AD-A009 282

A COMPARATIVE ANALYSIS OF RELIABILITY PREDICTION TECHNIQUES

Douglas Joseph McGowen

Army Materiel Command
Texarkana, Texas

April 1975

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER USAMC-ITC-02-08-75-103	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER AD-A009 282
4. TITLE (and Subtitle) A COMPARATIVE ANALYSIS OF RELIABILITY PREDICTION TECHNIQUES		5. TYPE OF REPORT & PERIOD COVERED FINAL
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Douglas J. McGowen		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department Maintenance Effectiveness Engineering USAMC Intern Training Center Red River Army Depot, Texarkana Texas 75501		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE April, 1975
		13. NUMBER OF PAGES 92
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release: Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Research performed by Douglas J. McGowen under the supervision of Dr. S. Bart Childs, Professor, Industrial Engineering Department, Texas A&M University.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Reliability, Prediction

PRICES SUBJECT TO CHANGE

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes various reliability prediction techniques utilized in the development of an equipment. The techniques described include prediction by similar system, similar complexity, function, generic part count, stress analysis, and degradation techniques. These are described and compared with respect to the characteristics, basic assumptions, typical applications, and relative accuracy.

DD FORM 1 JAN 73 1473 EDITI

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

FOREWORD

The research discussed in this report was accomplished as part of the Maintenance Effectiveness Engineering Graduate Program conducted jointly by the USAMC Intern Training concepts and results herein presented are those of the author and do not necessarily reflect approval or acceptance by the Department of the Army.

This report has been reviewed and is approved for release. For further information on this project contact Ron Higgins, Intern Training Center, Red River Army Depot, Texarkana, Texas 75501.

Approved:

RONALD C. HIGGINS
Department of Maintenance Effectiveness Engineering

For the Commander

JAMES L. ARNETT, Director, ITC

ABSTRACT

Research Performed by Douglas J. McGowen

Under the Supervision of Dr. S. Bart Childs

This report describes various reliability prediction techniques utilized in the development of an equipment. The techniques des··ribed include prediction by similar systems, similar complexity, function, generic part count, stress analysis, and degradation techniques. They are described and compared with respect to the characteristics, basic assumptions, typical applications, and relative accuracy.

ACKNOWLEDGEMENTS

For serving as the chairman of my committee and offering many helpful suggestions, I extend my appreciation to Dr. S. Bart Childs. For serving as members of my committee I wish to thank Dr. R. McNichols and Dr. J. Foster. I would especially like to thank my sister, LaVerne, for her support as well as her invaluable assistance in the composition, editing, and typing of this paper.

During the course of this work, the author was employed by the U.S. Army as a career intern in the AMC Maintenance Engineering Graduate Program. He is grateful to the U.S. Army for the opportunity to participate in this program.

CONTENTS

CHAPTER I

INTRODUCTION AND MECHANICS

INTRODUCTION

Reliability is defined "as the probability that a system will perform satisfactorily for at least a given period of time when used under stated conditions."(2)* This report discusses the area of reliability prediction which is defined as "the process of forecasting, from available failure rate information, the realistically achievable reliability of a part, component, subsystem, or system and the probability of its meeting performance and reliability requirements for a specified application."(1) Reliability predictions provide a source of quantitatively assessing system reliability before actual hardware models are constructed and tested. In the field of reliability analysis one is often faced with the problem of choosing a reliability prediction technique suitable for his specific problem.

---

*A parenthesized number refers to the source listed in the references at the end of this paper.

The real value of any numeric expression lies not in the number itself, but in the information it conveys and the use made of that information. To some, reliability prediction is a numbers game that can produce any number required. To others it is a frustrating experience and a nightmare. To those qualified in reliability engineering, predictions are no mystery and they can be accurate and meaningful if existing knowledge and techniques are properly applied. Reliability predictions do not, in themselves, contribute significantly to the reliability of a system. Rather, they constitute criteria for selecting courses of action that affect reliability. (1)

According to Feduccia(7), many times in the preparation and evaluation of a proposal, the main goal is the determination of a reliability number for the equipment. In the hurry of getting this number, it is often and very easily done that the limitations and the techniques used are overlooked. Feduccia states this has a two-fold handicap: (1) Reliability prediction errors because of technique misapplication, and (2) lack of feedback on possible technique improvements because their limitations are either overlooked or otherwise tolerated as part of the game. Tiger(27) states that the "use of reliability prediction has been handicapped by overemphasis on simplicity of technique. Reliability prediction consists of serial block diagrams and addition of part failure rates only for elements which are individually required for mission success, otherwise more complex probablistic analysis is necessary." He further comments that some people still think of reliability prediction in terms of simple serial block diagrams and addition of part failure rates;however, use of multi-functional systems, redundancy, special maintenance policies, new electronic devices, non-electronic hardware, and complex mission requirements in which different functions are required in the various mission phases emphasize the need for greater depth in reliability modeling. Keene(10) states that "too often there is overemphasis on obtaining predictions of a system's reliability and refining them to account for small changes or clarifications of the hardware. The truth is that the use of failure rates, the development of models of a system's reliability and the mechanics of generating reliability predictions are helpful only as they effect decisions about design, and their value can be judged only by that criterion." The optimum utilization of reliability prediction requires a complete understanding of the types of prediction possible and implications for their use at various stages of hardware development. During early planning phases little is known about the system or its contents, so prediction at this stage must be based on preliminary information with many assumptions. As the development progresses and the design becomes firm, considerably better information becomes available and many assumptions can be replaced with known facts or with better educated guesses based on specific details of the case.

Predictions are valuable when deciding among alternative designs. Several designs for a particular system or subsystem may be under consideration, and one of the factors which influences the choice is their relative reliabilities. This is equally true when various types of redundancy are being compared and when different components are being considered. Predictions also indicate those components and assemblies which contribute most toward total system failure probability. By defining potential problem areas, necessary corrective action can be taken to reduce the probability of failure and improve the system. A concentrated design effort can be made where it will be most beneficial to the system. Other corrective actions such as application of redundancy, change in components, incorporation of periodic maintenance procedures, and strict control of manufacturing processes and inspection can be carried out. Also, when the prediction indicates that, with normal development effort, the reliability objective will be met easily, unnecessary development costs can be saved, and funds can be saved, and funds can be transferred to other areas which may require more concentrated effort.(1)

Several reliability prediction techniques, varying in level of complexity and detail of application, are available to the reliability engineer. In general, the techniques in current use provide means for predicting total equipment or system reliability as a function of its defined design or functional characteristics. Also, to the extent possible considering the maturity of available data, most prediction techniques consider the statistical distribution of failures to permit reliability evaluation in a quantitative manner. During the life cycle time span, data describing the system evolves from a qualitative description of systems functions to detailed specifications and drawings suitable for hardware production. Therefore, reliability prediction techniques have been developed to accomodate the different reliability study and analysis requirements as the systems design progresses.

SCOPE

The intention of this paper is to present and compare different prediction techniques that are utilized through the system development of the hardware. The techniques were chosen on the basis of current usage. It is essential that proper techniques be used in each design phase. The various techniques are discussed by the author because they are currently being used by industry and government. System development tasks involving significant prediction activity can be classified in seven general task categories (1) feasibility study, (2) allocation study, (3) design comparison, (4) proposal evaluation, (5) trade-off study, (6) design review, and (7) design analysis. These task categories differ in principle objective, and are performed at different stages of the development program. However, the associated reliability predictions are performed using essentially the same basic procedure for any task category; the major difference in procedure being dictated by the particular phase of the system life cycle rather than by the objective of the task.

For purpose of this paper, the following six categories of prediction techniques are discussed:

(a). similar equipment techniques--The equipment under consideration is compared with similar equipment of known reliability in estimating the probable level of achievable reliability.

(b). similar complexity techniques--The reliability of a new design is estimated as a function of the relative complexity of the subject item with respect to a "typical" item of similar type.

(c). prediction by function techniques--Previously demonstrated correlations between operational function and reliability are considered in obtaining reliability predictions for a new design.

(d). part count techniques--Equipment reliability is estimated as a function of the number of parts, in each of several part classes, to be included in the equipment.

(e). stress analysis techniques--The equipment failure rate is determined as an additional function of all individual part failure rates, and considering part type, operational stress level, and derating characteristics of each part.

(f). degradation analysis techniques--Circuit tolerances, parameter drift characteristics, part variation, and other factors are considered together with stress levels in predicting the probability of circuit malfunction due to wear out or other types of degradation.

Reliability prediction techniques in each of these categories are described and compared in the subsequent chapters.

In the discussion of each technique the following format is followed:

(a). the characteristics

(b). basic assumptions

(c). typical applications

(d). relative accuracy.

CHAPTER DESCRIPTION

In Chapter II, the author has reported on any work already done in the comparison and analysis of prediction techniques. Any missing references on his part is an oversight and not intentional.

Chapter III is primarily allotted to the techniques used during the feasibility studies allocation studies, and proposal evaluation of the hardware. This breakout by the author resulted primarily from his review of references (17), (13), (21), and (7).

A discussion of the techniques employed during the design comparison, proposal evaluation, trade-off studies, design review, and design analysis of the hardware is covered in Chapter IV. Chapter V is delegated to a general discussion of the techniques and a critical look at reliability prediction in general. An effort is made to suggest ideas and problems to be investigated in the area of reliability prediction.

CHAPTER II

LITERATURE SURVEY

Much of the work relating to reliability has been done for the Department of Defense and various industries. Although an abundance of reliability information is available, no cumulative report has been prepared contrasting and analyzing the prediction techniques. In his report (7), Feduccia reviews two classes of prediction techniques. He refers to these as the feasibility (or ballpark) prediction procedures and the design (or stress-analysis) prediction method.

The design prediction methods were initially reported by the Rome Air Defense Command/Radio Corporation of America, ARINC, and VITRO. These techniques consist essentially of compilations of part failure rate information which is based on the premise that after the period of infant mortality and prior wearout, failure rate is constant. The part failure rates are usually expressed as a function of electrical and thermal stress, so before they can be assigned, the stresses under which each part in the system is operating must be determined. After rates are calculated, they are combined in some appropriate model to yield a failure rate for the system. He stresses that stress-analysis prediction method should begin in the design stage and continue through the prototype development. A serious shortcoming of this technique lies in the quality and nature of the data base. Another shortcoming lies in the time required to make the prediction. According to Feduccia, feasibility (or ballpark) prediction techniques provide a quick estimate within the "ballpark" of final reliability figures. These methods require only that the number of tubes or total parts in the system be known. Although a feasibility prediction cannot replace the detailed stress-analysis procedure, it can assist the design engineer in estimating the reliability of a proposed design and provides management with a valuable tool for use in preliminary planning. In 1963, the ARINC Research Corporation and the Federal Electric Corporation completed a RADC-sponsored effort aimed at developing a series of techniques for reliability prediction by function. These studies were addressed to defining equipment functions (such as power output, frequency, signal-to-noise ratio) and to determining correlations between the functions and equipment MTBF. With this series of techniques, the designer can obtain a MTBF estimate for his circuit or subsystem as soon as he knows the appropriate functions, usually in the very early planning stages of design. The systems studied were all ground-based and included communications and radar receivers, transmitters and associated equipment. These efforts were followed, in 1965, by a revision of the original equations, and the development of a prediction by function technique for data processing equipment. (17)

This series of techniques has some limitations. They are restricted by the data available from field experience. An effort has been made in this area by the Bird-Engineering-Research Associates, Inc. for the Aerospace Corporation. This effort resulted in the publication of a handbook containing, "A Series of Techniques for the Prediction of Reliability Throughout the Life Cycle of Ballistic and Space Systems from Design to Development."(9) This technique, developed for use in the conceptual phase of system development, includes methods for predicting the reliability of structural, propulsion, mechanical and electronic subsystems. Parameters found to correlate with system reliability are vehicle weight (for structural subsystems), missile thrust (propulsion subsystems) and complexity (for mechanical and electrical subsystems). Each of these parameters is known, or can be reasonably estimated, in the conceptual phase of system development, therefore, the techniques are useful as planning and management tools for forecasting early the probability of failure in new designs.

In his article, "The Status of Reliability Prediction," Clifford M. Ryerson (21), discusses the accuracy of twelve types of reliability prediction techniques. His breakout is given in Table 2.1. He gives a brief description of each technique but does not give a comparison and contrast of the various techniques. Some of his techniques are true prediction techniques, others are techniques related to prediction for project control or forecasting.

Military-Standard-Handbook 217A (14) discusses several prediction methods that are now being used. There is a discussion of how to perform prediction or reliability during early stages of equipment design following certain guidelines. There is also a section dealing with reliability data and stesses that are associated with parts.

The Rome Air Defense Center (17) takes a general look at reliability and reliability prediction. N.A. Walter, in his paper, "Reliability as a total Concept," (29) makes a brief mention of various prediction methods and in most cases gives several steps to use when utilizing the techniques he discusses. The techniques used in the feasibility studies, allocation studies, and proposed evaluation of the hardware are discussed in the next chapter. These phases of the hardware are critical areas as far as reliability is concerned. Here the proper techniques must be implemented in order to guide the project in the right direction and avoid costly refit or redesign of the system. It can also help to select the right alternative if there are more than one design consideration.

TABLE 2.1 RYERSON, "The Status of Reliability Prediction," 1969.

Prediction Techniques	Optimum Project Phase
1. Comparison of Similar Systems 2. Standardized Typical System Reliability	During Project Planning
3. Comparison of Similar Circuits And (Apportionment)	During System Design
4. Active Element Group Count 5. Generic Type Part Count	During Equipment Design
6. Detail Part Estimated Stress Analysis 7. Detail Stress Analysis 8. Deficiency Technique	During Prototype Perfection
9. Simulated Operation And (Part Screening)	Production Unit Testing
10. Environmental Testing 11. AGREE Testing	System Testing
12. Field Confirmation	Specified Use

CHAPTER III

EARLY PREDICTION METHODS

In the early, pre-design stage of system development, the designer needs some method of estimating the system reliability. This chapter is concerned with the various techniques utilized during pre-design stage to predict system reliability. Its main concern is with techniques used in the feasibility studies, allocation studies, and proposal evaluation of the hardware. In the initial stages of development, very little is known about the system configuration.

SIMILAR SYSTEMS

One of the most fundamental techniques employed is the similar system method. Often a preliminary estimation is required prior to the total definition of a system. At this stage little specific reliability information is available and the prediction must be based on the state-of-the-art in similar systems plus appropriate specific assumptions. The primary characteristics of this method is that it compares new equipment with similar equipment already in use. It is usually expressed in terms of mean time between failures (MTBF), failure rate, or similar parameters. The basic underlying assumption in this method of prediction is that it assumes an orderly evolution of equipment and that similar equipment exhibit similar reliability.(17) Among factors that are taken into consideration are system design, performance, manufacture, physical comparison, and project similarities. Collecting data from existing equipment under similar environmental and operating conditions should be taken into consideration.

In drawing conclusions about reliability utilizing this technique care should be exercised in using these results. At best, only a "ballpark" estimate is given. Calabro (5) refers to it as a guess. An example of the use of this technique is shown by Joseph Fragola in his paper, "An Illustration of Bayesian Analysis of a Weibull Process." (18) Another example of the use of this technique is NAVSHIP 93820 (Method A) Technique. (14) This method requires finding of the nearest equivalent system and noting the failure rate. Appendix A shows four steps to follow when utilizing this technique.

SIMILAR COMPLEXITY

Another method employed during this period of development is the similar complexity prediction method. This prediction method has been developed as a result of analysis which tend to show a correlation between equipment complexity and reliability. (14) The most common technique involves the use of graphical procedures relating failure rate to active element group count (AEG). The primary characteristic of this method is that equipment reliability is estimated as a function of the relative complexity of the subject item with respect to a "typical" item of a similar type. The primary assumption is that a correlation exists between reliability and complexity. (17) Adequate detail of the equipment design must be available in order to estimate the number of active elements in the equipment. (29) AEG's are defined as tubes, transistors, or other active element items and their associated circuitry. Because of different environments in which the equipment will be operated, provisions are provided for compensation.

A typical application of this method is given by Military-Standard 756A. (13) This is a graphical application of this technique. Application of the technique involves determining the number of active element groups in each functional block of the equipment. The graphs published in MIL-STD 756A is for determining reliability in terms of mean life between failures. The graph includes two bands indicating the probable range of achievable reliability for equipment to be operated in airborne and shipboard environments (Appendix B). The higher the MTBF values for a given number of series active elements represents the level of reliability that can be achieved with good reliability engineering and design effort. The procedure to determine functional complexity, from MIL-STD 756A is, "For each functional block, estimate the number of active elements necessary to perform the function. An active element shall be considered to be an electron tube or transistor, except that ten computer diodes and associated circuitry shall be considered equivalent to one active element in digital computers. To date, insufficient data have been collected to permit a further breakdown between equipment containing tubes, transistors, micro modules, and integrated circuits. Determine the corresponding failure rate of each block for the number of active elements by using chart 1."

Another technique in this class is NAVSHIP 93820 (Method B) technique. This provides failure rates per active elements per equipment type. (14) This implies that an element in a particular piece of equipment would have a different failure rate from an active element in another equipment because of different usage and a varying number of types of associated parts. Another method in this class is a refinement of NAVSHIP 93820 (Method A). (14) The procedure to follow is multiply the number of active elements in the new equipment divided by the number of active elements in the old equipment by the old equipment failure rate. This would yield the predicted failure rate for the new equipment. Another approach is to estimate the relative complexity of the new to the old equipment by the number of modules or circuits. From this an estimate might be made so that the new equipment will be one and one-half times more complex than the old. Therefore, the failure rate of the new equipment would be one and one-half times the failure rate of the old equipment. (14) Since recent studies of the state-of-the-art equipment (integrated circuits) show the old methods do not work, a weighing factor is incorporated. Bird-Engineering-Research Associates(9) have developed two methods similar to MIL-STD 756A. The only difference being that a procedure for determining AEG's is given.

FUNCTION

The final prediction technique for this stage of development is called prediction by function. The basic assumption is that there exists a correlation between reliability and function as well as between reliability and complexity. Prediction by equipment characteristics refers to the estimation of the reliability of an equipment using equations formulated on the basis of equipment class and similarity of functional performance. (12) The application of this prediction method is dependent on the availability of sufficient data which relates the reliability achievements of similar systems and their functional performance characteristics. The characteristics of interest are those which affect reliability significantly and can be quantified early in the design phase. (29) The data should be applicable to the latest design standards when operated under comparable environmental conditions.

The Federal Electric Corporation initiated a study to determine the reliability function equations in 1963. (24) In 1965 they expanded and refined their initial reliability by function techniques. The equipment under study were radar systems, communication systems, and electronic data processing systems. (25) Specific systems under study were selected on the basis of available field operational data, on the general range of the individual systems performance characteristics, on consideration of current and standard design practices, and on technical development in the state-of-the-art. The scope of the effort was restricted to a selected number of systems which met the criteria for selection. As a result the correlation analysis could not be developed across the complete range of system types within each category. (25) The resultant methods should be used carefully, especially in application involving systems of the type not included in the data base used to perform the correlation analysis.

Each system studied was divided into functional parts that represented a distinct operation necessary for the system to perform its required mission. For example, radar was divided into a transmitter, a receiver, and an indicator, representing the principle radar functions of transmit, receive, and indicate. This method gave a greater degree of freedom than simply studying the whole system. It also provided a logical basis for study of the correlations between certain characteristics peculiar to the function under investigation and the reliability of the functional hardware. Data was gathered from files on systems for which Federal Electric Corporation has or had operational and maintenance responsibility. In analyzing the data, a failure was defined as a detected cessation of ability to perform a specific function within previously established limits. Development of correlations using actual field reliability figures in terms of mean time between failures was the basic approach followed except in the case of radar receivers and transmitters. Here failure rates were used and were normalized to minimize the effect of complexity. A functional characteristic was defined as an "equipment characteristic which might be expected to have a significant relationship to reliability." (25) A regression analysis involves determining which of an equation's coefficients best fit the form of the equation to the observed data. To accomplish this, it is necessary first to develop the form of the equation and the measures of the independent variables.

Three types of correlation analysis were used. These included Rank Order Correlation, Linear Correlation of Two Variables, and Multiply Correlation with Two Independent Varibles.

The Rank Order Correlation was made to make initial comparisons between each functional characteristic and functional reliability. It was used as a screening procedure. Linear Correlation of Two Variables was used to fit a least squares line to the graphical plot of an independent variable and dependent variable. Once it has been determined that a linear relation exists, this statistical procedure is employed to determine the "best line" through the points. The value of this statistical procedure is that it gives a mathematical check on the validity of assuming a straight line. Having derived a least squares line it is possible to determine confidence bands around it. The Multiple Correlation allows for the simultaneous calculation of the linear effects of two independent variables on one dependent.

The verification of this technique was to apply the actual field reliability (MTBF or failure rate) of an equipment not used in the original correlation and comparing it with the value predicted using the resultant prediction equation. (25)

Seven pulsed radar types were used in the development of the equations. Correlation analysis were performed on radar using data given in Appendix C, and characteristics given in C. These are primarily for example and will not be shown for other equipment. Correlation was found between the characteristics of peak power and normalized failure rate of radar receivers. Normalized failure rate is arrived at by dividing field failure rate by the number of active element groups existing within a function. Again an active element group is defined as an electron tube and its associated parts. The equation for this is given by:

$$\text{Normalized failure rate} = 4.17\ (Pp)^{.32} \quad (3.1)$$

where Pp is peak power.

The same approach was taken with radar transmitters. Again a correlation was shown between normalized failure rate and peak power given by:

$$\text{Normalized failure rate} = 9.06\ (Pp)^{.36} \quad (3.2)$$

The above results lead to a study of the relationship of the combined functions of receiver and transmitter. Again the relationship was given by determining a correlation between normalized failure rate and peak power and was given by:

$$\text{Normalized failure rate} = 6.3\ (Pp)^{.30} \quad (3.3)$$

The resultant value is then multiplied by the number of active element groups anticipated in the design of the complete function. The verification of this was done using actual field MTBF of one type of radar. The predicted MTBF was 231 hours. The actual field MTBF was 237 hours. This fell within the confidence limit bounds.

The correlation analysis indicated a relationship between maximum pulse width and MTBF for radar display. The relationship is given by the line:

$$\text{MTBF} = 1483 + 3314 \log_{10} T \quad (3.4)$$

where T is the maximum pulse width. In verification field MTBF was 1533 hours while predicted values was 1483 hours. Again it fell within confidence interval.

As in the case of radar, the communication system was classified into two functions, receiver and transmitter. The only firm correlation that was developed existed between MTBF and maximum noise figure. The noise figure of a receiver is a measure of the extent to which the noise appearing in the receiver output, in the absence of a signal, is greater than the noise that would be present if the receiver were a perfect receiver from the point of view of generating the minimum possible noise. The resultant expression is given by:

$$MTBF = 2889\ e^{-.136N_f} \quad (3.5)$$

where N_f is the maximum noise figure in decibals. In verification, the calculated value of MTBF was 1743 to 2210. The predicted value of MTBF was 1920. This fell within acceptable confidence limits. Correlation analysis of the reliability of communications transmitters and the applicable characteristics indicated a relationship between power gain and actual MTBF. The resultant equation is given by:

$$MTBF = (6769)\ G^{-.624} \quad (3.6)$$

where G is power gain. In verification field MTBF was 903 hours and predicted was 867 hours which fell inside the confidence limits.

Again the correlation method was used in analyzing mulplex systems giving a relationship for MTBF and the number of channels being used. The following equation is:

$$MTBF = (783)\ e^{-.0178C} \quad (3.7)$$

where C is the number of channels. Again selecting a set to use in verification showed an actual MTBF of 764 hours with a predicted of 696 hours.

FECD's approach to electronic data processing systems was basically the same as utilized for radar and ground communication systems. That is, several representative EDP systems were investigated in order to determine logical functional breakdowns and associated characteristics which appear suitable for correlation with reliability. (25) For their study the FEDC chose to divide EDP systems into two general areas: (1) Central Processor and, (2) Peripheral Equipment.

The Central Processor is composed of functional units which control the operation of the input, output, and buffer equipment; mathematically operate on the data it receives; extract required data from memory; stores resultant data; and ultimately controls transmission to the output equipment. In other words, it consists of the arithmetic, control, and storage, or main memory functions. The peripheral equipment was defined as the input, output, buffer, auxiliary storage, and other equipment not under the direct control of the central processor. Again validity was checked by comparing it to a system in use.

From a correlation analysis, a relationship between central processor and the ratio of word size in bits to the add time in microseconds. The equation is given by:

$$MTBF = (524)\ e^{-.135W/A} \quad (3.8)$$

where A is the add time or time for one addition and W is for words. The predicted MTBF was 405 hours while the field MTBF was 328 hours. The predicted value fell within the confidence bands. No discussion of results were given on the peripheal equipment.

One other application of prediction by function is the Hughes Study. (15) Here, equipment was divided into six groups: radar, cathode ray tube, display, radio, transmitter, radio receiver, and buffering. It represented a total of fifty-two equipment, all ground or shipboard. The data was made up of ARINC's as well as Hughes's data. Thirty equipment characteristics were studied and although some were the same as the ARINC's, the majority were different. Regression analysises were done with the aid of a computer and three to four equations resulted for each equipment type. As an example, the following equations were developed for pulse radar:

(a). $\bar{\theta} = 159.4 - 20.5X_1$ (3.9)

(b). $\bar{\theta} = 214 - 6.9X_i - 24X_2$ (3.10)

(c). $\bar{\theta} = 50 - 10X_1 + 1.5X_2 - 1.5_3 + 1.24X_4$ (3.11)

where:

$\bar{\theta}$ = predicted MTBF (hrs)

X_1= peak power output (KW)

X_2= average output (KW)

X_3= prime power input (KW)

X_4= HDBK-217 prediction (hrs)

The equations are arranged in the order of their use since peak output would be the first characteristic known, equation b would be used second since the next characteristic normally determined is average output and similarly for the remaining equations. Similar sets of equations were determined for the other five equipment categories.

In his paper, "A Methodology for Software Reliability Prediction and Quality Control," (22) Schneidewind presents a procedure to follow in order to arrive at a prediction function for software reliability. His approach is basically to determine a reliability function based on shape of frequency function of empirical data, estimate the parameters, identification of reliability function by using goodness of fit tests, estimate parameter confidence limits, estimate function confidence limits, prediction of reliability and its various intended operating times, and finally a comparison of required reliability with predicted reliability. (22) He notes that the implementation is complicated by the fact that the time between troubles per fixed time interval is not a stationary process with respect to test time. As a result of a reduction in trouble rate as testing continues, the form of the distribution may remain the same over time but parameter values may change, or the actual form of the distribution may change. This means that a reliability function which is based on the total number of data points collected over the entire test period may not be an accurate predictor,because the data set is non-representative of the current state of the error occurence process. (22) He suggests that a smoothing technique could be used on the most current data points in order to obtain parameters estimates that would apply the next time. In other words, the parameters would be updated as testing continues. If the form of the distribution changes he notes that it would further complicate the problem in that the most appropriate form of distribution would be needed at each test period. He gives an example utilizing his technique assuming an exponential distribution form in reference 18. A method similar to Federal Electric Corporation was used by the Naval Air Development Center for non-avionics. (11)

The ARINC Research Corporation (24) initiated a study to develop a technique for predicting reliability of ground electronic systems prior to the actual design of the system. Their approach also was based on determining the relationships between system reliability and some of the more general characteristics of the system. One major requirement was that the resulting prediction be representative of the state-of-the-art. Therefore, observed field data was the foundation of the investigation. The relationships between reliability and system parameters were determined by a multiple regression analysis. A linear model of the form (24)

$$Y = B_0 + B_1X_1 + B_2X_2 + \dots B_nX_n \qquad (3.12)$$

where X_1, X_2, ... X_n represent system characteristics and B_1, B_2, ... B_n are the true regression coefficients relating these characteristics to reliability where Y is a measure of reliability. In this investigation Lne was used so that the basic regression equation became

$$Ln\bar{e} = b_o + b_1X_1 + b_2X_2 + \dots b_nX_n \qquad (3.13)$$

where b_i is a statistical estimate of B_i, and $\bar{e}$ is the predicted mean time between failures of a system. $Ln\bar{e}, X_1 \dots X_n$ are known for each system and solving the equations, one for each system, gives the best coefficients $b_o, b_1 \dots b_n$. The regression analysis with N parameters (in the optimal case N independent parameters) some of the parameters may not be significant so a portion of the task was to determine which parameters are related to reliability. Because of limited capacity, runs were made with subsets of system parameters. Volume II (25) of this report presents a step by step procedure for using this technique. The final supplement to this report is given by reference 4. One assumption made is the mean time to failure is exponentially distributed. Four equations were arrived at below:

I. $Ln\bar{e} = 7.173 - .801X_1 - .136X_2 - .596X_3 + .513X_5$ (3.14)

II. $Ln\bar{e} = 7.910 - .121X_8 - .740X_1 - .090X_2 - .359X_3$ (3.15)

III. $Ln\bar{e} = 2.731 - .484X_7 - 1.457X_6 + 2.206X_5 - .929X_9 - .139X_2$ (3.16)

IV. $Ln\bar{\theta} = 2.172 - .277X_2 + 2.327X_5 - 1.075X_3 - 1.770X_6 + .192X_4$. (3.17)

where $\bar{\theta}$ is predicted MTBF and X_i are equipment parameters.

X_1 = number of active elements by type

X_2 = number of cathode ray tubes

X_3 = number of transmitters

X_4 = highest frequency

X_5 = analog or digital

X_6 = steerable antenna

X_7 = maximum dc volts

X_8 = rated power

X_9 = ratio of turning range t highest frequency

The equation chosen is based on information given. Twenty-seven systems were observed in this experiment. The assumption was made that the design of new equipment will comprise elements and principles similar to those of the designs considered in this analysis.

ARINC also did a study directed toward developing a reliability prediction technique for monolithic integrated circuits (18). A model that expresses reliability as a function of device screening, sampling, system burn-in time, and field operating time was developed. The equation was derived through multilinear-regression analysis of field data of sixteen system types. The data was supplied by users or the manufacturers of the system. The equation fits to the Weibull distribution with the shaping parameter β being a constant while the scaling parameter α is a function of device screening and sampling tests plus system burn-in time. After determining the characteristics to be utilized the following prediction equation was derived:

$$R_w(t_2) = e^{-t_2^{2/3}/K} \quad (3.18)$$

where

$$K = 76{,}877e^{.025S_c + .00095S_a + .0064t_1}$$

S_c = screening score

S_a = sampling score

t_1 = system burn-in time

t_2 = field operating time

With the exception of field operating time, all variables in the equation can be controlled within wide limits during production. Another study was conducted much in the same way as before but on avionic equipment. (3) Table 3.1 shows the resultant prediction equations.

Appendix A of this paper presents the basic steps in utilizing the prediction by function technique. After initial reliability numbers are realized and farther work is done and more is known about the system, other techniques can be used to quantify prediction numbers. Chapter IV will be a discussion of these techniques.

ARINC, Avionics Reliability and Maintainability Prediction By Function, 1966.

TABLE 3.1

EQUIPMENT PREDICTION EQUATIONS

Equipment Classification	Equation Type	Equation	Parameter Range
Navigational and Radio Receiving Sets	I	$Ln\bar{\theta}=5.796-0.561(X_1)-0.336(X_2)+0.232(\ln X_3)$	$0.1\le X_1\le 4.5$ $0\le X_2\le 4$ $2\le X_3\le 500$
	II	$Ln\bar{\theta}=3.529-0.612(X_1)-0.345(X_2)+0.150(X_4)$	$0.1\le X_1\le 4.5$ $0\le X_2\le 4$ $15\le X_4\le 22$
Electromechanical Analog Navigational Computers	I & II	$Ln\bar{\theta}=1.806-0.120(X_5)+0.298(X_6)$	$3\le X_5\le 20$ $9\le X_6\le 13$
Indicators	II	$Ln\bar{\theta}=5.515-0.163(X_7)$	$2\le X_7\le 8$
Signal Processing/Generating Equipment	I & II	$Ln\bar{\theta}=6.283-0.0176(X_{13})$	$20\le X_{13}\le 168$
Radio Command Communications	I & II	$Ln\bar{\theta}=8.779-0.708(\ln X_{14})-0.354(\ln X_{15})$	$9\le X_{14}\le 400$ $2\le X_{15}\le 400$
High Power Radar Sets	I	$Ln\bar{\theta}=3.317-0.267(X_{16})-0.136(X_{17})+0.291(X_{18})$	$1\le X_{16}\le 4$ $2\le X_{17}\le 9$ $2\le X_{18}\le 4$
	II	$Ln\bar{\theta}=4.164-0.325(X_{16})-0.270(\ln X_7)$	$1\le X_{16}\le 4$ $5\le X_7\le 185$
Low Power Navigation & IFF Transmitting & Receiving Sets	I & II	$Ln\bar{\theta}=4.349-0.445(X_2)+0.350(X_8)$	$0\le X_2\le 5$ $0\le X_8\le 3$
Intercommunication Sets	I	$Ln\bar{\theta}=6.973-1.215(X_1)-1.155(X_9)$	$0.1\le X_1\le 2.0$ $4\le X_9\le 17$
	II	$Ln\bar{\theta}=7.108-0.0202(X_{10})-0.507(X_1)$	$20\le X_{10}\le 140$ $0.1\le X_1\le 2.0$
All Equipment	I	$Ln\bar{\theta}=2.986+0.242(X_{11})-0.507(X_1)$	$20\le X_{11}\le 10$ $0.1\le X_1\le 48.7$ $0\le X_2\le 11$ $5\le X_6\le 13$
	II	$Ln\bar{\theta}=4.707-0.141(\ln X_{10})+0.183(X_{11})-0.443(\ln X_{12})+0.0625(X_4)$	$14\le X_{10}\le 11,000$ $1\le X_{10}\le 10$ $4\le X_{12}\le 579$ $8\le X_4\le 22$

TABLE 3.1. continued

EQUIPMENT PARAMETERS DEFINITIONS AND QUANTIFICATION

Parameter Symbols	Parameter	Quantification
X_1	Volume	Equipment volume in cubic feet. Note: for Radio and Navigational Receiving Sets, the volume of any antenna which may be a part of the set is not included in the calculation.
X_2	Number of Interfacing Equipment	The number of other equipment, excluding indicators, that feed signals to or receive signals from this equipment.
X_3	Sensitivity	Measured in volts for a 10 db $\frac{S+N}{N}$
X_4	Packaging Characteristic Rating Characteristic — Rating Type of Enclosure Some cabinets pressurized — 0 No cabinets pressurized — 4 Vibration Isolation Some cabinets shock mounted — 4 No cabinets shock mounted — 0 Equipment Packaging Equipment in single package — 4	The sum of the ratings given to each characteristic for the equipment under study.

TABLE 3.1 continued

	Equipment in 2-4 packages	3	
	Equipment in 5-6 packages	2	
	Equipment in 9 or more packages	1	
	Type of Cooling		
	Forced air-refrigerated(at all times)	4	
	Forced air-inside ambient at all times	3	
	Convention	2	
	Refrigerated air on deck,outside ambient at altitude	1	
	Component Packaging		
	Modularized	0	
	Conventional Construction	4	
	Type of wiring		
	Printed Circuits	0	
	Conventional wiring	4	
X_5	Number of Signal Inputs Acceptable		The number of signals from other equipment which the equipment under study requires or can accomodate in its operation.
X_6	Equipment Feature Rating		The sum of ratings for the applicable individual design features.
	<u>Feature</u>	<u>Rating</u>	
	Power Supply		
	Power supply external to equipment	5	
	Solid State	4	
	Combination solid state and tubes	3	
	Tube	2	
	Rotating machinery	1	

TABLE 3.1 continued

	Tuning(operational) None required 4 Manual 3 Semi-automatic (auto-tune) 2 Fully automatic 1 Type of indicators None 4 Meters 3 Electro-mechanical 2 Cathode ray tube 1	
X_7	Number of LRU's LRU Function(MIL-STD-196 A Symbol): Air conditioning(HD) Amplifier(AM) Antenna,complex(AS) Antenna,simple(AT) Compensator(CN) Computer(CP) Control(C) Converter(CV) Coupler(CU) Indicator,cathode ray tube(IP) Indicator,Non C.R.T.(ID) Junction Box(J) Keyer(KY) Power Supply(PP) Receiver(R) Receiver/Transmitter(RT) Recorder(RD) Relay Box(RB) Switch(S) Transmitter(T)	The sum of the total quantity of each LRU included in the equipment complement.
X_8	Equipment Subfunction rating for Low Power Navigation and IFF Transmitting and Receiving Sets.	The rating of the subfunction.

TABLE 3.1 continued

	<u>Subfunction</u> <u>Rating</u> Doppler, TACAN, Radio Altimeters 1 Beacons 2 IFF Sets 3	
X_9	Number of Channels	The number of channels of operation for inter-communication sets.
X_{10}	Power Consumption	The steady state power in watts consumed by the equipment in its most power-consuming mode of operation. Note: Considers the "radiate" not the "standby" status of radar sets. "Steady state" implies that starting power requirements are not to be considered.
X_{11}	Equipment Function Rating <u>Classification</u> <u>Rating</u> <u>Function</u> Navigational Receiving Sets Loran 6 Radio Receiving Sets 3 Radio Navigation Sets 5 Direction Finder Equipment 5 Electromechanical Analog Navigation Computers 1 Indicator Group Indicators 3	The rating given to the equipment function.

TABLE 3.1 continued

	Signal Processing/ Generating Equipment Signal		
	Converter	2	
	Signal Analyzers	2	
	Coder-Decoder	10	
	Radio Command Communications		
	Radio Command Communications	2	
	High-Power Radar Sets		
	Intercept	1	
	Tracking	1	
	Side-Looking	1	
	Search	1	
	Fire Control	1	
	Bombing/Navigation	1	
	Acquistion	1	
	Low Power Navigational& IFF Transmitting&Receiving Sets		
	IFF	5	
	Doppler	2	
	Beacons	3	
	TACAN	2	
	Altimeters	2	
	Intercommunications		
	Intercom Sets	4	
X_{12}	LRU Rating LRU Function(MIL-STD-196 A Symbol)*		The sum of the products of the quantity of each of the LRU types shown below times the rating for that LRU type.

	Rating		Rating
HD	2	ID	2
AM	3	J	3
AS	4	KY	4
AT	1	PP	4
CN	2	R	4
CP	4	RT	4
C	3	RO	4

*See X_7 for definitions of symbols.

TABLE 3.1 continued

	CV 3 RE 4 CU 1 SA 2 IP 4	
X_{13}	Weight	The weight in pounds of the equipment. Note:For Radio Navigational and Receiving Sets, the weight of any antenna that may be a part of the set is excluded from the calculation.
X_{14}	Frequency	The highest frequency of operation in megacycles per second.
X_{15}	Power Output	The power in watts delivered to the antenna.
X_{16}	Number of Operational Functions or Capabilities Radar Set Functions: Airborne Early Warning and Control Anti-Intrusion Acquire on Jammer Acquisition Bombing Calibrating(Test Equipment) CW Illumination ECM Training Ground Controlled Approach Gun Fire Control Home on Jammer Height Finding Radar IFF/SIF Intercept Navigation Noise Jamming Projectile Intercept Radar Decoy Radar Beacon Radar Trainer	The total number of the contained by the radar set.

TABLE 3.1 continued

	Ranging Reconnaissance Search Track Any functions not otherwise listed of the same order	
X_{17}	NUMBER OF FEATURES FEATURES MTI Multiple Range ECCM Self Contained Computer Self Contained Display Variable Pulse Width Beam Shaping Variable Scan Characteristics Variable Range Bug Self Contained Gyro Contains Beacon Receiver	QUANTIFICATION The sum of the number of the features contained by the radar set.
X_{18}	TYPE OF ACTIVE ELEMENT GROUP TYPED AEG — Rating Transistor — 4 Tube, standard or miniature — 3 Tube, subminiature — 2 Electromechanical Devices — 1	Use Average Ratings if more than one type dominates

CHAPTER IV

LATE PREDICTION METHODS

This chapter concerns itself with reliability prediction techniques used during the design comparison, proposal evaluation, trade-off studies, design review, and design analysis of the hardware. The following three methods were chosen for discussion; part count technique, stress analysis technique, and degradation analysis techniques.

GENERIC PART COUNT

The basic assumption in the part count technique is that the average stress levels in new design are assumed to be approximate average levels of stress in previous designs. Also, nominal levels of environmental stress are assumed. The math model is exponential. (17) In other words, this prediction method makes use of average failure rates which are applicable to parts operating in similar environments of use. The detailed information of the operating part is not needed as this system requires only a measure of the system complexity in terms of part numbers. The data is acquired from field experience on a large variety of equipment. A part type includes those items which perform the same function, such as transistors, resistors, motors, etc. More precise definitions of generic part types are employed in order to gain better accuracy in the prediction method. These definitions take into account the types of construction and the rated stress levels to which parts can be subjected. For example, resistors may be divided into carbon film, metal film and wirewound types while transistors may be divided into signal and power types. The degree to which the generic part can be defined may be restricted during the design phase.

A weighing factor K is usually incorporated into the model to compensate for different environmental conditions. Usually the part failure rate data is found under laboratory conditions of stress and temperature. In actual field applications these parts are subjected to other stresses of various natures not specifically accounted for in the data. In order to provide a range of failure rates keyed to such additional usage stresses such as humidity, vibration, shock, handling, turn-on and turn-off, etc., found in actual applications, the K factors have been assembled from data based on field equipment failure rates. Thus, part failure rates determined can be modified depending on the intended end use by multiplying the base failure rate by the appropriate K factor. All the techniques used are essentially applied in the same manner, with the source of data being the major difference. Equipment failure rates are determined on part count(actual or estimated)by class or type. Application of the technique involves counting the number of parts of each class or type, taking this number and multiplying it by the generic failure rate for each part or class type, and adding all the products to get the failure rate for the equipment. Two sources of data are Volume II of the RADC Reliability Notebook (17) and MIL-STD-HDB 217A.

To apply this technique, the equipment under consideration is broken down according to the classes and types of parts. The total number of parts in each class and type is determined by actual count if possible. If an actual count is not possible, a good estimate of part count is required. (17) It is essentially a process of actually counting the number of parts of each class or type and multiplying this number by the generic failure rate for that particular class or type. These products are then summed accordingly.

For part class (14)

$$\lambda_t = \lambda_r M_r + \lambda_c M_c + \ldots \qquad (4.1)$$

where

λ_r = average failure rate for all resistors.

λ_c = average failure rate for all capacitors.

M_r = number of resistors.

M_c = number of capacitors.

λ_t = equipment failure rates,

or for part type, (17)

$$\lambda_t = \lambda_{r1} M_{r1} + \lambda_{r2} M_{r2} + \ldots \qquad (4.2)$$

where

λ_{r1} = failure rate for carbon composite resistors,

λ_{r2} = failure rate for metal film resistors,

M_{r1} = number of carbon composite resistors,

M_{r2} = number of metal film resistors,

λ_t = equipment failures rate;

or in summary (17)

$$\lambda_E = \sum_{i=1}^{n} N_i \lambda_i \qquad (4.3)$$

where

λ_E = equipment failure rate

N_i = the number of parts of type or class i included in the equipment

λ_i = average failure rate or failure rate of part of class or type i

n = the number of different type or class of parts included in the equipment

Again it must be noted that generic failure rate is the inherent number of failures per unit of time or cycles that will occur under laboratory conditions. Generic failure rates of components are obtained from failure data of previous tests. These rates are the basic failure rates to be adjusted for appropriate use conditions and other applicable considerations. (17)

For example, let

$$\lambda_E = K_E \lambda_O \qquad (4.4)$$

where

λ_E = mean failure rate under a specific use environment

λ_O = mean generic failure rate under an ambient use environment

K_E = environmental weighing factor

It is noted that some parts fail in application less than in vendor and laboratory tests. These K-factors are usually less than one. On the other hand, some fail more and thus have a weighing factor greater than one. Because different parts are affected to different degrees by each environment, it is necessary that K-factors be developed for each general set of environments. More accuracy would be attained by developing failure rates around each environmental factor (humidity, vibration, etc.) and to a degree around the specific level for each environmental factor. (17) An example of K-factors is shown in Appendix D. Appendix A shows a step-by-step procedure for utilizing this technique.

STRESS ANALYSIS

Another technique employed during this phase of the life cycle is the stress analysis technique. A more precise definition of the parts within the system is required so that reference can be made to the part failure data, which is expressed as a function of electrical, thermal, and mechanical stress. This permits a detailed part-by-part analysis of the system design to the extent that the effects of degrading stresses are considered in determining the failure rates of individual parts. (14) These techniques are similar in use, the difference being the source of failure rate data, and the corresponding differences in the procedures used in extracting data from the data source, and translating these data for application to a specific system. (14) Actual operating conditions of the parts are first verified to be within their specific rated capabilities. This action not only provides data for determining the part failure rates, but also ensures that any overstressed part is identified and subsquently eliminated from the system, either by the use of a different part or a new design configuration. Since details of system design are required in determining stress ratios, temperature and other application and environmental data, this prediction technique is only applicable during the later stages of design. (29) Once the failure rate data are determined, the reliability prediction is completed by combining the failure rates for each part in the system according to a pre-established mathematical model. In general, this will involve substituting the failure rates in the model to obtain the predicted reliability or MTBF of an element of the system, and combining system element reliabilities as appropriate to obtain a prediction of the overall system. (17) Because of the high level of complexity of modern systems, the application of the procedure consumes time and should be used when such detailed part by part analysis is warranted. Computer processing is "workable," but the initial stress analysis usually involves considerable effort at the engineering level. The characteristics of this prediction technique considers part type, operational and environmental stresses and derating characteristics associated with each individual part in predicting MTBF. One major assumption is that similar parts operated under similar conditions will exhibit comparable reliability. (1/)

This detailed part-by-part analysis of a system design permits the degrading effects of stresses. When utilizing this technique, operational and environmental stresses as well as other characteristics are determined for each part in the equipment or system. The characteristics and parameters must be defined and evaluated for each part class. A base failure rate is determined for each part. This is done by finding the stresses on each part. These stresses are usually in terms of electrical, mechanical, and thermal stresses. These stresses are usually given in decimal fractions indicating the ratio of actual stress to rated stress. The actual stress conditions can be determined by estimates, circuit analysis, actual measurements, planned derating criteria, or some other source. The rated stress is the stated rating for the part parameter without derating. Again consideration must be given for the K-factor adjustment. Failure rates are noted for each module or unit failure rate. Then the combined module or unit failure rates are used to obtain the subsystem failure rate or survival probability. Subsystem rates are then combined to get the system reliability model. MIL-STD-HDB 217A lists several assumptions that should be noted when using this technique. They are that most data do not include the failure rate for connecting devices such as soldering, wirewraps, etc. All part failure rates are based on part test data derived from vendor test and equipment manufacturer's test. K-factors are usually used to convert the failure rates shown to operational environment. The definition of a failure for a part under controlled test conditions usually differs from the definition of a failure for the part when used in an equipment. The application K-factors take this into account. Appendix A shows a step-by-step procedure to use when employing this technique.

DEGRADATION ANALYSIS

The final technique is degradation analysis. It is a general term usually applied to a variety of analysis techniques which permit an evaluation of the probable susceptibility of an equipment to variation or drift in circuit parameters. (17) Its basic characteristic is that it is usually implemented on a computer and by circuit analysis evaluation and optimizing is studied. It requires a mathematical model in terms of circuit equations.

One example of this technique is Monte Carlo Methods. (6) It involves the computer similation of an empirical approach whereby a number of copies of the network under study are constructed by sampling component parts at random from a representative population of these parts. Input data for a Monte Carlo Method must include the complete frequency distribution of each parameter. For example, a certain part valve is required, so a set of values, distributed in a manner representative of the actual part values, would be provided. Random selection of this value from this set would then simulate the random selection of a part. Selecting all input parameters this way, and solving the circuit equations using selected values, one set of output values results. Repeating the process over and over will then give a set of values distributed for the part. The Monte Carlo Method could be used in an analysis of a new complex system in which no past information is available. This type of analysis would enable one to gain information concerning which subsystems and components of the system are most critical.

Another technique in use under the degradation technique is the worst case method. These methods can be used to determine the worst case output for any variable. Still another technique is the parameter variation method. (17) This technique is used to provide information concerning part parameter drift stability, circuit performance-part parameter relationships, and certain circuit-generated stresses. In the general case, a parameter variation analysis would consist of solving circuit equations in an iterative manner until a solution is obtained for all probable combinations of input parameter values. In general, input data consists of nominal or mean values and estimated or assumed circuit parameters drift characteristics. A typical parameter method would be solved in steps by varying one or two parameters at a time while holding the rest at a nominal value. Solution of the circuit equations for each step would provide limiting values for parameters under investigation. This procedure is repeated for all parameters in the circuits. (17) Two other methods are mentioned in reference (17). They are worst case methods or moment methods. Only brief mention of them will be presented here. Worst case methods of circuit analysis can be used to determine the worst case conditions for any output variable of the circuit. The worst case methods are extensions of the parameter variation methods in that output variables are evaluated with reference to varying values of the input parameters. Moment methods utilize the mean and variance of the distributions of the input parameters to get the mean and variance of output variables. A list in MIL-STD-HDBK 217A of various degradation prediction techniques are listed in Appendix E. These will not be discussed in these papers but are included for the benefit of the reader. The following chapter is a discussion of prediction in general with the advantages and disadvantages of the prediction techniques. Also included are the author's summary and recommendations.

CHAPTER V

SUMMARY AND RECOMMENDATIONS

Reliability prediction should play a vital role in any development of a system. This check gives management and design people additional information for decisions. It serves to guide management throughout the life cycle of the equipment. Reliability prediction shows various design flaws and allows for their correction before the final design is completed and thus eliminates costly repair or refit. A reliability "number" should be taken in the context of its derivation. Reliability models do not predict reliability of an item in the sense of a guess which requires no input information; models can only predict, based on previous results with the same or similar items. The accuracy of an estimate depends on two factors:

(1). The validity of the model (equation) used.

(2). The validity of the numerical parameters used in the equation (data):

(a). were the parameters accurately derived (statistical techniques, sample size)?

(b). were the operating conditions the same as for the item being analyzed or , if different, were these differences accounted for?

It is therefore seen that a reliability model can only estimate reliability from known data describing the reliability of similar equipment, or from known physical laws and measurements.

Let us again summarize some of the problems associated with reliability prediction.

In predicting reliability by function or regression analysis, it is impossible to model every possible contingency which can affect performance in the real world and these prediction numbers are likely to be only a crude approximation of the real world. Most of the studies done in this area were restricted to only the equipment used and by the data available from field experience. Determination of similarity can be made by engineering judgement only, no hard and fast rule is yet available to do this in a quantitative fashion.

In prediction by function, the range of parameters may be outside those under consideration. Equations are valid for systems designed and fabricated according to the engineering practices of the time associated with the systems of this study program. A correlation exists between the year, complexity, and hardware improvements. Reliability studies applied throughout a system's life cycle enforce checks on reliability itself.

When utilizing any technique, where data is required, a fundamental limitation is the ability to accumulate data of known validity for each new application. Differences, such as environment, uses, operators, maintenance practices, measurement, and even definition of failure, can affect the data gathered.

When comparing similar systems, care must be exercised in the utilization of the reliability number. Differences in manufacturers, usage, and other factors could greatly influence the reliability. The stress analysis technique is one of the most accurate prediction methods available but it, too, has severe shortcomings. The most glaring shortcoming is, again, the data base. Much of the data now used was collected on limited sample sizes under conditions which lacked adequate controls or was derived by interpolation or even extrapolation. Variability in reliability for a part made by two different manufacturers or at different times by the same manufacturer is usually unknown.

Environmental factors must be treated with gross K-factors. This method of prediction is time consuming, especially for complex systems. This method does not account for or predict the occurence of drift failures.

Data is the prime disadvantage when utilizing the generic part count technique. Degradation analysis techniques are usually done on a computer. The computer cost for this method may become restrictive. This cost is related to the number of simulation runs and the complexity of the system. Another disadvantage is the man-hours required to perform the modeling. Engineering and design changes will, in general, prohibit any type of quick analysis of certain design changes.

When utilizing prediction techniques it must be remembered how and why the number was arrived at in the life cycle. They are guidelines used in the various stages of life cycle and are not "exact" figures that can be used to show the reliability of the equipment when in use or in the field. The methods covered in the text contribute greatly to reliability prediction. The reliability engineer should choose his technique so that it is not too bulky or hard to handle and yet not so simple as to have little meaning. If he allows himself to get involved with a large model that is not capable of giving a realistic picture of reliability, he has not accomplished his mission. On the other hand, if he allows himself to choose a simple model, unsuited for his needs, he may present a false feeling of confidence. The reliability engineer needs to evaluate his alternatives and choose the reliability prediction technique that most appropriately fits his system or equipment. He is then able to produce reliability numbers that have importance and can be used throughout the life cycle of the equipment.

The author suggests the following topics for further study. The topic that invariably was mentioned as a key problem was the data base. Methods of collecting data, both from field usage and test, need to be examined. Problem areas include unreported failures, data bases from replaced parts rather than failed parts, environmental conditions, people using the equipment or repairing it and even the definition of failure. One prediction technique not covered in the text is prediction by deficiency This technique needs further consideration. The author suggests combining some of the other techniques to get reliability numbers and comparing them to actual field data. Finally, reliability in the future should be studied and its place in management as well as design decisions and its ability to help guide the project through its life cycle should be defined.

APPENDIX A

Steps to follow when utilizing prediction techniques.

I. By similar system

A. Define new equipment relative to type and operational environment of use. Other characteristics of the equipment may assist in the definition, such as size and output requirements.

B. Identify an existing equipment which is the nearest equivalent, making careful note of any obvious differences which exist for which the prediction is desired.

C. Record the reliability data available on the nearest equivalent, and make adjustments for each difference noted in step B.

D. Draw conclusions concerning the level of reliability that will be obtained from the new equipment. Such conclusions assume similar equipment will exhibit similar reliability. The accuracy of the estimate depends on the quality of the recorded failure data which is available, and the ability of the analyst to make the necessary adjustments in order to reflect the reliabilty potential of the new equipment.

II. By function

A. Determine from data relative to similar equipment the functional characteristics of the design which gives the best correlation between failures per active element and functional value.

B. Estimate the functional value required for the new design, for which the prediction is required, and determine the failure rate per active element group from the data analyzed in step A.

C. Estimate the number of active element groups contained in the new design and multiply this by the failure rate per active element determined in step B.

III. Generic part count method

A. Determine the quantities of each generic part type used in the system for which the prediction is required.

B. Calculate the failure rate contribution of each generic part type by multiplying the quantity used by the average failure rate of a single generic part type.

C. Estimate the overall system failure rate by summing the contributions calculated for each generic part type in step B. (Corrections may be applied to either the generic part failure rates or overall system failure rate to reflect different environmental conditions of operation.

IV. Stress analysis

A. Prepare a list of parts in the equipment.

B. Determine the stresses and environment the part must operate in.

C. Get the proper K-factor and failure rate of part.

D. Combine module or unit failure rates. Combine these to get subsystem and combine these to get system.

APPENDIX B

REPRODUCED FROM MIL-STD-HDB 756A

The reliability estimate obtained from this chart represents a band of possible outcomes. The smaller failure rate values of the band are obtainable with good reliability engineering and design effort.

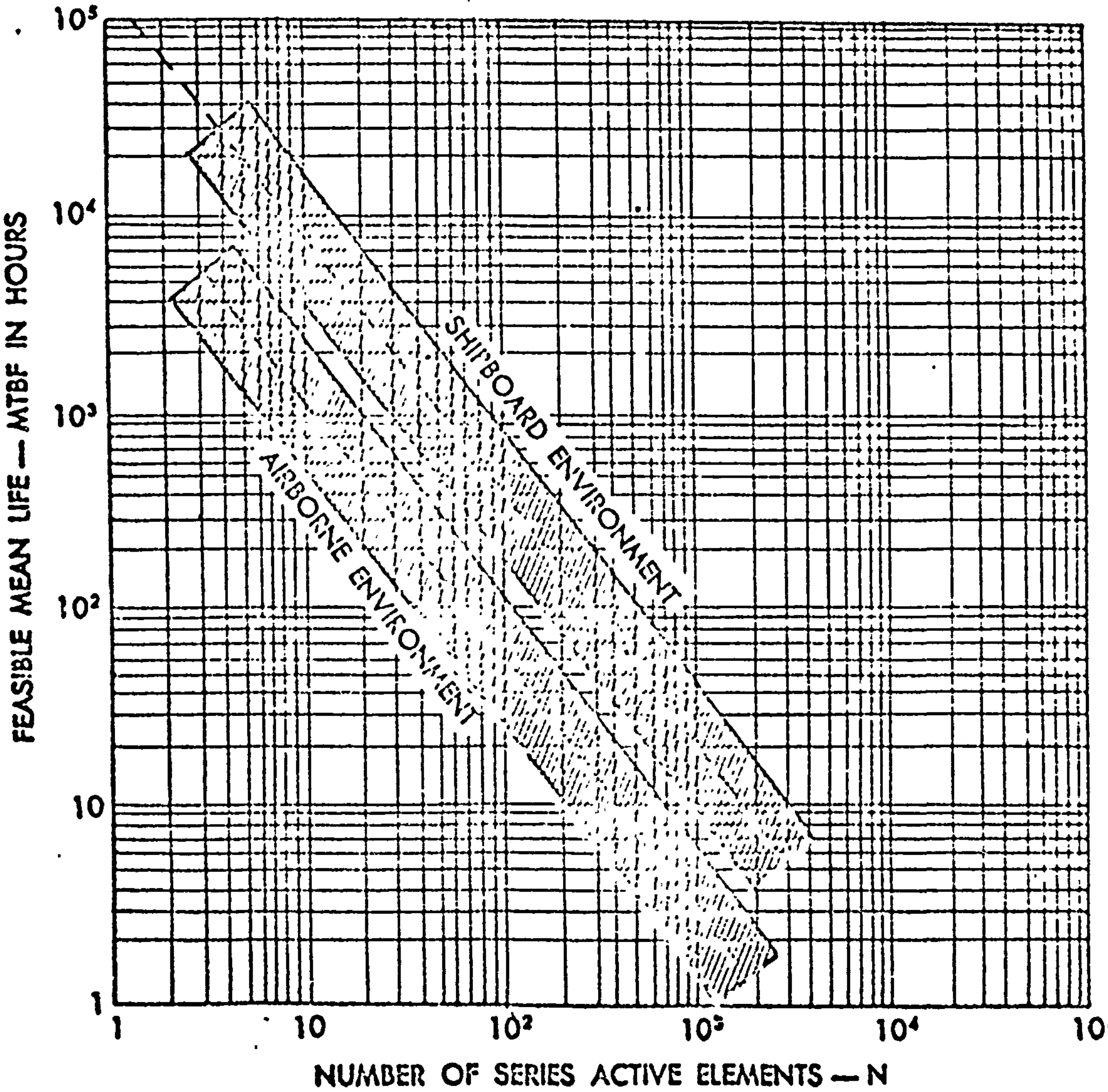

CHART 1. *Failure rate and MTBF versus functional complexity for electronic equipment*

APPENDIX C

SUMMARY OF RADAR SYSTEMS FUNCTIONAL CHARACTERISTICS

FUNCTIONAL CHARACTERISTICS	FPS-19	FPS-23	GPX-26	FPS-16	FPN-28
Operating Noise Figure(db)	8.3	6	11	10.3	13.5
Maximun Noise Figure(db)	10	7.5	11.5	11	14
Minimum Discernable Signal(-dbm)	109	140	80	100	92
Noise Safety Margin	.480	1.413	1.290	.175	.585
Maximum Rated CRT H.V.(KV)	12	N/A	N/A	3	10
Actual CRT H.V.(KV)	9	N/A	N/A	2	7.5
Maximum Actual CRT H.V.(KV)	3	N/A	N/A	1	2.5
CRT Persistence	P19	N/A	N/A	P1	P7
Minimum Receiver Bandwidth(mc)	1	.002	5	1.8	1.5
Peak Transmitter H.V.(KV)	28	6.8	3.5	30	26
Transmitter Pwr.Amp.Tube Gain(db)	N/A	30	6.5	N/A	N/A
Maximun Radar Range(mi)	160	50	190	200	50
PRF(PPS)	400	N/A	475	1707	1200
Peak Power(KW)	167	N/A	1.5	1000	500
Frequency Range(mc)	130	50	50	375	125
Duty Cycle	.0024	1	.000475	.001	.00096
Max. Pulse Width(us)	6	N/A	1	1	.8
Pulse Rise Time(us)	1	N/A	.2	.1	.2
Shortest Wavelength(CM)	22	57	28	5.4	10.3
Horizontal Beam Width(o)	1.25	30	5	1.2	2.2
Vertical Beam Width(o)	5.5	20	30	1.2	.5
Maximun Scanning Rate(RPM)	1.25	N/A	1.25	N/A	30
Average Pcwer (KW)	.4	1	.007	1	48
Pulse Fall Time(us)	1	N/A	.4	.1	.6
Antenna Gain(ob)	33	19	25	42	32
Unambiguous Range(mi)	220	N/A	180	50	70

REPRODUCED FROM "SYSTEM RELIABILITY," TOMMANEY.

SUMMARY OF RADAR SYSTEMS FUNCTIONAL CHARACTERISTICS continued

FUNCTIONAL CHARACTERISTICS	ARSR-1A	FPS-30
Operating Noise Figure(db)	8	7
Maximum Noise Figure(db)	8.5	11
Minimum Discernable Signal(-dbm)	109	120
Noise Safety Margin	.122	1.239
Maximum Rated CRT H.V.(KV)	12	12
Actual CRT H.V.(KV)	9.5	10
Maximum Actual CRT H.V.(KV)	2.5	2
CRT Persistence	P7	P19
Minimum Receiver Bandwidth(mc)	1	1.5
Peak Transmitter H.V.(KV)	28	.5
Transmitter Pwr.Amp.Tube Gain(db)	10.5	57
Maximum Radar Range(mi)	200	200
PRF(PPS)	360	385
Peak Power(KW)	5000	200
Frequency Range(mc)	70	60
Duty Cycle	.00072	.02
Max. Pulse Width(us)	2	52
Pulse Rise Time(us)	.3	1.5
Shortest Wavelength(CM)	22	47
Horizontal Beam Width(o)	1.35	2
Vertical Beam Width(o)	6.2	5.5
Maximum Scanning Rate(RPM)	6	5
Average Power(KW)	3.6	4
Pulse Fall Time (us)	.8	1.5
Antenna Gain(ob)	34.3	33.5
Unambiguous Range(mi)	240	230

REPRODUCED FROM "SYSTEM RELIABILITY," TOMMANEY.

SUMMARY OF RADAR RELIABILITY DATA ORIENTED BY FUNCTION

System	Function	Population	Total Operating Hours	Total Failures	Field MTBF (Hours)
FPS-19	Receive	58	508,080	446	1139
	Transmit	58	508,080	251	2024
	Display	58	508,080	58	4230
FPS-16	Receive	2	15,326	114	134
	Transmit	2	15,326	68	225
	Display	2	15,326	10	1533
FPS-23	Receive	118	1,033,680	647	1598
	Transmit	112	981,120	208	4717
	Display	N/A			
FPN-28	Receive	4	15,530	19	817
	Transmit	4	15,530	14	1109
	Display	4	15,530	12	1293
ARSR-1A	Receive	2	32,630	233	140
	Transmit	2	32,630	72	453
	Display	2	32,630	14	2318
GPX-26	Receive	58	508,080	57	8914
	Transmit	58	508,080	22	4165
	Display	N/A			

REPRODUCED FROM "SYSTEM RELIABILITY," TOMMANEY.

SUMMARY OF RADAR RELIABILITY DATA ORIENTED BY FUNCTION continued

System	Function	Normalized Failure Rates**
FPS-19	Receive	17
	Transmit	30
	Display	*
FPS-16	Receive	48
	Transmit	202
	Display	*
FPS-23	Receive	33
	Transmit	11
	Display	
FPN-28	Receive	24
	Transmit	112
	Display	*
ARSR-1A	Receive	71
	Transmit	130
	Display	*
GPX-26	Receive	5
	Transmit	11
	Display	

* Normalized Failure Rates were not Used for Displays

** Normalized Failure Rates are expressed as failures/10^6 hrs/ active element group

REPRODUCED FROM "SYSTEM RELIABILITY," TOMMANEY.

APPENDIX D

APPLICATION K-FACTORS FOR PART CLASSES

Part Type	Part Class	Fixed Ground	Vehicle Mounted Ground	Shipboard	Airborne
Diodes	Germanium	.75	3.5	.21	3.5
	Silicon	1.5	3.5	4.33	3.5
	Power	1	12	3.26	12
	Zener	1	3	2.75	3
	Varactor	1	5	--	5
	Microwave Mixer	1	5	--	5
	Microwave Detector	1	5	--	5
Fuses	All Types	1	6	--	6
Inductors	General	1.5	10	.23	10
	RF, IF Coils	1	8.6	.10	8.6
Low Population Parts	All Types	--	--	--	--
Minuteman Parts	All Types	1	--	--	--
Micromodules	All Types	1	--	10	--

REPRODUCED FROM MIL-STD-HDK 217A

APPLICATION K-FACTORS FOR PART CLASSES continued

Part Type	Part Class	Missile
Diodes	Germanium	10
	Silicon	10
	Power	18
	Zener	10
	Varactor	50
	Microwave Mixer	50
	Microwave Detector	50
Fuses	All Types	45
Inductors	General	20
	RF, IF Coils	14
Low Population Parts	All Types	--
Minuteman Parts	All Types	--
Micromodules	All Types	--

REPRODUCED FROM MIL-STD-HDK 217A

APPENDIX E

SUMMARIES OF TYPICAL ANALYTICAL TECHNIQUES

MANDEX Worst-Case Method

Type of Analysis: Steady state AC and DC worst-case

Mathematical Model Necessary: Circuit's simultaneous equations or matrix equation

Parts' Data Necessary: Nominal value and end-of-life limits

Output Information Received: Worst-case value of output variable compared with allowable value

Type of Circuits Suitable: Class A amplifiers, power supplies, all biasing(dc) circuits,Logic circuits etc.

MOMENT METHOD

Type of Analysis: Statistical

Mathematical Model Necessary: Circuit's simultaneous equation or matrix equation

Parts' Data Necessary: Mean(or nominal)value and standard deviation or variance of each input parameter and correlation coefficients when they exist

Output Information Received: The mean and variance of the distribution of each output parameter

Type of Circuits Suitable: Any circuit for which a mathematical model can be derived

MONTE CARLO METHOD

Type of Analysis: Statistical;predicts output variable distribution at any time; steady state ac or dc(Transient may be performed if

(cont'd from page 79)

if formula is available).

Mathematical Model Necessary: Circuit's simultaneous equation, matrix equation, transfer function(any mathematical representation including input parameter)

Parts' Data Necessary: Complete distribution of each input parameter at a time

Output Information Received: 20 cell histogram for each output variable

Type of Circuits Suitable: Any circuit for which a mathematical model can be derived.

VINIL METHOD

Type of Analysis: VINIL Method

Mathematical Model Necessary: Piece-wise linear equivalent circuits

Parts' Data Necessary: Application curves over operating and environmental ranges along with drift data

Output Information Received: Input characteristics(maximum& minimum) Transfer characteristics(maximum&minimun) Output characteristics(maximum&minimum)

Type of Circuits Suitable: Digital; Linear analog

SCAN AC Method

Type of Analysis: Linear sinusoidal dynamic analysis

Mathematical Model Necessary: Simultaneous complex variable

(cont'd from page 80)

equations with the real and the imaginary parts of the equations separated

Parts' Data Necessary: Nominal(mean);Minimum(-3);Maximum(+3)

Output Information Received: Families of frequency response curves;statistical variation of unknowns at any selected frequency;+3,-3 and mean of unknowns versus frequency (assumed)

Type of Circuits Suitable: Any linear circuit that contains frequency dependent devices and which is driven or is significantly analyzed with sinusoidal functions

---

SCAN Transient Method

Type of Analysis: Linear and non-linear transient analysis; differential equation solution

Mathematical Model Necessary: Simultaneous differential equations

Parts' Data Necessary: Nominal parts data;alternate sets of parts' data;Parts' data for the switched states

Output Information Received: Time response of linear or non-linear systems

Type of Circuits Suitable: All circuits for which the transient determining effects can be modeled.

(cont'd from page 81)

Parameter Variation Method

Type of Analysis: General;determines allowable parameter variation before design fails to function. Considers both one and a two-at-a-time parameter variation

Mathematical Model Necessary: Circuit's simultaneous equation or matrix equation

Parts' Data Necessary: A nominal value for each parameter and a range (in percent)

Output Information Received: Failure points for one and two-at-a-time parameter variation Schmoo plot determines safe operating envelope for design

Types of Circuits Suitble: Any steady state ac or dc circuit

SPARC (AEM-1, AEM-2, AEM-3) System of Programs

Type of Analysis: DC analysis;Transient analysis

Mat . matical Model Necessary: Equivalent circuits, equations, or matrices

Parts' Data Necessary: Nominal(mean);Minimum(-3);Maximum (+3)

Output Information Received: Solution of unknown in floating point fixed decimal output

Type of Circuits Suitable: All types, dc, bias, switching, non-linear effects, ac response and distributed parameter circuit servo loops and feedback systems

(cont'd from page 82)

SCAN DC Method

Type of Analysis: Linear static, Non-linear static

Mathematical Model Necessary: Linear or non-linear equations in appropriate matrix form with reasonable estimates of values of the unknowns affected by non-linear equations

Parts' Data Necessary: Nominal(mean);Minimum(-3);Maximum (+3)

Output Information Received: Nominal solutions, partial derivatives of unknown with respect to knowns, worst case values, and the probability of the unknowns being outside of specified limits

Type of Circuits Suitable: All circuits that can be described by linear and non-linear equations

REPRODUCED FROM MIL-STD-HDBK 217A

LIST OF REFERENCES

1. Amstadter, Bertram L. Reliability Mathematics, New York: McGraw-Hill Company, 1971.

2. ARINC Research Corporation. Reliability Engineering, Englewood Cliffs, New Jersey: Prentice-Hall, 1964.

3. Avionics Reliability and Maintainability Prediction By Function, ARINC Research Corporation, RADC-TR-66-509, 1966.

4. Balaban, Harold. "System Reliability By Function," ARINC Research Corporation, RADC-TDR-63-300, 1965.

5. Calabro, S.R. Reliability Principles and Practices, New York, New York: McGraw-Hill Company, 1962.

6. Davitt, Paul. "An Evaluation of Three Methods Used in Determining the Reliability of Complex Systems," Picatinny Arsenal, Dover, New Jersey: T''-2009, 1971.

7. Feduccia, Anthony J. "Reliability Prediction--Today and Tomorrow," Rome Air Development Center Research and Technology Division, Air Force System Command, Griffis Air Force Base, New York, 1967.

8. Tragola, Joseph. "An Illustration of Bayesian Analysis of a Weibull Process," Gruman Aerospace Company, RPMC-70-STP-10, 1970.

9. Handbook of Reliability Prediction Procedures for Ballistic and Space Systems,AD#470294,Bird-Engineering-Research Associates, Vienna, Virginia, 1965.

10. Keene, Samuel J. "Putting Predictions in Perspective," System Development Division, IBM Corporation, Boulder, Colorado, 1968.

11. Namaroff, J. "Development of Reliability Prediction Techniques for Non-Avionics," Naval Air Development Center, Warminister, Pennsylvania, NADC-73084-50, 1973.

12. Namaroff, J. "Development of Avionics Reliability Prediction Techniques," Naval Air Development Center, Warminister, Pennsylvania, NADC-50-7089, 1972.

13. Military-Standard-756A, "Reliability Prediction" 1963.

14. Military-Standard-Handbook-217A, Reliability Stress and Failure Rate Data For Electronic Equipment, 1965.

15. Non-Electric Reliability Notebook, Hughes Aircraft Company, RADC-TR-69-458, 1970.

16. Proceedings of Air Force Systems Command System Effectiveness Symposium, Bedford, Massachusetts, 1965.

17. RADC Reliability Notebook, Vol. I, TR-67-108, 1968.

18. Reese, J. "Reliability Prediction For Monolithic Integrated Circuits," ARINC Research Corporation, AD#742847, 1971.

19. Reliability Evaluation Program Manual. NAVORD CD 29304, 1973.

20. Roberts, Norman H. Mathematical Methods in Reliability Engineering, New York, New York: McGraw-Hill Company, 1964.

21. Ryerson, Clifford M. "The Status of Reliability Prediction," Annual West Coast Reliability Symposium, Vol. 10, Feb. 21, 1969.

22. Schneidewind, Norman F. "A Methodology For Software Reliability Prediction and Quality Control," Naval Post Graduate School, AD#754377, Monterrey, California, 1972.

23. Shooman, Martin L. Probablistic Reliability: An Engineering Approach, New York, New York: Mc-Graw-Hill Book Company, 1968.

24. "System Reliability Prediction By Function Volume I-Development of Prediction Techniques," ARINC Research

Corporation RADC-TDR-63-300, 1963.

25. "System Reliability Prediction By Function Volume II-Prediction Procedure," ARINC Research Corporation, RADC-TDR-63-300, 1963.

26. "System Reliability Prediction By Function," Federal Electric Corporation, RADC-TDR-63-146, 1963.

27. Tiger, B. "Does Reliability Prediction Help Make the System Go?" Defense Electronics Products, Radio Corporation of America, 1969.

28. Tommaney, Robert. "System Reliability Prediction By Function," Federal Electric Corporation, RADC-TR-6527, 1965.

29. Walter, N.A. "Reliability As a Total Concept," Admiralty Surface Weapons Systems, Portsmouth, TR-72-38, 1972.