.

CONTENTS

CONTENTS (continued)

CONTENTS (continued)

ILLUSTRATIONS

TABLES

SUMMARY

Under Research Project 990-7, ARINC Research Corporation performed an on-site reliability, availability, and maintainability (RAM) audit of Houston Lighting and Power T. H. Wharton Plant, Units 3 and 4. The units are the multishaft combined-cycle power plants that have been in combined-cycle operation since 1974. The objectives of the audit were as follows:

- Observe overhaul activities to identify RAM characteristics of plant equipments, including service lives
- Review plant records to determine root causes of unavailability
- Investigate relationships between operation/maintenance practices and RAM characteristics

The audit was performed between September 1982 and February 1983. During this period three combustion turbines were removed from service for major overhauls. Plant outage records were compiled and analyzed to establish priorities for technical investigations. The investigations consisted of observations of plant activities and discussions with plant personnel. More detailed investigation was not within the scope of the project.

Both general and specific conclusions resulted from this project. The following are the general conclusions:

- Outage reporting was adequate for detailed reliability, availability, and maintainability analyses.
- Analysis results can be used for cost-benefit studies on RAM improvements.
- RAM improvements are incorporated into the plant design when existing equipment service lives are expanded.
- The analysis methodology is validated by historical data.

Specific conclusions include the following:

- Scheduled maintenance of the turbine and combustion systems account for 64.1% of combustion turbine/generator unavailability.
- The control, protection, and monitoring system is responsible for 50.8% of the combustion turbine/generator outages and results in second-order effects on availability (low-cycle fatigue).
- Critical combustion turbine systems (lube oil, cooling and sealing air, fuel system) exhibit good reliability and availability.

The compilation and analyses of outage report data were performed on site without major expenditure of time, and yet they produced data that were compatible with cost-benefit studies of RAM improvements. Though simple in comparison with sophisticated RAM analysis, the methodology appears to be accurate and appropriate for utility use. This approach, combined with on-site technical expertise, may facilitate justification of RAM improvement expenditures.

Section 1

INTRODUCTION

This report documents ARINC Research Corporation's on-site investigation of the reliability, availability, and maintainability (RAM) characteristics of the Houston Lighting and Power T. H. Wharton Plant, Units 3 and 4. The study was conducted for the Electric Power Research Institute (EPRI) under EPRI Research Project (RP) 990-7. Technical direction was provided by Dr. Richard Duncan of EPRI's Advanced Power Systems Division. The investigative efforts included observation of maintenance activities, review of plant historical records, and technical discussions with site personnel concerning plant outages and problems observed during combustion turbine overhauls.

Data describing equipment performance are included in this report. These data are site-specific and reflect the equipment design, operating and maintenance practices, and other influencing parameters for this site only. Combined-cycle plant development has advanced rapidly, and operating procedures have a great effect on performance characteristics. Many of the problem areas identified in this report have been corrected in later units and are therefore not applicable to all machines of the same manufacturer. For these reasons it would be improper to use these data in general analyses of combined-cycle plants. The data are useful in some respects for other analyses, especially the mean downtime values, which reflect the best-effort approach of a utility dedicated to availability maintenance within the constraints common to most electric utilities.

PLANT BACKGROUND

Wharton Plant Units 3 and 4 are identical General Electric STAG 400 combined-cycle power plants, each rated at 297 megawatts with a heat rate of 8710 Btu/kWh. The units burn natural gas but have a provision for distillate oil operation. Each STAG unit consists of four combustion turbine/generators, four heat-recovery steam generators (HRSG), and one steam turbine/generator. Superheated steam at approximately 850°F and 900 psig is routed via common header to the steam turbine/generator rated at 110 MW. Steam turbine inlet pressure is variable as a function of number of combustion turbines/HRSGs on line. Each steam turbine is a straight condensing double-flow exhaust design, coupled to a hydrogen-cooled generator.

Condensate is returned to the HRSGs through the condensate pump, gland exhaust condenser, and boiler feedpump. Each unit relies on a deaerating hotwell for noncondensable-gas removal; there are no extraction feedwater heaters or deaerators. A simplified process flow diagram is presented in Figure 1-1. Figure 1-2 is the Wharton Plant Unit 4.

The eight combustion turbines began commercial operation in 1972 and 1973. The units were available for peaking duty during the installation of the heat-recovery steam generators and steam turbine generator. Both units were placed in commercial service in the combined-cycle mode by mid-1974. The units were operated as cycling units in 1974 and 1975. Because of load growth and maintenance considerations, the units were committed to baseload duty in 1976. They are currently in baseload application.

Since being installed, the equipment has experienced considerable maturation and modification. Possibly because of the newness of the design of the equipment and the utility's efforts to improve performance, the plant is still in the reliability-growth phase, with modifications directed toward improved performance/reliability continuing 11 years after initial installation. The modifications now under consideration are upgrades of components requiring overhaul/replacement in any event; thus the cost of improvement is modest.

Changes in administrative functions have occurred over the history of the plant. There has been a trend toward increased presence of supervisory personnel on site and increased reliance on dedicated utility maintenance crews. These crews replace "rolling maintenance" or contractor personnel, with the purpose of developing in-house expertise in turbine maintenance. The instrument and control department staffing has been increased, and preventive maintenance policies enhanced.

These changes have been made in recognition of the fact that the combined-cycle plant maintenance requirements are more frequent and less extensive than those of conventional fossil-fired generating units. Conventional plants rely on annual maintenance outages to perform necessary inspections and repairs. Because of the multiple-independent-unit configuration of Wharton Units 3 and 4, maintenance can be scheduled to make optimal use of manpower and spares, encouraging the use of on-site work force and supervision.

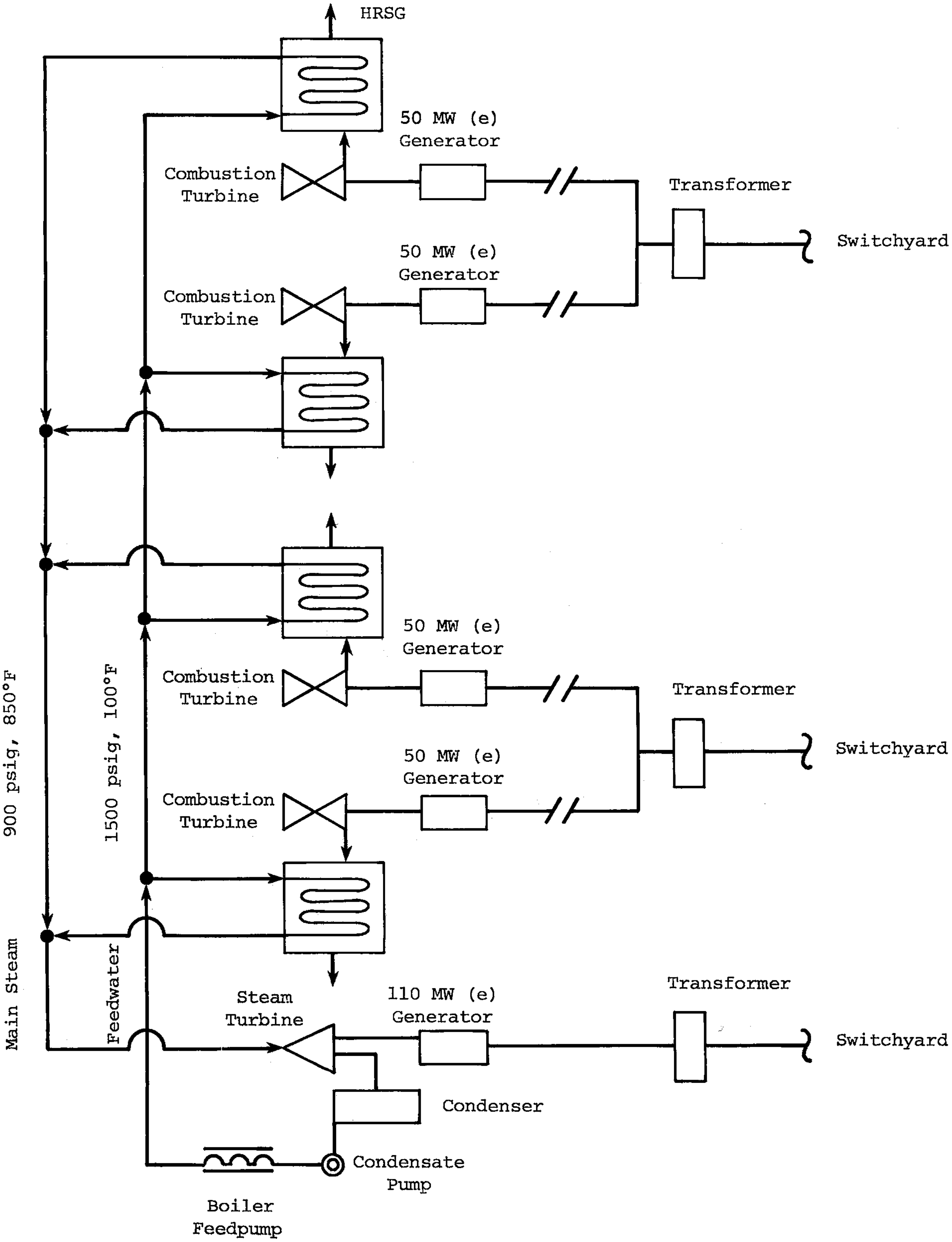

Figure 1-1. STAG 400 Flow Diagram

Figure 1-2. T. H. Wharton Unit 4

SCOPE

This project was chartered to observe turbine overhauls at the Wharton Plant and document the root causes of unreliability and unavailability. An on-site audit was determined to be the appropriate vehicle for encompassing all analyses of reliability, availability, and maintainability. The relationships between equipment reliabilities make it necessary to review all aspects of plant operation to permit proper analysis of equipment RAM characteristics. Therefore, RAM characteristics of key plant equipment were analyzed with an understanding of maintenance policies, plant operation, and administrative policies. The analysis addressed plant operational experience from January 1978 through October 1982, during which period 243,735 hours of combustion turbine operation were logged. The RAM analysis included all outage-causing events; equipment failures not causing an outage were not included in the data analyses.

OBJECTIVES

The purpose of the audit was to identify the frequency, magnitude, and root cause of outage-causing failures. This report was prepared to document one plant's history so that guidance would be provided for future equipment-improvement efforts. Another objective of the study was to correlate operations and maintenance practices with equipment part lives or failure frequency. Direct quantitative correlation was not within the scope of the project; established or suspected relationships are discussed in the technical discussion of the plant systems.

REPORT ORGANIZATION

Section 2 of this report presents the results of the outage-data analysis. Historical outage reports were reviewed to obtain an indication of the magnitude of the individual system contributions to outages and downtime. The outage reports were not of sufficient detail to permit determination of root causes of outages; however, they did provide information on the frequency and duration of the reported outages. These data were compiled and analyzed to establish priorities for the systems that should receive follow-up investigations.

Follow-up investigations were based on internal utility reports, visual observation of the equipment being overhauled, and informal interviews with plant personnel. Rather than being presented as a separate issue, the overhaul report is incorporated into Section 3, Technical Discussion. The discussions are segmented into systems corresponding to the outage-reporting system.

Section 4 summarizes the conclusions of the RAM audit. Data sheets on selected plant equipments are presented for reference in the Appendix.

Section 2

SUMMARY OF RELIABILITY, AVAILABILITY, AND MAINTAINABILITY (RAM) AUDIT

Historical outage records for the T.H. Wharton Plant were reviewed and analyzed to determine the root causes of unreliability and unavailability. Once the primary systems were identified, plant personnel were informally interviewed to determine the nature of the outage-causing events. The results of the audit are presented in this section and are combined with a technical discussion in Section 3. The data are segregated by system and presented in order from least reliable systems to most reliable systems. Both planned and unplanned outages are included in the data.

METHOD OF ANALYSIS

The outage reports for T.H. Wharton Plant Units 3 and 4 were compiled, and the following data were recorded for outage events:

- Date of event
- Duration of event
- Fired hours on unit at time of event
- Nature of event
- System responsible for event

These data were then compiled by the contributing system, and the total number of operating hours and number of events were determined. The operating hours for the electrical and fire protection systems were determined to be period hours. All other systems were reported as the number of combustion turbine fired hours. From these data the primary system RAM characteristics were determined. The mean time between outages (MTBO) was calculated by dividing the total operating hours by the number of outage-causing events. The mean downtime was calculated by dividing the total system downtime by the number of outage-causing events. The system availability was calculated by means of the point estimate of availability:

$$A = \frac{MTBO}{MTBO + MDT}$$

where

A = availability
MTBO = mean time between outages
MDT = mean downtime

The combustion turbine unit (CT) availability was calculated by use of the series rule for availability:

$$A_{unit} = A_{sys\ 1} \times A_{sys\ 2} \times A_{sys\ 3} \cdots A_{sys\ n}$$

where

A_{unit} = availability of combustion turbine unit
$A_{sys\ 1,2,3,n}$ = availability of primary systems

This rule is applicable where the failure of a primary system will result in failure of the unit. Since only unit outage reports were analyzed, only outage-causing system failures are included in the data base.

RAM AUDIT SUMMARY

Table 2-1 summarizes the CT system RAM characteristics. Combustion turbine/generator availability was calculated to be .75512 for the data period being analyzed. For reference, the utility availability data indicate a lifetime availability average of .7852 for all eight combustion turbine/generators. The steam system availability was calculated to be .89153. Utility records indicate a lifetime availability of .9030. These data are availability values, not equivalent availability, and include all outages, scheduled or not. The capacity factor for 1981 and 1982 was calculated by dividing gross megawatt generation by the maximum generation possible:

$$\text{Capacity factor} = \frac{\text{MW hours actually generated}}{\text{Capacity (nameplate)} \times \text{period hours}}$$

With nameplate ratings, the capacity factor calculated to be .77502.

Table 2-1

RAM DATA FOR CRITICAL SYSTEMS*

System	MTBO (Hours)	MDT	Availability
Combustion Turbine	543	163.3	.76879
Atomizing Air	48,747	82.4	.99831
Bearings	10,597	71.6	.99329
Combustion	3,339	340.0	.90758
Couplings	81,245	22.0	.99973
Compressor	243,735	504.0	.99794
Combustion Turbine Miscellaneous	12,828	90.6	.99299
Controls	1,042	19.7	.98144
Cooling and Sealing Air	48,747	7.6	.99984
Cooling Water	27,081	41.3	.99848
Combustion Turbine Electrical	24,167	45.0	.99814
Exhaust	60,933	72.5	.99881
Fire Detection	23,360	25.4	.99891
Fuel System	17,410	69.1	.99605
Hydraulic System	18,749	25.0	.99866
Inlet	40,622	14.0	.99967
Lubricating Oil	34,820	22.5	.99990
Load Section	34,820	409.0	.98839
Turning Gear	60,933	83.4	.99863
Start System	121,867	23.7	.99981
Turbine	16,249	1770.5	.90175
Water Injection	60,934	43.0	.99929
Generator	20,311	367.9	.98222 —
Heat Recovery Steam Generator	2,437	63.9	.97445
Steam Turbine Generator	8,427	43.6	.99485 —
Steam System BOP	2,809	80.5	.98337 —
Steam System Annual Inspections	11,797	1125.0	.91300
Steam BOP Miscellaneous	9,832	18.3	.99814 —

*Data obtained from HL&P outage reports.

Turbine
MTBO=1598
MDT = 85

consistent with
composite / Hi Serv factor units

Tables 2-2, 2-3, and 2-4 are rank orderings of combustion turbine systems for reliability, availability, and MDT. This report focuses on combustion turbine systems, although data on the other systems are provided. The remainder of this section concentrates on combustion turbine systems only.

Combustion Turbine/Generator Criticality Analyses

Discrete systems within the combustion turbine/generator train were analyzed to determine the key contributors to unavailability and unreliability. Planned and unplanned outages were considered in this analysis. The criticality analyses determined the frequency and duration of unit outages attributable to each system as indicated by the composite Wharton data base.

The analyses were performed by using availability and reliability models. The unit availability was calculated to be .75512 by multiplying the system availabilities:

$$A_{\text{unit}} = A_{\text{sys 1}} \times A_{\text{sys 2}} \times A_{\text{sys 3}} \cdots A_{\text{sys n}}$$

The criticality analysis for each system was performed by varying each system availability from its calculated availability to unity (1.00) one at a time, in effect, simulating a system with perfect availability. A quantitative assessment of each system's contribution to unit unavailability was made by comparing the original unit availability (.75512) with the adjusted unit availability.

For example, the turbine system contribution to unit unavailability was desired. The turbine system had an availability of .90175 (Table 2-3). Using the series rule:

$$A_{\text{unit}} = A_{\text{turbine}} \times A_{\text{sys 2}} \times A_{\text{sys 3}} \cdots A_{\text{sys n}} = .75512$$

$$A_{\text{unit}} = .90175 \times A_{\text{sys 2}} \times A_{\text{sys 3}} \cdots A_{\text{sys n}} = .75512$$

By substituting 1.000 for the turbine availability (.90175), a new unit availability was obtained:

$$A_{\text{unit}} = 1.000 \times A_{\text{sys 2}} \times A_{\text{sys 3}} \cdots A_{\text{sys n}} = .83739$$

Table 2-2

RELIABILITY RANK ORDERING*
(COMBUSTION TURBINE/GENERATOR SYSTEMS)

Ranking**	System	MTBO (Hours)
1	Controls	1,042
2	Combustion	3,339
3	Bearings	10,597
4	Combustion Turbine Miscellaneous	12,828
5	Turbine	16,249
6	Fuel System	17,410
7	Hydraulic	18,749
8	Generator	20,311
9	Fire Detection	23,360
10	Combustion Turbine Electrical	24,167
11	Cooling Water	27,081
12	Load Section	34,820
13	Lubricating Oil	34,820
14	Inlet	40,622
15	Cooling and Sealing Air	48,747
16	Atomizing Air	48,747
17	Exhaust	60,933
18	Water Injection	60,933
19	Turning Gear	60,933
20	Couplings	81,245
21	Starting System	121,867
22	Compressor	243,735

*Data obtained from HL&P outage reports.
**Rank-ordered from least reliable to most reliable.

Table 2-3

AVAILABILITY RANK ORDERING*
(COMBUSTION TURBINE/GENERATOR SYSTEMS)

Ranking**	System	Availability
1	Turbine	.90175
2	Combustion	.90758
3	Controls	.98144
4	Generator	.98222
5	Load Section	.98839
6	Combustion Turbine Miscellaneous	.99299
7	Bearings	.99329
8	Fuel System	.99605
9	Compressor	.99794
10	Gas Turbine Electrical	.99814
11	Atomizing Air	.99831
12	Cooling Water	.99848
13	Turning Gear	.99863
14	Hydraulic	.99866
15	Exhaust	.99881
16	Fire Detection	.99891
17	Water Injection	.99929
18	Inlet	.99967
19	Couplings	.99973
20	Starting System	.99981
21	Cooling and Sealing Air	.99984
22	Lubricating Oil System	.99990

*Data obtained from HL&P outage reports.
**Rank-ordered from lowest availability to highest availability.

Table 2-4

MEAN DOWNTIME RANK ORDERING*
(COMBUSTION TURBINE/GENERATOR SYSTEMS)

Ranking**	System	MDT (Hours)
1	Turbine	1770.5
2	Compressor	504.0
3	Load Section	409.0
4	Generator	367.9
5	Combustion	340.0
6	Combustion Turbine Miscellaneous	90.6
7	Turning Gear	83.4
8	Atomizing Air	82.4
9	Exhaust	72.5
10	Bearings	71.6
11	Fuel System	69.1
12	Combustion Turbine Electrical	45.0
13	Water Injection	43.0
14	Cooling Water	41.3
15	Fire Detection	25.4
16	Hydraulic System	25.0
17	Start System	23.7
18	Lubricating Oil	22.5
19	Couplings	22.0
20	Controls	19.7
21	Inlet	14.0
22	Cooling and Sealing Air System	7.6

*Data obtained from HL&P outage reports.
**Rank-ordered from longest mean downtime to shortest mean downtime.

If the turbine system had perfect availability, the corresponding unit availability would be .83783. The annual hourly contribution per turbine/generator was calculated by multiplying the difference in unit availability by the number of hours in one year (8760).

.83739 - .75512 = .08227

.08227 x 8760 hours/year = 720.68 hours/year

The turbine system had a calculated unavailability contribution of 720.7 hours per turbine/generator per year.

The results of the availability criticality analysis are shown in Table 2-5. A similar analysis was performed by evaluating system contribution to unreliability to determine the effect of each system on the unit mean time between outages. The results of this analysis are shown in Table 2-6.

The turbine section contributed 37.4% of the combustion turbine generator/ unavailability as a result of fixed interval inspection/overhaul. The interval is consistent with the manufacturer's recommendations; the duration of the inspections has been affected by the need for off-site repair of turbine nozzles or blading. Improvement in turbine system availability is possible through a larger inventory of spare turbine section parts (first-stage nozzles and a spare turbine rotor). Availability can also be improved by minimizing low-cycle-fatigue failures. These failures occur primarily in the first-stage nozzle and can be attributed in part to the incidence of false trips. Figure 2-1 shows the turbine with the upper casings removed.

Combustion inspections account for 34.9% of the combustion turbine/generator unavailability. These inspections are, again, fixed-interval scheduled events. Progress has been made in equipment improvement, and efforts continue. The combustion system availability is impaired by both the frequency and duration of maintenance events. Inspections are held twice annually, before and after the peak summer season. The inspection interval may not be the full 4000 hours planned. The priority is placed on equipment availability for the peak season, and all machines are made ready for uninterrupted service during the summer. A better situation for the utility would be an interval of 6000 to 8000 hours, so that combustion inspections could be held once in the spring.

Table 2-5

AVAILABILITY CRITICALITY ANALYSIS*
(COMBUSTION TURBINE/GENERATORS)

Ranking**	System	System Availability	CT Unit Availability		Outage Hours per Unit per Year Contribution
			Original	Adjusted	
1	Turbine	.90175	.75512	.83739	720.7
2	Combustion	.90758	.75512	.83201	673.6
3	Controls	.98144	.75512	.76940	125.1
4	Generator	.98222	.75512	.76879	119.7
5	Load Section	.98839	.75512	.76398	77.7
6	Combustion Turbine Miscellaneous	.99299	.75512	.76045	46.7
7	Bearings	.99329	.75512	.76022	44.7
8	Fuel System	.99605	.75512	.75811	26.2
9	Compressor	.99794	.75512	.75667	13.7
10	Combustion Turbine Electrical	.99814	.75512	.75652	12.3
11	Atomizing Air	.99831	.75512	.75639	11.2
12	Cooling Water	.99848	.75512	.75626	10.1
13	Turning Gear	.99863	.75512	.75616	9.1
14	Hydraulic	.99866	.75512	.75613	8.9
15	Exhaust	.99881	.75512	.75601	7.9
16	Fire Detection	.99891	.75512	.75594	7.2
17	Water Injection	.99929	.75512	.75565	4.7
18	Inlet	.99967	.75512	.75536	2.2
19	Couplings	.99973	.75512	.75532	1.8
20	Start System	.99981	.75512	.75526	1.3
21	Cooling and Sealing Air	.99984	.75512	.75524	1.1
22	Lubricating Oil	.99990	.75512	.75519	0.7

*Data obtained from HL&P outage reports.
**Rank-ordered from least available to most available.

Table 2-6

RELIABILITY CRITICALITY ANALYSIS*
(COMBUSTION TURBINE/GENERATOR SYSTEMS)

Ranking**	System	Combustion Turbine/ Generator MTBO		
		Original MTBO (Hours)	Adjusted MTBO (Hours)	MTBO Improvement (Hours)
1	Controls	529	1075.7	546.7
2	Combustion	529	628.8	99.8
3	Bearings	529	557.0	28.0
4	Combustion Turbine Miscellaneous	529	551.9	22.9
5	Turbine	529	547.0	18.0
6	Fuel	529	545.8	16.8
7	Hydraulic	529	544.5	15.5
8	Generator	529	543.3	14.3
9	Fire Detection	529	541.4	12.4
10	Combustion Turbine Electrical	529	541.0	12.0
11	Cooling Water	529	539.7	10.7
12	Load Section	529	537.3	8.3
13	Lubricating Oil	529	537.3	8.3
14	Inlet	529	536.2	7.2
15	Cooling and Sealing Air	529	535.0	6.0
16	Atomizing Air	529	535.0	6.0
17	Exhaust	529	533.8	4.8
18	Turning Gear	529	533.8	4.8
19	Water Injection	529	533.8	4.8
20	Couplings	529	532.6	3.6
21	Start System	529	531.5	2.5
22	Compressor	529	530.3	1.3

*Data obtained from HL&P outage reports.
**Rank-ordered from least reliable to most reliable.

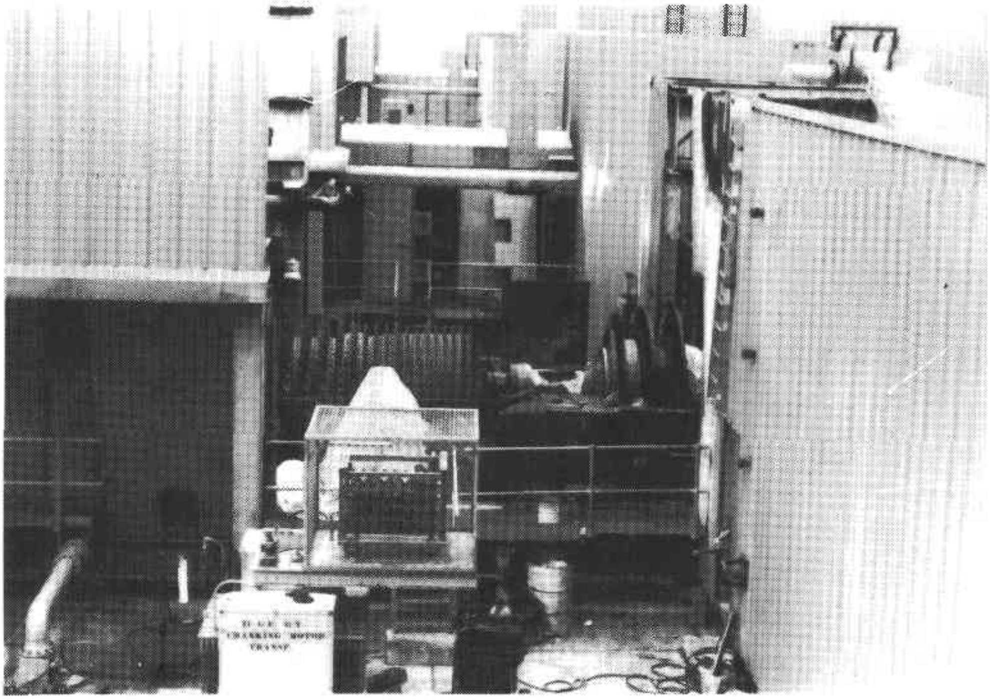

Figure 2-1. Combustion Turbine with Upper Casings Removed

Inspection intervals are limited by wearing of the transition piece seals and erosion of fuel nozzles. There is minor cracking of combustion components that may not be serious enough to limit the interval to 4000 hours. Environmental constraints are certainly significant in determining part lives; atomizing air for smoke reduction and water injection for NO_x abatement both impose maintenance penalties.

The control system is directly responsible for 6.5% of the combustion turbine/generator's unavailability. The control system outages are primarily the result of protective and monitoring equipment or wiring failures, often causing baseload trips. The low reliability of this system (MTBO = 1042 hours) corresponds to six baseload trips per year. These trips, in combination with the trips that occur as the result of identified failures in other systems, subject the combustion turbines to 10 baseload trips per year. This situation contributes significantly to low-cycle-fatigue failures of the combustion and turbine sections because of the rapid temperature fluctuations associated with a trip.

The control system has the poorest reliability, again because of malfunctions of protection and monitoring equipment. The physical controllers and control hardware are described as reliable and accurate; site personnel criticize the implementation of conservative protection that causes more problems than it prevents. Typical examples are combustion monitor trips, exhaust temperature protection trips, vibration trips, and wiring grounds or shorts. A common problem that is difficult to troubleshoot is a thermocouple that grounds intermittently. If the thermocouple grounds concurrently with a device or wiring ground or short, a voltage can be imposed on the thermocouple signal, causing an instantaneous trip. If both grounds are intermittent, the problem is extremely difficult to isolate.

There are two possible solutions to the problem. One is to minimize the thermal stresses induced during a trip by shutting the unit down in a controlled fashion rather than tripping the unit. The fired shutdown does not cut off fuel flow abruptly, but rather reduces it to a minimum level until a slow speed is attained. The other solution entails disabling some of the trip functions and relying on alarm or alarm/shutdown rather than trips. Implementation of either solution would reduce the frequency of thermal cycling in the turbine and combustion systems, although not without some risk of overlooking valid equipment hazards.

The generator section accounts for 6.2% of the combustion turbine/generator unavailability, because field failures (field ground failures) require a change-out of the generator field. The original fields were affected by the startup/shutdown cycling and have been replaced with modified fields to prevent recurrence. Five of the eight combustion turbine generators were affected.

The unavailability contribution of the generators is on the rise as the result of the degradation of stator bar insulation. The combined effects of vibrating bar sparking and oil/moisture contamination of the generators have caused deteriorated stator bar insulation. Restoration of the bars is an expensive and time-consuming process that will affect availability in the years to come. Two of the eight generators have been repaired thus far.

Four percent of the combustion turbine/generator unavailability is due to failures of the accessory gear box. These are commonly failures of the number 1 shaft thrust bearing, although journal bearings fail as well. One gear failure was reported. The thrust face failures may be attributed to dry accessory gear couplings and loss of coupling float.

The bearings contribute 2.3% of combustion turbine/generator unavailability, primarily as a result of leaking, which can result in compressor fouling and number 3 bearing load tunnel fires, as well as generator fouling, overheating, and insulation degradation. Although the bearing leaks are attributed to horizontal joint flanges or seals, the bearing drain pressure may be a contributing factor.

Heat Recovery Steam Generator Analysis

The heat recovery steam generator (HRSG) system is characterized by an MTBO of 2437 hours, an MDT of 63.9 hours, and an availability of .97445. The unavailability is equivalent to 223.8 downtime hours per HRSG per year.

Of the events reported, 63% were attributable to economizer tube leaks. This is a complex interrelationship problem traced back to quality control, tube design, and corrosion. It is discussed in greater detail in Section 3. A total of 20% of the outages were attributable to failures of circulating water pump seals. The seal failures are generally attributed to problems with the cooling water supply. A total of 12% of the outages were caused by feedwater control system problems. More incidents occur at startup because of small drum size, but these are not true outage events. Commonly, the boiler will trip on startup as a result of high drum level. The isolation damper cycles close, the drum level returns to normal, and startup is attempted again.

Wharton Plant personnel are very concerned with the HRSG tube leaks. The leaks affect heat rate as well as availability and are visually distracting. The economizer section can be replaced in a somewhat modular change-out, a solution that is now being investigated.

If the HRSG were considered part of the combustion turbine/generator train, the train availability would be .73584. This is a more realistic value for the combustion turbine/HRSG train, since the combustion turbine is not run without the HRSG available. The heat-rate penalty of simple-cycle operation makes such operation uneconomical unless load demand is large. The isolation damper is only partially successful in blocking hot gas from the HRSG; thus maintenance of the HRSG with the CT on line is generally not attempted.

A general criticism of the HRSG by site personnel is that it is not very well designed for outdoor applications. Water can be trapped in numerous harmful locations, causing rusting.

Steam System Analysis

The total steam system including steam turbine/generator and steam system balance of plant, has an availability of .89153. If the annual scheduled inspection is removed from consideration, the availability improves to .97648. The steam turbine/generator availability is equal to .99485. Most of the unavailability is attributable to the steam system balance-of-plant equipment, including condenser, circulating water system, and boiler feed and condensate pumps.

Problems were encountered in the condenser as a result of condenser tube scaling. Chemical cleaning removed the scale, and plant personnel have designed and installed equipment to control the pH, cycles, and chemical feed in the circulating water system. Other problems included failure of the circulating water pump expansion joint, which flooded the pump pit and submerged the pump motors. The system, in general, is handicapped by lack of redundancy in critical balance-of-plant equipments, including the boiler feedpump, the condensate pump, and the circulating water pump.

With the exception of one unit shutdown to repair a boiler feedpump motor bearing, all boiler feedpump problems were minor.

Section 3

TECHNICAL DISCUSSION

Equipment in the T. H. Wharton Plant, Units 3 and 4, are discussed in detail in this section, and are categorized by system. The reliability, availability, and maintainability (RAM) of each system are analyzed at system and subsystem levels. Data sheets summarizing RAM characteristics and problems for the systems shown in Table 2-1 are presented in the Appendix. A general technical discussion of these equipments is presented in this section.

BACKGROUND AND DEFINITIONS

Reliability is defined as the probability that a unit, system, subsystem, or component will perform satisfactorily for at least a given period of time. Availability is the probability that a unit, system, subsystem, or component is in operating condition at any given time and may be expressed as a decimal fraction between zero and one or as a percentage.

Availability is the percentage of time a piece of equipment is available for operation. A unit level operating availability is often calculated as the ratio of operating hours and reserve shutdown hours to total period hours:

$$A = \frac{\text{Operating hours + reserve shutdown hours}}{\text{Period hours}}$$

Availability for plant subsystems and components are calculated using the following relationship:

$$A = \frac{\text{MTBF}}{\text{MTBF + MDT}}$$

where

A = availability
MTBF = mean time between failures (hours)
MDT = mean downtime (hours)

This equation is normally used only for 100% utilization equipments that are either operating or failed. The baseloaded operation at Wharton approximates such utilization, and the calculated availability was validated by historical data within three percentage points. The basic relationship of availability to reliability and maintainability is evident in this equation. The greater the MDT with respect to the mean time between failures, the poorer the availability. A component can have a low mean time between failures and still have a good availability if the mean downtime value is also small. Components with large downtimes can achieve high availability only if the mean time between failures is large as well.

Mean downtime is one measure of maintainability. It incorporates the numerous aspects of all maintenance, troubleshooting, parts procurement, and active and inactive repair time.

The remainder of this section is a technical discussion of the RAM characteristics of the plant systems. Table 3-1 presents the rank ordering of 22 combustion turbine systems, showing the control system as having the poorest reliability (rank 22) and the compressor system as having the highest reliability (rank 1).

COMBUSTION TURBINE CONTROL SYSTEM

The RAM characteristics of the combustion turbine control system are:

- MTBO - 1041.6 hours
- A - .98144
- MDT - 19.7 hours
- Reliability Rank - 22
- Availability Rank - 20
- Maintainability Rank - 3

The control system is a significant direct contributor to unreliability and unavailability. It also has indirect effects that include turbine degradation from frequent trips and resultant low-cycle fatigue. The combined effects are discussed here.

Investigation of plant records and interviews with plant personnel revealed that the control components were reliable but that feedback, monitoring, and protection equipment was responsible for the majority of the problems. That is, malfunction or disruption of controlling signals, devices, and operators does not generally

Table 3-1

RANK ORDERING OF COMBUSTION TURBINE SYSTEMS

System	Reliability Ranking	Availability Ranking	Maintainability Ranking
Control	22	20	20
Combustion	21	21	5
Bearings	20	16	10
Combustion Turbine Miscellaneous	19	17	6
Turbine	18	22	1
Fuel	17	15	11
Hydraulic	16	9	16
Generator	15	19	4
Fire Detection	14	7	15
Electrical	13	13	12
Cooling Water	12	11	14
Load Section	11	18	3
Lubricating Oil	10	1	18
Inlet	9	5	21
Cooling and Sealing Air	8	2	22
Atomizing Air	7	12	8
Exhaust	6	8	9
Water Injection	5	6	13
Turning Gear	4	10	7
Couplings	3	4	19
Starting	2	3	17
Compressor	1	14	2

occur. The control system problems are focused on thermocouples, vibration sensors, flame scanners, fire detectors, limit switches, and the associated wiring. These devices are installed to provide a feedback on the operation of the controls, or identify equipment hazards such as high vibration, loss of flame, fire in a compartment, excessive exhaust temperature spread, or wrongly positioned valves or dampers. The protective equipment malfunctions frequently, resulting in turbine shutdowns. These events are more frequent than any other event at this site. Although the mean time to restore the control system is 19.7 hours, which is relatively low (see Table 2-1), the poor MTBO results in poor control system availability.

Control System Reliability

The control system has the poorest reliability of all the systems. This can generally be attributed to the complexity of the system and the hostile environment it must function in. Heat and vibration are responsible for numerous device failures. The shortcoming of this particular subsystem is that it cannot withstand component failure without an accompanying system failure (combustion turbine). This occurs as a result of control and protection philosophy and poor device isolation.

An example of the control philosophy can be seen in the loss of signal trips. Position indicators such as limit switches and fire detectors are installed in a fail-safe configuration such that loss of the signal due to faults in wiring or the device itself will result in a trip. Isolation problems are focused on thermocouples; wiring faults, shorts, or grounds have caused numerous trips by disrupting the temperature feedback circuits. These disruptions can be transient, are difficult to isolate, and subsequently recur.

The fail-safe strategy is responsible for a significant portion of the unreliability. If the first-order effects are analyzed, the strategy cannot be disputed. If equipment condition is in doubt, it is safer to shut the unit down than to operate in an unprotected mode. However, second-order effects, turbine fatigue, may be grounds for reconsideration. A control system trip results in severe thermal cycling of the hot gas section. The Wharton Plant is baseloaded; therefore, units are normally shut down only for scheduled maintenance. Control-initiated trips contribute significantly to the low-cycle-fatigue failure mechanism on these units. Inadequate control device isolation is a problem in that relatively minor wiring or component failures can result in turbine trips. Exhaust temperature thermocouples are good examples of control devices that are not adequately isolated. Two common failure modes are described below.

Thermocouple grounding is a frequent occurrence that in itself will not result in a unit trip. However, if another device on the unit grounds and a voltage to ground is induced, it is possible for a portion of this voltage to be transmitted back to the temperature-monitoring circuits. Thermocouple signals are in millivolts; accordingly, very low voltages can cause major misinterpretation of the control or protection system, and a trip signal is initiated. This failure mode is especially troublesome when the thermocouple ground or the other device ground occur intermittently, or occur only under operating conditions of heat and vibration. This failure is extremely difficult to troubleshoot, and it often results in numerous trips before the faults are located.

Another failure mode is a control thermocouple's failing by shorting outside the exhaust area. The new junction will read the ambient temperature at the junction and bias the average control temperature downward. The fuel system responds by adding more fuel to bring the exhaust temperature back up. A trip occurs when the exhaust temperature trip set-point is reached. Once again, this is easy to troubleshoot if the failure is "hard," but often the wiring shorts in the conduit and the failure is intermittent.

Several modifications to the control devices have been implemented to improve subsystem reliability. Major control or protection revisions have not been made. Device modifications include the use of extended thermocouples, upgraded limit switches, abrasion-resistant high-temperature wire, and conduit routed away from hostile environments. Current evaluations are focused on new types of flame scanners and vibration sensors.

Other steps taken to improve control system reliability have been implemented. The enhancement of the instrument and control staff has allowed the utility to improve its instrumentation and control maintenance. One preventive maintenance effort of this group is examination and functional testing of control devices at every combustion inspection. This concurrent maintenance is employed to detect potential problem areas before failures occur.

Control System Availability

As shown in Table 3-1, poor control system availability is attributable to poor MTBO rather than mean downtime. It also reflects first-order availability impacts only, not consequential effects.

Improvement of the control system's availability can be pursued through the use of high-reliability components or the reduction of the system's dependence on unreliable components. Efforts at Wharton are concentrated on improving the reliability of sensors, switches, and wiring. Generally no attempt is made to defeat instrumentation.

More sophisticated means of equipment protection could help reduce the number of trips. Most developmental work has focused on hardening control devices. An alternative to this approach is "smart" protection, with the ability to discern device or wiring failures from real equipment hazards. This approach would rely on redundant instrumentation, signal conditioning and isolation, and upstream/downstream signal evaluation. The optimal solution to control system unreliability is a combination of approaches.

Control System Maintainability

The mean downtime of 19.7 hours per event places the control system in the number 3 rank for maintainability. This value reflects a mean time only; many control system problems are resolved in one hour, and some take much longer.

Site comments focus on the troubleshooting problems encountered with the unit. Many control system problems are transient and their causes cannot be identified. Without annunciated indication of affected components, troubleshooting becomes a procedure of running the unit and waiting for the event to recur. Some failures are common enough that troubleshooting is easy for an experienced technician. The design of the existing annunciator does not accommodate all of the signal collection required for enhanced troubleshooting capabilities. Annunciators with enhanced capabilities are currently being added.

Other criticisms focus on the location of junction boxes in the unit. The boxes are generally considered inaccessible and their locations poorly selected with respect to conduit routing and box location. Off-base or outside cable routing is preferred to the existing methods from the standpoints of environmental exposure and troubleshooting accessibility.

COMBUSTION SYSTEM

The RAM characteristics of the combustion system are:

- MTBO - 3,339 hours
- A - .90758
- MDT - 340 hours
- Reliability Rank - 21
- Availability Rank - 21
- Maintainability Rank - 18

The combustion system ranks near the bottom in all three categories. It is, however, the most heavily stressed system of all, and considerable improvements in system reliability have been made. The incidents reported consist of 91.8% scheduled maintenance. The combustion system is serviced at fixed intervals to identify imminent failures, not failures that have already occurred.

Combustion System Reliability

The second highest contributor to unreliability is the combustion system. This situation is the result of fixed-interval maintenance, not component failure, but the fixed interval is required because relatively minor combustion system component failures can result in major damage to or degradation of the turbine system. Unbalanced combustion can cause high-cycle fatigue of turbine blading, and cracked or failed combustion components can cause foreign object damage (FOD) to the turbine section. Fuel nozzle pluggage or erosion can result in a disrupted flame pattern and subsequent damage to combustion parts. All combustion components have at one time or another contributed to the need for fixed-interval maintenance. There has been considerable hardware modification, however, making extended intervals possible.

Early problems in the combustion system consisted of cracking of liners and transition pieces. The cracking was due to a combination of thermal and mechanical fatigue resulting from the extreme combustion conditions that exist in combustion turbines. The steam system equivalent of the combustion system is the boiler furnace, and a 50 MW boiler furnace has a much larger surface area to disperse radiant heat and combustion pressure oscillations.

Significant progress has been made in the development of more reliable combustion components, but failures continue to occur in the combustion liners. Cross-fire tube overtemperature, another historical problem, has also been eliminated. The most severe problem that still exists is transition piece seal wear at the point of connection to the first-stage nozzle (Figure 3-1). However, fuel nozzle erosion is still a problem, as described in the fuel system discussion.

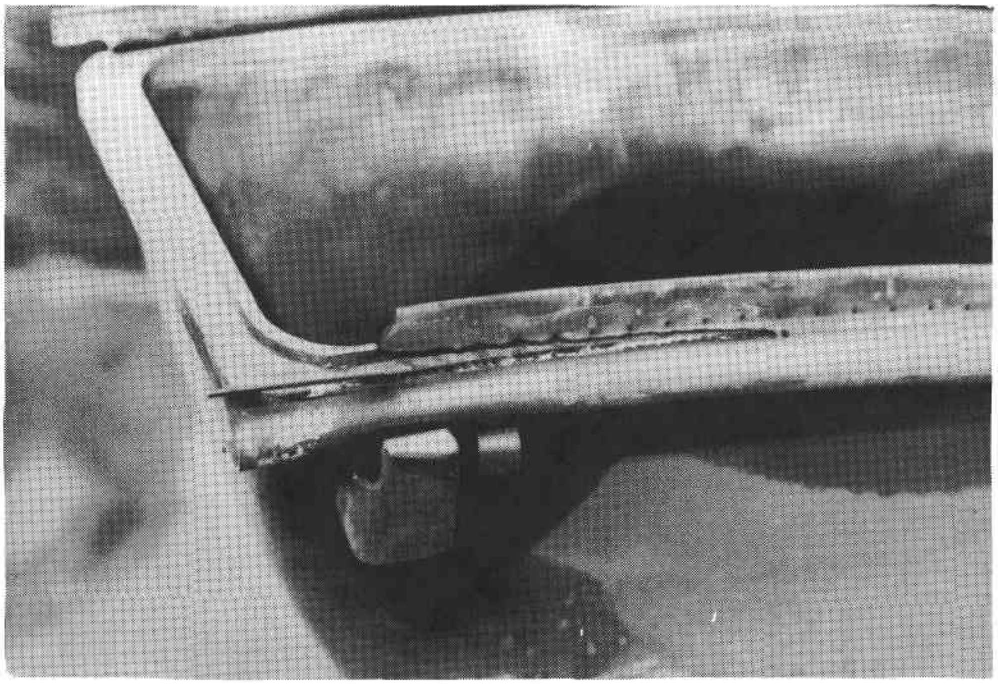

Figure 3-1. Transition Piece Seal Wear

Improvements have occurred as the result of using heavier walled liners and transition pieces as well as more sophisticated methods of cooling these components. Manufacturing processes that resulted in weak points (stress concentrators) have been eliminated. Areas exposed to high mechanical loading (bracket connections) have received increased attention directed toward minimizing metal temperatures by the insertion of cooling holes in adjacent metal. Lower metal temperatures result in better fatigue resistance. Heavier walled crossfire tubes and greater attention to fuel nozzle condition have resulted in higher reliability of the tubes as well.

Modest extension of inspection intervals continues, always tempered by the relatively small payback in comparison with the high cost of component failure. Combustion system condition monitoring consists of exhaust temperature monitoring, which will indicate problems with fuel nozzles or already failed combustion components. The reliability of these components will be improved by further reductions in their thermal and mechanical loads. The load reduction is being pursued in two areas: quiet combustion and dry NO_x abatement.

Both developments are proprietary, but the problems they address are not. Combustion pressure oscillations, or "noise," impose vibration loadings on the combustion components. This is a complex situation that can be minimized by replacing one large flame front with several smaller flame fronts. The noise problem is aggravated by water injection, which increases the amplitude of the pressure oscillations. Water injection is used to minimize thermal fixation of combustion air nitrogen by lowering peak temperatures encountered. The manufacturer is currently developing new combustion systems that will address the maintenance penalties imposed by water injection.

Thermal and mechanical loading can also be reduced through the implementation of a "fired shutdown" mode of operation, available as a control modification and discussed in the control subsection. This procedure reduces the rate of temperature drop in the combustion system during trips and normal shutdowns, thereby reducing thermal and mechanical stresses.

Combustion System Availability

A combustion system availability of .90758 significantly affects the overall combustion turbine availability, which is impaired as a result of long-duration (340 hours' MDT) shutdowns that occur frequently (3,339 hours' MTBO). The utility employs its own staff to perform inspections, and the inspection process has been streamlined within the constraints of utility operations. The criticality of proper installation of combustion hardware limits the opportunity to reduce downtimes. Any improvement in availability will probably be realized through improvement in reliability. The scheduling of combustion system maintenance provides a large range of acceptable availabilities; thus drastic improvement is not required. The site goal is an MTBO of 8,000 hours, or an availability of .9590.

Combustion System Maintainability

The combustion system's mean downtime of 340 hours places the system 18th in the maintainability rank ordering. A significant amount of work is accomplished in this time, and little time is lost from logistics delays. The system maintenance events are primarily scheduled and are often accompanied with concurrent maintenance of other systems, and the downtimes do not reflect crash efforts. More emphasis is placed on proper installation of parts than on finishing quickly. Administrative delays in the form of manpower dilution may occur if other maintenance activities are taking place. Figure 3-2 shows the distribution of combustion inspection durations.

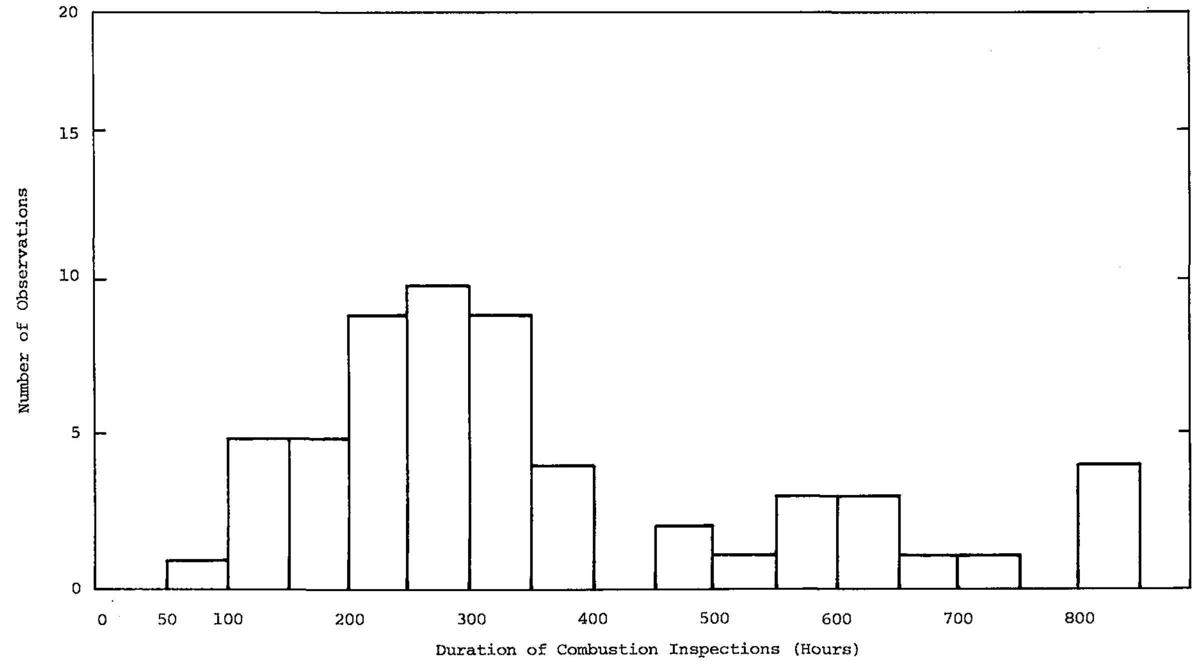

Figure 3-2. Distribution of Combustion Inspection Durations

Combustion inspection activities vary as a function of the results of the preceding inspection, but as a minimum the fuel nozzles, combustion liners, and transition pieces are removed. Because the unit can be fired on natural gas or fuel oil and has atomizing air and water injection, a large amount of piping must be removed to perform an inspection, contributing significantly to inspection durations. Removal of fuel nozzles and combustion liners is straightforward but can be time-consuming because of the close quarters. Transition piece removal is time-consuming, because the combustion wrapper is left in place and all work is completed in extremely limited space. Fuel nozzle maintenance is performed in parallel with other activities.

Maintenance durations could be shortened if larger enclosures were provided and the additional space were used to advantage in locating piping systems. Modularizing these turbines imposes maintenance penalties on the user. The current practice is to leave the enclosure intact for minor maintenance and remove it for major maintenance. Minor maintenance must thus be accomplished in a very confined space, with no provision for lifting equipment. A larger compartment with an overhead rail and 1/2-ton trolley chain hoist would eliminate the time-consuming manual handling of combustion components and the accompanying hazards to both personnel and equipment. Such a compartment would have to be field-assembled in the field, because it would not meet shipping size limitations, but it could be designed for easy erection and removal.

Finally, maintenance duration could be improved slightly by using a spare set of fuel nozzles on an exchange basis. This would result in only minor reduction of downtime, however, because fuel nozzle maintenance is performed in parallel with other activities.

COMBUSTION TURBINE/GENERATOR BEARINGS

The RAM characteristics of the combustion turbine/generator bearings are:

- MTBO - 10,597 hours
- A - .99329
- MDT - 71.6 hours
- Reliability Rank - 20
- Availability Rank - 16
- Maintainability Rank - 13

The bearings system consists of three turbine bearings and two generator bearings. In 21 of 23 reported events, the failure mode is leaking. The above-listed data reflect first-order effects, but significant second-order effects contribute to unavailability that is charged to the compressor and generator.

Oil leaks vary in severity depending on the bearing affected. Leakage of the #1 bearing has resulted in compressor fouling and performance degradation. Leaks at the #2 and #3 bearing can result in compartment or tunnel fires, which are not major fires but can result in bearing damage if the fire cannot be extinguished with the lube oil system in operation. Leaks at the #4 and #5 bearings can cause generator fouling, resulting in dirty windings, plugged cooling air passages, poor heat transfer, and stator bars that are "lubricated" in their slots. The presence of oil in the slots may contribute to stator bar movement or vibration and to the deterioration of insulation.

Bearing System Reliability

The third-highest contributor to unreliability is the bearing system. The dominant failure mode is leakage, with 43% of bearing leaks resulting in fires. Several steps have been taken to reduce the frequency of bearing leaks, but the problems persist. The leaks can occur at seals and horizontal joints, but it is suspected that the root cause is high bearing-drain pressure. The oil reservoir into which the bearings drain is mounted at the same elevation as the turbine base. Thus there is only about 2 feet of elevation difference between the bearing drain and the top of the oil reservoir. This situation is aggravated by long horizontal runs of drain piping, especially in the #3 bearing area. Sealing air is provided to the bearing seals to generate a higher pressure at the seal outlet, with only moderate success. A new bearing seal design is being evaluated.

Bearing Availability

The bearing system availability is a function of frequent occurrence and moderate duration of maintenance. If second-order effects such as compressor and generator fouling were included, bearings would be one of the major contributors to unavailability, behind the combustion and turbine systems. Bearing leaks resulting in compressor fouling impose significant performance penalties on the compressor, which are accounted for in fuel costs. Clearly, improvement of this system's availability must come from reliability improvement, not downtime reduction.

Bearing System Maintainability

The bearing system has a maintainability ranking of 13. Since more than one-half of the events reported occurred in the #3 bearing, which is located in the load tunnel, the mean downtime of 71.6 hours is quite good. An absolute minimum of 24 hours is required for cool-down before the #3 bearings can be worked on. The load tunnel is extremely tight and difficult to work in, but it appears not to impose a significant enough maintenance penalty to warrant changes.

COMBUSTION TURBINE MISCELLANEOUS

The RAM characteristics of the combustion turbine miscellaneous category are:

- MTBO - 12,828 hours
- A - .99299
- MDT - 90.6 hours
- Reliability Rank - 19
- Availability Rank - 17
- Maintainability Rank - 17

This category was created to handle those events of unknown or unidentified nature, operator errors, and acts of God such as lightning strikes. It is a significant contributor to the unreliability and unavailability of the plant, but cannot be treated in detail because of the diversity of the events.

TURBINE SYSTEM

The RAM characteristics of the turbine system are:

- MTBO - 16,249 hours
- A - .90175
- MDT - 1770.5 hours
- Reliability Rank - 18
- Availability Rank - 22
- Maintainability Rank - 22

The turbine section is the primary contributor to unavailability, the long outages being the primary factor. A significant portion of the unavailability is due to the logistics of replacement or repaired parts. The turbine section in its present modified configuration is considerably more reliable than the historical data indicate, but an MTBO of 20,000 to 25,000 hours will probably continue because of low-cycle fatigue.

Turbine System Reliability

The fifth least reliable system is the turbine section. As with the combustion system, most events reported are inspections or overhauls, although these events tend to be more on condition than at fixed intervals. The MTBO of 16,249 hours is an historical average; the current MTBO is closer to 20,000 hours. Extension of this interval is likely as experience is gained.

Combustion turbine nozzles and blading are possibly the most severely stressed components in any utility application, hence the failure modes tend to be fatigue-related. The three most common failure modes at T. H. Wharton are low-cycle fatigue of first-stage nozzles, creep fatigue of second-stage nozzles, and blade cracking of first- and second-stage rotating blades. The blade problem is an old one, related to cold-straightening procedures during manufacture and is no longer present. The creep-fatigue failures of second-stage nozzles has been corrected through modification of the nozzle design, reducing the cantilever stresses and stiffening the individual nozzle segments. This modification requires replacement of the second-stage nozzles and the first-stage turbine shroud blocks, which is taking place when the service life of these components is expended.

Low-cycle fatigue of the first-stage nozzle is a problem that is likely to continue. The first-stage nozzle is exposed to the highest-temperature combustion gas and, accordingly, receives the largest flow of cooling air to reduce metal temperatures. In the event of a normal shutdown, and especially in the event of a trip, the gas temperature drops rapidly, but cooling air temperature continues at only a slightly reduced rate. The metal temperature changes rapidly and is concentrated on the trailing edge of the nozzle vanes, where the metal is thinnest. Similar but less severe temperature swings occur at startup.

Fatigue cracking is an excellent example of how one system can cause other systems to experience failures that are not obvious through preliminary data analyses. Trips carry a significant nozzle service-life penalty, and the solution to extending nozzle life is to eliminate the trips or reduce the severity of each event. This can be accomplished by implementing the fired shutdown control change, which does not abruptly shut off fuel flow but reduces it to a minimum level that allows a slower and "hotter" deceleration. The modification reduces the maximum temperature gradients to which the nozzles will be subjected.

The same effects occur in the rotating blading but are not so apparent at the Wharton plant, because the blades were replaced earlier to resolve the cold-straightening problems and have not been exposed to as many cycles as the nozzle segments. Further, to withstand the greater stresses encountered, the buckets are thicker and stronger than the nozzle sections. The most significant problem with the turbine blading appears to be foreign object damage (FOD), which is minimal. One recent overhaul revealed rather extensive though repairable FOD as a result of crack convergence in a first-stage nozzle segment.

Turbine section corrosion and erosion are not problems at the Wharton Plant. The fuel is clean and sulfur-free, and the ambient air is apparently free of corrosive agents.

Low-cycle fatigue is the primary failure mode of the turbine section. Some fatigue will be induced through normal startups and shutdowns, but the Wharton Plant is primarily baseloaded; thus shutdown would normally be for scheduled maintenance only. Baseload trips are much more severe, one trip being roughly equivalent to eight normal shutdowns. Records for Units 31, 32, 33, and 34 were closely reviewed for trip-causing events only. In 120,987 total fired hours, 190 trips were recorded, for a mean time between trips of 637 hours. Table 3-2 is a rank ordering of the trip causes as reported in the General Electric Operational Reliability Analysis Program (ORAP) data system.

The 637-hour mean time between trips indicates that each unit will experience an average of 31 baseload trips in an inspection interval of 20,000 fired hours. The site personnel have made considerable progress in preventing trips through preventive maintenance of the control devices, the mean time between trips increased to 1015 hours in 1982, although there are still 20 trips in a 20,000-hour interval. The manufacturer is better qualified to determine the impact of part lives on baseload trips. It appears, however, that elimination of baseload trips would make it possible to extend inspection intervals.

Turbine Overhauls

Major overhauls of three combustion turbine units were conducted during the performance of the audit. The fired hours on the units varied from 35,000 to 42,000 hours. The overhauls were scheduled by taking into consideration system reserves as well as fired hours and were generally representative of 20,000-hour intervals. During previous overhauls, turbine section components had been replaced; however, the compressor sections were original.

Utility site personnel performed the overhauls, with support from utility "rolling maintenance" personnel. This is a relatively new approach at the Wharton Station, since previous overhauls were performed by contractors or rolling maintenance. The overhauls were staggered to optimize the use of personnel and spares. The first

Table 3-2

COMBUSTION TURBINE TRIP INITIATORS:
Units 31, 32, 33, 34 (1978-1982)*

Ranking	Cause	Number of Trips
1	Speedtronic Grounds	47
2	Unknown	40
3	False Fire Indications	15
4	Vibration Detection (False)	13
5	High Exhaust Temperature	12
6	Vibration Detection (Actual)	8
7	Operator Error	7
8	Servo Valve Failures	7
9	Thermocouples	6
10	Station Electrical Disruption	6
11	High Exhaust Temperature Differential	5
12	Limit Switch Failure	4
13	Compressor Bleed Valve Trip	4
14	Fire	3
15	Drum Level	3
16	Combustion Monitor	3
17	Generator Controls	2
18	Generator Differential	2
19	Loss of Flame	1
20	Hydraulic Supply Pressure	1
21	Lube Oil Temperature	1

*Data obtained from HL&P outage reports.

overhaul was aggressively scheduled, with the crew size varying between 11 and 14 men working 10-hour days. This level of effort was designed to support a 10-to-12-week overhaul duration.

Activities planned for the overhauls included repair or replacement of first-stage nozzles and first-stage buckets, replacement of second-stage nozzles with a modified design, and application of coatings to the compressor section's rotating and stationary blading. Generator field replacement and stator inspection were also planned. Replacement of turbine blading and removal and replacement of compressor blading was conducted off site, since it is not feasible to disassemble the rotor without special tooling in a service shop. Further, there is no field balancing capability for these units; a reassembled rotor must be shop-balanced. The overhaul consisted of disassembling the unit, transporting the rotor assembly to an off-site shop, and removing/replacing the stationary components. Parallel work minimizes any penalty arising from shipping the rotor off site.

Spare parts were critical in minimizing the overhaul duration. Nozzle sections are generally repairable, but the turnaround time for repairs to be completed can exceed six weeks. The utilization of spare nozzle sections permits work to proceed during rotor and stator component repairs. The first overhaul proceeded rapidly; the unit rotor was removed on the ninth day of the overhaul, and disassembly was completed in the fourth week. During this time the generator was found to have stator insulation problems. After seven weeks it was evident that the generator work would extend beyond the turbine overhaul; therefore, the overhaul scheduling was relaxed. The unit was placed back in service after 17 weeks.

Component condition in the turbine section indicated that the maintenance interval was appropriate. Low-cycle fatigue cracking in the first-stage nozzles was widespread, including one vane that lost material due to crack convergence. Other vanes indicated near-term crack convergence as well. The first-stage buckets showed evidence of Foreign Object Damage (FOD), presumably from the missing section of the first-stage nozzle vane. The second-stage nozzle showed extensive cracking in the outer sidewall on both sides of the vane (see Figure 3-3). The cracks occurred primarily on the center vane of the three vane segments and were attributed to a second-order effect of creep distortion. The service lives of these nozzle segments were expended. Second-stage buckets were in good condition, with minor FOD; the third-stage nozzle segments and buckets were also in good condition.

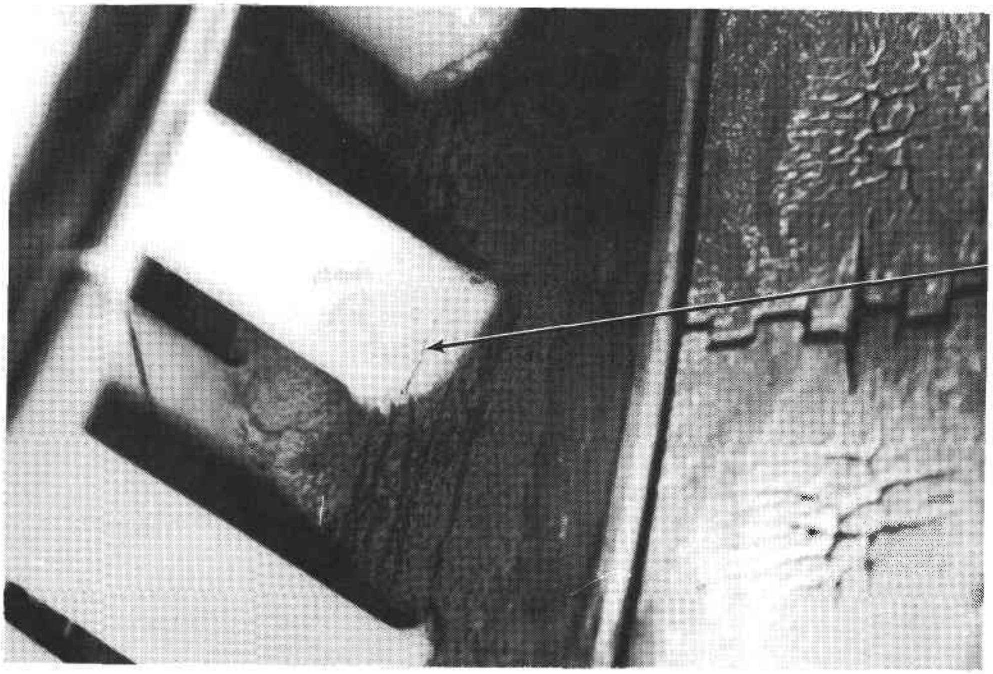

Figure 3-3. Second-Stage Nozzle Showing Evidence of Cracking

The compressor section showed extensive fouling and erosion. The Wharton units do not have inlet air filtration. The deposits were oily and were concentrated in the initial stages of the compressor. Erosion was most evident in the later stages, i.e., thinning of the trailing edge of the blading, which altered the profile of the blades. Performance of the compressor was apparently unaffected by the erosion or masked by the fouling effects. Erosion itself may not affect performance until metal loss is more severe, resulting in blades with rounded trailing edge tips.

Bearing condition was moderate, with minor wiping evident on two of the three bearings. Minor scoring of the rotor journal was also evident.

Numerous incidents of frozen or galled casing bolts and dowel pins were encountered during disassembly. The problem was most severe in the turbine section casing, which is subjected to high temperatures. The galled bolts do not normally result in major delay in disassembly, since the heads are burned off the bolts and the bolts removed at a later date when time permits. Considerable expenditure of manpower results in burning, drilling, or worrying out frozen or galled bolts. Anti-seize compounds are used during assembly.

The overhaul interval was justified by the condition of the first-stage and second-stage nozzle sections. Newly designed second-stage nozzle segments were installed upon reassembly. The "short sidewall" nozzle was designed to reduce cantilever loads that contributed to creep fatigue failures. This modification should significantly extend the 40,000-hour lifetime of the second-stage nozzles. Turbine bucket condition was good, with the exception of FOD. The limiting factor on overhaul duration appears to be first-stage nozzle cracking. The cracking is weld-repairable, and the nozzles have a service life of more than 40,000 hours; however, the fatigue cracking makes removal desirable at approximately 20,000-hour intervals. Extension of overhaul intervals will probably alleviate the rapid temperature cycling that contributes to low-cycle fatigue.

The overhaul of the second unit, which had several thousand fewer hours of operation, revealed similar but less extensive nozzle cracking. Compressor fouling and erosion were more severe. The third unit overhauled was in considerably better condition, but it had hot section repairs more recently than the other two units.

A typical overhaul cannot be described because of diversity of the three overhauls. The first unit had aggressive scheduling, which was relaxed because of generator rework. The compressor section was bead-blasted but not coated. The second and third units were less aggressively scheduled, primarily because they were being performed in parallel and the manpower and spare parts were diluted. These units were to receive compressor coatings, which requires extensive effort in removing the stator vanes (on site), unstacking the compressor rotor (off site), and shipping the blades to a facility qualified to apply the coatings. In summary, a typical overhaul at Wharton may last from 10 to 20 weeks, require from 2,000 to 5,000 man-hours to complete, and have widely variable parts costs depending on the parts replaced, repaired, or modified.

Turbine System Availability

The turbine system availability of .90175 is the lowest of all plant equipments. With the mean downtime held constant and the MTBO improved to 20,000 hours, an availability of .91867 would result. An MTBO of 25,000 hours would result in an availability of .93386. The turbine system availability for the next five years will probably fall somewhere in between these numbers. Turbine modifications to yield longer MTBOs have been completed, making further extension unlikely. Low-cycle fatigue will continue to limit availability.

Availability can be improved through reduction of logistics delays in performing turbine overhauls. The details will be discussed in a subsequent subsection. The effect of logistics delays on availability is discussed below.

When turbine maintenance is performed, the turbine rotor and first-stage nozzles are removed for repair/replacement of critical components. This repair takes place at off-site facilities, and a turnaround of four weeks is about as good as can be expected; it represents a 672-hour downtime penalty. Eliminating this logistics delay would result in an MDT of 1098 hours, a 38% reduction in downtime. This correlates to a new availability of .93670, or an availability improvement of .0349, which in turn corresponds to 306 extra hours of operation per year per turbine, or 2446 extra hours of operation per year at the station. Much discussion has been focused on the value of availability, which this report will not attempt to resolve, but in this case the Wharton Plant has the lowest heat rate of the utility's plants that burn the same-price fuel. It is safe to assume that there is a penalty in replacement cost of power based on fuel costs alone. The best way to address this issue is to identify the lost megawatt hours (MWh), in this case 171,360 MWh per year. For every dollar/MWh (mil/kWhr) of replacement power cost, $171,360 is expended. There is significant cost saving associated with reducing logistics delays.

Figure 3-4 is a photograph of the turbine rotor installed in Unit 41.

The costs associated with reduced logistics delays are significant, for a spare turbine rotor and first-stage nozzle would have to be purchased and used on an exchange basis. These costs can easily exceed $2 million. The cost-effectiveness of this approach is dependent on a great many factors not related to this report, but some of the basic costs and benefits of availability improvement can be demonstrated.

- We assume $5/MWh replacement power obtained as follows:

  9100 Btu/kWh heat rate at Wharton vs. 10,100 Btu/kWh replacement power heat rate

  $= 1000 \text{ Btu/kWh (heat rate differential)} \times 1000 \frac{\text{kWh}}{\text{MWh}}$

  $\times \$5.00/10^6\text{Btu} = \$5/\text{MWh}$

  Thus annual replacement power fuel savings

  = 171,360 MWh x $5.00/MWh = $856,800

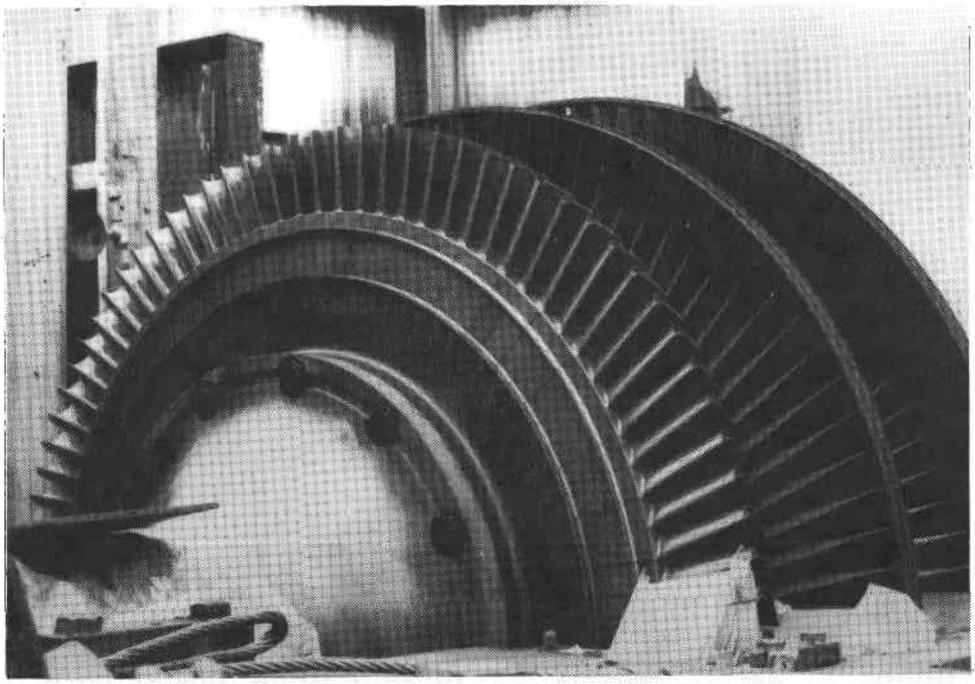

Figure 3-4. Turbine Rotor

- We assume $4,000,000 increased inventory costs (capital acquisition + one time inventory charge of 25%)

  Annual cost = $4,000,000 x fixed-charge rate (assume 18%)
  $4,000,000 x .18 = $720,000 annual costs

This simplified analysis reveals some of the benefits of enhanced inventory and subsequent availability improvement. It does not suggest that a spare rotor is a necessary addition; the capital may be better applied elsewhere.

Turbine System Maintainability

Turbine system maintenance durations are lengthy, with a mean downtime of 1770.5 hours. Figure 3-5 shows the distribution of maintenance durations during the period considered in this investigation. The maintainability of these units is negatively affected by three factors: logistics delays, modifications, and problems in disassembly.

The logistics delays consist of turnaround time for turbine rotor and first-stage nozzle repair. The capital cost requirements for a spare rotor and nozzle assembly may preclude their purchase. Accordingly, each maintenance event that requires

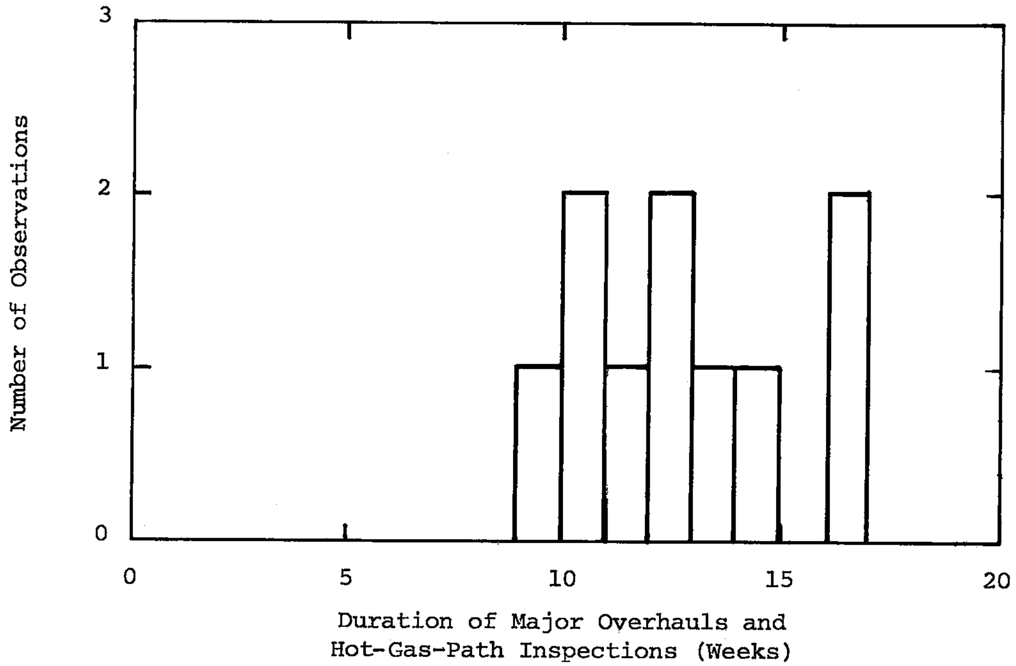

Figure 3-5. Distribution of Major Overhaul Durations (10 Observations)

turbine blading or nozzle repair is penalized with the time required to ship the rotor or nozzle to an off-site repair facility; disassemble, repair, and reassemble the parts; and ship back to the site. This process requires four weeks at least, generally more. Thirty to forty percent of the maintenance downtime is a result of these logistics delays.

The practice at the Wharton Plant is to use this downtime for restoration of seals, bearings, stator vanes, and other parts that can be worked on during this time. The work is scheduled to optimize manpower utilization and have the unit ready for reassembly when the rotor or nozzle assemblies are returned. Use of a spare rotor would require that this parallel work be completed in a much shorter time to take full advantage of the improved availability of major parts . Therefore, smaller parts must be stocked as well, including seals, bearing liners, and transition pieces, and that the entire overhaul be more tightly scheduled. It is safe to assume that spare parts provisioning of turbine rotors would not result in full improvement of the logistics delay but would still have a significant effect. The four-week downtime improvement and $4,000,000 capital costs are rough estimates reflecting the foregoing considerations.

A second factor in maintenance duration is parts modification. In the series of overhauls witnessed in the performance of this project, the second-stage nozzle was replaced with a modified design. The modification required moderate rework of the casing and first-stage shrouds, which required more time than a straight changeout. Turbine technology has continuously improved, and each overhaul affords the opportunity to upgrade the turbine to make use of new developments. The incremental cost of component improvement is minor if the modification is made during scheduled part replacements. Such actions result in a slightly longer maintenance outage but also result in an improved machine that will not require the same frequency of repairs.

The reliability growth achieved in this manner is unique to combustion turbines used as prime movers in utility applications. The manufacturer has designed compatibility into the newer machines in such a way that older machines can take advantage of technology improvements. The equipment can be uprated for performance or reliability as desired, resulting in equipment that improves as it gets older and resists obsolescence. Examples of major modifications of this nature at the Wharton Plant are replacement of the second-stage nozzles and application of coatings to compressor and stator vanes. As discussed in the combustion subsection, reliability growth has been significant here as well, and the process has not been concluded. The process aids the industry as well as the individual user, since the site has been used as a facility for testing modified designs before they are implemented in newly manufactured units.

The third factor affecting maintenance durations for the turbine is the turbine casing bolting. The bolts and dowel pins in the casing horizontal and vertical joints rust, seize, or gall in their holes, and an excessive expenditure of manpower is required to remove them. The current practice is to break several Allen wrenches on a bolt, burn the head off, remove the casing, and work the remainder of the bolt out while waiting for the rotor to be returned. Virtually every kind of anti-seize and rust penetrant has been used during assembly and disassembly with varying degrees of success, all minor. The problem focuses on the use of bolts threaded into blind holes in a casing that reaches high temperatures. The present market offering for this machine utilizes different alloys and platings and employ through studs rather than casing bolts. The advantage of studs is that nuts can be burned off and discarded without damaging the more expensive stud. The work might sound minor, but it generally takes five men five days to remove or burn bolts for casing removal, and then two men ten days to remove burned off bolts and restore casing holes.

FUEL SYSTEM

The RAM characteristics of the fuel system are:

- MTBO - 17,410 hours
- A - .99605
- MDT - 69.1 hours
- Reliability Rank - 17
- Availability Rank - 15
- Maintainability Rank - 12

The fuel system at the Wharton Plant is designed to handle both distillate oil and natural gas, although natural gas is the primary fuel. Overall system reliability and availability is enhanced by preventive maintenance performed during combustion inspections. At these events the fuel nozzles are inspected and restored and the fuel control devices calibrated and functionally tested.

Fuel System Reliability

The fuel system problems are fuel nozzle problems that result in exhaust temperature spread (12 of 14 events). The outages are taken to clean or replace fuel nozzles, correcting the spread and reducing the risk of high-cycle fatigue to the turbine blading. The fatigue occurs as the result of temperature and mechanical loading oscillations at high frequency.

Fuel nozzle problems are limited to pluggage and erosion. The pluggage was generally attributed to foreign material in the fuel system, possibly gasket material. Erosion has occurred consistently as the result of atomizing air velocity and contamination, and efforts continue to eliminate this problem. The efforts focus on removal of particulate matter from the atomizing air and development of fuel nozzles fabricated from erosion-resistant materials. The atomizing air is bled from the main compressor and boosted in an accessory gear-driven rotary blower. Since the unit lacks air filtration and erosive particles are ingested, an atomizing air filter is installed between the main compressor and the atomizing air compressor. The filters are removed every combustion inspection and are found to be dirty. The use of filters has not wholly resolved the erosion problem; hence, further nozzle development is being investigated.

The remainder of the fuel system has proven to be highly reliable. The only significant occurrence reported was seizure of the main accessory gear-driven distillate fuel oil pump, which is provided for dual fuel capability but rarely used. Infrequent use may have contributed to this failure.

Fuel System Availability

The fuel system availability of .99605 is reasonable for a critical system. As mentioned earlier, preventive maintenance efforts have paid off in reliability and availability in this system. To put availability engineering in perspective, if all 22 systems critical to the operation of the combustion turbine had an availability identical to that of the fuel system, the unit availability would be .91661. By the same token, if all systems were as reliable as the fuel system, the unit MTBO would be 791.4 hours. The availability improvement would be 16.15 percentage points. The reliability improvement would be a 262.4-hour increase in MTBF. The new availability would probably be highly regarded for utility applications. A mean time between failures of 791 hours will not be perceived as favorably. The requirement for a large number of systems to function concurrently places extremely high demands on the individual components and systems. The fuel system, if examined alone, appears to be highly reliable and of adequate availability. When examined in the context of unit reliability, it is evident that significant improvement is required to meet the demands of a high-reliability turbine.

Fuel System Maintainability

The fuel system maintenance activities focus on the fuel nozzles. Fuel nozzle maintenance is impaired by the number of piping connections made to each nozzle. These include fuel gas piping, fuel oil piping, atomizing air piping, and water injection piping. The fuel nozzle is a single-bodied integrated piece, all of which must be removed to be serviced. Improved maintainability could be achieved by designing the nozzle with removable subassemblies that did not require removal of all piping to service a particular part.

Fuel system maintainability is also impaired by the tight quarters in which maintenance must be performed. As mentioned earlier, larger compartments and piping systems designed for accessibility would reduce maintenance downtimes.

HYDRAULIC SYSTEM

The RAM characteristics of the hydraulic system are:

- MTBO - 18,749 hours
- A - .99866
- MDT - 25.0 hours
- Reliability Rank - 16
- Availability Rank - 9
- Maintainability Rank - 7

The hydraulic system provides the muscle for control functions, including fuel and inlet guide vane control. The system consists of a shaft-driven hydraulic pump, a motor-driven backup pump, filters, accumulators, and regulators. The problems encountered have been limited to hydraulic line breakage or leaks, low pressure due to dirty filters, and failed servo valves. This system is similar to the fuel system inasmuch as it is critical and generally perceived as being reliable. The system is configured with conventional hydraulic components, and the failure modes have been related more to dirty oil and piping leaks than to component failures. The system availability of .99866 would support a unit availability of .9709, well above a .95 goal. Failures are infrequent and restoration quickly accomplished. One complaint was registered against the hydraulic system maintainability. Most of the system components are located in the top of the lube oil reservoir. Work on the system must be accomplished through a hatch. This location also has benefits, especially in the event of a leak.

COMBUSTION TURBINE/GENERATOR SYSTEM

The RAM characteristics of the combustion turbine/generator system are:

- MTBO - 20,311 hours
- A - .98222
- MDT - 367.9 hours
- Reliability Rank - 15
- Availability Rank - 19
- Maintainability Rank - 19

The generator is an air-cooled, three-phase, wye-connected, 13,800-volt 2-pole machine run at 3600 rpm. It incorporates inertial air separation and air filtration for generator cooling.

The system is characterized by good reliability; however, incidents that do occur are major and require extensive shutdowns. Preventive maintenance is performed concurrently with turbine maintenance, limiting the impact of generator unavailability. The data presented here reflect nonconcurrent maintenance.

Generator System Reliability

The problems encountered with the generator are field grounds and vibration bar sparking. The field grounds are a generic problem related to the number of start/stop cycles and involve fatigue of the copper bars as they exit the field slots. The problem is being addressed by a field exchange program that replaces failed generator fields with remanufactured fields of an improved design. Five of the eight original fields have failed; none of the exchange fields have failed.

The vibrating bar sparking problem, a recently encountered one related to deterioration of the stator bar insulation within the stator slots, is considerably more significant. The deterioration is a result of mechanical vibration of the bars as the field poles pass each bar. It may be also related to movement as the result of loosening wedges installed to hold the bars in the slots.

The stator bars are coated with a semiconductive paint. The purpose is to conduct and discharge to ground (the stator frame) any corona currents surrounding the bar. If the bar were in intimate contact with the slot, this would be achieved. However, there will always be a clearance between the slot and the bar; as a result, the bar has room to vibrate. The vibration can result in bar sparking, or discharge of the corona, at high frequency. Although a relatively benign sparking, it can eventually result in degradation of the outer bar insulation, which exposes the more sensitive inner insulation. Degradation of this inner insulation may result in a phase-to-ground short within the stator frame.

A possible contributor to this problem is lube oil leaks at the generator bearings. Oil in the generator may reduce the friction between bar and slot and bar and support wedges, resulting in greater movement than if oil were not present. It is also possible for the oil to affect the support function of the bar wedges.

A resolution to this problem is the use of "ripple spring" shims, semiconductive plastic shim stock formed with ripples in it (Figure 3-6). The shims can be inserted between the stator bar and the slot to hold the bar in place and provide a grounding mechanism. These shims should be added only prior to degradation of the outer armor, because they are slid into position. If the armor has already deteriorated, insertion of the shim may cause more damage, insulation bunching, and a partially installed ripple spring.

Other failures of the generator were failure of an auxiliary switch on the main generator breaker and a ground in the excitation system wiring. Each event occurred only once.

Figures 3-7 and 3-8 are photographs of stator bars removed from one unit. The outer armor's degradation is visible in these pictures. Figure 3-9 is a photograph of the generator with the field removed showing the bars in their slots.

Another problem affecting reliability is the open-cycle air cooling provided on these generators. Even with inertial air separation, significant amounts of dirt, oil vapor, and moisture are introduced into the generator. This can cause insulation degradation as well as cooling disruption and subsequent overheating. Air-cooled generators are certainly more appropriate to peaking applications than base-load duty.

Generator Availability

The generator availability is .98222, a value that will decrease over the next five years as the units are removed from service and the insulation of the stator windings is restored. This restoration process is an extensive one with significant availability penalties. It will be performed concurrently with other maintenance when possible, but its duration is such that unavailability should increase.

There are no shortcuts to generator maintenance; it is the electrical equivalent of major overhauls. Installation of ripple springs and use of closed-cooling-cycle generators would benefit other users. More details of the generator maintenance are included in the following subsection.

Generator Maintainability

The generator mean downtime of 367.9 hours reflects the time required to remove and replace the generator field. This downtime is not representative of stator bar

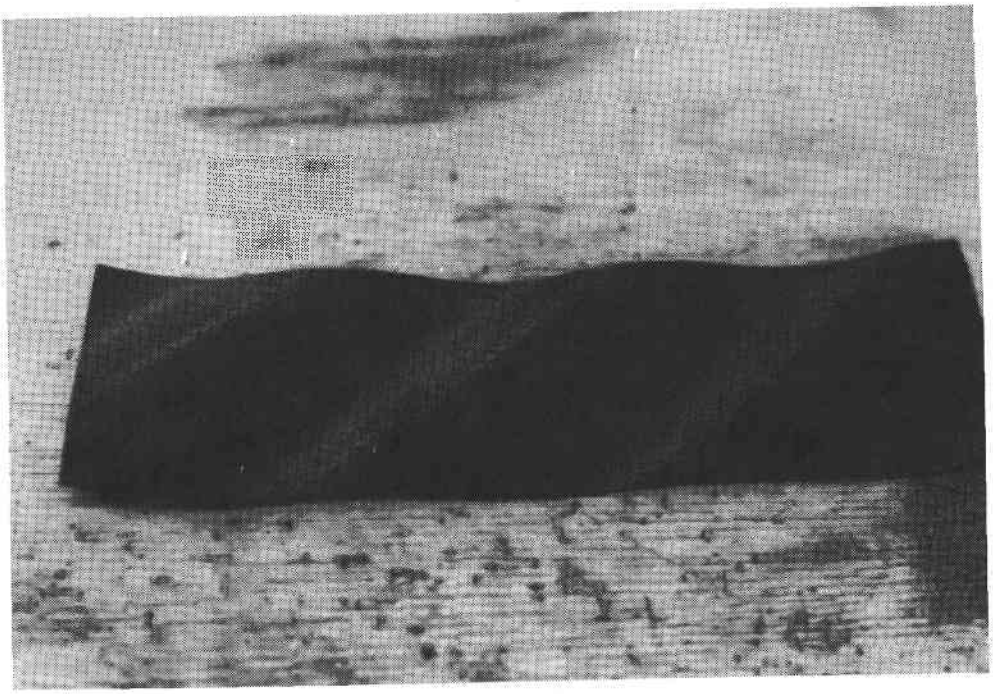

Figure 3-6. Generator Stator Bar Ripple Spring

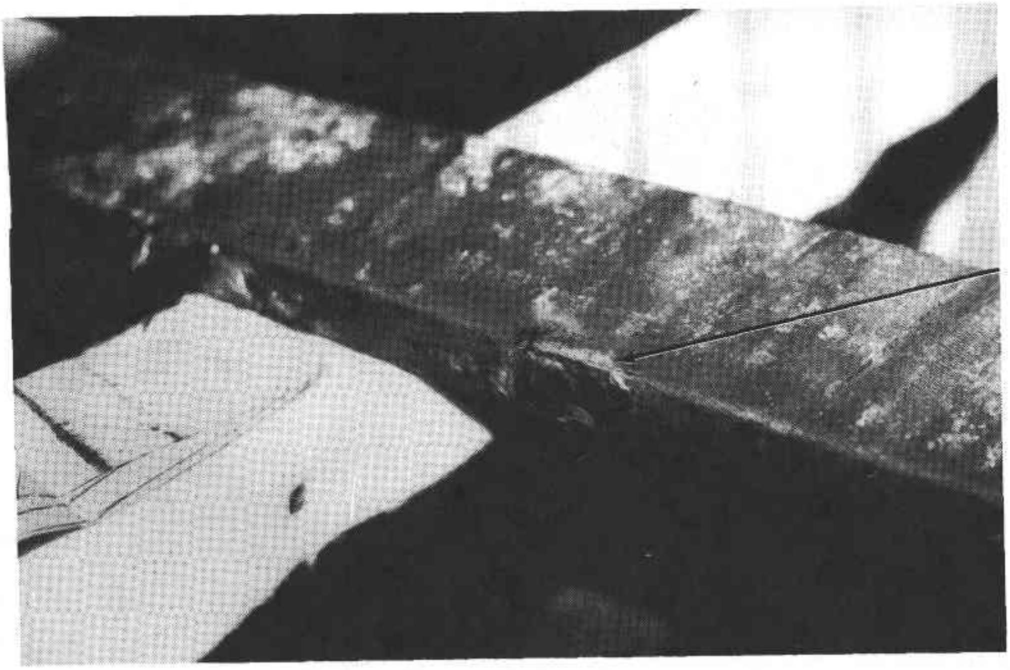

Figure 3-7. Generator Stator Bar Showing Affected Insulation

Figure 3-8. Degraded Stator Bar Insulation

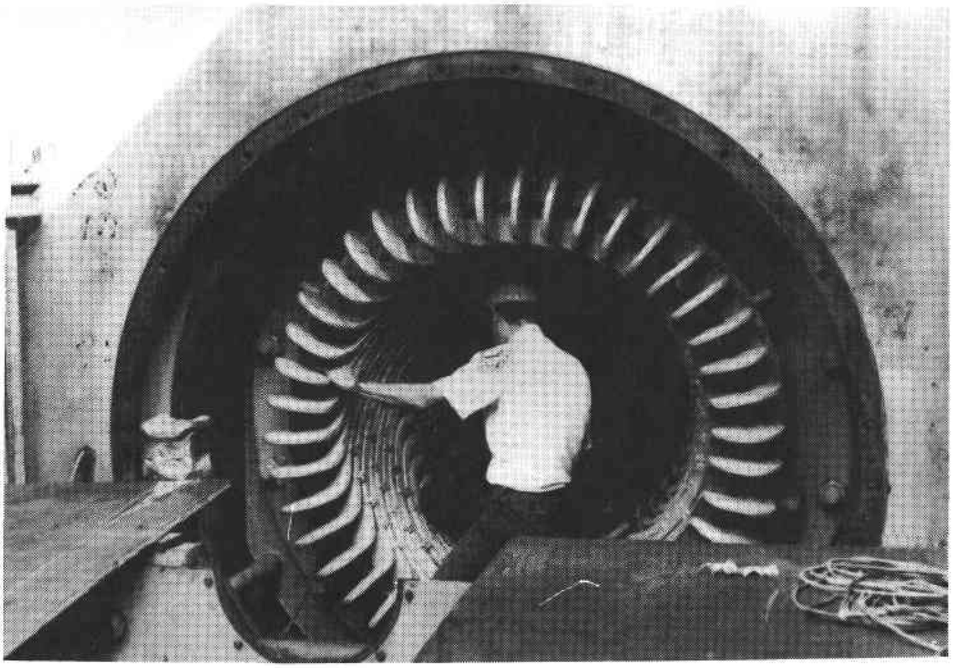

Figure 3-9. Generator End View

maintenance, the duration of which is closer to 1000 hours. Both durations are representative of active work time, not administrative or logistics delay, because extensive work is required to disassemble, inspect, repair, and reassemble generators.

A generator is a good example of equipment design that must balance maintainability with functional requirements. Only one aspect of the design that is not a functional requirement is undesirable: the use of the generator end for the turning gear. Newer units integrate the turning gear with the accessory gear. The turning gear then does not have to be removed for generator field removal. Except for that problem, field removal is straightforward, as the MDT would indicate.

Maintenance of stator bars is not so easily accomplished. Figure 3-10 is a photograph of the stator bar and turns in the process of disassembly. The close proximity of 13,800 volts to ground results in extreme insulating requirements. The bars are fabricated from copper strands for strength, fatigue resistance, and connection quality. Removal of a stator bar for inspection requires stripping the insulation, unbrazing the end turns, and removing that bar, as well as several adjacent to it. These requirements would be acceptable if it were possible to identify the suspect bars prior to disassembly. Two problems are encountered. The first is that it is not possible to inspect the bar insulation within the slot, even with a borescope without removing the bars. Figure 3-11 is a photograph of a bar removed from one unit. The white areas are those affected by vibrating bar sparking. The dark areas are relatively unaffected zones. The affected areas are those with contact to the stator frame. The black lines are gaps in the stator frame used for cooling air passages. When a borescope inspection is performed, the borescope is inserted up the passage and the insulation on the bar is viewed. All that is evident to the inspector is the dark unaffected line. The white affected zones immediately adjacent to the black lines are not visible through a borescope.

Isolating one or several affected bars is not particularly important in any case, because if one bar has failed or is showing signs of failure, the other bars are most likely affected as well, and the incremental cost of restoring all bars once repairs are started is well worth the avoided risk of a repeat failure.

It is important, however, to be able to identify the most severely affected generator if a problem like vibrating bar sparking is identified as prevalent, because unrepaired insulation may eventually result in a phase-to-ground short. If the short is minor and the protective relaying detects it and trips the unit off line in

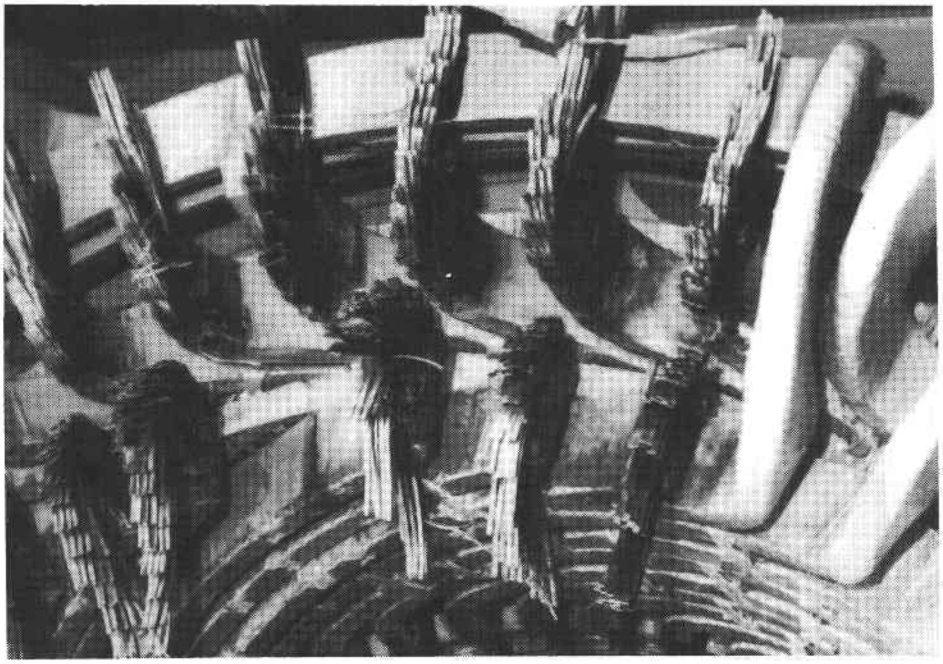

Figure 3-10. Generator End Turn Strands

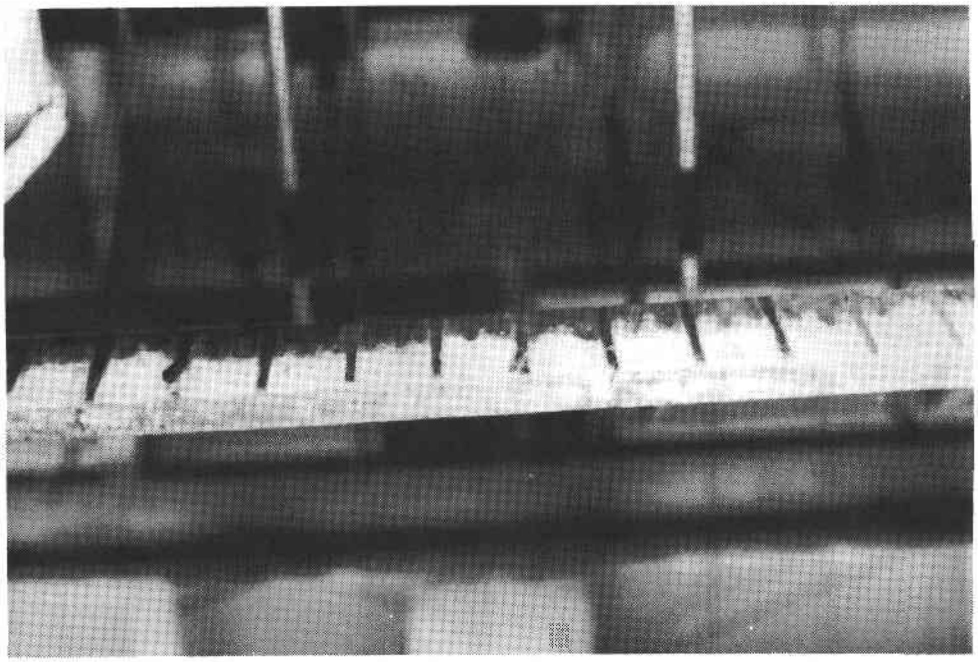

Figure 3-11. Generator Stator Bar Showing Effect of Vibrating Bar Sparking (White areas are affected regions; black lines correspond to cooling air passages)

time, damage to the stator frame may be avoided. However, if the short is not minor, or protective devices do not act quickly enough, major damage can occur to the stator frame, significantly increasing repair costs and durations. Thus it is important to be able to identify which generator on site has the most seriously degraded insulation and thus the highest probability of failure. That generator would be the candidate for immediate maintenance. However, the only current means of determining the extent of sparking is visual examination.

It may be possible to identify machines affected by bar sparking by the use of radio frequency (RF) monitoring of the neutral bus as developed by EPRI for other problem areas. Briefly, RF monitoring examines minute currents in the neutral bus at the high frequencies common in electrical discharge. This phenomenon is familiar to anyone who has an automobile without spark-suppression wiring. It is conceivable that RF monitoring with each generator on line may identify those machines with the most sparking, which would be the machines most likely to fail. Although this monitoring technique has proved effective in detecting broken strand sparking in end turns, it is not known whether it would be effective in detecting vibrating bar sparking.

FIRE DETECTION SYSTEM

The RAM characteristics of the fire detection system are:

- MTBO - 23,360 hours
- A - .99891
- MDT - 25.4 hours
- Reliability Rank - 14
- Availability Rank - 7
- Maintainability Rank - 8

Failures of the fire detection system were false indications of fire, not inability to detect or extinguish fires. The fire detection system consists of electrical fire (heat) detectors and a low-pressure CO_2 system. System failures were traced to failed detectors or shorted or burned wiring, all due to hostile environments. These problems were reportedly alleviated somewhat through installation of the off-base turbine compartment vent fan.

A limit switch located in the load compartment that indicates a load tunnel damper switch has failed on three occasions, tripping the unit. The failure mode in this instance was, again, hostile environments.

Restoration occurs relatively quickly, in 25.4 hours. There are complaints about difficulty in isolating the failed detector when one does fail, and there are criticisms that fire protection system grounds can disrupt other control or protection circuits.

COMBUSTION TURBINE ELECTRICAL SYSTEM

The RAM characteristics of the combustion turbine electrical system are:

- MTBO - 24,167 hours
- A - .99814
- MDT - 45.0 hours
- Reliability Rank - 13
- Availability Rank - 13
- Maintainability Rank - 11

The combustion turbine electrical system consists of the 13.8 kV bus duct from the generator, the 13.8 kV-to-480 V auxiliary power transformers, the 480 V motor control center, and 125 Vdc power system. Reported failures included:

- 480 volt transformer failures, unidentified (3 events)
- 480 volt motor control center problem, not identified (2 events)
- 13.8 kV-to-138 kV transformer problem, not identified (1 event)
- 13.8 kV bus duct phase-to-ground failure (1 event)

The only problem that could be reasonably labeled with a cause was the bus duct failure, which resulted from cracked bar insulation and possibly water leaking into the bus duct itself. The failure contributed to generator problems in that one phase migrated during the fault. This generator was later removed from service with a phase-to-ground short indication.

COOLING WATER SYSTEM

The RAM characteristics of the cooling water system are:

- MTBO - 27,081 hours
- A - .99848
- MDT - 41.3 hours
- Reliability Rank - 12
- Availability Rank - 11
- Maintainability Rank - 9

The cooling water system is an on-base closed system used to cool the lubricating oil and the turbine support legs. The water pump is accessory gearbox-driven, the cooling fan is motor-driven, and the air-to-water coolers are fin tube radiators.

Of a total of nine events, six were failures of the fan motor bearings. This is a large, vertically mounted fan generally inaccessible for lubrication, possibly contributing to the root cause. One failure of the water pump seal was reported, and the system was flushed to correct inadequate cooling in one instance.

LOAD SECTION

The RAM characteristics of the load section are:

- MTBO = 34,280 hours
- A = .98839
- MDT = 409.0 hours
- Reliability Rank - 11
- Availability Rank - 18
- Maintainability Rank - 20

The load section consists primarily of the accessory gearbox, for which seven events were reported. Five events were failed gearbox bearings, one event was two failed gears, and one event was an oil leak. The gearbox bearing problems were on the #1 shaft thrust bearing and were reported as wiped thrust or journal bearings. One incident was witnessed: the bearing had wiped, but with no indication of heat or vibration, the unit was left on line. Thrust wear continued until the bearing liner was consumed, and the thrust collar began wearing into the gearbox casing. The failure was not detected until the unit would not start, because the starting clutch limit switch was not making up.

Two factors may contribute to these failures. One is normal wear, which, if not detected by inspections, can result in bearing and shaft failure. The other factor is the accessory coupling's not "floating" to compensate for turbine rotor growth. This can occur if the coupling's small amount of oil leaks out and the unit is shut down for an extended period of time, such as for an inspection or maintenance. If the coupling freezes up, excessive thrust can be transmitted to the gearbox thrust bearing. Annual coupling inspections (every other combustion inspection) should prevent this occurrence. It would also be advisable to inspect the gearbox bearing at every hot-gas-path inspection (20,000 hours).

The system's availability is impaired as a result of the long outages. Although some portion of the time is logistics delay, the gearbox is located in a small and very crowded compartment and maintenance is extremely difficult, explaining in part why more inspections are not made. Both reliability and availability could be significantly improved by means of a larger compartment with minor lifting provisions for handling the gearbox cover.

LUBRICATING OIL SYSTEM

The RAM characteristics of the lubricating oil system are:

- MTBO - 34,820 hours
- A - .99990
- MDT - 22.5 hours
- Reliability Rank - 10
- Availability Rank - 1
- Maintainability Rank - 5

The lubricating oil system consists of a 2000-gallon oil reservoir, an accessory gear-driven lube oil pump, ac and dc motor-driven backup pumps, water-to-oil heat exchangers, paper pleated filters, and an electrostatic precipitator to return oil vapors to the reservoir.

The main problems encountered were pump seal leaks and piping leaks, but even these were only three events. Three instances of lube oil high temperature trips were traced back to the cooling water system. The lubricating oil system at Wharton must be considered reliable, and it is the leader in system availability. It may be a contributor to bearing leaks as the result of high tank pressure, but that is speculation at this time.

INLET SECTION

The RAM characteristics of the inlet section are:

- MTBO - 40,622 hours
- A - .99967
- MDT - 14.0
- Reliability Rank - 9
- Availability Rank - 5
- Maintainability Rank - 2

The inlet section consists of the inlet duct, inlet silencers, plenum, and inlet guide vane. There are no inlet air filters or inertial separators.

Problems reported were limited to inlet guide vane (IGV) malfunction or oscillation, which were generally attributable to other systems (controls, hydraulic servo valves) but were reported as IGV problems. Unreported problems included rusting of an inlet silencer fabricated from "muffler" steel, resulting in compressor ingestion of rust particles. This is blamed for compressor erosion, as well as atomizing air erosion of fuel nozzle tips. The offending material was removed, but erosion still occurs.

COOLING AND SEALING AIR SYSTEMS

The RAM characteristics of the cooling and sealing air systems are:

- MTBO - 48,747 hours
- A - .99984
- MDT - 7.6 hours
- Reliability Rank - 8
- Availability Rank - 2
- Maintainability Rank - 1

The cooling and sealing air systems consist of the compressor bleeds and associated piping and parts for nozzle, blading, and wheel cooling and sealing. Also included in the system is the compressor bleed valve used for compressor surge protection during startup and shutdown.

Reported problems are limited to the compressor bleed valve, and no problems resulted in compressor surge. The primary difficulties were associated with the hostile environment, because it affected the bleed valve limit switches and the bleed valve solenoid. Burned switches, contacts, and wiring were the predominant problems.

ATOMIZING AIR SYSTEM

The RAM characteristics of the atomizing air system are:

- MTBO - 48,747 hours
- A - .99831
- MDT - 82.4 hours
- Reliability Rank - 7
- Availability Rank - 12
- Maintainability Rank - 15

The atomizing air system provides air for fuel atomization to assure complete and smoke-free combustion. The air is bled off from the compressor discharge, cooled in an air-to-air cooler, filtered, and boosted with an accessory shaft-driven rotary lobe axial blower. Piping is stainless steel.

Problems were limited to the atomizing air compressor bearing and seal failure and piping leaks, for a total of five events (two bearing/seal failures). This is excellent reliability considering the operating conditions. The system is still hampered by erosion, but these problems are related more to the lack of air filtration in the inlet. Air filtration, provided after the air-to-air cooler, was added as a modification. Nozzle erosion is still present.

EXHAUST SYSTEM

The RAM characteristis of the exhaust system are:

- MTBO - 60,933 hours
- A - .99881
- MDT - 72.5 hours
- Reliability Rank - 6
- Availability Rank - 8
- Maintainability Rank - 14

The exhaust section consists of the plenum, diffuser, frame, and exhaust duct. The duct itself is fabricated with a carbon steel outer box, insulation, and a stainless steel inner liner.

Reliability problems were limited to exhaust leaks in the diffuser, which created excessive temperature in the load and #3 bearing compartments. These leaks occur as the result of distortion of the diffuser, which is drastic enough to stretch the bolts at the diffuser horizontal joint. Although only four events were reported and charged directly to the exhaust system, it is likely that numerous other failures, including thermocouple wiring failures, fire protection failures, and limit switch failures, can be traced back to exhaust leaking into compartments.

Two exhaust duct explosions occurred; however, they were the result of combustion or control system malfunctions. Other failures within the exhaust system occurred, primarily expansion joint failures, inner liner failures, and migration of insulation to the HRSG, where it fouls the fin tubes. Since these problems did not result in outages, they are not discussed in this section.

WATER INJECTION SYSTEM

The RAM characteristics of the water injection system are:

- MTBO - 60,934 hours
- A - .99929
- MDT - 43.0 hours
- Reliability Rank - 5

- Availability Rank - 6
- Maintainability Rank - 10

Demineralized water is pumped from storage tanks by high-pressure centrifugal pumps, flow-regulated, and injected as a mist in the combustion liner through the fuel nozzle to limit thermal fixation of combustion air nitrogen.

Only four outage-causing events were reported for the water injection system: two leaks, one control problem, and one broken nozzle.

Water injection, although a reliable system, creates unreliability in the combustion system by increasing dynamic pressure oscillations. This results in premature liner and transition piece failure. There is also indication of carryover of salts; however, there is no evidence that this has caused corrosion in the turbine.

TURNING GEAR SYSTEM

The RAM characteristics of the turning gear system are:

- MTBO - 60,933 hours
- A - .99863
- MDT - 83.4 hours
- Reliability Rank - 4
- Availability Rank - 10
- Maintainability Rank - 16

The turning gear system consists of an electric motor gear reduced to turn the generator rotor through a jaw clutch.

The turning gear has provided good service, which might be expected from baseloaded units, in which it is infrequently used. Problems have been limited to two gear problems, one solenoid failure, one unidentified leak, and jaw clutch repairs.

COUPLINGS

The RAM characteristics of the couplings are:

- MTBO - 81,245 hours
- A - .99973

- MDT - 22.0 hours
- Reliability Rank - 3
- Availability Rank - 4
- Maintainability Rank - 4

Two couplings are reported on: the main turbine generator coupling, which is a rigid hollow torque tube; and the accessory gearbox coupling, which is flexible splined coupling with axial float.

No main coupling failures were reported. Three accessory coupling events were reported; these involved high vibration at the #1 turbine bearing as the result of a dry coupling. The coupling hubs require a small amount of lubricating oil, which is sealed from leakage with an O ring. It will leak out eventually, however, and may cause vibration problems. It is possible that a dry coupling may also "freeze," resulting in loss of axial float required to compensate for turbine rotor growth.

STARTING SYSTEM

The RAM characteristics of the starting system are:

- MTBO - 121,867 hours
- A - .99981
- MDT - 23.7 hours
- Reliability Rank - 2
- Availability Rank - 3
- Maintainability Rank - 6

The starting system consists of a 900 horsepower 4160 volt electric motor and a torque converter, which are used to bring the turbine up to self-sustaining speed.

Only two events were reported -- one failure of the dump solenoid and one failure of the torque converter. The root cause of the torque converter failure is not known.

Torque converter and start motor reliability is a function of the number of start cycles, not the number of fired hours. For reference, the average number of starts per unit for these units is 406. Maintainability problems are the same as for the accessory gearbox: the limited space and lack of lifting provisions makes removal and reinstallation of the torque convertor very cumbersome.

COMPRESSOR SECTION

The RAM characteristics of the compressor section are:

- MTBO - 243,735 hours
- A - .99794
- MDT - 504 hours
- Reliability Rank - 1
- Availability Rank - 14
- Maintainability Rank - 21

The compressor section is a 17-stage axial compressor that operates at 3600 rpm. It has been the most reliable piece of equipment during the audit period, with only one reported outage -- to correct an air leak from the high-pressure compressor casing joint.

The compressor suffers from extensive fouling and erosion to a lesser extent. Some corrosive pitting was in evidence during recent overhauls. The erosion and fouling are the result of ambient air quality and #1 bearing oil leakage. Fouling and corrosion concentrated on the initial stages of the compressor; erosion is slightly more evident in the later stages. Figure 3-12 is a photograph of the initial stages of one machine.

This fouling may be alleviated somewhat through the use of coated compressor blading and more frequent water washing. Coated blading will be evaluated on at least one unit. The best solution to fouling is prevention through air filtration and elimination of oil leaks, which can be accomplished as a retrofit, but not without problems. Air filters are large structures, and they should be integrated into the plant layout. Compressor fouling is an expensive problem when fuel costs are calculated for lost efficiency, a factor that should be considered for all new installations of baseloaded or intermediate duty equipment.

Maintainability is acceptable for a major component such as this component. Because of the lower casing temperatures, the casing bolt seizing problem is not as prevalent as it is on the turbine casings.

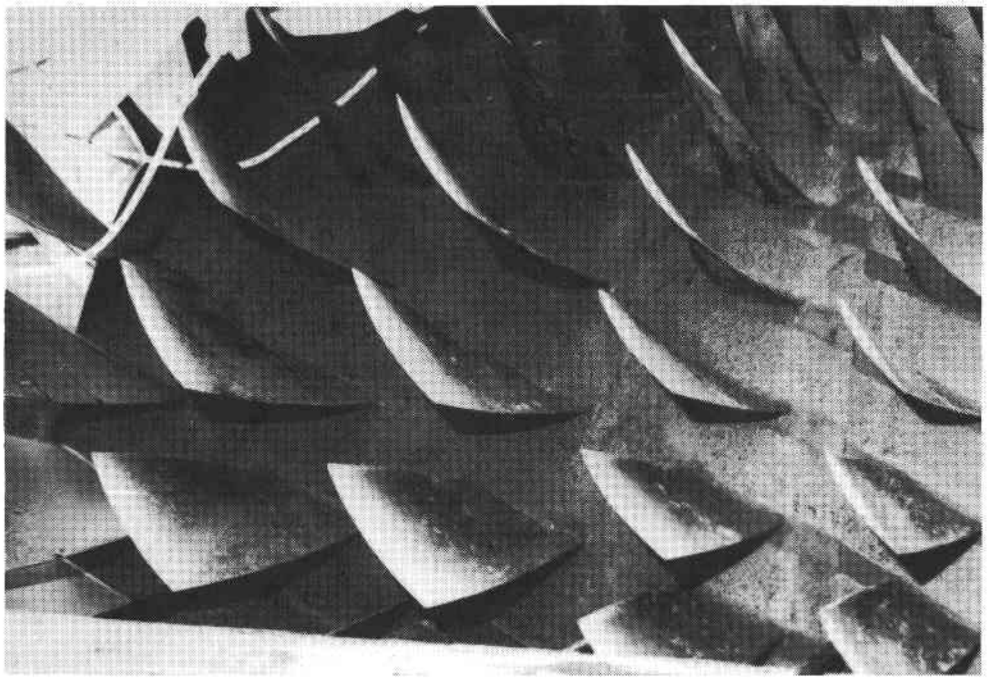

Figure 3-12. Compressor Blading Showing Fouling

HEAT RECOVERY STEAM GENERATOR

The heat recovery steam generator (HRSG) has a mean time between outages of 2,437 hours, a mean downtime of 63.9 hours, and a system availability of .97445. The system consists of eight drum-type unfired heat recovery steam generators and the associated circulating water pumps, piping, dampers, duct work, and valves. The steam generators are rated at 800 psig, 855°F steam with a flow of 240,000 pounds per hour. The boiler pressure is controlled by the steam turbine control valve (initial pressure controller) and is a function of the number of HRSGs on line. The feedwater inlet conditions are 1500 psig and 110°F. The HRSG is treated as a system; this section is divided into discussions of the four problem areas.

HRSG Tube Leaks

The most prevalent failure mode for the HRSGs is economizer tube leaks, which accounted for 63 of 100 reported events and are more prevalent than these numbers indicate. Tube leaks that resulted in or extended an outage were included; tube leaks that did not cause an outage or were repaired as concurrent maintenance were not included in the data.

The leaks are concentrated in the economizer section and occur primarily at the socket weld, where U bends are attached to the economizer tubes. Tube repairs have revealed significant loss of metal in the tube as well as in the U bend. This failure mode has been present since startup, although the root cause may have changed. Initial failures were attributed to quality control problems at time of manufacture, including porosity and inadequate penetration.

Figure 3-13 is a plot of fired hours between tube repair outages over the period of this audit. It is quite obvious that the frequency of tube failures is increasing. The data and plant operations were reviewed to determine the root cause of this situation. Metallurgical analysis of tube material was not within the scope of this project and was not performed; as a result there is no hard evidence of the failure mechanism.

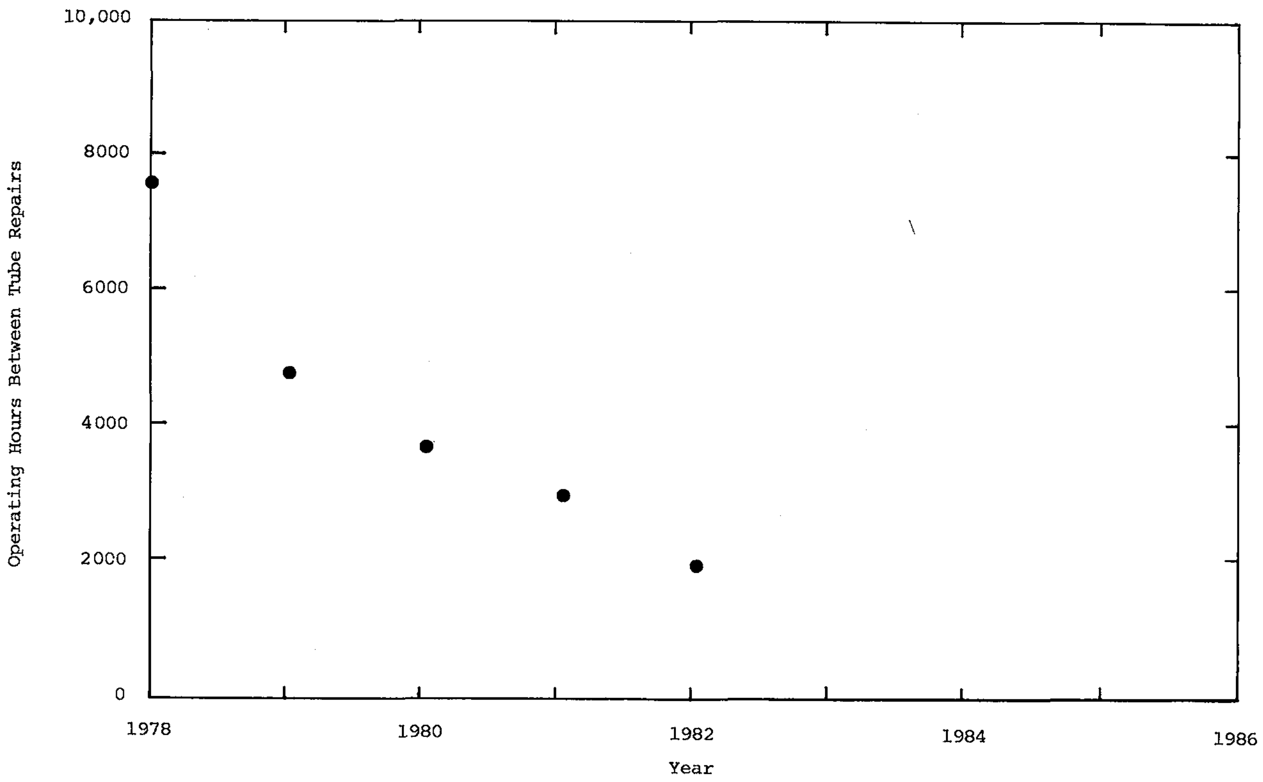

Figure 3-13. Economizer Tube MTBF Plot

Attack occurs on the external surfaces of the tube end turns. The sides of the economizer's end turn compartment have been removed many times on each HRSG and are not watertight. External corrosion occurs during shutdowns and is visible. External corrosion is also possible in operation, because the feedwater inlet temperature is only 110°F.

The design of the economizer may also contribute to localized corrosion, resulting in accelerated pitting attack. The use of socket well fittings creates crevices between the tube and the U bend, which may cause crevice corrosion due to ionization differences between the fluid in the crevice and the fluid in the tube, resulting in metal loss in the area of the weld.

Visual examination confirms this analysis to some extent. Several tube leaks were observed from initiation through repair. They started as small pinhole leaks and progressed over several weeks, increasing in size daily until shutdown was possible. Upon shutdown, the boiler drum was opened and the surface of the drum was found to be coated with a red oxide layer, consistent with oxygen attack. When tubes were removed or repaired, they were visibly thinner; i.e., metal loss had occurred.

As Figure 3-13 indicates, the future is not promising for the economizers at Wharton. The HRSG does incorporate a modular design that is amenable to replacement of the economizer alone.

HRSG Circulating Water Pump

The HRSG circulating water pump seals accounted for 20 outages. When the seals fail, there is significant loss of hot water, which makes operation impossible. No seals failed during the preparation of this report; thus none were available for examination.

The circulating water pump is a vertical low-speed centrifugal pump mounted at the bottom of the downcomer from the steam drum. There are no mud drums on this forced-circulation HRSG, and the pump is located at the low point of the HRSG. Possible causes of seal failures include contamination of the seal cooling water, loss of cooling water, or seal contamination during shutdown.

Feedwater Control System

Twelve outages attributable to the feedwater control system were reported. They were relatively minor problems involving erratic control of feedwater flow and drum-level indication or protection devices. Drum-level control is a significant problem at startup because of the small drum size and rapid "swelling" when heat is added to the HRSG. This problem did not result in many outages, however, since the dampers would be closed, the drum level dropped, and startup attempted again. Operator technique has managed to overcome these problems.

HRSG Dampers

Two dampers are included in the HRSG system. The bypass damper allows operation in the simple-cycle mode and is used during startup. The isolation damper isolates the combustion turbine from the HRSG and, again, is used during startup. Five events were recorded, all related to binding of dampers. A more significant problem is heat loss through the bypass damper, which is apparent with a unit on line. This loss may account for 1% or more of the heat input to the HRSG, at significant fuel cost. The ability to operate the combustion turbines in simple cycle is the benefit of having dampers. This benefit is of questionable value, for these units in simple cycle have a much greater heat rate and would be run only when all other generating sources are on line.

The use of dampers provides greater flexibility of operation during startup. Damper position can be modulated to permit rapid combustion turbine load ramping without exceeding thermal ramping limits of the HRSG. If dampers are not used, a slower ramp rate might be imposed on the combustion turbine. The effect of an extended startup may be insignificant to a baseloaded plant, but could be significant to the economics of cycling units. In addition, the use of dampers results in heat loss and higher heat rates; however, it also provides increased flexibility of operation, a feature that is generally not used at Wharton. It is a utility and site-specific question whether the increased flexibility is worth the heat loss penalty.

STEAM SYSTEM

The steam system consists of the main steam piping, steam turbine/generator, condenser, and steam-side balance-of-plant equipments. These elements are discussed separately.

Steam Turbine/Generator

The RAM characteristics of the steam turbine/generator are:

- MTBO - 8427 hours
- A - .99485
- MDT - 43.6 hours

The steam turbine/generator is a 110 MW 3600 rpm single-shaft nonreheat condensing turbine. The only significant outage reported against the steam turbine/generator was failure of the dc lube oil pump. The failure was detected during a test and resulted in an outage only because the pump is the last backup on the lube oil system in the event of ac power loss and it is not prudent to run without the pump. Other minor problems included a control ground, an electrohydraulic control piping leak, power supply trouble, a loss-of-excitation trip, and a vibration problem. None of these events resulted in more than 20 hours of downtime.

Scheduled maintenance for the steam turbine/generator results in a poorer availability than indicated in the data, because the outage reports identify these outages as steam-side annual maintenance, during which time other steam-side maintenance also takes place. In preference to charging the annual inspection to the steam turbine/generator, a separate category, annual inspections, was created.

Annual Inspections

The RAM characteristics associated with annual inspections are:

- MTBO - 11,797 hours
- A - .91300
- MDT - 1,125 hours

Annual inspections are performed to maintain all steam-side equipment, including HRSGs, condenser, steam turbine/generator, boiler feedpumps, condensate pumps, the circulating water system, and any other plant equipments in need of maintenance. The maintenance is preventive, and failures or imminent failures are not reported in the data analyzed.

Steam System Balance-of-Plant (BOP) Equipment

The RAM characteristics of the steam system BOP equipment are:

- MTBO - 2.809 hours
- A - .98337
- MDT - 80.5 hours

The boiler feedpump was responsible for 7 of 22 BOP equipment events. Only one event was major, a failed feedpump motor bearing, while the other six were feedpump trips, lube oil pressure switch failures, and sealing water piping leaks. The failed equipments were quickly restored, but because each plant has only one feedpump, a pump outage brings down the steam turbine, HRSGs, and, for all practical purposes, the combustion turbines.

Six events were charged to the circulating water system, with two pump trips and four expansion joint failures. The expansion joint failures were much more significant than might be expected. The pump is located in a pit at the same elevation as the buried pipe (Figure 3-14). When the expansion joint ruptured, the pit filled up with water, shorting the motor. What does not appear in Figure 3-14 is the circulating water pump for the other unit, which is located in the same pit and was also shorted.

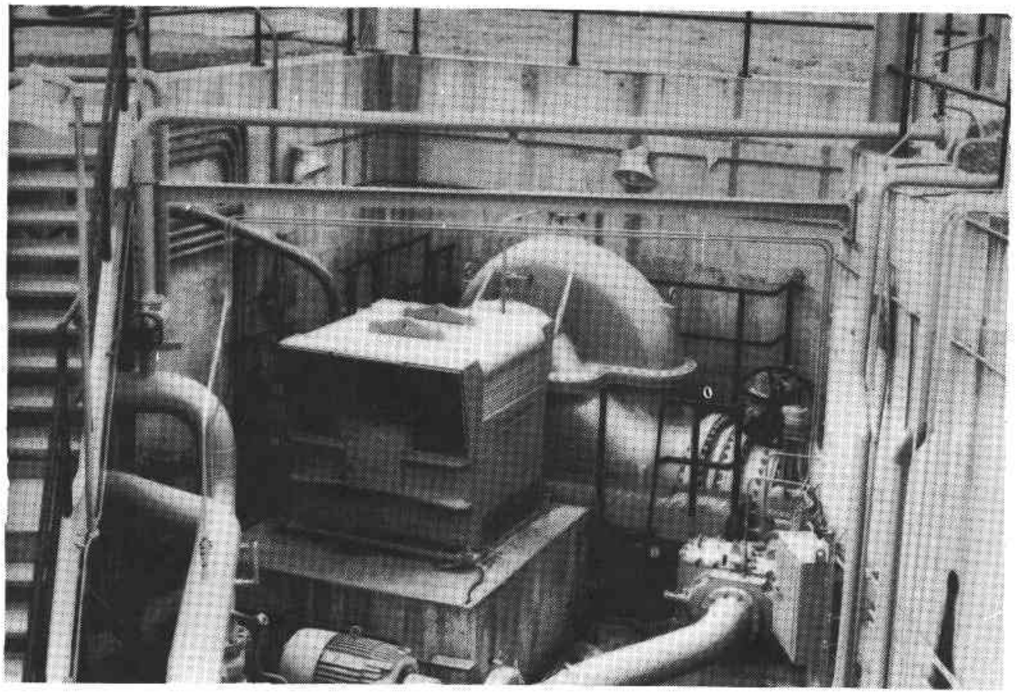

Figure 3-14. Circulating Water Pump Pit (Failure of expansion joint results in submerged motor)

Failure of a relatively inexpensive expansion joint caused two units to trip off line, resulting in a 300-hour outage, essentially poor plant design.

Four events were charged to the condensate pump. There is only one condensate pump, and its failure results in unit shutdown. Two trips, one bearing failure, and one expansion joint failure were reported.

Problems that were not reported as outages but did result in efficiency problems were caused by scale buildup on the water side of condenser tubes. The calcium carbonate scale was significant enough to retard heat transfer severely, but it was substantially removed by chemical cleaning. Plant-designed and -installed equipment provides the necessary chemical control to prevent further scaling.

Notable for the lack of problems they encountered are the vacuum pumps, for which no incidents or outages are recorded. The Nash centrifugal vacuum pumps are both efficient and reliable.

Steam Turbine/BOP Miscellaneous

The RAM characteristics of the steam turbine/generator miscellaneous equipment are:

- MTBO - 9,832 hours
- A - .99814
- MDT - 18.3 hours

This category includes events of unknown or unidentified origin, operator error, and acts of God.

Section 4

CONCLUSIONS

The purpose of the audit described in this report was twofold: (1) to define equipment RAM characteristics and (2) to identify the root causes of failures. The use of outage reports permitted definition of the RAM characteristics of the plant equipments. Evaluation of root causes through visual observations and informal interviews with plant personnel provides insight into failure mechanisms, but root cause identification remains informed speculation.

The following general conclusions resulted from the audit:

- Reporting detail is adequate to provide sufficient data for detailed reliability, availability, and maintainability analyses.
- Analyses results can be used for cost-benefit studies on RAM improvement efforts.
- RAM analyses showed that turbine availability is improving but generator and HRSG availability is deteriorating.
- Second-order and third-order RAM effects are present and may be significant. (Example: false protection trips causing low-cycle fatigue.)
- RAM improvements are incorporated into the plant design at small incremental cost when existing equipment service lives are expended.
- Insight into root causes of failure can be obtained through interviews with plant personnel.

RAM analyses can provide useful data for utility personnel when they are requesting or justifying additional budgets for RAM improvement efforts. Site personnel are aware of the problems and have identified solutions; the RAM analyses provide usable numerical values for quantification of the benefit. This is a major purpose of RAM analyses of existing equipment. Simple analyses performed in this project can be easily duplicated by plant personnel for cost-benefit evaluations.

Specific conclusions concerning the plant equipments are as follows:

- Scheduled maintenance of the turbine and combustion systems account for 65.1% of turbine/generator unavailability.
- The control, protection, and monitoring system is responsible for 50.8% of the unreliability and results in second-order effects on availability (trip-initiated low-cycle fatigue).
- Environmental considerations (atomizing air, water injection) have an impact on equipment reliability.
- Steam system reliability is not much better than combustion turbine reliability (steam system MTBO = 780.8 hours).
- Steam system availability is significantly better than combustion turbine availability (steam system availability = .89153).
- Critical systems (lube oil, cooling and sealing air, fuel system) demonstrate good reliability and availability.

APPENDIX

SYSTEM DATA SHEETS

This appendix consists of data sheets for the systems analyzed in this report. The data sheets, which appear in system alphabetical order, show the following:

- Number of outage-causing events
- Number of operating hours
- Mean time between outages
- Mean downtime
- System availability

A simple system description and a brief discussion of problems encountered are also provided. All data were obtained from HP&L outage reports, and the availability was calculated by using the point estimate of availability.

SYSTEM: ATOMIZING AIR

RAM Characteristics

Number of Outage-Causing Events: 5

Number of Operating Hours: 243,735

Mean Time Between Outages: 48,747 hours

Mean Downtime: 82.4 hours

System Availability: .99831

System Description

The atomizing air system supplies air for fuel atomization in the combustion liner. The compressor is a rotary-lobe axial blower driven by the accessory gearbox through a spline coupling. The atomizing air is taken from a CT compressor discharge bleed, and is cooled and filtered upstream from the compressor. The compressor discharge is piped to the fuel nozzles without subsequent cooling or pressure regulation. Most of the piping is stainless steel.

Problems

Problems included:

- Fuel nozzle erosion is caused by high-velocity air; filters not wholly adequate at improving erosion. Nozzle material changes made with limited success.
- Compressor failure (2 events); bearings and seals failed.
- Piping leaks (3 events); broken welds due to vibration.

SYSTEM: MAIN COMBUSTION TURBINE BEARINGS

RAM Characteristics

Number of Outage-Causing Events: 23

Number of Operating Hours: 243,735

Mean Time Between Outages: 10,597 hours

Mean Downtime: 71.6 hours

System Availability: .99329

System Description

The main turbine bearings system consists of five journal bearings, three on the turbine and two on the generator.

Problems

Problems included:

- Leaks, 21 of 23 events, are especially critical in #3 bearing located in tunnel of exhaust section. Oil leaks result in load tunnel fires (8 events), which can result in major bearing damage if fire cannot be extinguished. Oil leaks in generator contribute to stator armor degradation.
- Wiped bearing failures (2 events) are minor in view of number of operating hours.

SYSTEM: COMBUSTION

RAM Characteristics

Number of Outage-Causing Events: 73 (includes combustion inspections)

Number of Operating Hours: 243,735

Mean Time Between Outages: 3,339 hours

Mean Downtime: 340 hours

System Availability: .90758

System Description

The combustion system consists of 10 combustion cans, 10 transition pieces, all interconnected with crossfire tubes. There are 2 spark plugs and 2 flame detectors included in the system.

Problems

Initial design was characterized by frequent cracking and failure of combustion liners and transition pieces. Current design relies on heavier components and altered design liners, significantly reducing cracking problems. Modifications included flow sleeves, upgraded liners, and heavier crossfire tubes. Failure to fire is not a problem; infrequent temperature spreads are reported.

At least two explosions in the exhaust have occurred, and these are traced back to partial loss of flame and subsequent reestablishment. Flame detector and control modifications are under investigation.

Hardware problems have resulted in a 4000-hour inspection interval, causing a 5% loss of availability for combustion inspections alone. The long-term goal for intervals is 8000 hours.

Water injection for NO_x control is required in Houston. It is the general opinion that this results in excessive combustion "noise," which shortens part lives. Both dry NO_x and "quiet" combustion systems have been tested on site.

SYSTEM: CLEANING

RAM Characteristics

Number of Outage-Causing Events: N/A

Number of Operating Hours: N/A

Mean Time Between Outages: N/A

Mean Downtime: N/A

System Availability: N/A

System Description

There is no cleaning system per se. Compressor fouling does occur, and the compressor is water-washed after every combustion inspection by means of a portable tank/pump assembly and hoses. Cleaning generally takes 24 hours, most of the time used for blanking off atomizing air lines and cooling and sealing air lines, and for restoration upon completion. The cleaning is performed with the unit on "crank" and is effective.

SYSTEM: COUPLINGS

RAM Characteristics

Number of Outage-Causing Events: 3

Number of Operating Hours: 243,735

Mean Time Between Outages: 81,735 hours

Mean Downtime: 22 hours

System Availability: .99973

System Description

The coupling between turbine and generator is a rigid coupling. The accessory gear coupling is a floating coupling designed to accommodate axial growth as well as minor misaligment (floating shaft splined into coupling hubs).

Problems

Two reported events were accessory couplings running dry and causing excessive vibration at the #1 bearing. A small amount of oil is used in the coupling; it will eventually leak out. It is possible that this may result only in high vibration, but it also may damage the thrust bearing in the accessory gear box if the coupling does not "float."

SYSTEM: COMPRESSOR SECTION

RAM Characteristics

Number of Outage-Causing Events: 1

Number of Operating Hours: 243,735

Mean Time Between Outages: 243,735+ hours

Mean Downtime: 504 hours

System Availability: .99794

System Description

The compressor is a 17-stage axial compressor and also includes inlet guide vanes and compressor bleeds.

Problems

One reported event was a casing leak at the high-pressure end of the compressor. Other problems are fouling and erosion. These units are not equipped with air filtration; hence significant deterioration has occurred, impairing performance. Fouling is limited to the low-pressure blading (first seven stages). Erosion affects the entire compressor section, both rotating and stationary blades.

SYSTEM: COOLING AND SEALING AIR SYSTEM

RAM Characteristics

Number of Outage-Causing Events: 5

Number of Operating Hours: 243,735

Mean Time Between Outages: 48,747 hours

Mean Downtime: 7.6 hours

System Availability: .99984

System Description

The cooling and sealing air system consists of compressor bleed air used for nozzle, bucket, wheelspace, and cooling and sealing. The system includes compressor bleed valve used for surge protection on startup.

Problems

Reported problems are limited to compressor bleed valve limit switches causing control system trips. Switches would deteriorate because of heat and vibration of turbine enclosure, resulting in melted, opened, or grounded wiring and contacts. Modified vent fan design has alleviated these problems to some extent.

SYSTEM: COOLING WATER

RAM Characteristics

Number of Outage-Causing Events: 9

Number of Operating Hours: 243,735

Mean Time Between Outages: 27,081 hours

Mean Downtime: 41.3 hours

System Availability: .99848

System Description

Cooling water is supplied to lube oil coolers and turbine support legs. The water is cooled in fin-tube radiators; the water pump is accessory gear-driven. A motor-driven fan provides air flow for cooling.

Problems

Cooling water fan motor failures dominate (6 of 8 events). Vertical orientation of motor and fan may result in highly loaded bearings. Other problems were cooling water pump seal failure (1 event) and system flushing.

SYSTEM: ELECTRICAL

RAM Characteristics

Number of Outage-Causing Events: 12

Number of Operating Hours: 290,000

Mean Time Between Outages: 24,167 hours

Mean Downtime: 45 hours

System Availability: .99814

System Description

The electrical system consists of a dc power supply for controls and backup lube oil pumps plus emergency lighting. 480 Vac 3-phase power is provided for electrical auxiliary and support equipment. 13,800 V 3-phase switchgear and bus ducting, and 13.8-138 kV main power transformers are also included.

Problems

Problems encountered included:

●	13.8 kV to 480 V 3-phase	3 events
●	480 V motor control center short	2 events
●	13.8 kV bus duct shorting	
●	Phase to ground and phase to phase	1 event
●	4160 V start motor breaker problem (not identified)	1 event

The station dc power was originally interconnected between units; this was split. 138 kV inter-ties were separated between Units 3 and 4.

SYSTEM: ENCLOSURES

RAM Characteristics

Number of Outage-Causing Events: 0
Number of Operating Hours: N/A
Mean Time Between Outages: N/A
Mean Downtime: N/A
System Availability: 1.0

System Description

Separate enclosures include accessory base enclosure, turbine enclosure, and generator excitation and switch gear enclosures.

Problems

The turbine compartment vent fan located in the roof of the turbine compartment was subject to overheating and was in the way during turbine maintenance. A modification moved the fan off base and out of the way.

Compartments are generally perceived as being too small to accommodate maintenance. Enclosures must be disassembled for major maintenance activities.

SYSTEM: EXHAUST SECTION

RAM Characteristics

Number of Outage-Causing Events: 4
Number of Operating Hours: 243,735
Mean Time Between Outages: 60,933
Mean Downtime: 72.5 hours
System Availability: .99881

System Description

The exhaust section consists of an exhaust plenum, diffuser, frame, and ducting. The ductwork consists of a stainless steel inner liner, backed with insulation and enclosed by a carbon steel outer liner.

Problems

Reported events are limited to the creation of high temperatures in the load compartment because of exhaust leaks. Expansion joints fail; these are normally repaired at overhauls. Insulation migrating to finned tubes in the HRSG was also reported.

Extensive damage to the exhaust ducts has occurred as the result of explosions. These explosions were caused by combustion system/control system problems involving flame-out and reestablishment of flame.

SYSTEM: FIRE DETECTION/EXTINCTION

RAM Characteristics

Number of Outage-Causing Events: 15

Number of Operating Hours: 350,400

Mean Time Between Outages: 23,360

Mean Downtime: 25.4 hours

System Availability: .99891

System Description

The fire detection system consists of electrical fire detectors strategically located, with a CO_2 low-pressure system incorporating both rapid and extended CO_2 discharge.

Problems

Fire detectors and wiring fail and short out, causing trips. The CO_2 load tunnel damper limit switch fails in similar fashion (heat plus vibration).

SYSTEM: FUEL SYSTEM -- COMBUSTION TURBINE MOUNTED

RAM Characteristics

Number of Outage-Causing Events: 14
Number of Operating Hours: 243,735
Mean Time Between Outages: 17,410 hours
Mean Downtime: 69.1 hours
System Availability: .99605

System Description

The fuel system consists of the fuel nozzles, piping, valves, and devices mounted on the combustion turbine base. Provision for operation with gas or oil is included.

Problems

The major problem identified was exhaust temperature spread resulting from fuel nozzle problems (11 events). One main fuel oil pump shaft sheared (1 event). Leaking check valves in the purge air piping has caused problems.

SYSTEM: HYDRAULIC

RAM Characteristics

Number of Outage-Causing Events: 13
Number of Operating Hours: 243,735
Mean Time Between Outages: 18,749 hours
Mean Downtime: 25 hours
System Availability: .99866

System Description

The hydraulic system consists of the hydraulic pumps, piping, accumulators, regulators, and associated devices used for servo valve control of fuel valves, inlet guide vanes, and center bearing lift.

Problems

Problems encountered included hydraulic lines broken or leaking (6 events); dirty filters, resulting in low pressure (3 events); and failed servo valves (2 events).

SYSTEM: INLET

RAM Characteristics

Number of Outage-Causing Events: 6
Number of Operating Hours: 243,735
Mean Time Between Outages: 40,622 hours
Mean Downtime: 14 hours
System Availability: .99967

System Description

The inlet system consists of inlet ducts with silencers; there is no air filtration. Also included are the inlet guide vanes and the inlet plenum.

Problems

The inlet guide vane malfunctioned (6 events), primarily because of control system/servo valve malfunction. Muffler steel used in silencers rusted, possibly aggravating erosion in the compressor, atomizing air compressor, and fuel nozzles.

SYSTEM: LUBRICATING OIL

RAM Characteristics

Number of Outage-Causing Events: 7
Number of Operating Hours: 243,735
Mean Time Between Outages: 34,820 hours
Mean Downtime: 22.5 hours
System Availability: .99990

System Description

The system consists of a lube oil system with 2000-gallon oil tank, accessory gear-driven pump plus ac backup with dc emergency pump. Oil vapors are returned via an electrostatic precipitator. Cooling is accomplished in a water-to-oil heat exchanger. Paper-pleated lube oil filters are used for oil filtration.

Problems

Problems encountered included leaks in pump seals and piping (3 events) and high lube oil temperature attributable to cooling water system problems. Filter differential cannot be corrected with the unit on line.

SYSTEM: LOAD SECTION

RAM Characteristics

Number of Outage-Causing Events: 7

Number of Operating Hours: 243,735

Mean Time Between Outages: 34,820 hours

Mean Downtime: 409 hours

System Availability: .98839

System Description

The load section consists primarily of the accessory gearbox, driven from the compressor end of the unit through a spline type coupling. The torque converter couples to the #1 accessory gear shaft.

Problems

Problems included failed bearings, primarily the thrust bearing on the #1 shaft (4 events); teeth failed on #1 and #2 shafts (1 event); and oil leaks (2 events).

SYSTEM: TURNING GEAR

RAM Characteristics

Number of Outage-Causing Events: 4

Number of Operating Hours: 243,735

Mean Time Between Outages: 60,933 hours

Mean Downtime: 83.4 hours

System Availability: .99863

System Description

The turning gear is a motor-driven-gear-reduction driving the turbine generator through a jaw clutch on the generator end.

Problems

Problems encountered included gear damage (1 event), solenoid failure (1 event), and jaw clutch wear.

SYSTEM: STARTING SYSTEM

RAM Characteristics

Number of Outage-Causing Events: 2
Number of Operating Hours: 243,735
Mean Time Between Outages: 121,867 hours
Mean Downtime: 23.7 hours
System Availability: .99981

System Description

The starting system consists of a 900 horsepower, 4160 volt electric motor with a hydraulic torque convertor and jaw clutch that couples to the #1 accessory gear shaft.

Problems

Problems encountered included a dump solenoid failure (1 event) and torque convertor trouble (not identified, 1 event).

SYSTEM: TURBINE

RAM Characteristics

Number of Outage-Causing Events: 15
Number of Operating Hours: 243,735
Mean Time Between Outages: 16,249 hours
Mean Downtime: 17,700.5 hours
System Availability: .90175

System Description

The turbine section consists of a three-stage turbine, turbine nozzles, buckets, rotor, and casing.

Problems

Problems included low-cycle fatigue of first-stage nozzles, creep fatigue of second-stage nozzles, and blade cracking in initial design (corrected).

Comments

Events are major or hot-gas-path overhauls involving repair or replacement of turbine nozzles and blading.

SYSTEM: GENERATOR

RAM Characteristics

Number of Outage-Causing Events: 12
Number of Operating Hours: 243,735
Mean Time Between Outages: 20,311 hours
Mean Downtime: 3,679 hours
System Availability: .98222

System Description

The generator is a 13.8 kV, 3-phase, 2-pole, wye-connected, air-cooled generator; it operates at 3600 rpm, incorporates static excitation, and has an air blast generator breaker.

Problems

Problems included generator field ground (5 events) at end of slot, addressed with alloy change, and vibrating bar sparking, resulting in degraded stator bar insulation.

SYSTEM: CONTROLS

RAM Characteristics

Number of Outage-Causing Events: 234
Number of Operating Hours: 243,735
Mean Time Between Outages: 1041.6 hours
Mean Downtime: 19.7 hours
System Availability: .98144

System Description

The control system consists of a solid-state/relay logic controller (Speedtronic), with thermocouple feedback on exhaust temperature.

Problems

Problems included thermocouple failures and grounds, control wiring grounds, vibration pickup failures, and combustion monitor failures.

SYSTEM: HEAT RECOVERY

RAM Characteristics

Number of Outage-Causing Events: 100

Number of Operating Hours: 243,735

Mean Time Between Outages: 2,437 hours

Mean Downtime: 64 hours

System Availability: .97445

System Description

The heat recovery steam generator is a drum-type forced-circulation finned tube boiler, with modular economizer, evaporator, and superheater. The HRSG relies on convection heat transfer only; there are no afterburners. The HRSG generates 800 psig 855°F steam at approximately 240,000 pounds/hour: with feedwater inlet 1500 psig, 110°F water.

Problems

Economizer tube leaks (63 events) at socket weld U-tube bends are the predominant failures.

Circulating water pump seal failures (20 events) in the high-pressure circulating water pump is the second most prevalent problem.

Feedwater control system (12 events) consists of relatively minor problems involving erratic control and level indication/protection and drum-level control problems at startup.

Dampers (5 events) occasionally hang up; bypass damper leakage impairs heat rate and steam turbine output.

SYSTEM: WATER INJECTION

RAM Characteristics

Number of Outage-Causing Events: 4

Number of Operating Hours: 243,735

Mean Time Between Outages: 60,934 hours

Mean Downtime: 43 hours

System Availability: .99929

System Description

The water injection system consists of the centrifugal pumps, piping, and controls required for injection of demineralized water into the combustion chambers.

Problems

Problems include leaks and flow-control problems. More severe second-order effects occur in the combustion system as a result of water-injection-induced combustion pressure oscillations.

SYSTEM: GAS TURBINE MISCELLANEOUS

RAM Characteristics

Number of Outage-Causing Events: 19
Number of Operating Hours: 243,375
Mean Time Between Outages: 12,828 hours
Mean Downtime: 90.6 hours
System Availability: .99299

System Description

This category includes events of unknown or unidentified origin, operator error, and acts of God.

SYSTEM: STEAM-SIDE ANNUAL INSPECTIONS

RAM Characteristics

Number of Outage-Causing Events: 5

Number of Operating Hours: 58,989

Mean Time Between Outages: 11,797 hours

Mean Downtime: 1,125 hours

System Availability: .91300

System Description

This category incorporates annual inspections of steam-side equipment, including steam/turbine generator, HRSG, condenser, and balance-of-plant equipment.

SYSTEM: STEAM TURBINE

RAM Characteristics

Number of Outage-Causing Events: 7

Number of Operating Hours: 58,989

Mean Time Between Outages: 8,427 hours

Mean Downtime: 43.6 hours

System Availability: .99485

System Description

The steam turbine generator is a condensing type, 3600 rpm, 110 MW double-flow straight condensing steam turbine coupled to a hydrogen-cooled, 2-pole, wye-connected generator.

Problems

The only significant problem identified was failure of the dc lube oil pump (1 event).

SYSTEM: BALANCE-OF-PLANT STEAM TURBINE/HRSG

RAM Characteristics

Number of Outage-Causing Events: 21

Number of Operating Hours: 58,989

Mean Time Between Outages: 2,809 hours

Mean Downtime: 80.5 hours

System Availability: .98337

System Description

This system includes conventional steam system BOP, single condensate and boiler feed pumps, and single circulating water pumps.

Problems

The expansion joints on the condensate and circulating water system failed (6 events), a boiler feed pump motor bearing failed (1 event) and one circulating water pump motor shorted due to submergence in water when an expansion joint failed.

SYSTEM: STEAM TURBINE/BOP MISCELLANEOUS

RAM Characteristics

Number of Outage-Causing Events: 6
Number of Operating Hours: 58,989
Mean Time Between Outages: 9,832 hours
Mean Downtime: 18.3 hours
System Availability: .99814

System Description

This section was included to incorporate events with unknown or unidentified causes, operator error, or acts of God.

EPRI AP-3495

Below are five index cards that allow for filing according to the four cross-references in addition to the title of the report. A brief abstract describing the major subject area covered in the report is included on each card.

EPRI

EPRI AP-3495
RP990-7
Final Report
May 1984

Reliability, Availability, and Maintainability Audit of the T. H. Wharton Plant, Units 3 and 4, Houston Lighting and Power

Contractor: ARINC Research Corporation

This first-time reliability audit of a combined-cycle power plant produced a simple, yet effective, methodology for quantifying outage contributions of discrete plant components. These results will provide guidance for future equipment improvement efforts. 122 pp.

EPRI Project Manager: R. Duncan

Cross-References:
1. EPRI AP-3495
2. RP990-7
3. Power Generation Program
4. Combined-Cycle Power Plants

ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, CA 94303 415-855-2000

EPRI AP-3495

EPRI

EPRI AP-3495
RP990-7
Final Report
May 1984

Reliability, Availability, and Maintainability Audit of the T. H. Wharton Plant, Units 3 and 4, Houston Lighting and Power

Contractor: ARINC Research Corporation

This first-time reliability audit of a combined-cycle power plant produced a simple, yet effective, methodology for quantifying outage contributions of discrete plant components. These results will provide guidance for future equipment improvement efforts. 122 pp.

EPRI Project Manager: R. Duncan

Cross-References:
1. EPRI AP-3495
2. RP990-7
3. Power Generation Program
4. Combined-Cycle Power Plants

ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, CA 94303 415-855-2000

RP990-7

EPRI

EPRI AP-3495
RP990-7
Final Report
May 1984

Reliability, Availability, and Maintainability Audit of the T. H. Wharton Plant, Units 3 and 4, Houston Lighting and Power

Contractor: ARINC Research Corporation

This first-time reliability audit of a combined-cycle power plant produced a simple, yet effective, methodology for quantifying outage contributions of discrete plant components. These results will provide guidance for future equipment improvement efforts. 122 pp.

EPRI Project Manager: R. Duncan

Cross-References:
1. EPRI AP-3495
2. RP990-7
3. Power Generation Program
4. Combined-Cycle Power Plants

ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, CA 94303 415-855-2000

POWER GENERATION PROGRAM

EPRI

EPRI AP-3495
RP990-7
Final Report
May 1984

Reliability, Availability, and Maintainability Audit of the T. H. Wharton Plant, Units 3 and 4, Houston Lighting and Power

Contractor: ARINC Research Corporation

This first-time reliability audit of a combined-cycle power plant produced a simple, yet effective, methodology for quantifying outage contributions of discrete plant components. These results will provide guidance for future equipment improvement efforts. 122 pp.

EPRI Project Manager: R. Duncan

Cross-References:
1. EPRI AP-3495
2. RP990-7
3. Power Generation Program
4. Combined-Cycle Power Plants

ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, CA 94303 415-855-2000

COMBINED-CYCLE POWER PLANTS

EPRI

EPRI AP-3495
RP990-7
Final Report
May 1984

Reliability, Availability, and Maintainability Audit of the T. H. Wharton Plant, Units 3 and 4, Houston Lighting and Power

Contractor: ARINC Research Corporation

This first-time reliability audit of a combined-cycle power plant produced a simple, yet effective, methodology for quantifying outage contributions of discrete plant components. These results will provide guidance for future equipment improvement efforts. 122 pp.

EPRI Project Manager: R. Duncan

Cross-References:
1. EPRI AP-3495
2. RP990-7
3. Power Generation Program
4. Combined-Cycle Power Plants

ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, CA 94303 415-855-2000