Reliability and Availability Assessments of Selected Domestic Combined-Cycle Power-Generating Plants

Geg Holt

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Prepared by
ARINC Research Corporation
Annapolis, Maryland

ELECTRIC POWER RESEARCH INSTITUTE

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NOTICE

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ABSTRACT

This report presents the results of reliability and availability assessments performed with the cooperation of seven utilities operating combined-cycle power plants in service since 1974 to evaluate:

- Combined-cycle unit equivalent availability and equivalent forced outage rates
- System and component mean time between failures (MTBF) and mean downtime (MDT)
- Gas turbine reliability correlations with service hours, starting frequency, fuel type, and service factor

A data base was developed for 45 plant components or systems for the period 1978 through 1980; this led to recommendations for improving outage data collection for the purpose of reliability analyses.

In addition reliability, availability, and maintainability prediction models for several commercial combined-cycle plant designs were developed and validated.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This report under RP1319-6, entitled Reliability and Availability Assessments of Selected Domestic Combined-Cycle Power-Generating Plants, reviews and analyzes the plant outage records of seven plants operating 16 combined-cycle units. The data were collected from the cooperating utilities, were reviewed to ensure correctness, and then were analyzed for a variety of reliability and availability characteristics using an EPRI-sponsored computer-based model and other techniques as appropriate. For this study a data base was constructed from the plant outage data. It comprises 45 components for a three-year period from 1978 through 1980. The 16 units studied represent single-shaft and multishaft designs, low- and high-service factors, and oil- and gas-fired units. All of these units provide a total capacity of 2200 MW, which is over one-third of the domestic capacity for combined-cycle electric power generation in 1980.

This project is part of the Power Generation Program and the Reliability Subprogram of the Advanced Power Systems (APS) Division. The Power Generation Program is responsible for monitoring and assisting in the development of a number of electric power generating technologies. An important and near-term development of this program is a high-reliability, high-efficiency combined-cycle combustion turbine unit. The Reliability Subprogram is directed at making reliability and availability assessments of advanced power-generating systems and components to ensure that the most desirable systems and components are selected for construction and to facilitate necessary improvements in system reliability and availability. Reliability and availability models are constructed and used to make these evaluations and to provide a consistent basis for comparisons between systems.

These methods will enhance one of the APS Division's objectives of developing new components or units that are as reliable and available as possible in first commercial application, thereby reducing the problems and costs attendant on improvements made under operating conditions.

PROJECT OBJECTIVES

The study had three significant goals. The first goal was to develop independent assessments of a spectrum of units based on the careful analysis of plant outage records, including a review of these records with plant personnel to ensure accuracy. The measures of reliability and availability developed from the data included equivalent availability, equivalent forced outage rate, mean time between failures (MTBF), and mean time to restore. The second goal was to examine the relationship between reliability and various independent factors such as service hours, number of starts, and fuel type. Finally, it was planned to use the comprehensive and validated data base to evaluate the accuracy of the reliability model that was constructed for this and other predictive purposes.

PROJECT RESULTS

Need to split plants based on duty cycle.

The units analyzed in this study showed considerable variation depending on the service factor for which they were used. On the average, a unit with a high service factor (HSF) showed half as many failures (10 per year) as a low service factor (LSF) unit (20 per year). The difference in MTBF per turbine-fired hours was even greater: 600 hours for the HSF and 77 hours for the LSF. In general, the results agreed closely with those reported by the information gathering, processing, and distributing systems of the turbine manufacturers themselves. Of interest and significance is the fact that the highest MTBF was 1992 hours, a number representing high quality for any kind of power-generating unit.

Some unexpected relationships were confirmed by the analysis. For example, units which are used in baseload applications and which have high-service factors exhibit a more reliable and available performance than those in cycling applications. In 1980 HSF units, averaging 314 hours per start, showed 10 failures per year; LSF units, averaging 24 hours per start, showed 185 failures per year. The availability of each was 0.96 and 0.78 respectively. A somewhat surprising, but not completely definitive, finding is that these results are not dependent on fuel type; this is a conclusion from the analysis, and it should have further verification.

Finally, the model produced results that are in agreement with historical data, differing from the data by only 3%. Additionally, the basic data base developed for this study can be used for future work.

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CONTENTS

Section		Page
1	INTRODUCTION	1-1
	Background	1-1
	Scope	1-3
	Objectives	1-3
	Report Organization	1-4
2	TECHNICAL APPROACH	2-1
	Overview of Utility Data Needs and Analysis Methods	2-1
	The Historical Approach	2-2
	The Analytical or Probabilistic Approach	2-2
	Availability Modeling of Combined-Cycle Units	2-3
	Analysis of Component Outage Data	2-7
	Derivation of Component Failure Rates and Mean Downtimes	2-9
	Sensitivity Analyses	2-9
	Statistical Techniques Applied to Reliability Forecasting	2-10
3	THE RAM DATA BASE AND RESULTS OF AVAILABILITY MODELING	3-1
	Combined-Cycle Unit Descriptions	3-1
	Effectiveness Models	3-2
	Combined-Cycle Unit Performance Trends	3-9
	Reliability and Maintainability Data Base	3-13
	Component Sensitivity Analyses	3-18
4	RESULTS OF COMBUSTION TURBINE DATA ANALYSIS	4-1
	Combustion Turbine Reliability Growth	4-2
	The Effects of Service Factor and Starting Frequency on Combustion Turbine Reliability	4-3
	The Effects of Service Factor and Starting Frequency on Selected Combustion Turbine Components	4-6
5	RELIABILITY DATA PROCESSING PROBLEMS AND NEEDS	5-1
	Data Collection Problems and Deficiencies	5-1
	Reliability and Maintainability Data Requirements	5-2

Section		Page
6	CONCLUSIONS AND RECOMMENDATIONS	6-1
	Availability Modeling from RAM Data	6-1
	Analysis of Combined-Cycle Unit Performance	6-1
	Analysis of Component RAM Data	6-2
	Analysis of Combustion Turbine Reliability Data	6-2
	Major Utility Data Problems and Weaknesses	6-4
7	REFERENCES	7-1
APPENDIX A	TERMS AND DEFINITIONS	A-1
APPENDIX B	STATISTICAL METHODS FOR ANALYZING PLANT RELIABILITY DATA	B-1
APPENDIX C	DEFINING SYSTEM STATES	C-1
APPENDIX D	TURBINE COMPONENT PERFORMANCE STUDY	D-1

ILLUSTRATIONS

Figure		Page
2-1	Data Analysis Methodology	2-5
2-2	Effectiveness Profile	2-7
3-1	STAG 100 Unit Configuration	3-3
3-2	PACE 260 Unit Configuration	3-4
3-3	STAG 400 Unit Configuration	3-5
4-1	Reliability Growth Curve for 13 Gas-Fired HSF Turbines (1979-1980)	4-4
4-2	Effect of Service Factor on CT System Failure Rates	4-8
4-3	Effect of Fired Hours per Start on CT System Failure Rates	4-9
4-4	Effect of Service Factor on Electrical Controls (Other) Failure Rates	4-10
4-5	Effect of Fired Hours per Start on Electrical Controls (Other) Failure Rates	4-11
4-6	Effect of Service Factor on CT Unit, General, Failure Rates	4-12
4-7	Effect of Fired Hours per Start on CT Unit, General, Failure Rates	4-13
4-8	Effect of Service Factor on Lube Oil System Failure Rates	4-14
4-9	Effect of Fired Hours per Start on Lube Oil System Failure Rates	4-15
4-10	Effect of Service Factor on Air System Failure Rates	4-16
4-11	Effect of Fired Hours per Start on Air System Failure Rates	4-17
A-1	Effectiveness Profile	A-5
B-1	Lube Oil System Histogram	B-5
B-2	Use of Weibull Probability Paper to Derive α and β Values	B-7
B-3	Weibull Probability Distribution Function	B-9
B-4	Weibull Cumulative Probability Distribution	B-10
C-1	Multishaft Combined-Cycle Power Plant	C-2

TABLES

Table		Page
2-1	Plant Effectiveness Analysis	2-6
3-1	PACE 260 Unit Availability States by System	3-7
3-2	STAG 400 Unit Availability States by System	3-8
3-3	Performance Summary: HSF Units	3-11
3-4	Performance Summary: LSF Units	3-12
3-5	Composite System/Component RAM Data Summary for HSF Units	3-14
3-6	Composite System/Component RAM Data Summary for LSF Units	3-16
3-7	Component RAM Data Summary for HSF Units (1978-1980)	3-18
3-8	Component RAM Data Summary for LSF Units (1978-1980)	3-19
3-9	Example of Component Ranking Analysis	3-20
4-1	Performance Summary for HSF Unit Turbines, 1978-1980	4-5
4-2	Performance Summary for LSF Unit Turbines, 1978-1980	4-6
4-3	Turbine Performance Summary for 1978, 1979, and 1980	4-7
6-1	Combustion Turbine Performance	6-3
B-1	Calculations of Cumulative Hazard	B-6
C-1	System States for the Example Combined-Cycle Unit	C-4
D-1	Combustion Turbine Component Performance Summary for HSF Unit Turbines, by CT Code	D-3
D-2	Combustion Turbine Component Performance Summary for LSF Unit Turbines, by CT Code	D-7

SUMMARY

Under Research Project (RP) 1319-6, ARINC Research Corporation was selected by the Electric Power Research Institute (EPRI) to perform independent availability assessments of seven domestic utilities operating modern single- and multishaft combined-cycle power units. A single-shaft combined-cycle power unit is a single combustion turbine (CT), generator, and steam turbine power train driven via a common shaft. A multishaft unit is more than one CT system coupled to a single steam turbine. A primary objective of the assessments was to explore the feasibility of using reliability, availability, and maintainability (RAM) analyses techniques to predict availability. Other objectives were as follows:

- Determine what useful data products and information can be derived from RAM analyses.
- Derive a reliability and maintainability data base for key combined-cycle unit components.
- Develop appropriate analytical models for single- and multishaft units, which can be used by the utility industry to predict equivalent availability and equivalent forced outage rate, and will be suitable for design trade-off analyses.
- Assess the adequacy of utility outage data to support RAM analyses.
- Evaluate general performance trends in combined-cycle units used under varying service conditions and with various types of fuels.
- Perform an in-depth reliability assessment of CTs operated during the period 1978 through 1980.

The intent of the assessments was to quantify where possible reliability and availability (R&A) trends in power systems and components. It was not the intent to compare the performance of competing plant designs or products, as many variables influence the performance of these plants. These variables include changes in equipment technology; differences in plant age, service, and operation; maintenance practices; inspection intervals; and size and experience of maintenance crews.

Outage data for seven plants from the period 1978 through 1980 were analyzed by ARINC Research. The plants comprised 16 combined-cycle units -- nine oil-fired units with

low service factors (LSF), and seven gas-fired units with high service factors (HSF). All units were manufactured by the Westinghouse Electric Corporation or the General Electric Company. All were placed in service by the mid-1970s and were considered to be operationally mature. The total capacity of these 16 units was approximately 2200 megawatts (MW), representing more than one-third of the total domestic electric utility industry combined-cycle capability as of 1980. Consequently, these units were considered to be a representative sample of the industry. Outage data for 26 CTs of these units were also analyzed. Fired hours totaled 41,000 for oil-fired CTs and 235,000 for gas-fired CTs.

Outage data records consisted of plant maintenance logs and, when available, data forms used by the plants to serve private and public data processing services. Data were carefully edited and validated with the assistance of plant superintendents and personnel.

The following sections summarize the conclusions and recommendations derived from the RAM data analyses and combined-cycle unit availability assessments.

AVAILABILITY MODELING FROM RAM DATA

Development and application of availability modeling techniques from RAM data led to the following conclusions:

- Plant availability models developed for single- and multishaft units can predict equivalent availabilities within 3 percent of values derived from outage data.
- The assumption that component failure rates are constant over a period of one year is valid for plants that have reached operating maturity.
- Availability models have provided accurate forecasts of unit effectiveness* and can evaluate the effect of changes in component reliability on unit effectiveness.
- Availability models have identified and ranked those key components which, if improved to 100 percent availability, would yield the greatest improvement in unit effectiveness or equivalent forced outage rate (EFOR).

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*The term effectiveness is used herein to indicate the availability of a combined-cycle unit in the absence of scheduled maintenance and is approximately equal to (1 minus equivalent forced outage rate).

On the basis of the assessments, it is recommended that data processing services to the utilities provide RAM data feedback and consider the attributes of availability modeling.

ANALYSIS OF COMBINED-CYCLE UNIT PERFORMANCE

Analysis of outage data from the period 1978 through 1980 for nine oil-fired LSF units and seven gas-fired HSF units led to the following conclusions:

- Average effectiveness values for HSF and LSF units were 92 percent and 72 percent, respectively.
- Mean values of HSF unit effectiveness improved from 87.2 percent in 1978 to 95.6 percent in 1980.
- Mean values of HSF unit EFOR (calculated directly from outage data) improved from 11.9 percent in 1978 to 3.4 percent in 1980.
- Mean values of LSF and HSF unit equivalent availability were nearly equal (LSF units have more reserve standby time, which tends to inflate their equivalent availability).
- Mean values of LSF and HSF unit equivalent availability improved over the period; the best availability (87.6 percent) was achieved for HSF units in 1980.
- Mean LSF unit effectiveness declined significantly in 1980.

ANALYSIS OF COMPONENT RAM DATA

The following conclusions resulted from an analysis of combined-cycle unit component RAM data from the period 1978 through 1980:

- Turbine and heat recovery steam generator (HRSG) control failures accounted for the largest percentage of total forced outages for combined-cycle components.
- Turbine controls appeared to be a problem of equal concern to operators of both HSF and LSF units that exhibited average mean times between failures (MTBFs) of 785 hours (HSF units) and 480 hours (LSF units). Data records were generally inadequate to establish problem causes.
- Drum-level trips were the dominant cause of HRSG control failures.
- There were recurring failures within lube oil systems, fuel gas systems, air systems, fuel oil systems, and such catchall categories as "CT, General"; "HRSG, General"; and "Steam Turbine, General."
- Plant outage records received generally lacked sufficient detail to establish root causes of failures of components and systems.
- As a result of sensitivity analyses of individual units, turbine and HRSG control failures ranked high on the list of components which, if improved to 100 percent availability, would yield the greatest percentage-point improvement in unit effectiveness.

- Component mean downtime (MDT) values for LSF units were generally higher than those for comparable HSF units. (This may be because HSF units must get back on-line quicker and may experience shorter logistics delays.)

Turbine and HRSG control failures are not only nuisance problems to plant operators, but also significantly degrade equivalent availability because of poor MTBF. Controls should be investigated so that specific areas for product improvement may be defined.

ANALYSIS OF COMBUSTION TURBINE RELIABILITY DATA

Reliability data for 15 HSF gas-fired CT systems and 11 LSF oil-fired CT systems were analyzed. Table S-1 summarizes the performance of the CTs.

Table S-1

COMBUSTION TURBINE PERFORMANCE

Type of Turbine	Average Annual Failures per Turbine	Overall MTBF per Turbine (Hours)	Average Annual MDT per Turbine (Hours)	Average Annual Service Factor per Turbine	Average Annual Fired Hours per Start per Turbine	Total Combined Fired Hours
HSF Unit Turbines	10.3	600	36	0.74	252.0	235,000
LSF Unit Turbines	20.2	77	14	0.17	48.3	41,000

The analysis also led to the following observations and conclusions:

- The highest MTBF for an HSF unit turbine was 1992 hours, the highest MTBF for an LSF unit turbine was 489 hours.
- HSF unit CTs analyzed by use of 1978-1980 data exhibited reliability growth, which can be described by the relationship:

  $$MTBF = 83.3t^{0.184}$$

  where

  t = cumulative operating hours

- The failure rates of oil- and gas-fired CTs and some CT components were strongly affected by service factor (SF and fired hours per start (FHPS).

- CT failure rates increased dramatically for SFs less than 0.4 and FHPSs less than 150.

- The following relationship, developed by using multiple regression techniques for this data sample, describes the correlations between turbine failure rate, SF, FHPS, and fuel type:

  $$\ln \lambda = 11.48 - 0.58 \ln(\text{FHPS}) - 1.29(\text{SF}) - 0.07(\text{FT})$$

  where

  λ = failures per million hours of operation

  $$\text{FHPS (fired hours per start)} = \frac{\text{operating hours}}{\text{successful starts}}$$

  (correlation coefficient = 86 percent)

  $$\text{SF (service factor)} = \frac{\text{operating hours}}{\text{period hours}}$$

  FT (fuel type) = 0 for oil-fired turbines, 1 for gas-fired turbines

- FHPS had the strongest effect on turbine failure rates; fuel type had the least effect. Approximately 84 percent of the variance in the data could be explained by one variable -- FHPS.

These correlations suggested that turbine reliability should not be compared unless the service conditions are specified. More data are needed to quantify the effect of fuel type on CT failure rates, because little data exist for gas-fired turbines in midrange service and below and oil-fired turbines in midrange service and above. Also, with an expanded data base it would be feasible to use availability models to forecast plant performance by incorporating these correlations and time dependencies (e.g., reliability growth) into expressions of component failure rate.

Because turbine failure rate data analyzed were segregated as either LSF (oil-fired) or HSF (gas-fired), conclusions regarding the effect of fuel type on turbine failure rate could not be substantiated.

MAJOR UTILITY DATA PROBLEMS AND WEAKNESSES

The following conclusions were derived by assessing the adequacy of utility data to support RAM analyses:

- Utility outage records reflected different equipment nomenclatures, outage definitions, and outage cause codes, largely due to lack of consistency between public -- e.g., North American Electric Reliability Council/ Generating Availability Data System (NERC/GADS) -- and private -- e.g., General Electric Operational Reliability Analysis Program (ORAP), Westinghouse Reliability Availability Measurement Program (RAMP) -- data processing services.

- Outage records did not reflect actual man-hours to repair -- data needed to establish maintainability trends necessary to support maintenance planning.

- Outage records did not reflect operating hours on the equipment at the time of the forced outage -- data needed to establish failure distributions and reliability trends.

- Data records reflected too many catchall failure entries such as fuel gas system, lube oil system, air system, and controls.

- Noncurtailing maintenance events were generally not included in outage logs.

- It is difficult to identify from maintenance records those parts replacements or modifications occurring during planned maintenance.

Outage and maintenance data available from the operating utilities are adequate to support RAM trend analyses presented herein. Information needed to resolve data deficiencies and weaknesses is available directly from professional maintenance personnel and from utility maintenance records such as work request forms and overhaul reports. An organized effort to collect such information on a widespread basis would increase the workload of the utilities. However, current outage data formats can be improved to better meet the needs of plant operators.

The types of data used in NERC, Westinghouse, and General Electric plant performance reports (e.g., GADS, ORAP, RAMP) are similar. Utility data workload can be reduced once greater consistency in formats, outage codes and definitions, equipment names, and methods of analysis is achieved. With the addition of reliability and maintainability information at lower levels of plant components, utilities will benefit with more meaningful performance comparisons, problem identification, and problem impact analyses.

Section 1

INTRODUCTION

This report presents the results of a reliability, availability, and maintainability (RAM) assessment of 16 domestic combined-cycle power units and equipments operated by seven utilities. Output data from the period 1978 through 1980 were analyzed by ARINC Research Corporation for the Electric Power Research Institute (EPRI) under EPRI Research Project (RP) 1319-6. Technical direction was provided by Dr. Richard Duncan and Mr. Jerome Weiss of EPRI's Advanced Power Systems Division.

BACKGROUND

Combined-cycle power units were introduced in utility service in the early 1970s. These units derive power by combining one or more combustion turbines (CTs) of 50 megawatts (MW) or more with a single multistage steam turbine. Each turbine drives either an air- or hydrogen-cooled generator rotating at 3600 revolutions per minute (rpm). Steam is generated by hot (∿1000°F) CT exhaust gases being passed through heat recovery boilers and expanded in a steam turbine to enhance the unit's thermal efficiency. Heat recovery steam generators (HRSGs) and CTs are paired units. The CT can function in combination with or independently of its HRSG. Thus, the availability potential of these units is quite high, because power would be only partially curtailed should an outage occur to one of the primary power elements. Units can be of a multishaft design, whereby two or more CT and HRSG pairs mate with a single steam turbine; or they can be of a single-shaft configuration, whereby the CT, steam turbine, and a single generator are coupled via a common shaft. Plants can feature one or more of these units -- three single-shaft units, say, or two three-on-one units (i.e., three CTs and a steam turbine).

Combined-cycle plants therefore offer the utility industry great flexibility to meet almost any capability requirement in a compact layout. Furthermore, because these turbines can be fueled with natural gas in addition to distillate or residual oils, utilities can adjust to trends in fuel availability and cost. One important feature is that these units can be at full capacity within one hour after startup, thus providing efficient peaking service.

The ability of these units to achieve their full availability potential greatly depends on the achievement of high reliability and availability by the turbine and its ancillary equipments (i.e., the CT system). Although the turbine "flange-to-flange" unit has provided many plants with years of reliable service, the industry also recognizes that most forced outages of the CT system are caused by nuisance problems and failures of its ancillary equipment. The high number of turbine forced outages reported may be overshadowing plant availability and performance that would otherwise be considered good.

For years, the utility industry has managed and collected outage data records for the purpose of measuring the impact on plant availability of planned and unplanned maintenance. Utility engineers and maintenance personnel are keenly aware of those plant equipments which impose maintenance difficulties or may not be measuring up to performance standards because of poor design or workmanship, or misapplication.

Current outage data records can yield such information as plant forced outage rate, equivalent availability, operating availability, scheduled outage rate, and capacity factor. However, without extensive record searching and data analysis, it is difficult to establish or measure which of the forced outages significantly degrade plant availability and which are merely nuisance problems. Measures of reliability and maintainability such as mean time between failures (MTBF) and mean time to repair (MTTR) are certainly appropriate to the utility industry. If outage data records can be analyzed to derive such measures for many of the key components in a combined-cycle power unit, plant engineers will have an additional means to measure or compare equipment reliability performance. Moreover, if data permit, it may be feasible to determine how failures or repair actions are distributed in time, as in cases where failure rates may be changing with equipment age. Similarly, it may be feasible to identify or correlate the effect of specific plant operational variables (such as service factor, fuel selection, or cycling rates) on the MTBF of key plant systems such as CTs. This information would be extremely useful in anticipating equipment problems before they occur, as well as:

- Establishing appropriate preventive maintenance schedules
- Establishing realistic goals for critical plant equipment
- Planning sparing requirements
- Projecting maintenance crew sizes
- Identifying candidates for product improvement programs

However, two questions remain unanswered. First, are current plant outage data suitable to support development of a RAM data base, and what changes to present data capacity would be required? Second, what useful data analyses products could be derived from RAM data, and would such products be accurate and serve the needs of the utility industry? These questions and evaluations are explored in this document.

SCOPE

For this project, seven combined-cycle plants provided outage data and needed insight into plant operations. The plants comprised a total of 16 combined-cycle units. Seven of the units were gas-fired with a high service factor (HSF), and nine were oil-fired with a low service factor (LSF). Combined-cycle units were manufactured by Westinghouse Electric Corporation and the General Electric Company. Outage data from the period 1978 through 1980 were analyzed and carefully edited with the assistance of plant personnel. Data were cross-checked with General Electric and Westinghouse records, where available.

All plants assessed had at least three years' operating experience prior to 1978 and were considered to be operationally mature. Units operated over a wide range of service conditions; some exhibited excellent availability, while others exhibited poor to average availability. The units were considered to be a representative cross section of industry combined-cycle performance for the period studied. Data were excluded for two of the HSF units in 1978, as the units experienced major overhauls and saw little service. 1978 and 1979 data for two of the LSF units were excluded, because the validity of the data records could not be established. Data for all other units covered the full three-year period and were suitable for these assessments.

A total of 26 CTs used in 16 combined-cycle units were analyzed during this period. Fired hours totaled 235,000 for gas-fired turbines and 41,000 for oil-fired turbines. The total capacity of the 16 units was approximately 2200 MW, based on an average daily temperature of 80°F.

OBJECTIVES

The objectives of this project were as follows:

- Using plant outage data records, build a RAM data base, describing the MTBF and mean downtime (MDT) for plant components.
- Investigate the feasibility of using RAM analyses techniques to assess reliability and availability (R&A) measures of combined-cycle units and principal systems.

- Evaluate the quality and content of plant outage data records for supporting RAM analyses.
- Develop and validate appropriate availability models for the combined-cycle units analyzed during this project.
- Investigate the effect of fired hours, service factor, duty cycle, and fuel type on failure rates and components of turbine systems.
- Evaluate the combined performance of the combined-cycle units and turbines analyzed during this project.
- Determine improvements needed in collecting and processing outage data to better support the operating utilities.

This study will provide utilities with insight into general industry combined-cycle performance and will identify equipment reliability problems shared by the plants participating in the study.

REPORT ORGANIZATION

Section 2 of this report describes data assessment methodologies, assumptions, and equations used to derive RAM data from the outage records. Section 3 presents the results of the overall unit availability assessments, availability models, and the composite MTBF and MDT data for plant components. Section 4 presents the results of the CT data analysis, describing trends in CT reliability as affected by fuel type and service conditions. Section 5 addresses weaknesses and needed improvements in outage data reporting and sets forth the requirements for a central RAM data base to serve utilities desiring reliability data feedback. Section 6 presents conclusions and recommendations, and Section 7 is a list of references used for this report. Appendixes A through D provide definitions of terms and equations, examples of statistical methods for analyzing plant reliability data, procedures for defining system states, and a summary of CT component performance, respectively.

Section 2

TECHNICAL APPROACH

This section presents the fundamental concepts and methods used in our analysis of outage data records from the seven participating utilities. More technical detail is provided in a list of references following this report, and in selected appendixes.

OVERVIEW OF UTILITY DATA NEEDS AND ANALYSIS METHODS

Performance data are routinely collected to assist utility management in the following:

- Evaluating plant availability
- Evaluating and forecasting operating and maintenance (O&M) costs
- Planning scheduled maintenance
- Planning load and reserve requirements
- Identifying performance and design problems and planning corrective action programs

Plant data records normally account for all plant outages by type (e.g., forced or scheduled), duration, lost capacity, cause, plant system affected, and maintenance action required. When management needs are being considered, data analyses must assess not only the impact of outages that have occurred, but also the impact of those which could occur. Because utility data needs can vary considerably depending on plant design, operation, load, and reserve requirements, both historical and probabilistic approaches to data analysis are appropriate.

Historical data analyses are used in this report to derive directly from outage data such performance parameters as plant forced outage rate, scheduled outage rate, capacity factor, and operating availability (these terms are defined in Appendix A). If sufficient historical data exist, historical performance trends can be developed, giving insight into the frequency, duration, and magnitude of system outages. The historical approach, however, cannot readily evaluate the probability that an outage or failure will occur (information useful in forecasting generating capability and equipment outages) nor provide insight into the RAM criticality of plant equipment as affecting plant-forced outage rates.

Through the use of the probabilistic approach, combined-cycle plants can potentially achieve high availability by allowing operators and engineers to:

- Properly match the plant design and capacity with the operational requirements
- Successfully plan maintenance
- Understand the sensitivity of plant availability to component and system performance
- Maintain high CT reliability or low forced outage rates

The probabilistic approach founded upon the principles of reliability theory is a powerful tool, not only for guiding cost-effective product improvement efforts, but for assisting the utility planner in forecasting loss of load probability and allocating reasonable component R&A goals. For these reasons, the data analysis methods developed and applied throughout these RP1319-6 plant assessments combine the historical and probabilistic approaches.

The Historical Approach

The historical approach to assessing availability has a somewhat universal appeal to the electric power industry. In this approach all curtailments, including planned and unplanned events, are normalized in terms of equivalent outage hours lost at full capacity. Equivalent availability may then be calculated by using Equation 10 of Appendix A. Other parametric measures of plant performance can be derived directly from outage data by use of the other relationships presented in Appendix A. Many utilities, as well as private data processing services, automate this approach through the use of computer software.

The Analytical or Probabilistic Approach

There is a growing recognition within the utility industry that the analytical approach to reliability forecasting that has proved to be so useful in other industries can also assist power plant operations in availability forecasting. Application of the analytical approach to availability assessments blends reliability theory, operations research, systems engineering, and computer science. Quantitative RAM approaches (e.g., analytical modeling) focus on establishing the dependency and interaction among plant, system, and component performance. Such analyses can involve studies to determine optimum system configuration (such as sensitivity studies to identify reliability improvement candidates) and cost trade-off studies to determine the worth of availability improvement.

Availability is a measure of a system's performance in terms of its reliability and maintainability. MTBF and MDT are accepted measures of reliability and maintainability. A single value measure of plant component availability (A) can be derived from the expression $A = \frac{MTBF}{MTBF + MDT}$. The MTBF is the ratio of total operating hours to the total number of failures occurring during the period. The MDT is the ratio of the total downtime hours to the total number of failures. Expressed in these terms, availability is the percentage of the time period that the equipment was capable of operating.

When the availability of a combined-cycle power plant is being analyzed, mathematical models are sometimes utilized, whereby plant availability is expressed in terms of system availability or, if desired, system component availability. If component MTBF and MDT values are known, plant availability can be calculated by use of a series of mathematical expressions that correlate the probabilities of random failures and repairs occurring to components to various levels of plant capacity states. A combined-cycle plant may have many such states or partial capacity levels, depending on what equipments are operational and unoperational at some point in time. Analytical techniques are powerful tools in understanding how random failures and repairs to plant components interact and affect plant availability and output capacity. Therefore, if component failure rates and downtimes can be accurately predicted, analytical approaches are useful to utilities desiring a means for availability forecasting.

AVAILABILITY MODELING OF COMBINED-CYCLE UNITS

The methodology and level of sophistication of the analytical approach depend greatly on the objectives of the analyses and the quality of available RAM data. Availability modeling can be of value only when the interaction between the plant system and component availability is accurately modeled. Sufficient data should allow the analyst to establish low levels of component indenture -- at least at a level where the root cause of a failure can be identified.

Key steps in plant availability modeling are as follows:

- Identify RAM data sources (usually plant outage records), components, and component indenture levels.
- Develop reliability block diagrams describing the interaction between plant systems and components.
- Partition the unit by systems and develop fault trees for each system to reduce the complexity of the analysis.

- Define system states and associated capacity levels.
- Analyze component RAM data to calculate state probabilities, plant and system availabilities, and other performance measures.

These steps are discussed in the following paragraphs. References (1) through (5) provide detailed descriptions of modeling techniques and reliability theory and their application to power systems.

Figure 2-1 illustrates the two kinds of data analysis techniques. The analytical approach does not truly simulate plant operations. Rather, availability models describe a profile of the plant's expected capability over some specified time period (usually one year) during which component failures and repairs randomly occur. This measure of expected capability is called effectiveness (this term and others used herein are explained in more detail in Appendix A). Effectiveness is a measure of unit availability only over the time period defined as PH - RSH - $SPOH_2$ - SOH; hence it excludes all outages associated with scheduled or planned maintenance (i.e., SOH + $SPOH_2$). Periods of reserve standby are also excluded, because the plant is not operating, and failures cannot occur. The effectiveness measure also assumes that the CT system is either available for 100 percent power or unavailable for zero power.

The modeling approach may be illustrated by using as an example a plant consisting of three independent CT generator sets, each providing one-third of the plant's capability. As shown in Table 2-1, this plant can have no more than eight possible states. The availabilities for each CT system are A_1, A_2, and A_3. Each turbine is assumed to experience failures and repairs independently of the others. Application of probability multiplication rules will derive state probability values (P_k). Plant effectiveness (E) is calculated by using the following equation:

$$E = \sum_{k=1}^{8} E_k \qquad (2\text{-}1)$$

where

E_k = effectiveness of the associated state

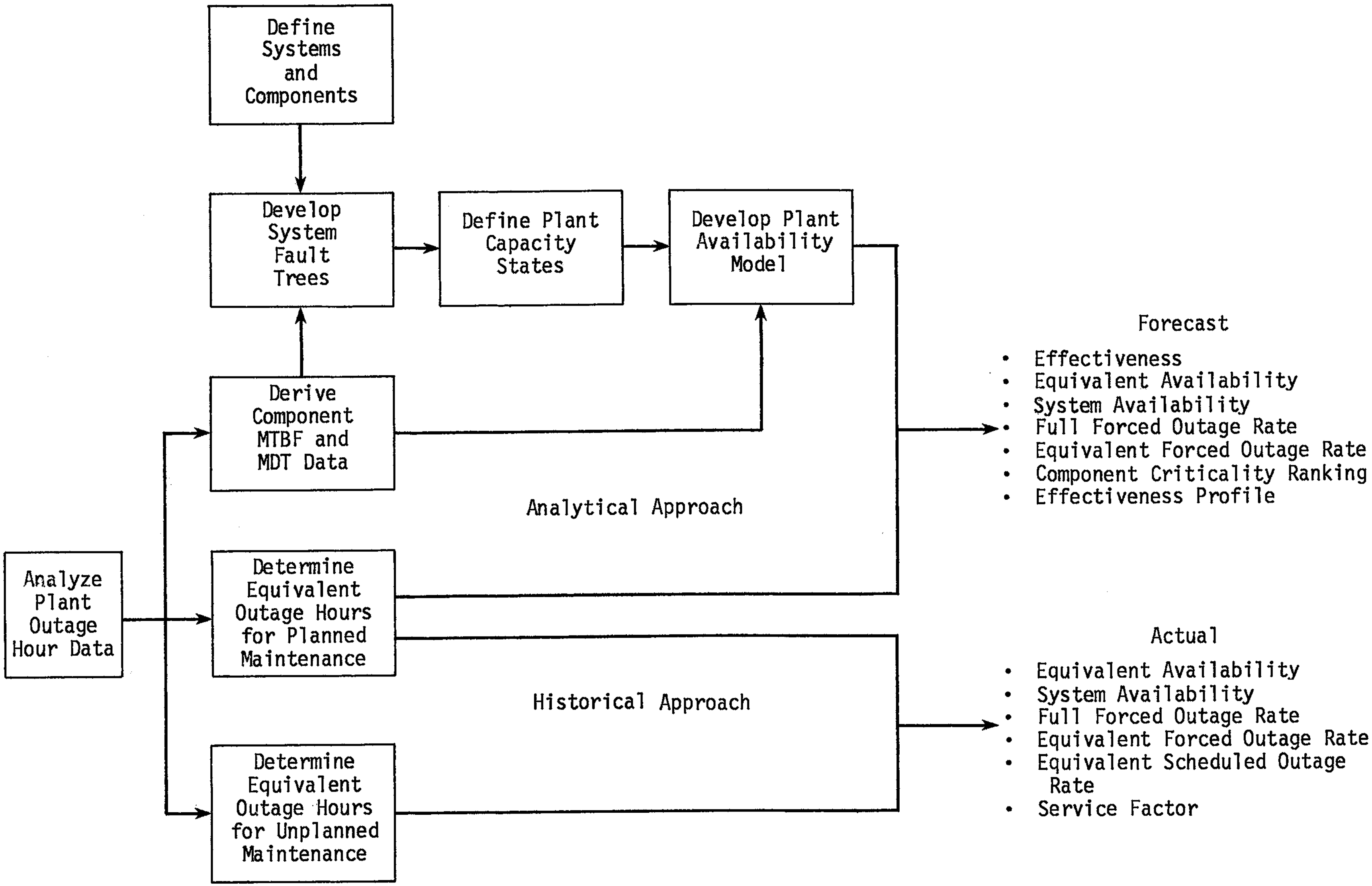

Figure 2-1. Data Analysis Methodology

Table 2-1

PLANT EFFECTIVENESS ANALYSIS

State (k)	Probability Expression (P_k)	Capacity (C_k) (Percent)	$E_k = P_kC_k$
1	$P_1 = A_1A_2A_3$	$C_1 = 100$	$E_1 = P_1C_1$
2	$P_2 = (1 - A_1)A_2A_3$	$C_2 = 66.67$	$E_2 = P_2C_2$
3	$P_3 = A_1(1 - A_2)A_3$	$C_3 = 66.67$	$E_3 = P_3C_3$
4	$P_4 = A_1A_2(1 - A_3)$	$C_4 = 66.67$	$E_4 = P_4C_4$
5	$P_5 = (1 - A_1)(1 - A_2)A_3$	$C_5 = 33.33$	$E_5 = P_5C_5$
6	$P_6 = (1 - A_1)(1 - A_3)A_2$	$C_6 = 33.33$	$E_6 = P_6C_6$
7	$P_7 = A_1(1 - A_2)(1 - A_3)$	$C_7 = 33.33$	$E_7 = P_7C_7$
8	$P_8 = (1 - A_1)(1 - A_2)(1 - A_3)$	$C_8 = 0$	$E_8 = P_8C_8$

$$\text{Plant Effectiveness (E)} = \sum_{k=1}^{8} E_k$$

Totaling the probabilities associated with each state will yield an effectiveness profile, illustrated in Figure 2-2. The shaded area of the figure represents plant unavailability because of planned or scheduled maintenance ($SPOH_2$ + SOH). The term $SPOH_2$ represents scheduled partial outage hours attributed to planned maintenance. All other scheduled partial outage hours are attributed to unplanned maintenance. For this example, the model predicts that the forced partial outage hours (FPOH) for States 2 through 7 will be FPOH = $(PH - RSH - SPOH_2 - SOH)\sum_{k=2}^{7} P_k$. The predicted full forced outage hours (State 8) is $(PH - RSH - SPOH_2 - SOH)P_8$. The equations presented in Appendix A can be used to derive typical data analysis products, as shown in Figure 2-1, either analytically or directly from outage date (historical approach). The results of either approach would normally be in close agreement.

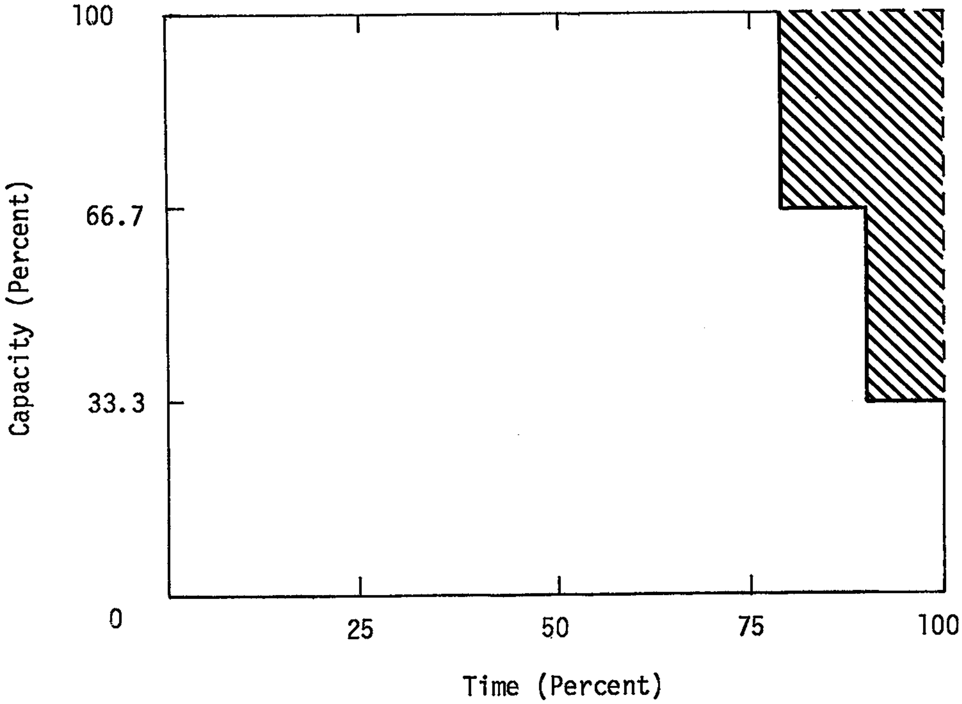

Figure 2-2. Effectiveness Profile

Availability modeling of a typical multishaft combined-cycle unit can become quite complex because of the large number of states required to fully describe the condition of the unit when failures occur and repairs are made to hundreds of components. For such cases the analyst resorts to system partitioning and fault tree concepts to reduce the complexity of the analysis. Reference (5) presents a detailed treatment of these concepts; Appendix C to this report describes the application of the concepts to a multishaft unit.

Analysis of Component Outage Data

Availability models developed for each plant analyzed herein required the use of outage data to calculate component failure rates and mean downtimes. Where historical data records were limited to the extent that distributions of component failures and repairs could not be established, failures and repairs were assumed to occur at a constant rate over a given interval of time. For a given data population, this assumption is statistically valid for estimating the mean. When averaged values of failure rates and mean downtimes are computed, the selection of a time interval over which data are to be analyzed is important. If the interval is too long, average failure rates may be significantly different from the actual sample mean, because failure could be occurring at a decreasing rate (i.e., reliability growth) or an increasing rate. If the interval is too short, data may be insufficient. These analyses used a data period of one year, which was found to yield good results for most systems analyzed.

If it is assumed that system uptimes are independent from system downtimes, it can be shown, using probability theory, that:

$$A_s = \frac{MTBF}{MTBF + MDT} = \frac{1}{1 + \tau_s \lambda_s} \quad (2\text{-}2)$$

where

A_s = system availability

$MTBF_s$ (mean time to failure) = $\frac{1}{\lambda_s}$

MDT_s (mean downtime) = τ_s

This system availability (A_s) is often called the point estimate of availability. Because failures are assumed to be exponentially distributed (i.e., constant failure rate), repairs restore the system to an as-new condition. It is further assumed that failures to system components occur randomly and are independent -- that is, a failure to one component does not stress the remaining unfailed components. If components are series-connected, whereby a failure of one component results in a failure of the system, the system failure rate (λ_s) is the sum of its component failure rates (λ_c), where:

$$\lambda_c = \frac{\text{total number of failures}}{\text{total system operating hours}} = \frac{1}{MTBF_c} \quad (2\text{-}3)$$

The system mean downtime (τ_s) is calculated as the weighted average of its components downtimes and is expressed as:

$$\tau_s = \frac{\sum \lambda_c \tau_c}{\sum \lambda_c} \quad (2\text{-}4)$$

where

$$\tau_c = \frac{\text{total component downtime (hours)}}{\text{total number of failures}}$$

The system availability expression (A_s) can be written as follows:

$$A_s = \frac{1}{1 + \sum \lambda_c \tau_c} \qquad (2\text{-}5)$$

The systems identified in these analyses were partitioned so that their components were series-connected; hence data were analyzed by use of the foregoing relationships. However, where systems are not series-connected, the appropriate system fault tree logic must be used to develop mathematical expressions for A_s.

Derivation of Component Failure Rates and Mean Downtimes

Plant maintenance records provide a weekly summary of all planned and unplanned outage events that result in power being curtailed. For a given unit, these records typically include the following:

- Date of event
- Type of outage
- Duration of outage
- Description and cause of outage
- Reserve shutdown hours
- Total fired hours on unit
- Number of starts (attempted and successful)

After the combined-cycle unit was partitioned into its appropriate systems, data for one year were reviewed to identify the system affected by each unplanned event (i.e., failure). The number of failures and downtime hours were totaled for each of the components identified. System operating or fired hours per year were obtained from plant data records or from hour meters on the equipments. Component failure rates and mean downtimes were then computed. For these analyses, unplanned outages resulting from false trips, operator errors, natural causes, or false starts of less than 0.1 hour were not considered to be failures (that is, successive failures-to-start occurring during one starting sequence were not counted as failures, so that the failure rates would not be distorted).

Sensitivity Analyses

Analytical approaches to availability assessments can highlight the impact that uncertainties in the data base have on calculated effectiveness values. For example, consider the cases where the predicted failure rate value with some confidence interval is known for a system or component, or where uncertainty exists in the estimated value. The availability model can be used to estimate the overall effect resulting from any variation in an MTBF, MDT, or availability value. Hence, the analyses may prove to be helpful in identifying where data should be strengthened or in justifying the need for reliability testing.

In the plant assessments described herein, components were ranked according to the following criteria:

- Case 1: Failure Rate - the change in plant effectiveness per change in component failure rate
- Case 2: Mean Downtime - the change in plant effectiveness per change in component mean downtime
- Case 3: Availability - the change in plant effectiveness per change in component availability
- Case 4: Power Gain - the increase in plant effectiveness (percentage points gained) when the availability of a component is considered to be 100 percent

Case 4 analyses provided a list of plant components ranked in order of which components would yield the greatest percentage-point improvement in unit effectiveness when made perfect (i.e., 100 percent availability). This ranking was helpful in selecting candidates for an availability improvement program. Since economics were not considered in these analyses, capital investment limitations may indicate that other actions could be more cost-effective.

Statistical Techniques Applied to Reliability Forecasting

An important product of the outage data analyses was a better understanding of plant equipment failure rates. The resulting combined-cycle RAM performance data base was the culmination of an in-depth review, validation, and analysis of numerous maintenance events. This data base, although limited to three years' operating experience, provided insight into general combined-cycle performance trends, data deficiencies, and equipment problem areas over a wide range of service conditions. RAM data for CTs and many CT components were extensive; however, data were less extensive for steam-side and plant service components.

As this data base expands, statistical techniques can be applied to develop:

- Probability distributions of MTBF values
- Suitable mathematical relationships for estimating MTBF and MDT values and the corresponding confidence limits

- Suitable mathematical relationships for correlating the dependency between MTBF and variations in service conditions (e.g., fuel type, service factor, starting frequency)

This information is of particular interest to the utility planner in planning appropriate scheduled maintenance intervals and to the research engineer in setting forth realistic reliability goals. There is extensive literature available on appropriate statistical techniques. References (3) and (4) provide detailed descriptions of methods for reliability forecasting. Appendix B briefly describes the methodologies used herein, including the use of Weibull distributions for estimating equipment MTBF, the estimation of confidence limits for MTBF and MDT values, and using reliability growth models to estimate equipment reliability growth.

Section 3

THE RAM DATA BASE AND RESULTS OF AVAILABILITY MODELING

This section summarizes the results of outage data analyzed for seven combined-cycle power plants and presents definitions of system states for the single- and multishaft units analyzed. Because these plants differ in configuration, equipment technology, service duty, and maintenance practices, references to equipment manufacturer or plant operator are omitted. The results of the analyses are presented to gain insight into general RAM trends in the utility industry and to consider units in both HSF and LSF operations. The data base spanned the period 1978 through 1980. Average MTBF and MDT values were calculated for seven gas-fired HSF units and nine oil-fired LSF units. An objective of these analyses was to demonstrate the feasibility of using RAM data as a management aid to improve utility operations.

COMBINED-CYCLE UNIT DESCRIPTIONS

Three combined-cycle unit configurations were modeled analytically -- STAG 100 and STAG 400 units manufactured by the General Electric Company, and PACE 260 units manufactured by the Westinghouse Electric Corporation. Six of the seven plants included in this study were placed in service before 1975; the seventh plant was placed in service in 1977. All were considered to be operationally mature. A combined-cycle unit usually has one or more CTs and HRSGs operating with a single steam turbine. The units analyzed all use modern Westinghouse 501 or General Electric Frame 7 turbines with capacities in excess of 50 MW. Most plants have dual-fuel (gas or oil) capability. The heat recovery boiler is of a finned-tube design, receiving hot (∿1000°F) exhaust gas from its companion CT and producing superheated (∿900°F) steam. Some combined-cycle units utilize afterburners, which increase steam generation capacity, thereby increasing plant capacity. An HRSG may also feature dampers, which bypass turbine exhaust from the HRSG, allowing the CT to operate without its HRSG. Superheated steam from the HRSG is channeled via a common header to a steam turbine, which is usually of a straight-condensing, single-flow, nonreheat design. Low-pressure steam exiting the steam turbine passes through a surface condenser. Condensate is pumped via condensate and boiler feedwater pumps to the HRSG. Electrical generators are driven directly off the CTs and steam turbine. Generators are either air- or hydrogen-cooled.

Figures 3-1, 3-2, and 3-3 are diagrams of these single- and multishaft units. In the single-shaft General Electric STAG 100 unit shown in Figure 3-1, approximately 60 percent of the total generating capacity is provided by the CT. The CT, steam turbine, and generator are connected to a common shaft and function together as a single power generation unit. All must operate together; independent CT operation is not possible. STAG 100 units using MS-7001E turbines have a net capacity of approximately 90 MW measured at 1000 feet and 80°F.

A Westinghouse PACE 260 unit featuring afterburners, shown in Figure 3-2, has a net capacity of approximately 260 MW and utilizes W-501B combustion turbines rated at approximately 75 MW each measured at 1000 feet and 80°F. The steam turbine is rated at approximately 110 MW with afterburners. Two circulating water pumps feed the condenser; two condensate pumps supply water from the condenser hot well to two boiler feedwater pumps (one for each HRSG). The cycle can operate without afterburners. Each turbine and HRSG pair can be operated independently of the other. This allows one turbine to be operated at rated load while the other is shut down during periods of low demand. Bypass dampers are incorporated to allow operation of the combustion turbine if its companion HRSG is inoperable.

A General Electric STAG 400 unit, shown in Figure 3-3, has a net capacity of approximately 350 MW when using MS-7001E turbines. The HRSGs are unfired and use forced water circulation in the evaporator. Bypass dampers are utilized, permitting independent CT operation should the companion HRSG be inoperable. However, it is normal practice for the CT to be shut down if a failure occurs to its HRSG. A unit uses only one condensate and one boiler feedwater pump; failure to either requires that the unit be shut down.

EFFECTIVENESS MODELS

As described in Section 2, the construction of an effectiveness model requires an understanding of both the plant partitioning process and plant operation. For a STAG 100 unit, the effectiveness model describes a series-connected system. That is, a failure of any system results in the unavailability of the unit. STAG 100 unit effectiveness (E) is calculated by the use of Eqs. 2-3, 2-4, and 2-5 and the following expression:

$$E = \frac{1}{1 + \sum \lambda_s \tau_s} \tag{3-1}$$

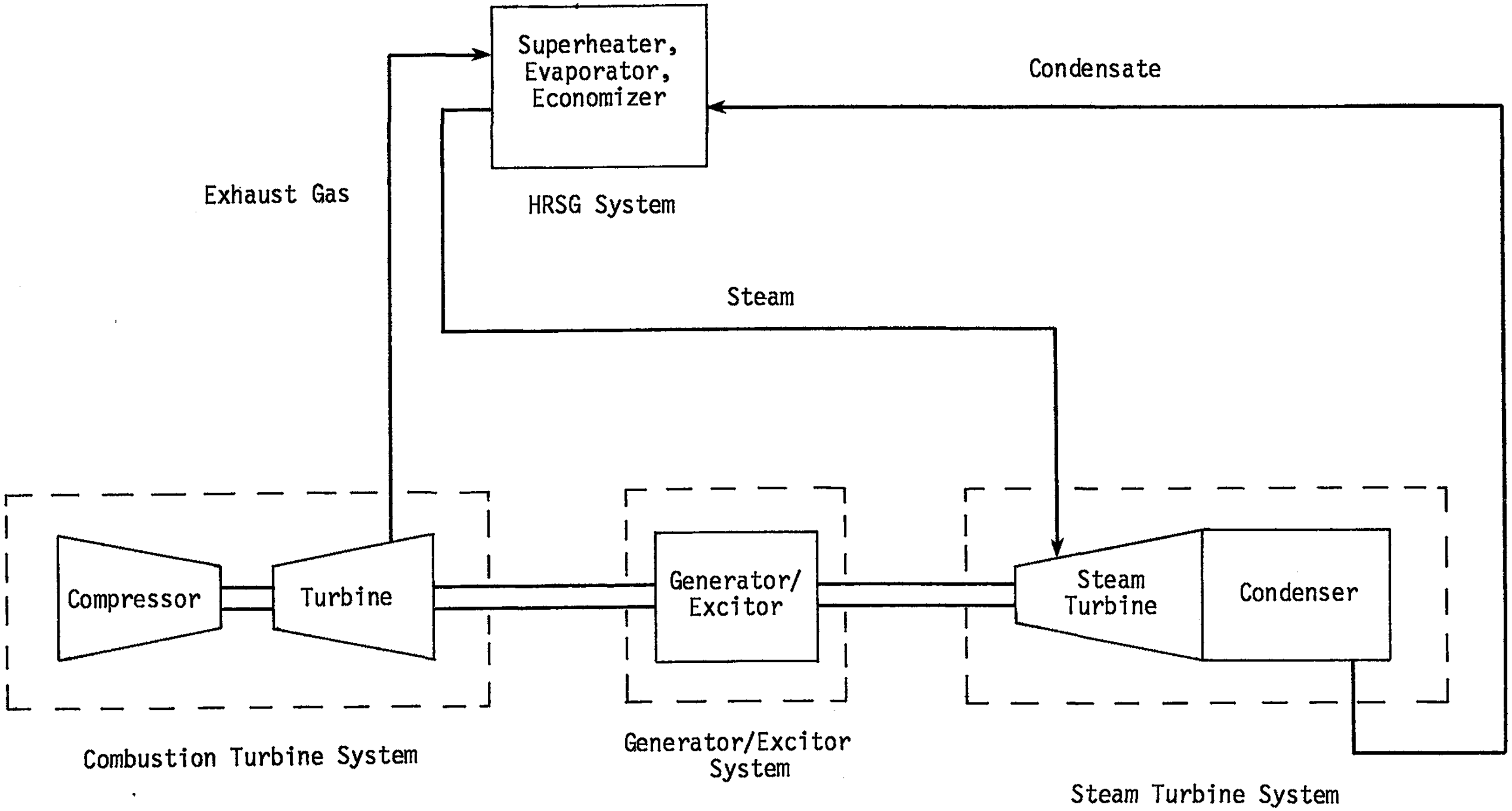

Figure 3-1. STAG 100 Unit Configuration

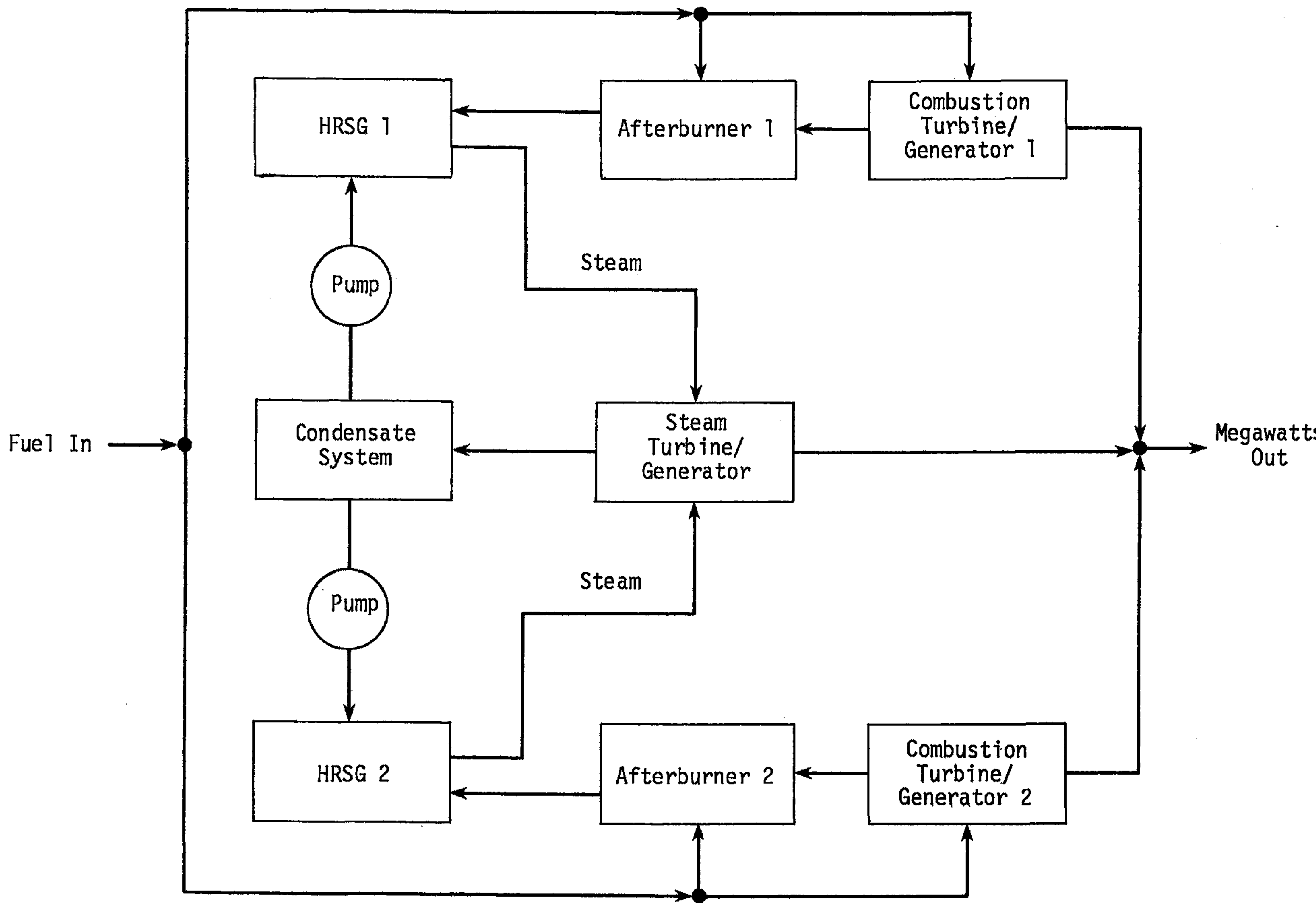

Figure 3-2. PACE 260 Unit Configuration

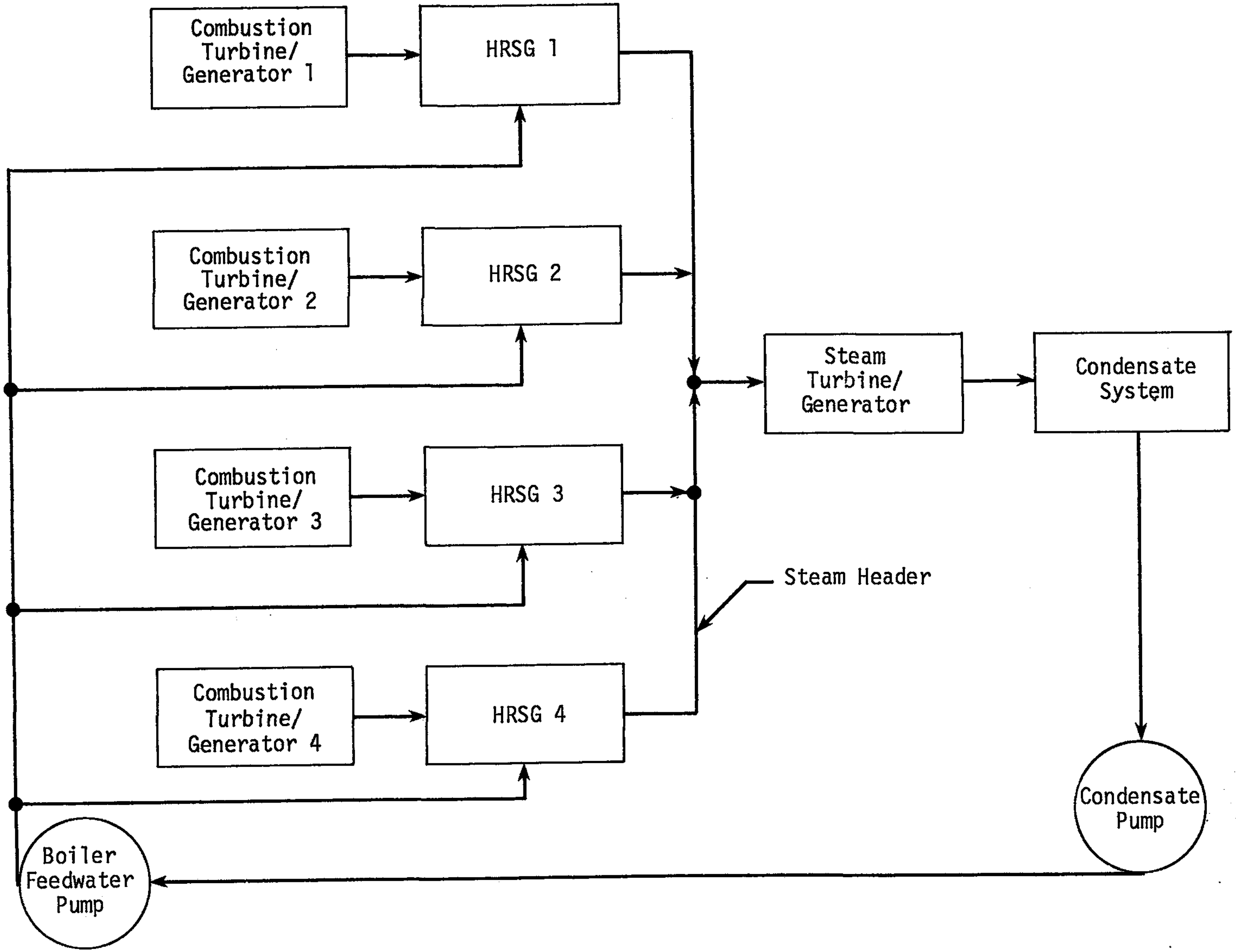

Figure 3-3. STAG 400 Unit Configuration

For a plant consisting of three STAG 100 units, plant effectiveness is derived by using the approach shown in Table 2-1.

For multishaft units like the PACE 260 or STAG 400, effectiveness models are described by numerous states and systems, shown in Tables 3-1 and 3-2. Each of these systems is described so that a failure of any component within a system results in a failure of the system. The states described include all capacity levels that can result from available or unavailable conditions of those systems. For example, the plant may not have actually operated in some of the states during the period being analyzed. The capacity percentages noted in Tables 3-1 and 3-2 vary from plant to plant, depending on the discrete capacity levels within power elements. As described in Section 2, there is a probability expression given a likelihood for each state. Effectiveness values calculated by use of these models are a measure of plant availability over the time period for which operations were planned ($PH - RSH - SPOH_2 - SOH$). Effectiveness excludes any time the unit may have been unavailable for planned maintenance (i.e., $SOH + SPOH_2$) or available during periods of reserve standby.

As shown in Appendix A, equivalent availability (A_e) can be related to effectiveness through the following expressions.

For a multishaft unit:

$$A_e = \frac{E(PH - RSH - SPOH_2 - SOH) + SPOH_2 - ESOH_2 + RSH}{PH} \qquad (3\text{-}2)$$

For a single-shaft unit:

$$A_e = \frac{E(PH - RSH - SOH) + RSH}{PH} \qquad (3\text{-}3)$$

Equivalent availability values for plant combined-cycle units can also be determined directly from outage data records. These values can be compared with those derived analytically to check the validity of the model and any assumptions made. In each of the seven plants assessed, equivalent availabilities calculated by using the effectiveness models agreed within 3 percent with those values derived directly from outage data records.

Table 3-1

PACE 260 UNIT AVAILABILITY STATES BY SYSTEM

System

State	CT 1	HRSG 1	AB 1	CT 2	HRSG 2	AB 2	ST	C	CWP	CP	Capacity (Percent)
1	0	0	0	0	0	0	0	0	0	0	100
2	0	0	1	0	0	0	0	0	0	0	89
3	0	0	0	0	0	1	0	0	0	0	89
4	0	0	1	0	0	1	0	0	0	0	78
5	0	1	<2	0	0	0	0	0	<2	<2	72
6	0	0	0	0	1	<2	0	0	<2	<2	72
7	0	1	<2	0	0	1	0	0	<2	<2	61
8	0	0	1	0	1	<2	0	0	<2	<2	61
9	0	1	<2	0	1	<2	0	0	<2	<3	43
10	0	0	<2	0	0	<2	1	0	<2	<2	56
11	1	<2	<2	0	0	0	0	0	<2	<2	50
12	0	0	0	1	<2	<2	0	0	<2	<2	50
13	1	<2	<2	0	0	1	0	0	<2	<2	39
14	0	0	1	1	<2	<2	0	0	<2	<2	39
15	1	<2	<2	0	0	<2	1	0	<2	<2	28
16	0	0	<2	1	<2	<2	1	0	<2	<2	28
17	1	<2	<2	0	1	<2	0	0	<2	<3	22
18	0	1	<2	1	<2	<2	0	0	<2	<3	22
19	1	<2	<2	1	<2	<2	<2	<2	<3	<3	0
20	0	0	<2	0	1	<2	1	0	<2	<2	43
21	0	0	<2	0	1	<2	1	0	<2	<2	50
22	0	1	<2	0	0	<2	1	0	<2	<2	50
23	0	<2	<2	0	<2	<2	<2	1	<3	<3	43
24	1	<2	<2	0	1	<2	1	0	<2	<3	22
25	1	<2	<2	0	<2	<2	<2	1	<3	<3	22
26	0	1	<2	1	<2	<2	1	0	<2	<2	22
27	0	<2	<2	1	<2	<2	<2	1	<3	<3	22
28	0	0	<2	0	0	<2	0	0	0	2	43
29	0	1	<2	0	<2	<2	<2	<2	<2	2	43
30	0	<2	<2	0	<2	<2	<2	<2	2	<3	43
31	0	0	<2	0	0	<2	0	0	0	1	78
32	0	0	<2	0	0	<2	0	0	1	0	78

Legend:
- CT - Combustion turbine
- HRSG - Heat recovery steam generator
- AB - Afterburner
- ST - Steam turbine
- C - Condensate system
- CWP - Circulating water pumps
- CP - Condensate pumps
- 0 - System is available
- 1 - System is unavailable
- <2 - One system is not operating and could be either available or unavailable
- 2 - Two of the systems are not operating and are unavailable
- <3 - One or two systems are not operating and could be either available or unavailable

Table 3-2

STAG 400 UNIT AVAILABILITY STATES BY SYSTEM

System

State	CT/HR 1	CT/HR 2	CT/HR 3	CT/HR 4	ST	C	Capacity (Percent)
1	0	0	0	0	0	0	100
2	1	0	0	0	0	0	75
3	0	1	0	0	0	0	75
4	0	0	1	0	0	0	75
5	0	0	0	1	0	0	75
6	1	1	0	0	0	0	50
7	1	0	1	0	0	0	50
8	1	0	0	1	0	0	50
9	0	1	1	0	0	0	50
10	0	1	0	1	0	0	50
11	0	0	1	1	0	0	50
12	1	1	1	0	0	0	25
13	1	1	0	1	0	0	25
14	1	0	1	1	0	0	25
15	0	1	1	1	0	0	25
16	1	1	1	1	0	0	0
17	0	0	0	0	1	0	65.2
18	1	0	0	0	1	0	48.9
19	0	1	0	0	1	0	48.9
20	0	0	1	0	1	0	48.9
21	0	0	0	1	1	0	48.9
22	1	1	0	0	1	0	32.6
23	1	0	1	0	1	0	32.6
24	1	0	0	1	1	0	32.6
25	0	1	1	0	1	0	32.6
26	0	1	0	1	1	0	32.6
27	0	0	1	1	1	0	32.6
28	1	1	1	0	1	0	16.3
29	1	0	1	1	1	0	16.3
30	1	1	0	1	1	0	16.3
31	0	1	1	1	1	0	16.3
32	X	X	X	X	X	1	0
33	1	1	1	1	1	0	0

Legend: CT/HR - Combustion turbine/heat recovery steam generator
ST - Steam turbine
C - Condensate system
0 - System is available
1 - System is unavailable
X - System is not operating and could be either available or unavailable

COMBINED-CYCLE UNIT PERFORMANCE TRENDS

The seven plants analyzed herein consisted of 16 units; seven of these demonstrated HSF operation, and nine demonstrated LSF operation during the data period. For two of the LSF units, only data for 1980 were analyzed. For two of the HSF units, only data for 1979 and 1980 were analyzed. Average service factors for HSF units during 1978, 1979, and 1980 were 81 percent, 88 percent, and 93 percent, respectively. Average service factors for LSF units during 1978, 1979, and 1980 were 27 percent, 16 percent, and 38 percent, respectively.

In these analyses, LSF unit data were distinguished from HSF unit data because of inherent operational differences such as maintenance policies, staffing, and parts sparing. The four measures of combined-cycle unit performance considered are as follows:

- Effectiveness (E) - a measure of the unit's inherent reliability, which is the percentage of time that the unit can produce full power at any time period excluding planned maintenance and reserve standby periods
- Equivalent availability (A_e) - the percentage of time that the unit can produce full power over the time period under consideration
- Equivalent forced outage rate (EFOR) - a measure of the unit's unavailability, which is the percentage of time that the unit cannot produce any power at any time period excluding planned maintenance and reserve standby periods
- Operating availability (OA) - the percentage of time that the unit can produce any power over the time period under consideration

Effectiveness values were one product of the availability models. For multishaft units, a scheduled partial outage (SPOH) can occur as a result of both failures and planned maintenance events. When failure rates for components were calculated, all $SPOH_1$-related failures were accounted for. Failures that resulted in full and partial outages of the unit (e.g., FPOH, FOH) and failures discovered during periods of reserve standby or planned maintenance were accounted for as well. Hence, as shown in Appendix A, effectiveness is expressed as:

$$E = 1 - \left[\frac{FOH + EFOH + ESOH_1}{PH - RSH - SPOH_2 - SOH}\right] \times 100 \qquad (3\text{-}4)$$

On the basis of the relationships defined in Appendix A, equivalent forced outage rate is expressed as:

$$EFOR = \left[\frac{FOH + EFOH}{PH - RSH - SOH}\right] \times 100 \quad (3\text{-}5)$$

Depending on the specific values of ESOH and $SPOH_2$, effectiveness can approximate 1 - EFOR for multishaft units. For single-shaft units, effectiveness equals 1 - EFOR, and equivalent availability equals operating availability, because there are no partial power curtailments.

Tables 3-3 and 3-4 summarize performance for the 16 units. The HSF units were all gas-fired; the LSF units were all oil-fired. Effectiveness values were derived by use of the appropriate availability models; other performance measures were derived directly from outage data records. The following observations were noted:

- Average effectiveness values for HSF and LSF units were 92 percent and 72 percent, respectively.
- Mean values of equivalent availability for LSF and HSF units were nearly equal. This is because LSF units have more reserve standby hours or may be exempting some planned maintenance during periods of reserve standby. These factors tend to inflate equivalent availability for LSF units.
- Mean values of equivalent availability for LSF and HSF units improved over the period.
- Tabulated values of E and 1 - EFOR agree closely; thus effectiveness may be used to approximate unit equivalent forced outage rates.
- Mean values of operating availability for LSF and HSF units improved over the period.
- Performance data for LSF units generally exhibited greater variance between high and low values than did data for HSF units.

For any unit, values may have changed considerably over the data period because of such factors as equipment modifications or major overhauls and plant load requirements. Although the data herein are a representative sample of industry operating experience, caution should be exercised in extrapolating results beyond the 1978 through 1980 period or in drawing inferences regarding the performance of competing plant design.

Table 3-3

PERFORMANCE SUMMARY: HSF UNITS
(VALUES IN PERCENT)

Unit	Type of Unit*	Effectiveness			Equivalent Availability			Equivalent Forced Outage Rate			Operating Availability		
		1978	1979	1980	1978	1979	1980	1978	1979	1980	1978	1979	1980
1	MS	N/A	87.9	92.6	N/A	73.2	87.9	N/A	10.6	6.2	N/A	83.3	99.5
2	MS	N/A	92.3	88.5	N/A	66.4	87.6	N/A	6.4	8.8	N/A	90.0	98.4
3	MS	99.1	99.1	98.5	86.0	78.6	69.9	0.9	0.9	1.6	99.5	99.6	97.3
4	MS	97.3	98.7	97.7	82.3	89.7	84.5	1.9	1.3	2.3	99.9	99.8	99.9
5	SS	96.7	87.8	98.5	87.7	81.4	94.4	2.5	2.1	1.3	87.7	81.4	94.4
6	SS	72.1	93.3	97.0	70.8	80.3	94.2	27.3	4.8	1.2	70.8	80.3	94.2
7	SS	70.6	87.8	96.2	54.9	87.1	94.4	27.0	7.4	2.3	54.0	87.1	94.4
Mean		87.2	92.4	95.6	76.3	79.5	87.6	11.9	4.7	3.4	82.6	88.8	96.6
Standard Deviation		14.5	4.9	3.7	13.7	7.9	8.7	13.9	3.6	2.9	19.5	8.2	2.5

Notes: Effectiveness values were derived from availability models.

Equivalent availability values were derived from Eqs. A-12 and A-15, Appendix A.

Equivalent forced outage rate values were derived from Eq. A-8, Appendix A.

Operating availability values were derived from Eq. A-9, Appendix A.

*MS - multishaft; SS - single shaft.

Table 3-4

PERFORMANCE SUMMARY: LSF UNITS
(VALUES IN PERCENT)

Unit	Type of Unit*	Effectiveness			Equivalent Availability			Equivalent Forced Outage Rate			Equivalent Forced Outage Rate**			Operating Availability		
		1978	1979	1980	1978	1979	1980	1978	1979	1980	1978	1979	1980	1978	1979	1980
1	SS	96.5	88.2	81.3	92.7	82.0	84.4	3.5	11.8	18.8	1.4	2.6	0.3	92.7	82.0	94.4
2	SS	97.5	95.5	99.6	85.5	90.3	94.2	2.5	4.8	0.5	1.2	1.3	0.1	85.5	90.3	94.2
3	SS	96.0	90.2	24.0	84.2	91.4	98.2	4.0	9.8	75.9	1.5	1.3	1.0	84.2	91.4	98.2
4	SS	99.4	98.2	99.2	92.0	74.6	98.2	0.6	1.7	0.8	0.4	0.8	0.1	92.0	74.6	98.2
5	SS	57.1	62.4	34.3	44.3	82.4	85.2	42.9	37.5	65.7	9.6	6.2	14.6	44.3	82.4	85.2
6	SS	66.8	62.2	27.8	69.4	63.1	71.5	33.1	37.8	72.2	10.1	6.8	16.2	69.4	63.1	71.5
7	SS	49.8	62.5	25.2	63.9	79.4	69.6	50.2	37.5	74.8	17.1	10.9	12.4	63.9	79.4	69.6
8,9	MS	N/A	N/A	73.1	N/A	N/A	68.0	N/A	N/A	20.0	N/A	N/A	3.5	N/A	N/A	98.5
Mean		78.9	80.1	57.1	76.0	80.5	84.9	19.5	20.1	41.1	5.9	4.3	6.0	76.0	80.5	88.7
Standard Deviation		20.6	16.9	33.4	17.7	9.7	13.3	21.7	16.7	34.1	6.4	3.8	7.1	17.7	9.7	12.0

Notes: Effectiveness values were derived from availability models.

Equivalent availability values were derived from Eqs. A-12 and A-15, Appendix A.

Equivalent forced outage rate values were derived from Eq. A-8, Appendix A.

Operating availability values were derived from Eq. A-9, Appendix A.

*MS - multishaft; SS - single shaft.

**Equivalent forced outage rates in this column are defined as $\frac{FOH + EFOH}{FOH + SH + RSH} \times 100$.

RELIABILITY AND MAINTAINABILITY DATA BASE

Tables 3-5 and 3-6 summarize MTBF and MDT data for combined-cycle components for the seven gas-fired HSF units and the eight oil-fired LSF units, respectively. These data were derived from plant outage and maintenance logs and data forms supplied directly to General Electric or Westinghouse private data processing services. Outage data were carefully edited and validated with the plant superintendents. Failure causes were identified at the lowest component level permitted by the records. The number of systems for which data were analyzed is noted in parentheses following the system identification. Failures, MTBF, and MDT values are shown for components of the systems. Total operating hours are shown for each of the components listed. For most components, data were insufficient to establish distributions; hence, average values were considered to be the best estimate of the population mean. The component MTBF for one year's operation is the ratio of the fired hours for its respective system to the component's total failures. Similarly, component MDT or average outage duration for that year is the ratio of its total outage hours to its total number of failures. As shown, HSF unit components exhibited higher MTBFs than did corresponding LSF unit components. Control failures within CT and HRSG systems was a recurring problem, exhibiting both a high number of failures (an aggravation factor) and poor MTBF. Most HRSG control failures were drum-level trips. Unfortunately, plant outage data records did not provide sufficient detail of the root cause of the problem. Electrical control failure events excluded manual control trips and any CT starting trips that resulted in downtimes of 0.1 hour or less.

Note, this includes non demand period.

The effect of MTBF and MDT on availability is demonstrated in Tables 3-7 and 3-8, which average the MTBF and MDT values tabulated in Tables 3-5 and 3-6 for 1978 through 1980. (Tables 3-7 and 3-8 list only the most prominent components that experienced recurring failures.) A high percentage of the total failures for burners (afterburner system) and fuel nozzles (CT system) were isolated to only one of the plants assessed -- 60 of 67 fuel nozzle failures and all 92 of the burner failures. Hence, these failures were excluded from Table 3-8. For the 1978 to 1980 period, CT controls for HSF and LSF units exhibited relatively poor reliability and availability. CT electrical control failures for the HSF units were nearly twice those for the LSF units. Of the 182 electrical control failures, 93 occurred during 1979 and 1980; these were isolated to one plant. Thus it would appear that when the total electrical control failures were normalized for the HSF units, they would be in more favorable agreement with the 98 failures noted for the LSF units. Aside from CT false trips and starting failures, CT electrical control failures were a major problem and concern to operators of both LSF and HSF units assessed herein.

Table 3-5

COMPOSITE SYSTEM/COMPONENT RAM DATA SUMMARY FOR HSF UNITS

System/Component*	1978 Failure Events	1978 Operating Hours**	1978 MTBF (Hours)	1978 MDT (Hours)	1978 Std. Dev. (Hours)	1979 Failure Events	1979 Operating Hours	1979 MTBF (Hours)	1979 MDT (Hours)	1979 Std. Dev. (Hours)	1980 Failure Events	1980 Operating Hours	1980 MTBF (Hours)	1980 MDT (Hours)	1980 Std. Dev. (Hours)
CT System (15) (15)		42,533					89,918					101,170			
CT Unit, General	12		3,544	67.1	63	12		7,493	32.9	29	19		5,325	19.0	19
Combustion Section (Other)	2		21,267	1,124.0	--	6		14,987	52.0	73	8		12,646	79.8	23
Fuel Oil Flow Dividers	0		--	--	--	0		--	--	--	0		--	--	--
Fuel Oil Pumps	2		21,267	78.5	--	0		--	--	--	0		--	--	--
Fuel Oil Filters	0		--	--	--	1		89,918	1.4	--	0		--	--	--
Fuel Oil Systems (Other)	0		--	--	--	1		89,918	1.9	--	2		50,585	1.8	--
Starting System	1		42,533	0.3	--	9		9,991	6.0	3	3		33,723	3.5	0
Lube Oil System	3		14,178	9.0	0	17		5,289	40.3	19	8		12,646	5.1	4
Air System	1		42,533	9.4	--	3		29,972	37.1	60	11		9,197	13.9	12
Electrical Controls (Other)	30		1,418	9.3	16	79		1,138	22.7	19	75		1,349	8.0	4
Compressor	0		--	--	--	2		44,959	61.6	--	0		--	--	--
Inlet Guide Vanes	2		21,267	0.7	--	5		17,984	4.9	6	5		20,234	2.4	1
Turbine Exhaust Section	0		--	--	--	2		44,959	7.2	--	2		50,585	942.8	--
Turning Gear System	1		42,533	21.5	--	2		44,959	148.2	--	3		33,723	113.3	162
Fuel Nozzles	3		14,178	18.7	0	4		22,480	3.1	2	1		101,170	16.0	--
Fuel Gas System	6		7,089	1.8	1	10		8,992	11.0	5	7		14,453	4.3	1
Liners	1		42,533	3.6	--	7		12,845	123.0	276	1		101,170	29.9	--
Cross Fire Tubes	0		--	--	--	0		--	--	--	0		--	--	--
Transition Ducts	0		--	--	--	4		22,480	426.7	0	0		--	--	--
Fire Detection System	1		42,533	2.5	--	3		29,973	33.3	0	3		33,723	17.7	13
Afterburner System (2)		12,899					15,643					14,055			
Burners	0		--	--	--	0		--	--	--	0		--	--	--
Ignitors	1		12,899	22.0	--	0		--	--	--	0		--	--	--
Afterburner (Other)	1		12,899	13.1	--	0		--	--	--	4		3,514	13.3	0

*The number of systems for which data were analyzed is noted in parentheses.
**Operating hours for components were the same as the operating hours for their respective systems.

(continued)

Table 3-5 (continued)

COMPOSITE SYSTEM/COMPONENT RAM DATA SUMMARY FOR HSF UNITS

System/Component	1978 Failure Events	1978 Operating Hours	1978 MTBF (Hours)	1978 MDT (Hours)	1978 Std. Dev. (Hours)	1979 Failure Events	1979 Operating Hours	1979 MTBF (Hours)	1979 MDT (Hours)	1979 Std. Dev. (Hours)	1980 Failure Events	1980 Operating Hours	1980 MTBF (Hours)	1980 MDT (Hours)	1980 Std. Dev. (Hours)
HRSG System (15)		42,478					89,886					100,995			
Economizer	0		--	--	--	8		11,236	101.4	0	9		11,222	91.0	10
Flue Gas System	0		--	--	--	1		89,886	17.0	--	0		--	--	--
Low Pressure Evaporator	0		--	--	--	2		44,943	69.1	--	5		2,020	85.2	6
Feedwater Valves	0		--	--	--	0		--	--	--	1		100,995	14.0	0
Boiler Water Circulating Pump	0		--	--	--	3		29,962	67.4	0	6		16,833	51.0	18
Controls	17		2,499	3.9	3	12		7,491	4.1	4	27		3,741	10.8	5
Steam Drum	6		7,080	3.2	1	1		89,886	1.0	--	0		--	--	--
Steam Systems (Other)	0		--	--	--	1		89,886	19.5	--	0		--	--	--
Feedwater Systems (Other)	0		--	--	--	0		--	--	--	0		--	--	--
HRSG, General	10		4,278	13.1	5	11		8,171	113.0	244	17		5,941	3.7	4
High Pressure Evaporator	0		--	--	--	0		--	--	--	3		--	86.7	0
Superheater	0		--	--	--	0		--	--	--	0		33,665	--	--
Steam Turbine System (7)		32,360					49,376					49,735			
Steam Turbine, General	2		16,180	296.0	--	6		8,229	61.4	82	2		24,868	9.8	--
Protection System	0		--	--	--	0		--	--	--	0		--	--	--
Gland Seal System	0		--	--	--	0		--	--	--	0		--	--	--
Lube Oil System	0		--	--	--	2		34,688	125.0	--	0		--	--	--
Steam Control System	2		16,180	4.0	--	2		24,688	6.4	--	7		7,105	6.1	5
Condenser	1		32,360	50.0	--	4		12,344	4.8	1	1		49,735	1.2	--
Circulating Water Pumps (9)	2	47,674	23,837	37.6	--	1	66,270	66,270	4.0	--	11	66,316	6,029	42.5	59
Condensate Pumps (9)	0	47,674	--	--	--	0	66,270	--	--	--	2	66,316	33,158	82.5	--
Boiler Feedwater Pumps (9)	1	42,854	42,854	3.1	--	1	62,075	62,075	23.0	--	1	59,292	59,292	9.0	--
Generators (19)	0	74,893	--	--	--	10	139,294	13,929	18.6	4	6	150,905	25,151	13.8	9

Σ = 233359

MTBF = 233359 / 141

MTBF = 1655 hrs

MDT = 4872 / 141

= 34 hrs

Σ = 141

131471 hrs

MTBF = 131471 / 64

= 2054 hrs

MDT = 2378 / 64

= 37 hrs

3yr Load Factor

(32360 + 49376 + 49735) / 183960 hrs = 71.5% ≈ CAP FACTOR

7 * 8760 * 3yr = TOTAL POSSIBLE PLANT HRS

Table 3-6

COMPOSITE SYSTEM/COMPONENT RAM DATA SUMMARY FOR LSF UNITS

System/Component*	1978 Failure Events	1978 Operating Hours**	1978 MTBF (Hours)	1978 MDT (Hours)	1978 Std. Dev. (Hours)	1979 Failure Events	1979 Operating Hours	1979 MTBF (Hours)	1979 MDT (Hours)	1979 Std. Dev. (Hours)	1980 Failure Events	1980 Operating Hours	1980 MTBF (Hours)	1980 MDT (Hours)	1980 Std. Dev. (Hours)
CT System (11)		17,733					10,074					13,140			
CT Unit, General	12		1,478	72.3	205	6		1,679	8.7	1	40		329	6.8	1
Combustion Section (Other)	1		17,733	0.3	--	4		2,519	0.8	4	10		1,314	16.7	0
Fuel Oil Flow Dividers	2		8,867	82.7	--	1		10,074	0.3	--	4		3,285	6.3	2
Fuel Oil Pumps	2		8,867	11.1	--	2		5,037	1.5	--	6		2,190	107.0	245
Fuel Oil Filters	0		--	--	--	1		10,074	2.6	--	9		1,460	3.4	0
Fuel Oil Systems (Other)	3		5,911	3.8	3	6		1,679	18.4	19	23		571	2.7	0
Starting System	9		1,970	3.3	4	2		5,037	0.7	--	10		1,314	11.3	9
Lube Oil System	6		2,956	37.8	40	8		1,259	54.1	57	8		1,643	21.7	27
Air System	14		1,267	10.8	7	10		1,007	16.9	19	2		6,570	4.8	--
Electrical Controls (Other)	32		554	4.7	6	29		347	123.0	155	37		355	5.3	4
Compressor	1		17,733	2.1	--	0		--	--	--	1		13,140	3.3	--
Inlet Guide Vanes	2		8,867	9.1	--	0		--	--	--	4		3,285	3.2	0
Turbine Exhaust Section	0		--	--	--	2		5,037	1.7	--	8		1,643	8.5	5
Turning Gear System	2		8,867	4.0	--	4		2,519	60.0	86	7		1,877	11.2	0
Fuel Nozzles	3		5,911	10.9	--	4		2,519	3.5	2	60		719	4.2	0
Fuel Gas System	14		1,267	2.2	1	3		3,358	2.3	1	5		2,628	9.4	2
Liners	0		--	--	--	0		--	--	--	0		--	--	--
Cross Fire Tubes	3		5,911	6.6	3	0		--	--	0	0		--	--	--
Transition Ducts	0		--	--	--	0		--	--	--	0		--	--	--
Fire Detection System	2		8,867	1.6	--	0		--	--	--	0		--	--	--
Afterburner System (4)		0					0					1,459			
Burners	0		--	--	--	0		--	--	--	92		16	8.9	0
Ignitors	0		--	--	--	0		--	--	--	0		0	--	--
Afterburner (Other)	0		--	--	--	0		--	--	--	0		0	--	--

*The number of systems for which data were analyzed is noted in parentheses.
**Operating hours for components were the same as the operating hours for their respective systems.

(continued)

based on 24 hr clock (all

$\left(\frac{11.3}{24}\right) 6.5 = 3.1$ hrs

Based on fired hrs

Table 3-6 (continued)

COMPOSITE SYSTEM/COMPONENT RAM DATA SUMMARY FOR LSF UNITS

1978

System/Component	Failure Events	Operating Hours	MTBF (Hours)	MDT (Hours)	Total Downtime	Std. Dev. (Hours)
HRSG System (11)		17,733				
Economizer	0		--	--		--
Flue Gas System	0		--	--		--
Low Pressure Evaporator	5		--	12.9	64.5	25
Feedwater Valves	0		--	--		--
Boiler Water Circulating Pump	0		--	--		--
Controls	45		394	2.6	117	2
Steam Drum	2		8,867	1.2	2.4	--
Steam Systems (Other)	0		--	--		--
Feedwater Systems (Other)	2		8,867	1.9	3.8	--
HRSG, General	0		--	--		--
High Pressure Evaporator	0		--	--		--
Superheater	0		--	--		--
(handwritten totals)	54				187.7	
Steam Turbine System (9)		17,733				
Steam Turbine, General	9		1,970	1.6	14.4	2
Protection System	0		--	--		--
Gland Seal System	0		--	--		--
Lube Oil System	4		4,433	9.0	36.0	10
Steam Control System	7		2,533	2.3	16.1	3
Condenser	2		8,867	3.6	7.2	--
Circulating Water Pumps (9)	7	17,733	2,533	19.6	137.2	16
Condensate Pumps (9)	6	17,733	2,956	36.3	217.8	33
Boiler Feedwater Pumps (9)	2	17,733	8,867	50.2	100.4	--
Generators (20)	12	17,733	1,470	8.5	102	4
(handwritten totals)	49				631.1 hrs	

1979

System/Component	Failure Events	Operating Hours	MTBF (Hours)	MDT (Hours)	Total Downtime	Std. Dev (Hours)
HRSG System (11)		10,074				
Economizer	0		--	--		--
Flue Gas System	0		--	--		--
Low Pressure Evaporator	0		--	--		--
Feedwater Valves	0		--	--		--
Boiler Water Circulating Pump	0		--	--		--
Controls	31		325	3.3	102.3	6
Steam Drum	0		--	--		0
Steam Systems (Other)	1		10,074	4.1	4.1	--
Feedwater Systems (Other)	0		--	--		--
HRSG, General	1		10,074	1.0	1.0	--
High Pressure Evaporator	0		--	--		--
Superheater	3		3,358	115.0	445	--
(handwritten totals)	36				552.4	
Steam Turbine System (9)		10,074				
Steam Turbine, General	10		1,007	6.7	67	3
Protection System	0		--	--		--
Gland Seal System	0		--	--		--
Lube Oil System	2		5,037	8.1	16.1	--
Steam Control System	18		560	7.0	126	5
Condenser	2		5,037	2.8	5.6	--
Circulating Water Pumps (9)	3	10,074	3,358	84.1	252.3	5
Condensate Pumps (9)	0	10,074	--	--		--
Boiler Feedwater Pumps (9)	1	10,074	10,074	19.2	19.2	--
Generators (20)	0	10,074	--	--		--
(handwritten totals)	36				486 hrs	

1980

System/Component	Failure Events	Operating Hours	MTBF (Hours)	MDT (Hours)	Total Downtime	Std. Dev. (Hours)
HRSG System (11)		13,140				
Economizer	14		939	15.8	221	0
Flue Gas System	3		4,380	29.0	87	0
Low Pressure Evaporator	10		1,314	14.3	143	0
Feedwater Valves	18		730	10.0	180	2
Boiler Water Circulating Pump	0		--	--		--
Controls	48		274	14.8	710.4	13
Steam Drum	5		2,628	3.0	15	0
Steam Systems (Other)	4		3,285	3.4	13.6	2
Feedwater Systems (Other)	1		13,140	6.0	6	--
HRSG, General	8		1,643	3.5	28	2
High Pressure Evaporator	0		--	--		--
Superheater	1		13,140	146.0	146	--
(handwritten totals)	112				1550	
Steam Turbine System (9)		9,025				
Steam Turbine, General	10		902	7.8	78	0
Protection System	2		4,513	30.7	61.4	0
Gland Seal System	1		9,026	2.0	2	--
Lube Oil System	3		3,009	45.8	137.4	31
Steam Control System	20		451	3.7	74	4
Condenser	5		1,805	7.6	38	0
Circulating Water Pumps (9)	9	19,929	2,214	36.4	327.6	8
Condensate Pumps (9)	2	19,929	9,965	4.0	8	--
Boiler Feedwater Pumps (9)	9	13,140	1,460	124.7	1122	159
Generators (20)	5	22,165	4,433	11.5	57.5	4
(handwritten totals)	66				1905.9 hrs	

$\Sigma = 40946$ hrs

$MTBF = \frac{40946}{202} = 202$

$MDT = \frac{2290}{202} = 11.3$

$\Sigma = 36832$ hrs

$MTBF = \frac{36832}{151} = 243$

$MDT = \frac{3023}{151} = 20.0$

9 STEAM TURB

11 GAS TURB

$\left(\frac{20}{24}\right)$ 6.5 hrs Avg solar/day = 5.4 hrs

Turbine, Circ water, Cond, Feed Pumps, Generators

SG AVAIL

SOL I: $\frac{187}{187+2.2} = .988$

TURB AVAIL COMB CYC: $\frac{243}{243+5.4} = .978$

SEGS assuming 0/6000: $\frac{8333}{8333+14.1} = .998$

HRSG COMB CYC: $\frac{202}{202+3.1} = .985$

Table 3-7

COMPONENT RAM DATA SUMMARY FOR HSF UNITS (1978-1980)

Component	System*	Total Failures	Average MTBF	Average MDT
Electrical Controls (Other)	CT	182	1,284	14.9
Controls	HRSG	56	4,167	7.3
CT Unit, General	CT	43	5,433	36.3
HRSG, General	HRSG	38	6,141	37.8
Lube Oil System	CT	28	8,344	26.9
Fuel Gas System	CT	22	10,619	6.8
Economizer	HRSG	17	13,727	95.9
Generators	--	16	22,818	16.3
Combustion Section (Other)	CT	16	14,601	180.4
Air System	CT	15	15,575	18.2

*CT - combustion turbine; HRSG - heat recovery steam generator.

COMPONENT SENSITIVITY ANALYSES

As discussed in Section 2, analytical models can be used to assess the relative effect that changes in component MTBF, MDT, or availability have on combined-cycle unit effectiveness. The degree of sensitivity will of course differ among utilities because of minor differences in plant designs. Sensitivity analyses can be helpful in determining whether improving component MTBF or reducing MDT will yield a worthwhile improvement in plant effectiveness (excluding economic considerations). For example, it may be desired to determine what gain in unit effectiveness could be expected in a STAG 400 unit if the availability of the boiler feedwater pump (BFP) were 100 percent (the BFP could be a single-point-failure item). One hundred percent availability would be approached by incorporation of a redundant BFP in the unit. Similarly, the plant operator may wish to assess what gain in unit effectiveness could be expected if the MTBF of the CT electrical controls were doubled. Therefore, changes in component failure rates or outage duration affect plant effectiveness differently. An availability model for a given plant design can, for example, rank these components according to the following criteria:

- Case 1: Failure Rate - the change in plant effectiveness per change in component failure rate

Table 3-8

COMPONENT RAM DATA SUMMARY FOR LSF UNITS (1978-1980)

Component	System*	Total Failures	Average MTBF	Average MDT
Controls	HRSG	124	330	7.4
Electrical Controls (Other)	CT	98	418	39.9
CT Unit, General	CT	58	706	20.5
Steam Control System	ST	45	818	2.0
Fuel Oil System (Other)	CT	32	1280	5.7
Steam Turbine, General	ST	29	1270	5.5
Air System	CT	26	1575	12.7
Lube Oil System	CT	24	1706	34.7
Fuel Gas System	CT	22	1861	3.9
Starting System	CT	21	1950	6.9
Circulating Water Pumps	--	19	2512	37.7
Feedwater Valves	HRSG	18	2275	10.0
Generators	--	17	2940	9.4
Low Pressure Evaporator	HRSG	15	2730	13.8

*HRSG - heat recovery steam generator; CT - combustion turbine; ST - steam turbine.

- Case 2: Mean Downtime - the change in plant effectiveness per change in component mean downtime
- Case 3: Availability - the change in plant effectiveness per change in component availability
- Case 4: Power Gain - the increase in plant effectiveness (percentage points gained) when the availability of a component is considered to be 100 percent

Table 3-9 is an example of component rankings for a multishaft combined-cycle unit. The results are not actual values, but serve only to illustrate how candidates for R&A improvement could be identified. As shown in case 4, if the CT controls could be made perfect (i.e., 100 percent availability), the unit could expect 0.60 percentage-point improvement in effectiveness or equivalent forced outage rate.

Table 3-9

EXAMPLE OF COMPONENT RANKING ANALYSIS (NOT ACTUAL DATA)

System/Component	System	Case 1	Case 2	Case 3	Case 4*
Electrical Controls (Other)	CT	1	1		1 (0.60)
Steam Turbine, General	ST	2	2	4	2 (0.55)
Circulating Water Pumps	--	3	3	5	3 (0.51)
Economizer	HRSG	4	4		4 (0.42)
Lube Oil System	CT	5	5		5 (0.22)
Combustion Section (Other)	CT	6	6		6 (0.10)
Turning Gear System	CT	7	7		7 (0.08)
Low Pressure Evaporator	HRSG	8	8		8 (0.07)
Condenser	Cond	9	9	1	9 (0.04)
Fire Detection System	CT	10	10		10 (0.04)
Condensate Pumps	Cond			2	
Boiler Feedwater Pumps	Cond			3	
Steam Turbine, General	ST			6	
Protection System	ST			7	
Gland Seal System	ST			8	
Lube Oil System	ST			9	
Steam Control System	ST			10	

Notes: Case 1 - Change in plant effectiveness per change in component failure rate

Case 2 - Change in plant effectiveness per change in component mean downtime

Case 3 - Change in plant effectiveness per change in component availability

Case 4 - Increase in plant effectiveness when the availability of a component is considered to be 100 percent

*Numbers in parentheses indicate percentage-point improvement.

Operators can perform these analyses for combined-cycle power plants having a reliability data base (as shown in Tables 3-5 and 3-6) and an appropriate availability model. Analytical approaches can therefore provide considerable insight into the impact of equipment failures or outage durations on plant operations. The analyses would also be helpful to plant engineers considering design changes that would alter systems states or state capability. It is strongly recommended that the operating utilities consider these advantages and establish internal capability for availability modeling.

Section 4

RESULTS OF COMBUSTION TURBINE DATA ANALYSES

The results presented in this section are directed at qualifying specific operational factors that affect CT reliability. In support of EPRI Contract RP1800-1 (6), the Westinghouse Electric Corporation has investigated the effect on CT failure rates of such factors as time, service factor, type of fuel, maintenance procedures, operational procedures, size and model, combustor temperature, vibration, humidity, number of starts, complexity, and design margin. Of these variables, the first six (time, service factor, type of fuel, maintenance procedures, operational procedures, and unit size and model) have been verified by using operational data records. An understanding of the correlation between turbine system/component failure rates and these independent variables is important in predicting expected turbine reliability under actual plant operating conditions. Prior to this effort, some of these results had been theorized, but had not actually been qualified.

Data analyzed included three years' operating experience for 15 HSF gas-fired CTs and 11 LSF oil-fired CTs. For each of these turbines and their components, identified in Tables 3-5 and 3-6, the following data were examined for 1978, 1979, and 1980:

- Failure rate (λ) in failures per million hours of operation ($\lambda = \frac{1,000,000}{MTBF}$)
- MDT in hours
- Fired hours per year
- Number of successful starts per year

Plant operators normally shut down the CT system to perform maintenance on a failed CT component. Hence the failure rate of a CT system is equal to the sum of its component failure rates. The MDT of a CT system is the weighted average of its component downtimes. These data were used to investigate the effects on turbine failure rates of four independent variables -- service factor (SF), fired hours per start (FHPS), fuel type (FT), and fired hours. The following sections qualify these correlations for CTs and selected components.

COMBUSTION TURBINE RELIABILITY GROWTH

Industry observations of turbine performance data indicate that failure rates tend to decrease with time, although reliability trends during early maturity (usually three years) are often difficult to establish. However, as early burn-in problems are corrected, preventive maintenance policies are established, and operators become more familiar with equipments, reliability improvement is observed for many turbines.

Statisticians use different forms of mathematical expressions and techniques to investigate reliability growth. One model developed by Duane (7) (see Appendix B) suggests that the failure rates (λ) for many mechanical components can be expressed as:

$$\theta(t) = at^{b} \tag{4-1}$$

where

$\theta(t)$ = cumulative MTBF
t = operating hours
a, b = constants determined by fitting a least-squares curve to the data

This relationship can be applied successfully to many CT systems. However, with the recent introduction of MIL-HDBK-189 (dated February 13, 1981), "Military Handbook, Reliability Growth Management," many other reliability growth models are now described in a single reference. The U.S. Army Material Systems Analysis Activity (AMSAA) model described in Appendix B is appropriate to quantify reliability growth in mechanical systems. The model is described as:

$$\lambda(t) = \alpha\beta t^{\beta - 1} \tag{4-2}$$

where

$\lambda(t)$ = instantaneous failure rate or the intensity function
α, β = parameters determined from the data analyses
t = time in hours

Because many variables can affect turbine reliability, it is appropriate to consider only those HSF turbines which have been in service for three or more years prior to 1979. On the basis of this criterion and the quality of data supporting this analysis, 13 of the 15 turbines operated during the period 1979 through 1980 were analyzed. The CT systems were composed of both General Electric and Westinghouse turbines. Figure 4-1 illustrates the resulting reliability growth function in terms of MTBF f(t). The α and β parameters are maximum likelihood estimates based on equations presented in MIL-HDBK-189. The calculated mean for this sample is 622 hours.

THE EFFECTS OF SERVICE FACTOR AND STARTING FREQUENCY ON COMBUSTION TURBINE RELIABILITY

Tables 4-1 and 4-2 are performance summaries for the 15 HSF unit turbines and 11 LSF unit turbines, respectively. Each turbine has a code that identifies the fuel and the year for which the data shown are applicable. The turbines are ranked by increasing failure rates. Table 4-3 presents an average performance summary for these turbines by year. Tables D-1 and D-2 of Appendix D present more detailed breakdowns of the individual failure events for each of the coded turbines. The general effect of service factor and fired hours per start on turbine failure rates is shown in Figures 4-2 and 4-3. Because there is little overlap between the oil- and gas-fired data in midrange service, it is difficult to establish whether fuel selection is a significant variable. However, both service factor and fired hours per start definitely affect turbine failure rates for both HSF and LSF units.

The data of Tables 4-1 and 4-2 were analyzed with multiple regression techniques in an effort to evaluate the relative effect of SF, FHPS, and FT on turbine failure rate and to determine if the data could be represented by a mathematical equation. Both a polynormal and a logarithmic relationship were used. The highest correlation coefficient of 86 percent was achieved by the logarithmic expression:

$$\ell n\, \lambda = 11.48 - 0.58\, \ell n(FHPS) - 1.29(SF) - 0.07(FT) \qquad (4\text{-}3)$$

where

fuel type = 0 for oil-fired turbines, 1 for gas-fired turbines

Eighty-two percent of the data variance can be explained by FHPS, 3.5 percent can be explained by SF, and 0.5 percent can be explained by FT. Therefore, for these data populations, FT would appear to have the least effect on predicted failure rates; FHPS would have the greatest effect. FHPS and SF are related through a common variable, time. Hence some interdependency exists that cannot be explained by the equation.

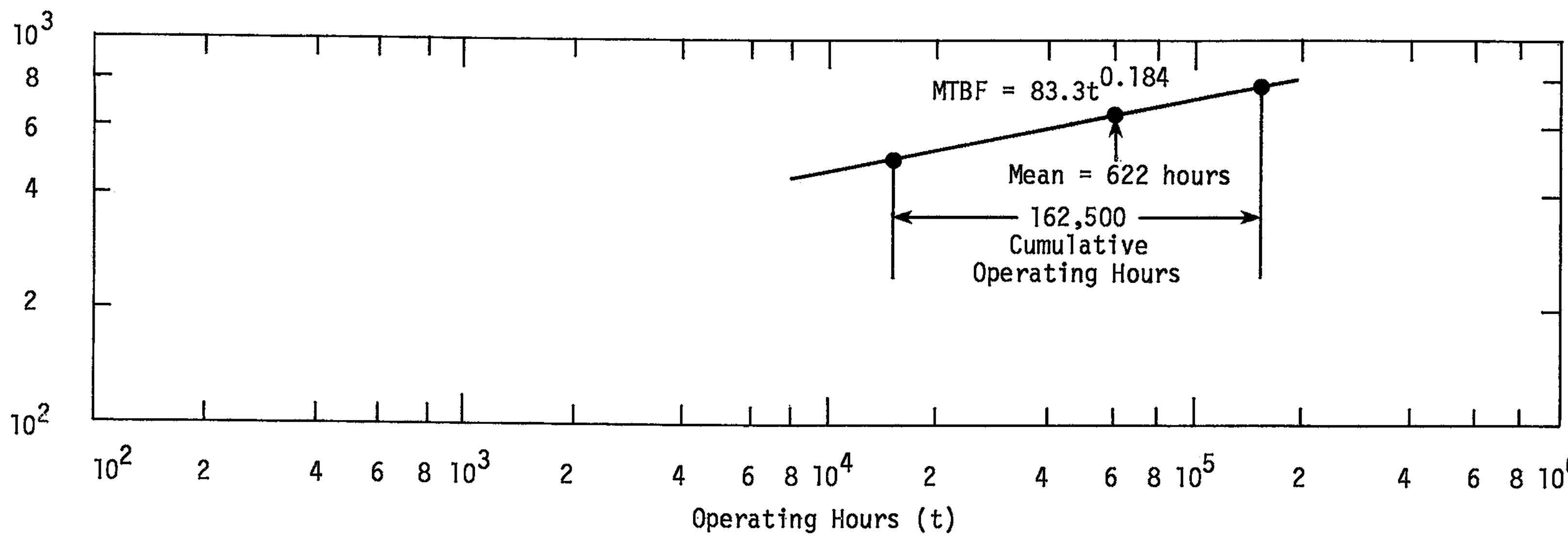

Figure 4-1. Reliability Growth Curve for 13 Gas-Fired HSF Turbines (1979-1980)

Table 4-1

PERFORMANCE SUMMARY FOR HSF UNIT TURBINES, 1978-1980

Code*	Number of Failures	Failure Rate (λ)**	Mean Downtine (Hours)	Service Factor	Fired Hours per Start
S80-G	3	603	14.7	0.77	357
U80-G	5	639	3.7	0.91	625
T78-G	5	670	42.8	0.77	286
T80-G	5	673	2.2	0.83	370
R80-G	4	687	3.6	0.90	238
O79-G	5	871	39.8	0.66	333
I80-G	7	992	17.1	0.80	286
U79-G	8	1016	9.9	0.90	303
S78-G	5	1044	235.9	0.55	116
J80-G	8	1081	16.3	0.84	244
S79-G	7	1090	25.9	0.73	128
P80-G	8	1117	28.2	0.82	345
Q79-G	7	1154	4.0	0.69	81
J79-G	9	1251	27.6	0.82	303
W79-G	9	1271	3.0	0.81	270
O80-G	9	1350	8.2	0.76	233
T79-G	11	1390	8.1	0.90	435
P79-G	7	1414	43.1	0.57	250
R79-G	8	1456	21.5	0.63	81
U78-G	10	1528	8.3	0.75	250
V78-G	10	1569	5.3	0.73	143
L80-G	12	1629	40.0	0.84	238
Q80-G	9	1663	1.8	0.84	588
W80-G	12	1767	2.6	0.78	227
R78-G	10	1840	196.0	0.62	76
Q78-G	13	1907	9.6	0.78	91
W78-G	12	1933	2.0	0.71	156
M80-G	15	1943	20.8	0.88	244
V79-G	14	2044	5.5	0.78	323
M79-G	12	2430	63.5	0.57	189
I79-G	14	2464	15.0	0.65	189
N80-G	15	2589	160.9	0.66	278
V80-G	16	2695	2.8	0.68	263
K80-G	20	2707	9.1	0.84	167
L79-G	19	3424	73.8	0.64	204
N79-G	16	3456	49.9	0.53	313
K79-G	21	4365	100.4	0.55	100
Average	10.3	1668	35.0	0.74	252

* S80-G: Turbine Identifier (S), Year (80), Gas-Fired (G)

**Failures per million hours of operation, $\lambda = \frac{1,000,000}{MTBF}$.

Table 4-2

PERFORMANCE SUMMARY FOR LSF UNIT TURBINES, 1978-1980

Code*	Number of Failures	Failure Rate (λ)**	Mean Downtime (Hours)	Service Factor	Fired Hours per Start
B80-0	0	0	0.0	0.07	31
D78-0	11	2,045	2.3	0.62	185
D79-0	6	2,184	6.9	0.31	94
A78-0	7	2,214	12.4	0.36	99
D80-0	1	2,293	2.4	0.05	87
B78-0	8	2,320	2.0	0.39	128
A79-0	4	2,795	0.7	0.16	84
C78-0	10	3,732	3.8	0.31	89
B79-0	12	5,816	7.9	0.24	69
A80-0	1	8,278	12.3	0.01	11
C79-0	10	10,452	8.3	0.11	53
G79-0	19	13,447	30.0	0.16	15
F79-0	9	13,493	21.8	0.08	11
G78-0	19	16,624	48.7	0.13	12
F80-0	8	17,095	81.7	0.05	8
H80-0#	197	18,711	6.3	0.30	10
E80-0	13	19,403	11.0	0.08	10
F78-0	30	21,806	11.2	0.16	12
E79-0	22	27,638	5.7	0.09	10
C80-0	1	37,313	0.7	0.01	27
E78-0	23	42,127	13.9	0.06	12
G80-0	13	44,369	3.4	0.03	6
Average	20.2	13,058	14.0	0.17	48.3

* B80-0: B = Turbine Identifier; 80 = Year; 0 = Oil-Fired

**Failures per million hours of operation, $\lambda = \frac{1,000,000}{MTBF}$.

#H80-0 represents the combined performance of four turbines.

THE EFFECTS OF SERVICE FACTOR AND STARTING FREQUENCY ON SELECTED COMBUSTION TURBINE COMPONENTS

Components exhibiting a high number of failures over the data period (see Tables 3-7 and 3-8) were selected for analysis. These components included electrical controls; CT unit, general; air system; fuel gas system; fuel oil systems (other); and lube oil system. Although data were more limited here than in the preceding CT system analysis, both SF and FHPS had an obvious effect on failure rates. This is illustrated in Figures 4-4 through 4-11.

Table 4-3

TURBINE PERFORMANCE SUMMARY FOR 1978, 1979, AND 1980 (ALL VALUES ARE AVERAGES)

	LSF Unit Turbines					HSF Unit Turbines				
Year	Failure Rate*	Mean Downtime	Availability	Service Factor	Fired Hours per Start	Failure Rate*	Mean Downtime	Availability	Service Factor	Fired Hours per Start
1978	13,023	13.8	0.848	0.290	76.7	1499	71.4	0.925	0.701	160
1979	10,832	11.6	0.877	0.164	48.0	1940	32.7	0.930	0.695	233
1980	21,066	16.8	0.780	0.074	23.7	1468	22.8	0.963	0.810	314

*Failure per million hours of operation, $\lambda = \frac{1,000,000}{MTBF}$.

Component data were too limited to determine how failures were distributed with time; however, a statistical treatment of the lube oil system failures was performed with Weibull techniques. The results, shown in Appendix B, serve to illustrate the concepts involved. Figure B-4 is of specific interest to plant engineers. Although it is based on industrywide experience, cumulative probability distributions of this form can be derived for a specific operating plant if sufficient failure data are on record. These distributions indicate the probability that a failure is likely at some time during the equipment's operation. With an expanded data base, such results are attainable for many combined-cycle components.

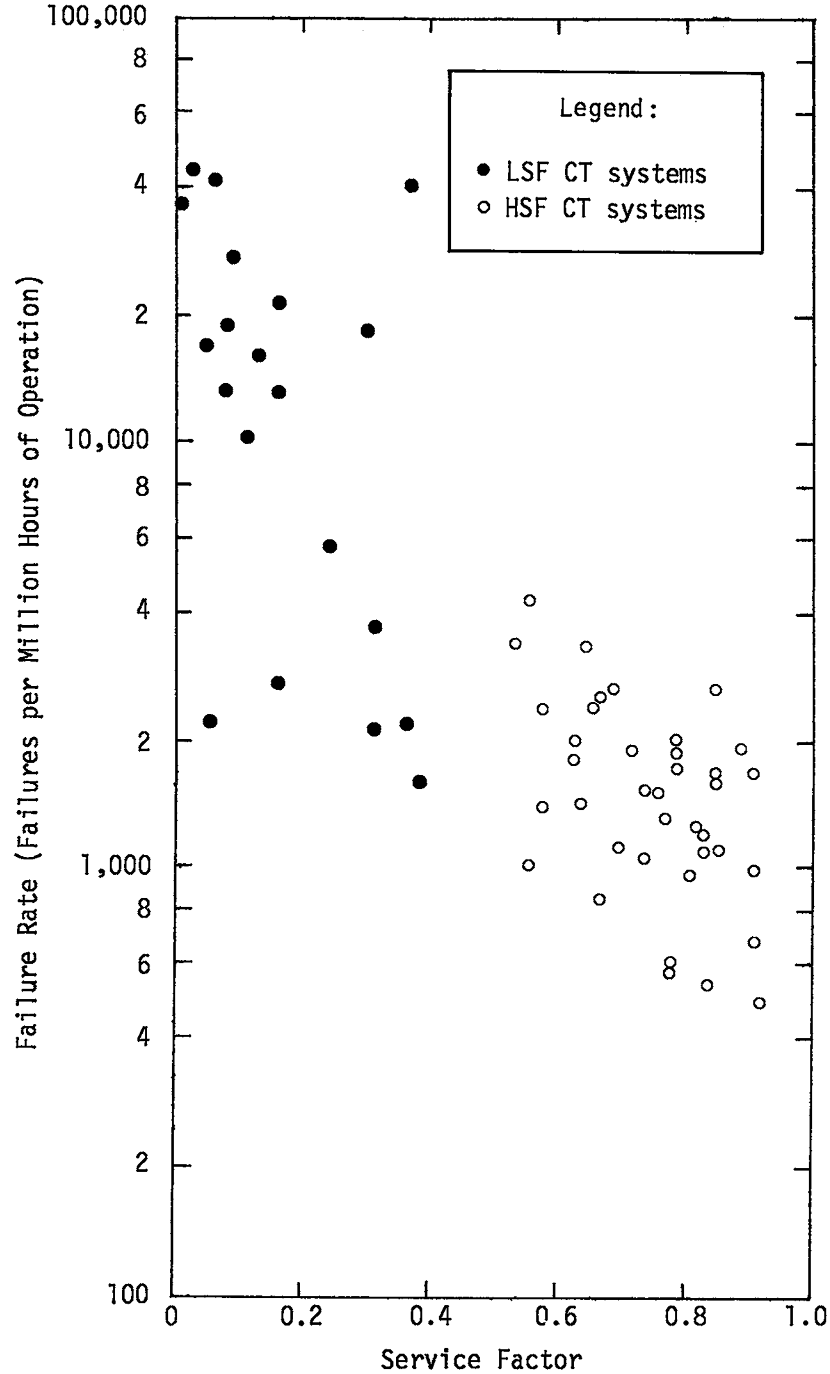

Figure 4-2. Effect of Service Factor on CT System Failure Rates

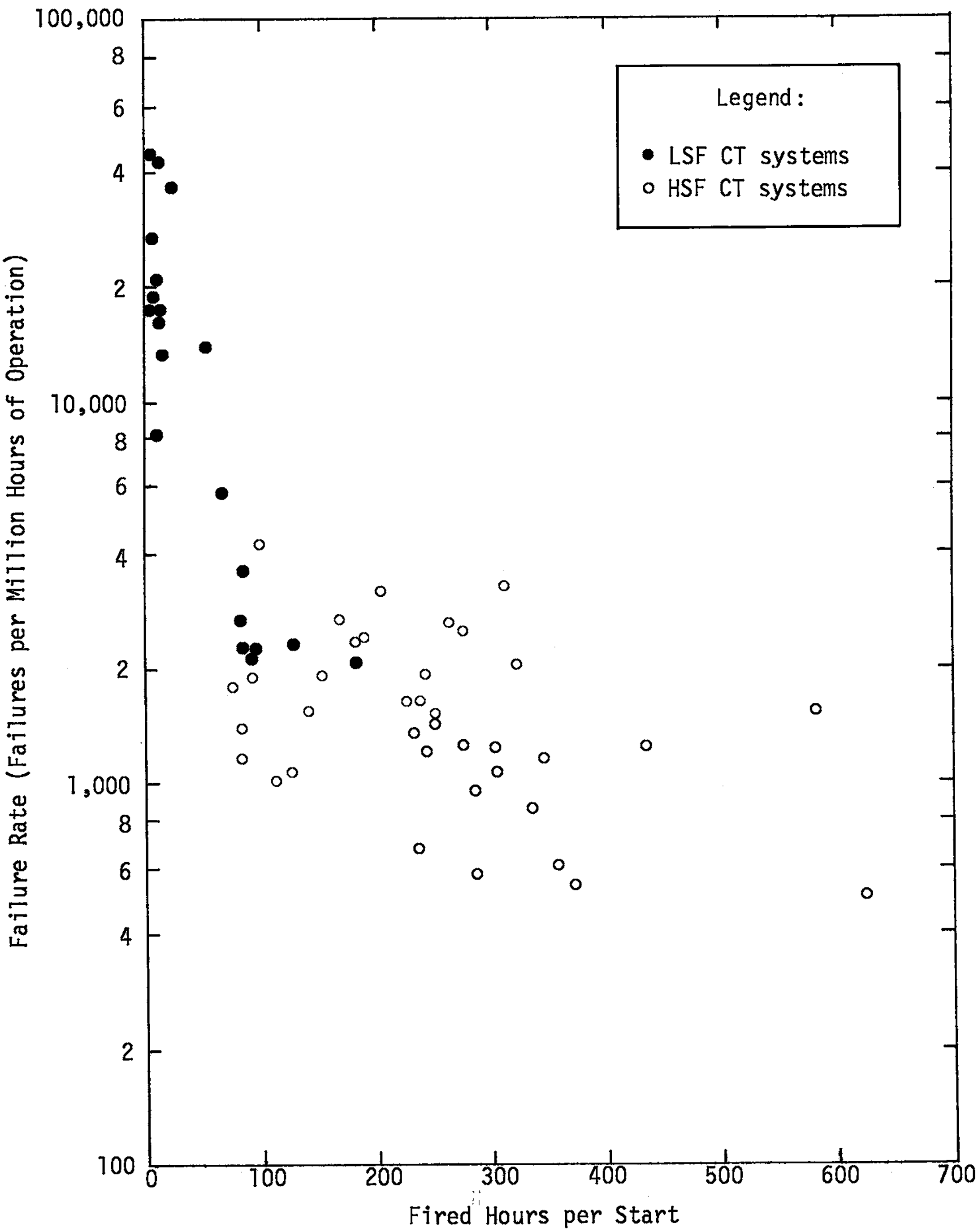

Figure 4-3. Effect of Fired Hours per Start on CT System Failure Rates

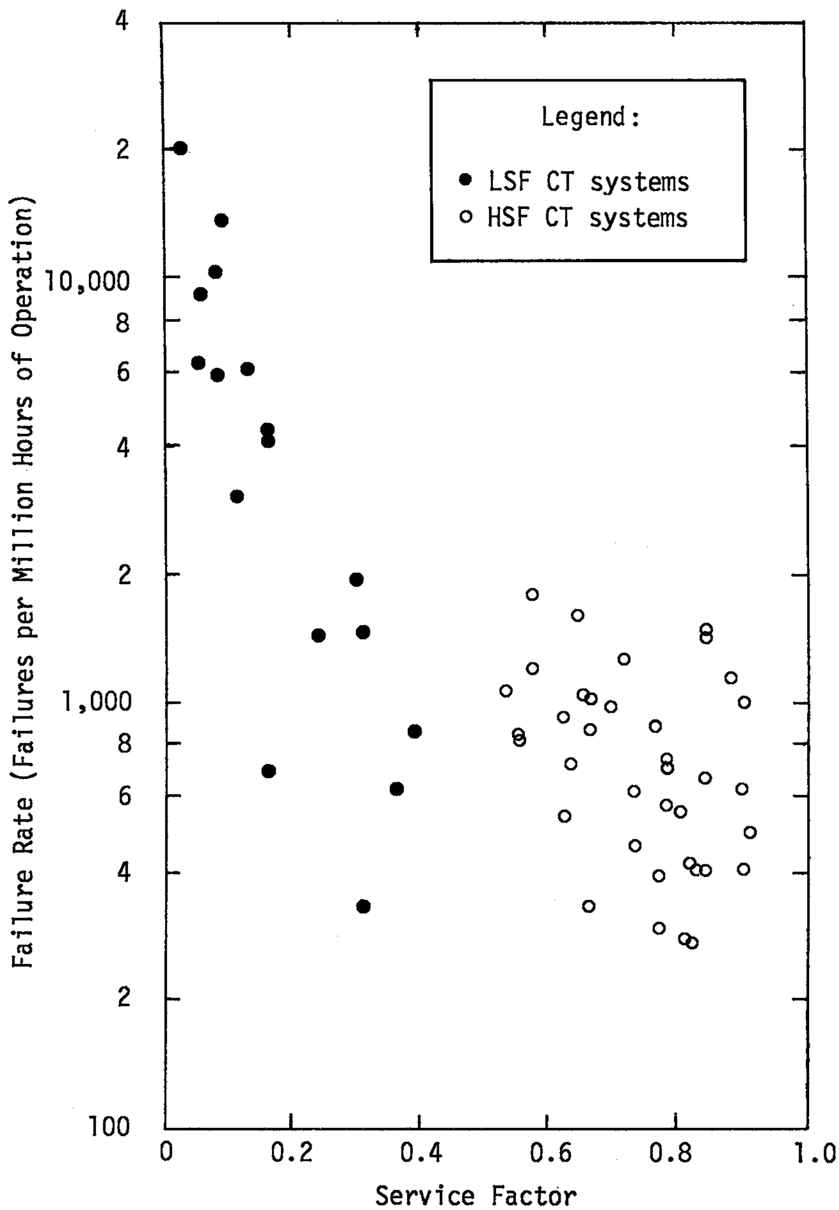

Figure 4-4. Effect of Service Factor on Electrical Controls (Other) Failure Rates

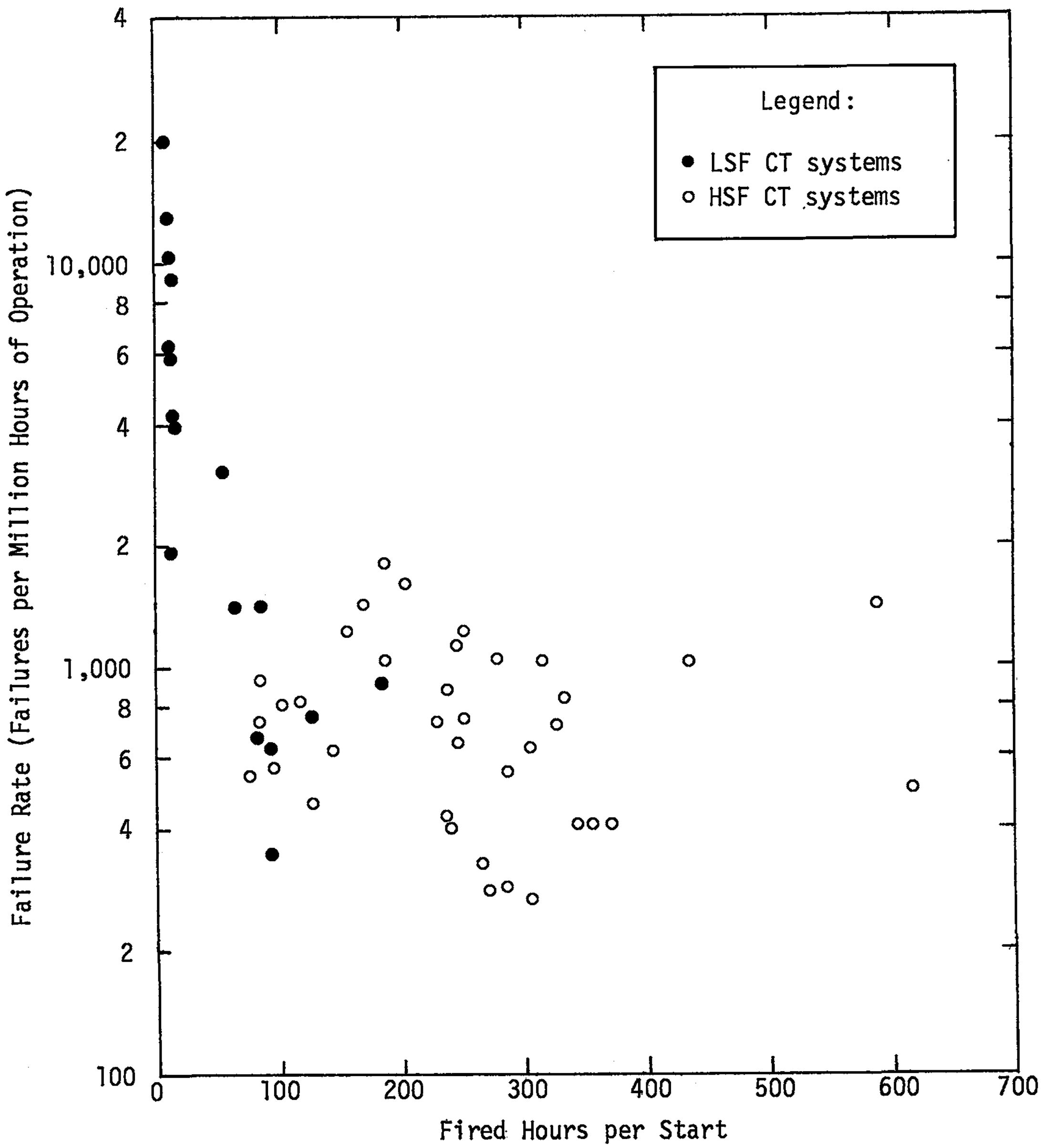

Figure 4-5. Effect of Fired Hours per Start on Electrical Controls (Other) Failure Rates

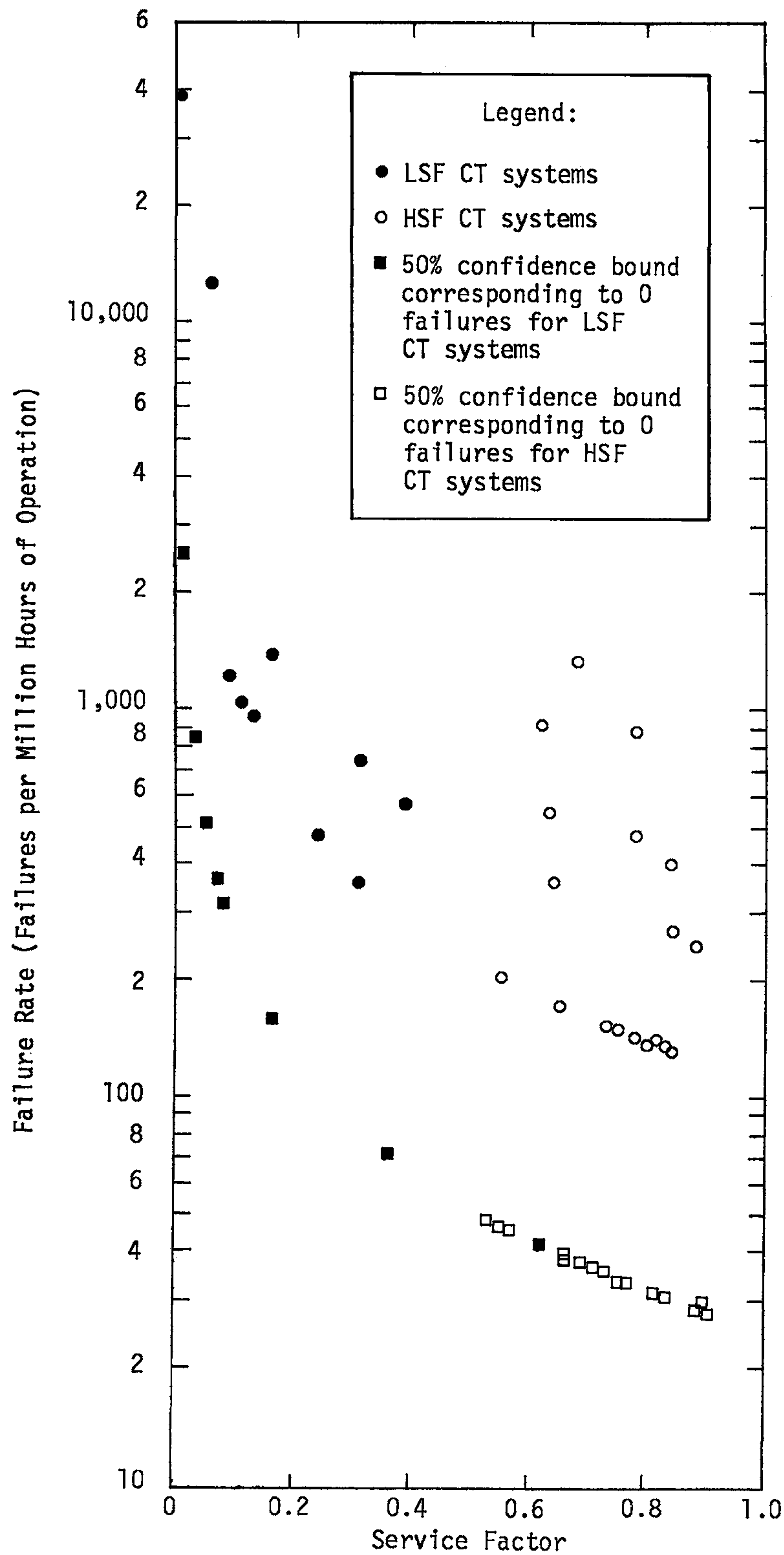

Figure 4-6. Effect of Service Factor on CT Unit, General, Failure Rates

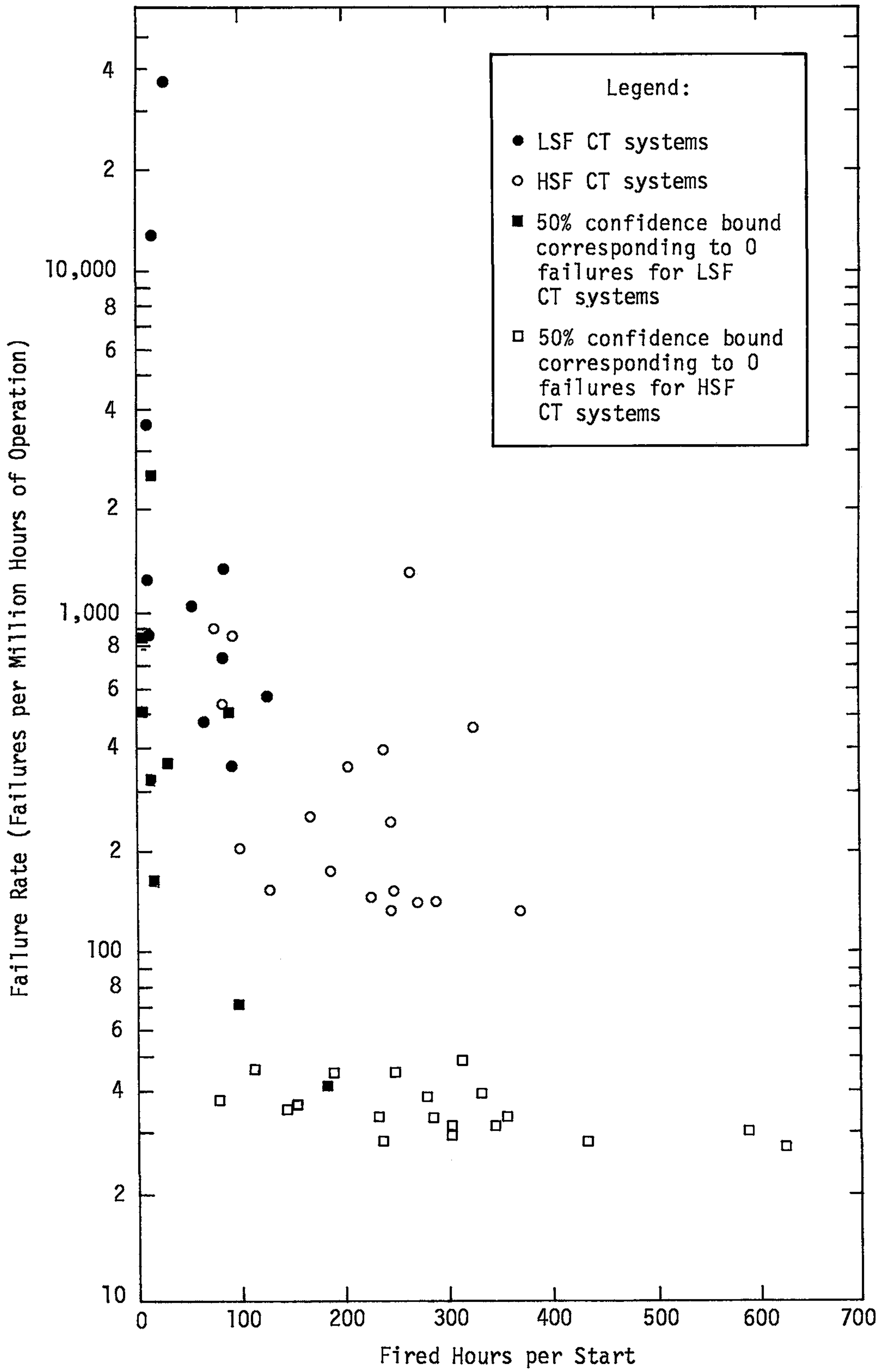

Figure 4-7. Effect of Fired Hours per Start on CT Unit, General, Failure Rates

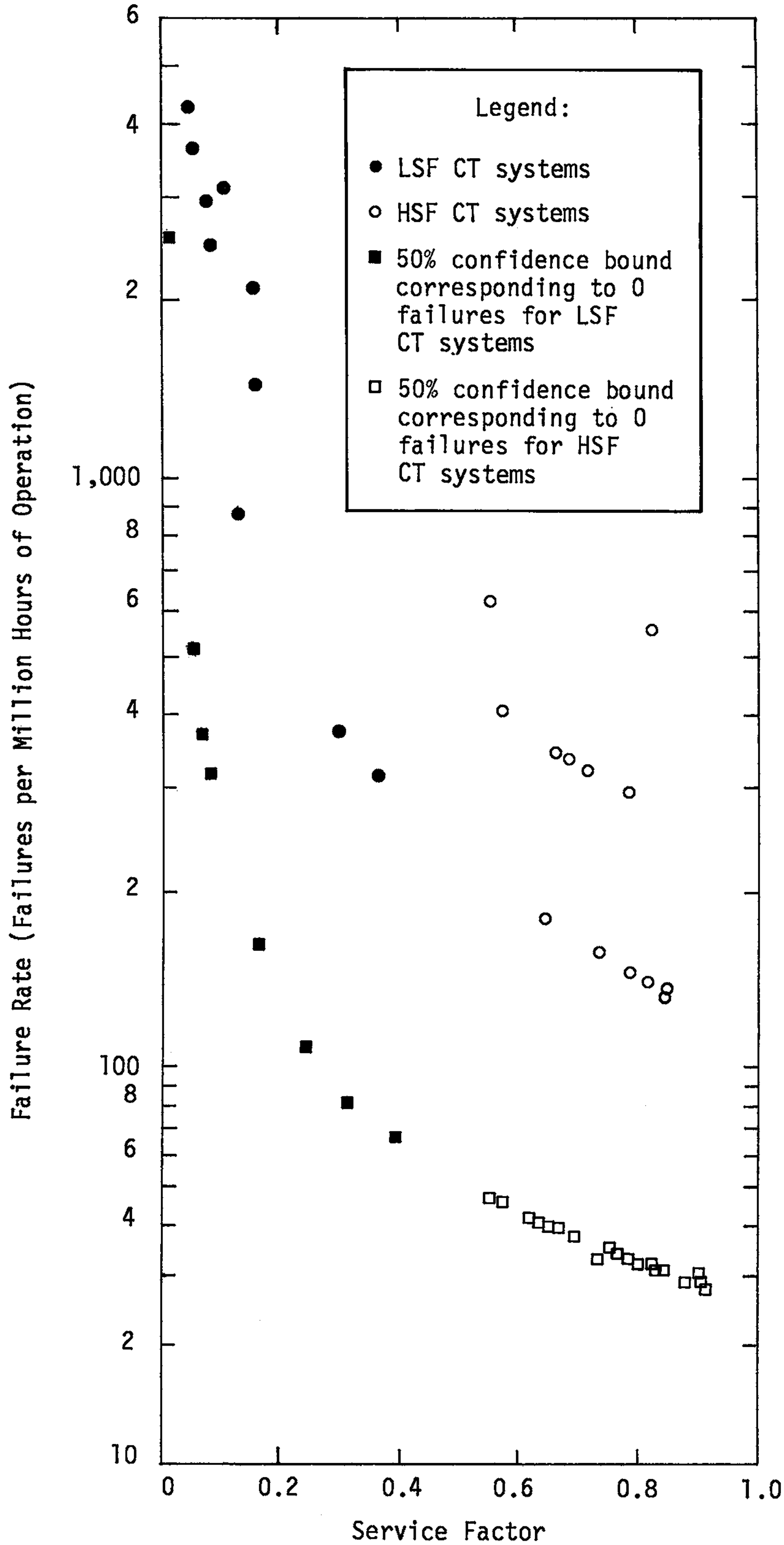

Figure 4-8. Effect of Service Factor on Lube Oil System Failure Rates

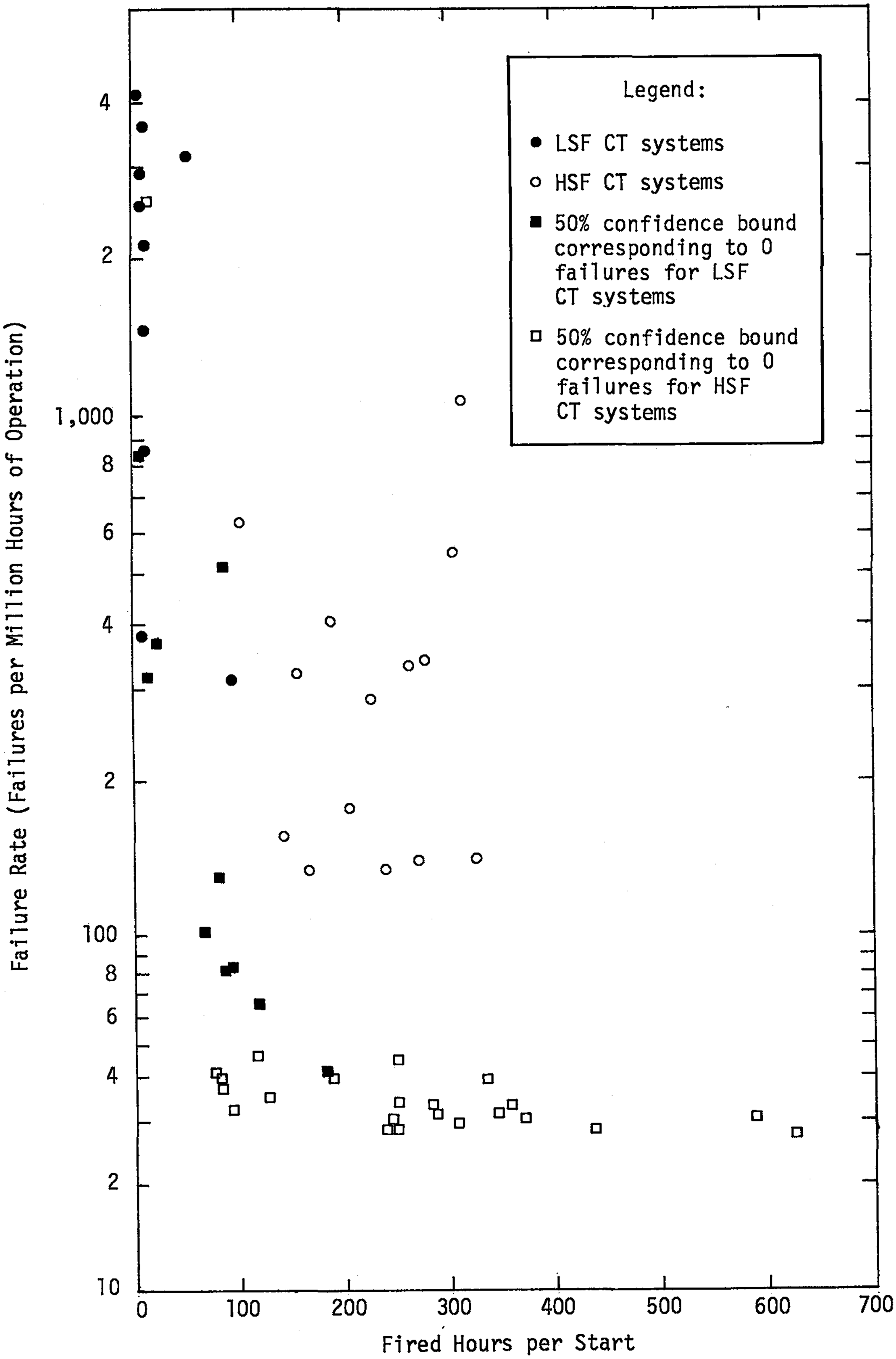

Figure 4-9. Effect of Fired Hours per Start on Lube Oil System Failure Rates

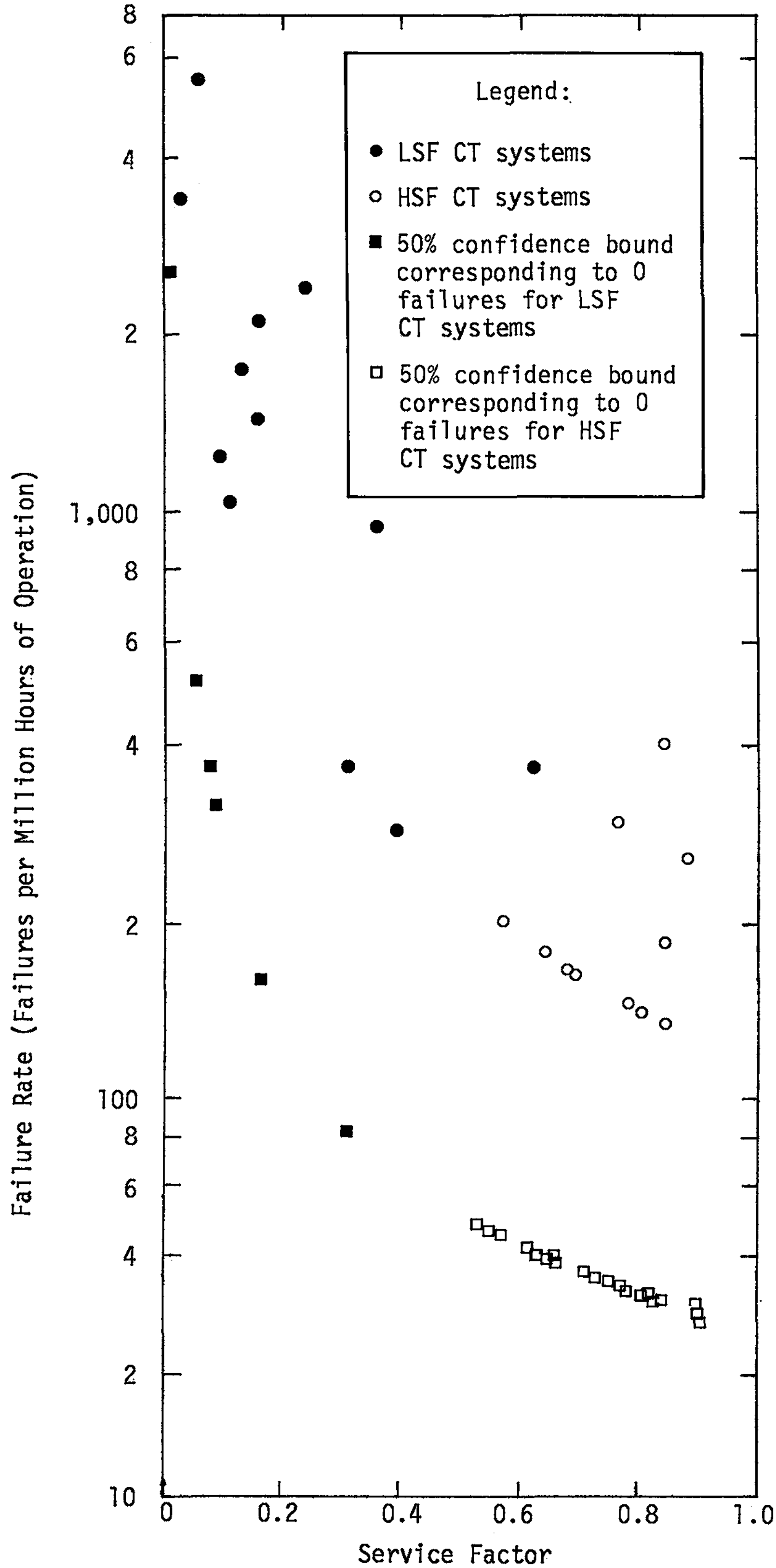

Figure 4-10. Effect of Service Factor on Air System Failure Rates

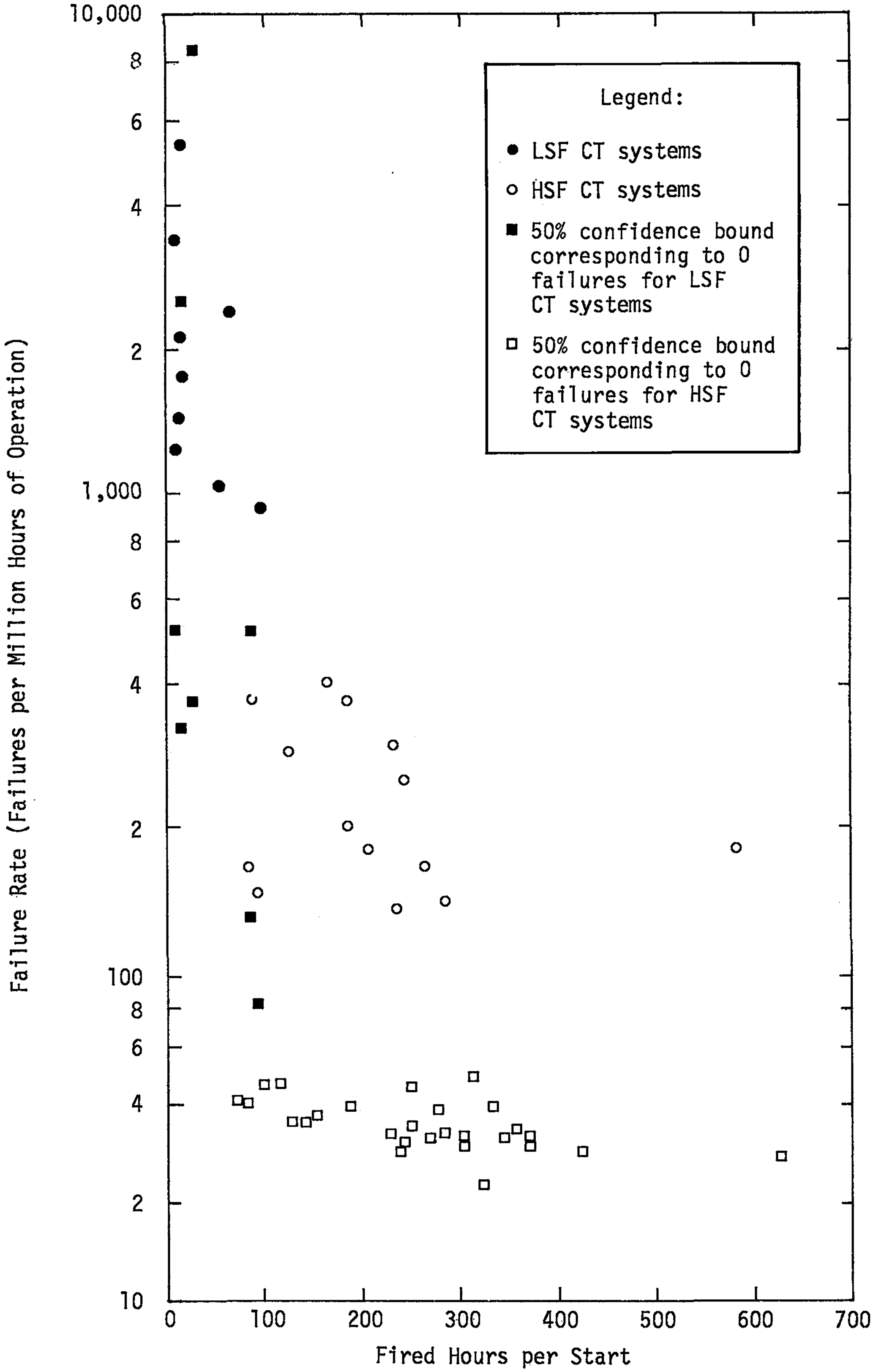

Figure 4-11. Effect of Fired Hours per Start on Air System Failure Rates

Section 5

RELIABILITY DATA PROCESSING PROBLEMS AND NEEDS

This section addresses specific problems in utility outage data reporting observed to have an impact on the effectiveness of both private and public data processing services. Requirements are set forth for the establishment of a data feedback service to the utility industry, which will provide, in a central source, RAM data for CTs and other combined-cycle plant systems.

DATA COLLECTION PROBLEMS AND DEFICIENCIES

The data management functions within operating utilities serve not only internal needs, but also the needs of private industry (e.g., equipment suppliers, plant manufacturers). In addition, outage data are often supplied to the North American Electric Reliability Council/Generating Availability Data System (NERC/GADS), and to EPRI. Some data transmittals are voluntary. During the performance of this contract, it was observed that the utilities transcribe outage data on different forms in support of Westinghouse Reliability Availability Measurement Program (RAMP) data processing services, General Electric Operational Reliability Analysis Program (ORAP) data processing services, GADS, and EPRI. Each form differs somewhat in the data reported. Other problems observed in outage reporting were as follows:

- Equipment nomenclatures are different.
- Problem cause codes (now described under NERC guidelines) for steam plant data collection are incomplete and, in some cases, inappropriate to describe combined-cycle plant systems.
- Outage codes are inconsistent -- some forms use codes such as class 1 (forced outage, operating) and MS (scheduled maintenance); while other forms use FOH for forced outage hours and SOH for scheduled outage hours.

Consequently, data errors and omissions are often introduced because of translation difficulties among forms. For some plants, these problems can cause a significant data management burden. Hence, plant personnel question the value and accuracy of any data feedback. They also tend to rely more on internal records for availability analyses of their plant and equipments, because (1) there is greater confidence in the internal records, and (2) plant personnel do not have to wait up to six months for any data feedback.

Not all failures are identified in outage reports. For example, outage reports generally fail to identify noncurtailing failures or parts replaced during reserve standby periods. Also, outage cause information is sometimes unclear, because the cause of an outage may not be determined until many days later (e.g., scheduled partial outage), and the records may not subsequently be updated. Hence, catchall identifiers like "CT, General," or "HRSG, General," or "Controls" have numerous entries. Failure to identify the root cause of an outage and the equipment affected is the major area where data quality could be improved. Occasional double counting of events resulting from outages that affect more than one power element was also observed in data records, as was misuse of the "Reserve Standby" classification.

RELIABILITY AND MAINTAINABILITY DATA REQUIREMENTS

As shown in these analyses, availability assessments can be approached by using historical or analytical approaches. The historical approach is used throughout the utility industry and analyzes events that have occurred or calculates the availability for a period that has elapsed. The analytical approach utilizes availability models and component MTBF and MDT data and is based on reliability data and probability theory. It can be used to predict both forced outages that could occur and the estimated plant availability. Reliability information and failure trends are an important part of data base management. For example, plant engineers may wish to know of a failure's occurring at any selected time during equipment operation to better plan preventive maintenance programs. The accuracy of these predictions depends predominantly on the accuracy of the availability models and the RAM data base. The RAM data presented herein reflect general industry experience and are used to establish trends in combined-cycle unit and equipment performance. Therefore, the data contained herein cannot be applied to a specific plant, as they represent a mix of service conditions and equipment types. On the basis of the analyses, two important conclusions were reached. First, outage data can be used as a basis for reliability and availability forecasting. Second, these analytical approaches provide accurate results and can be readily used by utilities desiring greater insight into equipment reliability, R&A trends, and areas of the plant warranting design improvement. Although three years of operating data has shown to be an effective basis for RAM modeling, it was concluded that more data are needed to substantiate many of the preliminary findings presented in this report.

To more effectively extend this work to the operating utilities and to enhance reliability analyses, the following additional data should be collected:

- Type of outage
- Cause of outage - identify root cause, faulty component, or line-replaceable unit affected
- Time to failure - identify equipment operating hours at the time of failure
- Man-hours to repair a failure
- Noncurtailing failures - identify any failure observed that did not cause an outage
- Component replacements or modifications - identify manufacturer and part number when part replacement or repair occurs during periods of planned maintenance

Section 6

CONCLUSIONS AND RECOMMENDATIONS

This section presents the conclusions derived from the RAM data analyses and combined-cycle unit availability assessments. Recommendations for suggested improvements in collecting, processing, and analyzing outage data are also presented.

AVAILABILITY MODELING FROM RAM DATA

Development and application of availability modeling techniques from RAM data led to the following conclusions:

- Plant availability models developed for single- and multishaft units can predict equivalent availabilities within 3 percent of values derived from outage data.
- The assumption that component failure rates are constant over a period of one year is valid for plants that have reached operating maturity.
- Availability models have provided accurate forecasts of unit effectiveness and can evaluate the effect of changes in component reliability on unit effectiveness.
- Availability models have identified and ranked those key components which, if improved to 100 percent availability, would yield the greatest improvement in unit effectiveness or EFOR.
- Effectiveness (E) values calculated by using availability models can be used to approximate the EFOR for multishaft units (i.e., $E \cong 1 - EFOR$).
- RAM analyses can guide management in planning effective maintenance and sparing policies.

On the basis of the assessments, it is recommended that data processing services to the utilities provide RAM data feedback and consider the attributes of availability modeling.

ANALYSIS OF COMBINED-CYCLE UNIT PERFORMANCE

Analysis of outage data from the period 1978 through 1980 for nine oil-fired LSF units and seven gas-fired HSF units led to the following conclusions:

- Average effectiveness values for HSF and LSF units were 92 percent and 72 percent, respectively.

- Mean values of HSF unit effectiveness and EFOR improved over the period.
- Mean values of LSF and HSF unit equivalent availability were nearly equal (LSF units have more reserve standby time, which tends to inflate their equivalent availability).
- Mean values of LSF and HSF unit equivalent availability improved over the period.
- Mean LSF unit effectiveness declined significantly in 1980.

ANALYSIS OF COMPONENT RAM DATA

The following conclusions resulted from an analysis of combined-cycle unit component RAM data from the period 1978 through 1980:

- Turbine and HRSG control failures accounted for the largest percentage of total forced outages for combined-cycle components.
- Turbine controls appeared to be a problem of equal concern to operators of both HSF and LSF units; however, data records were generally inadequate to establish problem causes.
- Drum-level trips were the dominant cause of HRSG control failures.
- There were recurring failures within lube oil systems, fuel gas systems, air systems, fuel oil systems, and such catchall categories as "CT, General"; "HRSG, General"; and "Steam Turbine, General."
- Plant outage records received generally lacked sufficient detail to establish root causes of failures of components and systems.
- Turbine and HRSG control failures ranked high on the list of components which, if improved to 100 percent availability, would yield the greatest percentage-point improvement in unit effectiveness.
- Component MDT values for LSF units were generally higher than those for comparable HSF units. (This may be because HSF units must get back on-line quicker and may experience shorter logistics delays.)

Turbine and HRSG control failures are not only nuisance problems to plant operators, but also significantly degrade equivalent availability because of poor MTBF. Controls should be investigated so that specific areas for product improvement may be defined.

ANALYSIS OF COMBUSTION TURBINE RELIABILITY DATA

Reliability data for 15 HSF gas-fired CT systems and 11 LSF oil-fired CT systems were analyzed. Table 6-1 summarizes the performance of the CTs.

Table 6-1

COMBUSTION TURBINE PERFORMANCE

Type of Turbine	Average Annual Failures per Turbine	Overall MTBF per Turbine (Hours)	Average Annual MDT per Turbine (Hours)	Average Annual Service Factor per Turbine	Average Annual Fired Hours per Start per Turbine	Total Combined Fired Hours
HSF Unit Turbines	10.3	600	36	0.74	252.0	235,000
LSF Unit Turbines	20.2	77	14	0.17	48.3	41,000

The analysis also led to the following observations and conclusions:

- The highest MTBF for an HSF unit turbine was 1992 hours; the highest MTBF for an LSF unit turbine was 489 hours.
- HSF unit CTs analyzed by use of 1978-1980 data exhibited reliability growth, which can be described by using suitable growth models.
- The failure rates of oil- and gas-fired CTs and some CT components were strongly affected by SF and FHPS.
- CT failure rates increased dramatically for SFs less than 0.4 and FHPSs less than 150.
- FHPS had the strongest effect on turbine failure rates; fuel type had the least effect. Approximately 84 percent of the variance in the data could be explained by one variable -- FHPS.

These correlations suggested that turbine reliability should not be compared unless the service conditions are specified. More data are needed to quantify the effect of fuel type on CT failure rates, because little data exist for gas-fired turbines in midrange service and below and oil-fired turbines in midrange service and above. Also, with an expanded data base it would be feasible to use availability models to forecast plant performance by incorporating these correlations and time dependencies (e.g., reliability growth) into expressions of component failure rate.

Because turbine failure rate data analyzed were segregated as either LSF (oil-fired) or HSF (gas-fired), conclusions regarding the effect of fuel type on turbine failure rate could not be substantiated.

MAJOR UTILITY DATA PROBLEMS AND WEAKNESSES

The following conclusions were derived by assessing the adequacy of utility data to support RAM analyses:

- Utility outage records reflected different equipment nomenclatures, outage definitions, and outage cause codes, largely due to lack of consistency between public (e.g., NERC/GADS) and private (e.g., General Electric ORAP, Westinghouse RAMP) data processing services.
- Outage records did not reflect actual man-hours to repair -- data needed to establish maintainability trends necessary to support maintenance planning.
- Outage records did not reflect operating hours on the equipment at the time of the forced outage -- data needed to establish failure distributions and reliability trends.
- Data records reflected too many catchall failure entries such as fuel gas system, lube oil system, air system, and controls.
- Noncurtailing forced outages were generally not included in outage logs.
- It is difficult to identify from maintenance records those parts replacements or modifications occurring during planned maintenance.

Outage and maintenance data available from the operating utilities are adequate to support RAM trend analyses presented herein. Information needed to resolve data deficiencies and weaknesses is available directly from professional maintenance personnel and from utility maintenance records such as work request forms and overhaul reports. An organized effort to collect such information on a widespread basis would increase the workload of the utilities. However, current outage data formats can be improved to better meet the needs of plant operators.

The types of data used in NERC, Westinghouse, and General Electric plant performance reports (e.g., GADS, ORAP, RAMP) are similar. Utility data workload can be reduced once greater consistency in formats, outage codes and definitions, equipment names, and methods of analysis is achieved. With the addition of reliability and maintainability information at lower levels of plant components, utilities will benefit with more meaningful performance comparisons, problem identification, and problem impact analyses.

Section 7

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Appendix A

TERMS AND DEFINITIONS

This appendix presents definitions of terms used in reliability assessments, as well as equations relating these terms. Definitions of effectiveness follow the list of equations.

TERMS AND DEFINITIONS

Available - Status of a unit or major piece of equipment that is capable of service, whether or not it is actually in service.

Available Hours (AH) - Time in hours during which a unit or major piece of equipment is available.

Base Loading - Running a unit at or near rated output.

Cranking Loading - Shutting down a unit on standby for auxiliary power during an emergency.

Cycling Loading - Running a unit at a load that varies widely with system demand.

Demand Period - Time interval each day that is the period of maximum demand on a particular system.

Economy Outage Hours - The theoretical value of economy outage hours (TEOH) is the difference between available hours and service hours. If the TEOH differs by less than 1% with the economy outage hours reported at the end of the year, they are considered to be equal and are flagged with Code 1. If the difference is more than 1% but less than 10%, they are flagged with Code 3, but the reported economy outage hours are still used. However, if the difference is greater than 10%, the calculated value of TEOH is used and flagged as Code 2.

Effectiveness (E) - The percentage of time that the unit can produce full power at any time, excluding planned maintenance and reserve standby periods.

Equivalent Availability (A_e) - The percentage of time that the unit can produce full power over the time period under consideration.

Equivalent Forced Outage Hours (EFOH) -

$$\frac{\text{FPOH} \times \text{loss in capacity due to partial outages}}{\text{MDC}}$$

Equivalent Scheduled Outage Hours (ESOH) -

$$\frac{\text{SPOH} \times \text{loss in capacity due to partial outages}}{\text{MDC}}$$

Equivalent Forced Outage Rate (EFOR) - $\left[\frac{\text{FOH} + \text{EFOH}}{\text{FOH} + \text{SH}}\right] \times 100$

Forced Outage - Occurrence of a component failure or other condition requiring the unit to be removed from service immediately or up to and including the following weekend.

Forced Outage Hours (FOH) - Time in hours during which a unit or major piece of equipment is unavailable due to a forced outage.

Forced Partial Outage - Occurrence of a component failure or other condition requiring the load on the unit to be reduced 2% or more immediately or up to and including the following weekend.

Forced Partial Outage Hours (FPOH) - Time in hours during which a unit or major piece of equipment is unavailable for full load due to a forced partial outage.

Hours Waiting (HW) - That portion of time for any outage during which no work can be performed, including time for cooling down equipment and shipment parts. This is time that could not be affected by a change in work schedule or the number of personnel working.

Maintenance Outage - Caused by a unit's being removed from service so that work on specific components that could have been postponed past the following weekend may be performed. The work is to prevent a potential forced outage and could not be postponed until the following season.

Maintenance Outage Hours (MOH) - Time in hours during which a unit or major piece of equipment is unavailable due to a maintenance outage.

Maximum Dependable Capacity (MDC) - Dependable main-unit capacity during winter or summer, whichever is smaller.

Noncurtailing Equipment Outage - Caused by a specific component's being removed from service for repair, resulting in a reduction in unit load of no less than 2%.

Nonoperating Equipment Test - Scheduled test or required operation of a backup system that is not normally operating.

Operating Availability (OA) - The percentage of time that the unit can produce any power over the time period under consideration.

Outage Cause - Component failure, preventive maintenance, or other condition requiring the unit or a component to be taken out of service or run at reduced capacity.

Peak Loading - Shutting down a unit and running it only during high demand periods.

Period Hours (PH) - Clock hours in the period under consideration (generally one year).

Planned Outage - Caused by a unit's being removed from service for inspection and/or general overhaul of one or more major equipment groups. The work is usually scheduled well in advance (e.g., annual boiler overhaul, five-year turbine overhaul).

Planned Outage Hours (POH) - Time in hours during which a unit or major piece of equipment is unavailable due to a planned outage.

Reserve Shutdown - Caused by a unit's being removed from service for economy or similar reasons. This status continues as long as the unit is out but available for operation.

Reserve Shutdown Hours (RSH) - Reserve shutdown duration in hours.

Scheduled Outage Hours (SOH) - Sum of maintenance outage hours and planned outage hours.

Scheduled Partial Outage - Occurrence of a component failure or other condition requiring the load on the unit to be reduced 2% or more, where this reduction could be postponed past the following weekend.

Scheduled Partial Outage Hours (SPOH) - Time in hours during which a unit or major piece of equipment is unavailable for full load due to a scheduled partial outage.

Service Hours (SH) - Total number of hours that the unit was actually operated with breakers closed to the station bus.

Unavailable - Status of a unit or major piece of equipment that renders it inoperable because of the failure of a component, work being performed, or other adverse condition.

Unit Year (UY) - Common denominator used to normalize data from units of the same type with different lengths of service. The following example contains 20 UY of experience from 4 units:

					Total
Unit	A	B	C	D	4
Years in Service	8	3	7	2	20 UY

EQUATIONS

$$\text{Service Hours (SH)} = PH - FOH - MOH - POH - RSH \tag{A-1}$$

$$\text{Available Hours (AH)} = SH + RSH \tag{A-2}$$

$$\text{Forced Outage Rate} = \left(\frac{FOH}{SH + FOH}\right) \times 100 \tag{A-3}$$

$$\text{Forced Outage Ratio} = \left(\frac{FOH}{PH - AH}\right) \times 100 \tag{A-4}$$

$$\text{Scheduled Outage Rate} = \left(\frac{SOH}{SH + SOH}\right) \times 100 \tag{A-5}$$

where

$$SOH = POH + MOH$$

$$\text{Capacity Factor} = \left(\frac{\text{Total gross MW hours}}{PH \times MDC}\right) \times 100 \tag{A-6}$$

$$\text{Service Factor (SF)} = \left(\frac{SH}{PH}\right) \times 100 \tag{A-7}$$

$$\text{Equivalent Forced Outage Rate (EFOR)} = \left(\frac{FOH + EFOH}{FOH + SH}\right) \times 100 \tag{A-8}$$

$$\text{Operating Availability (OA)} = \left(\frac{AH}{PH}\right) \times 100 \quad \text{(A-9)}$$

$$\text{Equivalent Availability } (A_e) = \left[\frac{AH - (EFOH + ESOH)}{PH}\right] \times 100 \quad \text{(A-10)}$$

DEFINITIONS OF EFFECTIVENESS

The availability model developed in this appendix considers only those randomly occurring failures of plant components which are observed when the plant is at partial or full capacity. Effectiveness excludes all planned maintenance events (i.e., SOH, $SPOH_2$). Effectiveness values derived from this model are a measure of plant availability of the time period PH - RSH - $SPOH_2$ - SOH.

On the basis of Figure A-1, effectiveness (E) in percent may be described empirically as:

$$E = \frac{(PH - RSH - SPOH_2 - SOH) - (EFOH + ESOH_1 + FOH)}{(PH - RSH - SPOH_2 - SOH)} \times 100 \quad \text{(A-11)}$$

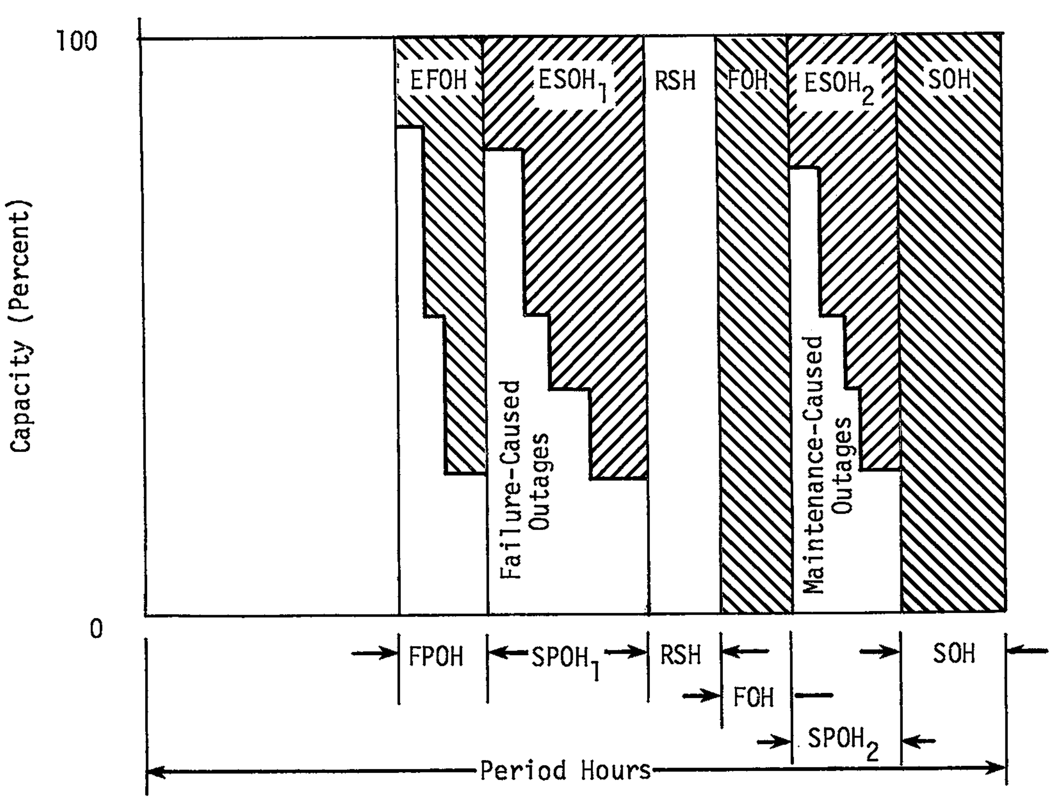

Figure A-1. Effectiveness Profile

The shaded areas of Figure A-1 represent all equivalent unavailable hours (i.e., $EFOH + ESOH_1 + FOH + ESOH_2 + SOH$). Equivalent availability (A_e) in percent may be expressed as:

$$A_e = \frac{PH - (EFOH + ESOH_1 + FOH + ESOH_2 + SOH)}{PH} \times 100 \qquad \text{(A-12)}$$

Eqs. A-11 and A-12 can be algebraically combined to relate E and A_e as follows:

$$A_e = \frac{E(PH - RSH - SPOH_2 - SOH) + SPOH_2 - ESOH_2 + RSH}{PH} \times 100 \qquad \text{(A-13)}$$

For a single-shaft combined-cycle plant where there are no partial outages, Eqs. A-11, A-12, and A-13 are reduced to:

$$E = \frac{(PH - RSH - SOH) - FOH}{PH - RSH - SOH} \times 100 = \left(1 - \frac{FOH}{PH - RSH - SOH}\right) \times 100 \qquad \text{(A-14)}$$

$$A_e = \frac{PH - FOH - SOH}{PH} \times 100 \qquad \text{(A-15)}$$

$$A_e = \frac{E(PH - RSH - SOH) + RSH}{PH} \times 100 \qquad \text{(A-16)}$$

Appendix B

STATISTICAL METHODS FOR ANALYZING PLANT RELIABILITY DATA

This appendix addresses statistical methods for analyzing plant reliability data. Additional explanation of reliability theory and data analysis may be found in MIL-HDBK-189, dated February 13, 1981.

RELIABILITY GROWTH MODELS

The phenomenon of reliability growth over time has been observed for many mechanical components and systems. Reliability growth may be achieved by instituting appropriate preventive maintenance programs or correcting design defects, or simply through an equipment familiarization process. The rate at which such improvements are made influences the rate of reliability growth. On the basis of observed data, mathematical functions can be used to describe reliability growth. One such function that has been found to be useful is the Duane model (7). J.T. Duane observed that the logarithm of cumulative mean time between failures (MTBF) was a linear function of the logarithm of time. That is:

$$\ln \Theta(t) = a + b \ln t \qquad \text{(B-1)}$$

where

$\Theta(t)$ = cumulative MTBF
t = operating hours
a, b = constants that calibrate the function

The constants a and b can be determined by fitting a least-squares curve to the data points. Care must be exercised in extrapolating this function. For example, the growth characteristics during the early maturity period of some equipments (e.g., 0 to 4 years) may be different than those during the period of 4 to 8 years.

MIL-HDBK-189 provides a summary of many other growth models in a single source. The U.S. Army Material Systems Analysis Activity (AMSAA) uses a Weibull-type process to investigate reliability growth. The AMSAA approach can be applied successfully to observe the change in instantaneous failure rate before and after an equipment modification. Where it is recognized that failure rates are not constant from one time interval to the next, an integer-valued process or nonhomogeneous Poisson process is used. The intensity function (ρ) or instantaneous failure rate at some point in time may be approximated by the following function:

$$\rho(t) = \alpha\beta t^{\beta - 1} \qquad \text{(B-2)}$$

where

time $(t) > 0$
α, β = parameters estimated from data

If $\beta = 1$, then $\rho(t) = \alpha$, which describes the exponential case. If $\beta < 1$, $\rho(t)$ is increasing, implying reliability growth. Conversely, if $\beta > 1$, the system reliability is deteriorating. Under this AMSAA model, the function $m(t) = \left(\alpha\beta t^{\beta - 1}\right)^{-1}$ describes the instantaneous or point estimate of MTBF at some time, t. The parameters α and β can be derived from maximum likelihood estimators; this analytical approach is considered to be the desirable approach. It is explained in MIL-HDBK-189.

RELIABILITY PREDICTION CONCEPTS

Reliability is the probability that an item will perform satisfactorily for a specified period of time under specified operating conditions. A measure of reliability can also be stated as a failure rate or as MTBF, which is defined as the ratio of total time (i.e., operating hours) to the number of failures that occurred during that time. If R denotes an integer value of reliability, and F denotes an integer value of unreliability, then R + F = 1. Values of R or F are therefore expressed as decimal fractions of unity. For equipments that exhibit changing failure rates with time, curves are drawn to describe the distribution of R(t) and F(t). If, for a sample of 50 components, the F(t) distribution curve shows that at some time the probability of failure is 0.20, then it is expected that 10 failures are likely to have accumulated by that time. This F(t) curve is often called a mortality curve or a cumulative probability distribution (CPD). If, for these 50 components, it is known how many of the components have failed during certain increments in time (e.g., 3, 6, 9, 12 months), then a histogram can be drawn. When the histogram is represented as a continuous curve, it is known as the probability distribution function (PDF). If the PDF can be represented by the mathematical relationship f(t), then:

$$F(t) = \int_0^t f(t)dt$$

The probability of a failure's occurring up to some value t can be calculated from this relationship. Similarly, the probability of a failure's occurring in some time interval can be calculated by integrating f(t)dt over that time interval. References (1) and (3) to this report provide additional information on reliability theory.

The function f(t) is used to describe the distribution of failure rates (λ) for a sample of identical equipments. Where failure rates remain constant, it can be shown that:

$$F(t) = \frac{df(t)}{dt} = \lambda e^{-\lambda t} \tag{B-4}$$

Where λ is not constant, the three-parameter Weibull PDF is often used; it is expressed as:

$$f(t) = \frac{\beta(t - \gamma)^{\beta - 1}}{\alpha} \exp\left[-\left(\frac{t - \gamma}{\alpha}\right)^{\beta}\right] \tag{B-5}$$

where

t = time to failure
γ = delay parameter
β = shape parameter
α = scale parameter

For components having no initial guaranteed minimum life period, γ is zero. The resulting two-parameter Weibull distribution is typically used to describe failure rate distributions of mechanical components. The shape parameter β can describe either a reliability growth phenomenon ($\beta < 1$), a constant failure rate ($\beta = 1$), or a wear-out phenomenon ($\beta > 1$). When $\beta = 1$, the Weibull relationship is reduced to the exponential form.

The two-parameter PDF is expressed as:

$$f(t) = \frac{\beta t^{\beta - 1}}{\alpha} \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \tag{B-6}$$

On the basis of Eqs. B-4 and B-5, the Weibull mortality curve F(t) is:

$$F(t) = 1 - \exp\left[-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}\right] \tag{B-7}$$

It is important to note that whereas normal and log normal distributions are referenced from the mean, the Weibull distribution is referenced from t = 0. For an actual mortality curve to conform to this requirement there must be a probability of failure at zero time. This can occur (1) when failures are the result of purely chance causes, and (2) when the form of the distribution is such that the tail becomes asymptotic to the t-axis at low values of t, as is the case in the normal distribution.

The mean of the Weibull PDF, when $\gamma = 0$, is an estimate of MTBF and is expressed as:

$$MTBF = \lambda^{1/\beta}\Gamma\left(\frac{1}{\beta} + 1\right) \tag{B-8}$$

For a given data set, α and β are determined graphically by using Weibull probability paper. The gamma function, $\Gamma(n)$, where $n = \frac{1}{\beta} + 1$, is determined from a gamma function table provided in most statistics texts.

To illustrate these concepts, failure data used in this study for the CT lube oil system were analyzed for the period 1978 through 1980. These failures occurred for nine gas-fired CTs and seven oil-fired CT, operating for a total of 226,607 fired hours.

LUBE OIL SYSTEM RELIABILITY ANALYSIS

On the basis of plant outage data records, 39 lube oil system failures were observed and analyzed for the period 1978 through 1980. Figure B-1 is a histogram of these failures. The probability of a failure's occurring between 8000 and 9000 calendar hours is 4/39, or 0.103. To determine an estimate of the MTBF, the general two-parameter Weibull PDF was applied. Instead of calendar hours, the time base to be considered was fired hours, which is more appropriate to the operators of CT equipments. Failure data were analyzed for each six-month period, beginning January 1, 1978 and ending December 31, 1980.

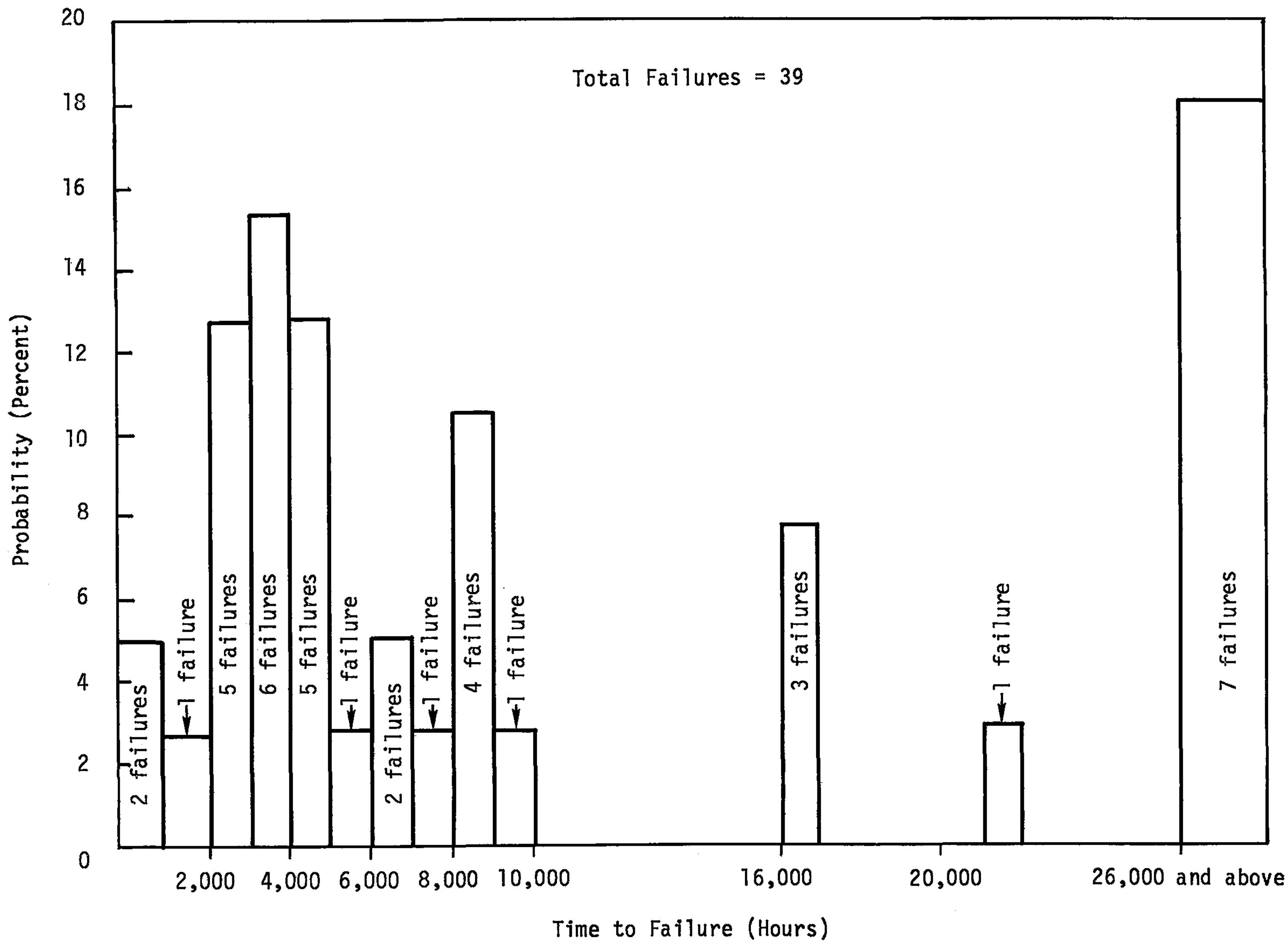

Figure B-1. Lube Oil System Histogram

All 16 lube oil systems were assumed to have begun operation at t = 0. An average time to failure (t) was calculated for each six-month interval by dividing the total actual lube oil system operating hours in the six-month interval by the total number of observed failures occurring in the interval. Hence, there were six intervals or data points from which to calculate the Weibull PDF. These six values of time were then ranked from smallest to largest, and the corresponding cumulative hazard values were calculated as shown in Table B-1. By definition, the percent hazard is equal to 100 divided by the number of failures.

Table B-1

CALCULATIONS OF CUMULATIVE HAZARD

Rank	Average Time to Failure (t)	Percent Hazard	Cumulative Hazard (Percent)
6	3,359	16.67	16.67
5	4,016	20.00	36.67
4	5,334	25.00	61.67
3	11,256	33.33	95.00
2	11,811	50.00	145.00
1	21,451	100.00	245.00

$$\text{Percent Hazard} = \frac{100}{\text{number of failures}}$$

Figure B-2 illustrates cumulative hazard plotted against average time to failure (t) on Weibull probability paper. A straight line was drawn through the data points by use of a least-squares curve fit. If the points could not be approximated by a straight line, a different PDF other than the two-parameter Weibull may have been more appropriate. Values of α and β were determined by using a graphical procedure. A line was drawn parallel to the fitted line that passes through the dot in the upper left-hand corner of the Weibull probability paper. The intersection of this fitted line with the shape parameter scale yielded the value of β (i.e., $\beta = 1.4$). Hence, data indicated that the lube oil system exhibited an increasing failure rate with time. The equation $a = t^{\beta}$, where t corresponds to a cumulative hazard of 100

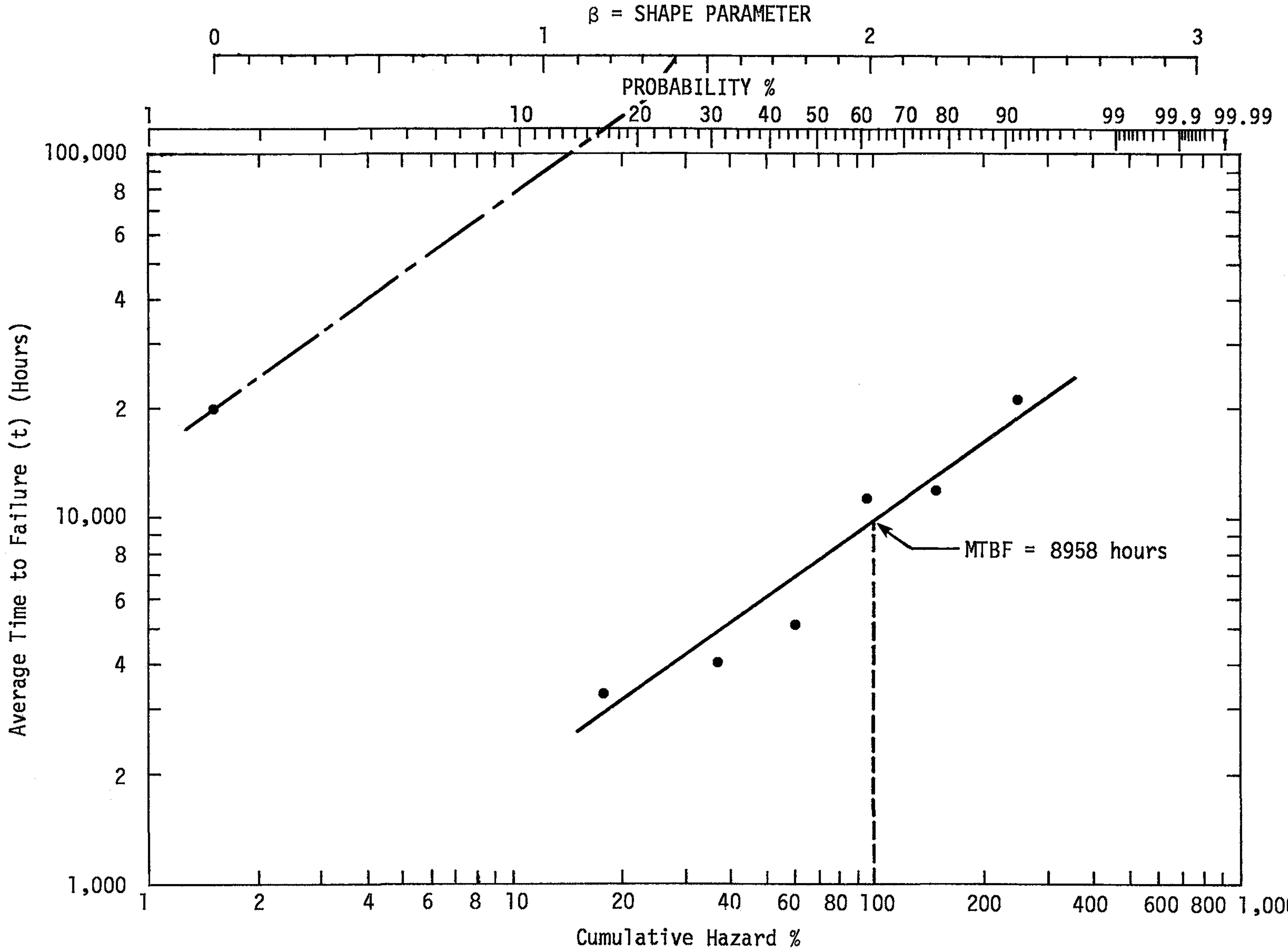

Figure B-2. Use of Weibull Probability Paper to Derive α and β Values percent, was used to calculate α. Hence, $\alpha = (9865)^{1.4}$, or 390,603. From Eq. B-8 and a table of Gamma functions, the MTBF was estimated as follows:

$$\begin{aligned} MTBF &= \lambda^{1/\beta}\Gamma\left(\frac{1}{\beta} + 1\right) \\ &= 390{,}603^{1/1.4} \left(\frac{1}{1.4} + 1\right) \\ &= 8{,}958 \text{ hours} \end{aligned}$$

where

$$\Gamma(1.7143) = 0.9114$$

Thus, from Eq. B-6, the Weibull PDF was determined to be:

$$\begin{aligned} f(t) &= \frac{\beta t^{\beta - 1}}{\alpha} \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \\ &= \frac{1.4t^{0.4}}{390{,}603} \exp\left[-\left(\frac{t}{390{,}603}\right)^{1.4}\right] \end{aligned}$$

This function is shown in Figure B-3.

The Weibull CPD or mortality curve was derived by using Eq. B-7; it is shown in Figure B-4. This relationship was used to derive the probability of 0.32 that the time to failure (TTF) for the lube oil system is 5000 hours or less. The probability that the TTF will fall within some selected range was calculated by subtracting the lower-limit probability from the upper-limit probability value corresponding to the TTF values selected. This mortality curve was helpful in establishing realistic MTBF goals.

LOG NORMAL PROBABILITY DENSITY FUNCTION

An accurate model for mean downtime (MDT)* would include the sum of all active repair times, all waiting times (including time spent waiting for work assignments, tool issues, and spare parts), all cool-down and startup times, and all times required to diagnose the problem. When the MDT for a system or component is to be estimated from historic data, it is usually found that downtimes will vary from very short durations to very long ones, depending on variations of all the

*Mean downtime is the ratio of total outage hours to the number of maintenance events occurring over the selected time period.

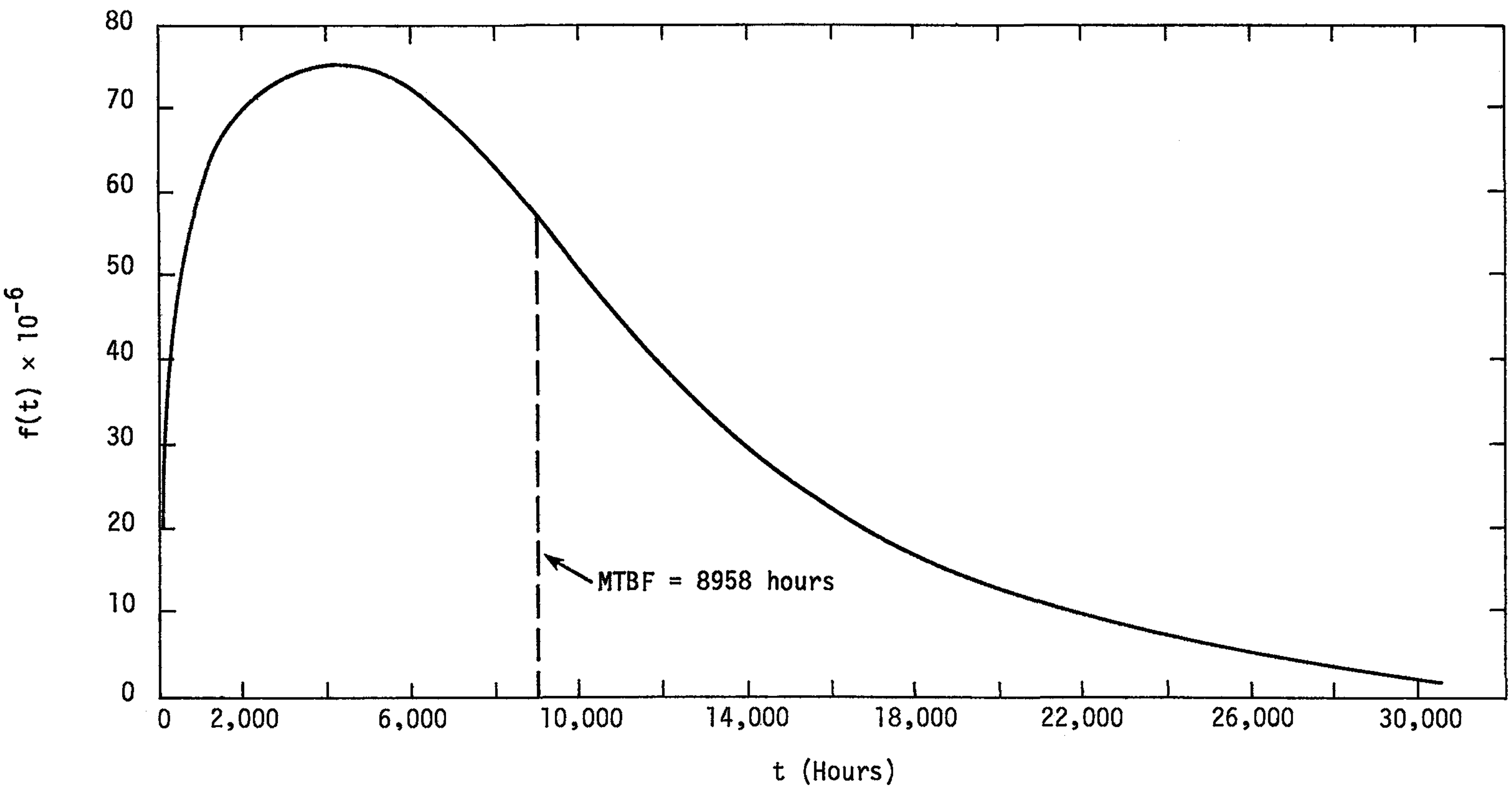

Figure B-3. Weibull Probability Distribution Function

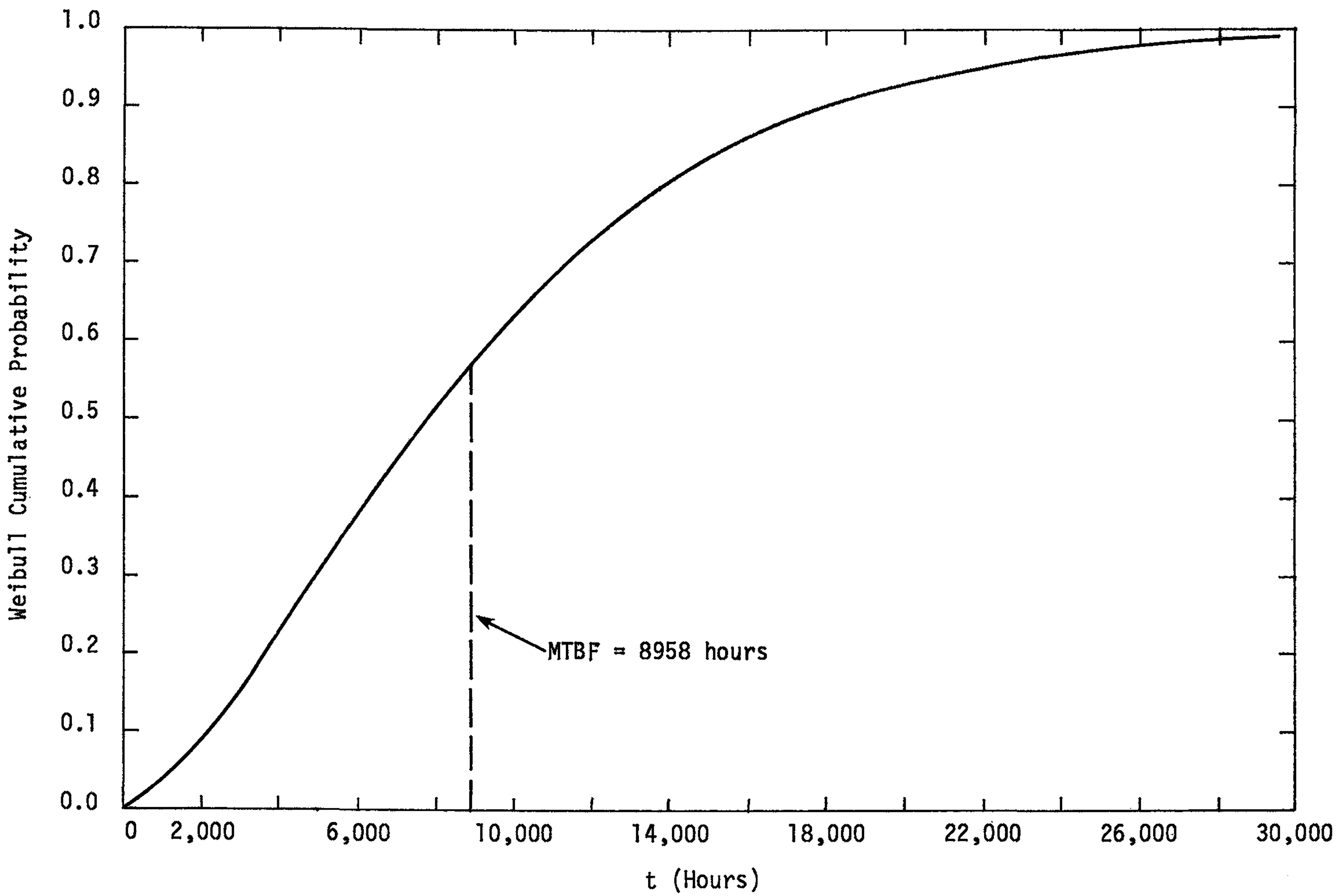

Figure B-4. Weibull Cumulative Probability Distribution aforementioned factors. Other factors that can contribute to this variability include the skill or size of the repair crew and human error. The problem becomes one of how best to handle these data to provide reasonable estimates of MDT. The log normal distribution is a PDF that fits many MDT data bases. When the logarithm of observed MDT data is distributed normally, it defines a log normal PDF, which is characterized by the following phenomena:

- The mode of the distribution (data elements occurring most frequently) is less than the median (middle data item).
- The median of the distribution is less than the mean.

Therefore, the log normal is a positively-skewed distribution that can be determined both graphically and analytically. Graphic procedures are generally used to verify whether a set of data is log normally distributed. If it is, certain analytical methods are used to estimate the mean. References (2) and (8) to this report provide a description of these methods.

CONFIDENCE INTERVAL ESTIMATES

Confidence interval estimates provide a measure of the relative precision that can be ascribed to a predicted or point-estimate value of MTBF or MDT. A confidence interval estimate is an interval about the mean. This interval is associated with a confidence level or probability expressed as a percent. For example, the 90 percent confidence interval about an MTBF value of 50 hours may range from 40 to 65 hours. This means that one can be 90 percent confident that the actual MTBF value will be within the interval of 40 to 65 hours, if the correct distribution has been assumed.

Upper and lower confidence levels for some point estimate of MTBF can be derived by using the chi-squared (χ^2) distribution tables and the following expressions:

$$\text{MTBF upper confidence limit (two-sided)} = \frac{2t}{\chi^2(1 - \frac{\alpha}{2}, 2n)} \qquad \text{(B-9)}$$

$$\text{MTBF lower confidence limit (two-sided)} = \frac{2t}{\chi^2(\frac{\alpha}{2}, 2n)} \qquad \text{(B-10)}$$

where

t = total operating hours

α = 0.1

n = number of failure events

Confidence bounds of mean downtime (τ) can be calculated from the Student's t distribution tables and the following expressions:

$$\tau \text{ (upper confidence limit)} = \bar{\tau} + \frac{s}{\sqrt{n}} \left\{ t\left(\frac{\alpha}{2}, n - 1\right) \right\} \qquad \text{(B-11)}$$

$$\tau \text{ (lower confidence limit)} = \bar{\tau} - \frac{s}{\sqrt{n}} \left\{ t\left(\frac{\alpha}{2}, n - 1\right) \right\} \qquad \text{(B-12)}$$

where

$\bar{\tau}$ = mean downtime
s = standard deviation
n = number of failure events
α = 0.1

Appendix C

DEFINING SYSTEM STATES

This appendix describes procedures used to define system states for a multishaft combined-cycle unit. System partitioning and fault tree concepts are introduced as methods for reducing the complexity of reliability and availability (R&A) analyses.

PARTITIONING SYSTEMS

A plant comprising one or more multishaft combined-cycle units can be difficult to model because of the complex interaction between plant systems and components. In most cases, plant units usually operate independently of one another, in the sense that outage events to one unit have no impact on the availability of the other units. In such cases, each unit (usually of identical design and capacity) can be analytically modeled, and the unit availabilities can be averaged to obtain a plant unavailability value for the data period considered. The task at hand, therefore, is reduced to partitioning the unit into systems and partitioning systems into components to a level consistent with components identified in plant outage reports.

Figure C-1 illustrates a simplified multishaft unit consisting of two CTs, two heat recovery steam generators (HRSGs), three generators, one steam turbine, and a condensate system. Each of the nine independent elements can be either up (available) or down (unavailable); hence 2^9 (or 512) possible states exist. A power capability ranging from 0 percent to 100 percent is associated with each state. However, for most combined-cycle units, a minimum of 50 elements or components is necessary to adequately describe the system and its operation. Clearly, the number of states must be reduced to facilitate the availability analysis. In the example of Figure C-1, if the HRSGs, CTs, and generators are treated as a single system, and the steam turbine, generator, and condensate system are treated as another system, the number of states is reduced to 2^3 (or 8). An underlying rule in the partitioning process is that all possible up or down conditions that result from system components acting singly or in combination with one another must result in an up or down condition to the system. In addition, all possible up or down conditions to these elements must result in the same output capability to the

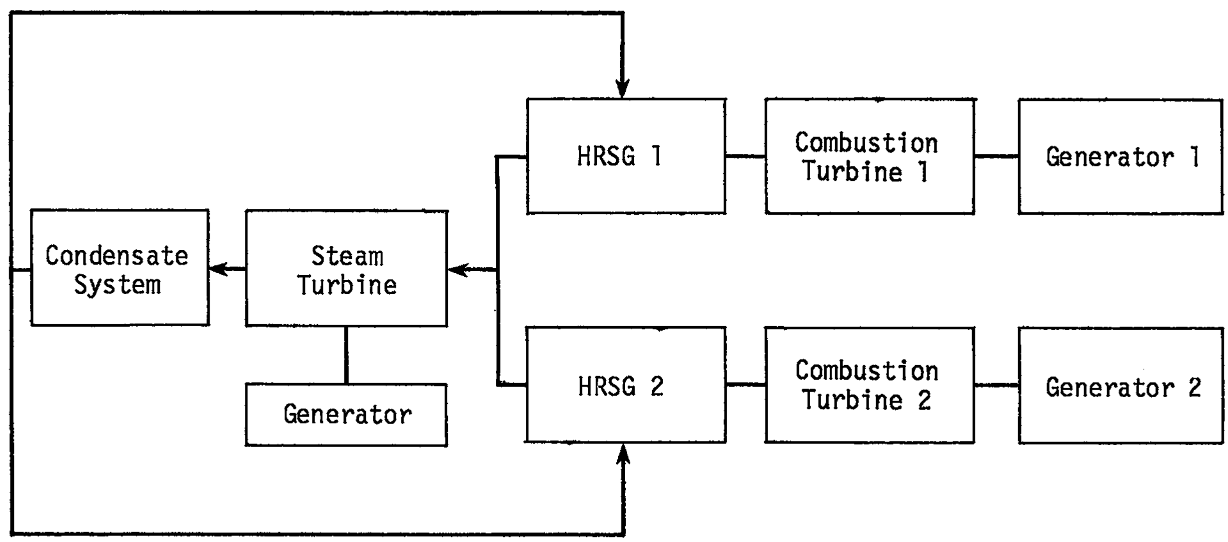

Figure C-1. Multishaft Combined-Cycle Power Plant

system. It is also desirable in the partitioning process to establish independency between each system to eliminate common cause failures.* Continuing the example, if an HRSG is unavailable, the output capacity of the system is zero. If the system is designed to allow power generation by bypassing the HRSG, then the HRSG must be treated as a separate system from the CT and generator. In this case, the unit would be described by five systems.

The partitioning process is frequently more complicated because of the component redundancy or capacity-sharing often evident in condensate or boiler feed unit pumps. In such cases, fault trees are often helpful in understanding the link between component performance and system performance. Fault trees illustrate ways in which a system can fail as a result of failures of its components. Components in most major systems (e.g., CTs, HRSGs, steam turbines) are series-linked, in that a failure of any one results in an unavailability of the system. However, where components are grouped as redundant pairs, both components must fail to cause an unavailability of the system. Hence the results of the fault tree analysis may influence the manner in which the analyst wishes to partition the unit. As was shown in Table 2-1 of Section 2, availability modeling requires the development of probability expressions that describe combinations of up or down conditions to systems and components. Fault trees are used to develop these expressions. However, in analyzing

*A common cause failure is a failure that can result to more than one system when initiated by a failure to a single cause or elementary part.

combined-cycle units, it is desirable to describe systems in which components are series-linked.

DEFINING SYSTEM STATES

A state is defined as one or more specific combinations of unavailable and available systems that result in a specific power output capability. A state definition depends, of course, on the combined-cycle unit design and the manner in which it is operated. A list of system states is the nucleus of the availability model. There is some conditional probability that a particular state will occur in a given time interval, depending on how failures randomly occur and combine within the various system fault trees. A state probability value (P_k) represents the fraction of the time interval (excluding scheduled maintenance) that the unit is available for operation. This value can be expressed in days per year if the time interval selected is one year. When P_k is multiplied by its corresponding capacity -- i.e., percent megawatt (MW) capacity -- the value represents that state's availability in terms of expected output capacity.

The particular level of plant capacity for a given state requires an understanding of what systems must be shut down given a failure and the power capability remaining for the unit. A list of system states includes all possible combinations of available and unavailable systems. States are mutually exclusive (no combination is listed more than once) and exhaustive (no combination is excluded).

The multishaft unit described in Figure C-1 may be used to illustrate the procedure of defining states. The unit may be partitioned into the following systems: CT 1/Gen, CT 2/Gen, HRSG 1, HRSG 2, ST/Gen/Cond. If afterburners are used, they would be included as additional systems, because failure of one or both afterburners would result in a new unit output capability. It is assumed that, should a steam-side failure occur, CT power generation would be possible, but only at reduced capacity. Each CT is capable of 50 MW; the steam turbine is capable of 50 MW. Total unit capability is 150 MW. If an HRSG fails, its corresponding CT capacity is reduced to 40 MW, the second CT is capable of 50 MW, and the steam turbine capacity is reduced to 45 MW. If a failure occurs within the condensate or steam turbine systems, the plant is operated simple-cycle at a capacity of 80 MW. Table C-1 lists all possible states. For each state, a probability expression may be derived on the basis of fault tree logic and quantification of the availabilities (A) of the systems in terms of component failure rates and mean downtimes. For example, the probability that the unit will be in State 10 (i.e., P_{10}) is $P_{10} = A_{CT\ 1}(1 - A_{CT\ 2})(1 - A_{ST/Cond})$.

Table C-1

SYSTEM STATES FOR THE EXAMPLE COMBINED-CYCLE UNIT

State	CT 1	HRSG 1	CT 2	HRSG 2	ST/Cond	Capacity (Percent)
1	0	0	0	0	0	100
2	1	X	0	0	0	50
3	0	0	1	X	0	50
4	1	X	1	X	X	0
5	0	1	0	0	0	63
6	0	0	0	1	0	63
7	0	1	0	1	0	53
8	0	X	0	X	1	53
9	1	X	1	X	1	27
10	0	X	1	X	1	27

Legend: 0 - system is available
1 - system is unavailable
X - system is not operating but could be available or unavailable

The probability associated with each HRSG is 1, because the X indicates that the condition of the HRSG has no effect on the state probability.

Appendix D

TURBINE COMPONENT PERFORMANCE STUDY

This appendix presents a performance summary for the 15 gas-fired CT systems in HSF applications and 11 oil-fired CT systems in LSF applications.

HSF TURBINE DATA

Table D-1 summarizes component failure and mean downtime data for 15 gas-fired CT systems for the period 1978 through 1980. Each turbine is identified by a code, which denotes the turbine unit by utility (first letter), the year operated (first two numerals), and the type of fuel (G = gas, O = oil). For eight of these 15 turbines, data from 1979 and 1980 were analyzed. Annual service factors and fired hours per start are also given for each turbine.

LSF TURBINE DATA

Table D-2 summarizes component failure and mean downtime data for 11 oil-fired CT systems for the period 1978 through 1980. Each turbine is identified by a code, as described for HSF turbines. Turbine code H80-O represents the composite performance of four turbine systems. All other codes represent individual turbine systems.

Table D-1

COMBUSTION TURBINE COMPONENT PERFORMANCE SUMMARY FOR HSF UNIT TURBINES, BY CT CODE*

Component	U80-G**	T80-G	T78-G	S80-G	R80-G	079-G	I80-G	U79-G	S78-G	S79-G	P80-G	Q79-G
CT Unit, General	0	1 137 1.0	0	0	0	0	1 142 22.3	0	0	1 156 72.0	0	0
Combustion Section (Other)	0	0	0	0	0	0	1 142 22.9	0	1 209 1146.7	0	2 279 72.2	0
Fuel Oil Flow Dividers	0	0	0	0	0	0	0	0	0	0	0	0
Fuel Oil Pumps	0	0	1 148 156.0	0	0	0	0	0	0	0	0	0
Fuel Oil Filters	0	0	0	0	0	0	0	0	0	0	0	0
Fuel Oil Systems (Other)	0	0	0	0	0	0	0	0	0	0	0	0
Starting System	0	0	0	0	0	0	0	0	0	0	0	0
Lube Oil System	0	0	0	0	0	0	0	0	0	0	0	0
Air System	0	0	0	0	0	0	1 142 40.9	0	0	0	0	1 165 2.0
Electrical Controls (Other)	4 502 13.0	3 411 4.3	2 296 7.5	4 402 14.1	4 687 3.6	5 871 39.8	4 566 8.3	5 635 10.6	4 835 8.2	3 467 1.0	3 419 8.2	6 989 4.3
Compressor	0	0	0	0	0	0	0	0	0	0	0	0
Inlet Guide Vanes	1 137 5.4	1 125 5.7	0	0	0	0	0	0	0	0	0	0
Turbine Exhaust Section	0	0	0	0	0	0	0	0	0	0	0	0
Turning Gear System	0	0	0	0	0	0	0	0	0	0	0	0
Fuel Nozzles	0	0	1 148 21.0	1 201 16.0	0	0	0	0	0	2 311 5.0	0	0
Fuel Gas System	0	0	1 78 4.0	0	0	0	0	0	0	0	1 140 7.0	0
Liners	0	0	0	0	0	0	0	3 381 5.5	0	1 156 96.0	0	0
Cross Fire Tubes	0	0	0	0	0	0	0	0	0	0	0	0
Transition Ducts	0	0	0	0	0	0	0	0	0	0	0	0
Fire Detection System	0	0	0	0	0	0	0	0		0	2 279 25.0	0
Service Factor	0.91	0.83	0.77	0.77	0.90	0.66	0.80	0.90	0.55	0.73	0.82	0.69
Fired Hours per Start	625	370	286	357	238	333	286	303	116	128	345	81

*The first entry in the columns is the number of failure events; the second is the number of failures per million hours of operation (λ); the third entry is mean downtime in hours.

** U80-G: Turbine Identifier (U), Year (80), Gas-Fired (G)

(continued)

Table D-1 (continued)

COMBUSTION TURBINE COMPONENT PERFORMANCE SUMMARY FOR HSF UNIT TURBINES, BY CT CODE

Component	J80-G	J79-G	T79-G	W79-G	O80-G	P79-G	R79-G	U78-G	V78-G	L80-G	Q80-G	W80-G
CT Unit, General	1 135 86.0	0	0	1 141 6.8	0	0	3 546 17.9	1 153 5.0	0	3 407 31.9	0	1 147 3.7
Combustion Section (Other)	0	1 139 10.8	0	0	0	0	0	0	0	0	0	0
Fuel Oil Flow Dividers	0	0	0	0	0	0	0	0	0	0	0	0
Fuel Oil Pumps	0	0	0	0	0	0	0	1 153 1.0	0	0	0	0
Fuel Oil Filters	0	0	0	0	0	0	0	0	0	0	0	0
Fuel Oil Systems (Other)	0	0	0	0	0	0	0	0	0	2 271 1.8	0	0
Starting System	0	0	0	1 141 2.4	0	0	0	0	1 157 0.3	0	0	0
Lube Oil System	0	4 556 7.0	0	1 141 7.6	0	0	0	0	1 157 15.5	1 136 19.4	0	2 295 1.9
Air System	0	0	0	0	2 300 4.5	0	0	0	0	1 136 1.8	1 185 4.5	0
Electrical Controls (Other)	5 676 7.8	2 278 30.6	8 1011 10.1	2 283 3.4	6 900 5.7	6 1212 49.6	4 728 1.8	5 763 7.6	4 627 2.5	3 407 9.5	8 1478 1.5	5 736 1.6
Compressor	0	0	0	0	0	0	1 182 111.0	0	0	0	0	0
Inlet Guide Vanes	1 135 2.1	0	0	1 141 0.6	0	0	0	0	0	0	0	1 147 2.4
Turbine Exhaust Section	0	0	0	0	0	0	0	0	0	0	0	0
Turning Gear System	0	1 139 145.9	0	0	1 150 30.7	0	0	0	1 157 21.5	1 136 300.6	0	0
Fuel Nozzles	0	0	0	0	0	0	0	1 153 31.8	0	0	0	0
Fuel Gas System	0	1 139 2.5	1 126 3.0	3 424 0.9	0	1 202 4.3	0	1 153 4.0	2 314 1.4	0	0	3 442 4.4
Liners	0	0	2 253 2.4	0	0	0	0	1 153 2.9	0	1 136 29.9	0	0
Cross Fire Tubes	0	0	0	0	0	0	0	0	0	0	0	0
Transition Ducts	0	0	0	0	0	0	0	0	0	0	0	0
Fire Detection System	1 135 3.2	0	0	0	0	0	0	0	1 157 2.5	0	0	0
Service Factor	0.84	0.82	0.90	0.81	0.76	0.57	0.63	0.75	0.73	0.84	0.84	0.78
Fired Hours per Start	244	303	435	270	233	250	81	250	143	238	588	227

(continued)

Table D-1 (continued)

COMBUSTION TURBINE COMPONENT PERFORMANCE SUMMARY FOR HSF UNIT TURBINES, BY CT CODE

Component	R78-G	Q78-G	W78-G	M80-G	V79-G	M79-G	I79-G	N80-G	V80-G	K80-G	L79-G	N79-G	K79-G
CT Unit, General	5 920 138.7	6 880 17.8	0	2 259 61.3	3 438 3.6	0	1 176 11.5	0	8 1348 3.5	2 271 0.9	2 361 50.1	0	1 208 139.9
Combustion Section (Other)	1 184 1101.0	0	0	2 259 4.2	0	0	0	3 518 154.2	0	0	2 361 17.3	1 216 200.7	2 416 33.2
Fuel Oil Flow Dividers	0	0	0	0	0	0	0	0	0	0	0	0	0
Fuel Oil Pumps	0	0	0	0	0	0	0	0	0	0	0	0	0
Fuel Oil Filters	0	0	0	0	0	0	0	0	0	0	0	0	1 208 1.4
Fuel Oil Systems (Other)	0	0	0	0	0	0	0	0	0	0	1 180 1.9	0	0
Starting System	0	0	0	0	0	0	6 1056 8.7	0	0	3 406 3.5	1 180 0.3	1 216 2.0	0
Lube Oil System	0	0	2 322 5.8	0	1 146 0.5	2 405 90.3	0	2 345 4.7	2 337 3.2	1 135 1.5	1 180 69.4	5 1080 48.3	3 623 52.7
Air System	0	1 147 9.4	0	2 259 1.6	0	1 203 0.9	0	0	1 168 2.1	3 406 30.4	1 180 108.5	0	0
Electrical Controls (Other)	3 552 54.8	4 586 1.5	8 1289 1.0	9 1166 19.8	5 730 0.9	9 1822 64.5	6 1056 22.6	6 1035 7.4	2 337 1.4	11 1489 7.0	9 1622 14.3	5 1080 27.5	4 831 18.6
Compressor	0	0	0	0	0	0	0	0	0	0	0	0	1 208 12.1
Inlet Guide Vanes	1 184 0.1	1 147 1.2	0	0	2 292 0.9	0	0	0	1 168 0.5	0	0	0	2 416 11.1
Turbine Exhaust Section	0	0	0	0	0	0	1 176 10.9	2 345 942.0	0	0	1 180 3.5	0	0
Turning Gear System	0	0	0	0	0	0	0	1 173 8.4	0	0	0	1 216 148.2	0
Fuel Nozzles	0	0	0	0	0	0	0	0	0	0	0	1 216 1.2	1 208 1.0
Fuel Gas System	0	1 147 0.9	1 161 1.4	0	3 438 20.0	0	0	1 173 5.3	2 337 2.2	0	0	1 216 33.9	0
Liners	0	0	1 161 3.6	0	0	0	0	0	0	0	0	0	1 208 744.0
Cross Fire Tubes	0	0	0	0	0	0	0	0	0	0	0	0	0
Transition Ducts	0	0	0	0	0	0	0	0	0	0	1 180 884.0	0	3 623 274.3
Fire Detection System	0	0	0	0	0	0	0	0	0	0	0	1 216 33.6	2 416 33.2
Service Factor	0.62	0.78	0.71	0.88	0.78	0.57	0.65	0.66	0.68	0.84	0.64	0.53	0.55
Fired Hours per Start	76	91	156	244	323	189	189	278	263	167	204	313	100

Table D-2

COMBUSTION TURBINE COMPONENT PERFORMANCE SUMMARY FOR LSF UNIT TURBINES, BY CT CODE*

Component	B80-0	D78-0	D79-0	A78-0	D80-0	B78-0	A79-0	C78-0	B79-0	A80-0	C79-0
CT Unit, General	0	0	1 364 0.3	0	0	2 580 1.3	2 1397 0.5	2 747 0.7	1 485 0.6	0	1 1045 3.0
Combustion Section (Other)	0	1 186 0.3	0	0	0	0	1 699 1.3	0	2 969 0.7	0	0
Fuel Oil Flow Dividers	0	0	0	0	0	0	0	0	0	0	0
Fuel Oil Pumps	0	0	1 364 0.3	0	0	0	0	0	0	0	1 1045 2.6
Fuel Oil Filters	0	0	0	0	0	0	0	0	0	0	0
Fuel Oil Systems (Other)	0	1 186 7.3	0	0	0	0	0	0	0	0	0
Starting System	0	1 186 0.3	1 364 0.4	0	1 2293 2.4	0	0	1 373 0.9	0	0	0
Lube Oil System	0	0	0	1 316 61.4	0	0	0	0	0	0	1 3136 19.1
Air System	0	2 372 3.7	0	3 949 6.5	0	1 290 3.3	0	1 373 5.6	5 2423 5.9	0	1 1045 2.0
Electrical Controls (Other)	0	5 929 1.9	1 364 0.6	2 633 1.2	0	3 870 1.4	1 699 0.3	4 1493 6.7	3 1454 18.9	0	3 3136 2.4
Compressor	0	0	0	0	0	0	0	1 373 2.1	0	0	0
Inlet Guide Vanes	0	0	0	0	0	0	0	0	0	0	0
Turbine Exhaust Section	0	0	0	0	0	0	0	0	0	0	0
Turning Gear System	0	1 186 0.2	2 728 19.9	0	0	0	0	0	0	0	1 1045 11.1
Fuel Nozzles	0	0	0	0	0	0	0	0	1 485 7.1	0	0
Fuel Gas System	0	0	0	1 316 3.3	0	2 580 2.8	0	0	0	1 8278 12.3	0
Liners	0	0	0	0	0	0	0	0	0	0	0
Cross Fire Tubes	0	0	0	0	0	0	0	0	0	0	0
Transition Ducts	0	0	0	0	0	0	0	0	0	0	0
Fire Detection System	0	0	0	0	0	0	0	1 373 1.0	0	0	0
Service Factor	0.07	0.62	0.31	0.36	0.05	0.39	0.16	0.31	0.24	0.01	0.11
Fired Hours per Start	31	185	94	99	87	128	84	89	69	11	53

*The first entry in the columns is the number of failure events; the second is the number of failures per million hours of operation (λ); the third entry is mean downtime in hours.

** B80-0: Turbine Identifier, Year, Oil-Fired

(continued)

Table D-2 (continued)

COMBUSTION TURBINE COMPONENT PERFORMANCE SUMMARY FOR LSF UNIT TURBINES, BY CT CODE

Component	G79-0	F79-0	G78-0	F80-0	H80-0	E80-0	F78-0	E79-0	C80-0	E78-0	G80-0
CT Unit, General	0	0	1 875 722.1	0	39 3704 7.0	0	0	1 1,256 0.3	1 37,313 0.7	7 12,821 20.2	0
Combustion Section (Other)	0	1 1499 0.3	0	0	10 950 16.7	0	0	0	0	0	0
Fuel Oil Flow Dividers	1 708 0.3	0	0	0	3 285 7.3	0	2 1454 82.7	0	0	0	1 3,413 3.1
Fuel Oil Pumps	0	0	1 875 21.6	1 2137 606.9	5 475 8.0	0	1 727 0.5	0	0	0	0
Fuel Oil Filters	0	0	0	0	9 855 3.4	0	0	1 1,256 2.6	0	0	0
Fuel Oil Systems (Other)	3 2123 36.0	0	1 875 2.1	0	22 2089 2.7	0	1 727 2.1	3 3,769 0.7	0	0	1 3,413 2.8
Starting System	1 708 1.0	0	3 2625 8.5	2 4274 3.9	5 475 20.2	2 2,985 0.9	1 727 0.3	0	0	3 5,495 1.0	0
Lube Oil System	3 2123 123.0	0	1 875 104.3	2 4274 0.7	4 380 10.1	2 2,985 65.7	2 1454 30.3	2 2,513 3.3	0	2 3,663 0.2	0
Air System	3 2123 23.7	0	2 1750 11.6	0	1 95 9.0	0	2 1454 13.5	1 1,256 66.0	0	3 5,495 21.7	1 3,413 0.6
Electrical Controls (Other)	6 4246 2.3	4 5997 0.4	7 6124 1.5	3 6410 15.3	21 1994 6.7	7 10,448 1.2	6 4361 1.1	11 13,819 3.8	0	5 9,158 18.0	6 20,478 0.4
Compressor	0	0	0	0	1 95 3.3	0	0	0	0	0	0
Inlet Guide Vanes	0	0	0	0	4 380 3.2	0	1 727 0.4	0	0	1 1,832 17.8	0
Turbine Exhaust Section	1 708 3.1	1 1499 0.3	0	0	6 570 11.2	2 2,985 0.5	0	0	0	0	0
Turning Gear System	0	1 1499 189.0	1 875 7.8	0	7 665 13.9	0	0	0	0	0	0
Fuel Nozzles	0	2 2999 2.4	0	0	60 5699 4.2	0	3 2180 10.9	0	0	0	0
Fuel Gas System	1 708 3.6	0	1 875 5.5	0	0	0	8 5814 1.8	2 2,513 1.7	0	2 3,663 0.9	4 13,652 8.7
Liners	0	0	0	0	0	0	0	1 1,256 1.9	0	0	0
Cross Fire Tubes	0	0	1 875 3.0	0	0	0	2 1454 8.4	0	0	0	0
Transition Ducts	0	0	0	0	0	0	0	0	0	0	0
Fire Detection System	0	0	0	0	0	0	1 727 2.2	0	0	0	0
Service Factor	0.16	0.08	0.13	0.05	0.30	0.08	0.16	0.09	0.003	0.06	0.03
Fired Hours per Start	15	11	12	8	10	10	12	10	27	12	6

EPRI AP-2536

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-2536
RP1319-6
Final Report
August 1982

Reliability and Availability Assessments of Selected Domestic Combined-Cycle Power-Generating Plants

Contractor: ARINC Research Corporation

Results of reliability and availability assessments performed at combined-cycle power plants are presented. The report includes an evaluation of (1) combned-cycle unit equivalent availability and equivalent forced-outage rates; (2) system and component mean time between failures and mean downtime; and (3) gas turbine reliability correlations with service hours, starting frequency, fuel type, and service factor. A data base was developed, and recommendations for improving outage data collection for reliability analysis are given. 114 pp.

EPRI Project Managers: J. Weiss, R. Duncan

Cross-References:
1. EPRI AP-2536 2. RP1319-6 3. Power Generation Program
4. Combined-Cycle Power Plants

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