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**The Role of Design Complexity in Forecasting
Reliability and Availability for Electric-Power-
Generating Units.**

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ABSTRACT

This report examines the relationship between design complexity and reliability and availability performance for fossil-fueled electric-power-generating units.

Multivariate regression analysis was applied to design complexity and reliability and availability performance data gathered from a representative sample of electric-power-generating units. Twelve predictive relationships or equations were developed as a result of employing this statistical procedure. Each equation was verified and assessed. Guidelines for applying the predictive relationships, including confidence limits, were also developed and are presented in this report.

A major result of this examination is a quantitative predictive tool that should be useful to the electric-power industry.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

RP1923, The Role of Design Complexity in Forecasting Reliability and Availability for Electric Power Generation Units, is part of the continuing effort to develop more accurate data for use in assessing the reliability and availability of advanced power systems. Such systems often have components and major subsystems that are technologically innovative and for which no field or laboratory experience is available. Consequently, there are no data for evaluating the potential or probable reliability or availability of the generating unit. Additionally, there are numerous instances in which field data do exist, but their validity is suspect as being nonrepresentative of the experience that is generally current and may be expected with a new installation.

To meet these needs it is desirable to have some method of generating data that can be accepted as being reasonably accurate. A previous project, RP1188, initiated the EPRI effort to generate more useful data on component failure rates and repair rates. A general methodology resulted from that effort, and is reported in EPRI Topical Report AP-1848. The present work was the first attempt to develop a specific method. The research was begun by collecting data on outage events from a number of interested and cooperating utilities. Multiple correlation techniques were then applied to develop relationships between reliability measures such as mean time between failures and unit characteristics such as size, fuel type, parts count, forced-outage parts count, training programs, and several other potential factors.

PROJECT OBJECTIVE

This was the first attempt to develop a specific, explicit means of forecasting accurate data when none were available or when the available data were believed to be inaccurate. Quantitative measures were sought; that is, the number of hours between failures, the number of hours to restore, equivalent availability, and others.

PROJECT RESULTS

Several formulas were developed to facilitate useful forecasts of such reliability and availability measures as mean time between failures, mean time to restore, and operating availability. At this very early stage the accuracy of results and the confidence that can be placed in the results are very limited, but both are advantageous additions and checks to methods such as failure modes and effects analysis and expert consensus. This work also opens up an avenue for further efforts that can lead to better forecasting and a check on available data that may be questionable.

Twelve equations were developed in two groups of six each. One group is intended to provide estimates during the conceptual and early design phases; the second group is for use in the detailed design and later phases, when more information is available. A representative of each group is given here.

$$\begin{aligned}\text{LOG (MTBFFO)} = & 5.4624 - (1.9825 \times 10^{-3}) \text{ MW} + 0.6701 \text{ UT} \\ & + 0.8138 \text{ FT} + 0.4639 \text{ CDT}\end{aligned}$$

Conceptual
Design Phase

$$\begin{aligned}\text{LOG (MTBF)} = & 4.1548 - (1.4731 \times 10^{-3}) \text{ MW} + 1.0296 \text{ UT} \\ & + 1.0045 \text{ FT} - (7.906 \times 10^{-3}) \text{ FOPC} + 1.5167 \text{ CDT}\end{aligned}$$

Detailed and
Later Phases

Key

CDT--Condenser type (use 1 for single pass and 0 for double pass)

FOPC--Forced-outage parts count (the number of parts, which if failed, would result in a forced outage for the unit)

FT--Primary fuel type (use 3 for gas, 2 for oil, and 1 for coal)

LOG--Natural logarithm

MTBF--Mean time between failures in hours

MTBFFO--Mean time between full forced outages in hours

MW--Nameplate megawatt output

UT--Usage type (use 1 for base load and 0 for cycle load)

The relationships developed in this study are not necessarily descriptions of causes and effects, although further work may prove this. Rather they are pragmatic results, derived by a specific technique, multivariate regression analysis, which is justified at this time by the useful accuracy realized in applications. Further

developments using the same techniques and others should improve the present quality level.

Jerome Weiss, Project Manager
Advanced Power Systems Division

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GLOSSARY

Available Hours (AH) - The time in hours during which a unit or major equipment is capable of service, whether or not it is actually in service.

AVAIL 1 - The amount of time in which a unit or major equipment is available over the period expressed as a fraction or a percent (when multiplied by one hundred) -- i.e., $AH \div PH$; commonly referred to as operating availability.

AVAIL 3 - A measure of availability for a unit or major equipment calculated as follows:
$$\frac{MTBF + MTTR}{MTBF}$$

AVAIL 4 - A measure of availability commonly referred to as equivalent availability and calculated as follows:
$$\frac{AH - (EFOH + ESOH)}{PH}$$

Equivalent Forced Outage Hours (EFOH) - The forced outage equivalent of a forced partial outage expressed as time in hours ($FPOH \times \text{size of reduction/MDC}$).

Equivalent Scheduled Outage Hours (ESOH) - The scheduled outage equivalent of a scheduled partial outage expressed as time in hours ($SPOH \times \text{size of reduction/MDC}$).

Forced Outages (FO) - The number of forced outage incidents (see FOH).

Forced Outage Hours (FOH) - The time in hours during which a unit or major equipment is unavailable due to the occurrence of a component failure or other condition which requires that it be removed from service immediately or up to and including the very next weekend.

Forced Partial Outages (FPO) - The number of forced partial outages (see FPOH).

Forced Partial Outage Hours (FPOH) - The time in hours during which a unit or major equipment is unavailable for full-load due to the occurrence of a component failure or other condition which requires that the load on it be reduced 2 percent or more immediately or up to and including the very next weekend.

Maintenance Outage Hours (MOH) - The time in hours during which a unit or major equipment is unavailable due to its removal from service to perform work on specific components that could not have been postponed past the very next weekend. This is work done to prevent a potential forced outage and which could not be postponed from season to season.

Major Equipment (ME) - Major group of equipment within a unit (e.g., boilers, generators, turbines, condensers).

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

Mean-Time-Between Failures (MTBF) - The average time in hours between interruptions in the service hours of a unit or major equipment due to an unplanned (i.e., forced, forced partial and/or scheduled partial) outage.

Mean-Time-Between-Full-Forced-Outages (MTBFFO) - The average time in hours between forced outages over the course of a period.

Mean-Time-To-Restore (MTTR) - The average time in hours required to return a unit or major equipment to service after experiencing an unplanned (i.e., forced, forced partial or scheduled partial) outage.

Nameplate Megawatt Output - The manufacturer's design megawatt per hour rating.

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

Planned Outage Hours (POH) - The time in hours during which a unit or major equipment is unavailable due to its removal from service for inspection or general overhaul. This work is usually scheduled well in advance (e.g., annual boiler overhaul, five year turbine overhaul).

Sample - A subgroup of the universe of interest.

Sampling Frame - An empirical representation of the universe of interest.

Scheduled Partial Outages (SPO) - The number of scheduled partial outages (see SPOH).

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

Service Factor (SF) - The amount of time in which a unit was actually operational over the period expressed as a fraction or a percent (when multiplied by one hundred) -- i.e., $SH \div PH$.

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

Universe (or Population) - The group of electric power generating units of interest -- fossil fueled steam or combined cycle units that are base or cycle loading and have a nameplate megawatt output of 70 or greater.

SUMMARY

The purpose of this study is to understand better the relationship between design complexity and the reliability and availability performance of electric power generating units; its focus is to test the hypothesis that a quantifiable and meaningful relationship exists. The objectives are twofold:

- Obtain a better understanding of design complexity and its effect on reliability and availability
- Develop and verify a method for quantifying and predicting the relationship between design complexity and reliability and availability

The achievement of these objectives required an approach that would yield testable and useful results.

The approach employed in this study may be summarized as consisting of two sequential steps:

- Identification, collection, and analysis of data provided by cooperating electric power companies to enable the contractor to derive design complexity and reliability and availability performance measures
- Application of statistical techniques to the data to develop, test, and refine predictive relationships

The data base resulting from the initial step contains design complexity and reliability and availability performance information from a random sample of electric power generating units. The sample is representative of the complete population (or universe) of units meeting the following criteria:

- Fossil fueled
- Steam units or combined cycle units
- Base or cycle loading
- "Nameplate" output of at least seventy megawatts

Table S-1 presents a comparison of significant characteristics of the sample and the collection of units from which it is drawn. The distribution of significant

characteristics of the sample and universe (or total collection of units) is relatively close, indicating sample representativeness.

Table S-1 SIGNIFICANT CHARACTERISTICS OF SAMPLE AND UNIVERSE (Expressed as a Percent of Total)*		
Characteristic	Percent of Sample	Percent of Universe
Gas Fired	10	18
Oil Fired	36	29
Coal Fired	54	53
1 to 5 Years of Operation	10	11
6 to 10 Years of Operation	24	16
11 to 20 Years of Operation	22	27
21 or more Years of Operation	44	42
Unknown Years of Operation	0	4
70MW to 199MW	38	55
200MW to 499MW	40	27
500MW to 799MW	14	14
800MW or more	8	4
*Entries are based on a total of 50 units for the sample and 1483 units for the universe; they were calculated by use of the following formula: $\frac{\text{number of units}}{\text{total number of units}} \times 100$		

The application of a statistical procedure known as multivariate regression analysis to the data resulted in the development of 12 quantitative relationships. Although these relationships or equations were derived from sample data that appear to be characteristic of the relevant population, only nine (less than one percent) of the nation's electric power generating companies supplied information and hence are represented in the data base. Despite this limitation, these equations may prove useful for predicting reliability and availability performance.

For each measure of reliability and availability performance (dependent variable) analyzed in this study, two types of predictive equations were developed. During the early conceptual stage of an electric power generating unit, specific design information such as the number of parts in the unit, is generally not known. Performing multivariate regression analyses with and without this type of information resulted in a set of "late" and "early" predictive equations. The early equations provide an estimate of the average performance of the unit over its useful life based on the minimal amount of information that would be available in the conceptual stage. The late equations are applicable to the detailed design and operational stages of an electric power generating unit. They can be used to forecast a unit's reliability and availability performance before its construction, thereby allowing for design improvements or, once the unit is operational, the late equations may be employed to guide equipment operation, maintenance, replacement, and retrofitting activities.

Table S-2 presents the 12 predictive relationships or equations developed in the study. Also shown in the table are the coefficients of determination (R^2 values) for each equation. The R^2 value ranges from zero to one and measures how well the independent (or predictor) variables (i.e., those on the right side of the equation) are able to explain variations from the average value for the dependent (or predicted) variable. A high R^2 value indicates that the predictive equation is a good mathematical description of a relationship existing among the data.

Eight independent or predictor variables were found to be significant for forecasting reliability and availability performance. Table S-3 summarizes which independent variables are employed in the late and early equations to predict reliability and availability performance.

All equations were subjected to verification. Each equation was applied to data from six electric power generating units selected at random that were not part of the data base used to derive the predictive equations. The predicted value for the reliability and availability performance variable for each unit, derived from using an equation, was compared with the actual value. In general, this technique yielded satisfactory results for all equations.

Applying any of the predictive equations is relatively straightforward -- numerical values are assigned to the independent (predictor) variables contained in the equation. As an example, to predict AVAIL 1 (operating availability) for a unit

Table S-2		
SUMMARY OF PREDICTIVE EQUATIONS		
Predictive Equations		R ²
Late Equations		
LOG (MTBF)	= 4.1548 - (1.4731 × 10 ⁻³) MW + 1.0296 UT + 1.0045 FT - (7.906 × 10 ⁻³) FOPC + 1.5167 CDT	0.8352
LOG (MTTR)	= 0.2253 + (4.9894 × 10 ⁻²) YO + (1.2065 × 10 ⁻³) MW + 0.7624 FT + (1.0201 × 10 ⁻²) PC - (1.2462 × 10 ⁻²) FOPC	0.6798
LOG (MTBFFO)	= 5.8741 + (4.1119 × 10 ⁻²) YO - (6.823 × 10 ⁻⁴) MW + 0.4842 UT + 0.5248 FT - (3.7949 × 10 ⁻³) FOPC	0.6217
AVAIL 1	= 0.9529 - (2.513 × 10 ⁻⁴) MW - (3.9306 × 10 ⁻⁴) PC + (3.42 × 10 ⁻²) CDT	0.6370
AVAIL 3	= 1.0819 - (4.9373 × 10 ⁻³) YO - (3.3851 × 10 ⁻⁴) MW + (6.4905 × 10 ⁻²) UT - (5.4569 × 10 ⁻⁴) PC + 0.1341 CDT	0.7113
AVAIL 4	= 0.9817 - (4.0407 × 10 ⁻³) YO - (3.8912 × 10 ⁻⁴) MW + (6.5902 × 10 ⁻²) UT - (5.7679 × 10 ⁻⁴) PC + 0.14 CDT	0.6290
Early Equations		
LOG (MTBF)	= 1.7497 - (2.5873 × 10 ⁻³) MW + 1.1986 UT + 1.9046 FT + 1.47 CDT	0.7284
LOG (MTTR)	= 2.5861 + (8.8698 × 10 ⁻⁴) MW + 0.8069 FT - 0.33 TP	0.4136
LOG (MTBFFO)	= 5.4624 - (1.9825 × 10 ⁻³) MW + 0.6701 UT + 0.8138 FT + 0.4639 CDT	0.5443
AVAIL 1	= 0.8328 - (3.3264 × 10 ⁻⁴) MW + (4.5077 × 10 ⁻²) FT	0.6038
AVAIL 3	= 0.8214 - (3.6029 × 10 ⁻⁴) MW + (3.9916 × 10 ⁻²) UT + 6.9036 × 10 ⁻² FT + 0.0537 CDT	0.5724
AVAIL 4	= 0.8015 - (4.1615 × 10 ⁻⁴) MW + (3.4337 × 10 ⁻²) FT + (6.2196 × 10 ⁻²) CDT	0.4996
<u>KEY</u> AVAIL 1 - Operating availability (available hours divided by period hours) AVAIL 3 - A point estimate of availability (MTBF divided by the sum of MTBF and MTTR) AVAIL 4 - Equivalent availability (AVAIL 1 adjusted for partial outages) CDT - Condenser type (use 1 for single pass and 0 for double pass) FOPC - Forced outages parts count (the number of parts, which, if failed, would result in a forced outage for the unit) FT - Primary fuel type (use 3 for gas, 2 for oil, and 1 for coal) LOG - Natural logarithm MTBF - Mean time between failures MTBFFO - Mean time between full forced outages MTTR - Mean time to restore MW - Nameplate megawatt output PC - Parts count TP - Number of training programs for maintenance and operating personnel UT - Usage type (use 1 for base load and 0 for cycle load) YO - Years of operation (see Appendix B)		

Table S-3

APPLICABILITY OF RELIABILITY/AVAILABILITY PERFORMANCE VARIABLES

Predictor or Independent Variable	Predicted or Dependent Variable											
	MTBF		MTTR		MTBFFO		AVAIL 1		AVAIL 3		AVAIL 4	
	E*	L**	E	L	E	L	E	L	E	L	E	L
Condenser Type (CDT)	X	X	X		X			X	X	X	X	X
Forced Outage Parts Count (FOPC)		X				X						
Fuel Type (FT)	X	X	X		X	X	X		X		X	
Megawatts (MW)	X	X	X	X	X	X	X	X	X	X	X	X
Parts Count (PC)				X				X				
Training Program (TP)				X								
Unit Type (UT)	X	X	X		X	X			X	X		X
Years Operation (YO)						X				X		X

*E = Early Equation
 **L = Late Equation

that has a nameplate output of 350 megawatts, comprises 275 major pieces of equipment, and uses a single pass condenser, the following late equation is employed:

$$\text{AVAIL } 1 = .9529 - (2.513 \times 10^{-4}) \text{ MW} - (3.9306 \times 10^{-4}) \text{ PC} + (3.42 \times 10^{-2}) \text{ CDT}$$

Inserting the appropriate values and solving we have:

$$\begin{aligned} \text{AVAIL } 1 &= .9529 - (2.513 \times 10^{-4}) \times 350 - (3.9306 \times 10^{-4}) \times 275 + (3.42 \times 10^{-2}) \times 1 \\ &= .79 \end{aligned}$$

Therefore, the average operating availability for this unit over its useful life is estimated to be 79 percent.

Section 1

INTRODUCTION

This report presents a study of the relationships between the design complexity inherent in an electric power generating system and its reliability and availability performance. The study was conducted by ARINC Research Corporation for the Electric Power Research Institute under Contract No. RP 1923-2. This section presents introductory information, the objectives, scope, and limits of the study and the organization of this report.

NATURE AND ROLE OF COMPLEXITY

During the formalization of reliability theory in the 1950s, it was recognized that as a system's complexity increased, its reliability decreased. This phenomenon was observed in electronic equipment and became the subject of much study. As a result of these studies, a quantified expression for relating electronic equipment reliability to complexity was developed; complexity was defined and measured in terms of parts count.

It is believed that the effects of complexity on the reliability of nonelectronic equipment is of the same general form as observed for electronic equipment. However, the difficulty in establishing uniform, consistent complexity measures has hindered quantitative development. Furthermore, complexity measures based on simple parts count has not provided an adequate means for handling redundancy, which has become more prevalent with miniaturization. Despite these difficulties, the general finding -- that complexity has a dominating effect on reliability -- provides a strong challenge to better understand complexity so that countervailing designs and operations and maintenance activities may be developed.

BACKGROUND

Electric power generating companies (i.e., utility companies) produce a vital commodity, one that is also unique. Unlike many consumer goods, large quantities of electricity cannot be produced by manufacturers and stored for later sale. Utility companies maintain no inventory of electricity. Instead, they must maintain sufficient generating capacity to serve, without interruption, their customers'

fluctuating demand for power. Facilities, as opposed to inventories of electricity, are kept in reserve (i.e., reserve shutdown) to be brought on line when demand warrants. This balancing operation -- matching supply and demand -- occurs virtually every instant throughout the year. The implications of this characteristic of electric power production are immense -- enough generating capacity must be built to serve the maximum coincident power demand -- the "peak load" -- on a utility's system.*

It follows that the efficient operation of a utility company is largely dependent upon the extent to which electric power may be generated on demand uninterrupted. Failure to respond to demand, due to either unplanned interruptions or curtailments in power, is a highly significant problem that is pervasive throughout the industry. At the user level, contingency planning is generally neither practical nor realistic -- i.e., "backyard" electric power generating units or direct purchase agreements with neighboring utility companies as alternative sources of electricity are not generally viable solutions. Contingency planning by the producers and distributors of electric power generally consists of wholesale purchasing arrangements with cooperating utility companies. Because the type, cause, and duration of electric power shortages can be so diverse, aside from purchasing agreements, reserve facilities, and limited parts inventories, developing more comprehensive measures to ensure constant power supply is often not cost-effective.

One approach to a long-run solution to the failure problems associated with electric power generating systems is to acquire a thorough knowledge of the contributing or causative factors. The concepts of reliability and availability provide alternative definitions and measures for the performance of electric power generating systems, units, pieces of equipment, or components. Identifying the key determinants of these performance measures is essential to reducing or eliminating failures and their effects. Design complexity has long been regarded as being significantly related to reliability and availability performance. More specifically, it has been theorized that for any reasonable measure of complexity, reliability will change as complexity changes. Therefore, to affect, control, or improve the reliability and availability of electric power generating systems requires a sound understanding of their relationship to design complexity.

*Paul F. Levy, "The Politics of Rate Reform," Technology Review, (February 1978), pp 37-43.

OBJECTIVES

This study is an attempt to understand better the relationship between design complexity and the reliability and availability performance of electric power generating systems; its focus is to test the hypothesis that a quantifiable and meaningful relationship exists. The objectives are twofold:

- Obtain a better understanding of design complexity and its effect on reliability and availability
- Develop and verify a method for quantifying and predicting the relationship between design complexity and reliability and availability

SCOPE AND LIMITS

The study will attempt to examine the hypothesis that quantifiable relationships exist between measures of design complexity and reliability and availability for electric power generating systems at the unit level. It is limited to electric power generating units that meet the following criteria:

- Fossil fueled
- Steam units or combined cycle units
- Base or cycle loading (i.e., non-peak loading)
- 70 megawatt output or larger

Although the focus of the analyses presented herein is specific, the findings of this study should provide a better understanding of the relationship between design complexity and reliability and availability for all types of power generating systems and provide a means for forecasting plant performance.

ORGANIZATION

Section 2 of this report describes the methodology, including the overall technical approach, development of variables, survey procedure and results, relevant characteristics of the data base, statistical techniques, and equation verification procedures. Section 3 presents the findings derived from applying multivariate regression techniques to the data. A discussion of the applicability of the predictive equations is contained in Section 4. Conclusions and recommendations based on the findings are presented in Section 5. Appendix A presents the survey questionnaire and Appendix B provides an explanation of the variables constructed for analysis. Appendix C presents a detailed description of the statistical techniques employed in the study. A graphical display of the verification results

is presented in Appendix D. Appendixes E and F present the confidence interval estimation procedures and the computer program for employing the predictive equations; both contain application examples.

Section 2

METHODOLOGY

This section describes the method used to examine the effect of design complexity on the reliability and availability performance of electric power generating units. It presents information on the variables selected and analyzed, survey procedure and results, and the statistical techniques employed to arrive at the predictive equations.

OVERALL APPROACH

The approach employed in this study may be summarized into two sequential steps:

- Identify, collect, and analyze data provided by cooperating electric power companies to derive design complexity and reliability and availability measures
- Apply statistical techniques to the data to develop, test, and refine predictive relationships

The first step entailed deciding which variables would likely be important to the development of a quantitative forecasting tool, constructing a suitable survey questionnaire to gather the desired information, developing a sampling frame (an appropriate list of units representative of all electric power generating units that are within the scope and limits of the study as discussed in Section 1), taking a random sample from the sampling frame to serve as recipients of the questionnaire, and collecting and tabulating the data.

The second step encompassed the application of multivariate regression techniques to the data collected to derive predictive equations and the iterative refinement and verification of the utility of the equations using performance and design complexity information from appropriate electric power generating units not contained in the data base subjected to the regression analysis. The following sections elaborate on the study method, describing the variables, survey results, data base characteristics, and statistical procedures in greater detail.

VARIABLE SELECTION AND ANALYSIS

The research problem addressed in this study may be viewed as an attempt to identify and quantify the relationship between design complexity and reliability and availability. Once the problem is reduced in this manner, the task of specifying variables that can be investigated empirically is lessened significantly.

Thirty-one variables were developed initially on the basis of previous studies in similar areas, "hands-on" experience, and engineering judgment. The survey questionnaire contained in Appendix A to this report was created to serve as the vehicle by which the information needed to construct and measure the variables would be obtained. Not all of the 31 variables are directly translatable to measures for design complexity or reliability and availability but were included because of their potential significance to the problem. For example, information was sought from electric power companies that allowed for the creation of climatic variables -- the average winter and summer temperature at the unit site. Whereas neither of these temperature variables is an explicit measure of design complexity, they may have significantly influenced certain engineering decisions, such as the design of cooling towers, thereby affecting more direct measures like parts counts. Also included were other variables to account for reliability and availability variation that could not be adequately explained by direct measures for design complexity (e.g., years of operation). Table 2-1 on the following page lists the independent (design complexity) and dependent (reliability and availability performance) variables initially selected. The 31 variables initially selected were reduced to 21 because the information needed to construct and evaluate all of the variables was not readily available from all of the utility companies participating in the project. The variables analyzed are listed in Table 2-1. Appendix B to this report contains information on the construction of those variables analyzed in the study. Definitions of terms used in the report are provided in the Glossary.

SURVEY PROCEDURE

To conduct this study required that a substantial amount of technical information be supplied voluntarily by electric power generating companies. A mail questionnaire was used to collect the desired information; telephone contact followed the return of the questionnaire to assure its accuracy and completeness. To improve the relatively low response rate typical of surveys conducted by mail, a strategy was developed that entailed selecting a special sampling frame and employing a three-stage survey technique.

Table 2-1	
VARIABLES OF INTEREST	
Variable	Analyzed
Independent	
Average Summer Temperature (AST)	Yes*
Average Winter Temperature (AWT)	Yes*
Years of Operation (YO)	Yes*
Megawatt Output (MW)	Yes*
Average Gross Winter Megawatt Output (AGWMW)	No
Average Gross Summer Megawatt Output (AGSMW)	No
Average Net Winter Megawatt Output (ANWMW)	No
Average Net Summer Megawatt Output (ANSMW)	No
Cycle Type (CT)	Yes*
Usage Type (UT)	Yes*
Cycle Count (CC)	No
Average Cycle Load (ACL)	No
Fuel Type (FT)	Yes*
Parts Count (PC)	Yes*
Forced Outage Parts Count (FOPC)	Yes*
Partial Outage Parts Count (POPC)	Yes*
Adjusted Parts Count (APC)	Yes*
Adjusted Forced Outage Parts Count (AFOPC)	Yes*
Adjusted Partial Outage Parts Count (APOPC)	Yes*
Boiler Type (BT)	No
Condenser Type (CDT)	Yes*
Boiler Feed Water Quality (BFW)	No
Air Pollution Equipment (AP)	No
Air Pollution Parts Count (APPC)	No
Number of Training Programs (TP)	Yes*
Dependent	
Operating Availability (AVAIL 1)	Yes*
Equivalent Availability (AVAIL 4)	Yes*
Mean Time Between Full Forced Outages (MTBFFO)	Yes*
Mean Time Between Failures (MTBF)	Yes*
Mean Time To Restore (MTTR)	Yes*
$MTBF \div (MTBF + MTTR)$ (AVAIL 3)	Yes*
*See Appendix B and the Glossary for construction and definition of variables analyzed.	

The sampling frame selected for the study consisted of utility companies that report on the performance of their respective generating units to the Generating Availability Data System (GADS) Program conducted by the North American Electric Reliability

Council (NERC).^{*} Sampling from this particular group of electric utility companies contributed significantly to the relatively high response rate to the survey for several reasons:

- A utility company could easily authorize the NERC to release much of the desired performance information from the GADS, thereby significantly reducing the burden of completing the questionnaire.
- A utility company's data gathering efforts for the NERC's GADS Program directly result in much of the information requested on the questionnaire.
- These utility companies are characteristically good survey respondents due to their participation in the GADS Program and, therefore, were expected to perform in a similar manner for this study.

Given the universe or population of interest in this study -- all steam or combined cycle electric power generating units that are fossil fueled, 70 megawatts or greater, and base or cycle loading -- the question as to the appropriateness of this sampling frame is important. None can ever be a perfect representation of the universe or population of interest. From a practical standpoint, a successful sampling frame is one that fits the purpose; the one selected for this project is well suited to the objectives of the study. Section 2.4 discusses the representativeness of the data base in greater detail.

Following the selection of a special sampling frame, the other element of the survey procedure consisted of a three-phased solicitation effort. The first phase consisted of a telephone survey to thirty electric utilities selected randomly from the sampling frame. This initial survey was undertaken to determine which utilities showed sufficient interest in the study to warrant sending them the questionnaire for their possible completion. The second phase entailed mailing the questionnaire to interested electric utility companies. The final phase involved telephone follow-up communications with the utilities that received questionnaires to clarify their responses or solicit information initially omitted by the respondent in the questionnaires completed and returned. If the questionnaire had as yet not been returned, telephone calls were made to determine its status and whether or not the information requested would be forthcoming.

^{*}NERC was formerly the National Electric Reliability Council. It publishes reports on the performance of major types of electric power generating units based on information supplied by electric utilities.

SURVEY RESULTS

Completed questionnaires were received from nine of the 30 electric utility companies surveyed, representing a response rate of 30 percent. Relevant information was supplied for 61 electric power generating units meeting the study boundaries summarized in the subsection entitled "Objectives" in Section 1 of this report. Five of the units could not be analyzed because of insufficient information. Fifty of the remaining 56 units were subjected to multivariate regression techniques. Six were used for verifying the resulting predictive equations (discussed in the subsection entitled "Early and Late Equation Development" later in this section).

Table 2-2 summarizes the significant characteristics of the data base of 50 units (also referred to as observations) subjected to multivariate regression techniques. The table shows that the sample is divided almost evenly between base and cycle loading units, with 46 percent of the total belonging to the former category and 54 percent to the latter. More than half of the units -- 54 percent -- are coal fired, 36 percent are oil fired, and 10 percent are gas fired. Approximately two-thirds of the units -- 66 percent -- have been in operation more than 10 years, whereas the remaining one-third has been operational 10 years or less. Seventy-eight percent are under 500 megawatts. The remaining 22 percent is split with two-thirds of the units being over 500 but less than 800 megawatts and one-third being 800 megawatts or more. Although it is not indicated in Table 2-2, it is nevertheless important that only eight percent of the units are of the combined cycle variety; hence the sample consists mostly of steam units.

Whether or not this sample is representative of the universe of electric power generating units of interest -- steam or combined cycle units that are fossil fueled, base or cycle loading, and have a nameplate megawatt output of 70 or greater -- is key to the study. The utility and applicability of the predictive equations developed from the sample data to all relevant (those within the universe of interest) units are largely dependent on this issue.

Information provided in the publication *Inventory of Power Plants in the United States: 1980 Annual*, prepared by the United States Department of Energy (DOE), was employed to develop Table 2-3 since it is believed to represent characteristics of the population of electric power generating units of interest. Although the DOE report does not differentiate between base, cycle, and peak load units, by purging from the inventory units with a nameplate megawatt output of less than 70 (since

Table 2-2					
SIGNIFICANT CHARACTERISTICS OF DATA BASE (Expressed as a Percent of Total)*					
Characteristic	Nameplate Megawatt Output				
	70 to 199	200 to 499	500 to 799	800 or more	Total
Base Loading	14	20	6	6	46
Cycle Loading	24	20	8	2	54
Gas Fired	0	2	8	0	10
Oil Fired	22	12	0	2	36
Coal Fired	16	26	6	6	54
1 to 5 Years of Operation	0	6	0	4	10
6 to 10 Years of Operation	8	10	6	0	24
11 to 20 Years of Operation	4	8	6	4	22
21 or More Years of Operation	26	16	2	0	44
Percent of Data Base	38	40	14	8	100
*Entries are based on a total of fifty units and calculated by use of the following formula: $\frac{\text{number of units}}{50} \times 100$					

the majority of peak load units are believed to have a nameplate megawatt rating less than 70) and those that are not fossil fueled, it is possible to obtain a relatively accurate estimate of the relevant universe of electric power generating units.

The representativeness of the sample with respect to the relevant universe may be ascertained by comparing Table 2-2 with Table 2-3. The sample distribution for fuel type approximates that of the universe; the former having 10, 36, and 54 percent of the units fired by gas, oil, and coal, respectively, whereas the latter shows 18, 29, and 53 percent fired by gas, oil, and coal, respectively. The age distribution for the sample and universe are also very similar, with the sample and universe showing, respectively, 66 percent and 69 percent of the units with more than ten years of operation and 34 percent and 27 percent with ten or fewer

Table 2-3					
SIGNIFICANT CHARACTERISTICS OF RELEVANT UNIVERSE OR POPULATION OF ELECTRIC POWER GENERATING UNITS (Expressed as a Percent of Total)*					
Characteristic	Nameplate Megawatt Output				
	70 to 199	200 to 499	500 to 799	800 or more	Total
Gas Fired	12	4	2	0	18
Oil Fired	19	7	2	1	29
Coal Fired	24	16	10	3	53
1 to 5 Years of Operation	2	4	4	1	11
6 to 10 Years of Operation	6	4	4	2	16
11 to 20 Years of Operation	11	11	4	1	27
21 or More Years of Operation	35	7	0	0	42
Unknown Years of Operation	1	1	1	1	4
Percent of Population	55	27	14	4	100
Source: <i>Inventory of Power Plants in the United States: 1980 Annual</i> United States Department of Energy (Washington, D.C.: U.S. Government Printing Office, June 18, 1981), pp. 18-270. *Entries are based on a total of 1483 units and calculated by use of the following formula: $\frac{\text{number of units}}{1483} \times 100$					

years of operation. In addition, the megawatt output distribution for the sample is fairly close to that of the universe. The former shows 78 percent of the units having a nameplate megawatt output of less than 500 and 22 percent with 500 or greater. The universe shows 82 percent of the units having a nameplate megawatt output of less than 500 and the remaining 18 percent with a rating of at least 500. In sum, it appears that the sample (comprising 50 units) from which the predictive equations were developed is a relatively accurate representation of the relevant universe of electric power generating units (based on the best available information). Although only nine of the nation's utility companies are represented

in the sample, it is believed that the study results provide an initial basis for reliability and availability inference (as will be discussed in more detail in Section 4).

STATISTICAL TECHNIQUE

Multivariate (or multiple) regression analysis was the statistical technique employed to develop the relationships between reliability and availability performance and design complexity and other related factors. It is a statistical procedure for obtaining a mathematical description of the relationship between some dependent variable (e.g., reliability and availability performance) and one or more independent variables (e.g., design complexity and other factors such as years of operation and training programs). For extended explanations of computational methods available for deriving multiple regression relationships, see any of the more advanced statistics or econometrics textbooks available. One such source is Johnson, J., *Econometric Methods* (New York: McGraw-Hill, Inc., 1963).

Many computer programs are available for performing multivariate regression analysis. The specific procedure used in this study was a computer program developed by ARINC Research Corporation. Appendix C to this report describes in detail the program and the manner in which it was employed.

EARLY AND LATE EQUATION DEVELOPMENT

Six independent variables analyzed in this study are not generally quantifiable during the conceptual and very early design stages of an electric power generating unit:

- Parts Count (PC)
- Forced Outage Parts Count (FOPC)
- Partial Outage Parts Count (POPC)
- Adjusted Parts Count (APC)*
- Adjusted Forced Outage Parts Count (AFOPC)*
- Adjusted Partial Outage Parts Count (APOPC)*

Detailed design information for a power generating unit would be necessary for the direct construction of these variables and a multitude of derived variables (e.g.,

*Parts count adjusted to account for redundancy in the design of the unit (see Appendix B).

parts count per megawatt -- $PC \div MW$). Performing multivariate regression analyses with and without these variables resulted in two sets of equations. For each dependent variable an early and a late predictive relationship was developed. The early equations were developed as a result of systematically omitting the variables that would not be known during the conceptual and very early design stages of a generating unit and the latter equations included them.

The utility of the early and late equations to an electric power generating company is quite specific. The early equations provide the utility company with an estimate of the average reliability and availability performance of a given unit over its useful life. This estimate is developed using a minimal amount of information, such as that generally available in the very early design or conceptual stage of a unit. The late equations are applicable to the detailed design and operational stages of an electric power generating unit. During the detailed design stage the late equations can be used to forecast a unit's performance over its useful life before its construction. This capability allows for testing the effect of alternative designs and modifications on performance. Once a unit has been constructed and is operational the late equations may be employed to guide equipment replacement and retrofitting activities by forecasting a unit's performance using the various equipment scenarios.

VERIFICATION PROCEDURE

Six electric power generating units were randomly selected to test the accuracy of the predictive equations. These six units were not used to derive the predictive equations -- i.e., they were not part of the data base of 50 observations -- and therefore comprise an "uncontaminated" data base of six observations which can satisfactorily assess the performance of the predictive relationships developed. Table 2-4 summarizes significant characteristics of the verification sample. Comparing Table 2-4 with Table 2-3 shows that the distribution of the verification sample is relatively close to that of the relevant universe of electric power generating units. For instance, both the verification sample and the universe consist of predominantly coal fired units and units that have been in operation at least 21 years. Furthermore, their respective megawatt distributions are fairly close -- both show a majority of units with a nameplate megawatt output of less than 500. The similarities indicate that the verification sample is representative of the relevant universe and therefore may be employed to assess the utility and applicability of the predictive equations.

Table 2-4					
SIGNIFICANT CHARACTERISTICS OF VERIFICATION SAMPLE (Expressed as a Percent of Total)*					
Variable	Nameplate Megawatt Output				
	70 to 199	200 to 499	500 to 799	800 or more	Total**
Base Loading	0	17	17	17	50
Cycle Loading	33	17	0	0	50
Gas Fired	17	0	0	0	17
Oil Fired	17	0	0	0	17
Coal Fired	0	33	17	17	66
1 to 5 Years of Operation	0	17	0	0	17
6 to 10 Years of Operation	0	0	0	17	17
11 to 20 Years of Operation	0	0	17	0	17
21 and More Years of Operation	33	17	0	0	50
Percent of Sample	33	33	17	17	100
*Entries are based on a total of 6 verification units and calculated by use of the following formula: $\frac{\text{number of units}}{6} \times 100$					
**Entries are rounded to nearest whole number.					

The verification procedure employed is relatively simple. Each predictive equation was applied to the data from the six electric power generating units in the verification sample. The value for the reliability and availability performance variable for each unit derived from using an equation (referred to as the predicted value) was compared with the actual value. Measuring the difference between predicted and actual values provides an indication of the potential accuracy and utility of the predictive equations. A relative difference of 30 percent or less between predicted and actual values for a reliability and availability performance measure is considered very good for equations derived from a relatively small sample and comprising rather gross predictor variables. Section 3 reports the results of applying the predictive equations to the verification sample data.

Section 3

FINDINGS

This section presents the predictive relationships or equations resulting from applying multivariate regression techniques to the sample data of 50 units. Twelve equations were developed -- a late and early equation for each of the six reliability and availability performance measures (or dependent variables) analyzed. The verification results for each equation are also presented in this section.

PREDICTIVE RELATIONSHIPS

The underlying hypothesis tested in this study was that a quantifiable and meaningful relationship exists between design complexity and the reliability and availability performance of electric power generating units. This hypothesis was accepted on the basis of the 12 equations developed, which are presented in Table 3-1. Also shown in Table 3-1 are the coefficients of determination or R^2 values for each equation. The R^2 value ranges from zero to one and measures how well the independent variables are able to explain variations from the average value for the dependent variable. A high R^2 value indicates that the predictive equation is a good mathematical description of a relationship existing among the data (in this instance the sample data base of 50 units). In short, the R^2 value measures the "goodness of fit" of the equation to the relationship existing among the data. Table 3-2 presents a chart summarizing the independent or predictor variables applicable to each equation.

The reliability performance equations predicting MTBF, MTTF, and MTBFFO employ the natural logarithmic form for the dependent variable whereas the availability performance equations predicting AVAIL 1, AVAIL 3, and AVAIL 4 use the arithmetic form. The "goodness of fit" to the data for the 12 equations is generally favorable. The amount of variation in the dependent variable (from its average value) that can be explained by the independent variables (as measured by the R^2 value for the equation) ranges from marginal -- 41 percent in the case of early MTTR -- to excellent -- as high as 84 percent for late MTBF.

Table 3-1		
SUMMARY OF PREDICTIVE EQUATIONS		
Predictive Equations		R ²
Late Equations		
LOG (MTBF)	= 4.1548 - (1.4731 × 10 ⁻³) MW + 1.0296 UT + 1.0045 FT - (7.906 × 10 ⁻³) FOPC + 1.5167 CDT	0.8352
LOG (MTTR)	= 0.2253 + (4.9894 × 10 ⁻²) YO + (1.2065 × 10 ⁻³) MW + 0.7624 FT + (1.0201 × 10 ⁻²) PC - (1.2462 × 10 ⁻²) FOPC	0.6798
LOG (MTBFFO)	= 5.8741 + (4.1119 × 10 ⁻²) YO - (6.823 × 10 ⁻⁴) MW + 0.4842 UT + 0.5248 FT - (3.7949 × 10 ⁻³) FOPC	0.6317
AVAIL 1	= 0.9529 - (2.513 × 10 ⁻⁴) MW - (3.9306 × 10 ⁻⁴) PC + (3.42 × 10 ⁻²) CDT	0.6370
AVAIL 3	= 1.0819 - (4.9373 × 10 ⁻³) YO - (3.3851 × 10 ⁻⁴) MW + (6.4905 × 10 ⁻²) UT - (5.4569 × 10 ⁻⁴) PC + 0.1341 CDT	0.7113
AVAIL 4	= 0.9817 - (4.0407 × 10 ⁻³) YO - (3.8912 × 10 ⁻⁴) MW + (6.5902 × 10 ⁻²) UT - (5.7679 × 10 ⁻⁴) PC + 0.14 CDT	0.6290
Early Equations		
LOG (MTBF)	= 1.7497 - (2.5873 × 10 ⁻³) MW + 1.1986 UT + 1.9046 FT + 1.47 CDT	0.7284
LOG (MTTR)	= 2.5861 + (8.8698 × 10 ⁻⁴) MW + 0.8069 FT - 0.33 TP	0.4136
LOG (MTBFFO)	= 5.4624 - (1.9825 × 10 ⁻³) MW + 0.6701 UT + 0.8138 FT + 0.4639 CDT	0.5443
AVAIL 1	= 0.8328 - (3.3264 × 10 ⁻⁴) MW + (4.5077 × 10 ⁻²) FT	0.6038
AVAIL 3	= 0.8214 - (3.6029 × 10 ⁻⁴) MW + (3.8916 × 10 ⁻²) UT + 6.9036 × 10 ⁻² FT + 0.0537 CDT	0.5724
AVAIL 4	= 0.8015 - (4.1615 × 10 ⁻⁴) MW + (3.4337 × 10 ⁻²) FT + (6.2196 × 10 ⁻²) CDT	0.4996
<p><u>KEY</u></p> <p>AVAIL 1 - Operating availability (available hours divided by period hours)</p> <p>AVAIL 3 - A point estimate of availability (MTBF divided by the sum of MTBF and MTTR)</p> <p>AVAIL 4 - Equivalent availability (AVAIL 1 adjusted for partial outages)</p> <p>CDT - Condenser type (use 1 for single pass and 0 for double pass)</p> <p>FOPC - Forced outages parts count (the number of parts, which, if failed, would result in a forced outage for the unit)</p> <p>FT - Primary fuel type (use 3 for gas, 2 for oil, and 1 for coal)</p> <p>LOG - Natural logarithm</p> <p>MTBF - Mean time between failures</p> <p>MTBFFO - Mean time between full forced outages</p> <p>MTTR - Mean time to restore</p> <p>MW - Nameplate megawatt output</p> <p>PC - Parts count</p> <p>TP - Number of training programs for maintenance and operating personnel</p> <p>UT - Usage type (use 1 for base load and 0 for cycle load)</p> <p>YO - Years of operation (see Appendix B)</p>		

Table 3-2

APPLICABILITY OF RELIABILITY/AVAILABILITY PERFORMANCE VARIABLES

Predictor or Independent Variable	Predicted or Dependent Variable											
	MTBF		MTTR		MTBFFO		AVAIL 1		AVAIL 3		AVAIL 4	
	E*	L**	E	L	E	L	E	L	E	L	E	L
Condenser Type (CDT)	X	X	X		X			X	X	X	X	X
Forced Outage Parts Count (FOPC)		X				X						
Fuel Type (FT)	X	X	X		X	X	X		X		X	
Megawatts (MW)	X	X	X	X	X	X	X	X	X	X	X	X
Parts Count (PC)				X				X				
Training Program (TP)				X								
Unit Type (UT)	X	X	X		X	X			X	X		X
Years Operation (YO)						X				X		X

*E = Early Equation
 **L = Late Equation

All of the late equations employ the MW variable and some direct measure for design complexity -- PC and/or FOPC. Years of operation (YO) is also a significant variable in more than half of the late equations. The late equations fit the data relatively well, with R^2 values ranging from 63 percent to 84 percent. Furthermore, they exhibit a slightly better fit than do the early equations, as evidenced by the R^2 values.

As in the late predictive relationships, the MW variable is present in every early equation. Fuel type (FT) is also an important predictor variable common to all of the early equations. The early equation for MTTR employs an independent variable which is found in no other equation, early or late -- i.e., Training Programs (TP). The interpretation of this variable in the context of this equation is fairly straightforward; training programs for operations and maintenance personnel help to reduce the average amount of time required to restore a failed unit to operation. Although the fit for the early equations is not as good as that for the late equations, they still are fairly good predictive relationships. To the extent that more is preferred to less, it is reasonable to expect that the equations based on more information (the late equations) would fit better than those using less. The R^2 values for the early equations range from 41 percent to 73 percent, with an overall average R^2 value of 56 percent. This compares favorably with the average R^2 value for the late equations of 69 percent -- a difference of only 13 percentage points or 23 percent using the early equations as a base.

VERIFICATION RESULTS

Table 3-3 summarizes the results of the verification procedure. The median absolute deviation (MAD), expressed as a percent, was calculated for each of the 12 equations and is presented in this table.* The MAD represents the median absolute relative difference between the predicted values (derived from the equation) and actual values for a dependent variable using the six verification units. It provides a measure of the accuracy of the predictive equations and an initial indicator of their potential as a useful forecasting tool (Section 4 will discuss this latter point in greater detail). An MAD value of 30 percent or less is considered very good for this application, primarily because the sample size is relatively small and the predictor variables are fairly gross measures. Appendix D to this report contains a graphic display of the results of the verification procedure.

*The median absolute deviation was used to prevent a large deviation between actual and predicted values for a single verification unit from seriously distorting the results.

Table 3-3 SUMMARY OF VERIFICATION RESULTS	
Prediction Equation	Median Absolute Deviation (Expressed as a Percent)
LATE AVAIL 1	12.0
EARLY AVAIL 1	12.0
LATE AVAIL 4	15.5
EARLY AVAIL 4	10.0
LATE AVAIL 3	11.5
EARLY AVAIL 3	13.0
LATE MTBF	38.0
EARLY MTBF	12.0
LATE MTBFFO	38.5
EARLY MTBFFO	44.0
LATE MTTR	62.0
EARLY MTTR	56.0

It was previously mentioned in this Section, in the subsection entitled "Predictive Relationships," that the late equations fit a relationship existing among the data better than the early equations, as evidenced by comparing the R^2 values. In addition, because the equations were developed from sample data representative of the relevant universe of electric power generating units on the basis of several characteristics, the late equations were expected to perform better (i.e., be more accurate) than the early equations in practice. However, this was not the case for this verification exercise. The verification results show the early equations to be slightly more accurate than the late variety, the former exhibiting an overall MAD of 24.5 percent and the latter 29.6 percent. One possible reason for this situation is that four of the values for independent variables of the verification units exceeded the ranges of the sample data values (e.g., the value for FOPC for one of the verification units is 462 whereas FOPC does not exceed 446 for any of the units included in the data base). Furthermore, the majority of these variables (with values outside the range of the sample data) are unique to the late equations. This would tend to cause greater disparities in the verification results for the late equations relative to the early type. A discussion of the relative predictive power of the late and early equations is contained in Section 4.

The verification results summarized in Table 3-3 show that most of the equations predicted reliability and availability performance fairly well. The late and early equations for AVAIL 1, AVAIL 3, AVAIL 4, and early MTBF predicted values for reliability and availability performance relatively close to the actual values, as evidenced by their respective MADs. In contrast, the late and early versions for MTTR and MTBFFO, as well as late MTBF, had appreciably higher MADs. The most accurate equation was early AVAIL 4, with an MAD of 10 percent; the worst equation was late MTTR, with an MAD of 62 percent.

In general, the verification procedure has shown that the equations developed can provide acceptable forecasts of reliability and availability performance. However, there are limitations to using these equations. Guidelines for applying these 12 equations, along with quantitative limitations and an example application are presented in Section 4.

Section 4

APPLICATION OF PREDICTIVE RELATIONSHIPS

This section describes the procedures to be followed in applying the 12 equations for predicting and evaluating the reliability and availability performance of electric power generating units. There are five sequential steps in the application procedure:

- Equation Selection
- Variable Quantification and Equation Applicability
- Point Estimation
- Confidence Interval Estimation
- Analysis and Interpretation

Each of these steps is discussed in detail below with the exception of the fourth step, which is detailed in Appendix E.

EQUATION SELECTION

The late and early equations are each developed to predict three measures of reliability (as well as maintainability) performance and three of availability performance:

- MTBF - Mean time between failures
- MTTR - Mean time to restore
- MTBFFO - Mean time between full forced outages
- AVAIL 1 - Operating availability
- AVAIL 3 - An availability measure - i.e., MTBF divided by the sum of MTBF and MTTR
- AVAIL 4 - Equivalent availability

Appendix B and the Glossary contain detailed information concerning the construction and definition of these alternative performance measures. The Section 2 subsection

entitled "Early and Late Equation Development" presented the rationale and methodology for developing the two sets (i.e., late and early) of predictive relationships. To repeat, the late equations are applicable later in the detailed design or operational stages of a generating unit when enough information is available to construct the complexity-related variables. In contrast, the early equations are applicable when the unit's design is in its infancy and complexity information is not available. Generally, the late equations should be used whenever possible. This is supported in part by the information presented in Table 3-1. The late equations exhibit a stronger mathematical description of a relationship existing among the data than the early equations, as evidenced by the R^2 values -- the average R^2 value for the late equations is 13 percentage points greater than that for the early equations. Another reason for selecting the late equations over the early variety whenever possible is their respective standard errors of estimate, or s values. The s value measures the way the sample data values for a dependent variable are dispersed about the average value. The s value measures the preciseness of the predicted value for the dependent variable. The smaller the s value, the more precision is attributed to the equation. Table 4-1 presents the 12 predictive equations and their respective s values. The average s value for the late and early equations may be easily calculated from the information provided in this table. The average s value for the early equations (0.4554) is approximately 23 percent greater than the average s value for the late equations (0.3708), indicating that in general, the late equations are more precise. In sum, the predictive power of the late equations is expected to be superior to that of the early variety in most applications. Section 3's subsection entitled "Verification Results" explains how the early equations may be, under specific circumstances, more accurate than the late equations. Certain other limitations are discussed in the subsection entitled "Analysis and Interpretation" later in this section.

VARIABLE QUANTIFICATION AND EQUATION APPLICABILITY

Applying the prediction procedure requires assigning numerical values to the independent variables in the equation. A description of the quantification procedure is provided in Table 4-2. Also provided in this table is the range of values for each variable that was represented by the sample.

The most valid application of a regression equation exists when it is used for a unit with variable values that fall within the range of the sample data. Even if all variables are within the boundaries, there is the possibility that the regression equation application is one of extrapolation rather than interpolation. This can occur if values for two or more variables constitute a combination not represented

Table 4-1		
SUMMARY OF PREDICTIVE EQUATIONS		
Predictive Equations		S
Late Equations		
LOG (MTBF)	= $4.1548 - (1.4731 \times 10^{-3}) \text{ MW} + 1.0296 \text{ UT} + 1.0045 \text{ FT}$ - $(7.906 \times 10^{-3}) \text{ FOPC} + 1.5167 \text{ CDT}$	0.6838
LOG (MTTR)	= $0.2253 + (4.9894 \times 10^{-2}) \text{ YO} + (1.2065 \times 10^{-3}) \text{ MW}$ + $0.7624 \text{ FT} + (1.0201 \times 10^{-2}) \text{ PC} - (1.2462 \times 10^{-2}) \text{ FOPC}$	0.7278
LOG (MTBFFO)	= $5.8741 + (4.1119 \times 10^{-2}) \text{ YO} - (6.823 \times 10^{-4}) \text{ MW}$ + $0.4842 \text{ UT} + 0.5248 \text{ FT} - (3.7949 \times 10^{-3}) \text{ FOPC}$	0.5694
AVAIL 1	= $0.9529 - (2.513 \times 10^{-4}) \text{ MW} - (3.9306 \times 10^{-4}) \text{ PC}$ + $(3.42 \times 10^{-2}) \text{ CDT}$	0.0711
AVAIL 3	= $1.0819 - (4.9373 \times 10^{-3}) \text{ YO} - (3.3851 \times 10^{-4}) \text{ MW}$ + $(6.4905 \times 10^{-2}) \text{ UT} - (5.4569 \times 10^{-4}) \text{ PC} + 0.1341 \text{ CDT}$	0.0727
AVAIL 4	= $0.9817 - (4.0407 \times 10^{-3}) \text{ YO} - (3.8912 \times 10^{-4}) \text{ MW}$ + $(6.5902 \times 10^{-2}) \text{ UT} - (5.7679 \times 10^{-4}) \text{ PC} + 0.14 \text{ CDT}$	0.1000
Early Equations		
LOG (MTBF)	= $1.7497 - (2.5873 \times 10^{-3}) \text{ MW} + 1.1986 \text{ UT} + 1.9046 \text{ FT}$ + 1.47 CDT	0.8680
LOG (MTTR)	= $2.5861 + (8.8698 \times 10^{-4}) \text{ MW} + 0.8069 \text{ FT} - 0.33 \text{ TP}$	0.9634
LOG (MTBFFO)	= $5.4624 - (1.9825 \times 10^{-3}) \text{ MW} + 0.6701 \text{ UT} - 0.8138 \text{ FT}$ + 0.4639 CDT	0.6263
AVAIL 1	= $0.8328 - (3.3264 \times 10^{-4}) \text{ MW} + (4.5077 \times 10^{-2}) \text{ FT}$	0.0735
AVAIL 3	= $0.8214 - (3.6029 \times 10^{-4}) \text{ MW} + (3.8916 \times 10^{-2}) \text{ UT}$ + $(6.9036 \times 10^{-2}) \text{ FT} + 0.0537 \text{ CDT}$	0.0875
AVAIL 4	= $0.8015 - (4.1615 \times 10^{-4}) \text{ MW} + (3.4337 \times 10^{-2}) \text{ FT}$ + $(6.2196 \times 10^{-2}) \text{ CDT}$	0.1136

in the data base. The predictive equations will be most useful with electric power generating units with characteristics similar to the significant characteristics of the data base presented in the subsection of Section 2 entitled "Survey Results."

Table 4-2

SUMMARY OF PREDICTOR VARIABLE CHARACTERISTICS

Prediction Parameter	Definition	Quantification	Parameter Range
Condenser Type (CDT)	The type of main condenser in the unit	0 - Double pass condenser 1 - Single pass condenser	0, 1
Forced Outage Parts Count (FOPC)	Number of major equipments which could cause a forced outage	Count of number of major equipments which could cause a forced outage*	31 to 446
Fuel Type (FT)	Primary fuel burned by the unit	1 - Coal 2 - Oil 3 - Gas	1, 2, 3
Megawatts (MW)	Nameplate output	Megawatts per hour	72 to 1150
Parts Count (PC)	Total number of major equipments*	Count of number of major equipments*	96 to 514
Training Program (TP)	Number of different types of training programs for operation and maintenance personnel	Count of number of training programs	1 to 5
Unit Type (UT)	Type of loading	0 - Cycle load 1 - Base load	0, 1
Years of Operation (YO)	Age of unit	Year of interest**	1 to 30
*Appendix A, pages A-11 through A-23, identifies what constitutes a major equipment. **See Appendix B for further dicussssion.			

POINT ESTIMATION

Table 4-1 provides the predictive equations for obtaining point estimates of reliability and availability performance measures. These estimates represent the average value of the reliability and availability performance variable that can be expected for the given set of predictor variable values. Also provided in the table are the standard error of estimate (or s value) for each equation that is used in confidence interval prediction (see Appendix E).

CONFIDENCE INTERVAL ESTIMATES

Confidence interval estimates provide a measure of the precision that can be ascribed to a predicted value for the dependent variable. A confidence interval estimate is an interval around the predicted value with which is associated a confidence level expressed as a percent. For example, assume that 50 is the predicted value or point estimate for a dependent variable and the range from 35 to 65 represents the 90 percent confidence interval. This means that the best estimate for the dependent variable is 50 and one can be 90 percent confident that the actual value is contained within the interval from 35 to 65. Appendix E to this report details two procedures for constructing confidence interval estimates. One is an easily applied approximate procedure and the other a more precise technique.

ANALYSIS AND INTERPRETATION

Care must be exercised in analyzing and interpreting the results derived from the application of multivariate regression analysis. A basic assumption in using the regression equations is that the generating unit under consideration has design complexity and reliability and availability performance relationships similar to those existing in the sample data base.

New technology, design practices, and operating and maintenance procedures can effect reliability and availability performance. The data base used is believed to be representative of current electric power generating units. If there is reason to believe that a major change in one or more of the above factors will take place for a new unit, then the predicted values must be adjusted accordingly.

Limited trade-off analyses may be performed using the predictive equations. This is demonstrated in the subsection entitled "Sample Application" which follows. Several aspects of the relationships between reliability and availability performance and design complexity are clear. Smaller systems have better reliability and availability when size is measured by megawatt output or parts count. Since the megawatt

output is normally a specified requirement, it is clear that a design that can minimize the parts count is desirable. For example, if one analyzes the equation for late MTBF, it can be concluded that for smaller units having 50 to 100 major pieces of equipment -- every 10 percent change in parts count changes MTBF by 4 percent to 8 percent. For medium size units (150 to 300 parts count), a 10 percent change in complexity changes MTBF by 12 percent to 25 percent. For larger units (parts count over 300), a 10 percent change in complexity can change MTBF by 30 percent or more. (A graph of the relationship between MTBF and FOPC is contained in the subsection entitled "Sample Application," below.) Similar relationships hold for the other dependent variables, although the complexity impact is not quite as severe.

It is also clear from the equations that units using single pass condensers perform more reliably than those using double pass condensers and that base load units are preferable to cycle load units from a reliability and availability viewpoint. Furthermore, the preference ranking for fuel type is gas, oil, and coal, with gas being most preferred. Thus, if reliability and availability performance were the only considerations, the data support the conclusion that the most reliable generating unit would be a gas-fired unit with a minimum number of parts and single pass condenser.

SAMPLE APPLICATION

The procedure for applying the predictive equations will be illustrated with a fictitious case. Assume that the following information is available for a hypothetical electric power generating unit:

- Nameplate megawatt output is 350.
- The primary fuel is coal.
- It is a base load facility.
- It comprises 275 major pieces of equipment.
- There are 200 major pieces of equipment which, if any single one failed, would result in a forced outage for the unit.
- It uses a single pass condenser.
- There are two training programs available for operations and maintenance personnel.

This information translates directly to values for the seven independent or predictor variables:

- MW = 350
- FT = 1
- UT = 1
- PC = 275
- FOPC = 200
- CDT = 1
- TP = 2

Four of the predictive equations require the years of operation variable (YO). The example presented here will forecast the unit's reliability and availability performance for the fourth year and therefore the value for years of operation will equal four.

Two measures of reliability performance and one measure of availability performance will be forecasted or predicted in this example:

- MTBF - Mean time between failures
- MTTR - Mean time to restore
- AVAIL 1 - Operating availability

Furthermore, because the unit is in operation, sufficient information is available to employ the late equations.

To predict MTBF we use the following (late) equation:

$$\begin{aligned}\text{LOG (MTBF)} &= 4.1548 - (1.4731 \times 10^{-3}) \text{ MW} + 1.0296 \text{ UT} + 1.0045 \text{ FT} \\ &\quad - (7.906 \times 10^{-3}) \text{ FOPC} + 1.5167 \text{ CDT}\end{aligned}$$

Inserting the appropriate values for the independent or predictor variables and solving we have:

$$\begin{aligned}\text{LOG (MTBF)} &= 4.1548 - (1.4371 \times 10^{-3}) \times 350 + 1.0296 \times 1 + 1.0045 \\ &\quad \times 1 - (7.906 \times 10^{-3}) \times 200 + 1.5167 \times 1 \\ &= 5.609\end{aligned}$$

We transform the logarithmic value to the arithmetic value for MTBF:

$$\begin{aligned}\text{MTBF} &= e^{5.609} \\ &= 2.7182818^{5.609} \\ &= 273\end{aligned}$$

To predict MTTR we use the following (late) equation:

$$\begin{aligned}\text{LOG (MTTR)} &= 0.2253 + (4.9894 \times 10^{-2}) \text{ YO} + (1.2065 \times 10^{-3}) \text{ MW} + 0.7624 \text{ FT} \\ &\quad + (1.0201 \times 10^{-2}) \text{ PC} - (1.2462 \times 10^{-2}) \text{ FOPC}\end{aligned}$$

Inserting the appropriate values for the independent or predictor variables and solving, we have:

$$\begin{aligned}\text{LOG (MTTR)} &= 0.2253 + (4.9894 \times 10^{-2}) \times 4 + (1.2065 \times 10^{-3}) \times 350 + 0.7624 \\ &\quad \times 1 + (1.0201 \times 10^{-2}) \times 275 - (1.2462 \times 10^{-2}) \times 200 \\ &= 1.922\end{aligned}$$

We transform the logarithmic value to the arithmetic value for MTTR:

$$\begin{aligned}\text{MTTR} &= e^{1.922} \\ &= 2.7182818^{1.922} \\ &= 6.8\end{aligned}$$

To predict AVAIL 1 we use the following (late) equation:

$$\begin{aligned}\text{AVAIL 1} &= 0.9529 - (2.513 \times 10^{-4}) \text{ MW} - (3.9306 \times 10^{-4}) \text{ PC} \\ &\quad + (3.42 \times 10^{-2}) \text{ CDT}\end{aligned}$$

Inserting the appropriate values for the independent variables and solving we have:

$$\begin{aligned}\text{AVAIL 1} &= 0.9529 - (2.513 \times 10^{-4}) \times 350 - (3.9306 \times 10^{-4}) \times 275 \\ &\quad + (3.42 \times 10^{-2}) \times 1 \\ &= 0.79\end{aligned}$$

In sum, it is predicted that the unit will experience a mean time between failures of approximately 273 hours and an operating availability of 79 percent on average over its useful life. Furthermore, it is forecasted that in the fourth year of operation the unit will have a mean time to restore of 6.8 hours. In the subsection "Confidence Interval Estimates" earlier in this section, there was a statement that confidence limit estimates can be developed for a predicted value or point estimate of a dependent variable. Appendix E to this report describes the procedure for

developing confidence limit estimates. Also contained in Appendix E is a demonstration of applying this procedure using the predicted value for AVAIL 1 or operating availability developed in this example (79 percent).

The subsection "Analysis and Interpretation," earlier in this section, stated briefly that limited trade-off analyses were possible using the predictive equations. This can be illustrated using the late equation for MTBF and the example data. Suppose that the trade-off between MTBF and FOPC is of interest. Varying the value for FOPC in the equation while keeping the values for all other independent variables fixed results in a range of values for (late) MTBF. Eight values for FOPC were selected in addition to the FOPC value of 200 used for the hypothetical unit. Table 4-3 presents these values and the corresponding values for MTBF. Figure 4-1 presents a curve constructed by plotting the values for MTBF and FOPC in Table 4-3. The curve clearly shows that as the value of FOPC increases MTBF decreases. More specifically, if it were possible to reduce the value of FOPC for the hypothetical unit from 200 to 100 (or by 50 percent), the resulting effect on its MTBF would be a 120 percent increase (or from 273 to 601).

Table 4-3	
TRADE-OFF VALUES FOR MTBF AND FOPC	
FOPC	MTBF*
100	601
125	494
150	405
175	332
200	273
225	224
250	184
275	151
300	124
*Arithmetic value calculated using the following formula: $\text{Log (MTBF)} = x$ $\text{MTBF} = x^e$ where $e = 2.7182818$

Figure 4-1. Trade-Off Between MTBF and FOPC

Section 5

CONCLUSIONS AND RECOMMENDATIONS

This section presents conclusions resulting from an assessment of the study findings. Following the conclusions are recommendations for areas worthy of further study and future courses of action.

CONCLUSIONS

Two major conclusions are provided in response to the objectives of this study:

- Design complexity has a significant effect on the reliability and availability performance of electric power generating units.
- The relationship between design complexity and reliability and availability performance can be quantified to yield meaningful prediction equations.

The quantitative relationships developed in this study provide a method for forecasting the reliability and availability performance of electric power generating units before and during the operational stage. This ability can provide the electric power generating industry with valuable information for design evaluation, planning, operation, and maintenance purposes. Furthermore, a utility company's decision-making process can be enhanced significantly by applying confidence intervals to the reliability and availability performance forecasts, thereby conveying an explicit measure of the risk associated with planned activities.

The predictive power of the equations as measured by the usual evaluative statistics (e.g., coefficient of determination or R^2 values) is considered to be generally good for this type of application. However, improved predictive relationships are expected to result from performing this type of analysis at a lower level of indenture. For instance, analyzing the performance of major pieces of equipment using pipe-feet, number and type of valves, mechanical parts, etc., for measures of complexity. The sample size was adequate for this initial examination of the issue and the same data fairly well represented the relevant universe of electric power generating units. However, only a small percentage of utility companies were included in the sample. With a larger sample, it would be possible to stratify

by classes of generating systems to permit consideration of additional relevant predictor variables.

The development of a single complexity measure for electric power generating units was not attempted because of the large variation in component types and functions in the data base. Instead, a number of discrete measures were used that were directly related (e.g., by parts count) or indirectly related (e.g., by megawatt output) to complexity. The hypothesis that complexity measures can be adjusted to meaningfully account for redundancy was not confirmed, but it is an avenue worth further study, which may yield significant results when this analysis is performed at lower levels of indenture.

RECOMMENDATIONS

Several suggestions for further important efforts in this area include the following:

- Obtain a more comprehensive sample of the electric power generating industry (only nine, or less than one percent, of the nation's electric power generating companies are represented by the sample information)
- Develop predictive relationships for specific types of major equipments (e.g., condenser, boiler, turbine, generator)
- Develop predictive relationships for specific types of units according to several criteria (e.g., usage type, cycle type, fuel type)
- Concentrate on developing relationships for greater levels of indenture (e.g., the effect of control system design on performance)
- Intensify efforts to gather information on variables that were of interest to this study but were not analyzed due to a lack of complete data (e.g., boiler type, air pollution parts count) (see Table 2-1)

These suggestions are offered with the expectation that they will help direct future study efforts.

Appendix A

SURVEY QUESTIONNAIRE

This appendix presents the questionnaire that was mailed to randomly chosen power generating companies in order to collect the desired information. The questionnaire was followed by telephone contact to assure accuracy and completeness.

QUESTIONNAIRE/DATA COLLECTION FORM

ARINC Research Corporation is currently under contract to the Electric Power Research Institute (i.e., EPRI Contract RP 1923-2) to study the role of design complexity in forecasting reliability. This questionnaire is designed to obtain information relevant to the study. The major objective of this project is to obtain a better understanding of the complexity factors which influence the availability and reliability of power generation systems. A significant output of the study will be the development of a tool that may be used to predict power system performance as a function of complexity. The knowledge gained from this project is expected to benefit electric power generating companies by providing an improved basis for the design, construction, operation and maintenance leading to more cost-effective services.

This questionnaire should be completed for each unit of a power plant that meets each of the following criterion:

- . Single or combined cycle
- . Base or cycle loading
- . Nameplate megawatt output of 70 or larger
- . Fossil fueled

The questions in Section IV - Design or Complexity Information - need only be answered once for units which are essentially identical provided those units that are of similar design are identified.

Please become familiar with the attached questionnaire. A member of ARINC Research Corporation's technical staff will be contacting you by telephone within ten days to discuss the questionnaire. Please contact Mr. David M. Berkey (301) 266-4713 should you have any questions or comments.

I. Identification Information

The following questions are designed to gather information that will aid in identifying the unit in question should it be necessary to clarify specific answers or request additional information.

1. Company Name: _____
2. Plant Name or Number: _____
3. Plant Location (city & state): _____
4. Unit Name or Number: _____
5. This unit is essentially identical in design or complexity to (list other identical units): _____

NOTE: If there are two or more identical units, the design or complexity questions need only be answered for one of the units provided those which are identical are identified.

II. Descriptive Information

Please describe the operating characteristics of the unit in question by providing the relevant information requested below.

1. Year unit first placed in operation: _____
2. Unit "nameplate" output: _____ MW/hour
3. Please indicate the unit's average output over the 1977-1980 period by completing the table below.

<u>YEAR</u>	<u>AVERAGE MW/HOUR GROSS</u>		<u>AVERAGE MW/HOUR NET</u>	
	<u>WINTER</u>	<u>SUMMER</u>	<u>WINTER</u>	<u>SUMMER</u>

1977

1978

1979

1980

4. Unit type (Check one):

☐ Single cycle ☐ Combined cycle

5. What was the unit's primary usage over the 1977-1980 period? (check one):

☐ Base load ☐ Cycle load

6. If the unit had been used for cycle loading over the 1977-1980 period, please indicate:

A. Number of times per day unit would be cycled: _____

times per day.

B. Average load unit would cycle to: _____ MWe

7. If the unit changed its primary usage from base to cycle loading over the 1977-1980 period, give year unit first began operating as a cycle load unit: _____.

8. Primary fuel burned by the unit over the 1977-1980 period was (check one):

☐ Oil; indicate number or type: _____

☐ Coal; indicate type: _____

☐ Natural Gas

☐ Other (please explain): _____

III. Performance Information

Seventeen pieces of performance information concerning the overall unit in question and four types of major equipment are requested for the years 1977-1980. This type of data will be used to develop alternative measures of availability and reliability. Please complete the tables on the following pages by furnishing the relevant information you have available. For your convenience, the appendix to this questionnaire/data collection form contains the NERC/EEI definitions for these seventeen performance items.

If you have supplied this type of information to the Edison Electric Institute (EEI) or the National Electric Reliability Council (NERC), it may be more agreeable to authorize the NERC, who currently has responsibility for these type of data, to relinquish it directly to ARINC Research Corporation. Please inform us of your decision when contacted by a member of our technical staff.

1. OVERALL UNIT

PERFORMANCE ITEM	YEAR			
	1977	1978	1979	1980
PERIOD HOURS (PH)				
SERVICE HOURS (SH)				
AVAILABLE HOURS (AH)				
FORCED OUTAGE HOURS (FOH)				
FORCED PARTIAL OUTAGE HOURS (FPOH)				
MAINTENANCE OUTAGE HOURS (MOH)				
HOURS WAITING (HW)				
EQUIVALENT FORCED OUTAGE HOURS (EFOH)				
RESERVE SHUTDOWN HOURS (RSH)				
NUMBER OF FORCED OUTAGES (FO)				
NUMBER OF FORCED PARTIAL OUTAGES (FPO)				
PLANNED OUTAGE HOURS (POH)				
SCHEDULED PARTIAL OUTAGE HOURS (SPOH)				
NUMBER OF MAINTENANCE OUTAGES (MO)				
NUMBER OF PLANNED OUTAGES (PO)				
NUMBER OF SCHEDULED PARTIAL OUTAGES (SPO)				
EQUIVALENT SCHEDULED OUTAGE HOURS (ESOH)				

2. BOILER

PERFORMANCE ITEM	YEAR			
	1977	1978	1979	1980
PERIOD HOURS (PH)				
SERVICE HOURS (SH)				
AVAILABLE HOURS (AH)				
FORCED OUTAGE HOURS (FOH)				
FORCED PARTIAL OUTAGE HOURS (FPOH)				
MAINTENANCE OUTAGE HOURS (MOH)				
HOURS WAITING (HW)				
EQUIVALENT FORCED OUTAGE HOURS (EFOH)				
RESERVE SHUTDOWN HOURS (RSH)				
NUMBER OF FORCED OUTAGES (FO)				
NUMBER OF FORCED PARTIAL OUTAGES (FPO)				
PLANNED OUTAGE HOURS (POH)				
SCHEDULED PARTIAL OUTAGE HOURS (SPOH)				
NUMBER OF MAINTENANCE OUTAGES (MO)				
NUMBER OF PLANNED OUTAGES (PO)				
NUMBER OF SCHEDULED PARTIAL OUTAGES (SPO)				
EQUIVALENT SCHEDULED OUTAGE HOURS (ESOH)				

3. GENERATOR

PERFORMANCE ITEM	YEAR			
	1977	1978	1979	1980
PERIOD HOURS (PH)				
SERVICE HOURS (SH)				
AVAILABLE HOURS (AH)				
FORCED OUTAGE HOURS (FOH)				
FORCED PARTIAL OUTAGE HOURS (FPOH)				
MAINTENANCE OUTAGE HOURS (MOH)				
HOURS WAITING (HW)				
EQUIVALENT FORCED OUTAGE HOURS (EFOH)				
RESERVE SHUTDOWN HOURS (RSH)				
NUMBER OF FORCED OUTAGES (FO)				
NUMBER OF FORCED PARTIAL OUTAGES (FPO)				
PLANNED OUTAGE HOURS (POH)				
SCHEDULED PARTIAL OUTAGE HOURS (SPOH)				
NUMBER OF MAINTENANCE OUTAGES (MO)				
NUMBER OF PLANNED OUTAGES (PO)				
NUMBER OF SCHEDULED PARTIAL OUTAGES (SPO)				
EQUIVALENT SCHEDULED OUTAGE HOURS (ESOH)				

4. CONDENSER

PERFORMANCE ITEM	YEAR			
	1977	1978	1979	1980
PERIOD HOURS (PH)				
SERVICE HOURS (SH)				
AVAILABLE HOURS (AH)				
FORCED OUTAGE HOURS (FOH)				
FORCED PARTIAL OUTAGE HOURS (FPOH)				
MAINTENANCE OUTAGE HOURS (MOH)				
HOURS WAITING (HW)				
EQUIVALENT FORCED OUTAGE HOURS (EFOH)				
RESERVE SHUTDOWN HOURS (RSH)				
NUMBER OF FORCED OUTAGES (FO)				
NUMBER OF FORCED PARTIAL OUTAGES (FPO)				
PLANNED OUTAGE HOURS (POH)				
SCHEDULED PARTIAL OUTAGE HOURS (SPOH)				
NUMBER OF MAINTENANCE OUTAGES (MO)				
NUMBER OF PLANNED OUTAGES (PO)				
NUMBER OF SCHEDULED PARTIAL OUTAGES (SPO)				
EQUIVALENT SCHEDULED OUTAGE HOURS (ESOH)				

5. TURBINE

PERFORMANCE ITEM	YEAR			
	1977	1978	1979	1980
PERIOD HOURS (PH)				
SERVICE HOURS (SH)				
AVAILABLE HOURS (AH)				
FORCED OUTAGE HOURS (FOH)				
FORCED PARTIAL OUTAGE HOURS (FPOH)				
MAINTENANCE OUTAGE HOURS (MOH)				
HOURS WAITING (HW)				
EQUIVALENT FORCED OUTAGE HOURS (EFOH)				
RESERVE SHUTDOWN HOURS (RSH)				
NUMBER OF FORCED OUTAGES (FO)				
NUMBER OF FORCED PARTIAL OUTAGES (FPO)				
PLANNED OUTAGE HOURS (POH)				
SCHEDULED PARTIAL OUTAGE HOURS (SPOH)				
NUMBER OF MAINTENANCE OUTAGES (MO)				
NUMBER OF PLANNED OUTAGES (PO)				
NUMBER OF SCHEDULED PARTIAL OUTAGES (SPO)				
EQUIVALENT SCHEDULED OUTAGE HOURS (ESOH)				

IV. Design or Complexity Information

To obtain complexity information design data is required. Seventeen systems and their respective major pieces of equipment have been identified as being generic to a power generating unit. These are listed in the table on the following pages. Please complete this table by furnishing the relevant information you have available. The systems and major equipments may or may not accurately reflect the way in which the unit in question is viewed. Please delete those systems/equipments which are not appropriate and add those that are in the space provided. Please remember that this information need only be supplied once for identical units provided those which are identical are identified.

System/ Major Equipment	Quantity	If the piece of equipment is totally unavailable, indicate whether a full (F), partial (P) or no (N) outage will result	If more than one piece of equipment is present, indicate number needed to avoid unit shutdown	If more than one piece of equipment are present but not required to operate unit, indicate whether back-up pieces are Active (A) or Inactive (I)
1. Fuel Oil System				
Fuel Oil Storage Tank				
Fuel Oil Storage Tank Heater				
Duplex Strainer				
Main Fuel Oil Heater				
Main Fuel Oil Pump				
Fuel Oil Recirculation Line				
Fuel Oil Burner Heater				
Fuel Oil Booster Pump				
Fuel Oil Burner				
Fuel Oil Burner Recirculation Line				
Fuel Oil Safety				
Fuel Oil Flow Meter				
Other (Please explain):				

System/ Major Equipment	Quantity	If the piece of equipment is totally unavailable, indicate whether a full (F), partial (P) or no (N) outage will result	If more than one piece of equipment is present, indicate number needed to avoid unit shutdown	If more than one piece of equipment are present but not required to operate unit, indicate whether back-up pieces are Active (A) or Inactive (I)
2. Coal Handling System				
Car Dumper				
Bradford Breaker				
Stacker Reclaimer				
Conveyor System				
Magnetic Separator				
Coal Feeders				
Coal Pulverizers				
Coal Burners				
Coal Safety				
Coal Bunkers				
Other (Please explain):				

System/ Major Equipment	Quantity	If the piece of equip- ment is totally un- available, indicate whether a full (F), partial (P) or no (N) outage will result	If more than one piece of equipment is present, indicate number needed to avoid unit shutdown	If more than one piece of equipment are present but not required to operate unit, indicate whether back-up pieces are Active (A) or Inactive (I)
3. Ash Handling System				
Soot Blowers				
Surge Tank				
Ash Hoppers				
Klinker Grinder				
Ash Transport Pumps				
Hydrobin				
Precipitators				
Segregating Valves				
Primary and Secondary Collectors				
Ash Silo				
Hydromixer				
Air Washer				
Fly Ash Exhauster				
Ash Safety				
Other (Please explain):				

System/ Major Equipment	Quantity	If the piece of equipment is totally unavailable, indicate whether a full (F), partial (P) or no (N) outage will result	If more than one piece of equipment is present, indicate number needed to avoid unit shutdown	If more than one piece of equipment are present but not required to operate unit, indicate whether back-up pieces are Active (A) or Inactive (I)
4. Main Steam System				
Boiler				
Economizer				
Steam Drums				
Water Walls				
Headers				
Downcomer				
Superheater				
Reheater				
Safety Valves				
Fans				
Air Heaters				
Stop Valves				
Control Valves				
Turbines				
Steam Safety				
Other (Please explain):				

System/ Major Equipment	Quantity	If the piece of equipment is totally unavailable, indicate whether a full (F), partial (P) or no (N) outage will result	If more than one piece of equipment is present, indicate number needed to avoid unit shutdown	If more than one piece of equipment are present but not required to operate unit, indicate whether back-up pieces are Active (A) or Inactive (I)
5. Turbine Steam Seal System (if any, please explain):				
6. Extraction Steam System				
Extraction Non Return Valves				
Other (Please explain):				
7. Condensate System				
Condenser				
Condensate Pump				

System/ Major Equipment	Quantity	If the piece of equipment is totally unavailable, indicate whether a full (F), partial (P) or no (N) outage will result	If more than one piece of equipment is present, indicate number needed to avoid unit shutdown	If more than one piece of equipment are present but not required to operate unit, indicate whether back-up pieces are Active (A) or Inactive (I)
7. (Continued)				
Low Pressure Heaters				
Deaerator				
Other (Please explain):				
8. Feed System				
Feed Booster Pump				
High Pressure Heaters				
Boiler Feed Pump				
Other (Please explain):				

System/ Major Equipment	Quantity	If the piece of equipment is totally unavailable, indicate whether a full (F), partial (P) or no (N) outage will result	If more than one piece of equipment is present, indicate number needed to avoid unit shutdown	If more than one piece of equipment are present but not required to operate unit, indicate whether back-up pieces are Active (A) or Inactive (I)
9. Circulating Water System				
Intake Structure				
Trash Rakes				
Circulating Water Pumps				
Water Box Vacuum Pumps				
Other (Please explain):				
10. Plant Air Systems				
Air Compressor				
Air Coolers				
Moisture Separator				

System/ Major Equipment	Quantity	If the piece of equipment is totally unavailable, indicate whether a full (F), partial (P) or no (N) outage will result	If more than one piece of equipment is present, indicate number needed to avoid unit shutdown	If more than one piece of equipment are present but not required to operate unit, indicate whether back-up pieces are Active (A) or Inactive (I)
10. (Continued)				
Air Receiver				
Air Dryer				
Other (Please explain):				
11. Auxiliary Steam System				
Auxiliary Boilers				
Reboilers				
Other (Please explain):				

System/ Major Equipment	Quantity	If the piece of equipment is totally unavailable, indicate whether a full (F), partial (P) or no (N) outage will result	If more than one piece of equipment is present, indicate number needed to avoid unit shutdown	If more than one piece of equipment are present but not required to operate unit, indicate whether back-up pieces are Active (A) or Inactive (I)
12. Closed Cooling Water System (if any, please explain):				
13. Turbine Lubricating Oil System				
Oil Pumps				
Oil Coolers				
Oil Filters				
Other (please explain):				

System/ Major Equipment	Quantity	If the piece of equipment is totally unavailable, indicate whether a full (F), partial (P) or no (N) outage will result	If more than one piece of equipment is present, indicate number needed to avoid unit shutdown	If more than one piece of equipment are present but not required to operate unit, indicate whether back-up pieces are Active (A) or Inactive (I)
14. Water Pretreatment System				
Well Water Pumps				
Well Water Surge Tank				
Filtered Water Tank				
Reactivator				
Gravity Filters				
Clearwell				
Other (Please explain):				
15. Electrical Distribution System				
Generator				
Exciter				

System/ Major Equipment	Quantity	If the piece of equipment is totally unavailable, indicate whether a full (F), partial (P) or no (N) outage will result	If more than one piece of equipment is present, indicate number needed to avoid unit shutdown	If more than one piece of equipment are present but not required to operate unit, indicate whether back-up pieces are Active (A) or Inactive (I)
15. (Continued)				
Transformers				
Circuit Breakers				
Disconnects				
Switchgear				
Motor Control Center				
Other (Please explain):				
16. Hydrogen Cooling System (if any, please explain):				

System/ Major Equipment	Quantity	If the piece of equipment is totally unavailable, indicate whether a full (F), partial (P) or no (N) outage will result	If more than one piece of equipment is present, indicate number needed to avoid unit shutdown	If more than one piece of equipment are present but not required to operate unit, indicate whether back-up pieces are Active (A) or Inactive (I)
17. Fire Protection System				
Fire Main System				
Deluge System				
CO ₂ System				
Halon System				
Foam System				
Other (Please explain):				

18. What type of boiler is on the unit (check one)?

____ Once through

____ Drum-type

____ Other (please explain): _____

19. What type of condenser is on the unit (check one)?

____ Single Pass

____ Double Pass

V. Operating Environment Information

The environment in which the unit is operating is an important consideration when examining the relationship between design complexity and reliability or availability. Please respond to the following questions with the relevant information you have available.

1. The pollution characteristics of the unit's primary source of boiler feed water is as follows (please complete noting that milligrams/liter or mg/l is equivalent to parts per million or PPM)

A. ____ PPM total dissolved solids

B. ____ PPM total suspended solids

C. ____ PPM total volatile solids

D. ____ PPM hardness

E. ____ PPM manganese

F. ____ PPM iron

G. ____ PPM chloride

H. ____ pH

I. ____ other (please explain):

2. Air pollution control technology on the unit consists of
(check those items that are appropriate):

___ Scrubbers

___ Precipitators; type:

A. ___ mechanical

B. ___ electrostatic

C. ___ hot

D. ___ Other (Please explain): _____

___ Bag houses

___ Other (Please explain): _____

3. Air pollution control technology contains (indicate quantity)
___ pieces of major equipment.

4. Please check those types of training programs that are practiced
by your company for operations and maintenance personnel.

___ Training programs for newly hired employees

___ Periodic training programs or refresher courses

___ Training programs concerning newly acquired major pieces of equipment

___ Highly specialized or system/equipment-specific preventative
maintenance training programs

___ Other (Please explain): _____

Appendix

Major Equipment - Major group of equipment within a unit, such as:

boiler, reactor, generator, steam turbine, condenser.

Maximum Dependable Capacity (MDC) - The dependable main-unit capacity

winter or summer, whichever is smaller.

Available - The status of a unit or major piece of equipment which is

capable of service, whether or not it is actually in service.

Base Loading - When a unit is generally run at or near rated output.

Cycling Loading - When a unit is generally run but at a load which varies

widely with system demand.

Forced Outage - The occurrence of a component failure or other condition which

requires that the unit be removed from service immediately or

up to and including the very next weekend.

Forced Partial Outage - The occurrence of a component failure or other

condition which requires that the load on the unit be reduced 2%

or more immediately or up to and including the very next weekend.

Maintenance Outage - The removal of a unit from service to perform work on

specific components which could have been postponed past the

very next weekend. This is work done to prevent a potential forced

outage and which could not be postponed from season to season.

Peak Loading - When a unit is generally shut down and is run only during high

demand periods.

Reserve Shutdown - The removal of a unit from service for economy or similar reasons. This status continues as long as the unit is out but available for operation.

Available Hours (AH) - The time in hours during which a unit or major equipment is available; SH+RSH.

Demand Period - The time interval each day which is the period of maximum demand on a particular system.

Equivalent Forced Outage Hours (EFOH) - $[\text{Forced Partial Outage Hours} \times \text{Sixe Reduction/MDC}]$

Forced Outage Hours (FOH) - The time in hours during which a unit or major equipment was unavailable due to a Forced Outage.

Forced Partial Outage Hours (FPOH) - The time in hours during which a unit or major 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 could be performed. This includes time for cooling down equipment and shipment of parts. This is time that could not be affected by a change in work schedule or the number of men worked.

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

Period Hours (PH) - The clock hours in the period under consideration.
(Generally one year).

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

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

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

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

Equivalent Scheduled Outage Hours (ESOH) - Scheduled partial outage hours X size of reduction/MDC.

Scheduled Partial Outage - The occurrence of a component failure or other condition which requires that the load on the unit be reduced 2% or more but where this reduction could be postponed past the very next week.

Appendix B

CONSTRUCTION OF VARIABLES ANALYZED

This appendix shows how the dependent and independent variables analyzed in this study were constructed.

AVAIL 1 = $AH \div PH$; commonly referred to as operating availability

AVAIL 3 = $MTBF \div (MTBF + MTTR)$

AVAIL 4 = $[AH - (EFOH + ESOH)] \div PH$; commonly referred to as equivalent availability*

Average Summer Temperature (AST) - The average temperature for the period April through September for the nearest major city to the location of the unit; average temperatures were derived from the following source: *Statistical Abstract of the United States: 1978*, United States Department of Commerce (Washington, D.C.: U.S. Government Printing Office, September 1978), p. 219.

Average Winter Temperature (AWT) - The average temperature for the period October through March for the nearest major city to the location of the unit; average temperatures were derived from the *Statistical Abstract of the United States: 1978*, United States Department of Commerce (Washington, D.C.: U.S. Government Printing Office, September 1978), p. 219.

Condenser Type (CDT) - A dummy variable was employed; a one was assigned to single pass condensers and a zero to double pass condensers.

Cycle Type (CT) - A dummy variable was employed; a one was assigned to a steam unit and a zero to a combined cycle unit.

Forced Outage Parts Count (FOPC) - The total quantity of major pieces of equipment which, if completely unavailable, would result in a forced outage.

*EFOH = $(FPOH \times \text{size of reduction}) \div MDC$

ESOH = $(SPOH \times \text{size of reduction}) \div MDC$

Fuel Type (FT) - Coal, oil, and gas fired units were respectively assigned the values one, two, and three for this variable.

$$MTBF = SH \div (FO + FPO + SPO)$$

$$MTBFFO = PH \div (FO + 1)$$

$$MTTR = (FOH + EFOH + ESOH) \div (FO + FPO + SPO) *$$

Partial Outage Parts Count (POPC) - The total quantity of major pieces of equipment which, if completely unavailable, would result in a partial outage.

Parts Count (PC) - The total quantity of major pieces of equipment

Training Programs (TP) - The number of training programs offered for operations and maintenance personnel at the unit site.

Usage Type (UT) - A dummy variable was employed whereby a one was assigned to base load and a zero to cycle load units.

Years of Operation (YO) - The number of years of operation; a measure of the (operational) age of the unit. For equations that do not contain the years of operation (YO) variable, the predicted value can be considered to be an average value over the useful life of the unit. However, for the four equations that contain the YO variable, the value of the dependent variable represents an average for the year of interest selected. For instance, using a YO value of 4 in the equation for Late MTTR would give the average MTTR for the fourth year of operation.

Section IV of the survey instrument (or questionnaire) identified 17 systems and their respective major pieces of equipment as being generic to an electric power generating unit. The various parts count measures detailed below were derived from the information provided in that section by the respondents.

Adjusted Parts Count (APC), Adjusted Forced Outage Parts Count (AFOPC), Adjusted Partial Outage Parts Count (APOPC) - Each of these complexity measures was developed to account for redundancy in the design of the unit. Each variable - APC, AFOPC,

$$\begin{aligned} *EFOH &= (FPOH \times \text{size of reduction}) \div MDC \\ ESOH &= (SPOH \times \text{size of reduction}) \div MDC \end{aligned}$$

APOPC - was derived by multiplying individual elements of its unadjusted counterpart (i.e., PC, FOPC, POPC) by the ratio $MTBF_{m,m}/MTBF_{m,n}$; where $MTBF_{m,m}$ is the mean time between failures for a unit comprising m parts, all of which are required for successful operation and $MTBF_{m,n}$ is the mean time between failures for a unit comprising n parts where n is greater than m and only m of which are required for successful operation. The procedure used to arrive at $MTBF_{m,m}$ and $MTBF_{m,n}$ is relatively straightforward. Consider a unit which has a total of n parts but only m of these are required for successful operation. Assuming that all units are active, the reliability equation for operation ($R_{m,n}$) over time t is as follows:

$$R_{m,n}(t) = \sum_{x=m}^n \binom{n}{x} [R(t)]^x [1 - R(t)]^{n-x}$$

We now use the fact that for any z and for N an integer,

$$(1 - z)^N = \sum_{j=0}^N (-1)^j \binom{N}{j} z^j,$$

yielding

$$\begin{aligned} R_{m,n}(t) &= \sum_{x=m}^n \binom{n}{x} [R(t)]^x \sum_{j=0}^{n-x} (-1)^j \binom{n-x}{j} [R(t)]^j \\ &= \sum_{x=m}^n \binom{n}{x} \sum_{j=0}^{n-x} (-1)^j \binom{n-x}{j} [R(t)]^{j+x} \end{aligned}$$

Assuming a constant failure rate of λ for each part, we have $R(t) = e^{-\lambda t}$, resulting in the equation

$$R_{m,n}(t) = \sum_{x=m}^n \binom{n}{x} \sum_{j=0}^{n-x} (-1)^j \binom{n-x}{j} e^{-(j+x)\lambda t}$$

Using the general relationship for mean time between failures

$$MTBF_{m,n} = \int_0^{\infty} R(t) dt$$

we have

$$\begin{aligned}
 \text{MTBF}_{m,n} &= \sum_{x=m}^n \binom{n}{x} \sum_{j=0}^{n-x} (-1)^j \binom{n-x}{j} \int_0^{\infty} e^{-(j+x)\lambda t} dt \\
 &= \sum_{x=m}^n \frac{n!}{x!} \sum_{j=0}^{n-x} (-1)^j [j! (n-x-j)! (j+x)\lambda]^{-1}
 \end{aligned}$$

If no redundancy were present, then there would be m units, all required and the following relationship:

$$\text{MTBF}_{m,m} = \frac{1}{m\lambda}$$

The resulting ratio, $\text{MTBF}_{m,m}/\text{MTBF}_{m,n}$ is used to measure complexity for a unit of " n,n " design.

Appendix C

STATISTICAL TECHNIQUE

Detailed explanations of the statistical procedure and multiple regression computer program used in this study are contained in this appendix.

STATISTICAL TECHNIQUE

Multivariate (or multiple) regression analysis was the statistical technique employed to develop the relationships between reliability and availability performance and design complexity and other factors. Using this technique assumes that the reliability and availability performance of an electric power generating unit can be written in the following general form:

$$\begin{aligned} f_o(R) = & b_o + b_1 f_1(X_{11}, X_{21}, \dots, X_{r_1 1}) + b_2 f_2(X_{12}, X_{22}, \dots, X_{r_2 2}) \dots \\ & + b_n f_n(X_{1n}, X_{2n}, \dots, X_{r_n n}) \end{aligned}$$

where

$f_o(R)$ is some function (transformation) of a reliability/availability performance parameter, R

r_j is the number of prediction parameters in the j^{th} subset

x_{ij} is the i^{th} prediction parameter in the j^{th} subset; $i = 1, 2, \dots, r_j$

$f_1, f_2, \dots, f_n$ are functions of the X s

$b_o, b_1, \dots, b_n$ are computed regression coefficients

The above form is linear with respect to the regression of coefficients but not necessarily linear with respect to R or the Xs. For example, an equation such as

$$\log R = b_0 + b_1 (X_1 X_2) + b_2 e^{X_3}$$

may be used as it satisfies the above form:

$$n = 2; r_1 = 2; r_2 = 1; f_0 = \log, f_1 = \Pi; f_2 = e; X_{11} = X_1; X_{12} = X_2;$$

$$X_{12} = X_3$$

The linearity condition, with respect to the regression coefficients, allows the use of a least squares procedure for estimating the coefficients.

The specific multiple regression procedure employed in this study is a program developed by ARINC Research Corporation. The program uses a stepwise selection procedure to determine which variables are statistically significant to form the regression equation. The analyses performed in this study employed a nominal value of 25 percent for the significance level. The most significant variable is selected first on the basis of its simple correlation to the dependent variable. The next variable selected is one that reduces the standard error of the estimate by the largest amount. The stepwise procedure also reexamines all selected variables at each stage to determine if one should be dropped because of variables added later.

The program also provides a number of statistics useful for analyzing the regression results. This includes the standard error of estimate, standard deviations of the computed regression coefficients, and corresponding "t" ratios for determining significant departures from zero. Also included, if desired, are calculations of predicted versus observed values and calculation of Gauss multipliers, which are used to determine a confidence band for a predicted value (see Appendix E).

Perhaps the most useful summarizing statistic provided is the multiple correlation coefficient, R. This statistic ranges between zero and one and is a measure of the strength of the calculated regression relationship. A low value indicates a poor relationship while a high value indicates a strong relationship. The square of R is known as the coefficient of determination. It measures the percent of variation in the dependent variable that is explained by the independent or predictor variables.

One further feature of the program is its capability to perform transformations of variables to allow for non-linear relationships without having to develop a new data base. The transformation capability also allows for generation of derived variables. For example, during the analyses, a complexity density variable was developed in the form of parts count per megawatt output ($PC \div MW$) and was analyzed in an attempt to provide greater predictive power, although it did not prove to be a significant explanatory variable. Considering that for each variable and derived variable there are a number of possible transformations (e.g., logarithms, reciprocals, powers), there are literally thousands of combinations that could be considered. Engineering judgment and several guidelines were adopted to reduce the candidate sets to a manageable number. Specific guidelines include the following:

- Variables considered to have a second-order effect on reliability performance were excluded initially (e.g., average climatic summer and winter temperature - AST and AWT).
- Variables exhibiting little variation among the units in the study were excluded initially (e.g., only four of the 56 units employed in this study were of the combined cycle variety while the remaining 52 were steam units and therefore the cycle type variable -- CT -- was excluded initially).
- Variables that might be difficult to quantify during the initial variable construction stages were assigned lower priority than others (e.g., a complexity variable that accounts for design redundancy in the unit was developed; because of the relatively complex way it is quantified, this variable was given lower priority when choosing complexity measures).
- Variables that were highly correlated with one or more other variables were given lower priority than others (e.g., several sets of variables showed, as expected, relatively high correlation. This was particularly true of the complexity variables pertaining to parts counts. In cases where a choice had to be made, the simpler of the measures was used first, as when the parts count complexity measure was chosen over the forced outage parts count.)

Following these guidelines reduced the number of candidate independent and dependent variables significantly.

A computed regression coefficient theoretically represents the amount of change in the dependent variable for each unit change in the associated independent variable. For a variety of reasons, which include chance occurrences, high intercorrelations, and the omission of one or more important variables, the sign of a computed regression coefficient may be intuitively unacceptable.

To minimize potential problems, the expected sign of the regression coefficient was developed when the direction of change of the reliability or availability

parameter was clear. For example, experience has shown that a reliability performance measure such as mean-time-between-failures (MTBF) should decrease as design complexity increases. However, in some instances it is not clear what the appropriate sign for the coefficient should be. As an example, for the years of operation (YO) variable one could argue that reliability performance should decrease for older systems due to metal fatigue and wearout. Conversely, since failed items are replaced with new parts that may be inherently more reliable due to technology improvements, an operational reliability growth phenomenon may be in force. Thus, for this parameter we allowed either sign. Table C-1 summarizes the initial sign restrictions placed on the candidate prediction parameters and provides a brief explanation for the choice.

<p style="text-align: center;">Table C-1</p> <p style="text-align: center;">SIGN RESTRICTIONS FOR PARAMETERS OF INDEPENDENT VARIABLES ANALYZED</p>		
Independent Variable	Expected Sign(s)	Brief Rationale
Average Summer Temperature (AST)	-	Reliability and availability performance are expected to improve as extremely hot climatic temperatures are reduced.
Average Winter Temperature (AWT)	+	Reliability and availability performance are expected to improve as extremely cold climatic temperatures are improved.
Years of Operation (YO)	+,-	Age may or may not degrade reliability and availability performance, depending on the presence and strength of reliability growth phenomena.
Megawatt (MW)	-,+	Reliability and availability performance are expected to improve with smaller sized units, but when predicting MTTR, a "+" is justifiable because larger units may require longer restoration time.
Cycle Type (CT)	+	Simple cycle units are expected to have greater reliability and availability than complex cycle units due to the relative simplicity of their design; a dummy variable was used to account for cycle type by using a value of one for simple cycle units and zero for complex cycle units.

Table C-1 (continued)

Independent Variable	Expected Sign(s)	Brief Rationale
Usage Type (UT)	+	Base load units are expected to have relatively greater reliability and availability performance than cycle load units since the latter type of use is characterized by extreme and varying levels of utilization that help advance failures; a dummy variable was used to account for usage type by using a value of one for base load and zero for cycle load.
Fuel Type (FT)	+	Coal, oil and gas were assigned the values one, two and three respectively. Fuel types assigned higher values are expected to adversely affect reliability and availability performance relatively less than those assigned lower values.
All Parts Count Measures*	-, +	Reliability and availability performance are expected to be greater for units with fewer parts -- i.e., less complex; although when predicting MTTR, a "+" is justifiable because many parts would lengthen diagnostic time, thereby increasing MTTR.
Condenser Type (CDT)	+	Units employing single pass as opposed to double pass condensers are expected to be more reliable. A dummy variable was used to account for CDT by assigning a value of one for single pass condensers and zero for double pass condensers.
Training Programs (TP)	+, -	Training programs for operations and maintenance personnel are expected to improve reliability and availability performance -- i.e., more training is better; although when predicting MTTR a "-" is justifiable because less training may result in longer restoration/repair time.
*Parts count (PC), forced outage parts count (FORC), partial outage parts count (POPE), adjusted parts count (APR), adjusted forced outage parts count, and adjusted partial outage parts count (APOPC).		

Appendix D

VERIFICATION RESULTS

Figures D-1 through D-12 graphically depict the results of the verification procedure. Each figure presents a plot diagram of predicted versus actual values for the dependent variable of all six verification units. The 45 degree line drawn in each figure represents a "perfect prediction" or zero error -- i.e., for all points along this line the predicted and actual values for the dependent variable are the same. The median absolute deviation (MAD) between predicted and actual values (i.e., the vertical distance, regardless of sign, between the plotted points and the perfect prediction line) provides a measure of the accuracy of the predictive equations.

D-2

Figure D-1. "Late" MTBF: Verification Results

Figure D-2. "Early" MTBF: Verification Results

Figure D-3. "Late" MTTR: Verification Results

Figure D-4. "Early" MTTR: Verification Results

Figure D-5. "Late" MTBFFO: Verification Results

Figure D-6. "Early" MTBFFO: Verification Results

Figure D-7. "Late" AVAIL 1: Verification Results

Figure D-8. "Early" AVAIL 1: Verification Results

Figure D-9. "Late" AVAIL 3: Verification Results

Figure D-10. "Early" AVAIL 3: Verification Results

Figure D-11. "Late" AVAIL 4: Verification Results

Figure D-12. "Early" AVAIL 4: Verification Results

Appendix E
CONFIDENCE INTERVAL ESTIMATION PROCEDURE
AND EXAMPLE APPLICATION

This appendix describes in detail two procedures for estimating confidence intervals. Each procedure is demonstrated with an example.

Confidence interval estimates provide a measure of the relative precision that can be ascribed to a predicted value. Two procedures for developing confidence interval estimates are presented in this appendix. One procedure is an approximate technique which is easily applied whereas the other provides more precise confidence interval estimates. Both procedures are based on the standard error of estimate, or s value, for the predictive equations that are presented in Table 4-1 in the main body of this report.

The following equations are applicable to the approximate procedure:

- Lower Confidence Limit

$$\theta_L = \hat{\theta} - t_{(\alpha/2, d)} \times (s/\sqrt{m})$$

- Upper Confidence Limit

$$\theta_U = \hat{\theta} + t_{(\alpha/2, d)} \times (s/\sqrt{m})$$

where

θ = a reliability and availability performance parameter

$\hat{\theta}$ = point estimate of θ

θ_L = lower confidence limit

θ_U = upper confidence limit

$t_{(\alpha/2,d)}$ = t statistic for a 100(1- α)% two-sided confidence interval based on d degrees of freedom (see Table E-1 for t values)

s = standard error of estimate (see Table 4-1)

m = number of data points in the sample

For the precise procedure, the factor $s/\sqrt{m}$ given above is replaced by another expression:

- Lower Confidence Limit

$$\theta_L = \hat{\theta} - t_{(\alpha/2,d)} \times k$$

- Upper Confidence Limit

$$\theta_U = \hat{\theta} + t_{(\alpha/2,d)} \times k$$

where

$$k = s \left(\frac{1}{m} + \sum_{i=1}^r c_{ii} x_i^2 + 2 \sum_{j=i+1}^r \sum_{i=1}^{r-1} c_{ij} x_i x_j \right)^{1/2}$$

and

r = the number of independent or predictor variables

c_{ij} = a computed statistic, called the Gauss multiplier, developed through the regression analysis

x_i = deviation ($X_i - \bar{X}_i$) where X_i is the value of the i^{th} prediction parameter in the equation and $\bar{X}_i$ is the mean value for that parameter in the data sample. (See Table E-2 for $\bar{X}_i$ values.)

The value of k is always greater than $s/\sqrt{m}$ and thus the approximate confidence interval procedure always gives a narrower interval range than the precise interval. In fact, the approximate procedure gives the same results as the precise method when each predictor variable is exactly equal to the mean value used in the sample.

For most practical purposes, the approximate procedure may be used unless there are one or more predictor variables that are near a boundary value of the data base. It is possible that the confidence limit estimates may exceed the allowable range of

<p>Table E-1</p> <p>CONSTANTS FOR DEVELOPING CONFIDENCE INTERVAL ESTIMATES*</p>			
t Statistics (Approximated by standardized normal variate)			
Type of Interval	Confidence Level (1- α)		
	80	90	95
One-Sided Interval	.84	1.28	1.645
Two-Sided Interval	1.28	1.645	1.96
*Sample Size, m = 50			

the availability performance values (i.e., zero to one) because a variable combination existing in practice does not exist among the sample data. In this instance, a one-sided interval estimate should be used. To construct a one-sided interval, use the appropriate equation but replace the $t_{(\alpha/2, d)}$ value with $t_{(\alpha, d)}$. Since the sample consists of 50 units, the standardized normal deviate can be used in lieu of the t statistic for either the one-sided or two-sided case.

For equations involving the natural logarithm, the above equations apply to untransformed variables. For example, the above equations give lower and upper limits for LOG MTBF. The inverse logarithmic transformation must be applied to convert these limits to limits on MTBF.

Table E-1 provides the constants necessary to implement the confidence interval procedure. These constants are independent of the equation being used. Table E-2 provides the required data for each of the 14 prediction equations.

Table E-2

FACTORS FOR DETERMINING CONFIDENCE
LIMITS FOR PREDICTION EQUATIONS

Equation	Variable i - Code	Mean Value $\bar{X}_i$	Gauss Multipliers (E-z = number $\times 10^{-z}$)
MTBF (late)	1 MW	343.22	$c_{11} = 4.04E-7$
			$c_{12} = -4.53E-5$
			$c_{13} = 1.00E-4$
			$c_{14} = 6.61E-7$
			$c_{15} = -2.30E-5$
	2 UT	0.46	$c_{22} = 0.115$
			$c_{23} = 0.050$
			$c_{24} = 1.00E-4$
			$c_{25} = 2.62E-2$
			$c_{33} = 0.121$
	3 FT	1.56	$c_{34} = 5.34E-4$
			$c_{35} = -3.58E-3$
			$c_{44} = 4.69E-6$
			$c_{45} = -2.77E-5$
			$c_{55} = 0.105$
	4 FOPC	169.28	
	5 CDT	0.70	
MTTR (late)	1 YO	16.70	$c_{11} = 4.77E-4$
			$c_{12} = 1.49E-5$
			$c_{13} = 1.92E-3$
			$c_{14} = -3.31E-5$
			$c_{15} = 1.01E-7$
	2 MW	343.22	$c_{22} = 1.12E-6$
			$c_{23} = -2.33E-4$
			$c_{24} = -2.78E-6$

Table E-2 (continued)

Equation	Variable i - code	Mean Value $\bar{X}_i$	Gauss Multipliers (E-z = number $\times 10^{-z}$)
MTTR (late) (continued)	3 FT	1.56	$c_{25} = 2.66E-7$
			$c_{33} = .135$
			$c_{34} = 7.22E-4$
			$c_{35} = 1.83E-4$
	4 PC	258.52	$c_{44} = 1.37E-5$
			$c_{45} = -5.79E-6$
	5 FOPC	169.28	$c_{55} = 7.51E-6$
MTBFFO (late)	1 YO	16.70	$c_{11} = 3.97E-4$
			$c_{12} = 8.19E-6$
			$c_{13} = -1.40E-4$
			$c_{14} = -2.38E-4$
			$c_{15} = -1.41E-5$
	2 MW	343.22	$c_{22} = 5.68E-7$
			$c_{23} = -4.25E-5$
			$c_{24} = -1.06E-4$
			$c_{25} = -9.57E-7$
			$c_{33} = 0.108$
	3 UT	0.46	$c_{34} = 5.09E-2$
			$c_{35} = 1.12E-4$
			$c_{44} = 0.121$
	4 FT	1.56	$c_{45} = 5.41E-4$
			$c_{55} = 5.18E-6$
	5 FOPC	169.28	

Table E-2 (continued)

Equation	Variable i - Code	Mean Value $\bar{X}_i$	Gauss Multipliers (E-z = number $\times 10^{-z}$)
AVAIL 1 (late)	1 MW	343.22	$c_{11} = 3.85E-7$ $c_{12} = -4.76E-7$ $c_{13} = -1.21E-5$
	2 PC	258.52	$c_{22} = 2.62E-6$ $c_{23} = -5.67E-5$
	3 CDT	0.70	$c_{33} = 9.82E-2$
AVAIL 3 (late)	1 YO	16.70	$c_{11} = 6.76E-4$ $c_{12} = 1.76E-5$ $c_{13} = -8.50E-4$ $c_{14} = -2.51E-5$ $c_{15} = -6.06E-3$
	2 MW	343.22	$c_{22} = 8.51E-7$ $c_{23} = 1.28E-5$ $c_{24} = -1.22E-6$ $c_{25} = -1.56E-4$
	3 UT	0.46	$c_{33} = 0.115$ $c_{34} = -2.69E-4$ $c_{35} = 4.94E-2$
	4 PC	258.52	$c_{44} = 4.34E-6$ $c_{45} = 5.81E-5$
	5 CDT	0.70	$c_{55} = 0.168$

Table E-2 (continued)

Equation	Variable i - Code	Mean Value $\bar{X}_i$	Gauss Multipliers (E-z = number $\times 10^{-z}$)
AVAIL 4 (late)	1 YO	16.70	$c_{11} = 6.76E-4$
			$c_{12} = 1.76E-5$
			$c_{13} = -8.50E-4$
			$c_{14} = -2.51E-5$
			$c_{15} = -6.06E-3$
	2 MW	343.22	$c_{22} = 8.51E-7$
			$c_{23} = 1.28E-5$
			$c_{24} = 1.22E-6$
	3 UT	0.46	$c_{25} = -1.56E-4$
			$c_{33} = 0.115$
	4 PC	258.52	$c_{34} = -2.69E-4$
			$c_{35} = 4.94E-2$
	5 CDT	0.70	$c_{44} = 4.34E-6$
			$c_{45} = 5.81E-5$
			$c_{55} = 0.168$
MTBF (early)	1 MW	343.22	$c_{11} = 3.11E-7$
			$c_{12} = -3.12E-5$
			$c_{13} = -2.48E-5$
			$c_{14} = -2.69E-5$
	2 UT	0.46	$c_{22} = 0.113$
			$c_{23} = 3.85E-2$
			$c_{24} = 2.68E-2$

Table E-2 (continued)

Equation	Variable i - Code	Mean Value $\bar{X}_i$	Gauss Multipliers (E-z = number $\times 10^{-z}$)
MTBF (early)	3 FT	1.56	$c_{33} = 5.98E-2$ $c_{34} = -4.27E-4$
	4 CDT	0.70	$c_{44} = 0.105$
MTTR (early)	1 MW	343.22	$c_{11} = 3.00E-7$ $c_{12} = -1.56E-5$ $c_{13} = 4.03E-6$
	2 FT	1.56	$c_{22} = 0.0458$ $c_{23} = 1.24E-3$
	3 TP	3.06	$c_{33} = 1.22E-2$
MTBFFO (early)	1 , MW	343.22	$c_{11} = 3.11E-7$ $c_{12} = -3.12E-5$ $c_{13} = -2.48E-5$ $c_{14} = -2.69E-5$
	2 UT	0.46	$c_{22} = 0.113$ $c_{23} = 3.85E-2$ $c_{24} = 2.68E-2$
	3 FT	1.56	$c_{33} = 5.98E-2$ $c_{34} = -4.27E-4$
	4 CDT	0.70	$c_{44} = .105$
AVAIL 1 (early)	1 MW	343.22	$c_{11} = 2.99E-7$ $c_{12} = -1.60E-5$
	2 FT	1.56	$c_{22} = 4.57E-2$

Table E-2 (continued)

Equation	Variable i - Code	Mean Value $\bar{X}_i$	Gauss Multipliers (E-z = number 10^{-z})
AVAIL 3 (early)	1 MW	343.22	$c_{11} = 3.11E-4$
			$c_{12} = -3.12E-2$
			$c_{13} = -2.48E-5$
			$c_{14} = -2.69E-5$
	2 UT	0.46	$c_{22} = 0.113$
			$c_{23} = 3.85E-2$
			$c_{24} = 2.67E-2$
	3 FT	1.56	$c_{33} = 5.98E-2$
			$c_{34} = -4.27E-2$
	4 CDT	0.70	$c_{44} = 0.105$
AVAIL 4 (early)	1 MW	343.22	$c_{11} = 3.02E-7$
			$c_{12} = -1.41E-5$
			$c_{13} = -1.95E-5$
	2 FT	1.56	$c_{22} = 0.047$
			$c_{23} = -9.59E-3$
	3 CDT	0.70	$c_{33} = 9.89E-2$

The procedure for estimating confidence limits will be demonstrated using the predicted value for AVAIL 1 or operating availability (79 percent) derived in Section 4, subsection "Sample Application," in the body of the report. Both the approximate and precise procedures will be performed. In both cases, two-sided confidence interval estimates will be developed at the 90 percent confidence level -- i.e., a t value of 1.645 will be used.

The lower (θ_L) and upper (θ_U) confidence interval estimate equations for the approximate procedure are:

$$\theta_L = \hat{\theta} - t_{(\alpha/2, d)} \times (s/\sqrt{m})$$

$$\theta_U = \hat{\theta} + t_{(\alpha/2, d)} \times (s/\sqrt{m})$$

Inserting the appropriate values and solving we have:

$$\theta_L = .79 - 1.645 \times (.0711/\sqrt{50})$$

$$= .79 - .01$$

$$= .78$$

$$\theta_U = .79 + 1.645 \times (.0711/\sqrt{50})$$

$$= .79 + .01$$

$$= .80$$

Therefore, using the approximate procedure the confidence interval for AVAIL 1 is from 78 percent to 80 percent. In short, the best estimate for AVAIL 1, given the hypothetical unit as described in Section 4, subsection "Sample Application," is 79 percent and one can be 90 percent confident that the actual value is contained in the interval from 78 to 80 percent.

The lower (θ_L) and upper (θ_U) confidence interval estimate equations for the precise procedure are:

$$\theta_L = \hat{\theta} - t_{(\alpha/2, d)} \times k$$

$$\theta_U = \hat{\theta} + t_{(\alpha/2, d)} \times k$$

where

$$k = s \left(1/m + \sum_{i=1}^r c_{ii} x_i^2 + \sum_{j=i+1}^r \sum_{i=1}^{r-1} c_{ij} x_i x_j \right)^{1/2}$$

For $r = 3$, as in this example, k may be written as follows:

$$k = s \left[1/m + c_{11} x_1^2 + c_{22} x_2^2 + c_{33} x_3^2 + 2 (c_{12} x_1 x_2 + c_{13} x_1 x_3 + c_{23} x_2 x_3) \right]^{1/2}$$

Inserting the appropriate values in the equation for k and solving we have:

$$\begin{aligned} k &= .0711 [1/50 + (3.83E - 7 \times 45.97) + (2.62E - 5 \times 271.59) \\ &\quad + (9.82E - 2 \times .09) + 2 \{ (-4.76E - 7 \times 6.78 \times 16.48) \\ &\quad - (1.21E - 5 \times 6.78 \times .30) - (5.67E - 5 \times 16.48 \times .30) \}]^{1/2} \\ &= .012 \end{aligned}$$

Inserting the appropriate values in the precise confidence limit estimate equations and solving we have:

$$\begin{aligned} \theta_L &= .79 - (1.645 \times .012) \\ &= .79 - .02 \\ &= .77 \end{aligned}$$

$$\begin{aligned} \theta_U &= .79 + (1.645 \times .012) \\ &= .79 + .02 \\ &= .81 \end{aligned}$$

Therefore, using the precise procedure the confidence interval for AVAIL 1 is increased. To repeat, the best estimate for AVAIL 1 for the hypothetical unit is 79 percent, and one can be 90 percent confident that the actual value for AVAIL 1 is contained in the interval 77 percent to 81 percent.

Appendix F

COMPUTER PROGRAM AND APPLICATION EXAMPLE

This appendix presents a computer program to implement the prediction equations and confidence interval procedures developed in this study. The program is written for the Apple II microcomputer using Applesoft BASIC programming language. For the most part, standard BASIC language instructions are used and therefore the program should be easily translated to another computer system.

The computer program provides complete directions and is therefore self-explanatory. The program listing is shown in Figure F-1. Figure F-2 demonstrates employment of the program for predicting MTBF, MTTR and AVAIL 1 for the hypothetical unit used in the "Sample Application" subsection of Section 4.

\
JST\
JLIST

```

4 HOME : VTAB 10
5 INPUT "DO YOU NEED INSTRUCTIONS Y/N? ";A$
6 IF LEFT$(A$,1) = "Y" THEN GOSUB 9000
10 CLEAR : HOME : DIM C(14,5,5),B(14,5),X(14,5),NV(14),L(14),NM$(14)
11 DIM V(14,5),S(14),NQ(25),G(14)
12 NA = 0
13 G$ = CHR$(7);D$ = CHR$(4)
15 GOSUB 4000
17 HOME
20 PRINT "RELIABILITY/AVAILABILITY PREDICTION *": PRINT
22 NA = 0
23 PRINT "          DECEMBER,1981"
24 PRINT
25 INPUT "SYSTEM NAME ";N$: PRINT
30 PRINT "1-MTBF": PRINT "2-MTTR": PRINT "3-MTBFFO"
40 PRINT "4-AVAIL1"
42 PRINT "5-AVAIL3"
45 PRINT "6-AVAIL4": PRINT
50 INPUT "ENTER CHOICE - CODES 1-6? ";A$: PRINT
55 A = VAL(A$): IF A < 1 OR A > 6 THEN PRINT G$: GOTO 50
57 IF A >= 4 THEN A = A + 1
60 INVERSE : PRINT "E";: NORMAL : PRINT ">ARLY OR ";: INVERSE : PRINT "L"
   ;: NORMAL : PRINT ">ATE ";:
62 INPUT A$
65 T$ = LEFT$(A$,1): IF T$ < > "E" AND T$ < > "L" THEN PRINT G$: GOTO
   60
70 T = 0: IF T$ = "E" THEN T = 7
72 EQ = A + T
75 PRINT
80 NQ(0) = EQ
300 REM : VARIABLE INPUT
310 INVERSE : PRINT "N";: NORMAL : PRINT ">EW DATA OR ";: INVERSE : PRINT
   "C";: NORMAL : PRINT ">HANGE DATA ";: INPUT X$
320 X$ = LEFT$(X$,1): IF X$ < > "N" AND X$ < > "C" THEN PRINT G$: GOTO
   310
330 IF X$ = "C" GOTO 700
390 REM : NEW SET OF DATA
395 HOME
400 PRINT : PRINT "ENTER VALUES FOR VARIABLES SHOWN"
403 PRINT
405 NA = 0
410 FOR J = 1 TO NV(EQ)
420 Z = X(EQ,J)
430 PRINT P$(Z);" ";: INPUT V(EQ,J)
432 PRINT
435 NEXT
437 FOR J = 1 TO NV(EQ)
438 Z = X(EQ,J)
439 U(J) = 0:O(J) = 0:F(J) = 0
440 IF FX(Z) = 1 GOTO 480
450 IF V(EQ,J) < MN(Z) THEN U(J) = 1

```

Figure F-1. Computer Program

```

460 IF V(EQ,J) > MX(Z) THEN O(J) = 1
470 GOTO 500
480 IF V(EQ,J) < MN(Z) OR V(EQ,J) > MX(Z) THEN F(J) = 1
500 NEXT
510 REM : PROVIDE INFO ON BOUNDARY CHECK
520 FOR J = 1 TO NV(EQ)
525 Z = X(EQ,J)
530 IF U(J) = 0 AND O(J) = 0 AND F(J) = 0 GOTO 600
540 IF U(J) = 1 THEN PRINT V(EQ,J); " VALUE FOR ";CD$(Z); " IS LESS THAN S
    AMPLE MINIMUM OF ";MN(Z)
550 IF O(J) = 1 THEN PRINT V(EQ,J); " VALUE FOR ";CD$(Z); " EXCEEDS SAMPLE
    MAXIMUM OF ";MX(Z)
560 IF F(J) = 1 THEN PRINT V(EQ,J); " VALUE FOR ";CD$(Z); " IS OUTSIDE RAN
    GE OF ";MN(Z); "-" ;MX(Z)
600 NEXT
605 PRINT
610 INPUT "DO YOU WISH TO INSPECT OR CHANGE ANY VALUES (Y/N)?";C$
620 IF LEFT$(C$,1) < > "Y" AND LEFT$(C$,1) < > "N" GOTO 610
630 IF LEFT$(C$,1) = "N" GOTO 800
700 REM DATA CHANGE ROUTINE
705 DC = 0: REM FLAG TO NOTE IF ANY DATA IS CHANGED
710 IF NA < > 0 THEN GOSUB 3000
715 PRINT "ENTER CODE,VALUE (0,0 TO END)
716 PRINT
718 PRINT "          CURRENT"
720 PRINT "CODE  VAR.  VALUE"
725 PRINT
730 FOR J = 1 TO NV(EQ)
732 G(J) = 0: REM :G(J)=1 IF JTH VARIABLE CHANGED IN CURRENT ITERATION
735 Z = X(EQ,J)
740 PRINT "   ";J; "   ";CD$(Z); TAB( 13);V(EQ,J)
745 NEXT
747 PRINT
750 PRINT "CODE "; CHR$(44); "VALUE ";: INPUT J,VJ
770 IF J = 0 GOTO 785: - REM CHECK FOR END OF INPUT
775 IF J < = NV(EQ) AND J > = 1 THEN DC = 1:G(J) = 1:V(EQ,J) = VJ: GOTO
    750
776 PRINT G$; " CODE OUTSIDE RANGE-REENTER": GOTO 750
785 IF DC = 1 THEN NA = NA + 1:NQ(NA) = EQ
790 GOTO 437
800 REM : POINT ESTIMATE
810 PE = B(EQ,0)
820 FOR J = 1 TO NV(EQ)
830 PE = PE + B(EQ,J) * V(EQ,J)
840 NEXT
850 IF L(EQ) = 0 GOTO 880
860 PE = EXP (PE)
880 PE = ( INT (1000 * PE) ) / 1000
900 REM OUTPUT RESULTS
910 PRINT : PRINT NM$(EQ); " = ";PE
915 IF DC = 0 THEN NA = NA + 1:NQ(NA) = EQ
920 PRINT : REM NEW MENU
930 PRINT "1- CHANGE OR DISPLAY DATA"
940 PRINT "2- CONFIDENCE LIMITS"
950 PRINT "3- NEW REL./AVAIL. EQUATION"
960 PRINT "4- NEW SYSTEM"

```

Figure F-1. (continued)

```

970 PRINT "5- END"
975 PRINT
980 INPUT "ENTER CHOICE-CODE 1-5? ";A$
985 PRINT
990 A = VAL (A$): IF A < 1 OR A > 5 GOTO 980
1000 ON A GOTO 700,2000,30,10,9999
2000 REM  CALCULATION OF CONFIDENCE LIMITS
2002 SUM = .02
2005 PRINT : INPUT "CONFIDENCE LEVEL (%):80,90 OR 95 ? ";CL$
2006 IF CL$ < > "80" AND CL$ < > "90" AND CL$ < > "95" THEN PRINT G$:
      GOTO 2005
2007 IF CL$ = "80" THEN CP = 1.28
2008 IF CL$ = "90" THEN CP = 1.645
2009 IF CL$ = "95" THEN CP = 1.96
2010 FOR I = 1 TO NV(EQ)
2015 Z = X(EQ,I)
2020 SUM = SUM + C(EQ,I,I) * (V(EQ,I) - M(Z)) ^ 2
2030 NEXT
2040 FOR I = 1 TO NV(EQ) - 1
2045 ZI = X(EQ,I)
2050 FOR J = I + 1 TO NV(EQ)
2055 ZJ = X(EQ,J)
2060 SUM = SUM + 2 * C(EQ,I,J) * (V(EQ,I) - M(ZI)) * (V(EQ,J) - M(ZJ))
2070 NEXT : NEXT
2075 CE = PE
2080 CF = S(EQ) * SQR (SUM)
2081 IF L(EQ) = 1 THEN CE = LOG (PE)
2085 LC = CE - CP * CF:UC = CE + CP * CF
2090 IF L(EQ) = 0 GOTO 2094
2092 LC = EXP (LC):UC = EXP (UC)
2094 LL = INT ((LC * 1000)) / 1000:UL = INT ((UC * 1000)) / 1000: PRINT

2095 CL = VAL (CL$)
2100 PRINT CL;" % CONFIDENCE LIMITS ARE:"
2110 PRINT : PRINT "      ";LL;"      ";UL
2900 GOTO 920
3000 REM  GET CURRENT VALUES OF SAME DEPENDENT VARIABLES
3010 FOR I = 1 TO NV(EQ)
3012 IF S(I) = 1 THEN 3070
3015 FOR K = 0 TO NA
3020 FOR J = 1 TO NV(NQ(K))
3030 IF X(EQ,I) < > X(NQ(K),J) GOTO 3050
3040 V(EQ,I) = V(NQ(K),J)
3050 NEXT J
3060 NEXT K
3070 NEXT I
3100 RETURN
4000 REM  READ NAMES OF DEP VAR & LOG CODE
4002 FLASH
4003 HTAB 13
4005 VTAB 10: FLASH : PRINT "READING IN DATA"
4006 NORMAL
4010 FOR I = 1 TO 7
4020 READ NM$(I),L(I)
4030 NM$(I + 7) = NM$(I):L(I + 7) = L(I)
4040 NEXT

```

Figure F-1. (continued)

```

4050 DATA MTBF,1,MTTR,1,MTBFFD,1,SF,1,AVAIL1,0,AVAIL3,0,AVAIL4,0
5000 REM INFO ON PREDICTOR VARIABLES
5030 P*(1) = "CDT-CONDENSER TYPE: 0=DOUBLE PASS;1=SINGLE PASS"
5040 P*(2) = "CT-CYCLE TYPE: 0=COMBINED CYCLE;1=SINGLE CYCLE"
5050 P*(3) = "FOPC-FORCED OUTAGE PARTS COUNT"
5060 P*(4) = "FT-FUEL TYPE: 1=COAL;2=DIL;3=GAS"
5070 P*(5) = "MW-MEGAWATT OUTPUT/HR"
5080 P*(6) = "PC-PARTS COUNT"
5090 P*(7) = "TP-NUMBER OF O&M TRAINING PROGRAMS"
5100 P*(8) = "UT-UNIT TYPE: 0=CYCLE LOAD;1=BASE LOAD"
5110 P*(9) = "YO-YEARS IN OPERATION"
6000 REM ; READ NUMBER OF PREDICTOR VARIABLES FOR EACH EQN
6010 FOR I = 1 TO 14: READ NV(I): NEXT
6020 DATA 5,5,5,3,3,5,5,4,3,4,3,2,4,3
6030 REM ; READ PREDICTOR VARIABLE CODES
6040 FOR I = 1 TO 14
6050 FOR J = 1 TO NV(I)
6060 READ X(I,J)
6070 NEXT J: NEXT I
6080 DATA 5,8,4,3,1,9,5,4,6,3
6090 DATA 9,5,8,4,3,5,2,6
6100 DATA 5,6,1,9,5,8,6,1
6110 DATA 9,5,8,6,1,5,8,4,1
6200 DATA 5,4,7,5,8,4,1,5,2,4
6205 DATA 5,4
6210 DATA 5,8,4,1,5,4,1
6300 REM ; READ CONSTANTS OF EQNS.
6310 FOR I = 1 TO 14
6320 FOR J = 0 TO NV(I)
6330 READ B(I,J)
6340 NEXT J: NEXT I
6350 DATA 4.1548,-1.4731E-3,1.0 296,1.0045,-7.906E-3,1.5167

6360 DATA .1754,4.9894E-2,1.2065E-3,.7624,1.0201E-2,-1.2462E-2
6370 DATA 5.833,4.1119E-2,-6.823E-4,.4842,.5248,-3.7949E-3
6380 DATA -1.3742,-2.9621E-4,1.3729,-5.7713E-4 : REM SF(LATE)
6390 DATA .9529,-2.513E-4,-3.9306E-4,3.42E-2: REM AVAIL1 LATE
6400 DATA 1.077,-4.9373E-3,-3.3851E-4,6.4905E-2,-5.4569E-4,.1341: REM A
VAIL3 LATE
6410 DATA .9777,-4.0407E-3,-3.8912E-4,6.5902E-2,-5.7679E-4,.14: REM AVA
IL4 LATE
6420 DATA 1.7497,-2.5873E-3,1.1986,1.9046,1.47 : REM MTBF EARLY
6430 DATA 2.5861,8.8698E-4,.8069,-.33 : REM MTTR EARLY
6440 DATA 5.4624,-1.9825E-3,.6701,.8138,.4639 : REM MTBFFD EARLY
6450 DATA -1.5399,-4.1234E-4,1.3336,5.9348E-2 : REM SF EA RL
6460 DATA .8328,-3.3264E-4,4.5077E-2 : REM AVAIL1 EARLY
6470 DATA .8214,-3.6029E-4,3.8916E-2,6.9036E-2,.0537 : REM AVAIL3 EAR
LY
6480 DATA .8015,-4.1615E-4,3.4337E-2,6.2196E-2: REM AVAIL4 EARLY
7000 REM READ IN CONFIDENCE LIMIT FACTORS
7002 FOR K = 1 TO 9: READ M(K): NEXT
7004 DATA .7,.92,169.3,1.56,343.2,258.5,3.06,.46,16.7: REM MEANS
7008 FOR I = 1 TO 14
7010 FOR J = 1 TO NV(I)
7020 FOR K = J TO NV(I)
7030 READ C(I,J,K)

```

Figure F-1. (continued)


```

7040 NEXT : NEXT : NEXT
7100 DATA      4.04E-7,-4.53E-5,1E-4,6.61E-7,-2.30E-7, .115, .050, 1E-4
,2.62E-2,.121, 5.34E-4,-3.58E-3,4.69E-6,-2.77E-5,.105
7102 DATA      4.77E-4,1.49E-5,1.92E-3,-3.31E-5,1.01E-7, 1.12E-6, -2.33E-4,
2.78E-6,2.66E-7,.135,7.22E-4, 1.83E-4,1.37E-5,-5.79E-6,7.51E-6
7104 DATA      3.79E-4,8.19E-6,-1.4E-4,-2.38E-4,-1.41E-5,5.68E-7,-4.25E-5,-1.
06E-4,-9.57E-7,.108,5.09E-2,1.12E-4, .121,5.41E-4,5.18E-6
7106 DATA      3.87E-7,3.61E-5,4.42E-7,.354,-4.108,3.06E-6
7108 DATA      3.85E-7,-4.76E-7,-1.21E-5,2.62E-6, -5.67E-5, 9.82E-2
7110 DATA      6.76E-4,1.76E-5,-8.5E-4,-2.51E-5, -6.06E-3, 8.51E-7, 1.28E-5,
1.22E-6, -1.56E-4,.115,-2.69E-4,4.94E-2, 4.34E-6, 5.81E-5,.168
7112 DATA      6.76E-4,1.76E-5,-8.5E-4,-2.51E-5, -6.06E-3, 8.51E-7, 1.28E-5,
1.22E-6, -1.56E-4,.115,-2.69E-4,4.94E-2, 4.34E-6, 5.81E-5,.168
7114 DATA      3.11E-7,-3.12E-5, -2.48E-5,-2.69E-5, .113, 3.85E-2, 2.68E-2, 5
.98E-2,-4.27E-4, .105
7116 DATA      3.00E-7,-1.56E-5, 4.03E-6, .0458, 1.24E-3, 1.22E-2
7118 DATA      3.11E-7,-3.12E-5, -2.48E-5,-2.69E-5, .113, 3.85E-2, 2.68E-2, 5
.98E-2,-4.27E-4, .105
7120 DATA      3.38E-7,-1.12E-4, -2.70E-5, .320, 3.13E-2, 4.87E-2, 2.99E-7, -
1.60E-5, 4.57E-2
7122 DATA      3.11E-7,-3.12E-5, -2.48E-5,-2.69E-5, .113, 3.85E-2, 2.68E-2,
5.98E-2,-4.27E-4, .105
7124 DATA      3.02E-7,-1.41E-5, -1.95E-5, .047, -9.59E-3, -9.89E-2
7500 REM READ STANDARD ERROR OF ESTIMATES
7510 FOR I = 1 TO 14
7520 READ S(I)
7530 NEXT
7550 DATA      .6838,.7278,.5694, .0988, 7.1123E-2, .0727, .1000, .8680, .963
4, .6263, .1028, 7.3509E-2, .0875, .1136
7800 REM CONF LIMITS FACTORS
7810 CL(1) = 1.28:CL(2) = 1.645:CL(3) = 1.96
8000 REM
8010 FOR I = 1 TO 9
8020 READ MN(I),MX(I),FX(I)
8030 NEXT
8040 DATA      0,1,1,0,1,1,31,446,0,          1,3,1,72,1150,0,96,514,0,1,
5,          1,0,1,1,1,31,0
8050 REM NAMES FOR PREDICTOR VARIABLES
8060 FOR I = 1 TO 9
8070 READ CD$(I)
8080 NEXT
8090 DATA      CDT,CT,FOPC,FT,MN,PC,TP,UT,YO
8900 RETURN
9000 REM : INSTRUCTION SUBROUTINE
9005 HOME
9010 PRINT "THIS PROGRAM IMPLEMENTS THE PROCEDURE FOR ESTIMATING RELIABIL
ITY AND AVAILABILITY PARAMETERS OF ELECTRIC POWER GENERATING SYSTEMS

9015 PRINT "DESCRIBED IN THE REPORT:"
9018 PRINT : PRINT
9020 PRINT "THE ROLE OF DESIGN COMPLEXITY IN FORECASTING RELIABILITY AND
AVAILABILITY OF ELECTRIC POWER GENERATING UNITS"
9021 PRINT : PRINT "EPRI REPORT *****": PRINT
9025 GOSUB 9400
9030 PRINT "THE PROGRAM PROVIDES ESTIMATES FOR THE FOLLOWING RELIABILITY/
AVAILABILITY PARAMETERS"

```

Figure F-1. (continued)

```

9031 PRINT
9032 PRINT "MTBF    AVAIL1"
9033 PRINT : PRINT "MTTR    AVAIL3"
9034 PRINT : PRINT "MTBFFO  AVAIL4"
9035 PRINT
9045 GOSUB 9400
9060 PRINT : PRINT "    FOR EACH PARAMETER,TWO EQUATIONS ARE PROVIDED,AS
    FOLLOWS:"
9062 PRINT : PRINT "EARLY -APPLICABLE EARLY IN THE DESIGN STAGE WHEN COMP
    LEXITY INFORMATION IS NOT AVAILABLE"
9064 PRINT : PRINT "LATE - APPLICABLE LATER IN THE DESIGN STAGE OR IN THE
    OPERATIONAL STAGE WHEN MORE DETAILED DESIGN INFORMATION IS AVAILABLE
    "
9066 PRINT : PRINT "THERE ARE EIGHT PREDICTION PARAMETERS. AT MOST, FIVE
    ARE USED IN ANYONE EQUATION. THE PREDICTION PARAMETERS ARE AS FOLLOWS
    :": PRINT
9070 GOSUB 9400
9095 PRINT
9100 PRINT "1-CDT:CONDENSER TYPE (SINGLE PASS OR DOUBLE PASS)"
9101 PRINT
9104 PRINT : PRINT "2-FOPC: FORCED OUTAGE PARTS COUNT"
9106 PRINT : PRINT "3-FUEL:FUEL TYPE"
9108 PRINT : PRINT "4-MW:MEGAWATT PER HOUR"
9110 PRINT : PRINT "5-PC:PARTS COUNT"
9112 PRINT : PRINT "6-TP:NUMBER OF TRAINING PROGRAMS"
9114 PRINT : PRINT "7-UT:UNIT TYPE (CYCLE OR BASE)"
9116 PRINT : PRINT "8-YO:YEARS OF OPERATION"
9120 GOSUB 9400
9130 PRINT : PRINT "IN ADDITION TO PROVIDING POINT ESTIMATES, CONFIDENCE
    INTERVAL PREDICTIONS ARE ALSO PROVIDED FOR THE"
9135 PRINT "RELIABILITY/AVAILABILITY PARAMETERS OF INTEREST."
9137 PRINT : PRINT "THE PROGRAM IS SELF PROMPTING AND ALLOWS YOU TO VARY
    THEVALUES OF THE PREDICTION PARAMETERS IN ORDER"
9138 PRINT "TO PERFORM TRADE-OFF AND SENSITIVITY ANALYSES."
9140 PRINT : PRINT "THE USER SHOULD REFER TO THE REPORT REFERENCED ABOVE
    TO OBTAIN MORE DETAILS ON THE DEVELOPMENT OF THE PREDICTION "
9142 PRINT "EQUATIONS AND THEIR USE."
9190 PRINT : PRINT "PRESS ANY KEY TO START MAIN PROGRAM"
9195 GET A$: IF A$ = "" GOTO 9195
9200 HOME : RETURN
9400 PRINT : PRINT "PRESS ANY KEY TO CONTINUE"
9405 GET A$: IF A$ = "" GOTO 9405
9410 HOME : RETURN
9500 STOP
9999 END

```

Figure F-1. (continued)

JRUN

DO YOU NEED INSTRUCTIONS Y/N? Y

THIS PROGRAM IMPLEMENTS THE PROCEDURE FOR ESTIMATING RELIABILITY AND AVAILABILITY PARAMETERS OF ELECTRIC POWER GENERATING SYSTEMS DESCRIBED IN THE REPORT:

THE ROLE OF DESIGN COMPLEXITY IN FORECASTING RELIABILITY AND AVAILABILITY OF ELECTRIC POWER GENERATING UNITS

EPRI REPORT #####

PRESS ANY KEY TO CONTINUE

THE PROGRAM PROVIDES ESTIMATES FOR THE FOLLOWING RELIABILITY/AVAILABILITY PARAMETERS

MTBF AVAIL1

MTTR AVAIL3

MTBFFD AVAIL4

PRESS ANY KEY TO CONTINUE

FOR EACH PARAMETER, TWO EQUATIONS ARE PROVIDED, AS FOLLOWS:

EARLY - APPLICABLE EARLY IN THE DESIGN STAGE WHEN COMPLEXITY INFORMATION IS NOT AVAILABLE

LATE - APPLICABLE LATER IN THE DESIGN STAGE OR IN THE OPERATIONAL STAGE WHEN MORE DETAILED DESIGN INFORMATION IS AVAILABLE

THERE ARE EIGHT PREDICTION PARAMETERS. AT MOST, FIVE ARE USED IN ANYONE EQUATION. THE PREDICTION PARAMETERS ARE AS FOLLOWS:

PRESS ANY KEY TO CONTINUE

1-CDT: CONDENSER TYPE (SINGLE PASS OR DOUBLE PASS)

2-FOPC: FORCED OUTAGE PARTS COUNT

3-FUEL: FUEL TYPE

4-MW: MEGAWATT PER HOUR

5-PC: PARTS COUNT

6-TP: NUMBER OF TRAINING PROGRAMS

7-UT: UNIT TYPE (CYCLE OR BASE)

8-YO: YEARS OF OPERATION

PRESS ANY KEY TO CONTINUE

IN ADDITION TO PROVIDING POINT ESTIMATES, CONFIDENCE INTERVAL PREDICTIONS ARE ALSO PROVIDED FOR THE RELIABILITY/AVAILABILITY PARAMETERS OF INTEREST.

Figure F-2. Application Example

THE PROGRAM IS SELF PROMPTING AND ALLOWS YOU TO VARY THE VALUES OF THE PREDICTION PARAMETERS IN ORDER TO PERFORM TRADE-OFF AND SENSITIVITY ANALYSES.

THE USER SHOULD REFER TO THE REPORT REFERENCED ABOVE TO OBTAIN MORE DETAILS ON THE DEVELOPMENT OF THE PREDICTION EQUATIONS AND THEIR USE.

PRESS ANY KEY TO START MAIN PROGRAM

READING 'IN' DATA

* RELIABILITY/AVAILABILITY PREDICTION *

DECEMBER, 1981

SYSTEM NAME TEST CASE

1-MTBF

2-MTTR

3-MTBF_{FD}

4-AVAIL₁

5-AVAIL₃

6-AVAIL₄

ENTER CHOICE - CODES 1-6? 1

E>ARLY OR L>ATE ? L

N>EW DATA OR C>HANGE DATA ? NB

ENTER VALUES FOR VARIABLES SHOWN

MW-MEGAWATT OUTPUT/HR ? 350

UT-UNIT TYPE: 0=CYCLE LOAD; 1=BASE LOAD ? 1

FT-FUEL TYPE: 1=COAL; 2=OIL; 3=GAS ? 1

FOPC-FORCED OUTAGE PARTS COUNT ? 200

CDT-CONDENSER TYPE: 0=DOUBLE PASS; 1=SINGLE PASS ? 1

DO YOU WISH TO INSPECT OR CHANGE ANY VALUES (Y/N)? N

MTBF = 272.82

1- CHANGE OR DISPLAY DATA

2- CONFIDENCE LIMITS

3- NEW REL./AVAIL. EQUATION

4- NEW SYSTEM

5- END

ENTER CHOICE-CODE 1-5? 2

CONFIDENCE LEVEL (%): 80, 90 OR 95 ? 90

Figure F-2. (continued)

90 % CONFIDENCE LIMITS ARE:

203.268 366.169

- 1- CHANGE OR DISPLAY DATA
- 2- CONFIDENCE LIMITS
- 3- NEW REL./AVAIL. EQUATION
- 4- NEW SYSTEM
- 5- END

ENTER CHOICE-CODE 1-5? 3

- 1-MTBF
- 2-MTTR
- 3-MTBFQ
- 4-AVAIL1
- 5-AVAIL3
- 6-AVAIL4

ENTER CHOICE - CODES 1-6? 2

E>ARLY OR L>ATE ?L

N>EW DATA OR C>HANGE DATA ?C
ENTER CODE,VALUE (0,0 TO END)

CODE	VAR.	CURRENT VALUE
------	------	------------------

1	YQ	0
2	MW	350
3	FT	1
4	PC	0
5	FQPC	200

CODE ,VALUE ?1,5
CODE ,VALUE ?4,275
CODE ,VALUE ?0,0

DO YOU WISH TO INSPECT OR CHANGE ANY VALUES (Y/N)?N

MTTR = 6.837

- 1- CHANGE OR DISPLAY DATA
- 2- CONFIDENCE LIMITS
- 3- NEW REL./AVAIL. EQUATION
- 4- NEW SYSTEM
- 5- END

ENTER CHOICE-CODE 1-5? 2

CONFIDENCE LEVEL (%):80,90 OR 95 ? 90

90 % CONFIDENCE LIMITS ARE:

4.293 10.887

Figure F-2. (continued)

1- CHANGE OR DISPLAY DATA
 2- CONFIDENCE LIMITS
 3- NEW REL./AVAIL. EQUATION
 4- NEW SYSTEM
 5- END

ENTER CHOICE-CODE 1-5? 3

1-MTBF
 2-MTTR
 3-MTBF/D
 4-AVAIL1
 5-AVAIL3
 6-AVAIL4

ENTER CHOICE - CODES 1-6? 4

E>ARLY OR L>ATE ?L

N>EW DATA OR C>HANGE DATA ?C
 .ENTER CODE,VALUE (0,0 TO END)

CURRENT
 CODE VAR. VALUE

1	MM	0
2	PC	275
3	CDT	1

CODE ,VALUE ?1,350
 CODE ,VALUE ?0,0

DO YOU WISH TO INSPECT OR CHANGE ANY VALUES (Y/N)?N

AVAIL1 = .791

1- CHANGE OR DISPLAY DATA
 2- CONFIDENCE LIMITS
 3- NEW REL./AVAIL. EQUATION
 4- NEW SYSTEM
 5- END

ENTER CHOICE-CODE 1-5? 2

CONFIDENCE LEVEL (%):80,90 OR 95 ? 90

90 % CONFIDENCE LIMITS ARE:

.771 .81

1- CHANGE OR DISPLAY DATA
 2- CONFIDENCE LIMITS
 3- NEW REL./AVAIL. EQUATION
 4- NEW SYSTEM
 5- END

ENTER CHOICE-CODE 1-5? 5

Figure F-2. (continued)