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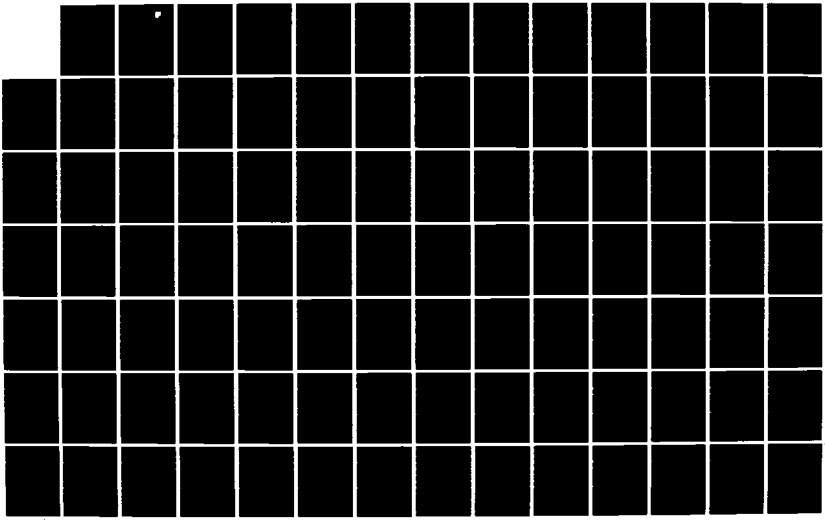

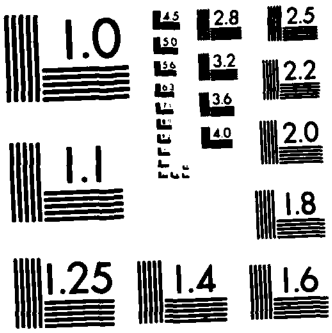
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Final Technical Report
September 1982

VALIDATION OF MAINTAINABILITY PREDICTION

Lockheed Electronics Co., Inc.

W. DuBlanica, J. Kubeck and E. Edwards

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, NY 13441

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

Validation of Maintainability Prediction Techniques prescribed in RADC-TR-78-169 was performed. The techniques for preliminary and detailed predictions were applied to three (3) representative samples of electronic equipment.

The detailed predictions were then compared with demonstrated field performance on equipments that have in excess of one million system

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) hours of combined operation. The new time synthesis prediction technique proved to be a distinct improvement in maintainability prediction methodology over existing techniques. In addition, the time synthesis model provides a structured means of assessing the maintainability design in its early and final stages, thereby determining if the system maintainability requirements will be achieved.

The standards for removal and replacement actions were analyzed in detail and modifications recommended. In order to provide further accuracy to the Maintainability Prediction Technique, appropriate times for the tasks of preparation and spare retrieval are recommended as adjuncts to MTTR. Although these factors are not design driven, they do contribute to corrective maintenance time and are necessary factors to ensure accurate predictions. To expand the ease and efficiency in using the new Maintainability Prediction Technique, an interactive computer program should be developed.

Maintainability, as with all technologies, is continuously changing. It is recommended that Maintainability Standards be established in the areas of Built-In-Test (BIT), Fault Tolerant Circuitry, Self-Test/Self-Diagnosis capability to meet the needs of maintainability in the future.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

Maintainability prediction/analysis is one of the critical activities in equipment design and development. It has an impact on man-power needed, availability, life cycle cost, logistic support, training/skill levels, and test equipment required. Current maintainability prediction techniques are indirect, complex in application, marginally accurate, and do not take into account system engineering design characteristics. As a result, techniques for maintainability modelling and trade-offs are virtually nonexistent. Therefore, new maintainability prediction/analysis techniques were developed under RADC contract F30602-76-C-0242, "Maintainability Prediction and Analysis Study". These techniques are based on a time synthesis model which will result in a more accurate prediction and direct quantification of fault isolation/Built in Test (BIT) characteristics. Two separate prediction procedures were developed; namely: a detailed procedure and a preliminary procedure. The preliminary procedure is applicable in early system development when detailed design characteristics are not available and is based on design concepts. The detailed procedure is applicable when detailed design characteristics are available and should be more accurate. Both procedures can be applied to any equipment or system and at any level of maintenance. These procedures provide the tools for assessing and evaluating the maintainability of modern equipments, including direct accountability of the fault isolation/BIT capabilities, packaging, replaceable item make up, and component failure rates. This will allow the designer to make rational maintainability design trade-offs.

The primary objective of this program was to validate and evaluate the maintainability prediction/analysis techniques developed under RADC contract F30602-76-C-0242. The investigation included validating the techniques by comparisons of available maintenance field data to predicted maintainability parameters; evaluating the availability of the information necessary to use the techniques; evaluating the cost effectiveness of the techniques; and determining what, if any, modifications can be made to improve the accuracy and practicality of the techniques.

Preliminary and detailed predictions of Mean Time to Repair (MTTR) were made on three equipments; namely: the MK86 Fire Control System, Missile Test and Readiness Equipment (MTRE), and Malfunction Detection and Analysis Recording Equipment (MADAR). Predictions were made at the organization, intermediate, and depot maintenance levels. Statistical techniques were then used to compare the predicted values of MTTR to available maintenance field data. This report presents results of the investigations made under RADC contract F30603-81-C-0081 and recommendations for modifications to the maintainability prediction techniques to improve their accuracy and practicality. It is divided into eleven major sections with appendices and was prepared in accordance with CDRL item A002 and DI-S-3591A/M. Section 2.0 provides a detailed description of the equipments and sources of maintenance field data used in the investigation. The predictions made are detailed in section 3.0, which include the ground rules followed, the availability of the data necessary to perform the predictions, and their impact on performance and schedule. Sections 4.0-8.0 address data collection and reduction, qualitative analysis; quantitative analysis; and the use of supplemental inputs. Section 9.0 relates to maintainability trends. Conclusions and recomendations are given in sections 10.0 and 11.0 respectively. The appendices provide backup material for the report.

2.0 BACKGROUND

This section provides the background information for the Validation of Maintainability Prediction Program. The equipments used to validate the prediction methods are described. Included are; equipment user, where the equipment is used, a brief functional description, physical configuration and the maintenance concept.

Also included in this section are descriptions of the sources used to obtain maintenance field data. These sources include user rer ts and Lockheed Electronics Company (LEC) field engineering personn

2.1 Equipments Used

Three electronic systems were used in this program. The systems have logged hundreds of thousands of hours of field operational time and are representative of modern electronic equipment. They include digital, analog, and radio frequency circuitry. The three systems are the MK86 Fire Control System, Missile Test and Readiness Equipment (MTRE), and Malfunction Detection and Analysis Recording Equipment (MADAR).

2.1.1 MK86

The MK86 is an advanced weapon control system used by the Navy aboard its destroyer class ships. The MK86 is divided into four groups; namely: the SPQ-9 Radar, the SPG-60 Radar, the Display Group, and the Data Group. The SPQ-9 Radar is the surface search radar which consists of 5 units. The SPG-60 Radar is the air radar and consists of 5 units. The Display Group consists of 3 Units and the Data Group consists of 3 Units. The MK86 uses current technology in radar, optics, and digital and analog circuitry.

The maintenance concept includes maintenance aids to assist in fault isolation. They consist of hardware and software tools that help the technician test, adjust and troubleshoot the MK-86. These aids include Unit Maintenance Panels, Alarm Indicators, Meters, Video test patterns and Test modes of operation. Alarm indicators are provided in various units of the MK-86 to alert operators and maintenance personnel to system malfunctions. The alarms on the Control Officers Console (COC) are overall system level; whereas, other alarms are related to a particular functional subsystem. Meters are provided in various units for monitoring power supplies and critical signals to help isolate malfunctions. Operator controls and indicators are also used in fault isolation.

2.1.2 MTRE

MTRE is used on submarines. Its major function is commanding the missile to perform functions that prepare it for launch. In addition, MTRE evaluates missile feedback to ensure that each commanded function has been completed satisfactorily.

MTRE utilizes a modular door-type construction and consists of two doors hinged separately on a vertical support post which permits independent movement of either door. The replaceable items consist mostly of standard plug in modules, with a few nonstandard modules. The standard modules are secured by holdown studs and keying devices. The keys on each module prevent the insertion of the wrong type module into a connector.

MTRE can be operated in several different modes, one of which is a maintenance mode. In the maintenance mode, the BIT capabilities of MTRE are used as a maintenance aid in both equipment checkout and fault isolation. By manipulating controls on the display control panel, the technician can produce a series of simulated operating conditions and evaluate the status of the MTRE. Signals normally received from fire control and the missile are simulated within the MTRE itself. If a malfunction is detected, the technician can operate the MTRE to isolate the fault.

2.1.3 MADAR

The MADAR is used on Air Force C-5 aircraft. It monitors selected subsystems, detects malfunctions, and records data on magnetic tape. The tape is retrieved for analyzing the malfunctions. The replaceable items at the organizational level include a Central Multiplex Adapter (CMA) unit, approximately 20 Automatic Signal Acquisition Remote (SAR-A) units, 12 Manual Signal Acquisition Remote (SAR-M) units and a Maintenance Data Recorder (MDR) unit. No corrective maintenance is performed on the line replaceable items at the organizational level. All corrective maintenance on line replaceable items is performed at the intermediate or depot level. No corrective maintenance task involves more than one level of maintenance.

2.2 Data Sources

The primary sources of maintenance field data were user reports and user generated Trouble/Failure Reports (TFR's). Field engineering personnel provided assistance in refining the data. The following are brief descriptions of the data sources for each of the equipments.

2.2.1 MK86

Maintenance field data for the MK86 was obtained from a computer listing from Naval Ship Weapons Systems Engineering Station (NSWSES). This listing gives an account of maintenance actions in sequential order, with the starting and completion times and dates. The actions are separated into the following status codes.

CODE	STATUS
4	Corrective Maintenance
5	Awaiting Spares
6	Undergoing Modifications
7	Awaiting Help
8	Administrative Delay
9	Support Equipment

The only times that were included in the MTTR were those for actions with status code 4, Corrective Maintenance. The maintenance data source for the computer listing was the 2 KILO form which is the standard Navy form for submitting maintenance data.

2.2.2 MTRE

The primary source of maintenance field data for MTRE was the TFR generated by the maintenance crew on the submarine. The information on these forms includes the unit failed, the type of maintenance performed and the time taken to perform the maintenance. The times stated include the fault isolation time, the remove time and the replace time. The logistic delay time is not included.

2.2.3 MADAR

Maintenance field data for MADAR was derived from Air Force Maintenance records. The information in these records includes the failed unit, the type of failure, the action taken, the type of maintenance, and the maintenance manhours. This information was coded and had to be decoded using an Air Force Handbook. The maintenance manhours includes only active maintenance times.

3.0 PREDICTION METHOD

The maintainability prediction techniques validated in this study are those presented in RADC-TR-78-169, "MAINTAINABILITY PREDICTION AND ANALYSIS STUDY." The Preliminary procedure is described in Section 5.2, "Early Prediction Procedure", and the Detailed procedure is described in Section 5.1, "Detailed Prediction Procedure" of RADC-TR-78-169.

3.1 Ground Rules

Ground rules are established to determine the factors that have to be considered in performing a maintainability prediction. The ground rules defined are:

- Predicted Parameter
- Tasks included in prediction
- Types of failures included in prediction
- Maintenance Levels

Ground rules which were applied to the three systems used for this study are as follows:

. Predicted Parameter

The parameter that was predicted for each system was Mean Time to Repair (MTTR). MTTR has been the prime measure of maintainability. It is the maintenance parameter which is most easily understood and the most easily derived from field maintenance data.

. Tasks Included in the Predictions

The tasks included in the predictions are those associated with active maintenance time only. Times associated with logistics delays, administrative delays and awaiting outside help are not included.

Active maintenance tasks include fault isolation, disassembly, interchange, reassembly, and checkout. However, the disassembly, interchange, and reassembly times were combined into a single category, called remove/replace time. The predicted MTTR did not include preparation or spare retrieval times.

. Types of Failures Included in the Predictions

The types of failures which were considered in these predictions were single hard failures. Neither intermittent nor secondary failures were considered in the prediction process.

. Maintenance Levels

The Maintenance Levels included in this study are the Organizational, Intermediate, and Depot.

. Organizational Level

The Organizational Level of maintenance refers to those maintenance actions performed on the system in the field. These maintenance actions are normally performed by the user's maintenance force. The ability of the technician performing the maintenance and the test equipment available are variable. Maintenance tasks at this level involve replacing defective subassemblies in order to get the system back in operating condition. The defective subassemblies are then sent to the depot to be repaired, or to an intermediate level for further testing. It is important that maintenance actions at the Organizational Level be performed as accurately as possible. There is a direct relationship between maintenance activities at this level and the operational availability of the system.

In view of the fact that the operational availability of the system is affected, the ability of the maintenance technician and the availability of test equipment are variable, maintainability must be built into the equipment. That is, the equipment must contain enough BIT to enable a technician with little experience to fault isolate to a defective subassembly in a reasonable time with little or no additional test equipment. However, BIT adds to the acquisition cost of the system, so that a system should have just enough BIT to ensure that the availability requirement of the equipment is met.

The maintainability prediction techniques should be able to allow the maintainability engineer to make trade-offs in BIT early in the design phase of the equipment.

. Intermediate Level

The Intermediate Level of maintenance refers to maintenance that occurs in the field, either at the system site or some central location. However, maintenance is usually performed by specially trained technicians, or even representatives from the equipment's manufacturer. The types of maintenance handled at this level are normally that which the regular maintenance crew cannot handle. Included in this type of maintenance are major system overhauls, system anomolies or intermittent conditions. Maintenance times are less related to system design and more related to the skill of the technician performing the maintenance and the availability of test equipment.

. Depot Level

The Depot Level refers to maintenance performed at the depot on the defective subassemblies that were replaced at the Organizational or Intermediate levels. Maintenance is performed by highly trained, experienced technicians, and test equipment is available, but varies from depot to depot. Since it is not practical nor cost effective to include any significant degree of BIT at the subassembly level, the maintenance times are almost entirely related to the technician's skill and/or the test equipment capabilities.

Maintenance times at the Depot Level do not directly affect the operational availability of the system, but can affect life cycle costs and the availability of spare subassemblies at the Organizational Level.

3.2 Preliminary Predictions

The Preliminary Prediction procedure is described in section 5.2, "Early Prediction Precedure", of RADC-TR-78-169, "MAINTAINABILITY PREDICTION AND ANALYSIS STUDY." This procedure is applicable in the early design phase of a system. It can be implemented based on design concepts, and then refined as more details become available.

The first step in performing the preliminary prediction, after the ground rules have been established, is to make a list of replaceable items and their failure rates. In the early phases of the design, the list of replaceable items may be derived from the block diagram, and their failure rates may be estimated using the parts count prediction technique of MIL-HDBK-217.

Next, all unique ways of performing each elemental repair activity are described on a worksheet similar to the one shown in figure 3-1 and the time for each activity type is synthesized. Elemental repair activities include fault isolation, remove/replace and checkout. The descriptions and times for these activities can be derived from the design concepts and the appropriate time standards. Activities which do not apply to a particular situation are left out.

The failure rate of each Replaceable Item (RI) is then associated with the corresponding activity types that pertain to it. The worksheet for this is shown in figure 3-2. After that, the MTTR for the system is computed as the sum of the weighted averages of the elemental repair times.

A sample of a Preliminary Prediction is included in Appendix A.

3.3 Detailed Prediction

The Detailed Prediction Procedure is described in section 5.1, of RADC-TR-78-169, "MAINTAINABILITY PREDICTION AND ANALYSIS STUDY." This procedure can be applied only after the detailed design of the system has begun. In order to implement the detailed prediction, schematics and mechanical drawings are required as well as a block diagram and a reliability prediction. A Failure Modes and Effects Analysis (FMEA) would also be helpful in correlating Fault Detection and Isolation outputs (FD&I outputs) to replaceable items (RI's).

In performing the detailed prediction, the ground rules are established and then a list of replaceable items and their failure rates is compiled. This list is prepared from actual parts lists and the reliability prediction.

Next, the Fault Detection and Isolation outputs are identified. The FD&I outputs can be derived from the schematics or if it is available from the FMEA. After the FD&I outputs are identified, they are

MTTR Element (m)	v	Description of the v^{th} Method	T_{m_v}	λ_{m_v}

Figure 3-1. RI Data Analysis Sheet - B

				Preparation				Fault Isolation				Spare Retrieval				
RI Description	λ	Qty	λ x Qty	$\lambda_{P_{1n}}$	$\lambda_{P_{2n}}$	• • •	$\lambda_{P_{V_{pn}}}$	$\lambda_{FI_{1n}}$	$\lambda_{FI_{2n}}$	• • •	$\lambda_{FI_{V_{FI}}n}$	$\lambda_{SR_{1n}}$	$\lambda_{SR_{2n}}$	• • •	• • •	
RI_1																
RI_2																
RI_3																
⋮																
RI_n																
Totals $\Sigma\lambda$																

Figure 3-2. RI Data Analysis Sheet - A

correlated to the replaceable items. This is the most important and probably the most difficult part of the prediction. It requires a thorough knowledge of the system. The correlation of RI's and FD&I outputs results in the creation of the FD&I correlation trees. These trees are used to construct the maintenance flow diagram. A sample correlation tree is shown in figure 3-3.

The maintenance flow diagram is a step by step outline of what a technician does, the FD&I outputs he observes, and the decisions he makes from the time that a failure is detected until the system is operational again. A time line analysis is performed to determine the times for each activity in the maintenance flow diagram. The total time to repair the system is determined for each combination of RI and FD&I output by summing the times for each activity performed in order to get from the beginning of the flow diagram to the particular RI and FD&I output combination. A sample maintenance flow diagram is shown in figure 3-4.

Finally, the MTTR for each RI is calculated as a weighted average of the total time for each combination of that RI and FD&I output. The system MTTR is computed as the weighted average of the MTTR's of each RI.

Appendix B contains a sample of a Detailed Prediction.

3.4 Availability of Data during Development Phase

The data necessary to implement both the Preliminary and Detailed Procedures was available for the three equipments used in this study.

3.4.1 Preliminary Prediction

The Preliminary Prediction requires that the following data be known: the replaceable items and their failure rates, the fault isolation

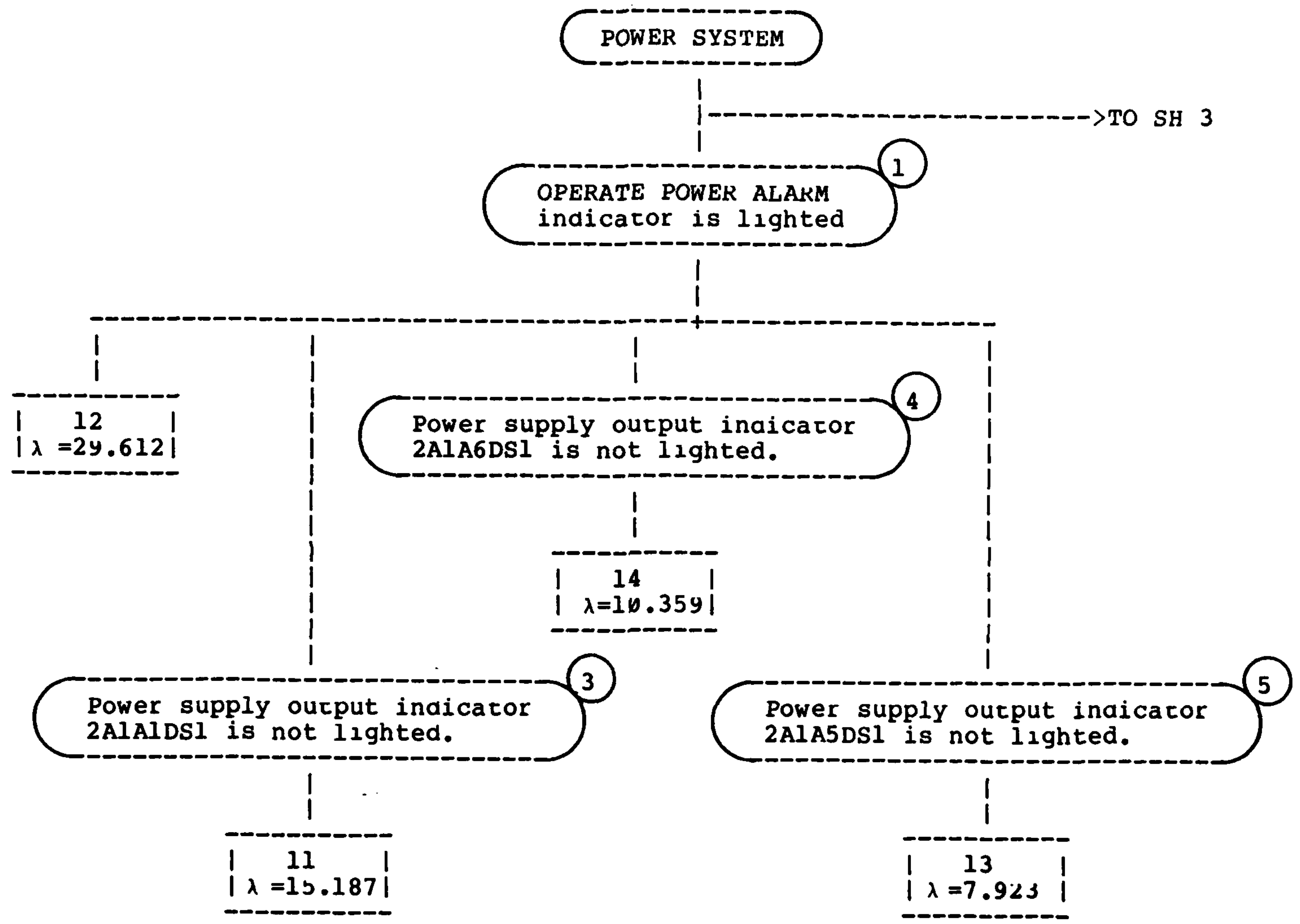

Figure 3-3. Sample Correlation Tree

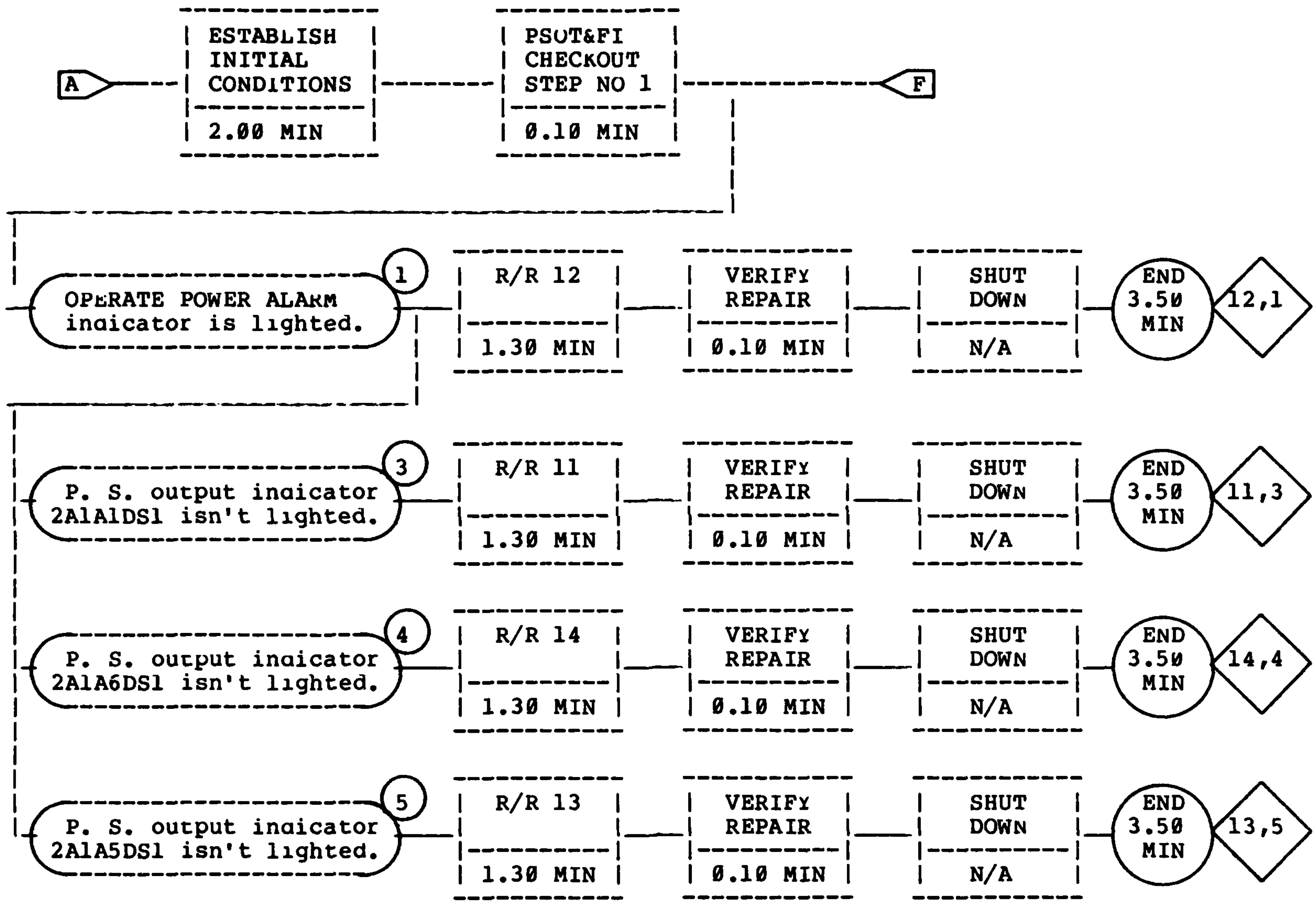

Figure 3-4. Sample Maintenance Flow Diagram

concept, the packaging concept, and the maintenance concept. These are items which are known or can be estimated in the early design phases of a system development.

3.4.2 Detailed Procedure

The Detailed Procedure requires that the following data be known: the replaceable items and their failure rates, the fault detection and isolation outputs, the effects of a failure on the system, and the maintenance concept. These items are known in the detailed design phase of the project. The replaceable items and their failure rates can be derived from the reliability prediction. The fault detection and isolation outputs and the failure effects can be obtained from the system block diagram, FMEA, BIT analysis and schematic diagrams.

3.5 Impact on Performance and Schedule

3.5.1 Performance

Operational Availability is impacted by maintenance time which must be within specifications to help achieve high Operational Availability. The prediction techniques in RADC-TR-78-169 provide a structured, logical approach to predict a system's maintenance time, which is related to the system's design.

The designer can then assess the effect of alternative designs in order to make rational trade-offs. This not only ensures that the system will meet its maintainability requirements, but will do so in an effective way.

3.5.2 Schedule

Implementing the Prediction Procedures will not adversely affect the schedule of the equipment developement. The predictions would be performed in parallel with the design effort.

3.6 Prediction Development

In parallel with the data collection and reduction procedures, preparation of Preliminary and Detailed Maintainability Predictions were carried out for each of the three representative systems chosen for use in this study. These predictions were performed in accordance with RADC-TR-78-169 "MAINTAINABILITY PREDICTION AND ANALYSIS STUDY," which is designed to update the earlier outdated maintainability prediction techniques specified in MIL-HDBK-472. Over 400 predictions at the replaceable item level were made.

4.0 FIELD DATA COLLECTION AND REDUCTION

The next five sections describe and summarize the results of the comparison made between the time synthesis predicted and the observed maintainability parameters. The general approach taken to assess the prediction model performance was to collect and summarize field repair/maintenance data on representative equipments and use statistical techniques to determine the numerical validity of the model. Supplemental methods such as the use of time and motion studies allowed further assessments to be made. The results reflect the most important considerations affecting the accuracy and usability of the Maintainability Prediction Technique. Addressing these considerations should yield a higher degree of correlation between predicted and observed maintainability estimates.

The Maintainabilty Prediction model as presented in RADC-TR-78-169 is designed to provide an estimate of the anticipated mean time to repair (MTTR) for a piece of equipment. The need for an accurate and complete model, which can be implemented easily during the design/development phase of a system, exists since manpower requirements and system availability estimates hinge on the assumed validity of the prediction technique.

The extent to which a model can be validated is a function of the quality and quantity of data available. In the case of the Maintainability Prediction Technique, two data options exist as follows:

1. Make use of data collected from in-house repair activities such as rework facilities or depot shops.

2. Make use of data collected from TFR's (Trouble Failure Replacement Reports) or engineering service reports which represent repair activities as reported on installed equipment.

Both data sources have advantages and drawbacks. The use of in-house repair data provides more control but is less representative since operator skill, motivation, and test equipment availability tend to be less variable then under field conditions. Field data, with its advantage in representing the "unstructured" maintenance environment is most desireable. After consideration of the relative merits of each data source, it was decided that field data should be employed in validating the Maintainability Prediction Technique. This is primarily because the measured maintainability parameters (mean time to repair, maximum time to repair, etc.) are most often assessed using field data, and hence the prediction should be based on the same source of data that is used to measure maintainability. In addition, manpower requirements for field service work are typically dominant to those of depot or shop level work, the latter being more centralized. Finally, it was noted that the source of data for development of the Maintainability Prediction Technique appearing in RADC-TR-78-169 was primarily shop, depot and rework facilities.

The use of field repair data was supplemented by inputs from LEC field engineers. In addition, time and motion studies were performed at LEC to assess the validity of the times specified in tables 48 & 49 of RADC-TR-78-169. The field data used consisted of the following elements only:

- preparation
- fault isolation
- spare retrieval
- disassembly
- interchange
- reassembly
- alignment
- checkout
- start up

A quantitative assessment of the Maintainability Prediction Technique at the maintenance task level is possible when supplemented by use of field engineering inputs and time and motion study assessments. As described in the following sections, these comparisons yield important insight into the validity, accuracy, and completeness of the Maintainability Prediction Technique.

As outlined in Section 2.0 of this report, three representative systems were chosen to form the weapon systems platform upon which the data collection activities were focused. The system and the level at which maintenance data is available are shown in Table 4-1. The necessary maintenance reports or summarized listings were collected on each system. These were examined to determine their format and then reduced and entered into a computerized data base to facilitate analysis and manipulation.

Careful quality control was established to ensure that each data entry was complete and unbiased. Ground rules set up to govern quality control varied from equipment to equipment, depending on the format of the input data. In the case of MTRE, for example, the input elements were manually transfered from field service reports and TFR's to data entry sheets, subject to the following conditions:

a) All records reduced must contain a valid entry for the field corrective maintenance time. What constitues a valid entry is any record whose corrective maintenance time was not omitted and not equal to 0 (zero). In addition, a valid corrective maintenance time does, by definition, exclude awaiting spares time (logistics delay time). It was a simple task to determine by reading the TFR whether or not the documented corrective maintenance time included any logistics delay time. Usually, if a repair could not be completed due to lack of adequate spares, a separate

SYSTEM/EQUIPMENT NOMENCLATURE	USING COMMAND/ SERVICE	LEVEL AT WHICH MAINTENANCE DATA IS AVAILABLE		
		ORGAN.	INTERMEDIATE	DEPOT
MK-86 Gun Fire Control System	U.S. NAVY	X		
MTRE Missle Test & Reaoiness Equip.	U.S. NAVY	X		
MADAR Malfunction Detection Anaiysis/Recording Equipment	U.S. AIR FORCE	X	X	X

Table 4-1 Weapon Systems Platform used to Validate the Maintainability Predictions

(related) TFR was prepared when spares became available. In some cases, however, the maintenance time as recorded on the TFR corresponded to an elapsed time of several days. This was unreasonable and was excluded from the data base. Therefore, an upper limit was established for the value that corrective maintenance time could assume to prevent undue bias. Ten hours was taken to be that limit based on engineering judgement. As it turned out less than 2% of the repair times exceeded ten hours. Most of these were as a result of intermittent conditions.

b) All records reduced must, in addition, result in the replacement of an item for which a maintainability prediction has been performed in accordance with the procedure documented in RADC-TR-78-169. Maintenance actions that result in the removal and replacement of connectors, fuses, and other hardware for which no predicted value of maintainability has been established, could not be considered in the analysis at the RI (replaceable item) level.

A similar set of quality control guidelines were established for the other systems in the weapon systems platform, and were used to screen data elements. Upon completion of this, the entire data base was sorted and a hard copy print was obtained for use in analysis procedures.

5.0 QUALITATIVE ASSESSMENT

Two levels of comparison were performed for both detailed and preliminary prediction methodologies as modeled in RADC-TR-78-169. The qualitative assessment analyzes and discusses the model structure, completeness, usability, and similar subjective measurements of performance. Conversely, the quantitative assessment concerns itself with the numerical aspects of the model such as accuracy and bias. Combined, these two treatments provide a full understanding into the capabilities of the Maintainability Prediction Technique.

The detailed maintainability prediction methodology rests on the validity of a time synthesis model. This model as applied to maintenance simply states that the predicted time to repair of an item can be synthesized or built up from the times necessary to perform each task which constitutes the maintenance action. These elements can then be defined in any degree of detail, ranging from very course (e.g. remove failed module) to ultra fine (move right arm to tool box, grasp tool, return arm to cabinet, etc.) More detail would normally give greater accuracy, but in the case of maintainability the process quickly becomes self-defeating and no increase in accuracy is achieved beyond a certain level of detail.

The general model of the detailed prediction is of the form:

$$(MTTR)_P = \frac{\sum_{n=1}^{N} \lambda_n R_n}{\sum_{n=1}^{N} \lambda_n}$$

16 24 BLANK

where

$(MTTR)_p$ = Prediction value of the mean time to repair

λ_n = Failure rate of the nth RI excluding any undetected failure rate.

R_n = Mean repair time of the nth RI as computed from:

$$R_n = \frac{\sum_{j=1}^{J} \lambda_{nj} R_{nj}}{\sum_{j=1}^{J} \lambda_{nj}}$$

where

J = Number of unique fault isolation results

λ_{nj} = Failure rate of the nth RI under the jth fault isolation output

R_{nj} = mean repair time o the nthRI given the jth fault isolation output has occurred. Rnj is computed from:

$$R_{nj} = \sum_{m=1}^{M_{nj}} T_{mnj}$$

where

M_{nj} = Total number of maintenance task or elements (preparation, fault isolation, etc.) required to correct a failure of the nth RI under the jth fault isolation output.

T_{mnj} = average time require to complete the mth maintenance task when a failure of the nth RI occurs under the jth fault isolation output.

This detailed maintainability prediction model defines elemental tasks and associated task times (Tmnj) for each fault isolation output resulting from the failure of a replaceable item. These elemental times are then added together to yield a total (mean) time estimate (Rnj). A second (weighted) summation over all fault isolation outputs gives the estimated mean repair time for each replaceable item. Summing over all RI's with a weighting by failure rate yields the predicted maintainability for the system. The use of weighted sums corrects for the unequal distribution of fault isolation outputs and failures among replaceable items in the system.

The Preliminary prediction model employs a slightly different approach in computing maintainability. The general equations for the preliminary model are defined as:

$$\text{MTTR} = \sum_{m=1}^{M} \bar{T}_m$$

$$= \bar{T}_P + \bar{T}_{FI} + \bar{T}_{SR} + \bar{T}_D + \bar{T}_I + \bar{T}_R + \bar{T}_A + \bar{T}_C + \bar{T}_{ST}$$

where $\bar{T}_m$ = average time to perform the mth elemental maintenance task

m = elemental maintenance task subscript

P = preparation	D = Disassemmbly	A = Alignment
FI = Fault Isolation	I = Interchange	C = Checkout
SR = Spare Retrieval	R = Reassembly	ST = Start-up

The parameter $\bar{T}m$ is then determined from one of the two following equations.

$$\bar{T}_m = \frac{\sum_{n=1}^{N} \lambda_n T_{mn}}{\sum_{n=1}^{N} \lambda_n}$$

where

N = the total number of primary RI's

λ_n = the failure rate of the nth RI

T_{mn} = the time required to perform the mth elemental task of the nth RI

$$\bar{T}_m = \frac{\sum_{v=1}^{V_m} \lambda_{mv} T_{mv}}{\sum_{v=1}^{V_m} \lambda_{mv}}$$

where

V_m = the number of unique ways of performing the mth elemental task.

λ_{mv} = the failure rate associated with the set of faults involving the vth method of performing the mth elemental task.

T_{mv} = the time required to perform the mth elemental task using the vth method.

The preliminary maintainability prediction model is based on the same general philosophy as that of the detailed technique. The average time to complete a maintenance element is synthesized from the number of unique ways of performing that task and the relative frequencies of occurrence. The total predicted MTTR is then simply the sum of the average times for each elemental task. Again, provision exists in the model structure to treat different philosophies of fault isolation and correction. (e.g. isolation to a group of RI's, single access with iterative replacement).

After examining the general model equations presented, the following summary can be made. The maintanability prediction technique as described is based on a logical and sound methodology. The model is structured so as to provide clear definition of the necessary inputs and calculations required in the computation of maintainability parameters. The definition of elemental tasks (such as preparation, fault detection, spare retrieval, etc.) allows for a complete modelling of maintenance, while enabling sufficient flexibility in application to equipment type and environment. Field maintenance is initiated based on failure symptoms. The prediction technique is structured around the identification of unique fault isolation outputs, thereby offering a high degree of usability. Provisions exist within the structure of the model to allow for treatment of any level of fault isolation from 100% manual to 100% automatic as well as adaptabilty to any maintenance philosophy (repair at the LRU, SRU, piece part level, etc.). No significant shortcomings were identified with the general model structure, format, or content.

6.0 QUANTITATIVE ASSESSMENT

In order to measure the performance of the Maintainability Prediction Technique, comparisons were made between theoretical predictions and observed field results. (A discussion of predictions and data collection activities may be found in Sections 3.0 and 4.0 of this report, respectively.) The reduced data for each system were plotted in histogram form to visually inspect for data quality and to assess the underlying distribution. The mathematical formulation of maintainability (see Appendix C) traditionally recognizes three common distributional forms. Most frequently, the distribution of maintenance time for complex systems is taken to be lognormal based on experience.

Figure 6-1 plots the maintenance time distribution for the Missile Test Readiness Equipment (MTRE). The fact that the distribution is very much skewed right (i.e. many observations clustered at small values of maintenance time) suggests lognormality. The fact that only positive maintenance times exist, and zero maintenance times are prohibited (by definition) is further reason to suspect that the underlying probability density function will be lognormal.

This hypothesis may be verified in several ways. One of the simplest of these is to make use of a transformation of variables. That is, if a random variable x is lognormally distributed, then the variable y = log x will follow a normal distribution. Therefore, the distribution of the logarithms of the corrective maintenance times (log Mct) should yield a normal distribution if the maintenance times (Mct) are lognormally distributed. Figure 6-2 shows the observed distribution of the quantity log Mct for the data shown in the previous figure and found in Appendix D. The class interval size has been increased to smooth out the fluctuations in observed frequency. It is easily seen that the skewness of the prior distribution has been removed by using the log transformation. The chi-squared test concludes no significant departure from normality.

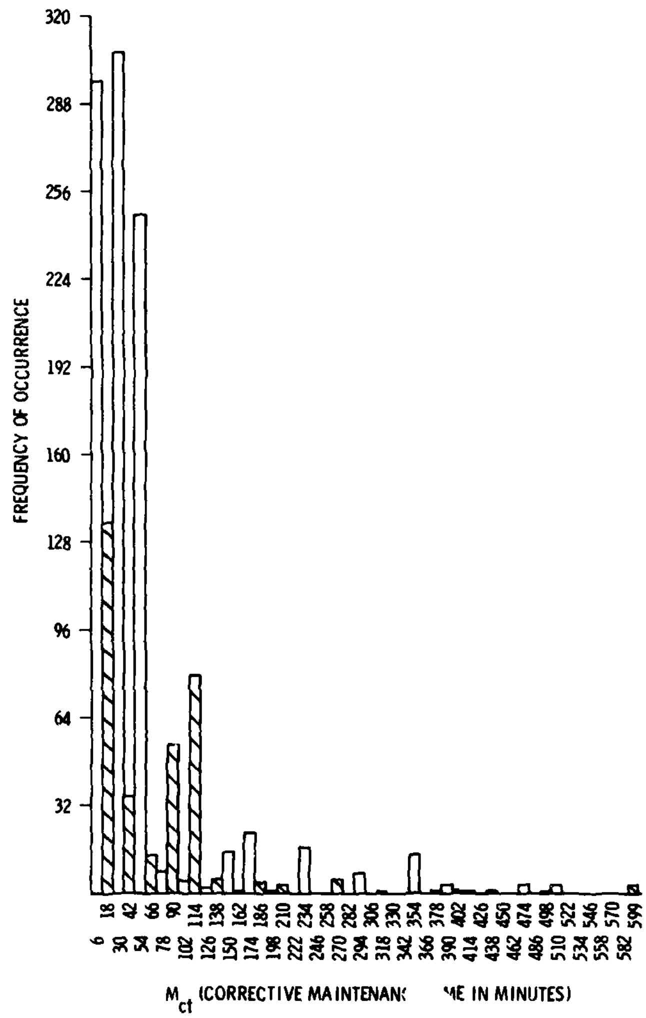

Figure 6-1. Distribution of Corrective Maintenance Times For MTRE System Data

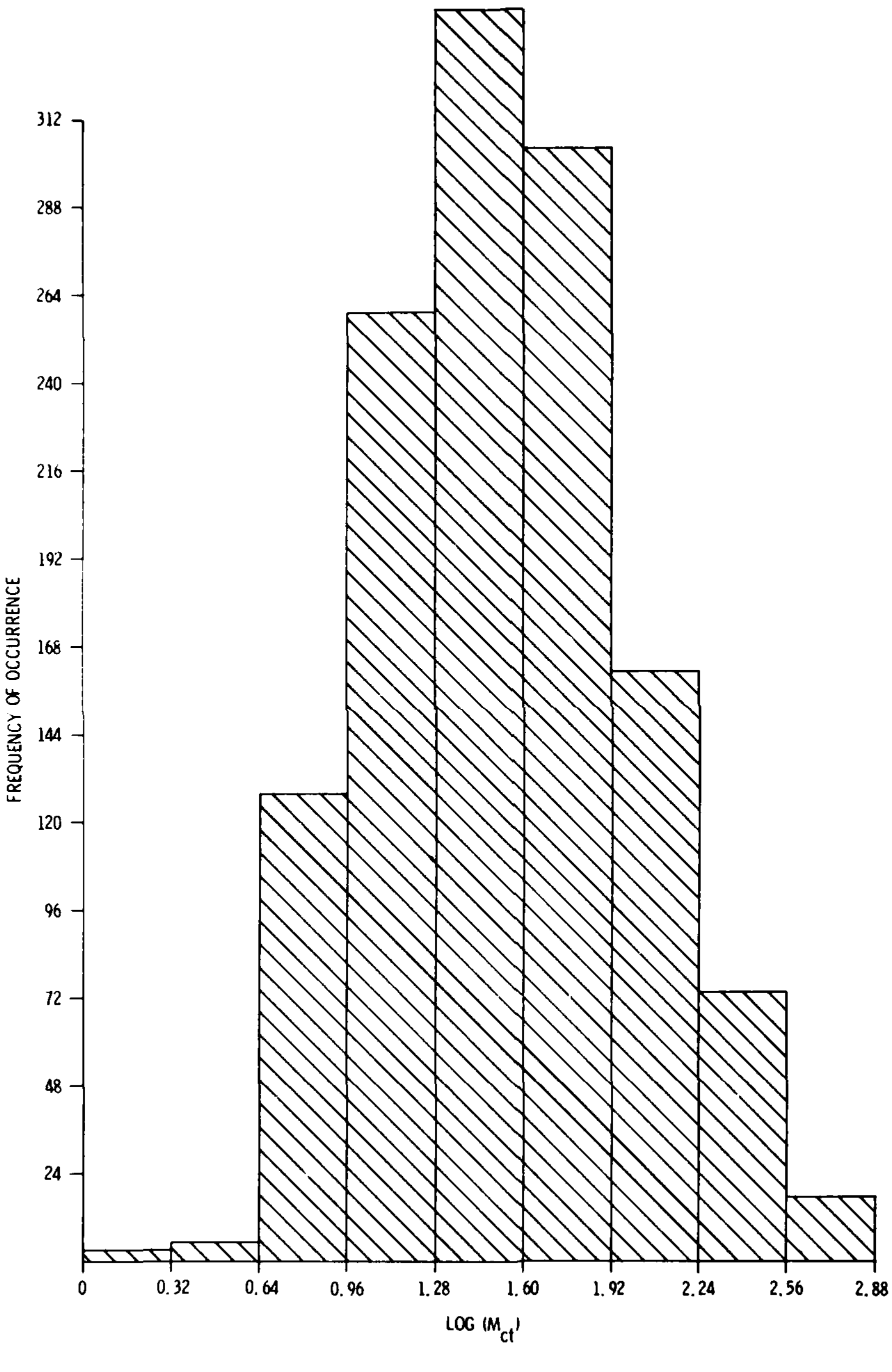

Figure 6-2. Distribution of the Parameter Log M_{ct} For MTRE System Data

After determination of the governing distribution an effort was made to assess the numerical performance of the maintainability prediction model. The lowest level at which this could be undertaken was the replaceable item level. Table 6-1 presents the results of a typical set of replaceable items with the performance characteristics summarized. The mean and median of the distribution of repair times observed for each RI are shown along with the difference between the observed and predicted maintenance times. Due to the unsymmetrical nature of the lognormal distribution, the mean has a tendency to be unduly influenced by large, infrequently occurring values of maintenance time. Therefore, the median is more representative of the time required to complete a typical maintenance action. As the data in Table 6-1 indicate, the range of differences between the median and predicted maintenance times is 6.64 - 53.59 minutes. The average difference is 23.09 minutes. This is consistent with the data for the system level. The median of the distribution of maintenance times at the system level turns out to be equivalent to the mean of the distribution of log Mct. Hence the median is found to be

$$= \text{antilog}\ (\overline{\text{Log Mct}})$$

$$= \text{antilog}\ (1.55) = 35.5\ \text{min.}$$

The predicted MTTR at the system level is 7.43 minutes, giving a difference of 28.07 minutes. This agrees reasonably well with the data for the RI level, and shows that the detailed prediction as performed accounts for approximately 21% of the observed mean corrective maintenance time.

The direction of bias can easily be seen from the data of Table 6-2. This table presents the same replaceable items as found in Table 6-1. and for each, shows the percentage of the field observations which fall below and above predicted mean time to repair. For an unbiased

TABLE 6-1
Maintainability
Characteristics for Typical Replaceable Items

REPLACEABLE ITEM REFERENCE DESIGNATOR	MEAN TIME TO REPAIR (PREDICTED)	MEAN TIME TO REPAIR (OBSERVED)	MEDIAN TIME TO REPAIR (OBSERVED)	(Mct) - (MTTR)p	($\tilde{M}$ct) - (MTTR)p
1A1A14	19.51	87.01	60	67.50	40.49
1A1A15	23.56	79.28	60	55.72	36.44
1A1A16	25.36	72.23	60	46.87	34.64
1A1A17	24.76	95.14	60	70.38	35.24
1A2A3	4.20	45.58	30	41.38	25.80
1A3A1	4.10	53.27	30	49.17	25.90
2A1A1	4.93	22.78	12	17.85	7.07
2A1A5	6.79	98.40	30	91.61	23.21
2A1A6	4.85	39.90	18	35.05	13.15
2A2A1	8.50	53.22	30	49.72	21.50
2A2A3	7.38	58.18	27	50.80	19.62
2A2A4	7.62	34.12	15	26.59	7.38
2A2A6	6.25	38.63	24	32.38	17.75
2A3A10	3.51	43.40	30	39.89	26.49
2A3A11	5.36	36.69	30	31.33	24.64
2A3A12	5.36	28.88	29	23.52	23.64
2A3A14	5.36	37.72	22	32.36	16.64
2A3A16	4.56	42.90	25	38.34	20.44
2A3A17	4.88	52.38	30	47.50	25.12
2A3A18	7.14	56.20	60	49.06	52.86
2A3A22	6.14	116.0	60	109.59	53.59
2A3A3	5.36	29.88	13.5	24.52	8.14
2A2A4	5.36	34.87	30	29.51	24.64
2A3A6	5.36	36.82	12	31.46	6.64
2A3A8	7.88	31.72	18	23.84	10.12
2A3A9	5.96	49.28	15	43.22	9.04
2A4A1	5.50	58.03	30	52.53	24.50
2A4A6	6.20	28.92	18	22.72	11.80

TABLE 6-2

Distribution Percentage of Observed Corrective Maintenance Time for Typical Replaceable Items

REPLACEABLE ITEM REFFERENCE DESIGNATOR	MEAN TIME TO REPAIR (PREDICTED)	PERCENTAGE OF DISTRIBUTION < (MTTR)p	> (MTTR)p	DIRECTION OF BIAS PESSIM.	OPTOM.
1A1A14 (101)	19.51	3.96	96.04		X
1A1A15 (80)	23.56	3.75	96.25		X
1A1A16 (75)	25.36	66.67	33.33	X	
1A1A17 (81)	24.76	3.70	96.30		X
1A2A3 (24)	4.20	0	100		X
1A3A1 (48)	4.10	0	100		X
2A1A1 (23)	4.93	4.35	95.65		X
2A1A5 (20)	6.79	15.00	85.00		X
2A1A6 (10)	4.85	10.00	90.00		X
2A2A1 (45)	8.50	13.33	86.67		X
2A2A3 (44)	7.38	18.18	81.82		X
2A2A4 (38)	7.62	23.68	76.32		X
2A2A6 (62)	6.25	14.52	85.48		X
2A3A10 (35)	3.51	0	100		X
2A3A11 (35)	5.36	0	100		X
2A3A12 (49)	5.36	4.08	95.92		X
2A3A14 (46)	5.36	2.17	97.83		X
2A3A16 (63)	4.56	0	100		X
2A3A17 (16)	4.88	6.25	93.75		X
2A3A18 (10)	7.14	O	100		X
2A3A22 (12)	6.41	8.33	91.67		X
2A3A3 (32)	5.36	3.13	96.87		X
2A3A4 (31)	5.36	0	100		X
2A3A6 (38)	5.36	5.26	94.74		X
2A3A8 (29)	7.88	18.52	81.48		X
2A3A9 (39)	5.96	7.96	92.31		X
2A421 (33)	5.50	0	100		X
2A4A6 (13)	6.20	7.69	92.31		X

model, one would expect on the average to have the distribution of data points above and below the predicted value to be approximately equal. If bias cannot be entirely eliminated from a model, then a shift towards conservatism is usually preferable to a shift towards optimism. The field data shown here indicates a consistant and significant bias towards optimism in predictions. This trend is further reflected in this data at the system level, where 9.63% of the field observations fall below the predicted MTTR, leaving 90.37% above the predicted value.

The existence of an optimistic bias in both the preliminary and the detailed prediction models is supported by data from all equipments sampled in this study. A summary of these results at the system level is shown in Table 6-3. For the detailed procedure, the difference between observed and predicted MTTR ranges from 50.69 - 257.51 minutes. In terms of a ratio of (MTTR)o to (MTTR)p, the data shows values of 4.7 - 11.6. The preliminary prediction difference gives a range of 31.64 - 257.51 minutes.

In summary, the available field maintenance data shows a large discrepancy between observed and predicted MTTR. The case of similar discrepancies in previous prediction methodologies, (such as in the existing MIL-HDBK-472) has been attributed to a variety of factors such as spares retrieval, level of technician skills, availability of test equipment, and environmental conditions. These factors and others influence maintainability and lead to the lack of correlation of predicted and observed MTTR. The variations in these influences affects prediction accuracy. Therefore in view of variability in these factors, the only recommended changes based on available field maintenance data would be to add specific times for:

- Preparation
- Spare retrieval

SYSTEM	PREDICTED MTTR (MTTR)p		OBSERVED DATA (MTTR)o		(MTTR)o-(MTTR)p	
	DETAILED PROCEDURE (MINUTES)	PRELIMINARY PROCEDURE (MINUTES)	MTTR (MINUTES)	NUMBER OF RECORDS	DETAILED PROCEDURE (MINUTES)	PRELIMINARY PROCEDURE (MINUTES)
MK-86	23.40	20.68	110.91	640	87.51	90.23
MTRE	9.19	28.24	59.88	1298	50.69	31.64
MADAR	24.25	24.25	150.60	4577	126.35	126.35

TABLE 6-3.

Summary of Maintenance Field Data Comparisons
for Representative Study Systems

These tasks are clearly part of a maintenance action, and although they are addressed in the general maintainability model, no times are listed to be used as typical estimates. Even though variability exists in the times required to perform the tasks, some constant time estimates should be added as a first approximation in order to allow for a complete modeling of maintainability.

The data given in Table 6-4 shows the effect of modifying the maintainability prediction on the correlation with observed field data. The modified prediction now takes into account the time required for Preparation and Spare Retrieval activities, and makes use of revised time standards for remove and replace tasks. (See Sections 7 and 8 for further details on these modifications.) The result of these modifications is a noticeable improvement in the agreement of predicted MTTR with field data.

Fault Isolation, when performed manually, is a particularly variable aspect of MTTR because it is dependent on factors that are not easily defined or measured. Manual fault isolation is heavily impacted by quality and availability of operating manuals, training and skill levels of technicians, test equipment availability, and system complexity. However, new technologies allow for improvements in BIT and self test/diagnosis capabilities that make fault isolation instantaneous nearly 100% of the time.

SYSTEM	PREDICTED MTTR (MTTR)p		OBSERVED DATA (MTTR)o		(MTTR)o-(MTTR)p	
	DETAILED PROCEDURE (MINUTES)	PRELIMINARY PROCEDURE (MINUTES)	MTTR (MINUTES)	NUMBER OF RECORDS	DETAILED PROCEDURE (MINUTES)	PRELIMINARY PROCEDURE (MINUTES)
MK-86	81.80	76.36	110.91	640	29.11	34.55
MTRE	53.38	91.48	59.88	1298	6.50	-31.60
MADAR	83.50	83.50	150.60	4577	67.10	67.10

TABLE 6-4.

Maintenance Field Data Comparisons
Using Modified Predictions

7.0 USE OF FIELD ENGINEERING INPUTS

In order to further validate the Maintainability Prediction techniques formulated in RADC-TR-78-169, Lockheed Electronics Company supplemented the field data base with additional inputs from LEC field service engineers. The extensive experience of field service representatives was used to establish representative times for the maintenance tasks of preparation, and spare retrieval. The following summarizes the inputs from the field engineers.

TASK	TYPICAL ESTIMATE	RANGE
Preparation	5 minutes	1-7 minutes
Spare Retrieval	30 minutes	10-45 minutes

Adding the above time estimates to the predictions performed in this study results in an average of approximately 35 percent improvement in accuracy.

Additional inputs from LEC field engineers identified fault isolation time as a major factor affecting maintainability. Fault isolation time is difficult to estimate since it is largely a function of technician skill, operating manual quality, the availability of test equipment, and the level of system BIT.

8.0 TIME AND MOTION STUDIES

Since the nature of the existing field data did not allow direct comparison of elemental task times (such as inserting an IC into a socket), a separate effort was undertaken to generate data for use in verification of the elemental task times reported in RADC-TR-78-169, Tables 48 and 49, (see Appendix E). Time and motion studies similar to those used to generate the prediction techniques, were carried out in house to simulate a variety of maintenance tasks. Studies were made at room ambient, and bench top conditions. Technician level personnel were used in the study. The study was performed under two conditions;

A) repetitive conditions - these time studies consisted of performing a specified task frequently to assess the increase in maintenance proficiency associated with repetitive maintenance actions.

B) single occurance conditions - these time studies consisted of performing a specified task once, followed by a sequence of different tasks, each performed only once, as will be seen in a typical field maintenance environment.

Table 8-1 presents a summary of some sample elemental tasks chosen from the data found in Appendix F. The task description is given along with the time standard found in Table 48 of RADC-TR-78-169. Next, the average time observed for each task in Condition A and Condition B is presented, based on the data obtained during the time and motion studies. The results of these time studies indicated that the task times reported in RADC-TR-78-169, Table 48 tends to correlate well with condition A. In terms of the ratio between observed values and corresponding Table 48 values for the same task, a range of 0.9-1.2 was observed for repetitive conditions. The nominal value of 1.1 indicates that the task times listed in Table 48

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tend to be indicative of conditions resulting from repetitive performance of the task. Such conditions are not the norm for the maintenance environment associated with military systems. In addition, the fact that field maintenance is performed under conditions other than room ambient and bench top conditions tends to support longer times than those of Table 48 in RADC-TR-78-169 for non-repetitive tasks. The results of condition B studies indicated an observed range for single occurance tasks to be from 1.8-2.4 times the values of Table 48. The difference on the average was close to 2.0, which suggests that the task times should be doubled to more accurately reflect the maintenance environment for non-repetitive tasks. These times will further be impacted by temperature conditions and performance of maintenance tasks at other than bench top conditions such as above deck maintenance, etc.

The use of this modification to the time standards presented in Table 48 of RADC-TR-78-169 results in an average of approximately 15% improvement in accuracy based on the predictions performed in this study. The improvement for each study system can be seen by comparing the data found in Table 6-3 with that of Table 6-4.

TIME STANDARD NUMBER	DESCRIPTION	RADC-TR-78-169 (MINUTES)	AVERAGE TIMES DERIVED FROM TIME AND MOTION STUDY: CONDITION A (MINUTES)	CONDITION B (MINUTES)
1	Standard Screws	0.42	0.40	0.81
3	Captive Screws	0.35	0.40	0.63
10	Drawhook Latch	0.06	0.08	0.13
12	Butterfly Latch	0.10	0.13	0.22
17	Screw Terminal	0.68	0.61	1.40
25	BNC (single pin) Connector	0.17	0.19	0.38
29	Friction Locking	0.38	0.41	0.71
37	Module	0.20	0.21	0.40
55	Drawer (large)	0.19	0.19	0.45

Table 8-1 Summary of Standard Times from Table 48 of RADC-TR-78-169 and Observed Interchange Times

9.0 MAINTAINABILITY TRENDS

In addition to the maintainability prediction techniques developed in RADC-TR-78-169, a number of other considerations regarding maintainability require commentary. Maintainability predictions should accurately reflect demonstrated maintainability in the field. The accuracy of these predictions is necessary for purposes of man-power planning and estimating the impact of maintainability on Operational Availability.

New technology trends require additional considerations regarding maintainability concepts and requirements. Technology developments such as embedded microcomputer systems, distributed computer networks and VHSIC (Very High Speed Integrated Circuits) provide the means of substantially improving maintainability.

It has long been recognized that operator dependent fault detection and fault isolation drive maintainability time. Built-In-Test (BIT) must be designed and specified to acheive systems where fault detection and isolation are virtually instantaneous, accurate, and not dependent on operator skill levels.

9.1 Additional Maintainability Prediction Factors

In addition to the traditional elements that comprise MTTR, consideration should be given to other factors that in fact get counted as MTTR in field data and impact the total amount of time required to perform corrective maintenance. These factors are preparation and spare retrieval. Both range and median values for these factors should be developed for a variety of environments in order to get a more accurate prediction of maintenance time.

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9.2 Microcomputer (uC) Self Test/Diagnosis

Maintainability of future military systems must address embedded uC system self-test/diagnosis capabilities and requirements. Standards of self-test/diagnosis and the hardware/software that must be built into a uC system for purposes of self-test/diagnosis have to be established. General concepts and considerations relating to this problem are discussed. Each system would have the additional hardware/software that is required to service the system, diagnose its problems, fault detect, fault isolate to the replaceable module level, indicate test results, and indicate go/no-go condition. Typically, this self test/diagnosis capability can be accomplished with approximately 4-5K bytes of addition ROM.

Several considerations should be taken into account in designing the hardware for optimum maintainability. In a multi-card system, it is advantageous to have the self-test/diagnosis hardware on one card. Typically these components include the CPU, buffer, clock, ROM (self-test) and RAM (self-test). By isolating self test/diagnosis hardware to the one "self-test" card, the user is assured that self test/diagnosis is disabled only if that one card fails. If no diagnostic data is received at all, the fault can be isolated to the one "self-test" card. For example, in a ten card system with equal reliability, the "self test" capability will account for only one of 10 failures.

Software tests would be devised for a self-test/diagnosis capability. Software tests would in sequence test the following elements of the uC system:

CPU
ROM
RAM
I/O PERIPHERAL DEVICES

The following are tests that would have to be developed in order to check a uC System:

CPU software test module:

- Address and data register tests
- ALU flag tests
- Arithemtic routine tests
- Decrement and branch sequence tests
- BIT set, clear tests

ROM software test module:

- Checksum test
- Address decoding verification test
- ROM identification test

RAM software test module:

- Data Lines Test
- Address Verification Test
- Cycle Time/Refresh Test

I/O software test module:

- Serial I/O Test
- Parallel I/O Test

Criteria for self test/diagnosis requirements must be developed. Standard software modules for self test/diagnosis for MIL-SPEC microprocessors are required. uC self test/diagnosis is an entire subject unto itself that needs to be formally studied and incorporated into maintainability standards, in that future equipments will be uC based.

9.3 Fault Tolerant uC Based Systems

Maintainability of uC based systems should address the subject of fault tolerance. With today's very large scale integeration (VLSI) technology, adding less than a complete parallel path with 100% redundant hardware can result in higher reliability than multiple parallel systems. Concepts and standards regarding fault tolerance methodology should be developed as an integral part of maintainability. The incorporation of fault tolerance capability into a uC based system can have a favorable impact on life cycle cost. In addition to the vastly improved reliability, additional benefits of a Life Cycle Cost nature such as reduced maintenance, logistics spares, training, etc. can be realized. Concepts are discussed as possible approaches that can be made to establish standards for fault tolerant design.

Where mission criticality dictates, fault tolerance is essential. Systems requiring very high reliability may use the concept of majority voting redundancy. This type of redundancy guarantees valid operation so long as only a single hardware module failure occurs. In the majority voting redundancy scheme, outputs are compared simultaneously. If there is disagreement, the one defective hardware module is "outvoted" by the two majority hardware modules. The defective hardware module is then isolated from the system. The majority voting redundancy method would be used where a fault is to be masked from the system and the user. Figure 9-1 is a block diagram of a majority voting redundancy scheme.

Simpler fault tolerant techniques can be employed in systems where the fault need not be masked from the user and system and where the mission permits the switching in of a spare in the event of a fault either by operator control or automatically. A scheme of dynamic redundancy can be incorporated into a uC system without major increases in cost or weight. Techniques such as cross-strapping of two power supplies and two microcomputers in which one power supply and one microcomputer failure can be tolerated provides a means of substantially improving the reliability and maintainability of a system versus the use of two single line parallel systems. Figure 9-2 shows the block diagrams for the two single line parallel system and the cross-strapping system.

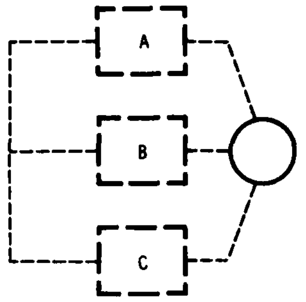

Figure 9-1. Majority Voting Redundancy Block Diagram

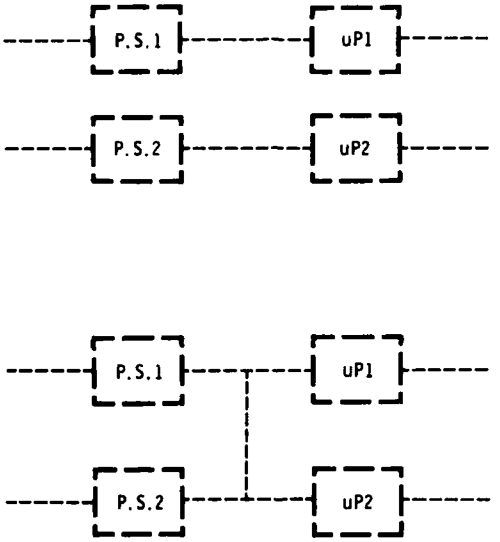

Figure 9-2. Cross-Strapping Block Diagram

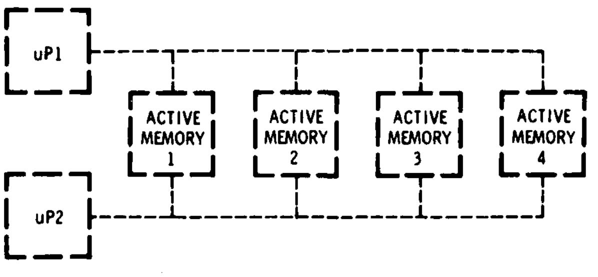

Figure 9-3. Fault Tolerant Block Diagram

Memory devices contribute heavily to the failure rate of uC systems. Memory portion of a uC system can be divided up and spared in a manner where a fault in one block will not cause other memory blocks to be inoperative. The faulty memory block can be detected and isolated from the uC system and replaced with a spare automatically. This fault tolerant technique is illustrated in Figure 9-3.

This form of redundancy is more efficient in the use of hardware and provides an improved MTBF over two single parallel strings. Use of error checking/correcting techniques and components substantially enhances the fault tolerant capabilities of memory devices. Standards for various techniques of error checking/correction such as byte parity, check sum, Hamming code, etc. need to be established to enhance system reliability and maintainability.

9.4 Built-In-Test (BIT)

In order to meet more demanding performance requirements electronic equipments are becoming more complex. BIT improves maintainability and availability, and reduces the demands on operator training and skill levels.

BIT has two functions; fault detection and fault isolation. End-to-end tests are used to determine if a system is capable of performing its mission. In the end-to-end test the BIT applies stimuli to the input of the system. Outputs are then compared with expected values, and a determination is made as to whether or not the system is functioning properly. If a fault is detected, then tests are made on the system's functional blocks in order to isolate the cause of the malfunction. Testing of the functional blocks is also performed to detect marginal operation which has not shown up at the system level.

The usefulness of BIT can be adversely affected by a high false alarm rate, resulting in a large number of unnecessary maintenance actions and a lack of confidence on the part of maintenance personnel in the BIT indications.

To preclude false alarms, a retry technique should be employed. That is, when BIT senses a fault in a signal path, it should test that same path two more times and only then declare a fault if all three tests fail.

BIT testing should not interfere with the normal operation of the system. If on-line testing is used, it should be done during system idle time. Also, the BIT stimuli put into the system should be structured so that it cannot cause erroneous commands that could be detrimental. The BIT hardware should be isolated from the rest of the system so that a failure in the BIT will not cause the system to malfunction.

Standards for fault detection and fault isolation need to be established for BIT. These standards should be expressed as a percentage of equipment fault that can be detected and a percentage of faults that can be isolated to a single replaceable item or to multiple replaceable items.

10.0 CONCLUSIONS

Based on the study performed, the following conclusions can be drawn regarding the Maintainability Prediction Techniques found in RADC-TR-78-169:

1) Remove and replace times listed in Tables 48 & 49 are optimistic when applied to field maintenance.

2) Time standards for preparation and spare retrieval should be incorporated to more accurately predict maintenance time.

3) Maintainability Prediction Procedures are capable of predicting maintainability of electronic equipment based on system design characteristics.

4) Data required to implement prediction procedure is available during system development process.

5) Performing the prediction procedure does not affect system development scheduling.

6) Both the Preliminary and Detailed Prediction Procedures are able to point out areas in the maintainability design of a system that can be improved to meet maintainability specifications.

7) The prediction procedures are especially applicable to the Organizational level of maintenance. The prediction procedures are somewhat less applicable to the Intermediate and Depot level of maintenance from a maintenance design viewpoint.

11.0 RECOMMENDATIONS

The following recommendations are being offered to improve the accuracy and practicality of the Preliminary and Detailed Maintainability Prediction and Analysis Techniques presented in RADC-TR-78-169:

1) Double the remove and replace times listed in Tables 48 & 49 of RADC-TR-78-169.

2) Add the following range and mean time values for preparation and spare retrieval:

	RANGE	MEAN	
Preparation	1-7	5	minutes
Spare Retrieval	10-45	30	minutes

3) Develop an interactive computer program for the maintainability prediction procedures. Use PASCAL programming language. Update to Ada at some later time.

4) Develop additional standards for maintainability relating to new technology developments. Develop standards for:

   - BIT
   - Fault Tolerant uC base systems
   - Self-Test/Diagnosis capabilities for uC based systems
   - Criteria for error detection and correction

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APPENDIX A

SAMPLE PRELIMINARY PREDICTION

PRELIMINARY MAINTAINABILITY PREDICTION

FOR

MTRE

AT THE

ORGANIZATIONAL LEVEL

MTRE
REPLACEABLE ITEMS

N	NAME	REF DES	PART NUMBER	FR (F/10^6 HRS)
1	Voltage Divider	1A1A14	2401068	6.918
2	Voltage Divider	1A1A15	2401069	6.583
3	Voltage Divider	1A1A16	2401070	6.583
4	Voltage Divider	1A1A17	2401071	5.704
5	Mode SW Logic	1A2A1	1897012	11.506
6	Mode SW Logic	1A2A2	1897012	11.506
7	Comparator Load	1A2A3	2400830	0.749
8	TRACER Pwr Sup	1A3A1	1897015	30.440
9	TRACER Logic No. 1	1A3A3	2400711	31.833
10	TRACER Logic No. 2	1A3A4	1897039	31.243
11	Missile Pwr Sup	2A1A1	1897019	45.562
12	Power Control Logic	2A1A3	1897020	59.223
13	Indexing Pwr Sup	2A1A5	1897021	23.077
14	Index Com Pwr Sup	2A1A6	2716281	31.078
15	Comparator	2A2A1	2372254	52.701
16	C3 Denote No.1	2A2A2	2400693-1	7.172
17	Comparator	2A2A3	2372254	52.701
18	Comparator	2A2A4	2372254	52.701
19	C3 Denote No. 2	2A2A5	2400700-1	3.985
20	Denote Logic	2A2A6	2729061	28.782
21	C3 Prepare No. 1	2A3A1	2400657-1	7.172
22	C3 Prepare No. 5	2A3A2	2400682-1	3.187

N	NAME	REF DES	PART NUMBER	FR (F/10^6 HRS)
23	Comparator	2A3A3	2372254	52.701
24	Comparator	2A3A4	2372254	52.701
25	C3 Prepare No. 2	2A3A5	2400664-1	6.374
26	Comparator	2A3A6	2372254	52.701
27	C3 Prepare No. 3	2A3A7	2400670-1	6.374
28	Comparator	2A3A8	2372254	52.701
29	Comparator	2A3A9	2372254	52.701
30	Comparator	2A3A10	2372254	52.701
31	Comparator	2A3A11	2372254	52.701
32	Comparator	2A3A12	2372254	52.701
33	Comparator	2A3A14	2372254	52.701
34	Prepare Status	2A3A15	2400721	46.428
35	Sequencer Clock	2A3A16	2400634	34.468
36	Return to Ready	2A3A17	2400626	50.576
37	NO-GO Hold	2A3A18	2400622	66.582
38	Prepare Override	2A3A19	2716280	54.525
39	Power Transfer	2A3A20	1897030	59.399
40	C3 Prepare No. 4	2A3A21	2400676-1	6.374
41	Prepare Logic No. 2	2A3A22	2716279	66.931
42	Prepare Logic No. 1	2A3A23	2716278	64.610
43	Input-Output	2A4A1	2331915	47.765
44	Binary 4 Count	2A4A2	1897044-1	16.417
45	Binary 4 Count	2A4A3	1897044-1	16.417
46	Binary Logic No. 1	2A4A4	1897045	44.617

N	NAME	REF DES	PART NUMBER	FR ($F/10^6$ HRS)
47	Binary Logic No.2	2A4A5	1897046	59.022
48	4 Step Count	2A4A6	1897047	16.613
49	4 Step Count	2A4A7	1897047	16.613
50	4 Step Count	2A4A8	1897047	16.613
51	4 Step Count	2A4A9	1897047	16.613
52	Mode Switch	1A2	2401291	64.016

PRELIMINARY PREDICTION SHEET - A

RI (N)	FR ($F/10^6$ HR)	FAULT ISOLATION FR(FI1N) ($F/10^6$ HR)	DISASSEMBLY/ REASSEMBLY FR(D/R1N) ($F/10^6$ HR)	INTERCHANGE FR(I1N) ($F/10^6$ HR)	INTERCHANGE FR(I2N) ($F/10^6$ HR)	INTERCHANGE FR(I3N) ($F/10^6$ HR)	CHECKOUT FR(C1N) ($F/10^6$ HR)
1	6.918	6.918	6.918	-	6.918	-	6.918
2	6.583	6.583	6.583	-	6.583	-	6.583
3	6.583	6.583	6.583	-	6.583	-	6.583
4	5.704	5.704	5.704	-	5.704	-	5.704
5	11.506	11.506	11.506	11.506	-	-	11.506
6	11.506	11.506	11.506	11.506	-	-	11.506
7	0.749	0.749	0.749	0.749	-	-	0.749
8	30.440	30.440	30.440	30.440	-	-	30.440
9	31.833	31.833	31.833	31.833	-	-	31.833
10	31.243	31.243	31.243	31.243	-	-	31.243
11	45.562	45.562	45.562	45.562	-	-	45.562
12	59.223	59.223	59.223	59.223	-	-	59.223
13	23.077	23.077	23.077	23.077	-	-	23.077
14	31.078	31.078	31.078	31.078	-	-	31.078
15	52.701	52.701	52.701	52.701	-	-	52.701
16	7.172	7.172	7.172	7.172	-	-	7.172
17	52.701	52.701	52.701	52.701	-	-	52.701

RI	FR	FAULT ISOLATION FR(FI1N)	DISASSEMBLY/ REASSEMBLY FR(D/R1N)	INTERCHANGE FR(I1N)	FR(I2N)	FR(I3N)	CHECKOUT FR(C1N)
(N)	(F/10^6 HR)	(F/10^6 HR)	(F/10^6 HR)	(F/10^6 HR)	(F/10^6 HR)	(F/10^6 HR)	(F/10^6 HR)
18	52.701	52.701	52.701	52.701	-	-	52.701
19	3.985	3.985	3.985	3.985	-	-	3.985
20	28.782	28.782	28.782	28.782	-	-	28.782
21	7.172	7.172	7.172	7.172	-	-	7.172
22	3.187	3.187	3.187	3.187	-	-	3.187
23	52.701	52.701	52.701	52.701	-	-	52.701
24	52.701	52.701	52.701	52.701	-	-	52.701
25	6.374	6.374	6.374	6.374	-	-	6.374
26	52.701	52.701	52.701	52.701	-	-	52.701
27	6.374	6.374	6.374	6.374	-	-	6.374
28	52.701	52.701	52.701	52.701	-	-	52.701
29	52.701	52.70'	52.701	52.701	-	-	52.701
30	52.701	52.701	52.701	52.701	-	-	52.701
31	52.701	52.701	52.701	52.701	-	-	52.701
32	52.701	52.701	52.701	52.701	-	-	52.701
33	52.701	52.701	52.701	52.701	-	-	52.701
34	46.428	46.428	46.428	46.428	-	-	46.428
35	34.468	34.468	34.468	34.468	-	-	34.468

RI (N)	FR ($F/10^6$ HR)	FAULT ISOLATION FR(FI1N) ($F/10^6$ HR)	DISASSEMBLY/ REASSEMBLY FR(D/R1N) ($F/10^6$ HR)	INTERCHANGE FR(I1N) ($F/10^6$ HR)	INTERCHANGE FR(I2N) ($F/10^6$ HR)	INTERCHANGE FR(I3N) ($F/10^6$ HR)	CHECKOUT FR(C1N) ($F/10^6$ HR)
36	50.576	50.576	50.576	50.576	-	-	50.576
37	66.582	66.582	66.582	66.582	-	-	66.582
38	54.525	54.525	54.525	54.525	-	-	54.525
39	59.399	59.399	59.399	59.399	-	-	59.399
40	6.374	6.374	6.374	6.374	-	-	6.374
41	66.931	66.931	66.931	66.931	-	-	66.931
42	64.610	64.610	64.610	64.610	-	-	64.610
43	47.765	47.765	47.765	47.765	-	-	47.765
44	16.417	16.417	16.417	16.417	-	-	16.417
45	16.417	16.417	16.417	16.417	-	-	16.417
46	44.617	44.617	44.617	44.617	-	-	44.617
47	59.022	59.022	59.022	59.022	-	-	59.022
48	16.613	16.613	16.613	16.613	-	-	16.613
49	16.613	16.613	16.613	16.613	-	-	16.613
50	16.613	16.613	16.613	16.613	-	-	16.613
51	16.613	16.613	16.613	16.613	-	-	16.613
52	64.016	64.016	64.016	64.016	-	64.016	64.016
TOTALS	1762.062	1762.062	1762.062	1736.274	25.788	64.016	1762.062

RI DATA ANALYSIS SHEET-B

MTTR ELEMENT (m)	TYPE (v)	DESCRIPTION	Tmv (min)	mv (F/10^6)
Preparation	1	N/A	-	-
Fault Isolation	1	Off-line Diagnostics and Operator Interpretation	24.00	3492.94
Spare Retrieval	1	N/A	-	-
Disassembly/ Reassembly	1	Unlatch Upper and Lower Door Latches, and Open Outer Door, Reverse Process	0.27	3492.94
Interchange	1	R/R Type III Module	1.03	3403.14
	2	R/R Voltage Divider	11.84	25.79
	3	R/R Mode Switch	31.06	64.02
Alignment	1	None	-	-
Checkout	1	Run Diagnostic	0.30	3492.94

COMPUTATION OF MTTR

$$MTTR = \overline{T}_{FI} + \overline{T}_{FC} + \overline{T}_{C}$$

$$MTTR = 24.00 + 3.67 + 0.57$$

$$MTTR = 28.24 \text{ min.}$$

$$\overline{T}_{FC} = \overline{S}_I \left(\overline{T}_{D/R} + \overline{T}_I \right)$$

$$\overline{S}_I = \frac{50\left(\frac{1+1}{2}\right) + (70-50)\left(\frac{1+2+1}{2}\right) + (95-70)\left(\frac{2+3+1}{2}\right) + (100-95)\left(\frac{3+6+1}{2}\right)}{100}$$

$$\overline{S}_I = 1.9$$

$$\overline{T}_{D/R} = \frac{\sum_{v=1}^{1} \lambda_{D/Rv} \, T_{D/Rv}}{\lambda_T}$$

$$\overline{T}_{D/R} = \frac{3492.94 \times 0.27}{3492.94}$$

$$\overline{T}_{D/R} = 0.27 \text{ min.}$$

$$\overline{T}_I = \frac{\sum_{v=1}^{3} \lambda_{Iv} \, T_{Iv}}{\lambda_T}$$

$$\overline{T}_I = \frac{(3403.14 \times 1.03) + (25.79 \times 11.84) + (64.02 \times 31.06)}{3403.14 + 25.79 + 64.02}$$

$$\overline{T}_I = 1.66 \text{ min.}$$

$$\overline{T}_{FC} = 1.9(0.27 + 1.66)$$

$$\overline{T}_{FC} = 3.67 \text{ min.}$$

$$\overline{T}_{FI} = \frac{\sum_{v=1}^{1} \lambda_{FIv} \, T_{FIv}}{\lambda_T}$$

$$\overline{T}_{FI} = \frac{3492.94 \times 24.00}{3492.94}$$

$$\overline{T}_{FI} = 24.00 \text{ min.}$$

$$\overline{T}_{C} = S_I \frac{\sum_{v=1}^{1} \lambda_{Cv} \, T_{Cv}}{\lambda_T}$$

$$\overline{T}_{C} = 1.9 \times \frac{3492.94 \times .030}{3492.94}$$

$$\overline{T}_{C} = 0.57 \text{ min.}$$

TIME SYNTHESIS

R/R MODE SWITCH

Item	Description	Qty	Time (min)	Qty x Time (min)
1	Loosen setscrew	2	0.100	0.20
2	Remove knob	1	0.100	0.10
3	Loosen holdown clamp	8	0.283	2.26
4	Remove type III module	4	0.515	2.06
5	Remove connector w/jackscrew	17	0.200	3.40
6	Unscrew 8-32 screw	6	0.967	5.80
7	Interchange module	1	1.000	1.00
8	Fasten screw	6	1.130	6.80
9	Tighten holdown clamp	8	0.283	2.26
10	Secure connector w/jackscrew	17	0.283	4.82
11	Install type III module	4	0.515	2.06
12	Replace knob	1	0.100	0.10
13	Tighten setscrew	2	0.100	0.20
	Total			31.06

R/R VOLTAGE DIVIDER

Item	Description	Qty	Time (min)	Qty x Time (min)
1	Remove knob	1	0.100	0.10
2	Remove lead on terminal board	3	0.350	1.05
3	Remove machine screw	4	0.967	3.87
4	Interchange unit	1	0.200	0.20
5	Replace machine screw	4	1.130	4.52
6	Replace lead on terminal board	3	0.667	2.00
7	Replace knob	1	0.100	0.10
	Total			11.84

APPENDIX B

SAMPLE DETAILED PREDICTION

DETAILED MAINTAINABILITY PREDICTION

FOR

MTRE

AT THE

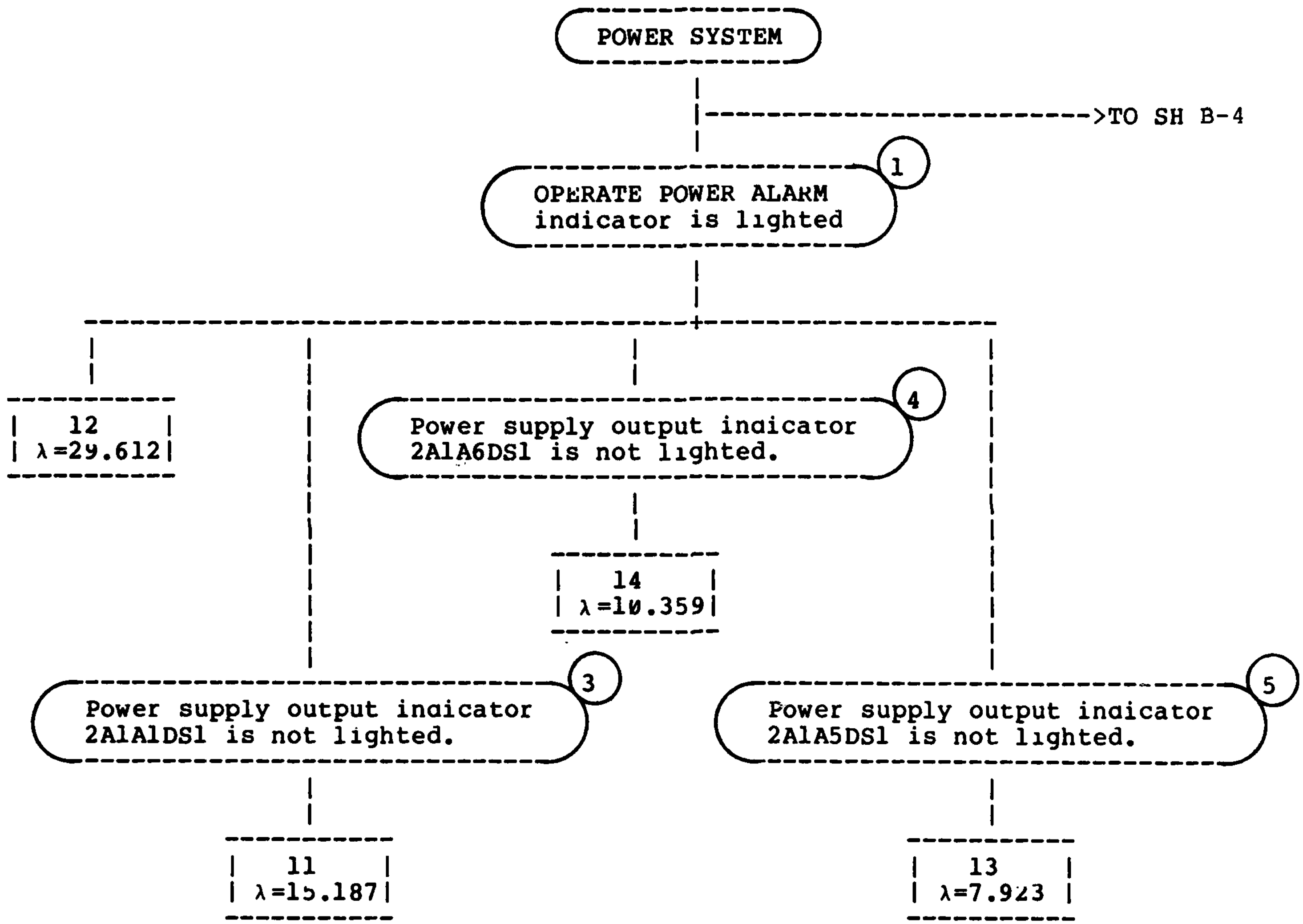
ORGANIZATIONAL LEVEL

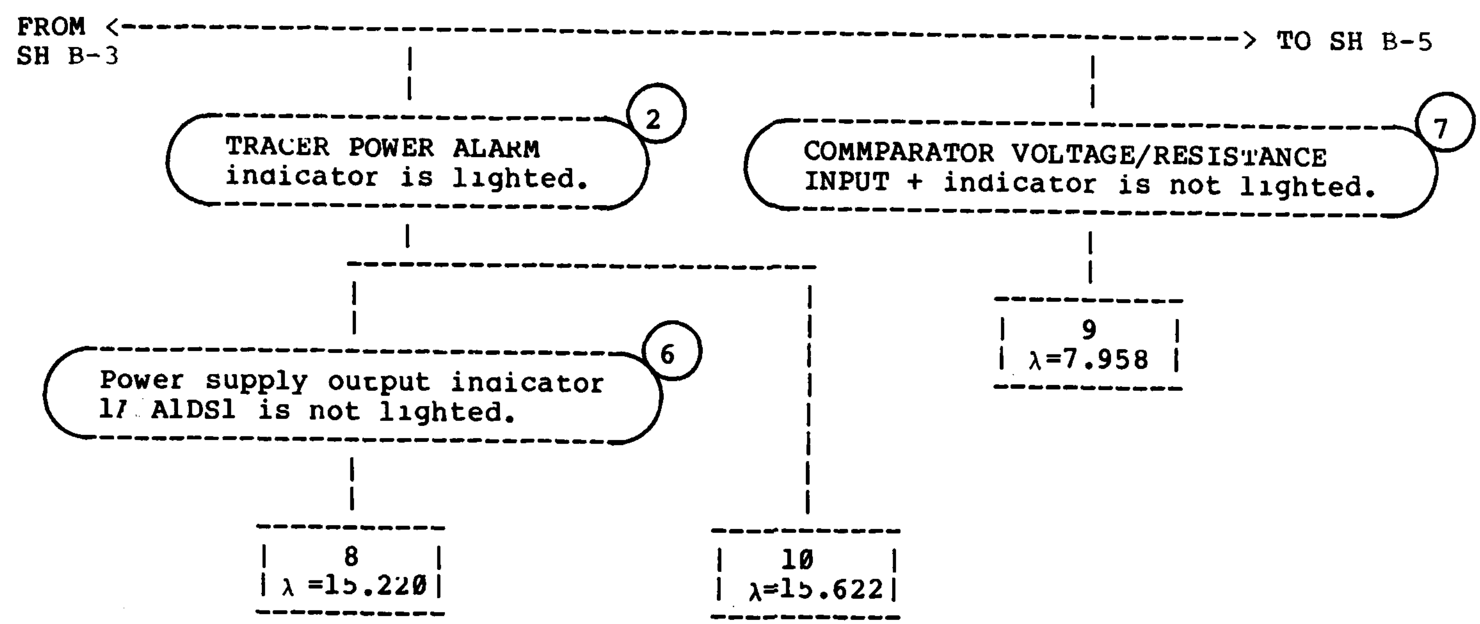
FAULT DETECTION AND ISOLATION OUTPUTS

MTRE

POWER SYSTEM OPERATIONAL TEST AND FAULT ISOLATION

Check-out Procedure Step No.	J	FD&I Outputs
1	1	OPERATE POWER ALARM indicator is lighted.
	2	TRACER POWER ALARM indicator is lighted.
	3	Power supply output indicator 2A1A1DS1 is not lighted.
	4	Power supply output indicator 2A1A6DS1 is not lighted.
	5	Power supply output indicator 2A1A5DS1 is not lighted.
	6	Power supply output indicator 1A3A1DS1 is not lighted.
3	7	COMPARATOR VOLTAGE/RESISTANCE INPUT + indicator is not lighted.
4	8	Voltage reading between 1A1TP2 and 1A1TP3 is not within +39.93 to +40.05 range.
5	9	Voltage reading between 2A1A1TP2 and 2A1A1TP1 is not within +38 to +54 range.
6	10	Voltage reading between 2A1A6TP2 and 2A1A6TP1 is not within +28 to +32 range.
7	11	Voltage reading between 2A1A5TP5 and 2A1A5TP1 is not within +13 to +17 range.


POWER SYSTEM
TO SH B-4
1
OPERATE POWER ALARM indicator is lighted
12 λ=29.612
4
Power supply output indicator 2A1A6DS1 is not lighted.
14 λ=10.359
3
Power supply output indicator 2A1A1DS1 is not lighted.
11 λ=15.187
5
Power supply output indicator 2A1A5DS1 is not lighted.
13 λ=7.923



FROM SH B-3
TO SH B-5
TRACER POWER ALARM indicator is lighted.
2
COMMPARATOR VOLTAGE/RESISTANCE INPUT + indicator is not lighted.
7
9
λ=7.958
Power supply output indicator
AlDS1 is not lighted.
6
8
λ =15.220
10
λ=15.622

FROM
SH B-4

(8) Volt. between 1A1TP2 and TP3 is not within +39.93 to +40.05 range.

8
λ=15.220

(9) Volt. between 2A1A1TP2 and TP1 is not within +38 to +54 range.

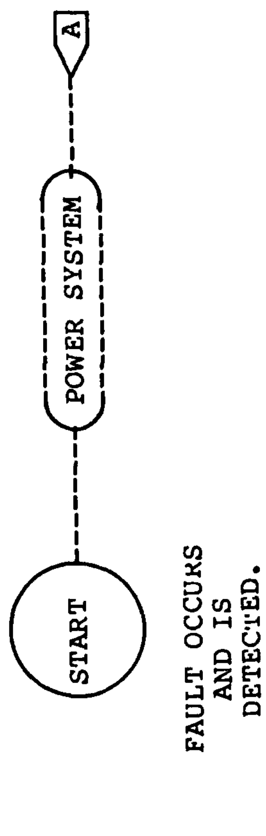
11
λ=15.187

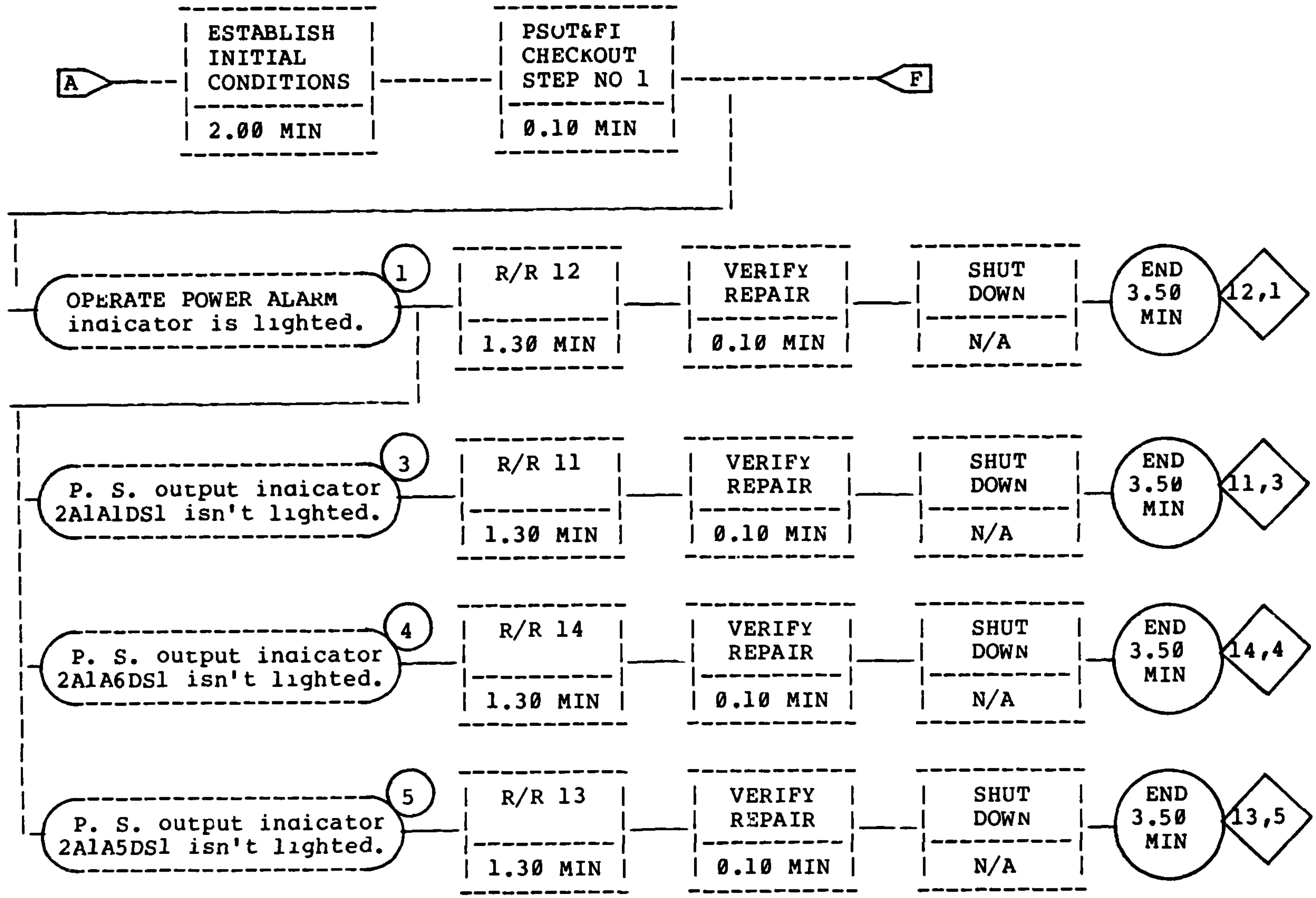
(10) Volt. between 2A1A6TP2 and TP1 is not within +28 to +32 range.

14
λ=10.359

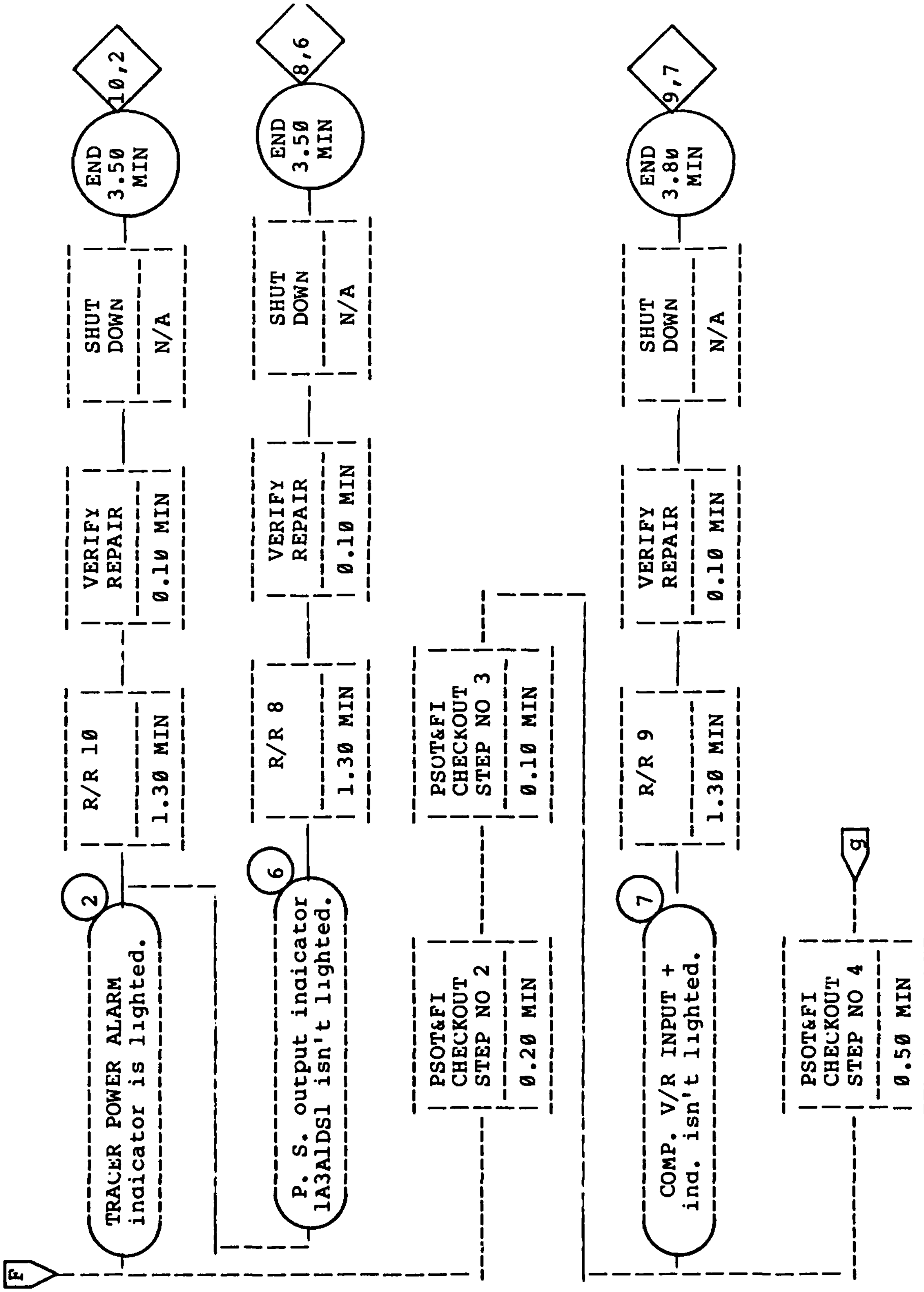
(11) Volt. between 2A1A5TP2 and TP1 is not within +13 to +17 range.

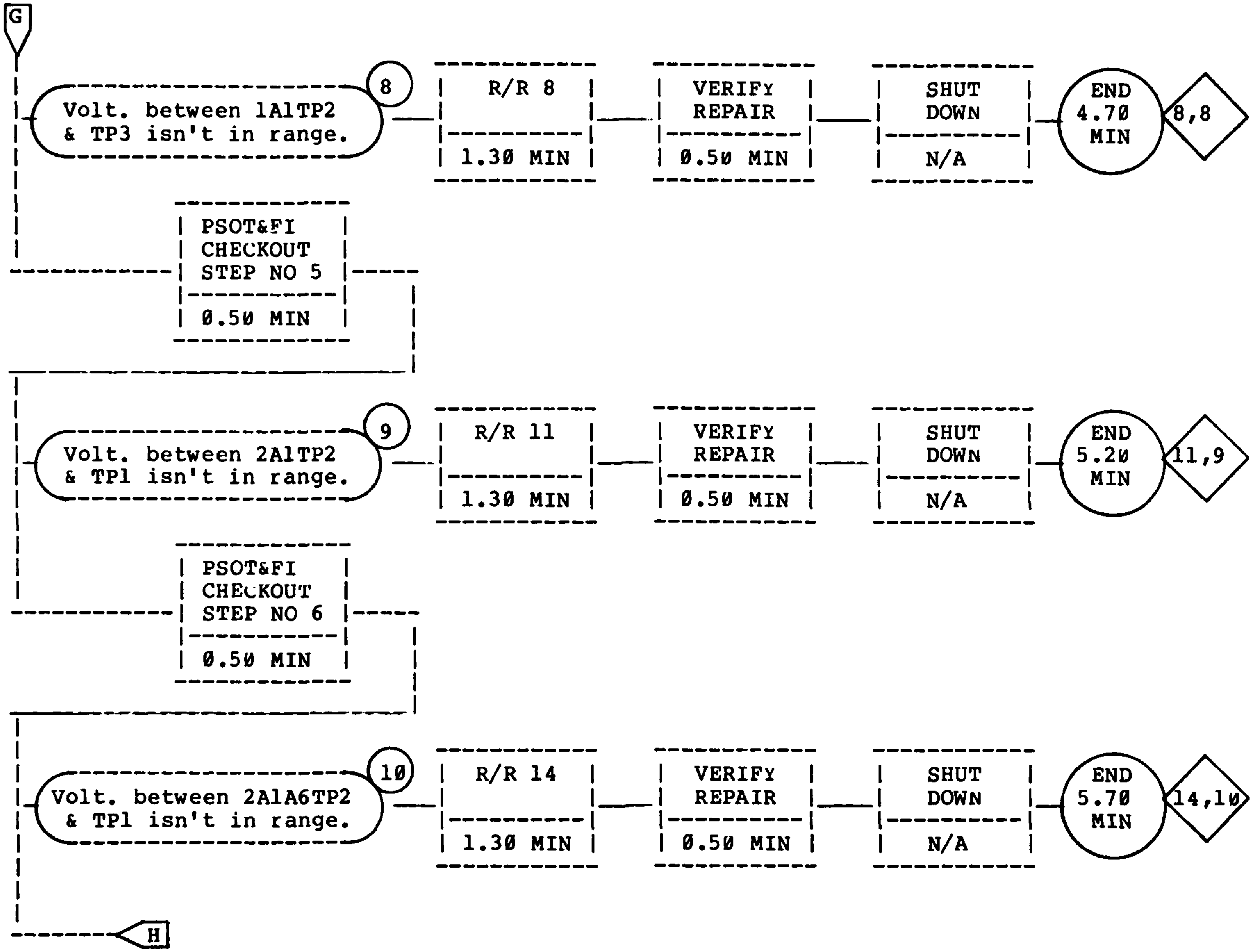
13
λ=7.923

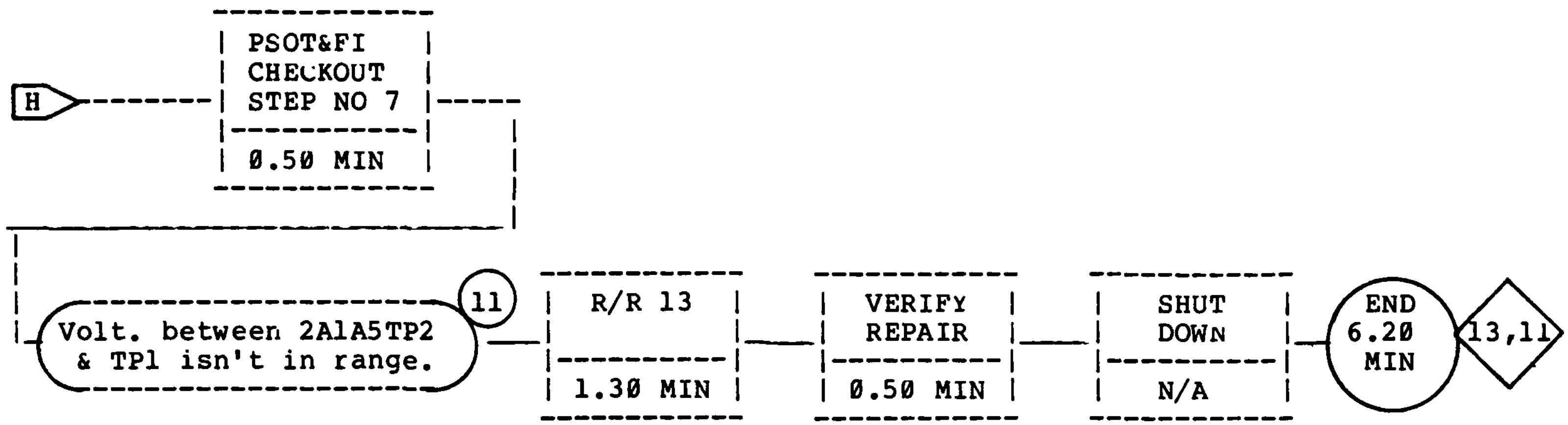

A
POWER SYSTEM
START
FAULT OCCURS AND IS DETECTED.



A
ESTABLISH INITIAL CONDITIONS
2.00 MIN
PSOT&FI CHECKOUT STEP NO 1
0.10 MIN
F
1
OPERATE POWER ALARM indicator is lighted.
R/R 12
1.30 MIN
VERIFY REPAIR
0.10 MIN
SHUT DOWN
N/A
END 3.50 MIN
12,1
3
P. S. output indicator 2A1A1DS1 isn't lighted.
R/R 11
1.30 MIN
VERIFY REPAIR
0.10 MIN
SHUT DOWN
N/A
END 3.50 MIN
11,3
4
P. S. output indicator 2A1A6DS1 isn't lighted.
R/R 14
1.30 MIN
VERIFY REPAIR
0.10 MIN
SHUT DOWN
N/A
END 3.50 MIN
14,4
5
P. S. output indicator 2A1A5DS1 isn't lighted.
R/R 13
1.30 MIN
VERIFY REPAIR
0.10 MIN
SHUT DOWN
N/A
END 3.50 MIN
13,5


F
TRACER POWER ALARM indicator is lighted.
2
R/R 10
1.30 MIN
VERIFY REPAIR
0.10 MIN
SHUT DOWN
N/A
END 3.50 MIN
10,2
P. S. output indicator 1A3A1DS1 isn't lighted.
6
R/R 8
1.30 MIN
VERIFY REPAIR
0.10 MIN
SHUT DOWN
N/A
END 3.50 MIN
8,6
PSOT&FI CHECKOUT STEP NO 2
0.20 MIN
PSOT&FI CHECKOUT STEP NO 3
0.10 MIN
COMP. V/R INPUT + ind. isn't lighted.
7
R/R 9
1.30 MIN
VERIFY REPAIR
0.10 MIN
SHUT DOWN
N/A
END 3.80 MIN
9,7
PSOT&FI CHECKOUT STEP NO 4
0.50 MIN
g


G
8
Volt. between 1A1TP2 & TP3 isn't in range.
R/R 8
1.3Ø MIN
VERIFY REPAIR
Ø.5Ø MIN
SHUT DOWN
N/A
END 4.7Ø MIN
8,8
PSOT&FI CHECKOUT STEP NO 5
Ø.5Ø MIN
9
Volt. between 2A1TP2 & TP1 isn't in range.
R/R 11
1.3Ø MIN
VERIFY REPAIR
Ø.5Ø MIN
SHUT DOWN
N/A
END 5.2Ø MIN
11,9
PSOT&FI CHECKOUT STEP NO 6
Ø.5Ø MIN
1Ø
Volt. between 2A1A6TP2 & TP1 isn't in range.
R/R 14
1.3Ø MIN
VERIFY REPAIR
Ø.5Ø MIN
SHUT DOWN
N/A
END 5.7Ø MIN
14,1Ø
H


H
PSOT&FI CHECKOUT STEP NO 7
Ø.5Ø MIN
Volt. between 2A1A5TP2 & TP1 isn't in range.
11
R/R 13
1.3Ø MIN
VERIFY REPAIR
Ø.5Ø MIN
SHUT DOWN
N/A
END 6.2Ø MIN
13,11

RI (N)	8			9			10			11			12			13			14		
FR(N)	30.440			31.833			31.243			45.562			59.223			23.077			31.078		
FD&I OUTPUTS (J)	K	FR	R	K	FR	R	K	FR	R	K	FR	R	K	FR	R	K	FR	R	K	FR	R
1													1	29.612	3.5						
2							1	15.622	3.5												
3										1	15.187	3.5									
4																			1	10.359	3.5
5																1	7.923	3.5			
6	1	15.220	3.5																		
7				1	7.958	3.8															
8	1	15.220	4.7																		
9										1	15.187	5.2									
10																			1	10.359	5.7
11																1	7.923	6.2			

COMPUTATION OF MEAN TIME TO REPAIR

For a Replaceable Item:

$$R_n = \frac{\sum_{j=1}^{J} \lambda_{nj} R_{nj}}{\sum_{j=1}^{J} \lambda_{nj}}$$

$$R_8 = \frac{(15.22 \times 3.50) + (15.22 \times 4.70)}{15.22 + 15.22}$$

$R_8 =$ 4.10 min.

For the System:

$$MTTR = \frac{\sum_{n=1}^{N} \lambda_n R_n}{\sum_{n=1}^{N} \lambda_n}$$

$$MTTR = \frac{16206.68}{1762.74}$$

MTTR = 9.19 min.

APPENDIX C

MAINTAINABILITY MATHEMATICS

APPENDIX A

MAINTAINABILITY MATHEMATICS

The underlying probability density function used to describe the distribution of repair times is usually taken to be one of three common forms. [1]

1 Normal Distribution - Provides a description of maintenance tasks or elements such as preparation, space retrieval, removal, and replacement where technical skill is not an important influence. Tasks which are normally distributed consistently require a fixed time to complete with little variation.

The probability density function for the normal distribution is given by

$$f(t = Mct) = \frac{1}{S_{Mct}\sqrt{2\pi}} \, e^{-\frac{\left(Mct_i - \overline{Mct}\right)^2}{2(S_{Mct})^2}}$$

where

Mct_i = Repair time for the i th maintenance task or action

$\overline{Mct}$ = Mean or average repair time for N observations

$$\overline{Mct} = \frac{\Sigma\,(Mct_i)}{N}$$

S_{Mct} = Standard deviation of the repair time distribution for N observations

$$S_{Mct} = \sqrt{\frac{\Sigma\,(Mct_i - \overline{Mct})^2}{N-1}}$$

$$= \sqrt{\frac{N\Sigma(Mct_i)^2 - (\Sigma\, Mct_i)^2}{N(N-1)}}$$

N = Number of observations

1 See NAVORD-OD39223, Section 2-31 and Appendix A

2 Exponential Distribution - Refers to maintenance tasks or actions where the corrective maintenance times Mct_i are independent of previous maintenance experience. The distribution would apply, for example, in the case where repairs are made by substitution of assemblies, one at a time, until the defective assembly has been isolated.

The probability density function for the exponential distribution is given by:

$$f(t = Mct) = \frac{1}{\overline{Mct}} e^{-\frac{Mct_i}{\overline{Mct}}}$$

where Mct_i and $\overline{Mct}$ are as defined above.

3 Lognormal Distribution - Applies to most maintenance tasks or actions which are comprised of several subsidiary tasks of unequal frequency and time duration. This distribution is the one most frequency applied to complex equipment and systems.

The probability density function for the lognormal distribution is given by

$$F(t = Mct) = \frac{1}{S_{\log Mct}\sqrt{2\pi}} e^{-\frac{(\log Mct_i - \overline{\log Mct})^2}{2(S_{\log Mct})^2}}$$

where Mct_i is as defined above, and

$S_{\log Mct}$ = Standard deviation of the repair time distribution for N observations

$$S_{\log Mct} = \sqrt{\frac{N\,\Sigma(\log Mct_i)^2 - (\Sigma \log Mct_i)^2}{N(N-1)}}$$

$$= \sqrt{\frac{\Sigma(\log Mct_i - \log Mct)^2}{N-1}}$$

$\log Mct_i$ is the logarithm of the corrective maintenance time for the i^{th} maintenance task or action.

$\overline{\log Mct}$ = mean or average of the logarithms of the corrective maintenance times for N observations.

$$\overline{\log Mct} = \frac{\Sigma \log Mct_i}{N}$$

Estimation of parameters such as the mean and standard deviation from sample data can be made using the above equations. For the lognormal distribution, the median is found from the antilog of the mean of the distribution of log Mcti.

Mct = median time to repair (50% percentile)

$$Mct = \text{antilog}\ (\overline{\log Mct}) = \text{antilog} \left(\frac{\Sigma \log Mct_i}{N} \right)$$

APPENDIX D

SAMPLE OF MAINTENANCE FIELD DATA

MTRE FIELD MAINTENANCE DATA

FAILED ITEM REF DESIG	FAILED ITEM PART NUMBER	ACTION TAKEN	CORRECTIVE HOURS	MAINT TIME MINUTES	REF NUMBER
1A1A14	2401068	ADJ	1	10	510
1A1A14	2401068	NONE	0	15	511
1A1A14	2401068	NONE	1	30	930
1A1A14	240168	REP	0	15	114
1A1A14	2401068	REP	1	0	938
1A1A14	2401068	REP	1	12	1548
1A1A14	2401068	RPL	0	15	610
1A1A14	2401068	RPL	0	18	955
1A1A14	2401068	RPL	0	24	887
1A1A14	2401068	RPL	0	24	918
1A1A14	2401068	RPL	0	30	2
1A1A14	2401068	RPL	0	30	15
1A1A14	2401068	RPL	0	30	30
1A1A14	2401068	RPL	0	30	164
1A1A14	2401068	RPL	0	30	251
1A1A14	2401068	RPL	0	30	605
1A1A14	2401068	RPL	0	30	674
1A1A14	2401068	RPL	0	30	677
1A1A14	2401068	RPL	0	30	691
1A1A14	2401068	RPL	0	30	716
1A1A14	2401068	RPL	0	30	787

MTRE FIELD MAINTENANCE DATA

FAILED ITEM REF DESIG	FAILED ITEM PART NUMBER	ACTION TAKEN	CORRECTIVE HOURS	MAINT TIME MINUTES	REF NUMBER
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	79Ø
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	884
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	891
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	911
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	915
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	917
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	921
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	923
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	984
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	985
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	1Ø39
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	1Ø45
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	1Ø49
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	1144
1A1A14	24Ø1Ø68	RPL	Ø	3Ø	1185
1A1A14	24Ø1Ø68	RPL	Ø	35	665
1A1A14	24Ø1Ø68	RPL	Ø	45	558
1A1A14	24Ø1Ø68	RPL	Ø	45	8ØØ
1A1A14	24Ø1Ø68	RPL	Ø	5Ø	568
1A1A14	24Ø1Ø68	RPL	Ø	54	1348
1A1A14	24Ø1Ø68	RPL	1	Ø	274

AD-A123 707 VALIDATION OF MAINTAINABILITY PREDICTION(U) LOCKHEED ELECTRONICS CO INC PLAINFIELD N J W DUBLANICA ET AL. SEP 82 RADC-TR-82-185 F30602-81-C-0081 2/2

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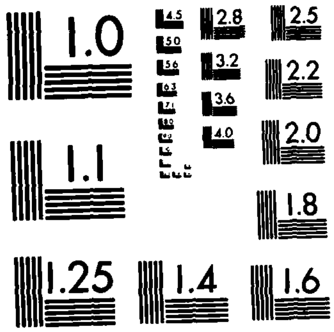

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

MTRE FIELD MAINTENANCE DATA

FAILED ITEM REF DESIG	FAILED ITEM PART NUMBER	ACTION TAKEN	CORRECTIVE HOURS	MAINT TIME MINUTES	REF NUMBER
1A1A14	2401068	RPL	1	0	340
1A1A14	2401068	RPL	1	0	341
1A1A14	2401068	RPL	1	0	350
1A1A14	2401068	RPL	1	0	355
1A1A14	2401068	RPL	1	0	443
1A1A14	2401068	RPL	1	0	447
1A1A14	2401068	RPL	1	0	499
1A1A14	2401068	RPL	1	0	650
1A1A14	2401068	RPL	1	0	651
1A1A14	2401068	RPL	1	0	672
1A1A14	2401068	RPL	1	0	759
1A1A14	2401068	RPL	1	0	762
1A1A14	2401068	RPL	1	0	768
1A1A14	2401068	RPL	1	0	823
1A1A14	2401068	RPL	1	0	825
1A1A14	2401068	RPL	1	0	859
1A1A14	2401068	RPL	1	0	975
1A1A14	2401068	RPL	1	0	1254
1A1A14	2401068	RPL	1	0	1304
1A1A14	2401068	RPL	1	0	1305
1A1A14	2401068	RPL	1	0	1306

MTRE FIELD MAINTENANCE DATA

FAILED ITEM REF DESIG	FAILED ITEM PART NUMBER	ACTION TAKEN	CORRECTIVE HOURS	MAINT TIME MINUTES	REF NUMBER
1A1A14	2401068	RPL	1	0	1307
1A1A14	2401068	RPL	1	0	1308
1A1A14	2401068	RPL	1	0	1327
1A1A14	2401068	RPL	1	0	1343
1A1A14	2401068	RPL	1	0	1344
1A1A14	2401068	RPL	1	0	1346
1A1A14	2401068	RPL	1	5	26
1A1A14	2401068	RPL	1	30	609
1A1A14	2401068	RPL	1	30	707
1A1A14	2401068	RPL	1	30	711
1A1A14	2401068	RPL	1	30	926
1A1A14	2401068	RPL	1	30	937
1A1A14	2401068	RPL	1	30	952
1A1A14	2401068	RPL	1	30	1250
1A1A14	2401068	RPL	1	48	416
1A1A14	2401068	RPL	2	0	376
1A1A14	2401068	RPL	2	0	747
1A1A14	2401068	RPL	2	0	782
1A1A14	2401068	RPL	2	0	966
1A1A14	2401068	RPL	2	0	972
1A1A14	2401068	RPL	2	0	973

MTRE FIELD MAINTENANCE DATA

FAILED ITEM REF DESIG	FAILED ITEM PART NUMBER	ACTION TAKEN	CORRECTIVE HOURS	MAINT TIME MINUTES	REF NUMBER
1A1A14	2401068	RPL	2	0	1027
1A1A14	2401068	RPL	2	18	717
1A1A14	2401068	RPL	2	30	544
1A1A14	2401068	RPL	2	30	945
1A1A14	2401068	RPL	2	30	949
1A1A14	2401068	RPL	3	0	525
1A1A14	2401068	RPL	3	0	783
1A1A14	2401068	RPL	3	5	668
1A1A14	2401068	RPL	3	20	829
1A1A14	2401068	RPL	4	0	398
1A1A14	2401068	RPL	4	0	1206
1A1A14	2401068	RPL	5	13	614
1A1A14	2401068	RPL	5	50	272
1A1A14	2401068	RPL	6	0	843
1A1A14	2401068	RPL	6	0	850
1A1A14	2401068	RPL	8	0	833
1A1A14	2401068	RPL	8	30	1360
1A1A14	2401068	RPL	11	0	589
1A1A14	2401068	RPL	16	7	704

APPENDIX E

TABLES 48 AND 49 FROM RADC-TR 78-169

TABLE 48. ELEMENTAL MAINTENANCE ACTIONS

Time Standard Number	Description	Standard Times: Remove (min.)	Standard Times: Replace (min.)	Standard Times: Interchange (min.)	Reference Figure
	FASTENERS				
1	Standard Screws	0.16	0.26	0.42	14
2	Hex or Allen Type Screws	0.17[2]	0.43[1]	0.60[1]	15
3	Captive Screws	0.15[1]	0.20[1]	0.35[1]	16
4	Dzus (1/4 Turnlock)	0.08	0.05	0.13	17
5	Tridair Fasteners	0.06	0.06	0.12	18
6	Thumbscrews	0.06[1]	0.08[1]	0.14[1]	19
7	Machine Screws	0.21	0.46	0.67	20
8	Nuts or Bolts	0.34	0.44	0.78	21
9	Retaining Rings	NA	0.27	NA	22
	LATCHES				
10	Drawhook	0.03	0.03	0.06	23
11	Spring Clip	0.04	0.03	0.07	24
12	Butterfly	0.05	0.05	0.10	25
13	ATR (spring loaded, pair)	0.45	0.69	1.14	26
14	Lift & Turn	0.03	0.04	0.07	27
15	Slide Lock	NA	NA	NA	28
	TERMINAL CONNECTIONS				
16	Terminal Posts (per lead)	0.22	0.64	*	29
17	Screw Terminals	0.23	0.45	0.68	30
18	Termipoint	0.22	0.30	*	31
19	Wirewrap	0.09	0.24	*	32
20	Taperpin	0.07[2]	0.07[2]	0.14[2]	33

TABLE 48. ELEMENTAL MAINTENANCE ACTIONS (Continued)

Time Standard Number	Description	Standard Times Remove (min.)	Standard Times Replace (min.)	Standard Times Interchange (min.)	Reference Figure
	TERMINAL CONNECTIONS (cont.)				
21	PCB a) Discretes	0.14[3]	0.17[3]	*	34
22	b) Flatpacks	0.14[3] per lead	0.13[3] per flatpack	*	34
	c) DIP ICs				
23	• 8 pin	0.46[3]	0.52[3]	*	34
	• 14 & 16 pin	0.90[3]	0.86[3]	*	34
	CONNECTORS				
25	BNC (single pin)	0.07	0.10	0.17	35
26	BNC (multi pin)	0.07	0.12	0.19	35
27	Quick Release Coax	0.04	0.04	0.08	36
28	Friction Locking	NA	NA	NA	37
29	Friction Locking with one Jack Screw	0.18	0.20	0.38	38
30	Thread Locking	0.09	0.17	0.26	39
31	Slide Locking	0.09	0.12	0.21	40
	PLUG IN MODULES				
32	DIP ICs (into DIP sockets)	0.07	0.14	0.21	41
	CCAs (without tool) (guided)				
	• 40 pin	NA	NA	NA	42
33	• 80 pin	0.04	0.07	0.11	42
	CCAs (with tool) (guided)				
34	• 40 pin	0.06	0.07	0.13	43
35	• 80 pin	0.09	0.08	0.17	43

TABLE 48. ELEMENTAL MAINTENANCE ACTIONS (Continued)

Time Standard Number	Description	Standard Time Remove (min)	Standard Time Replace (min.)	Standard Time Interchange (min.)	Reference Figure
	PLUG IN MODULES (cont.)				
	CCAs (without tool) (not guided)				
	• 40 pin	NA	NA	NA	44
36	• 80 pin	0.04	0.16	0.20	44
37	Modules	0.09	0.11	0.20	45
	MISCELLANEOUS				
38	Strip Wire	–	–	0.10	–
39	Cut Wire of Sleeving	–	–	0.04	–
40	Dress Wire with Sleeving	–	–	0.21	–
41	Crimp Lugs	–	–	0.27	46
42	Form Leads (per lead)	–	–	0.03	47
43	Trim Leads (per lead)	–	–	0.03	–
44	Adhesives	0.55[4]	0.13[4]	0.68[4]	–
45	Conformal Coating	2.20[4]	0.23[4]	2.43[4]	–
46	Soldering A) Terminal Posts	–	–	0.22	48
47	B) PCB	–	–	0.06	49
48	Reflow Soldering	–	–	0.25	–
49	Tinning Flatpacks (dipping)	–	–	0.30	–
50	Desoldering A) Braided Wick	–	–	0.16	50
51	B) Solder Sucker	–	–	0.09	51
52	Form Flatpack Leads (Mechanically)	–	–	0.11	52
53	Clean Surface	–	–	0.29[4]	–
54	Panels, Doors, & Covers	0.04	0.03	0.07	53

TABLE 48. ELEMENTAL MAINTENANCE ACTIONS (Continued)

Time Standard Number	Description	Standard Time Remove (min.)	Replace (min.)	Interchange (min.)	Reference Figure
	MISCELLANEOUS (cont.)				
55	Drawers (Large)	0.09	0.10	0.19	54
56	Display Lamps	0.10	0.11	0.21	55
57	Threaded Connector Covers	0.11	0.14	0.25	–

1. data obtained from RADC-TR-70-89, Maintainability Prediction and Demonstration Techniques
2. data obtained from Hartmeyer, F.C., Electronic Industry Cost Estimating Data
3. does not include soldering/desoldering
4. these times apply to small areas

NA - no data available

* indicates that other times are involved in the interchange activity

TABLE 49. COMMON MAINTENANCE TASKS

Description	Elements of Removal*	Remove (min.)	Elements of Replacement*	Replace (min.)	Interchange (min.)
1. R/R of transistor from a PCB	50(3), 21A(3), 53	1.19	42(3), 21B(3), 47(3), 43(3), 53	1.16	2.35
2. R/R of a transistor from terminal posts	50(3), 16A(3), 53	1.43	42(3), 16B(3), 43(3), 46(3), 53	3.05	4.48
3. R/R of an axial component from a PCB	50(2), 21A(2), 53	0.89	42(2), 21B(2), 47(2), 43(2), 53	0.87	1.76
4. R/R of an axial component from terminal posts	50(2), 16A(2), 53	1.05	42(2), 16B(2), 43(2), 46(2), 53	1.69	2.74
5. R/R of a radial component from a PCB	50(2), 21A(2), 53	0.89	21B(2), 43(2), 47(2), 53	0.81	1.70
6. R/R of a radial component from terminal posts	50(2), 16A(2), 53	1.05	42(2), 16B(2), 43(2), 46(2), 53	1.69	2.74
7. R/R of a termi-point connection	18A	0.22	39, 20B	0.34	0.56
8. R/R of a wirewrap connection	19A	0.09	39, 38, 19B	0.38	0.47
9. R/R of a 16 pin IC from a PCB	50(16), 24A, 53	3.75	24B, 47(16), 43(16), 53	2.59	6.34
10. R/R of a 16 pin flatpack	50(16), 22A(16), 53	5.09	49, 52, 22B, 48, 53	1.06	6.17
11. R/R an 8 pin IC from a PCB	50(8), 23A, 53	2.03	23B, 47(8), 43(8), 53	1.53	3.56

*Numbers in these columns pertain to the time standard numbers in Table 48. A and B refer to removal and replacement times respectively. The number in parentheses refers to the quantity of each action.
R/R = removal and replacement

APPENDIX F

SAMPLE OF TIME AND MOTION STUDY DATA

OBSERVED INTERCHANGE TIMES (MINUTES) CONDITION A - REPETITIVE

TIME STANDARD NUMBER	1	3	10	12	17	25	29	37	55
	0.59	0.50	0.07	0.11	0.66	0.21	0.35	0.18	0.18
	0.39	0.36	0.09	0.18	0.81	0.17	0.34	0.20	0.16
	0.33	0.40	0.08	0.12	0.68	0.07	0.50	0.15	0.25
	0.35	0.42	0.08	0.12	0.63	0.20	0.31	0.15	0.25
	0.49	0.43	0.05	0.07	0.58	0.23	0.29	0.26	0.23
	0.28	0.31	0.10	0.16	0.57	0.16	0.43	0.22	0.30
	0.56	0.47	0.06	0.14	0.43	0.13	0.48	0.18	0.17
	0.46	0.25	0.09	0.11	0.74	0.22	0.33	0.23	0.18
	0.35	0.41	0.08	0.08	0.73	0.22	0.52	0.23	0.17
	0.36	0.40	0.11	0.18	0.55	0.19	0.44	0.19	0.09
	0.35	0.37	0.10	0.15	0.43	0.17	0.43	0.12	0.27
	0.33	0.43	0.07	0.19	0.48	0.31	0.46	0.23	0.21
	0.45	0.42	0.06	0.20	0.53	0.10	0.32	0.19	0.20
	0.55	0.33	0.09	0.13	0.64	0.20	0.46	0.26	0.22
	0.41	0.45	0.10	0.07	0.71	0.21	0.47	0.24	0.11
	0.39	0.30	0.10	0.09	0.58	0.19	0.41	0.17	0.08
	0.52	0.66	0.11	0.07	0.69	0.24	0.29	0.17	0.18
	0.25	0.44	0.07	0.15	0.61	0.24	0.43	0.28	0.24
	0.30	0.38	0.09	0.18	0.63	0.18	0.51	0.25	0.24
	0.34	0.27	0.06	0.10	0.57	0.21	0.44	0.24	0.14
N	20	20	20	20	20	20	20	20	20
	0.40	0.40	0.08	0.13	0.61	0.19	0.41	0.21	0.19
	0.10	0.09	0.02	0.04	0.10	0.05	0.08	0.04	0.06

OBSERVED INTERCHANGE TIMES (MINUTES) CONDITION B - SINGLE OCCURANCE

TIME STANDARD NUMBER	1	3	10	12	17	25	29	37	55
	0.81	0.42	0.14	0.19	1.17	0.24	0.74	0.37	0.42
	1.01	0.60	0.07	0.08	1.61	0.33	0.58	0.40	0.56
	0.78	0.77	0.11	0.15	1.42	0.46	0.82	0.38	0.54
	0.78	0.62	0.19	0.23	1.25	0.31	0.97	0.42	0.54
	1.08	0.41	0.13	0.29	1.23	0.41	0.74	0.37	0.41
	0.72	0.59	0.15	0.14	1.41	0.48	0.68	0.34	0.45
	0.76	0.53	0.08	0.18	1.66	0.48	0.69	0.48	0.32
	0.88	0.86	0.09	0.31	1.25	0.33	0.69	0.38	0.46
	0.85	0.82	0.21	0.27	1.74	0.25	0.47	0.46	0.35
	0.84	0.52	0.15	0.25	1.46	0.39	0.56	0.36	0.54
	0.70	0.90	0.15	0.19	1.25	0.29	0.72	0.25	0.43
	0.69	0.76	0.19	0.28	1.33	0.28	0.73	0.59	0.52
	0.78	0.53	0.15	0.25	1.42	0.47	0.49	0.40	0.51
	0.70	0.78	0.08	0.16	1.63	0.44	0.58	0.42	0.44
	0.70	0.63	0.15	0.11	1.19	0.34	0.87	0.51	0.46
	0.36	0.71	0.09	0.17	1.43	0.60	0.77	0.35	0.51
	1.25	0.75	0.18	0.35	1.27	0.37	0.81	0.44	0.34
	0.89	1.03	0.07	0.24	1.51	0.40	0.91	0.23	0.43
	0.[illegible]9	0.53	0.12	0.33	1.45	0.35	0.70	0.33	0.43
	1.17	0.72	0.06	0.26	1.39	0.33	0.67	0.42	0.42
N	20	20	20	20	20	20	20	20	20
	0.81	0.63	0.13	0.22	1.40	0.38	0.71	0.40	0.45
	0.21	0.18	0.05	0.07	0.16	0.09	0.13	0.08	0.07

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