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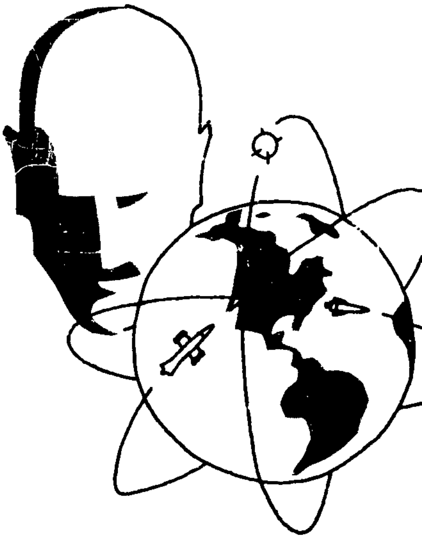

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PROCEEDINGS
OF
ESD MAINTAINABILITY CONFERENC
12 - 13 March 1963

L. G. HANSCOM FIELD, BEDFORD, MASSACHUS

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MAINTAINABILITY CONFERENCE

12 - 13 March 1963

Building 1728

Sponsored by:

Electronic Systems Division (ESD)
Directorate of Technical Services

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A SHORT MESSAGE

This Conference emphasizes the continued interest of the Electronic Systems Division in the technical and managerial elements of Maintainability Engineering.

The systems being developed by the ESD are usually non-mission orientated; that is, they are required to provide almost continuous performance (availability of approximately unity) of their respective functions. Such systems must be capable of allowing rapid recognition of failure locations and a restoration to failure-free performance.

Speakers at this Conference will indicate the increasing burdens placed upon the Air Force logistic and maintenance capability during the development of weapon and support systems since World War II.

The Air Force has taken steps to combat this situation. Quantitative statements for maintainability, design approaches, demonstration techniques and support system analysis are finding their way into system contracts. In addition, a management philosophy and approach has been generated for Maintainability Engineering.

The ESD has included Maintainability Engineering work elements and quantitative requirements in contracts over the past years. Several speakers will indicate past and current ESD approaches to Maintainability.

It is obvious that Maintainability Engineering is a dynamic discipline. Today's methods or techniques will be obsolete tomorrow. The ESD intends to reflect this changing Maintainability technology in their contracts.

It is our hope that all in attendance at this Conference will obtain a better understanding of the Air Force approach to Maintainability Engineering and will recognize, as we do, the excellent work being done by industry engineers in the field of Maintainability Engineering.

George H Allen

GEORGE H. ALLEN
Project Officer,
Maintainability Conference

Conference Committee

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Mr. J. Horowitz - ESST - Facilities

Mr. R. DeMilia - ESST - Reservations

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Summary of
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"The Air Force Maintainability Program"

Lt Col E. Fallon, Hq. USAF

Discussion of five topics relating to the Air Force Maintainability Program.

- -- Maintainability and what it is.
- -- The Air Force Maintainability Policy.
- -- Industry's role in our program.
- -- The Maintainability Specification, MIL-M-26512B.
- -- What Maintainability means to the design engineer.

"In the marathon to assure system maintainability, the Air Force has taken the first steps. It still has a way to go. However, the first steps were major ones. Maintainability has been recognized as a significant design parameter, tools to achieve it are being improved and industry is giving the Air Force full cooperation in the total program. The task ahead is to give the program management attention, to the end that maintainability is as integral to the system as is reliability or performance."

MAINTAINABILITY - DEFINITIONS AND CONCEPTS

Presented by

Jerome E. Horowitz
Staff Reliability Engineer

The Maintainability Conference

Electronic Systems Division - AFSC
L. G. Hanscom Field
Bedford, Massachusetts

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SUMMARY

One of the major problems experienced by the Air Force has been high maintenance costs in its systems inventory. In part, this is due to lack of complete understanding, in the early stages of the contract, between the using arm, the procuring agency and the producer. This has stemmed from lack of clean-cut definitions of the terms and requirements involved in "Maintainability". This paper attempts to relate the terminology used with its systems concept and analyzes the definitions involved into finite terms. These terms will be incorporated into contractual documents and specifications issued by ESD.

INTRODUCTION

The*AGREE Report published in 1957 states that "A great deal of sound work has been done to enable engineers to design easily maintainable electronic systems, but they must be educated in the subject and compelled to study it, assimilate it, and incorporate it in the systems which they are presently designing. The surest way to do this is to include an iron-clad maintainability requirement in the specifications for each new system, giving maintainability an operational definition of the type set out above and rigorously testing and enforcing it. If this is done, the design engineer will provide the maintainability the services so desperately needed."

Granted then that the engineers know "how" then "why" is maintainability such a problem? In part at least, this appears to be due to a problem of "communications" on one side and to semantics and basic understanding on the other. Contractors will usually give us what we need if we can specify it and it is within practical limits or "the state of the art".

To illustrate the problem of agreement or disagreement on terms, let me illustrate some of the definitions available for such a simple term as failure. (Show on View Graph)

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*"Reliability of Military Electronic Equipment" - page 336, dtd 4 June 1957.

DEFINITIONS OF FAILURE

(1) Failure - The cessation of ability of an item to meet the minimum specified performance. (MIL-STD-829 - Page 11)

(2) Failure - A malfunction which cannot be corrected by the operator by means of controls normally accessible to him during routine operation of the device and which results in inoperativeness or substandard performance. (Reliability, Principles & Practices - Page 296 - Calabro)

(3) Failure - The occurence of unsatisfactory performance by some specified criterion. (Arinc - Page XII - Publication No 123-7-196)

(4) Failure - A failure is a cessation of ability to perform a specified function or functions within previously established limits on the area of interest. It is a malfunction which is beyond adjustment by the operator by means of controls normally accessible to him during the routine operation of the device. This requires that measurable limits be established to define satisfactory performance of the function. (Martin Co. - Definitions pertaining to reliability - Page 23)

Failure was generally defined above as the cessation of the ability to meet a specified performance but there are other fine points also. Keep in mind there are several types of failures: "Catastrophic" in which the failure is sudden and usually complete (such as an open in a resistor or a short in a capacitor) and there are "Creeping" failures or degrading types in which for example power output on a set decreases. Failures can also be classified as "Independent" or "Secondary" depending on whether they are the real causes of the trouble or if in turn, due to their failing another part was caused to fail; for example, a voltage dropping Resistor shorts, in turn the tube is burned out. We have 2 failures; one, the "R" is independent; the tube is secondary.

The definition of failure is critical in specifying Reliability, Maintainability or Availability. Care must be taken, especially when speaking about a system or subsystem to define adequately the mode of operation and the specific failure mechanism or limits. It must also be stated which failures will be considered relevant and which are not. It is possible to have equipment and subsystem failures but still retain mission availability.

To obtain specific performance then, requires that we at least agree on what the terms mean and be able to identify responsibility. "Maintainability" as an engineering science, is about in the same position today that "Reliability" was some five years ago. At that time, reliability meant "something trust-worthy" or "that which could be depended on." Under present usage, it is a probability statistic defined as: "the probability that a given equipment will operate in a satisfactory manner for a given period of time in its stated environment." By contrast, "Maintainability" is defined in MIL-STD-829 as "The characteristics (both qualitative and quantitative) of material design and maintenance resource planning which make it possible to meet operational objectives with minimum expenditures of maintenance effort (manpower, personnel skill, test equipment, technical data maintenance support, facilities) under operational environmental conditions in which scheduled and unscheduled maintenance will be performed."

This puts us at somewhat of a disadvantage in trying to define contractually what we are looking for since it is not a directly measurable item. However, AFR 66-29 requires that Quantitative Maintainability Requirements be specified. In MIL-STD-829, the AF has defined some of the terms that are used in Maintainability. Since this is the only AF document we have at this time, we will use it as a base and add such new terms as needed.

Let us first get the overall perspective as to where maintainability fits into the AF weapons system and then we will break out the major considerations into their components and allocate responsibilities. In a piece of equipment or a system, it is fine to talk of reliability, maintainability or availability but we are really interested in "system effectiveness". That is the probability of a system (or equipments) performing its mission when operated under specified conditions.

This can be illustrated by Fig 1 (show on view graph) which is a modification of a study performed by *ARINC for the Air Force. This illustrates the concepts associated with system effectiveness and the time categories involved. When possiblethe time category is shown as a block and its concept designation is shown in parenthesis. This type of designation is used only where time is "pure". If it must be combined with some non-operating time category (for example "availability" is a probability involving several time elements) we use the "concept" name only.

Usual relationships are shown by solid lines, and special types of relationships are shown by dotted lines. The combination of active repair time and operation time to give intrinsic availability is shown by a dotted line for two reasons. First, improvement in this characteristic must be achieved by the manufacturer, since it is primarily concerned with built-in equipment properties -- assuming, of course, that the user is staying within design limits. In the second place, it does not fit easily in the chain with maintainability, since active repair time is involved in both maintainability and intrinsic availability, while operating time is included in intrinsic availability but is not involved in maintainability.

For simplicity, the chart omits one relationship which could have been shown by a dotted line from free time to down time. This would have indicated the problem arising from non-continuous equipment use. Since free time does not exist for equipment in continuous use, a simple chaining of time categories is possible for this case. However, under conditions of intermittent use, there is a chance that down time may overlap free time, thus reducing the degrading effect of down time on operational readiness and hence on effectiveness.

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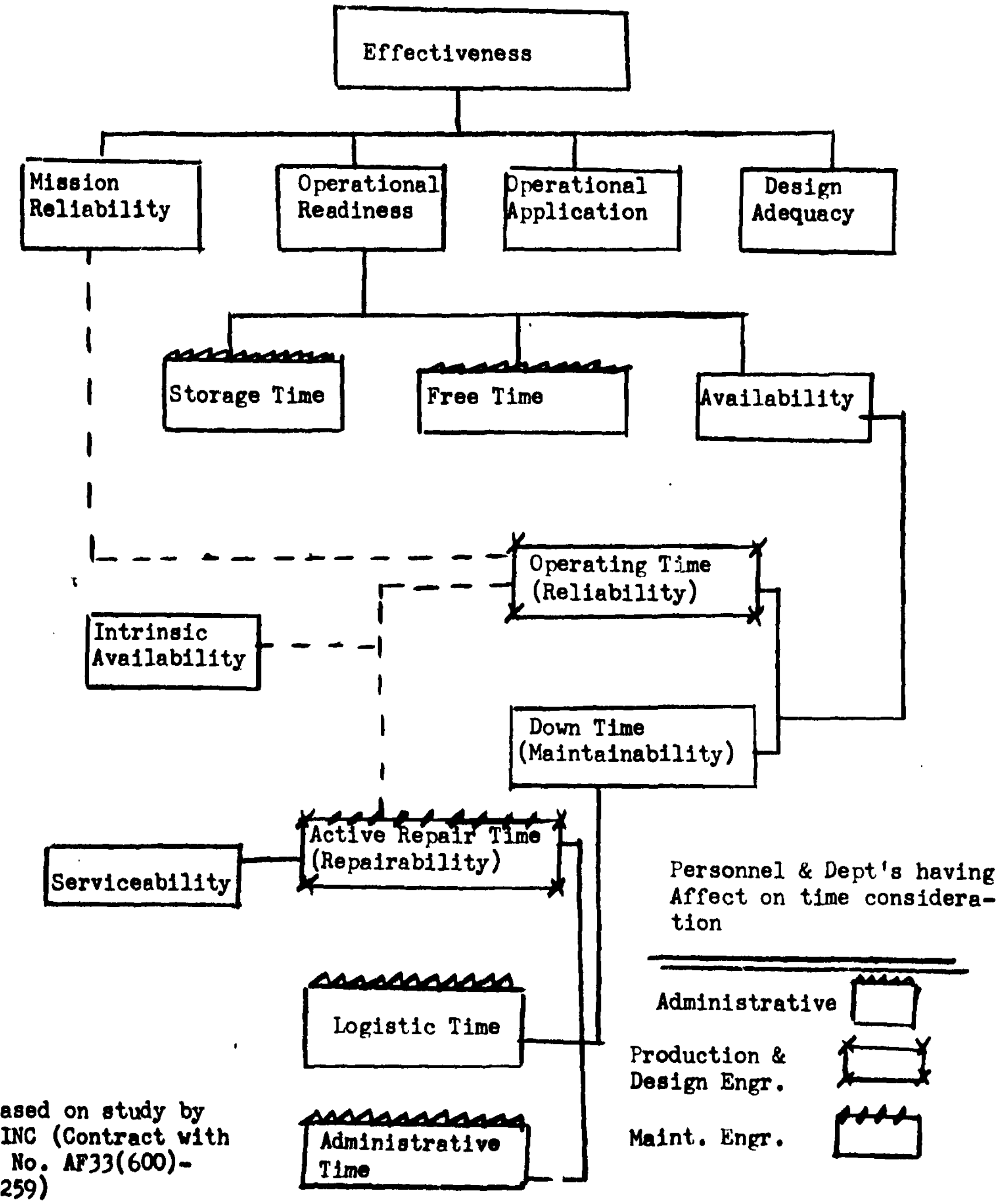
*AF Contract 33(600)40259

CONCEPTS ASSOCIATED WITH SYSTEM EFFECTIVENESS*



*Based on study by ARINC (Contract with AF No. AF33(600)-40259)

Figure 1

DEFINITIONS OF CONCEPTS

System Effectiveness is the probability that the system can successfully meet an operational demand within a given time when operated under specified conditions.

Reliability is the probability that the system will perform satisfactorily for at least a given period of time when used under stated conditions.

Mission Reliability is the probability that, under stated conditions, the system will operate in the mode for which it was designed (i.e., with no malfunctions) for the duration of a mission, given that it was operating in this mode at the beginning of the mission.

Operational Readiness is the probability that, at any point in time, the system is either operating satisfactorily or ready to be placed in operation on demand when used under stated conditions, including stated allowable warning time. Thus, total calendar time is the basis for computation of operational readiness.

Operational Application - The probability that a system is used in the environment for which it has been designed.

Availability is the probability that the system is operating satisfactorily at any point in time when used under stated conditions, where the total time considered includes operating time, active repair time, administrative time, and logistic time.

Intrinsic Availability is the probability that the system is operating satisfactorily at any point in time when used under stated conditions, where the time considered is operating time and active repair time.

Design Adequacy is the probability that the system will successfully accomplish its mission, given that the system is operating within design specifications.

Maintainability (Operational) is the probability that, when maintenance action is initiated under stated conditions, a failed system will be restored to operable condition within a specified total down time.

Repairability is the probability that a failed system will be restored to operable condition within a specified active repair time with a given manpower expenditure.

Serviceability is the degree of ease or difficulty with which a system can be repaired.

DEFINITIONS OF TIME CATEGORIES

Operating Time is the time during which the system is operating in a manner acceptable to the operator, although unsatisfactory operation (or failure) is sometimes the result of the judgment of the maintenance man.

Down Time is the total time during which the system is not in acceptable operating condition. Down time can, in turn, be subdivided into a number or categories such as active repair time, logistic time, and administrative time.

Active Repair Time is that portion of down time during which one or more technicians are working on the system to effect a repair. This time includes preparation time, fault-location time, fault-correction time, and final check-out time, for the system and perhaps other subdivisions as required in special cases.

Logistic Time is that portion of down time during which repair is delayed solely because of the necessity for waiting for a replacement part or other subdivision of the system.

Administrative Time is that portion of down time not included under active repair time and logistic time.

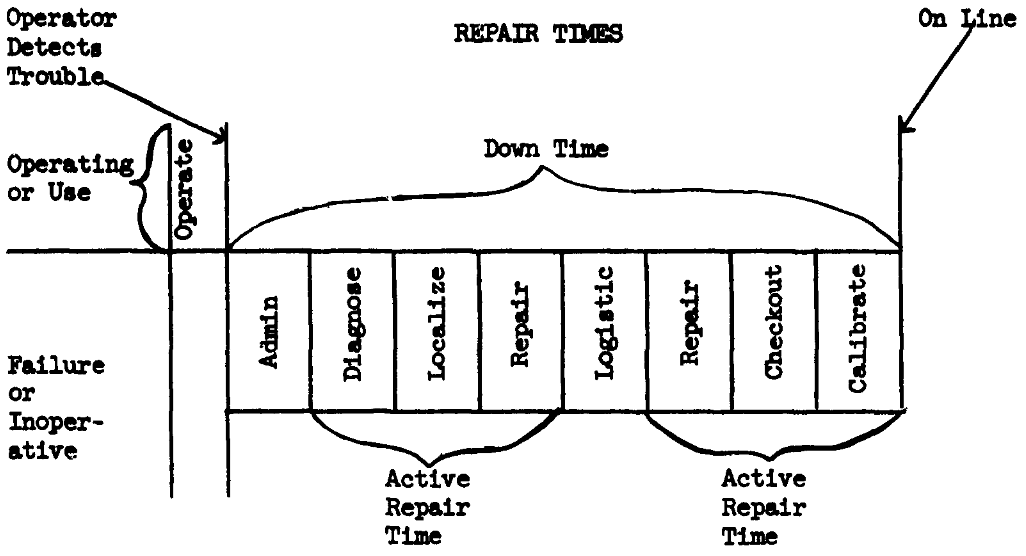
Free Time is time during which operational use of the system is not required. This time may or may not be down time, depending on whether or not the system is in operable condition.

Storage Time is time during which the system is presumed to be in operable condition, but is being held for emergency -- i.e., as a spare.

AVAILABILITY

We have now fitted availability, maintainability and time into the overall concept of system effectiveness. Let us now look at these breakdowns into their finer subdivisions. "Availability" basically is the percentage of time the equipment/system is usable, taking into account its "Reliability" (MTBF) and its "operational Maintainability" (MDT). For ESD purposes in the real world we must be more specific and see what the finer, more detailed divisions are.

We have Figure 2 (Time Breakdown of Systems/Equipment). (Show view graph) Actual quantification examples will be covered by the next speaker.



Availability (Sometimes referred to as Operational Availability) = Probability that the system or equipment is operating satisfactorily at any point in time when used under the specified conditions. This includes all down time.

$$A_o = \frac{\text{MTBF (Including Ready Time and Operating Time)}}{\text{MTBF} \neq \text{MDT}}$$

Availability (inherent) = The probability that the system or equipment when used under stated conditions in an ideal support environment shall operate at any given time. A_i excludes ready time, logistic time, administrative time.

$$A_i = \frac{\text{MTBF (operating time only)}}{\text{MTBF} \neq \text{MTTR (active time only)}}$$

You will note now that we have modified the "downtime" and the "uptime" by several additional time subdivisions. They may have a strong effect on the probability statistic.

It is important to note that in continuous operating systems such as most ESD Command and Control systems, preventive maintenance is included in downtime (MDT) as well as corrective maintenance and must be used in your calculations.

(Fig 2)

ANALYSIS OF DOWNTIME

Administrative Downtime or Waiting Time - Downtime, other than supply downtime during which work is not being done on the system.

Active Maintenance Downtime - The time during which work is actually being done on the system/equipment from the time of recognition of an occurrence of failure to the time the equipment is back in operation at its specified performance level. Includes both preventive and corrective maintenance.

Here we start our actual maintenance work. This involves the "detection" that the operation of the equipment/system is unsatisfactory, to "localize" the trouble to the component or rack involved. The "Diagnosis" which is the determining of the location of the malfunction the "Primary maintenance" (which will be defined later), "replacement" or the part or plug in unit. "Test" of the equipment and going back on the air and "check out." It usually takes longer to localize and diagnose the trouble than it does to do the actual repair.

Supply Downtime or Logistic Downtime - That time during which work is not done on a system because of the unavailability of a needed item from the usual supply.

Total Downtime - The number of calendar hours that a system is not available for use, including time for active maintenance, both corrective and preventive; supply downtime, due to unavailability of a needed item; and waiting or administrative time, during which work is not being done on the system.

MAINTAINABILITY

We should differentiate now between "maintainability"- the capability for an equipment to be restored to condition and "maintenance" which is the work done on the equipment. Maintainability, like Reliability is a design parameter.

Design for Maintainability - Those features and characteristics of a system/equipment design which reduce requirements for support including tools and test equipment, facilities, spares, training and highly skilled personnel required to perform maintenance and which improve the capability to accept maintenance actions.

These items are gone into in somewhat greater detail in Section 3 of MIL-M-26512B. This specification carries considerable weight and should be incorporated into your contracts and subcontracts. To assure compliance it should be monitored closely. We are not adverse to trade-offs in maintainability but we do want them documented.

These factors are quite inclusive. They cover the equipment proper, the tools and test equipment to support it, and the personnel which operate and maintain it.

Keep in mind that by designing more readily maintainable equipment and alternate modes of operation (back up modes) we can improve "Availability".

MAINTENANCE

Maintenance - All actions necessary for the retaining of material in, or restoring it to serviceable condition, including servicing, repair, modification, modernization, overhaul, inspection, condition determination and initial processing of support items.

We have Figure 3 (Maintenance Levels and Organization) (Show on View Graph) which covers the basic breakdown of Air Force Maintenance activity. In essence Air Force Maintenance is based on the three echelon system: "Organizational", "Field", and "Depot". By the illustration given we can see the organizations involved, work assigned, personnel assigned, and points of operation.

MAINTENANCE LEVELS AND ORGANIZATION

	Organization	Work	Location	Personnel
Organizational	Using Command	Trouble shooting Alignment Calibration Performance Test Periodic Inspections Preventive Maintenance Corrective Maintenance Remove and Replace components TCTO Compliance	At site	Repairmen, Operators Tech Skills 3 to 7
Field	Using Command	Bench check of components Repair of parts TO compliance Calendar inspections Functional acceptance checks Testing Calibration TCTO compliance	At site, or field maintenance shop, or mobile repair shop	Repairmen Skill Level 3 to 7
Depot	Logistics Command	Major overhaul Complete rebuilding TCTO compliance TO compliance	At site by depot teams, or at Depots	Contractor personnel or Repairmen Skill Level 3 to 7

(Fig 3)

Maintenance (Organizational) - The maintenance which a using organization performs on its own equipment at the equipment site or flight line. Consists of trouble-shooting functions; necessary alignment, calibration, and performance test; prelaunch, preflight daily, or other periodic inspections; preventive and corrective maintenance, and removing and replacing components.

Maintenance (Field) - The maintenance normally performed at the maintenance shop located at the equipment site. However, it may be necessary to perform field maintenance on the installed equipment or flight line for certain items that are difficult or impossible to remove because of size or method of installation. Consists of the bench check of components, repair of unserviceable parts; accomplishing technical order compliance and calendar inspection; performing functional acceptance checks on equipment initially received from supply sources; and testing, calibration, and reclamation as authorized.

This is the work usually done by the maintenance shop at the main base site. Sometimes it is done by mobile repair shops. On occasion, due to special problems, they may do work on the installed equipment. Personnel are part of the using command.

Maintenance (Depot) - That maintenance which is beyond the responsibility or the capability of the using command. Involves work performed on material requiring major overhaul or complete rebuilding of components. Normally accomplished at Air Force Logistic Command facilities or commercial maintenance shops, but sometimes performed in the field by depot maintenance teams. This is the work usually performed by the AFLC Depots and corresponds to 5th echelon maintenance in Army units. It is supposedly capable of complete rebuilding of equipments. Frequently, this is contractor maintenance.

Repair Facilities - Let us consider now the AF Maintenance Organizational set up. Basically, it is performed in 3 echelons namely Organizational, Field, and Depot. Before going into the MIL-STD-829 definitions, I would like to analyze what we expect from "Maintenance." This involves "all actions necessary for the retaining of material in, or restoring it to a serviceable condition. Maintenance includes servicing, repair, modification, modernization, overhaul, inspection, condition determination, and initial provisioning of support items." You will note that this includes preventive maintenance ("retaining of materiel") and corrective maintenance ("Restoring it to a serviceable condition").

I'd like to bring in here two variations on the basic definitions by adding: "Primary Maintenance" - "The technique of performing a maintenance action in minimum time without isolating the specific cause of failure." For example: replacing a defective plug-in unit. "Secondary Maintenance" which is defined as "a maintenance action on the replaceable unit to restore the unit to specified performance." This is usually done away from the original equipment as a bench operation. Considerably more equipment (test, etc.) is usually required. Frequently, this is beyond the scope of "Organizational maintenance."

Total Maintenance

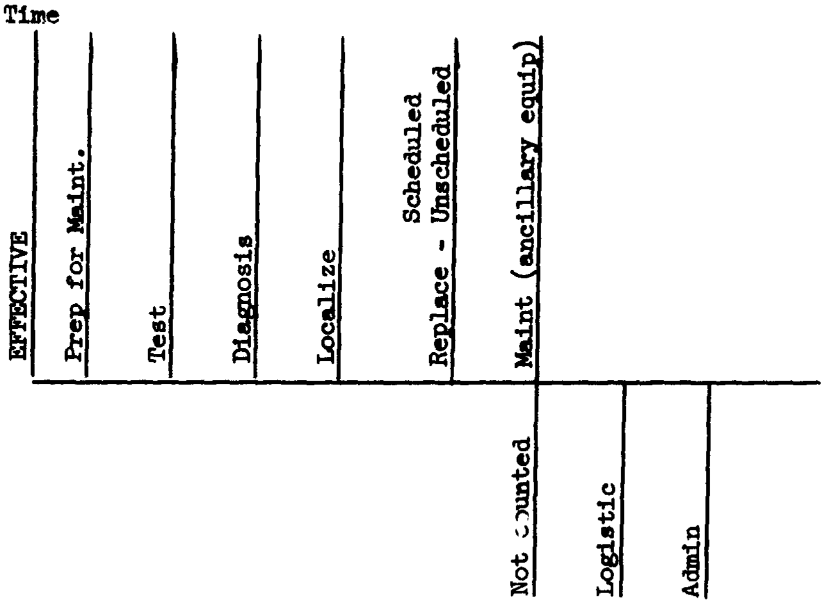
a. "Preventive Maintenance" - That maintenance performed to maintain a system or equipment in satisfactory operational condition by providing systematic inspection, detection and correction of incipient failures before they occur or develop into major failures. Keep in mind that this means "downtime" just as much as when we refer to "corrective maintenance" of operating equipment but we call this "scheduled downtime". In standby equipment this does not affect availability. We may replace parts still functioning in a satisfactory manner because of schedule replacement, or because marginal testings has indicated trouble may be near. P.M. is substitute for improved reliability or quality but it does not improve reliability of itself. It does help to improve "operational readiness".

b. "Corrective Maintenance" - That maintenance performed on an unscheduled basis to restore equipment to a satisfactory condition by providing correction of a failure which has caused degradation to the equipment below its specified performance. Here are the repairs to equipment which has failed or malfunctioned. It involves use of maintenance personnel as distinguished from adjustments which can be performed by the operator such as frequency drift, correction, etc. Within the concept of corrective maintenance, redundancy can be considered. In general, there is a "switchover redundancy" in which a failure is compensated for by another unit being put into service, "switchover standby redundancy", and "priority redundancy" where the second unit is in operation at all times. In some of our systems, we have redundancy on a priority basis in which some equipment which in use may be used to carry on the prime job.

NOTE: All maintenance time should be logged in with proper breakdown given. AFM 66-1 is the basic manual covering Air Force procedures. This is being modified for Electronic Systems reporting.

Effective Maintenance Time - (See Fig 4) (Show on View Graph)

Effective Maintenance Time - The cumulative summation of (but not limited to) all the time spent by maintenance people in; preparing equipment for maintenance, testing and inspecting to isolate faulty components and systems, performing scheduled or unscheduled removal, replacement and repair of systems and/or components, maintaining and operating ancillary equipment associated with the end article. This maintenance does not include logistic time lost from actual maintenance due to delays caused by lack of parts and components. It does not include administrative time by maintenance, accounting, clerical, and supervisory personnel.



(Fig 4)

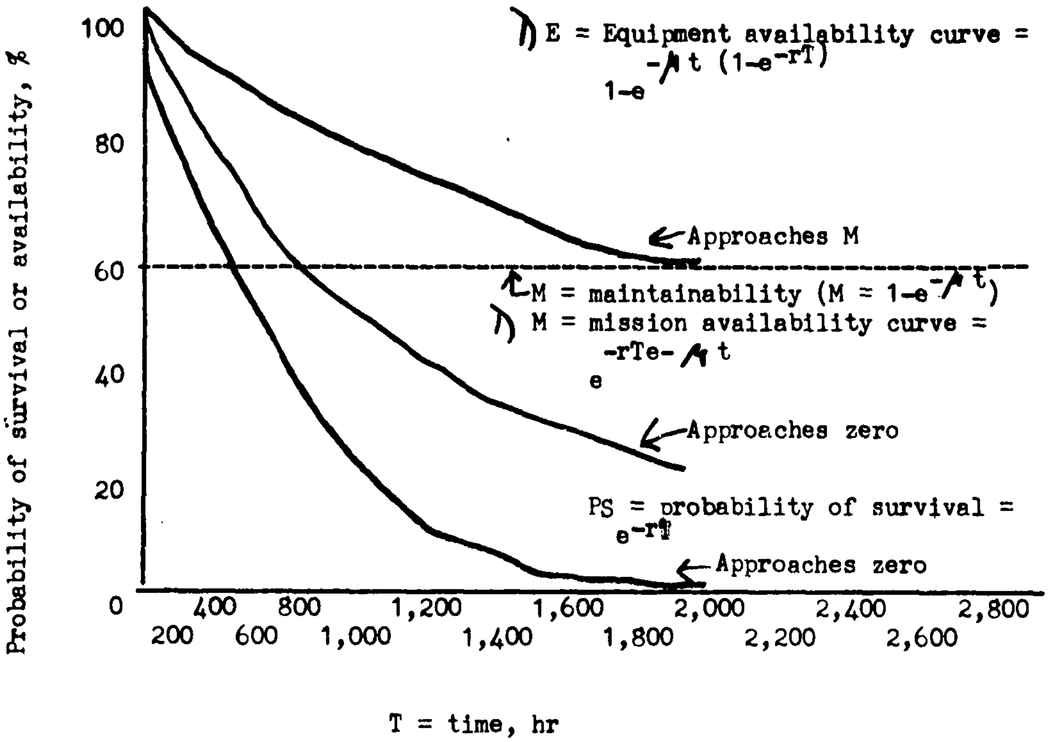
Note the above is active time. It does not include admin. time or supervisory personnel unless actively engaged in maintenance work.

An important point however in our work at ESD is that our systems (C&C) generally call for continuous operation and frequently have redundant equipment sections or subsystems. Perhaps we need a few new definitions to cover these conditions to help analyze what we can expect in operations.

For "Mission Availability", we define it as the probability that a stated percentage of missions of time duration "T" will not have any failure in any mission which can not, through repairability, be restored to service in a time equal to, or less than the time constraint "t".

For "Equipment Availability" - The probability that a stated percentage of equipment will be available for use at time "T" due to the combined effect of the survivors and units restored to service through repairability, in a time equal to, or less than, the time constraint "t."

By use of these definitions, we can now develop the mathematical relationship between Reliability-Ps, Equipment Availability-ηE, and Mission Availability -ηM.



(1)

These will be developed by the next speaker but the graph illustrates the relationship of "Maintainability(Operational)" to improving the P_s.

(1) Chart and definitions from
Reliability Principles and Practices
by S.R. Calabro (McGraw-Hill)

1 Atch
MIL-STD-829

QUANTITATIVE MEASURES OF MAINTAINABILITY

S. R. CALABRO

AEROSPACE ELECTRONICS TECHNOLOGY, INC.

SUMMARY

This paper stresses the importance of specifying maintainability in a quantitative manner, and compares the advantages of doing this over past qualitative descriptions. It also includes the mathematical models which are used for time availability, mission availability, and equipment availability. The importance of the time constraint is also stressed and a nomograph which facilitates trade-offs between maintainability and reliability is explained.

In the past, many of the definitions of maintainability were qualitative in nature. As an example, a typical Department of Defense definition states that:

> "Maintainability is a quality of the combined features and characteristics of equipment design which permits or enhances the accomplishment of maintenance by personnel of average skill under natural and environmental conditions under which it will operate".

It is obvious that such qualitative definitions are subject to various interpretations, and because of this, quantitative definitions have been developed. For example, a current definition of maintainability is:

> [1] "Maintainability is the probability that a device can be restored to operational effectiveness within a given period of time when the maintenance action is performed in accordance with prescribed procedures".

Another quantitative definition is that of repairability in MIL-STD-829 (USAF):

> "Repairability is the probability that a system/equipment will be repaired once started, in a given period of time with a given manpower expenditure".

It should be noted that both these definitions assess the probability of the maintenance action being performed within a given period of time. This time interval has been labelled the "time constraint". This is an important concept because it puts a time limi-

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[1] The definition of maintainability is a quote from "Reliability Principles and Practices", Page 113, by S. R. Calabro, published by McGraw-Hill Book Co.

tation on the maintenance activity which is necessary to achieve mission success.

If we assume that repair time is exponentially distributed, it facilitates the development of the quantitative measure of maintainability. Despite arguments to the contrary wherein it is claimed that the exponential is not the proper distribution to use, since the limit of all distributions is the exponential, its use is within the acceptable limits of accuracy for prediction techniques. This is no different than the practice which has been successfully used in reliability prediction techniques, despite the fact that in some instances, the exponential is not completely applicable.

If the mean time to repair is labelled ϕ, we can express the probability of performing zero repairs in time t as exp $(-t/\phi)$. Therefore, the probability of performed one or more repairs in time t, or the repairability is the unity complement, namely:

$$R = 1 - e^{-t/\phi} \qquad (1)$$

Since the reciprocal of ϕ represents the repair rate u expressed in terms of number of repairs per hour, the repairability equation can, therefore, be expressed in terms of u, instead of ϕ, as:

$$R = 1 - e^{-ut}$$

Having established the repairability equation, it should now be a relatively simple task to predict the maintainability of a device once the time constraint and mean time of repair have been established. The mean time of repair is dependent on at least the following: the maintenance discipline which will be employed; the qualifications and training of maintenance personnel; and the types of tools and test equipment which will be used. All of these, in turn, being a function of any cost limitations.

Moreover, these factors have a bearing on the time it will take to diagnose, localize, and repair a failure. For example, if the maintenance discipline prescribes that failures will be repaired at the part level, we will obtain a different repair time than if pluggable or throwaway replacements are specified.

When protypes are involved in a contract, the mean time of repair can be determined as illustrated in the following example.

[1] Example: Data from a reliability test were collated and tabulated below. Calculate ϕ and u. What is R expressed in per cent for l hr? 2 hr? 10 hr? What conclusions can be drawn from the calculated results?

Solution. Raw data were re-arranged as shown. Column 1 shows the number of times that a repair action occurred, with a duration as indicated in Column 2. The totals for each Column are shown. The mean repair time ϕ is the ratio of the sum of Column 3 to the sum of Column l.

[1] See example 9-1 "Reliability Principles and Practices" by S. R. Calabro, published by McGraw-Hill Book Co., Page 121.

(1) Frequency of occurrence	(2) Duration of each maintenance action in hours	(3) Product of Columns 1 and 2
2	1	2
4	2	8
7	3	21
13	4	52
16	5	80
16	6	96
24	7	168
10	8	80
6	9	54
4	10	40
3	11	33
1	12	12
106 Total number of occurrences	78	646 Total maintenance hours

* These data were rounded off to the nearest hour merely to simplify calculations.

$$\phi = \frac{646}{106} = 6.09 \text{ hr.}$$

$$u = \frac{1}{\phi} = \frac{1}{6.09} \text{ repairs per hour}$$

Substituting in equation (1):

$$R\ (1\ \text{hr}) = 1 - e^{-0.162} = 15 \text{ per cent}$$

$$R\ (2\ \text{hr}) = 1 - e^{-2(0.162)} = 28 \text{ per cent}$$

$$R\ (10\ \text{hr}) = 1 - e^{-10(0.162)} = 80 \text{ per cent}$$

The results highlight the obvious fact that for a given repair rate, the greater the value of t, the greater the probability of repair.

If no prototypes are available or if testing time is limited, the repairability may be predicted by simulating each repair action step by step in a manner similar to time and motion study techniques. A wooden mock-up may be used for this purpose or applicable time and motion study time units for various skill levels.

The next example features a typical repairability prediction at the component level.

[1] Example: A radio receiver consists of 5 components, namely: power supply, R-F stage, Mixer, I-F stage, and Power Output stage. The failure rate for the entire receiver was predicted to be 176.37 per cent failures/1000 hr.

(a) Estimate the value of the mean time between failure, m and repair rate, u for the receiver if the replacement times for each component are equal and 0.1 hour in duration.

(b) Estimate the value of ∅ and u if the failure rates of each component expressed in terms of per cent per/1000 hr are respectively 15.28, 40.28, 33.58, 54.34, and 32.89, and the estimated replacement times for each component in hours are respectively 0.1, 0.15, 0.2, 0.3, and 0.4.

Solution.

$$\text{(a)}\quad m = \frac{1}{0.0017637} = 567 \text{ hr}$$

Since the replacement times for each component are equal, their relative frequency of failure is not considered and, therefore, the replacement time of 0.1 hr is the mean repair time of the receiver ∅. The repair rate of the equipment u_e is:

$$u_e = \frac{1}{\emptyset_e} = \frac{1}{0.1} = 10 \text{ repairs per hr.}$$

(b) When the replacement times are not equal for each component, we must first tabulate the data as shown in the following table. Assume a mission time T of 1000 hrs.

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[1] See example 12-2 "Reliability Principles and Practices" by S. R. Calabro, McGraw-Hill Book Co., Page 219.

TABULATION OF DATA

(1) Nomenclature	(2) Probability of failure of each component in time T. $P_f = 1-e^{-rT}$	(3) Relative failure frequency	(4) Estimated component replacement time ϕ_c hr	(5) Product of columns 3 and 4
PS	0.148	$\frac{0.148}{1.463} = 0.101$	0.1	0.0101
R-f	0.330	$\frac{0.330}{1.463} = 0.225$	0.15	0.0337
Mixer	0.286	$\frac{0.286}{1.463} = 0.196$	0.20	0.0392
I-f	0.417	$\frac{0.417}{1.463} = 0.285$	0.30	0.0855
PO	0.282	$\frac{0.282}{1.463} = 0.193$	0.40	0.0772
		$\Sigma f = 1.000$	$\Sigma f\phi_c =$	0.2457

$$\phi_e = \Sigma \frac{f\phi_c}{N_a}$$

where: f = frequency

ϕ_c = mean time to repair component

N_a = total number of repair actions $\left\{\text{i. e., in this case the sum of the relative frequencies which is unity}\right\}$

Substituting we get: $\phi_e = \frac{0.2457}{1} = 0.2457$

and $u = \frac{1}{\phi_e} = \frac{1}{0.2457}$ = 4.48 repairs per hour

The foregoing example represents a simplified version of the basic techniques which can be used to predict mean time to repair.

It must be realized, however, that many more factors must be considered, all of which have an effect on ø. RCA is currently working on a contract with the Rome Air Development Center, which although following similar prediction ideas, is much more sophisticated and detailed. It is expected that this study will add significantly to quantitative measurement techniques for maintainability.

Once having determined or predicted the mean time to repair; and the failure rate it now becomes possible to express availability quantitatively. The most familiar, but by no means the only measure of availability, being the up time ratio (UTR). The UTR is the ratio of the mean time between failure (MTBF) to the sum of the MTBF and mean down time.

It can also be expressed in terms of u and r as follows:

$$\Lambda = \frac{u}{r + u}$$

There are two other measures of availability which should be of some interest. These are mission availability and Equipment or Product availability.

"Mission availability is the probability that a stated number of missions of time duration T will not have any failure in any mission which cannot, through maintainability, be restored to service in a time equal to, or less than, the time constraint t".[1]

"Equipment availability is the probability that a stated percentage of equipment will be available for use at time T due to the effect of the survivors and units restored to service through maintainability in a time equal to, or less than, the time constraint t".[1]

The mathematical expressions for these two forms of availability are respectively:

$$\Lambda_M = e^{-rTe^{-ut}} \qquad (3)$$

$$\Lambda_E = 1 - e^{-ut}(1 - e^{-rT}) \qquad (4)$$

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[1] See pages 125 and 126, "Reliability Principles and Practices by S. R. Calabro, published by McGraw-Hill Book Co.

Figure 1 shows the curves for probability of survival, P_s, when no maintainability is practiced, and Mission and Equipment availability when $u = 4$, $t = 0.25$ hr and $r = 0.001$ fph.

It should be noted that the P_s curve approaches zero at a much faster rate than the mission availability curve, Λ_M. This is due to the fact that those missions which have no failure exceeding 0.25 hours in duration are considered to be a success. It should be obvious, therefore, that the greater the time constraint which can be permitted, the more the economy and greater the success of missions so defined.

The Equipment availability curve never approaches zero because as the mission time approaches infinity, the probability of survival of original units approaches zero, and therefore, the percentage of survivors with failures not exceeding more than t hours to repair approach a limiting value as an assymptote and equation 4 becomes the maintainability equation

$$M = 1 - e^{-ut}.$$

[1]Figure 2 shows a nomograph which is a very useful tool for the designer. Through its use, for a required equipment availability, he can trade off between reliability and maintainability.

It consists of three scales. The extreme left-hand scale plots the average number of failures rT which product is symbolized as d. Similarly $b = ut$ on the right-hand scale is representative of the average number of repairs which can be performed in time t for a given value of u.

Thus for a required value of Λ_E, a compromise can be made between the most economically values of b & d, which will provide the availability. This also determines the failure rate, r, and repair rate, u, once the mission time, T, and time constraint, t, have been determined by mission requirements.

For small values of d Λ_E and Λ_M are approximately equal (see figure 1). For larger values, a similar nomograph can be constructed for Λ_M.

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[1] See page 133, "Reliability Principles and Practices", by S. R. Calabro, published by McGraw-Hill Book Co.

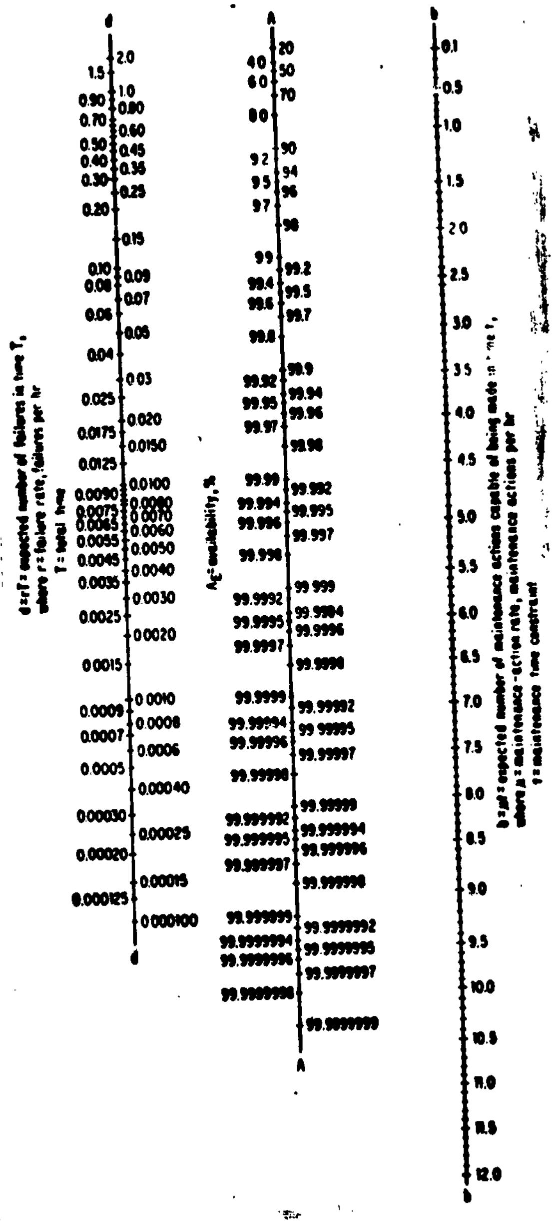

Fig. 2. Nomograph showing relationship between A_E, d and b.

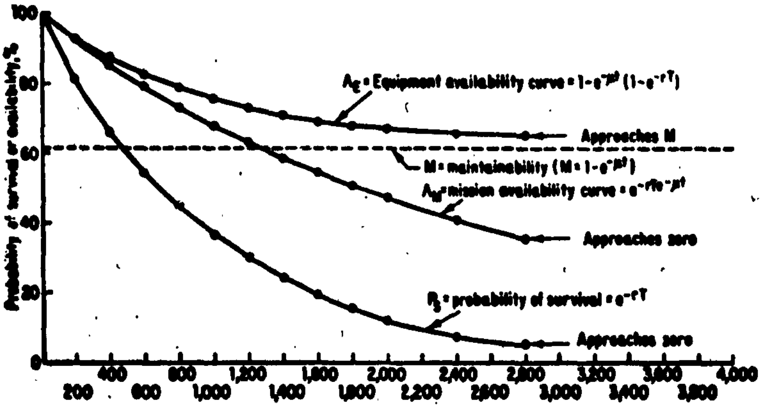

Fig. 1. Relationship between A and P_s. Availability and probability-of-survival curves. $u = 4$, $t = 0.25$ hr, $r = 0.001$ fph.

ON THE SPECIFICATIONS
OF
RELIABILITY, MAINTAINABILITY,
AND
AVAILABILITY REQUIREMENTS

by

Anthony Coppola

Rome Air Development Center
Griffiss AFB NY

Presented at
Maintainability Conference
12-13 March 1963

Electronic Systems Division
Laurence G. Hanscom Field
Bedford, Massachusetts

ON THE SPECIFICATIONS
OF
RELIABILITY, MAINTAINABILITY,
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SUMMARY

The preparation of adequate Reliability, Maintainability and Availability requirements involves the careful consideration of the form presents its own potential problems and these must be anticipated at the time the contractual documents are prepared. Disputes between the Air Force and the contractor can be avoided by careful preparation of requirements and such care will repay its cost.

INTRODUCTION

Air Force experience with Reliability, Maintainability and Availability requirements (R&M requirements) has revealed the recurrence of various problems which may be avoided by proper clarification of the requirements in the contractual documents. This paper will deal with the documentation of R&M requirements and, hopefully, will help the reader to minimize his future R&M contractual problems.

AGENCIES INVOLVED

Although the procuring activity designated by the Air Force is directly responsible for documenting contractual R&M requirements, both the using agency and a technical office specializing in R&M should also be involved. The needs of the user are, of course, of primary importance and must be considered in formulating R&M requirements. It is the job of the R&M specialists to advise the procuring activity of the best approach to satisfy these needs under the time money and manpower constraints imposed on the procurement. The results of the efforts of all three agencies should then be an appropriate and realistic contractual requirement; these properties will be established by the form and magnitude of the requirement.

COMMON FORMS OF R&M REQUIREMENTS

a. MTBF

The requirement form most often employed has been Mean Time Between Failures (MTBF); this is the most appropriate form for procurement on the equipment (rather than system) level. The most frequent dispute arising from the use of this form is over the definition of failure. A contractor will often request that failures of certain parts, such as pilot lights, monitor circuitry, etc. not be counted against the equipment during reliability demonstration. The acceptability of such a request should be established when the requirement is written; it may be decided to permit such a procedure. As a general rule, however, failure should be defined as any departure from specified performance. If a pilot light is specified, failure of that light should be counted against the equipment. Many disputes will be eliminated if this point is established in advance.

b. MTR

Maintainability must be also specified and a Mean Time to Repair (MTR) requirement should accompany the MTBF requirement. On the same subject, a quantitative requirement defining an acceptable preventive maintenance period should be also clearly established.

c. Availability

Although MTBF and MTR are sometimes utilized for system procurements, availability requirements are more common. These requirements invoke their own problems. The first question that must be answered by the procurement documents is, simply, "when is the system considered available?" This may be when every component is available or when a certain minimum number is available. Either way is acceptable, depending on the particular system involved, and both have been used in different Air Force procurements. The form desired must, however, be stated in the procurement document, and when appropriate, the minimum number of components necessary for system availability must be stated.

Another problem with availability is the definition of component availability. The usual formula for availability is:

$$A = \frac{MTBF}{MTBF + MTR}$$

However, MTR does not include preventive maintenance time and it is sometime replaced in the formula by Mean Down Time (MDT). Again either term may be acceptable, but the desired one must be clearly specified. It should also be noted that the use of MTBF in the formula requires a definition of component failure.

d. Effectiveness

Finally, the use of various measures of effectiveness is possible. These measures, which include, for example, kill probability, incorporate R&M requirements with performance criteria in an overall specified probability of system success. While this is a worthwhile endeavor it requires extreme care in its use. System effectiveness is dependent on operating environment and thus the requirement must be based on a given, even if completely hypothetical environment. In addition, all the factors affecting system effectiveness must be demonstrable as the confidence in the achievement of the required effectiveness can be no greater than the confidence obtained for the achievement of the least measurable factor.

SELECTING THE MAGNITUDE OF THE REQUIREMENT

Once the form of the requirement is established, a figure must be selected. This figure must never be less than that obtainable without special effort under the existing State of the Art. Even "off the shelf" equipment should never be permitted to possess less reliability than its complexity indicates is within a normal capability. Selecting requirements for this type of equipment, as well as determining the magnitude of effort required to meet the needs of the user in any procurement, requires some measure of the existing State of the Art. The following are three methods employed by RADC as indicators of the State of the Art in equipment reliability.

a. Previous Equipment

The most obvious indicator of the State of the Art in reliability is that achieved by previous equipments. For this reason, reliability figures available to RADC are filed and consulted as necessary. Shortcomings of this method are that not all equipment experience finds its way to the files, statistical significance of data received is often undeterminable and the degree of similarity between existing and proposed equipments may be questionable. This method should, therefore, be utilized with caution.

b. Complexity Formulas

Another approach employed by RADC to determine a State of the Art figure is the use of formulas relating equipment failure rate to its parts count. Formulas have been developed for radar and communications equipment and for data processing equipment. The former is presented in specifications MIL-R-26474 and MIL-R-27070 as a means for determining quantitative requirements when no operational requirement is stated in the other procurement documents. Drawbacks to the method include the fact that the parts complement is usually not available before procurement of the equipment and thus the formulas indication of the State of the Art cannot be checked against the users needs before the procurement action begins.

c. Prediction by Function

The latest measure of the State of the Art in reliability under development by RADC is the prediction of reliability by equipment function. This method will permit the prediction of the reliability achievable in an equipment by State of the Art methods from an examination of the major functions of that equipment. For example, current studies relate the MTBF of a pulsed radar to its peak power output. Publication of this method is immanent and it will provide the procuring activity with a valuable tool for establishing realistic reliability figures in the future.

OTHER FACTORS TO BE CONSIDERED IN DOCUMENTING REQUIREMENTS

It should now be obvious that a definition of failure must be established at the time the requirements are documented. On this problem are hinged most of the disputes between contractors and the Air Force about R&M requirements. Other items, however, also cause difficulties, and some of these items are:

a. Requirements vs. Goals

The specified figures are R&M requirements not goals. It would be most helpful if contractors would cease changing these words in the contractual documents they prepare. Cases have existed where four successive versions of a contractor generated specification have labelled R&M requirements as goals despite repeated rejection by the Air Force. The only way to correct this situation is for the Air Force to stand firm on calling a requirement a requirement until the contractors are convinced that it is, indeed, a requirement.

b. Unrealistic Requirements

A requirement does not have to be too lenient to be unrealistic. One Air Force system even now possesses a requirement for operation "24 hours a day, 365 days a year." This requires perfection and such requirements are generally as enforceable as no requirements at all. (The system in question, fortunately, has been subjected to a thorough reliability program and hence has not been cause for alarm. However, the Air Force could have been in serious difficulties in enforcing this requirement if the contractor did not accept its intent.)

c. Follow-up Requirements

It is not sufficient to specify only the R&M requirements. It must be clearly required for the contractor to pursue an active program for achieving these requirements. This program should include design guidance and review, prediction and verification of achievement. There must be sufficient documentation for the Air Force to monitor program progress. It is well to remember that the contractor must deliver only those items specified regardless of any verbal promises to do better.

d. Verification

The demonstration of achievement of the R&M requirements must be specified. Such demonstration is costly and time consuming; without it, however, any R&M problems with the equipment must be corrected in the field after the contractor's liability has ended. This is far more costly and time consuming. There are many ways for demonstrating reliability with varying degrees of confidence. The advice of a R&M specialist in determing the tests to be required would be of great value. On this point, it should be stressed that the method of test must be compatible to the requirement. If, for example, the requirement is computed on the basis of a parts count, then the failure of any part on the list must be counted regardless of the actual effect on equipment performance.

CONCLUSION

The reader should not conclude from the preceding discussion that contractors should not be trusted. He should, however, realize that the Air Force has a right to insist on delivery of only those items specified in the contractual documents. In addition, any items not clear or well defined may result in disputes which, however settled, do not benefit either the contractor or the Air Force in the long run. It is far better to spend days in preparation of a clear, appropriate and realistic requirement than to risk months of dispute and a final unsatisfactory solution. If the reader will do no more than apply some extra thought to the preparation of the next requirement with which he is involved, this paper will have been worth its presentation.

AFSC MAINTAINABILITY POLICY

by

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Hq AFSC

Presented at
Maintainability Conference
12-13 March 1963

Electronic Systems Division
Laurence G. Hanscom Field
Bedford, Massachusetts

AFSC MAINTAINABILITY POLICY

Major William P. Crumpacker

Hq AFSC

By now there should be little doubt by anyone that Maintainability (M) is essential if our systems are to be effective. M is a definite requirement that cannot be brushed aside or given just lip service. It is not going to go away. Close monitoring beginning at DOD is a reality. Non-compliance at any level is a risky venture. Past records and data from reporting systems such as AFM 66-1 and AFM 65-110 show the tremendous impact of poor M. As our systems become more complex, and they will, it doesn't take much forecasting to show that they may become virtually impossible to maintain so as to meet availability requirements and accomplish their mission. As far as costs go, it is rapidly becoming a matter, not of spending dollars early to reduce the total cost, but spending now so the total cost will be economically feasible.

The AFSC policies are concerned with M beginning with the receipt of the SOR. This assumes that we are ready with all the knowledge necessary to provide the required M. We still need to increase our knowledge of M but today with what we know we can achieve M. We have our policies, regulations, specifications, etc. that are necessary to promote a fine system M program, yet there is still some degree of apathy or reluctance on the part of managers to forge ahead. The management aspects are solid and follow an approach that has been proven to be successful many times. Perhaps a discussion of the comments received by AFSC that question the validity or soundness of the M program will reveal more than a mere listing of current policies.

These evidently are the points that need clarification.

1. How should M requirements be expressed?

Here we are talking about quantitative M requirements. There is no one numerical figure that has been developed that can express systems M requirements for all types. AFR 66-29A gives some guidance regarding statements of requirements. For the using command the operational ready rate is probably the most important factor. M is not the only contributor to this factor but it is an important and integral part of it. The availability requirement used frequently by ESD in L systems is almost synonomous with operational ready rate. To take a step closer to pure M the apportionment and breakdown of available time to perform defined maintenance tasks is one of our best measures of M. These can be expressed in terms of MTTR, remove and replace times, turnaround time, servicing times, checkout times, etc. Subsystems should be allocated a limit of contribution to downtime and MTCE manhours. These do not consider cost particularly but do allow determination of discrete time requirements to meet mission objectives. Meeting time requirements does not particularly assure ease nor economy of maintenance. The maintenance manhours/task, skills, support equipment, etc. are also important requirements or limitations that must be expressed. Requirements must be related to the 3 levels of maintenance with primary emphasis on organizational, field next, and then depot. Statements of requirements have been recognized as a major problem in M and I would like to mention a few actions being taken to resolve it. There was a symposium at Seattle hosted by Boeing on this subject. The 2nd Annual AF/Industry meeting at Andrews 26 - 28 March has a panel devoted to measurement of M and the AF M Manual now being written is to give guidance at all levels on how to express M requirements.

Obviously these requirements must be in the SOR, PSPP, SPP, RFP's and be stated in the contract. Many of our comments come from SPO organizations regarding negotiations. One that worries me is the remark that the contractor hired a M expert with a PHD and that he, through a series of questions that would probably baffle most of us, confused the situation to a point where the M requirement was deleted because the AF negotiator was convinced we didn't know what we wanted. This is not the teamwork we envision. It may be true our requirements need more definitization and clarification is in order, but the failure to resolve these questions during RFP and prenegotiation contacts with the Air Force and waiting until the last minute leaves reasonable doubt as to good intentions of all involved. This situation, though infrequent, can easily be corrected by proper planning by both parties and getting together to reach a mutual understanding. Maintainability has progressed beyond the question of whether quantification is required. It is a definite requirement. General statements such as "the system should be easy to maintain" are completely unacceptable as well as quantified values that are stated as goals or objectives in contracts. They are almost meaningless except as targets above a specified minimum acceptable requirement that must be met.

2. How can we be sure our requirements are realistic?

This question normally comes from the uninformed after a long series of other questions about why M in the first place. Worrying about the possibility of unrealistic requirements is not as big a problem as determining what M is required to assure the mission accomplishment. Conceivably a new system will not be able to perform because it cannot be maintained without advances in M beyond our capabilities. I would hope this would be recognized early. It may be that the system would truly not be feasible. We are getting close to that situation now with some of the systems envisioned. R & M data, along with AFM 66-1 and AFM 65-110 data, can to a great extent tell us what is feasible or realistic. If the requirement appears too stringent, there are many tradeoffs that can be effected before and certainly after the SOR by both the Air Force and the contractor.

3. Where do we get the money?

[redacted]

Additional requests for money for M is basically a result of lack of planning. This problem is intensified when we try to back into some already going programs. M is then a separate package that can be bought or not. Funds were never planned for it as they should have been and it becomes another one of those "abilities" that are considered by some to be nice to have but we cannot afford. Costing M is somewhat akin to costing speed or altitude for an aircraft. When we have to back into a program we must get a cost figure but on a new one it is an integral part of the systems cost and not a package on the side that can easily be cut in a cost reduction exercise. If we believe we have a balanced program at the beginning we should maintain such a balance and when cuts occur balance them also. On a new system we should never ask the contractor to bid and quote costs with and without M. The many checkpoints established for review of SORs, PSPPs, SPPs and contracts are catching those documents early that do not have M requirements. We at Hq AFSC are now reviewing all contracts for definitization over a certain amount for R and M requirements and disapproving those that are not satisfactory. We do not arbitrate on the level of the requirements but determine if they comply with current directives. Most Divisions have set up an internal check with the Division procurement review board and the Division R & M office to assure their approval at Hq AFSC. Provisions in RFBs and letter contracts are still a problem. A revision to the AFPI has been submitted that will include R & M provisions in RFBs as a check list item. PMI 1-9 now includes M program and MIL-M-26512B as check list items for technical proposal work statements. A major effort is underway to eliminate letter contracts or at least reduce the time between them and definitization. All of these actions, for a large part, are to assure initial funds and eliminate those last minute added on requests.

4. What about MIPRs?

AFSC policy on this is that if we are the acquisition agency we request the M requirements of the product and funds or obtain a signed waiver from the other service or agency stating no requirement exists. If it is a joint use system, AF will include the AF requirement. If another service is the acquisition agency the AF will include the M requirement with funds. This should come out in AFSCR 70-2 shortly.

5. Do we really need M people in the SPO?

The answer is definitely yes. It is one of our basic M policies. The M programs in our systems programs must be managed. Contract work statements alone cannot take the place of an M coordinator in the SPO. Furthermore, we require the contractor to identify an organization or individual responsible for the contractor's M effort. We must provide a matching focal point and manager that can and will manage the program. This position is required by AFSCR 80-9 and must be maintained. Without this man actively managing a program involving millions of your dollars M can easily slip through the crack in spite of contract requirements. Continued reliance on the Division M staffs only perpetuates the problem.

Today we do not have an abundant supply of qualified people for these positions. Some of the proposed training courses would help but now the selection of the best qualified man will have to do. M is such an interesting and challenging area that anyone assigned in the area for any length of time usually becomes enthused and shortly thereafter becomes quite proficient. We are working toward getting an AF specialty code for M personnel. This is a recognized requirement that should be met as soon as possible.

6. Now a question or request from industry: A common base for bidding.

This is a serious problem and no doubt is frustrating to contractors, especially those that are highly motivated to have the best M effort. The demonstration requirements appear to be the questionable area. Too often competitive contractors are left on their own to develop a demonstration plan without guidance as to the degree of assurance desired by the Air Force. The costs are volatile in this area and the contractor can easily price himself out by presenting an excellent program that is beyond our needs. I believe the "A" appendix of MIL-M-26512B that ESD uses is the best guidance in this area we have. We are hoping to get industries' views on this at the AF/Industry meeting and resolve this problem for all types of systems.

7. What about M data and status reporting?

The M status reporting of our systems is a requirement that will soon be an essential part of overall system status reports. The new AFSCR 80-1 Reliability requires a quarterly report on AFSC Form 144. Maintainability reporting in terms of MTTR and max downtime is included with R to aid in reporting availability as is used in some of the L systems of ESD. This is a first attempt at M status reporting and is tailored more for ESD than other Divisions.

Eventually we hope to be able to cover all types of systems. This, in conjunction with a proposed R & M data collection and feedback system compatible with and including AFM 66-1 and AFM 65-110, should provide some needed M standards and reflect the state of the art regarding system and equipment M.

These questions or comments about M reveal the common criticisms that appear to prevent the wholehearted acceptance needed. The vagueness concerning how to express M requirements must be clarified. We hope to standardize the parameters to the extent possible so requirements can be understood by all. If funding for M is included at the beginning it will be supported. The AFSC must increase the number of people assigned to M.

Quantitative M is a relatively new engineering discipline. Time and maintenance manhours were approached first because they are essential to mission accomplishment. We must progress to those parameters that define costs, spares, specialized equipment and tools, skills and other resources including depot support. We expect to rely quite heavily on the logistics command in jointly developing these other parameters.

In closing I would like to commend the ESD/RADC team and their contractors for their contributions in advancing M. The M studies conducted, "A" appendix of MIL-M-26512B, and the techniques used for M analysis and tradeoffs in some of the L systems are all examples of some of the most advanced M technology. Finally, more conferences such as this that extend beyond just M people talking to themselves and include the Divisions and SPO managers are needed to increase the knowledge and appreciation of the definite requirement for and means of achieving systems M.

ESD POLICY ON MAINTAINABILITY ENGINEERING

by

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Chief, Engineering Requirements Division

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ESD POLICY ON MAINTAINABILITY ENGINEERING

By

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SUMMARY

The ESD interpretations of the Air Force and Systems Command policies and directives relative to the design for maintainability during research and development of Command and Control systems are presented. The definition and mission of "L" Systems is described, the organizational structure indicated and the general modus operandi outlined.

The interrelation of maintainability with reliability is discussed in terms of availability for systems of long mission times along with the necessity for trade-off between these various characteristics.

Typical contractual statements for "L" Systems are cited with accompanying program plan development.

DEFINITION AND MISSION OF "L" SYSTEMS

The breadth and variation of the Air Force Systems Command's efforts require a means of categorizing these efforts into subelements for management and control. The AFSC program structure was developed to provide the criterion whereby each AFSC job is categorized in the program structure PS 400L through PS 499L. The command and control systems, often referred to as "L" Systems, are composites of equipment, skills, and techniques which, while not instruments of combat, are capable of performing the clearly defined function of enabling a commander to exercise continuous control of his forces and weapons in all situations by providing him with the information needed to make operational decisions and the means for passing on these decisions.

A complete system includes all subsystems, related facilities, equipment, materiel, services, and personnel required for operation of the system so that it can be considered a self-sufficient unit in its intended operational environment. The mission of these systems may then be stated as that of collecting, transmitting, processing and displaying information for command decisions and for control of forces, weapons and aerospace vehicles. From this simple mission statement for the systems developed by the Electronic Systems Division (ESD) we get a vivid picture of the importance of this work to the defense and survival of our nation and our allies. Without these systems there could be no early warning, detection, interception nor destruction of aggressor weapons in time to prevent destruction of our nation and resources.

To develop these systems, various USAF organizations have been amalgamated into a well coordinated team to provide a concurrent and harmonious approach to the task of providing electronic systems for command and control of aerospace forces. This team is comprised of representatives from research and development, logistics, training and the various using commands with specific system acquisition responsibilities being assigned to a specific System Program Office (SPO) identified by a program structure designator between 400L and 499L. Technical support for the program is provided by the Rome Air Development Center (RADC) at Griffiss AFB, Rome, New York and non-profit organizations such as MITRE. The officer in charge of the SPO has the official title of the System Program Director and as such is charged with the responsibility to develop and to deliver the first complete system to the using command on schedule, at the lowest cost possible and with the highest practicable capability, reliability and maintainability.

MAINTAINABILITY REQUIREMENT

The Department of Defense, Headquarters USAF, and the Air Force Systems Command have recognized the importance of maintainability in the system concept. They have issued directives and regulations to stress its considerations during early planning and feasibility study stages, as well as the need for comprehensive reliability and maintainability programs for operational development projects. These requirements are clearly enunciated in AFR 66-29A Maintainability Program for Systems, Subsystems, and Equipments and AFSCR 80-9 Research and Development Maintainability. These policies and procedures are implemented by the ESD Policy Letter No. ( ), and ESDR 80-( ) Research and Development Maintainability which are included as appendices 1 and 2 respectively.

We at ESD are dedicated to the maintainability precepts called forth in these documents and strive to enforce them to the maximum degree commensurate with the program requirements; however, we feel that our problems are slightly varied from those of other divisions. The Command and Control Systems are faced with excessively lengthy mission time, but on the other hand are blessed with the capability to perform maintenance on these ground systems. With these possibilities in mind, the ESD stresses the importance of "availability" which permits trade-offs between the design parameters, performance, reliability and maintainability. By achieving a short mean-time-to-repair (MTTR), a lower mean-time-between-failure (MTBF) can be tolerated and yet achieve the high percentage of availability demanded of the system. For this reason the reliability and maintainability program is considered as one whereby the optimum balance between all characteristics are sought to obtain the minimum system total cost and yet achieve the operational requirements with the desired confidence.

ESD POLICY ON MAINTAINABILITY

Maintainability is recognized as a major design factor and in conjunction with performance and reliability provides a major contribution to system effectiveness. Therefore, it shall be a prime consideration in the source selection, planning, design, development, production, equipment installation and operation of all electronic systems within the cognizance of the ESD. Each System Program Office responsible for the development of electronic systems, subsystems or equipments, will provide the necessary direction and control to achieve the required maintainability of that equipment.

Quantitative maintainability requirements shall be established for all electronic systems to be developed within the cognizance of ESD. These requirements shall be incorporated into each Request for Proposal (RFP), Proposed System Package Program (PSPP), System Package Program (SPP), Statement of Work (SOW), system/equipment specification and other contractual documents released to contractors.

These maintainability requirements will be expressed in terms of mean-down-time (MDT) with a constraint on the maximum or extreme value an individual down time will be allowed to assume. The constraint will be expressed as a probability (usually 90%) that no individual down time will exceed a specified interval of time.

These quantitative requirements shall extend through the contractors to the subcontractor and vendor levels. Each prime contractor will be required to impose quantitative maintainability requirements on each contractor which are compatible with the overall system requirements and will require subcontractor demonstration that the imposed requirements have been met or exceeded.

To assist in achieving the quantitative maintainability requirements, each overall system program will provide for an adequate contractor maintainability effort as prescribed in AFR 66-29A and MIL-M-26512B. What is considered to be adequate is determined by the program schedule, the type of equipments to be incorporated into a system, and the statement of quantitative maintainability requirements. However, each system program will provide at least the following key maintainability work elements:

a. Predictions, at selected milestones, of achieved system maintainability.

b. Formal maintainability design reviews.

c. Collecting, processing and analyzing downtime data from all scheduled tests.

d. Corrective action for causes of unmaintainability.

e. Demonstration of quantitative maintainability requirements.

f. Review of all ECP's and non-ECP's for maintainability effects.

g. Submission of periodic reports on maintainability program progress.

Each system program will contain major maintainability program milestones at which the SPO will review the progress of contractors and will take the necessary action to keep the maintainability program compatible, effective, and correctly time phased with other elements of the overall program.

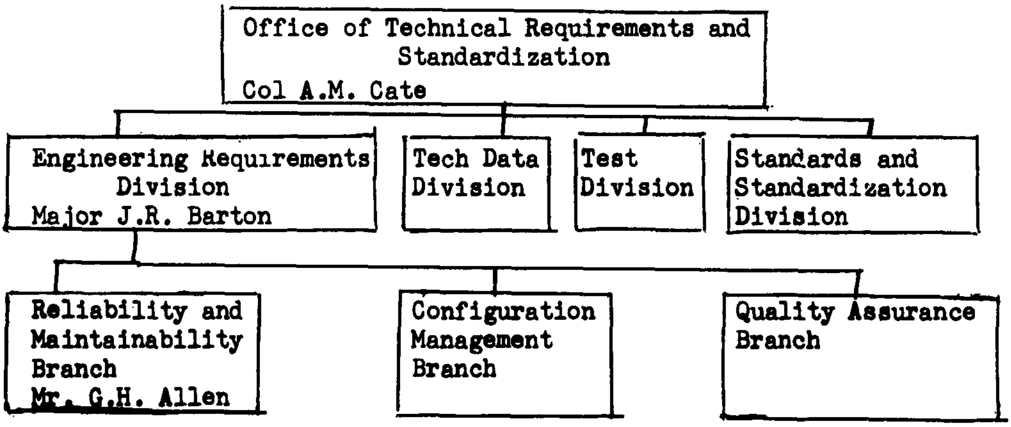
Funds will be provided for maintainability programs in submission of any initial program funding requests and in the awarding of contracts. Funding adequacy is determined on the basis of system complexity, nature of the equipment to be incorporated into the system, the level of quantitative requirements, and the depth and scope of each maintainability program element.

Each SPO will maintain complete, factual, and timely information regarding the status of all maintainability program elements for continuous review and program control within the SPO and for preparation of reports as required by higher Air Force management levels.

A staff office (OPR) for maintainability will be manned to provide staff guidance and assistance as necessary to assure a vigorous and aggressive maintainability program.

MAINTAINABILITY ORGANIZATION

The organization established at the ESD and assigned the responsiblity for the staff management of all maintainability efforts is as indicated in Figure 1.



The responsibilities, functions and procedures to be followed in implementation and enforcement of the maintainability programs are clearly defined in ESDR 80-( ), Research and Development Maintainability. A copy of this regulation is attached.

MAINTAINABILITY PROGRAM

The requirement for an aggressive and effective maintainability program has been established in AFR 66-29A and AFSCR 80-9 and implemented by the ESD via ESDR 80-( ) Research and Development Maintainability and ESD Policy Letter No. ( ).

The basic vehicle utlized to implement the maintainability program is MIL-M-26512B and Appendix A thereto for demonstration. This specification is by necessity general in nature and was written to be equally applicable to electronic, aeronautical, ballistic and space systems. For this reason ESD has found it necessary to supplement the instructions contained in this specification and its appendix with more explicit guidance in the preparation of PSPP's, SPP's. SOW's, Specifications, Requests for Proposals (RFP's) and contractor Reliability/Maintainability Plans. In addition, ESD recognizes that guidance must be provided all bidders in the form of a briefing in order that all may have a clear understanding of what is expected in the R&M effort for the system.

After a contractor has been selected, ESD provides more explicit instructions and direction in order to obtain the type of program needed by the Air Force to support the design and development of a specified system. This guidance provides a firm requirement for specific tasks to be accomplished by the contractor, time phasing of events, contractor monitoring procedures, and methods of communication.

Bidders' Briefing. The ESD's Staff Reliability/Maintainability Coordinators participate in bidders' briefings as required. The purpose of this participation is to: (1) review, interpret, and answer questions relative to the numerical requirements for R&M; (2) explain overall ESD philosophy in its approach to maintainability (availability); and (3) outline and recommend the type and quantity (or depth) of information needed for evaluation of bidders' R&M proposals. We feel that the proposal submitted by the prospective contractor as a result of this meeting provides a very important document for it is here the major input by the contractor for the R&M plan is found. This document thus provides the basis for the definitized and approved R&M plan.

Program Plan. Immediately after selection of a contractor, a meeting is held with the successful bidder to formalize and definitize the R&M Program Plan. The basic document submitted as part of the bidder's proposal is amplified so as to provide an accurate description of the contractor's effort in compliance with the quantitative system requirements. The proposed R&M Program should be comprised of the plan or strategy to be employed in achieving the design for reliability and maintainability; prediction of the quantitative figures to be achieved by their proposed system; the organizational structure and the lines of communication between the various activities; the design review structure, its authority and modus operandi; the corrective action loop; a description of the experience and achievements on past programs which involved numerical requirements; and where possible, a comparison of unit operational or achieved MTBF's on similar systems with predicted component MTBF's on the proposed system or subsystems. It is this proposed plan that is discussed in minute detail and amplified to meet ESD's requirements. The purposes of this meeting with the contractor are to establish a series of tasks to be accomplished based on the proposed plan and system requirements; the tasks definitized by accurate task description; calendar time duration; time phasing and manhour allocation to perform these tasks; establish monitoring or review points; discuss the contractor's procedures for monitoring subcontractor and vendor activities; establish lines of communication between the procuring activity and the contractor and his subcontractors; identify personnel involved in the effort and define their respective responsibilities; and establish the type and content of reports to be submitted to the Air Force and the schedule to be followed.

Task Requirements. There are several tasks that are considered extremely important to the R&M Program to assure that the specified requirements are met. It is important that quantitative requirements be clearly defined, but we feel that the design review provides the most powerful tool available to us to assure that prime consideration has been accorded the reliability and maintainability design parameters early in design and that continued emphasis is placed on this function throughout the acquisition cycle. For this reason ESD is emphasizing this task to a greater degree than all others. Tasks meriting specific discussion as a minimum are as follows:

1. Design Reviews. Design reviews are expected to be accomplished with varying emphasis and frequency throughout a program. In the initial conception stages of a system, the reliability and maintainability groups should review the proposed configuration for such points as the use of standard circuits of proven reliability, compare pump-fed systems with pressure-fed systems, liquid rocket engines with solid rocket engines, one computer manufacturer with another, etc. With such comparisons, a paper study may be accomplished to obtain an estimate of the system reliability and maintainability figures of merit. The system configuration which is decided upon is then reviewed in detail. Such reviews and evaluations by the reliability, maintainability, and quality control groups will be scheduled for all significant designs before they are finalized. Design Review Check Lists should be employed to assure complete coverage of the design factors and will include a detailed examination of the design documents, drawings, and specifications.

The ESD expects to participate in these design reviews and is especially interested in the overall strategy employed to attain the reliability, maintainability and performance requirements; circuit application; component application; parts application; stress analysis (margin of safety); and physical or mechanical reviews. Should the responsible ESD agency not attend any such meeting, detailed minutes of the transactions, corrective actions, and follow-up procedures shall be provided for review as an appendix to the periodic report.

2. Statistical Engineering Activities. The reliability and maintainability program shall incorporate optimum utilization of statistical planning and analysis. This shall include the application of such methods as design of experiments, analysis of variance, and other methods particularly suited to the design and development phases, and the use of statistical quality control methods in the manufacturing process. A mathematical model must be maintained throughout the program which presents a continuous representation of the reliability of the system.

3. Establish and Maintain a Failure Reporting, Analysis and Feedback System. The contractor shall have a system for collecting, analyzing, and recording all failures that occur in-plant as well as those that occur at test or installation sites. This system shall be described and the applicable flow-charts provided to indicate the routing of such failure reports for analysis, corrective action, and follow-up. The forms utilized for this reporting system shall include all the necessary data to enable analysis and shall be compatible with the procuring activity's failure reporting system.

4. Recommend Milestones or Monitoring Points. Program monitoring commences with the award of the contract and continues through the phases of design, production, installation, and operation. It is essential that specific points be identified that are suitable for formal review of the program efforts. The Air Force requires at least eight such review points as specified in AFR 80-5 and USAF Bulletin 506, but additional points may be designated based upon the system requirements.

5. Management of Subcontractor and Vendor Efforts in Reliability, Maintainability, and Quality Control. It is essential to good program management that a detailed plan be formulated that imposes specific requirements and procedures on the subcontractor and supplier. These requirements should be in sufficient detail to assure that such subsystems or equipments meet the apportioned reliability and maintainability requirements and the quality control standards.

6. Human Engineering. The product assurance program shall apply the principles of human engineering in all operations during manufacture, test, maintenance, and operation of the system or subsystem where personnel are involved. The design should incorporate those engineering features that minimize the possiblity of degrading reliability and maintainability through human error. Human engineering personnel shall participate in the approval of all designs and proposed tests to assure that the principles in MIL-STD-803 have been incorporated in the design and are reflected in the test plans.

7. Effects of Storage, Packaging, Transportation, Handling and Maintenance. The effects of the above on the reliability of the product shall be considered in the design of the equipment and any special storage, packaging, transportation, handling and maintenance requirements shall be made known to the Air Force.

8. Establish controls to assure that all handbooks reflect the true system configuration and that the operation and maintenance instructions reflect all equipment changes and procedural improvements.

9. Prepare a manloading chart to depict the projected manpower expenditures. Such information as manpower allocations per task and the time phasing of task accomplishment will be added.

10. Test and Demonstration. Test activities not only involve incoming inspection of parts and materials and qualification of non-standard parts, but also environmental and operational testing of elements, subsystems, and complete systems. Detailed test and demonstration plans shall be prepared to demonstrate the operational and performance requirements of the contract with the specified degree of reliability and maintainability. In addition, a planned and scheduled program of functional testing of equipment shall be conducted during design and development phases to estimate the reliability and maintainability achieved and to provide data feedback to be used as a basis for improvements in design.

11. Quality Control System. Written descriptions of the quality control procedures to be utilized in management of the contractor, subcontractor and supplier activities will be prepared.

12. Compile and submit failure data summaries periodically.

13. Prepare spare parts lists based upon mathematical model and applicable parts failure rates.

14. Maintain a weak links chart that depicts such information as the component failing most frequently, the corrective action required, the action agency and the status of the corrective action.

15. Establish Training Program for Key Personnel. Such programs should take full cognizance of previous reliability/maintainability and quality control education negotiated on other programs and be planned to supplement that training with lectures, pamphlets, and posters.

16. Prepare and submit periodic reports which contain the detailed accomplishments by task during the reporting period. Specific entries should be made on the current predicted and achieved values of reliability and maintainability. Problem areas that are known to exist or are anticipated should be listed along with the planned courses of action to correct or alleviate such problems.

Failure data summaries and other data specified should be affixed as a part of the report.

Examples of actual tasks included in active contracts are indicated in Appendix #3.

CONCLUSIONS

The success of the Reliability and Maintainability Program is a direct function of the excellence of the program plan, the effectivity of the organization and personnel involved, and the clear understanding by all participants of the requirements, procedures, and philosophy underlying the development plan. It is believed that this paper has provided you with the ESD policies and procedures in implementation of those established by Hqs USAF and AFSC.

The program plan provides an orderly approach to the design, development and production of reliable and maintainable equipment and deserves special attention by all personnel concerned with its execution. The preparation and definitization of the plans affords several useful purposes: (1) it is a valuable exercise for the personnel to participate in the reliability and maintainability groups' approach to the problem; (2) the coordination, definitization and description of the tasks or work items, assures understanding and agreement between not on the contractor personnel, but the procuring activity as well; (3) it delineates the area of responses and describes the activities of the associated groups; and (4) it serves as an important contractual document that reflects an official working document agreed upon by all agencies involved.

The finished Reliability and Maintainability Program Plan discussed and developed by this method precludes any future misunderstandings as regards intent and scope of each task and facilitates the monitoring of the program by the procuring activity.

APPENDIX 1

ESD Policy Letter No. ( )

Maintainability in Electronic Systems

1. Statement of Policy

Maintainability will be a prime consideration in the source selection, planning, design, development, production, equipment installation, and operation of all electronic systems within the cognizance of the Electronic Systems Division (ESD). Maintainability is recognized as one of the major characteristics, in conjunction with system reliability, performance, and cost which contributes to overall electronic system effectiveness. Therefore, each office responsible for managing specific systems will provide direction and control to achieve required Maintainability of systems within their cognizance.

2. Need for Quantitative Maintainability Requirements

Quantitative Maintainability requirements will be established for all electronic systems. These requirements will be incorporated into each PSPP, SPP, system specification, SOW and other contractual documents released to contractors. Provisions will be made for the demonstration of the stated quantitative requirements at a selected milestone within each overall system program.

3. Statistical Nature of Quantitative Maintainability Requirements

System quantitative Maintainability requirements will be expressed in terms of mean-down-time (MDT) with a constraint on the maximum or extreme value an individual downtime will be allowed to assume. This constraint will be expressed as a probability (usually 90%) that no individual DT will exceed a specific amount of time.

Prime contractors will be required to impose quantitative Maintainability requirements, which are compatible with the overall system requirements, on individual subcontractors and to provide for subcontractor demonstrations that imposed requirements have been met or exceeded.

4. Maintainability Program and Its Elements

To assist in achieving the quantitative Maintainability requirements, each overall system program will provided for an adequate contractor Maintainability effort in accordance with AFR 66-29 and MIL-M-26512. The degree of adequacy is dependent on the program schedule, the type of equipments to be incorporated into a system, and the statement of quantitative Maintainability requirements. However, each system program will provide at least the following key Maintainability work elements:

a. Predictions, at selected milestones, of achieved system Maintainability.

b. Formal maintainability design reviews.

c. Collection, processing and analysis of downtime data from all scheduled tests.

d. Corrective action for causes of unmaintainability.

e. Demonstration of quantitative maintainability requirements.

f. Review of all ECP's and non-ECP's for maintainability effects.

g. Submission of periodic reports on maintainability program progress.

Each system program will contain major maintainability program milestones at which a SPO will review the progress of contractors and will take necessary corrective action to keep the maintainability program compatible, effective, and correctly time-phased, with other elements of the overall program.

5. Funds for Maintainability Programs

Adequate funds will be provided for maintainability programs in submission of any initial program funding requests and in the awarding of contracts. Funding adequacy is determined on the basis of system complexity, nature of the equipments to be incorporated into the system, the level of quantitative requirements, and the depth and scope of each maintainability program element.

6. Reports to Higher Air Force Levels and Status Documents

It is a management responsibility to provide direction and control to each element of a maintainability program. Each SPO will maintain complete, factual, and timely information regarding the status of all maintainability program elements for continuous review and program control within a SPO and for reports, as required, to higher Air Force management levels.

7. Staff Assistance

Staff assistance in the area of maintainability will be provided to each SPO by the Office of Primary Responsibility in accordance with ESD Regulation 80-( ).

APPENDIX 2

ESDR 80-( )

ESD REGULATION (Proposed)
No. 80- ( )

HQ ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
Laurence G. Hanscom Field, Bedford, Mass.

Research and Development

MAINTAINABILITY

THIS REGULATION ASSIGNS RESPONSIBILITIES FOR THE IMPLEMENTATION, MANAGEMENT, AND CONTROL OF MAINTAINABILITY PROGRAMS WITHIN THE ELECTRONIC SYSTEMS DIVISION (ESD). THIS REGULATION IMPLEMENTS THE PROVISIONS OF AFSCR 80-9, FURTHER AMPLIFIES ESD POLICY LETTER NO. ( ) WHICH RELATES TO MAINTAINABILITY, AND IS IN ACCORDANCE WITH THE REQUIREMENTS OF AFR 66-29 AND MIL-M-26512.

1. Appointment of a SPO Maintainability Monitor and General Functions:

a. Each SPO Director will appoint a qualified individual (or individuals) who will have prime responsibility within a SPO for establishing SPO-contractor maintainability programs, monitoring the progress of each contractor on his approved maintainability program, and making recommendations to appropriate SPO personnel for necessary redirection of any maintainability program. This individual (or individuals) will distribute within the SPO all approved policies, regulations, bulletins, and specifications pertaining to maintainability and will advise the SPO Director of any significant changes to these policies, regulations, bulletins, and specifications affecting SPO plans, operations, and/or the acqusition of equipments.

b. The individual (or individuals) assigned the responsibility of maintainability monitor will be identified to the Office of Primary Responsibility by name, office symbol, stop number, telephone number, and room/building number. His training and experience in maintainability will also be submitted.

2. Office of Primary Responsibility. Deputy for Technical Services, ESSTE-2, will serve as Office of Primary Responsibility. This office will:

a. Assist each SPO in the establishment of quantitative maintainability requirements and methods of demonstration.

b. Assist each SPO in establishing design for maintainability philosophy and procedures.

c. Assist each SPO in the establishment of elements of maintainability programs.

d. Assist each SPO in the negotiation with contractors of maintainability program elements.

e. Assist each SPO in periodic reviews of contractor progress on maintainability programs and furnish recommendations to each SPO with regard to improving either contractor performance or necessary redirection of the scope and intent of each reviewed maintainability program.

f. Participate, as required, in any briefings on maintainability presented at bidders' conferences.

g. Participate, as required, in source selection boards to assure proper emphasis on maintainability.

h. Compile, maintain, and distribute to each SPO approved management procedures, methods, and instructions for maintainability programs.

i. Provide each SPO with copies of all approved policies, regulations, bulletins, and specifications on maintainability and assist in interpreting these documents for application on particular SPO contracts.

j. Provide the ESD member on the AFSC Maintainability Task Force and other representative groups. Represent the ESD in effecting necessary coordination in maintainability matters with other Divisions and Centers of AFSC, USAF, DOD, other services, and industry, except as this responsibility may be delegated for specific aspects of a problem.

k. Arrange, as necessary, limited attendance conferences on maintainability which involve industry and SPO participation. The purpose of these conferences is to explain fully the current approved policies, regulations, bulletins, and specifications on maintainability.

l. Cooperate with the Deputy for Technology and the Deputy for Advanced Planning in developing long-range plans for studies and research in maintainability techniques.

m. Chair and distribute agenda and minutes of monthly meetings with SPO maintainability monitors.

n. Cooperate with the Training Office in developing and in conducting maintainability education programs.

o. Review all PSPP, SPP, Specifications, and Work Statements for compliance to approved policies, regulations, bulletins, and specifications on maintainability.

p. Provide the active staff element necessary to assure implementation of adequate and uniform policies and procedures on all maintainability matters within the ESD. This will involve review and interpretation of all maintainability policies, procedures, bulletins, and specifications and regulations issued by higher headquarters.

3. <u>Specific Functions of a SPO Maintainability Monitor</u>:

a. Act as a general focal point within the SPO for all matters pertaining to maintainability.

b. Assist the Office of Primary Responsibility, as required in the development of maintainability policies, regulations, bulletins, and specifications.

c. Assist other SPO personnel in establishing design for maintainability philosophy and procedures.

d. Provide contractors with detailed instructions regarding maintainability program requirements.

e. Review contractor maintainability program plans and initiate any corrective actions designed to bring plans within the scope and intent of approved policies, regulations, bulletins, and specifications on maintainability.

f. Take necessary action to insure that proper quantitative maintainability requirements are incorporated into PSPP's, SPP's, SOW's System Specifications, and all contractual documents furnished contractors by the SPO.

g. Establish appropriate maintainability program monitoring points with contractors.

h. Conduct maintainability program reviews at the established monitoring points. At these meetings, the SPO maintainability monitor will:

(1) Review and determine the adequacy of the overall progress of the maintainability program. Assistance from the OPR and/or RADC (see paragraph 4) will be requested sufficiently in advance of these meetings in order that these organizations will be able to provide the requested support.

(2) Discuss the adequacy of all maintainability program reports submitted to the SPO.

(3) Review any maintainability problems affecting compliance to the quantitative maintainability requirements and insure by follow-up that timely corrective action is planned or being taken.

(4) Review the adequacy of contractor's design for maintainability techniques.

(5) Determine the overall progress toward the achievement of the quantitative maintainability requirements.

(6) Determine that the contractor's corrective action system is correctly functioning and that maintainability engineers and others involved in the corrective action process are aware of their respective responsibilities.

i. Following each maintainability program review, a SPO maintainability monitor will:

(1) Document his findings and recommendations.

(2) Review his findings and recommendations with appropriate SPO personnel in order that any corrective recommendations can be implemented.

(3) Furnish to the OPR a copy of findings, recommendations, and SPO actions to be taken or taken on the reviewed maintainability program.

j. Periodically, review each maintainability program with the SPO Director.

l. Attend and participate in the scheduled monthly meetings of SPO maintainability monitors.

4. Maintainability Support Functions of RADC:

a. Provide technical support to the SPOs, upon request, in the following areas:

(1) Establishment of quantitative maintainability requirements.

(2) Establishment of design for maintainability philosophy and procedures.

(3) Review of maintainability mathematical models, maintainability demonstration plans, and other technical reports.

(4) Review of contractor progress on a maintainability program.

b. Specific individuals will be designated by RADC to the SPOs and the OPR as to the individuals assigned to provide the support defined in paragraph 4a.

c. Provide a central office for the collection, evaluation, and dissemination of applicable maintainability statistics (mean downtime, mean time to repair, repairability values, etc.).

d. Furnish consultant service in the application of the information required by paragraph 4c to current and future maintainability programs.

e. Manage contracts for an/or conduct research in maintainability techniques on projects assigned to RADC.

f. Provide an associate member on the AFSC Maintainability Task Force and other representative groups.

g. Provide, upon request, a member for source selection boards.

h. Provide consultant service to ESD elements on technical advancements in the areas of maintainability prediction, analysis, and demonstration.

i. Attend and participate in scheduled monthly meetings of SPO maintainability monitors.

j. Attend monthly coordination meetings on maintainability matters with the OPR.

5. <u>Maintainability Support Functions of Deputy for Technology (ESR)</u>:

a. Establish a maintainability research and advanced development program, based on current and future ESD system requirements. This program should include at least components application techniques, circuit techniques, materials and processes, packaging, repair vs throw-away maintenance concepts.

b. Assume responsibility for the planning, funding, and implementation of research programs in the areas indicated in paragraph 5a.

1 Attachment
Check List

CHECK LIST

Ten Key Actions to Be Taken By A SPO Maintainability Monitor

1. Assist in establishing quantitative maintainability requirements.

2. Assist in defining design for maintainability philosophy and procedures.

3. Arrange for maintainability program plan submission and determine the adequacy of the plan.

4. Arrange for establishment of a mathematical model which relates maintainability and other system characteristics. The model is to be used for trade-offs analyses, corrective actions evaluations, and prediction calculations.

5. Require a contractor to have a maintainability design review plan and procedure. Arrange to participate in selected reviews.

6. Establish SPO-contractor maintainability program monitoring points. Conduct program reviews at these points. Determine the adequacy of the means employed by a prime contractor to control the maintainability efforts of his subcontractors.

7. Require that a contractor has a well defined corrective action procedure for eliminating (or reducing in effect) the causes of unmaintainability.

8. Arrange for submittal and review of maintainability program reports.

9. Assist in establishing maintainability demonstration philosophy and procedures and arrange for review of test plans and test results.

10. Arrange that maintainability program reports and findings are submitted to other SPO activities (reliability, system engineering, logistics, etc.) for their use in performing their functions.

APPENDIX 3

Sample Tasks from ESD Contracts on R&M Programs

1. Equipment R/M Design Reviews (Task I, NUDETS Program)

DESIGN ASSISTANCE

Preferred Parts List

A preferred parts list (PPL) will be developed for the 477L System in accordance with MIL-E-4158B and will be supplied to the equipment design activity for parts selection criteria. In the case of subcontractor supplied equipment, subcontractors will be required to comply with this list except that existing subcontractor parts lists may be used subsequent to approval. In these cases, back-up data relative to parts application and acceptibility will be required.

Parts Approval

Parts approval will be based upon the PPL. Components or parts recommended or required in equipment design, but not identified in the PPL, will be subject to Air Force approval in accordance with the requirements of MIL-E-4158B. For the 477L prototype equipment, deviations or relaxation of MIL-E-4158B application may be granted, concurrent with customer approval.

Part Application Aids and Recommendations

A Project Data Book (PDB) for the 477L Prototype has been prepared for the equipment designer's assistance. This PDB will be periodically updated throughout the life of the program to include the following:

a. PPL
b. Part standards (voltages, signal levels, impedances, etc.)
c. Input/output specifications
d. Responsible project design engineers
e. Reliability application and de-rating information
f. Design review procedures.

Design Review

Design reviews will be conducted by reliability/maintainability engineers for each equipment to ensure compliance with reliability/maintainability objectives. Reviews will include review and signoff of equipment schematics and drawings prior to release to production.

These reviews will be conducted in accordance with the attached design review checklist, and in accordance with the Project Data Book. Records of design review will be made available to the USAF upon request. Exhibit B, Parts I, II and III, and Exhibit C of the availability program plan are also attached. In the case of subcontractor supplied equipment, design review will be performed by the subcontractor in accordance with provisions of paragraph 3.5. In cases of commercial equipment with experienced field usage, experienced data will be submitted as part of a design review.

Corrective Action Recommendations

Reliability/maintainability recommendations resulting from design reviews will be documented, and a report of action by the cognizant design engineer will be required.

Evaluation of Proposed Changes

Proposed changes in the design of equipment will be reviewed by reliability/maintainability engineers in compliance with paragraphs 4.1, 4.2, 4.3 and 4.4. Reliability/maintainability apportionments and predictions will be up-dated as necessary.

2. Subcontractor Control (Task V, EMT)

Description of the Task

Quality Assurance will perform surveillance of subcontractors of equipment in two areas of effort. (1) quality control and (2) reliability and maintainability. The quality control system of each subcontractor shall be monitored by Quality Assurance to determine compliance to established criteria for the following:

a. Quality control procedures
b. Drawing and change control
c. Supplier surveillance by the vendor
d. Receiving inspection and test
e. Inspection and test during manufacturing
f. Process control
g. Calibration of measuring instruments
h. Final inspection and test
i. Proper sampling inspection
j. Methods to indicate inspection status
k. Control of discrepant materials
l. Storage of materials
m. Quality control records
n. Packing and shipping control
o. Corrective Action system.

Using MIL-Q-9858 as a guide, Quality Assurance will require corrective action for all elements of the above for which each subcontractor does not comply. Quality Assurance representatives shall perform surveillance of the quality control systems of the subcontractors by means of survey checklists, day to day observations, witnessing of processes and inspections, performing inspections, as necessary, and witnessing final inspections and acceptance tests.

Quality Assurance will monitor the following areas of the reliability and maintainability program of each equipment subcontractor:

a. General reliability program of the subcontractor
b. Compliance to detailed equipment design specifications
c. Compliance to service conditions
d. Dependability of materials and parts
e. Compliance to performance requirements
f. Equipment maintainability characteristics
g. Human Factors
h. Personnel job tasks and reliability indoctrination
i. Reliability analysis (MTBF) with subcontractors reports in accordance with the requirements of each subcontract.

After the award of each purchase order or subcontract for equipment, a Quality Assurance Engineer will begin coordination of the subcontractor's reliability, maintainability and quality control program. Problem areas will be promptly reported in order that Quality Assurance can obtain corrections. Checklists and other control media will be developed under Task 14.

Duration of Task

The program will start immediately when purchase orders are awarded to subcontractors. Surveillance of an equipment manufacturer shall be discontinued after he has satisfied all obligations of his contract.

3. System Reliability/Maintainability Mathematical Model (Task A, Big Rally II)

Identification of the Task

Establish and modify, as necessary, a system reliability/maintainability mathematical model.

Description of the Task

_____ will develop a mathematical model for system reliability/maintainability from field data and available equipment evaluations. Circuit availability calculated from the model shall use the equipment configuration where transmission is over the most hazardous path, since there are many possible sources and destinations for a particular transmission, then any other path would have a higher circuit availability. At least one model for each of the three phases on the installation of the system could be developed for comparison during interim operation and maintenance, but only an assumed configuration for the final system shall be used for developing the model. Establishment of the model will utilize available information on equipment MTBF, MTTR, propagation path failure, failure rates etc., where such information is available on equipment and systems of essentially the same complexity. In addition, the configuration of the power generating equipment is not known, so a likely configuration will be assumed. The model will measure the effect of these criteria on channel availability. The model will be developed using established statistical analysis techniques by the Equipment and Systems Evaluation Department with system information coordinated by the Systems Planning Department and the Quality Assurance Department.

Duration of the Task

The development of the model will begin in April and extend through the middle of May.

Man Loading (Man Months)

	Dec.	Jan.	Feb.	Mar.	Apr.	May
Manager, Quality Assurance				.02	.02	.01
Senior Engineer					.35	.15
Senior Statistician					1	.5
Engineering Aide					.5	.5
Stenographer					.2	.2

VALUE ANALYSIS

by

Robert L. Bidwell

Martin Company

Presented at
Maintainability Conference
12-13 March 1963

Electronic Systems Division
Laurence G. Hanscom Field
Bedford, Massachusetts

VALUE ANALYSIS

Robert L. Bidwell

Martin Company

Around the turn of the century, many companies had become so large that top management was no longer in direct contact with everything going on in their company. Furthermore, these companies were so complex that management had to direct their energies toward planning, policy, and general administration rather than individual efforts or methods. Hence, the efficiency expert, the time and motion study man, came into being. This man was a tool of management used to put more value into certain operations of the company. "Time is money" Ben Franklin said, and the efficiency expert improved the company's position by giving more value to time.

It was almost a half century later than another expert in search of increased value entered the picture. He was and still is looking for ways to improve design, to perform the same function at lower cost or, if possible, to eliminate the function altogether. He is the Value Engineer, sometimes known as a Value Analyst.

The Air Force definition of the function of Value Engineering AFR 70-16 reads as follows:

> "Value Engineering is a proven cost prevention and cost reduction technique. Properly applied, the technique (1) identifies the function of a product or service, (2) establishes a dollar value for that function and (3) endeavors to provide that function at the lowest cost without degradation of performance or quality."

At Martin-Orlando, we call the overall program Value Analysis. Personnel supporting this effort are charged with securing greater value and reliability. Simplicity is their by-word. They work to eliminate unnecessary functions. Complexity in design normally adds more detail parts which are susceptible to failure and need to be maintained in the field. All of this adds cost and decreases value. Our Value Engineer's effort to eliminate unnecessary functions is an extremely important part of Value Analysis but it is only a part of the complete cost reduction effort. We have organized our attack on costs and oriented to the total cost of doing business - not just engineering, not just time and motion studies but encompassing the entire business operational spectrum. At Martin-Orlando we say that Value Analysis is everybody's business, from the general manager to the mail boy.

Such a program starts with the aggressive support and intense interest from the general manager and flows throughout the plant to all levels of operation. The organization of the program ensures that a cost reduction in one area does not mean more work or cost for someone else in another area. It allows the man in finance to work with a man in purchasing to make a savings on an item ordered in the engineering department. We are continually reducing the tendency to add safety factors upon safety factors which result in overdesign in the names of safety or reliability when these things could be accomplished adequately at much lower cost. Value Analysis strives for reliability, but at the same time it ensures that a part with a maximum life cycle requirement of ten years is not designed to last for 100. Only through this type or organized cost reduction can maximum savings be realized. This type of full cooperation between groups has made our program at Martin-Orlando a living thing. We all work toward common goals and individual goals and these goals are real and measurable.

Let's be more specific. Let's look into this Value Analysis program. Eliminating unnecessary functional costs does not just happen; you must make it happen. First of all, since we decided this must be a plant-wide program, everybody must understand what Value Analysis is and why we need it. Furthermore, they must understand Value Analysis methods and techniques. In other words, they must understand what they can do to contribute to the program. To achieve this understanding, classes and seminars are conducted; pertinent articles and editorials are placed in the company periodicals. In addition, a continuing promotional campaign reminds people of their duty and shows some of the results of Value Analysis throughout the plant.

A Value Analysis team, lead by an experienced Value Engineer, puts the program into effect on each project. The team representatives come from Finance, Procurement, Manufacturing, Engineering, etc. This group has a full time job. They identify and analyze functional requirements of a system or an assembly and aid others on the project who have cost savings ideas. Page and line schedules are kept so that management can see how the Value Analysis activities are progressing, from concept to implementation. Budgets are transferred and program personnel monitor the changes, ensuring progress. A Value Analysis team should show a net return of approximately 5-1 on its operating expenditure. One such team at Martin-Orlando returned a net of 23-1 over a one year period.

Let's take one Value Analysis study item on which this team worked and look at the results. A standard tube clip has three functions; (1) Mechanical fastener, (2) R.F. Shield, (3) Heat Sink. Analysis indicates that these functions can be performed for a few cents each on a volume basis. As a result of such an analysis, costs were reduced approximately 98% while performing these same functions with equal reliability. The Martin-Orlando Value Analysis organization has trained representatives in each section and department of the company, from procurement to the paint shop. These representatives help promote the program to their people, aid in following through on Value Analysis recommendation, and record pertinent data.

Our Value engineers go to work on a project when the initial study is being made and continue their efforts through research and development, production and field support. During the early stage of development is the best time to accomplish functional cost versus performance analysis before tools or other non-recurring costs are fixed, forcing implementation costs to cut deeply into any savings. This, of course, is the hardest place to measure savings, but it is also where simplification efforts are most fruitful in producing long term savings.

An integral and vital part of any successful Value Analysis program is the customer. His wholehearted cooperation is a must. First of all, the customer can supply the incentive and recent ASPR's and AFR's make this easier to accomplish. While patriotic duty and personal pride in doing the best job at the lowest possible cost are fine incentives, there is nothing like the possibility of increased company profits to enlist the strong support of management. For example, if you reduce costs on fixed price contracts by one million dollars, you have actually increased your sales effectiveness as much as fifteen million dollars. We also have fixed price with incentive clause type contracts at Martin-Orlando, and in this case both the contractor and the customer realize profits from Value Analysis. Let's look at the million dollar figure again. If we share this savings on a 70-30 percent basis with the customer, we still have a savings of $300,000. It would require additional sales in the neighborhood of $4,500,000 to bring in this kind of profit to the company. The customer, of course, has made a savings of $700,000. No wonder Value Analysis and incentive contracts win favor with management and with the services.

But, the customer's responsibility is not over with the signing of the contract. We pointed out that these contracts enable us to save millions of dollars but the contractor cannot save a cent without the cooperation of the customer.

The customer has a still bigger job if we are to realize the full potential that the Value Analysis effort can produce. He must be fully informed on the contractor's program; how it is organized, how much is being saved, and he must recognize and support the study of potential savings. He must be able to sort out the normal experience curve reactions to increased production from the Value Analysis contributions and measure the contractor's program on the basis of net realized results. The customer's part is a big one; he must be aware of the many things he can do to aid the effort and he must be aware of the roadblocks which can be placed in the way of progress.

Reaction times to Value analysis recommendations are critical. Deriving benefits from changes often depends on working them into the production schedule at a certain time. A delay can be costly or may even negate any advantage to the change. The customer must be set up to react to Value Analysis suggestions on a 30 day basis and should be able to make immediate decisions on simple problems.

One thing which would help both the contractor and the customer is a technically qualified person from the customer's office located in the contractor's locality, armed with the authority to approve qualified change recommendations. He can also assist in securing approvals from a higher authority when Class I changes are necessary.

The customer's engineering staff and his local representative must be willing to challenge the status quo. When the contractor finds a better, more efficient way to perform a function, the customer must be willing to re-evaluate his requirements expeditiously to see if the new way can meet his needs and vice versa. If a tolerance or finish is challenged, the customer should look at his specifications and decide if the tolerance or finish is really needed for this application. Again, prompt action and local authorization cannot be overemphasized.

The ever increasing squeeze on company profits and the rising cost of defense items can be stopped. It takes a highly organized program, hard work, and cooperation between the customer and the contractor. A Value Analysis program can be successful. We have made it successful at Martin-Orlando.

CONTRACTOR IMPLEMENTATION OF A MAINTAINABILITY PROGRAM

by

W. ROBERT GIBSON

Maytag Support Development Corporation

Presented At

Maintainability Conference

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ELECTRONIC SYSTEMS DIVISION

Laurence G. Hanscom Field

Bedford, Massachusetts

CONTRACTOR IMPLEMENTATION OF A MAINTAINABILITY PROGRAM

W. ROBERT GIBSON

Maytag Support Development Corporation

Impetus for the generation of a contractor maintainability program most generally finds its origin in one of four circumstances; (1) specific direction from the customer; (2) interest in the improvement of a product line; (3) to meet or beat competition; or (4) by uncontrolled organizational evolution. The reasons for implementing a maintainability program have little influence on its success other than the impact on the motivation of the responsible personnel. The ultimate success of the program is dependent upon the application of technically accurate engineering techniques and administratively sound management tools with which to establish, monitor, control and evaluate maintainability activities. These actions must be in technical consonance and appropriately time phased with the overall system development effort.

Incorporating a maintainability endeavor into the development, testing and production cycle for a complex system gives rise to administrative problems born of any design control or monitoring function. Among these are: increased overhead costs; additional coordination, reporting and justification requirements; as well as, added paper work. Each of these items represents an undesirable restraint on system development and management.

The technical problems associated with the implementation of a complete maintainability program are even more serious and complex than those presented by administrative inconveniences. Since maintainability is a characteristic inherent in equipment configuration, maintainability stipulations must be expressed as system technical requirements. These requirements must be: scientifically correct; in support of the system mission; and useful in developing design trade-offs.

Thus, the contractor is confronted with what would appear, at first glance, to be a complex montage of "profit-eating" administrative and technical problems. The severity of these problems is overshadowed, however, by somewhat obscure contractor benefits and urgency to provide maximum feasible ease and economy of maintanance for military systems.

The necessity for returning military equipment to service in the shortest possible time requires no explanation. The urgency to minimize equipment maintenance expenditures is exemplified by the Air Force expenditure last year of over 6 billion dollars for equipment maintenance. By comparison, the national debt created by four years of the American Civil War was 2.65 billion. Significant improvement in the ease and economy of complex electronic system maintenance can be attained through improved maintainability contracting methods, program control, program integration and personnel motivation.

CONTRACTING REQUIREMENTS

Customer delineation of detailed operational requirements and system support restraints is essential to the realistic implementation of a contractor maintainability program. In turn, contractor personnel must provide the cognizant System Program Office (SPO) with sufficient maintainability planning information to allow an accurate evaluation of the intended scope, depth and methodology of program implementation. Individual considerations and attendant priorities to be used in maintainability design trade-offs should also be included in all proposals and statements of work for Electronic Systems Division equipment.

The basic goal of the Electronic Systems Division reliability program is to provide the Air Force using commands with electronic equipment that will perform their designed functions for the longest possible time without repair, adjustment, calibration, equipment condition verification and/or modification. The Electronic Systems Division maintainability program is directed toward supplementing equipment reliability by reducing the effort, materials and time required to perform these actions. Equipment operational goals can best be met by contractor system effectiveness programs that include a well defined maintainability program that is complementary in concept and timing to other technical efforts.

A. RELATIONSHIP TO MISSION REQUIREMENTS

Maintainability design requirements must be stated in terms of the basic mission for which the equipment is intended. Time to repair, as the sole measure of maintainability, is acceptable only when constant availability of equipment is essential to achieving mission objectives. The use of interchangeable equipment and/or function redundancy, often increases the time available to perform maintenance on a functionally sub-standard item. In such a case, additional effort can be directed toward attaining economies in the types, complexity, and numbers of support tools, equipment, facilities, materials, and personnel required to perform established maintenance actions.

The best trade-off between the ease with which essential maintenance can be performed and the economy of the operation must be established for each system, sub-system, assembly, sub-assembly and component. As an example, System X is required to meet a particular military need in a remote area. The cognizant SPO possibly would provide the contractor with the following items as part of the basic system planning data:

1. Operating Environment:

   (a) Self-contained, trailer-mounted, for use in temperate and near arctic locales.

2. Maximum Allowable Downtime:

   (a) Five hours per week; no single outage to exceed one hour.

3. Assigned Operating and Maintenance Personnel:

   (a) Duties: Required to both operate and maintain the radar system and all supporting equipment. (i.e., power generation and distribution, communications, etc.)

   (b) Skill Levels: 5 and 7 (minimum of 2 years technical experience).

   (c) Courses Completed: Basic electronics, OJT on similar systems, and specialist course.

4. Maintenance Policy:

   (a) Repair: Remove and replace sub-assemblies, components, and parts while equipment is in place. Repair of removed items on site by bit and piece replacement, with 8 hour rear echelon response to equipment requests.

   (b) Calibration: Not to be more frequent than once each 7 operating days using the tools and test equipment provided.

   (c) Adjustments: To be completed as part of normal operation using the tools and test equipment allocated.

   (d) Functional Checkout: To be provided by a built-in signal simulator, comparator and readout system.

5. Maintenance Facilities:

   (a) Work Area: 6' x 8' containing a 3' x 5' work bench.

   (b) Storage Area: 480 cu. ft. capacity adjustable shelving space.

   (c) Equipment Available: Hand tools (kit contents described multimeters, VTVM, oscilloscope (specifications) etc.

6. Equipment Power Sources: (Beyond system operating requirements)

   (a) 1 KW 110 - 120 volts, 60 cycle

   (b) 1 KW 110 - 120 volts, 400 cycle ± 1 cycle

   (c) Pneumatic - none

   (d) Hydraulic - none

Contractor response to these criteria should include an outline of the specific guidance to be provided designers and system support planners in the following areas:

(1) Apportionment of allowable downtime between preventive maintenance, calibration and malfunction correction for all equipment levels.

(2) Restriction of circuitry, physical layout and packaging to accommodate all on site maintenance actions using the allocated tools, test equipment and facilities.

(3) Guidelines in the development of trade-offs between downtime, incorporation of additional tools, test equipment, personnel skill requirements, etc.

It becomes apparent that developing a system configuration that requires the use of large, delicate, high power requirement support equipment is impractical in this instance. The customer must be given tangible evidence that the contractor design and planning personnel are given adequate and timely information concerning system technical requirements and limitations. Further assurance is required by the customer that appropriate methodologies have been provided to dynamically implement the above guidance.

Proper initiation of a realistic maintainability program is significantly effected by contractor identification, interrelation and feedback of these considerations to the contracting agency. This interchange of planning data must be included in the technical proposal and continue throughout the design activity into actual operation.

B. DEFINITIVE GOALS

The total hours required for all system maintenance can be directly related to the maximum allowable downtime established for the entire system. In a similar manner, the total number, types, and complexity of the tools, test equipment and facilities needed to perform maintenance can be easily compared to the total allocation of these items. Since any given system is composed of a series of equipment items, each of these entities must be assigned its portion of the overall allocation of the maintainability requirements outlined in MIL-M-26512. These goals must be specific and stated in appropriate units of measurement for the convenience of generating the cumulative goals and/or requirements in each of the above areas.

As an example; a unit of a hypothetical system has been assigned the following maintainability goals:

Mean time to perform any maintenance action: 5 minutes.

Maximum allowable downtime: 1 hour per/100 hours of actual operation.

Tool restrictions: All field maintenance action to be completed requiring no more than the following items: 1 slot head, 6' blade, insulated screwdriver; 1 pair 3' long nose insulated pliers; and 1 - 500 watt soldering iron.

Test equipment restrictions: All field maintenance to be completed requiring no more than the following items: 1 shelf-contained multimeter (range specifications); 1 VTVM (specifications); 1 special signal source (specifications); 1 oscilloscope.

Personnel restrictions: All malfunction recognition, isolation and repair, calibration, adjustments, and preventive maintenance must be capable of being performed by a single 5 level mechanic (detailed qualifications) within established time limits.

In addition to the above items, special restrictions may well be imposed on the work area, climatic conditions, overhaul cycle, preventive maintenance cycle, calibration accuracies and tolerances, etc.

Detailed maintainability requirements must also be stated for off-the-shelf and Government Furnished Equipment, as well as, for new design. It must be recognized that the benefits gained from a stringently controlled maintainability design effort can be negated by the inappropriate selection of an item of GFE to be used with a new design.

At times, technical necessities will dictate contractor receipt of a waiver on a given system support restriction. For instance, state-of-the-art limitations may force the use of test equipment that requires more power, space and/or personnel skills than are allocated. Appropriate adjustments in the system support capability are required, in such circumstances, in order that technical goals might be met.

C. PROGRAM MILESTONES

Proper sequencing, timeliness of program direction and adequate statusing of maintainability achievements are essential ingredients in the management of a meaningful maintainability program. All maintainability program actions must be clearly identified and properly sequenced in order that they might be directly related to the overall technical program schedule. Completion of certain maintainability program actions is prerequisite to the initiation of subsequent activities. Specific activities in the development of good equipment maintainability characteristics must be tied to major milestones in the technical program.

The sequencing of events, time periods and common tie points established between maintainability and system schedules will vary widely between programs. Certainly, the maintainability program for a communication "black-box" would be significantly different in the depth of application than that employed on a massive search radar. It should be noted, however, that the scope of the maintainability considerations would be approximately the same in both instances.

The following is a listing of typical maintainability actions that are required during the various technical program phases:

TECHNICAL PROPOSAL

Stipulate the maximum allowable expenditures of system support resources on the system and sub-system levels.

Determine the maximum allowable downtime for the overall system and the individual sub-systems.

Develop the methodology for implementing the maintainability program within the contractor organization.

Prepare a detailed maintainability program plan.

Generate a maintainability program schedule of events related to the overall technical development program.

Predict equipment maintainability characteristics.

INITIAL DESIGN

Implement the maintainability technical effort.

Generate detailed maintainability design and planning direction.

Monitor the design of system equipment.

Participate in design reviews prior to the release of the engineering drawing.

Assist in the development of design trade-offs.

Generate detailed data required to plan training, technical manuals, spare parts, etc.

EQUIPMENT FABRICATION

Monitor equipment fabrication to determine specific assembly problems that would be maintenance problems in an operational environment.

Monitor the checkout of newly fabricated equipment to determine the accuracy of the maintainability predictions and verify the capability of allocated equipment to perform necessary field maintenance.

Prepare recommendations for changes to equipment design and/or maintenance procedures in order to eliminate noted problems.

The actions listed above are representative of the many maintainability activities that must be carefully planned and statused to assure proper program control. Each of the specific milestones determined by the SPO to be important to a given program must be statused as part of the contractual reporting requirements. In addition, the current status of the maintainability effort should be continuously available for customer inspection.

D. TECHNICAL RELATIONSHIPS

Maintainability is not an end unto itself. Neither is the existence of a contractor maintainability program a panecea for all technological and logistics ills. It is instead, another mechanism, which when realistically applied in consonance with other technical disciplines, can dramatically improve total system effectiveness.

The ease and economy with which a front panel gusset on an electronic chassis can be removed and replaced in the field is of little concern. The reliability of simple mechanical devices of this type is such that maintenance actions are required only as a result of physical damage. Real concern for maintainability characteristics is generated, however, whenever an item of relatively low reliability is part of an operational system. The amount of interplay between the reliability and the requirements for ease and economy of maintenance increases as inherent reliability decreases. Value engineering, human factors, and quality assurance activities also share common interests with maintainability.

The requirements established and the responsibilities assigned each of these areas within the contractor organization must be carefully scrutinized for points of interface with surrounding areas. Each of these interfacing points must then be evaluated in terms of required data exchanges and elimination of duplication.

It must be recognized that maintainability is a system design parameter that must be included in trade-offs with other design restraints. The implementation of a maintainability program must also be accomplished with comparable enthusiasm and technical integrity as that exhibited by similar programs.

E. CONTRACT STIPULATIONS

The military contract has, at times, become an awesome thing to industrial organizations. In many instances, there has been a growing tendency on the part of the contractor to become less and less specific in the statement of the character, quality and at time the quantities of material and/or services to be delivered to the military service. This tendency is not indicative of a contractor attempt to evade contractual or moral responsibilities. It is, however, symptomatic of the constantly tightening technical requirements that loom in front of military equipment planners. These needs are subsequently reflected in the specifications levied against the contractor. The urgency of the demands leaves little time to generate truly quantitative requirements. Thus, a qualitative requirement is levied against the contractor that is open to interpretation as to what constitutes an accurate statement of work, proper implementation and/or satisfactory performance. This sometimes imponderable series of events has led, more often than not, to extreme conservatism on the part of the contractor in promising to deliver a somewhat etherial characteristic in a product.

In recognition of the contractor's dilemma, the maintainability technical office at Electronic Systems Division Headquarters has launched an aggressive in-house program to identify system maintainability requirements, methods of implementation and standards of acceptable performance in specific detail. These requirement- are stated in finite units of measure that are related to the true technical mission of the system under consideration. In addition, the acceptable level of performance is specifically stated for the guidance of the cognizant SPO.

To date, one of the major objections to including maintainability requirements in an incentive type contract has been the inability to specifically state goals, milestones, and standards of performance. Electronic Systems Division maintainability personnel are confident that their recent activities in these areas have negated this objection.

PROGRAM CONTROL

The difference between profit and loss is control. Control in this context is not intended to convey the idea of rigid adherance to a particular grouping of previously established ground rules. Quite the contrary, our interest is in the development of flexibility of operation and the capability to direct and/or redirect any portion of the maintainability program with the conviction of faith in the decisions reached. The application of sound management practices in conjunction with technical ingenuity can provide this kind of flexibility in any contractor maintainability program.

A. IDENTIFICATION OF FUNCTIONS

The detailed function required in order to effectively implement the maintainability stipulations as set forth in the basic contract must be identified in minute detail. Each of these specific functions must then be set forth in a detailed statement of work and related to all other functions of a similar nature. This examination of function is necessary to determine the best possible sequencing of events and to eliminate duplication. Following the sequencing of the various required actions, a detailed schedule of events must be completed and coordinated with the system schedule of activities.

> The identification of detailed data requirements upon which to base the maintainability program is exemplary of this process. The maintainability data generation cycle begins with the determination of exactly what bits of information are needed to accurately determine the maintainability characteristics of equipment design. Once identified, it becomes apparent that the data can be used in numerous other operations as a basis for logistics support planning. As an example, the number, types and frequency of required maintenance action; the tools, test equipment (standard and special) and the numbers, types and skills of personnel required to perform maintenance

activities are required to determine the maintainability characteristics of a design. This data is equally important to persons generating technical publications, spare parts inventories, training programs, and contractor technical services. The determination of how the data is to be gathered and the method of distribution and updating is peculiar to each program. Accurate scheduling of the complete data gathering and distribution process becomes the key to successfully controlling the time and expense incurred in implementing this segment of the maintainability program.

A similar process is required in the identification, sequencing, scheduling, implementing, statusing and evaluating other maintainability program functions.

B. DEPTH OF IMPLEMENTATION

The degree of sophistication in a maintainability program can be judged by the appropriateness of the depth of implementation. As mentioned previously, the number of considerations taken into account in the evaluation of maintainability characteristics on any given equipment level remain the same for all types of systems. The extent to which these considerations are applied, must of necessity, vary between programs. It must also be recognized that the amount of paper work and internal coordination required in the implementation of a maintainability program must be kept to some predetermined level.

The needs of the military customer must be used as the guidelines in seeking the appropriate level of maintainability activity for a particular system. Anticipated maintenance actions to be performed by the using organization and/or back-up logistic support organizations are fundamental in determining required maintainability characteristics.

This process can be exemplified by the case of a hypothetical system to be used in a remote location. The nature of the equipment under consideration is such that hermetically sealed solid state modules are required in 75% of the circuitry. Mean time to repair limitations established by the customer necessitate the use of plug-in modules for in-place removal and replacement of faulty items. Epoxy encapsulation negates the possibility of repairing the individual modules, thus, eliminating the need to perform maintainability functions below the complete module level. A decision to make each of the modules repairable at the field location would change the depth of implementation required to achieve customer ease and economy of maintenance goals.

A definite reason must be identified by the contractor for each of the functions performed in the name of attaining good system maintainability. Inability on the part of the contractor to justify internal activities to this degree is indicative of poor program control.

C. PROGRAM STATUSING

The identification of functions and the determination of the depth of implementation to be given those functions provides the maintainability program manager with a sizing of the work that confronts his organization. From this point on, the ability to determine the exact point to which the program has progressed toward stated goals is of extreme importance. The initiation and conclusion of each maintainability function must be scheduled with regard to the overall technical program. Each of the finite products coming from these actions must also be inserted into program schedules.

> In the case of the maintainability data generation activity, the start dates must be subsequent to the availability date for the data itself. The anticipated date of completion must be prior to the earliest need date for the down stream functions that the data is to support. The simplicity of this example is almost absurd, however, this basic point in program management has been the nemesis of numerous contractor maintainability programs.

The accurate status of all facets of the maintainability program should be included in the periodic progress reports contractually required by the SPO. Accuracy in decisions to redirect a program is largely dependent on the managers ability to specifically judge progress in relation to contractual requirements.

D. MAINTAINABILITY DEMONSTRATION

The actual accomplishments of the maintainability effort must be demonstrated under the requirements of MIL-M-26512. Demonstration of the true maintainability characteristics inherent in equipment design provide proof of acceptable performance by the contractor and a source of data for further improving equipment maintainability characteristics. Firm methodologies must be generated that allow the efficient utilization of all maintainability feedback information generated as a result of required demonstration and/or actual field experience. Particular attention should be given to the up-dating of the basic planning data from which the logistics support needs were originally derived.

MOTIVATION OF COMPANY AND PERSONNEL

The genesis of a maintainability program may well be the urgent demand of the customer, but this impetus is not sufficient in itself to adequately perpetuate the program in a dynamic manner. Sustenance of a top quality technical activity must be based on the motivation of the individual personnel involved in the implementation of the program. This motivation is essential to achieving the level of competent performance that will make the maintainability effort truly meaningful to both the contractor and the customer. The motivation for the company, as a whole, is derived from the capability to define, control and evaluate the overall activities in such a fashion as to allow the attainment of contractual goals within the allocated budget.

Personal gratification in the accomplishment of a technical activity in the best possible manner is the most effective motivating force for maintainability personnel. The availability of technically sound engineering aids and implementation mechanisms is the most effective manner of instilling confidence in maintainability personnel. A high degree of technical integrity in a maintainability effort significantly effects the enthusiasm of the implementing group, and sharply increases the degree of program acceptance by the design engineering staff.

The value of a maintainability program lies in the ability to adequately motivate the individual engineer to incorporate MIL-M-26512 requirements into his every action. This degree of motivation is in turn dependent upon the integrity of the' technological foundation and the administrative methodologies. Nothing short of excellence in these areas will produce the required results.

There is no doubt, that implementing a worthwhile maintainability program represents a challenge to contractor administrative and technical resources. However, these efforts are not without significant reward. It has been demonstrated, that detailed definition of maintainability requirements; realistic programming; technical integrity in design guidance; and meticulous management control will generate: a simple design; time, manpower, and material savings; a more competitive product; and a happier customer.

MINUTEMAN GUIDANCE MAINTAINABILITY

by

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J. J. Hendrick

Autonetics, A Division of North American Aviation, Inc.

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SUMMARY

The Minuteman guidance system is an example of a complex electronic system designed for extremely high availability. The basic system was developed in the absence of a formal maintainability program, though an advanced model system development program has been started with maintainability being given serious consideration.

The results of the two programs are reviewed from the maintainability viewpoint, and the basic approach proposed for a formal program is presented.

INTRODUCTION

As present-day electronics systems increase in complexity, the problem of keeping these systems available for performing tasks for which they were designed becomes increasingly significant. Closely paralleling the availability problem is the related problem of the extremely high cost of maintenance and repair, spares, facilities, and redundant systems required to ensure minimum capabilities of the using organization. It is axiomatic that one way to minimize cost is to increase the percentage of time during which specific systems are available to perform the tasks for which they were designed. Certainly, new concept and approaches must be encouraged and tried.

The Minuteman guidance system is an example of a system developed under a radical concept with the objective of increasing system availability. Briefly, the concept was to design a system with reliability high enough to preclude maintenance during its normal useful life. The actual reliability goals were set surprisingly high, considering the complexity of the system and the state-of-the-art. With this concept it was only natural that all low-reliability components and features of the system had to be either eliminated or redesigned for greater reliability. For those components or features that traditionally were included primarily to facilitate maintenance, it seemed logical to simply eliminate them since no field maintenance would normally be required to repair failures. As a result, connectors, for example, were eliminated in the early design in favor of spot-welded conductors. All electronic components were integrally packaged to facilitate functional considerations and minimize cabling and weight. The system was hermetically sealed in a dome welded to the base, and was pressurized with an inert gas. An advantage of the sealed concept, in addition to heat transfer considerations, was that higher reliability would result from preclusion of unskilled maintenance attempts. The maintenance concept for the sealed package was simple. In case of catastrophic failure, the entire sealed unit would be replaced with a spare and returned to the factory or depot for repair.

It became apparent very early in the development program, however, that some of the approaches were erroneous, and, before design was very far along some changes were considered mandatory. It was decided that connectors would be necessary to facilitate removal of modules. Later in the design cycle, it was decided to repackage the modules to facilitate production checkout and system maintenance. At some expense, the system was repackaged in such a way that the computer could be separated from the rest of the system after the hermetically sealed dome was removed. This way, each could be manufactured and checked out as separate subsystems. Further, whenever malfunctions were discovered in the computer during guidance system repair, the entire computer could be quickly replaced with a spare with minimum system down time. No changes were made to the hermetically sealed packaging concept.

With the hindsight that comes during the latter stages of a program, one sees clearly what should have been done differently; at the same time, it is profitable to evaluate carefully the results of previous programs. In the case of the Minuteman guidance system, it is interesting to note that some of the basic changes were in the interests of maintainability. Further, the maintenance concept called for all maintenance internal to the hermetically sealed package to be performed at a special depot. In the process of determining the tooling and test equipment required to equip the depot, one fact became evident. The depot maintainability of the guidance package could have been improved had there been a specific program during early system design to anticipate, plan, and specify exact maintainability parameters.

The Minuteman guidance system development program began several years before any significant emphasis was placed upon the subject of maintainability by the military forces or by industry. At that time, no specific maintainability requirements were placed on the system, but many other specifications and conditions relative to weight, volume, reliability, environment, power, etc., were imposed upon the development engineering team. In some cases, compromises between conflicting requirements were necessary and trade-off studies were required to optimize the various factors. It was small wonder, then, that factors such as maintainability, which were not quantitatively specified or imposed upon the development team, were sacrificed during the trade-off studies.

The Air Force, in mid-1959, focused attention on the subject of maintainability by releasing specification MIL-M-26512. Still, it was not until MIL-M-26512A was released in December 1960, a year and a half later, that a maintainability program was well defined. It was during 1960 that Autonetics concluded there was a need for a separate organization specifically responsible for complete support systems engineering. The result was the establishment of a Logistics Engineering Organization charged with the responsibility of ensuring adequate support of Autonetics products. Consideration of the approaches to be taken toward fulfilling this responsibility and influences brought on by the emphasizing of maintainability by the Department of Defense led to the establishment of a Maintainability Engineering Unit within the Inertial Navigation Logistics Engineering Group. This unit was assigned responsibility for ensuring overall systems maintainability, including the influencing of prime equipment designs so as to minimize support systems requirements. It was reasoned that the physical location of the Maintainability Engineering Unit within the Logistics Department would help preserve the point-of-view of the using organization when analyzing designs for maintainability.

BASIC MINUTEMAN GUIDANCE SYSTEM MAINTAINABILITY

Although no formal maintainability program was set up for the basic Minuteman guidance system, considerable thought was apparently given by the customer to the problems of maintenance within the using organization. The basic approach, however, was to make the system so reliable that maintenance tasks such as remove/replace or physical adjustments would be essentially precluded. To accomplish the desired goals, an extensive and comprehensive reliability development program was implemented from the basic element manufacture through system level design.

Unfortunately, the interpretation of reliability is commonly vague. It would appear that many are aware that the rigid definition of reliability -- "The probability that a system will not fail within a specified time period when operating under specified design considerations" - - does not, in fact, account for all factors pertaining to effective use of equipment. Consequently, the word "reliability" has been twisted to fit many situations where effectiveness is actually under consideration, and the word "reliability" is commonly used in place of the word "availability". The end result is considerable difficulty in interpretation of quantitative values.

The validity of this observation is apparent from the fact that using organization maintenance considerations turned out to be primarily in terms of availability rather than reliability alone. In a technical sense, certain types of guidance system failures requiring circuit adjustments occur rather frequently. Because the missile is operationally unavailable when these failures occur, automatic scheduled maintenance was designed into the system to offset the effects of the failures. Design trade-offs were required to attain the optimum approach, and, as it turned out, the results serve as an example of one extreme of the manual-to-automatic spectrum of possible means of performing maintenance.

Examples of such automatic maintenance are: recalibration of inertial instruments, and checkout of complete missile functions for in-specification performance. Periodic recalibration is necessary for the inertial instruments because the scale factors and biases under the present state-of-the-art can be expected to drift out of the extreme tolerance requirements after a certain period of time. While these out-of-tolerance drifts do not constitute failures in the sense that the instruments no longer perform, they do constitute failures in the sense that specified missile operation cannot be met unless some adjustment is made to regain in-specification performance. During the calibration procedure, scale factors and biases are also compared against no-go limits to check for catastrophic failure.

Missile system checkout is also required to ensure, to a very high probability, that missiles assumed to be ready for launch actually are ready. Although failures requiring manual maintenance occur at an extremely low rate, failures will eventually occur and eventually all missile systems will fail. The failures must be discovered quickly enough to ensure operational requirements for ready missiles at the moment of need. The approach selected for accomplishing system checks and recalibrations was to use the guidance system computer for automatic checkout. The basic programs for the checks are stored in the computer, while test sequencing is controlled by logic functions provided in the operational ground equipment. Basic system status and performance are checked every minute, and gyro drift rates are checked every 16 minutes. All failure detection is based upon a "go, no-go" concept, with key circuit parameters sampled and compared with established limits stored in the computer program.

A major design trade-off consideration relative to automatic maintenance was the location of computer circuitry necessary for system checks, but not required for flight. Because weight is an extremely critical factor relative to missile range, it would be logical to eliminate everything from the missile that is not absolutely essential during flight.

It was determined, however, that the computer necessary for missile guidance was capable of performing essentially all checkout requirements. Had additional requirements been placed on the ground, much of the airborne computer, including memory functions, would have required duplication and interface signals would have greatly increased. Requirements for buffer and driver amplifiers would have essentially cancelled any potential weight savings by the addition of modules and connectors. As it turned out, careful expansion of basic computer circuitry for flight increased the airborne weight by a very small percentage. The input-output communication requirements were held to only five encoding lines (for targeting and startup), and total operational-site reliability was increased through reduction of components. Test sequencing and no-go logic were built into the command and control console which basically provided encoding and decoding communications between the missile system and the launch control facility. This approach lightened missile weight without the disadvantages mentioned earlier, since the necessary communication was already available.

In the normal operational mode, the Minuteman guidance system is considered to be operational unless a no-go signal is received by the launch control facility. Upon receipt of a no-go, a maintenance crew is dispatched to the missile site. The troubleshooting procedure consists of determining whether the malfunction is in the missile or in the operational ground equipment. If it is the ground equipment, the malfunctioning drawer is replaced. If the trouble is in the guidance system, an appropriate repair crew is dispatched to the site to remove and replace the entire guidance package. The missile is next activated and processed through self-checks and into the strategic alert mode of operation. A targeting crew arrives then to target the missile.

The malfunctioned guidance system, after replacement with a spare, is returned to the special repair depot for repair. At this point, the welded, hermetically-sealed guidance package must be cut open before any repair can be attempted. From the maintainability standpoint, this feature is not the most desirable. Other unmaintainable features, typical of complex equipment designed to meet stringent weight, volume and performance requirements, are also evident. One such feature is the lack of test point accessibility in some areas; another is the subsystem layout, which makes it difficult to repair one subsystem without disassembling others. It is difficult at this point to determine what improvement could have been possible under the same design considerations had maintainability requirements been formally specified. It is apparent, however, that the problems had to be overcome by the various support elements provisioned.

IMPROVED MINUTEMAN GUIDANCE SYSTEM PROGRAM

Inevitably, the success of the initial Minuteman program brought on demands for an improved version. The result is a new program wherein a lighter, still more reliable and maintainable guidance system is being developed. The increased requirements of performance flexibility, reliability, and weight reduction have made it necessary to consider microcircuit electronics. As a result, new types of maintainability problems are emerging.

Although the improved Minuteman program does provide for a limited maintainability program, various factors have resulted in its reduction to an austere level. The effort began very early in the program as participation with the preliminary engineering team and with specific responsibility for determining the logistics concept and making maintainability recommendations. A cost and availability study was made for various design configurations of the guidance system and maintenance philosophy.

Initial maintainability recommendations called for a design that would allow remove/replace of guidance subsystems through the side of the missile without the necessity for removing the re-entry vehicle. This approach would have required a different work platform than that now provided for the basic configuration. Access to the subsystems by removable missile skin or pullout design would have to be provided; sufficient test point accessibility and test equipment would be desirable, with maximum use of the guidance system computer utilized in conjunction with the test equipment. A positive safety device to disarm all ordnance squibs and the re-entry vehicle would be required to prevent accidents during hot tests.

The philosophy was desirable from a cost and missile availability standpoint. Direct support cost could be lowered because demand for heavy equipment for removing the re-entry vehicle and guidance package and associated crews could be eliminated and a complete guidance system spare would seldom be required. Subsystem spares and portable test equipment could be carried by the fault isolation crews.

It was quantitatively shown that since the missile in-commission availability was already extremely high, a reduction in the out-of-commission time would not significantly increase the availability of the missile. However, reducing the out-of-commission time would significantly reduce the equivalent dollar cost of "spare" missiles and using organization complexes while preserving overall effectiveness.

It was determined, however, that weight would be excessive due to structural requirements. As it turned out, the subsystem that would have to be removed most frequently, the stable platform, is also the heaviest and most cumbersome package requiring the most care in shock and vibration isolation. This consideration reduced attractiveness of providing for partial guidance subsystem maintenance at the using organization level.

Another approach investigated was the possibility of replacing guidance subsystems from the top of the missile with the re-entry vehicle removed. Structural problems requiring control of the center-of-mass of the system made it desirable to mount packages on the underside of the basic structure. This requirement caused the packages to be inaccessible with the guidance package mounted to the missile third stage. Therefore, the cost advantage was decreased to only the difference between the cost of a complete system spare and subsystem spares.

As must be expected, not all recommendations relative to maintainability can be incorporated into any program. In the case of the Minuteman improved guidance system, overriding requirements included safety, structural problems, weight limitations, and a desire not to significantly change the maintenance concept for the using organization.

Through close coordination with the responsible design engineers, however, significant improvement is contemplated in the system packaging concept which represents a compromise between optimum design from the maintainability point-of-view and other requirements. Basically, the single, welded, hermetically-sealed guidance package is being eliminated in favor of several subsystem packages. This one change alone represents a vast improvement in system-level maintainability. In addition, low power level flight control electronics from all three missile stages will be packaged within the guidance system. This change increases the missile third stage weight slightly, but overall missile maintainability will be vastly improved. Many control unit failures which require removal of the complete missile in the basic configuration can be corrected on the improved system by removal of the guidance and control package only.

In addition to easily removed packages, it is planned that the separate outer skin of the basic system will be eliminated in the improved system, the complete wiring harness will be easily removed in one piece, and cooling lines will feature quick disconnects. Mounting fasteners will be of a common type and minimum amount. Basic design criteria yet to be determined include system level test point requirements, and access and internal packaging of the subsystem.

GENERAL MAINTAINABILITY PROGRAM

The course of events surrounding the Minuteman guidance system development has been encouraging in a number of respects relative to advancement in the field of maintainability. It is apparent that there are still many opinions, on the part of both customer and contractor, as to the extent of need for maintainability program, scope of such programs, and approach of the program. On the other hand, the fact that there is currently a program contracted for proves that there is general agreement that maintainability must be given serious consideration.

Currently, there is very little theoretical work available relative to techniques and procedures that will permit maintainability problem areas to be crystalized or particular areas to be evaluated and compared with an operational system as a whole. The problem faced, then, when embarking upon a full-scale maintainability program, is how does one actually accomplish the desired intention of a basic program. It is reasonable that sound, realistic approaches for accomplishing the desired intentions of maintainability programs must be developed and presented if proposed programs are to be accepted. The approach taken relative to Minuteman guidance was that systems analysis from a maintainability point-of-view must become common if true design for maintainability is to ever occur. Solid trade-offs must be possible with other design objectives. Based on these concepts, a study was initiated to define all the significant parameters and their relationships. Fundamental techniques were developed, and the use of advance probability techniques and transfer function theory was found to be highly useful in evaluating parameter relationships and their meaning to the prime hardware and its support elements.

The basic program is essentially in accordance with specification MIL-M-26512B; however, there is much left unsaid in this specification relative to how its requirements can actually be implemented. For completeness, the overall prevailing philosophy as to program requirements is briefly reviewed.

First, a maintainability program involving integrated maintainability design optimization between subsystems and the support system must be accomplished by a single responsibility to be effective. The reason is that maintainability is not a function of hardware design alone, but of the support environment and maintenance procedures as well. It is possible for a given equipment design to be highly maintainable in one maintenance environment and grossly unmaintainable in a different environment. Under such situations, it becomes impossible to simply specify design goals and expect individual design engineers to meet them without providing relatively detailed specifications as to the planned test equipment, maintenance procedures, throw-away level, personnel, and troubleshooting logic with respect to the system, subsystems, and lowest level reparable component.

The problem of optimizing all factors and possibilities to the greatest extent, relative to maintenance, requires a true systems engineering type analysis and study, and requires high-caliber technical personnel. Basic design and support decisions must be made during study and preliminary design phases, and must satisfy all other design criteria. These decisions must be made such that a high probability exists that detailed design for maintainability of the prime equipment and the support system will bear out the preliminary design decisions. Thorough studies are required to determine the most optimum combination of support system and prime equipment system design that will allow the other design criteria and the operational requirements to be met. In making these studies, a full appreciation of the various means for carrying out the detailed design is required. A variety of systems engineering analytical tools are necessary to adequately handle the many interrelated parameters, and hardware functional concepts must be thoroughly understood. In addition, the characteristics of the various support elements and their costs must be well understood. Finally, of extreme importance, the customer's operational environment must be understood in depth, and all interface criteria must be coordinated with the customer and associate contractors. The task can be very challenging!

After preliminary design decisions are made, detailed designs must be continuously examined to ensure that the basic intent of the maintainability program is actually being carried out and to make further recommendations where maintainability problems exist. Test points, built-in test equipment, test point isolation, and logical packaging must be determined. Input and output interface design and corresponding checkout confidence levels for adequate interchangeability must be specified and designs reviewed to ensure that spares availability goals will be met and that unnecessary maintenance time will be reduced. These activities require close coordination with the design engineers who design the prime equipment, and with the maintenance analysis engineers who determine detailed test equipment and other support requirements. All of the engineers must be provided with the basic maintainability guideline criteria specified in updated documents for that purpose or in other internal control specifications. In addition, technical manuals and training courses should be considered and recommendations made. The basic intent is to ensure that the many contributors to the maintainability of a large complex program are developing about a single philosophy.

Early in the program, an overall analysis should be performed to predict the maintainability and availability likely to result at the time of analysis. As the program progresses, analysis must be maintained current so that there will be a high degree of confidence that the required maintainability will be achieved at demonstration test time. Also, a valuable tool is available for determining the areas that are major causes of a lack of required system maintainability.

Prior to customer acceptance of the equipment design, a maintainability demonstration test should be performed. It is obviously impractical to simulate all possible failures in a complex system enough times to obtain a minimum sample size to calculate the achieved maintainability with maximum confidence. All tests, therefore, must be carefully chosen, and something less than guaranteed accuracy must be acceptable. Specification MIL-M-26512B provides considerable guidance in the area of test selection.

Simulation of the test environment can also present a problem. Ideally, the test environment should duplicate the customer field environment after the learning curve period. In normal cases, it is impossible to duplicate exactly the field environment even at the beginning of the learning curve since deliverable field test equipment normally is not available at the time the test is conducted, even if it has already been designed. A similar situation exists regarding personnel, facilities, and manuals. When all test results are assimilated, some correction factor must be applied to account for such conditions.

Another problem in establishing the test plans is the assembly level and maintenance organization level at which tests will be conducted. If the assembly and test contractor is to conduct the tests on a complete system, then subsystem test requirements must be well coordinated with the contractor.

There are many other considerations which must be made in planning a maintainability demonstration test, such as cost and subcontractor-supplied equipment. An early start is essential to ensure adequate preparation. Specification MIL-M-26512B requires that a final test plan be submitted to the Air Force 60 days prior to scheduled first-article delivery. The preliminary plan should be submitted much earlier, and an explanation of the plan for test result analysis should be included.

An acceptable maintainability demonstration test should not end the maintainability program. All effort up to first-article delivery will only ensure to a high-confidence level that maintainability of the system in the field will be acceptable. There can be no complete guarantee that maintainability in the field will be acceptable until it is demonstrated in actual field environment after the learning curve becomes reasonably constant. To accomplish final evaluation, a data system is required that allows the finalized key parameters of the availability/maintainability analysis conducted during the development program to be determined. If key parameters fall within the predicted values, it can be assumed that field maintainability goals have been achieved. If not, a plan must be developed to identify the reason and determine corrective action. This effort can be achieved by treating all field deficiency data in the same manner as any other operational effectiveness problem, such as design deficiency, low reliability, and inadequate manuals or training. The important point is that corrective action is taken as a continuing part of the maintainability program begun during initial study phases of the system design, using and modifying the same maintainability/availability model developed then.

To implement the program outlined above, the following standardized statement of work, which could be included in a proposal or contract, is presented:

A. During the preliminary design phase, determine the necessary mean-time-to-repair (MTR) goals to ensure intended mission effectiveness. This determination will necessarily include formulation of an operational availability model and subsequent analysis to establish relationship between MTR, MTBF, and reaction time goals for the specific mission. This analysis is to be based upon operational and higher assembly operating requirements, and the equipment functional concept.

B. During the preliminary design phase, establish goals for system repairability, spares availability, maintenance equipment availability, and mean-task-time (MTT) for each operational mode required in the overall mission cycle so that the overall MTR goal for each mode can be realized.

C. During the preliminary design phase, establish a list of all expected maintenance actions for each operational mode, including remove/replace, adjustments, tuneups, scheduled and non-scheduled actions, etc. Using goal operational reliability MTBF's for each action, determine budget goal MTT's for each expected action. Specify in internal control specifications.

D. Determine the firm Logistic Concept (including maintenance philosophy) for the system. The Using Level maintenance concept to be based upon analysis of the budget goal MTT's, preliminary system functional operation, and certain operational and support considerations. Specify necessary requirements in internal control specifications.

E. Conduct design reviews, working closely with the design engineers, to evaluate component, subassembly, and system design in terms of capability to meet required MTT's while conforming to the established maintenance philosophy. Consider packaging, test points, built-in test equipment, test isolation requirements, interchangeability, checkout specifications, etc, for all levels of maintenance. Make necessary design recommendations or revision to MTT budget goals or maintenance philosophy as resulting from trade-off studies, keeping in mind that overall mission effectiveness in the field is the ultimate goal. Document and/or specify all requirements assumed for personnel, facilities, training, manuals, support equipment, spares, etc, to ensure a basis for designing the necessary requirements into the support system. Maintain current a prediction of achieved values for all MTT budget goals, overall MTT goal, and MTR goal as based on the continuing evaluation and analysis.

F. Publish and maintain a "design for maintainability handbook" for design engineers, including general system philosophy and requirements; maintenance task level requirements and philosophy. Update as required to prevent gross misrepresentation of latest requirements.

G. Perform special studies as required to determine the validity of support assumptions made or proposed for MTT evaluation relative to economic and/or functional feasibility; complex trade-off studies requiring adjustment of availability, reliability, reaction time, and other goals; realistic support equipment requirements relative to cost (automatic vs manual, etc); and other area effecting the MTT. Develop special tests, conduct or monitor tests, and analyze test results to establish most suitable system design where paper analysis is not conclusive or satisfactory.

H. Formulate an adequate Maintainability Demonstration Test Plan, obtain customer approval, determine and procure special facility, personnel, or support equipment, conduct tests, analyze tests, and project results in terms of field operation. Make recommendations and adjustments in support system requirements as feasible, if goal maintainability is not indicated. (To be part of the pre-first-delivery demonstration tests for operational hardware.)

I. Formulate an Achieved-Field-Maintainability Evaluation Plan, obtain customer approval, collect and analyze data in the light of R&D analysis, and make applicable recommendations. To be conducted as part of the operational data analysis program to determine weapon system effectiveness and perform corrective action. (This effort may be funded on a separate contract from the R&D contract.)

NOTE: In some cases, items A, B, and C may be partially accomplished on a study program funded separately from the R&D contract.

MAINTAINABILITY THEORY AND APPLICATION

It is essential to have a theoretical understanding of the relationship of the many parameters influencing maintainability and availability if trade-off studies and maintainability analysis and prediction are to be anything more than intuitive in nature. Lack of a general theory is the main stumbling block for effective maintainability programs.

The theory and techniques upon which the Advanced Minuteman guidance system maintainability program was proposed in briefly presented.

The goal for system designs should generally be to achieve the required operational availability to perform the "ultimate" mission with the lowest possible total cost consistent with performance requirements.

> DEFINITION: Availability is defined as the expected percentage of time specified performance will be obtained out of a specified interval of time.

By general observation of existing systems, it can be concluded that "ultimate" mission effectiveness of a system may be accomplished by prior operation in submission modes such as standby-off and standby-on modes. The ultimate mission effectiveness is therefore often a function of submode operational availabilities (Figure 1).

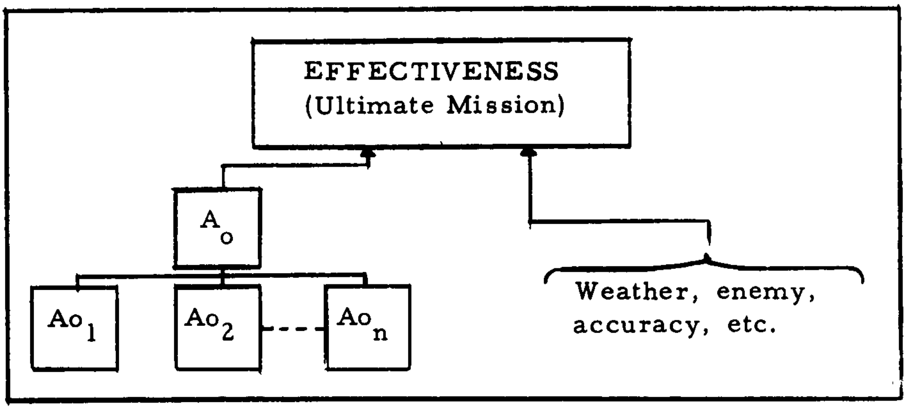


Figure 1. Ultimate Mission Effectiveness as a Function of Submode Operational Availabilities. Among other factors, system effectiveness is a function of being operationally available. Availability for the ultimate mission may be a function of sub mission mode availabilities.

This leads to

$$A_o = A_{ic} - A'_{o_{ic}} \tag{1}$$

where

A_o = operational availability for any given mission mode and where

$A_o + A'_o \equiv 1$, where $A_o{}'$ signifies unavailability, or "not" available

A_{ic} = availability of in-commission equipment

$A'_{o_{ic}}$ = operational unavailability even though the equipment is in commission. Includes such parameters as reaction time.

A_{ic}, becomes the parameter of interest here. If a system is out-of-commission (scheduled or unscheduled) it needs maintenance. If it is agreed that maintainability somehow measures efficiency of maintenance, then A_{ic} will contain the maintainability parameter.

The average or probable time a system is in commission can be defined as

$$A_{ic} = \frac{T_{ic}}{T_{ic} + T_{oc}} = \frac{T_{ic}}{T_m} \tag{2}$$

where

T_{ic} = sum of time in commission within t_m

T_{oc} = sum of time out of commission within t_m

T_m = a specified mission time, where 'mission' is used in a broad sense.

The parameter of interest is T_{oc}. If lower-case t represents individual time-instances within total time T, then

$$T_{oc} = \overset{n}{\underset{i=1}{\text{[illegible]}}} t_{oc_i} = t_{oc_1} + t_{oc_2} + \ldots + t_{oc_n} = n\, t_{oc} \tag{3}$$

where

$$t_{oc} = \frac{t_{oc_1} + t_{oc_2} + \ldots + t_{oc_n}}{n}. \tag{4}$$

The number of down instances, n, can be expected to be,

$$n = \lambda_{ic} T_{ic} + \lambda_{oc} T_{oc} \tag{5}$$

Where λ_{ic} and λ_{oc} are the "quasi" failure rates of the systems when in commission and out of commission respectively. "Quasi" failure rates differ from the usual failure rate in that the quasi failure rate is not limited to inherent failures resulting from proper application, but includes all forms of mishandling. In short, it is the "operational" failure rate. Also, in this simplified derivation, λ_{oc} is "adjusted" to account for the fact that ϕ failures during T_{oc} does not necessarily mean $\phi\, t_{oc}$ time contributed to T_{oc}.

From (3) and (5)

$$T_{oc} = t_{oc} \left(\lambda_{ic} T_{ic} + \lambda_{oc} T_{oc} \right) \tag{6}$$

so that

$$A_{ic} = \frac{T_{ic}}{T_{ic} + t_{oc} \left(\lambda_{ic} T_{ic} + \lambda_{oc} T_{oc} \right)} \tag{7}$$

For the case where $\lambda_{oc} T_{oc} \ll \lambda_{ic} T_{ic}$

$$A_{ic} = \frac{T_{ic}}{T_{ic} + t_{oc} \lambda_{ic} T_{ic}} = \frac{1}{1 + t_{oc} \lambda_{ic}} \tag{8}$$

If $t_{oc} \equiv$ MTR = a "statistical measure" of maintainability,

and λ_{ic} = 1/MTBF = operational failure rate,

Then

$$A_{ic} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTR}} \tag{9}$$

(as shown in MIL-M-26512B if MTR is replaced by $\overline{\text{M}}$)

The above process defines the basic relationship of maintainability to operational availability. The intent is according to specification MIL-M-26512B. However, the simplicity of MIL-M-26512B definitions can be misleading to those who have not thoroughly studied the subject. It is sufficient to comment that MIL-M-26512B should be revised to eliminate possible confusion among the users. While equation (9) represents the basic definition of system A_{ic} for some mode of operation, it is also useful to write,

$$A_{ic} = A_{ic_1} A_{ic_2} \dots A_{ic_n} = \prod_{i=1}^{n} A_{ic_n} ; \tag{10}$$

where

A_{ic_i} = " task" or "subsystem" availabilities of a "series" system.

A "task" availability may be useful where it is desired to determine system availability in terms of all possible maintenance tasks required to repair all possible malfunctions in a system. "Subsystem" availabilities may be desirable where several independent subsystems make up a system and it is desirable to control the design-for-availability of each subsystem separately.

The notation of equation (10) is valid only for a "series" system, or a system wherein if any one subsystem is unavailable, the system is unavailable. Equation (10) requires reformulation for "parallel" (redundant) and for "series-parallel" systems. All major Minuteman subsystems are in series. Also, all subsystems of the guidance system, which is a subsystem of Minuteman, are likewise in series.

In this paper, MTR is roughly equivalent to $\overline{M}$ in specification MIL-M-26512B. However, MIL-M-26512B indicates that $\overline{M}$ assumes that 100-percent support is available. The previous derivation for A_{ic} resulting in equation (9) shows the same form as given in MIL-M-26512B, but is based upon total downtime in a specified time interval. It is well known that it is common for equipment to be out-of-commission for periods of time much longer than active maintenance time due to lack of spares or test equipment or other elements of support. It is axiomatic that 100-percent support cannot be guaranteed. The cost of support rises exponentially as the probability of having full support at a given time and location increases.

From an overall cost viewpoint there exists a trade-off between probability that support is available (converted to the time intervals for which there is no support per maintenance occurrence) and "active" maintenance time. There is not usually a great overall advantage to being able to quickly go through the motions of maintenance only to insert long waiting time intervals between beginning and end of a maintenance task. A spare system must be placed in operation to take the place of the out-of-commission system in any event.

It is true that for maintainability demonstration tests, it is impractical to simulate support availability; therefore, 100-percent support must be assumed. This assumption reduces the test to the case of measuring mean-task-time (MTT) only, which is satisfactory for test purposes if the results are properly interpreted.

During design evaluation and determination of goals, however, it is necessary to properly consider the design requirements of the elements of support in order to determine the MTT requirements and spares availability (A_s) requirements. Design review activity directly deals with both parameters; MTT primarily with factors such as test points, packaging, and built-in test equipment; A_s primarily with interchangeability, which is a function of interface design tolerances and ranges, and of checkout tolerances and thoroughness.

This rational leads to Figure 2, which illustrates a functional block diagram relationship for MTR. MTT appears to most closely approach $\overline{M}$ in MIL-M-26512B.

In Figure 2, MTT is shown to be a function of n tasks, each of which is a function of malfunction isolation time, correction time, and verification-of-repair time. It is often convenient to examine task times in terms of the three latter parameters. The parameters in Figure 2 that are not assigned a particular notation must be determined in detail for each specific equipment design and support environment in most cases.

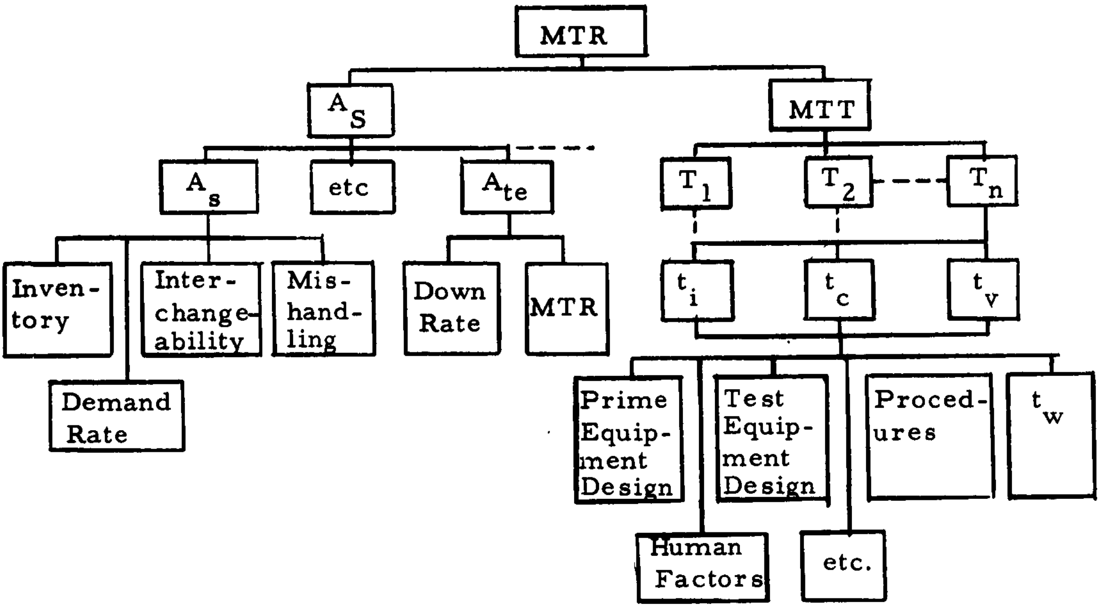
It is well to make several pertinent points at this time:

1. All parameters leading to A_{ic} can be handled either as system average values, with some dispersion about the mean, or as subsystem values. Laws of statistics must be observed. Few parameters dealt with can be considered as absolute values, except for limited applications.

2. If normal weapon system operation within the using organization consists of several submode operational availabilities (Figure 1), simultaneous consideration of corresponding parameters must be made. Parameter values may be drastically different, i. e., in one mode of operation a given malfunction may be corrected by replacing the system; in another mode by replacing a drawer; while in another by replacing a module within the drawer, which is still in the system.

3. Designed-in waiting time, t_w, must be considered in MTT. This is largely a function of the normal support environment. When evaluating MTT, while assuming 100-percent support, this factor cannot be ignored since it exists even if the planned support is available. Such factors as time to warm up test equipment, assemble repair gear, and fetch a spare are intended to be part of t_w as opposed to the time lost if the test equipment is inoperative, or if supply is out of spares.

4. Figures 1 and 2 apply to the using level. All levels of maintenance above the using level are for the sole purpose of keeping spares available at the using organization. If the cost per new spare is less than the cost per overhauled spare, then a throw-away policy should be implemented, assuming emergency requirements does not excessively increase inventory requirements for new spares.



MTR - Mean time to repair

MTT - Mean task time

A_S - Support availability

A_s - Spares availability

A_{te} - Test equipment availability

T_n - n_{th} maintenance task

t_i - Time to isolate malfunction

t_c - Time to correct malfunction

t_v - Time to verify repair of malfunction

t_w - Inherent waiting time

Figure 2. MTR Relationship

Thus, the requirements on A_s will influence many higher level maintenance factors, such as mean turn around time, emergency supply techniques, etc.

Although not applicable in exactly the same sense, Figure 2 can, however, be utilized in a similar approach for designing and evaluating maintenance requirements at all higher levels of maintenance. In fact, Figure 2 can be reconstructed under the A_s term in Figure 2, for each provisioned spare required at the using level, to account for that portion of A_s coming from overhauled spares. The process can again be repeated under the A_s term reappearing for each component being overhauled until all spares at the highest level of maintenance appear as new spares (bits and pieces and throwaway modules). Figure 3 shows how a new MTR is established for each required spares availability at each maintenance level.

The notion of subsystem availabilities in equation (10) makes it possible to establish subsystem or task maintainabilities. This approach provides a useful tool for combining individual maintenance task parameters in arriving at an overall system value and also for comparing task values to each other or to a mean value in order to spotlight those tasks contributing least to desired system level availability.

The analysis approach throughout study and R&D phases should rely upon several postulates:

1. Maintainability optimization should be weighted with corresponding operational reliability rather than on an independent basis. In other words, availability is the prime consideration to the customer; systems should not be made maintainable solely for the sake of maintainability.

2. All possible system malfunctions can be corrected by one of a finite number of independent maintenance tasks.

   DEFINITION: A malfunction is any occurrence where specified operation/outputs are not present while operating within specified design environment with specified inputs.

3. A maintenance task is defined as any or all actions taken to correct a given malfunction (scheduled, unscheduled, marginal, or catastrophic).

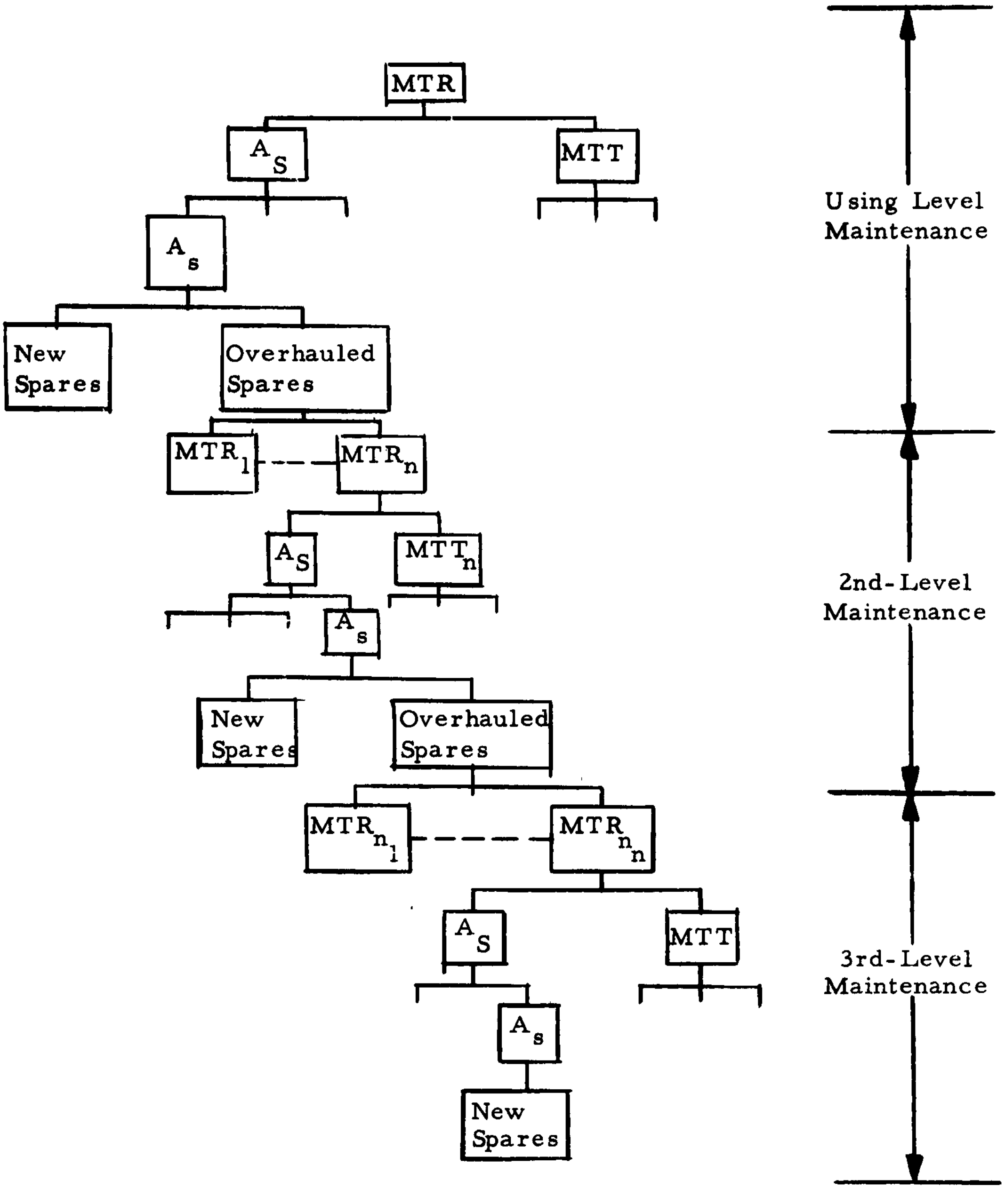


Figure 3. Relationship of MTR's at Various Levels of Maintenance

4. The total number of tasks necessary to correct any malfunction is equal to the number of separately identifiable remove/replace and adjustment possibilities required to correct all possible failures. The number of necessary tasks is a function of design and maintenance philosophy.

5. A maintenance task that does not cause a system to be operationally unavailable is considered to take zero time duration to perform. Man-hours expenditures must therefore be determined separately.

6. A failure is not considered to have occurred until it has been detected. The probability that a system is thought to be in commission, but is actually out-of-commission, must be considered separately from the maintainability analysis.

7. Unavailability due to malfunctions caused by out-of-specification inputs (vibration, shock, temperature, power, signals) is charged to the source of the input.

Utilizing the above postulates, all tasks are predicted, starting at the earliest system synthesis phase, by close coordination with the preliminary design team and design engineers.

The nominal task availability goal is determined. A downrate goal is then determined by applying an operational factor to the inherent reliability goal assigned the hardware associated with each task. A maintainability MTR goal is then determined for each task.

Each task is analyzed from the hardware viewpoint to determine basic checkout requirements. A tentative test procedure, test equipment characteristics, and test logic requirements are determined.

The tentative support requirements for all tasks are then compared to determine basic similarities and gross differences. The results are next translated into a more detailed interpretation of how the basic requirements may be carried out. This phase is necessarily integrated with determination of the Logistics Concept. Operational requirements and general customer policies, pertaining to maintenance and support, are applied as constraints that limit the number of possible different solutions. A likely concept is determined, based upon overall cost to support the predicted maintenance tasks and the ability to meet the required MTR goal for each task at the using organizational level.

Cost per task is estimated and may be broken into component costs for such parameters as cost to keep spares available, cost to isolate a malfunction, cost to correct a malfunction, etc. Also, that portion of cost that is a function of malfunction rate is useful.

Cost and time per task and other suitable factors are utilized as the basis for alternate solutions in the areas of problem tasks. Tasks may be eliminated by repackaging or by changing the functional concept or maintenance concept. Tasks may be reduced in frequency by increasing inherent reliability or by decreasing the operational multiplying factor that accounts for mishandling or misapplication of components within the system. Tasks may be simplified or carried out by differing procedures by adding built-in test equipment, adding or relocating test points, providing isolation circuitry, repackaging, new functional design, etc.

The preceding steps are applied with differing degrees of effort, depending upon the stage of hardware design and personnel involved. The ease with which the steps are applied depends also upon the degree of cooperation, amount of quantitative data, and the analytical tools available to the maintainability engineer, and, of course, his qualifications. The steps outlined above are basically straightforward. The problem lies with the tools for carrying the steps out.

It is felt that one of the more significant keys to the actual analysis of systems to determine optimum packaging, necessary test points, and test logic based upon information outputs from the system for every unique type of failure, is the use of transfer function techniques. A complete system transfer function diagram drawn to a level that allows identification of finite transfer function blocks to a particular removable/replaceable package or adjustment is required.

The starting point for such a diagram can be that used for determining system performance characteristics. However, these are usually simplified on the basis that a component operates only within the in-specification range. Many parameters are considered zero or negligible in the performance analysis, but a parameter will not be negligible if it "fails." The resulting effect on the rest of the system may be interesting from a maintenance point of view. Also, in performance design, cross-coupling between various open or closed loops in the system and unnecessary but possible inputs to the system may be considered negligible. Such factors may be extremely important in troubleshooting and in setting ambient conditions necessary for effective troubleshooting and checkout.

After the prime system is blocked out, the transfer functions external to the system for test and checkout can be added. The external parameters will likely include human factors characteristics.

Overall evaluation of such a system of transfer functions can lead to determination of minimum parameters that must be measured and the accuracy required for a given probability of isolating a given faulty transfer function to a remove/replace package or an adjustment. The best troubleshooting technique can also be determined. Completely solving such a complicated system of transfer functions can be difficult, if not impractical. However, considering that the usual case is where a system has but one failure at a time, individual solutions can be simplified a great deal.

If a solution cannot be made simple, this is a clear sign that the actual troubleshooting will likely also be difficult and special test procedures or design may be necessary.

The usefulness of the above approach is felt to have only been touched on. There must be many theorems and short cuts that can be derived for use in specific situations. It remains for the motivated maintainability engineer to discover them.

The other prime tool utilized a great deal is probability and statistical techniques, including advanced techniques such as Markov Chain and Queuing theories which, in general, are the tools of Operations Research. These are especially useful when considering the optimum means of providing the various elements of support at all maintenance levels, including spares, test equipment, personnel, facilities, manuals, etc. Similar techniques are also required to relate the many maintainability characteristics, such as MTT and support element availabilities to the MTR parameter and in relating MTR, reliability and reaction time to operational availability, and for combining submode availabilities to determine ultimate mode availability. There is room for many application techniques to be developed here also.

MAINTAINABILITY DEMONSTRATION

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SUMMARY

The Rome Air Development Center (RADC) has recognized two broad objectives of maintainability programs - to increase the availability of systems/equipment and to reduce the cost of operational support throughout service life. RADC has strived to achieve these objectives both from a design viewpoint aimed at determining man-machine relationships to reduce the burden on the maintenance technician and from a technique aspect for a better understanding of the problems associated with the quantification and measurement of maintainability.

The successful implementation of "maintainability" in an equipment or system program depends in large measure upon:

a. The specification of definitive maintainability requirements.

b. The implementation of proper maintainability design procedures.

c. The means for providing assurances that the requirements have been met.

This paper describes the approach that has been under study by the Rome Air Development Center. The procedure used to measure the factors which influence design for maintenance is described. The specification of system/equipment requirements and the demonstration procedures as reflected in Specification MIL-M-26512B are discussed. Validation of the demonstration procedure is also furnished.

SECTION I

The Maintainability Technique Study, Contract AF30(602)-2057, initiated by Rome Air Development Center, has as its objective to develop a procedure whereby the factors which affect the maintainability of electronic equipment can be identified, measured and improved. Further, that a prediction technique be formulated that would provide the capability to quantitatively specify, predict, test and demonstrate the maintainability of new systems and equipment. In addition, the technique should possess the capability of being applied in the early design stages of equipment development and provide design cycle control through development and production.

To provide this capability, answers to the following questions were needed:

a. What are the factors of maintainability that affect equipment availability and service life?

b. How can these factors be expressed in quantitative terms?

c. How does the support environment including maintenance personnel, spares, test equipment and facilities affect maintainability?

d. What is the relationship of equipment design to maintainability?

To provide a systematic approach to the program, five formal phases were established. These phases include: (1) development of a research plan; (2) data collection; (3) data reduction; (4) development of the prediction method; and (5) trial application and validation.

The design of the research plan, Phase I, consisted of a statement of the hypothesis and an exploration of the factors believed to affect maintainability. Measurement techniques and techniques of analysis leading to the development of a prediction methodology were developed.

The fundamental hypothesis established early in the study program was that maintenance time is a function of three (3) major parameters, design, personnel and support. Each contributes to the maintenance time required to restore an equipment to satisfactory operating condition. Therefore, the technique developed must be capable of relating these parameters to a common denominator.

After reviewing the requirements for a prediction technique, it was felt that the most suitable denominator to which the parameters could be reduced and a quantitative maintainability figure expressed, was time. Two reasons for this choice are:

1. Time is universally meaningful and expresses the various aspects of maintenance understood by both operational and development agencies and is a measurable quantity.

2. Time is a true measure of the influence of maintainability on operational capability.

Phase II, the data collection program, provided the raw material from which the required relationship could be derived. Since no means existed for measuring the parameters of design, personnel and support, it was necessary to devise a system for determining their magnitude.

Maintenance task performance was recorded for three ground electronic equipments at eight (8) operational field sites and under controlled conditions at three additional locations. Maintenance task time data was collected and the time requirements for the performance of each of eight (8) major elements of maintenance task was recorded to the nearest tenth of a minute. These elements included: (1) assemble and disassemble; (2) test and measurement; (3) remove and replace; (4) checkout; (5) clean and lubricate; (6) secure materials; (7) prepare reports; and (8) contingency items. Additional data was obtained by means of checklists which related the influence of inherent design, personnel requirements and logistic support on the ease of performing maintenance. Since the elements of maintainability vary for each maintenance task, it was necessary to score the checklists for each maintenance task. The score for each question could vary from 0 to 4 depending upon the condition of the characteristic being measured. The sum of the individual scores, when observed over a number of tasks, provided a meaningful total of the influence of the characteristic in question on maintenance time.

A comprehensive processing of the field data was accomplished in Phase III. All data was screened for completeness, clarity and summarized with respect to equipment task measurements. Means, variance, distributions and overall equipment reliability were determined. The distribution of the checklist scores was found to be normally distributed. Maintenance time, however, was distributed log normally; hence, a log transformation was used to determine if the transformed data would fit a normal distribution pattern. A test for goodness of fit (Komolgorov-Smirnov Test) of the log maintenance data was performed to determine if the real distribution was log normal. The results of the test verified that log technician time forms a normal distribution.

The prediction technique was developed during Phase IV. The use of a prediction technique during the design phase of a new equipment considers primarily the design parameter. This dictated the development of an expression relating maintenance design criteria to time requirements. Using regression analysis techniques, a downtime equation was developed relating expected downtime to checklist scores for physical design features, design as it relates to facilities and design as it relates to maintenance skills. To facilitate the interpretation of the checklists scores into maintenance downtime, a nomograph was developed embodying the downtime equation which is expressed as $\log M_{ct} = 3.54651 - 0.02512A - 0.03055B - 0.01093C$. Use of the nomograph involves the plotting of the checklist scores for A, B and C on the nomograph and reading the expected downtime for a particular maintenance task. Repeated application of this procedure for a number of tasks provides the means for predicting the mean and maximum downtime for the system or equipment.

The application of the prediction technique to evaluate an equipment's maintainability is approached from a sampling basis. There are five (5) distinct steps in the application of the technique.

1. Determination of sample size.
2. Selection of tasks.
3. Performance of a maintainability analysis.
4. Scoring of the checklists.
5. Prediction of downtime.

The sample size to be used is dependent upon the statistical accuracy and confidence level desired. The sample size "N" is determined from the relationship $N = \left(\frac{\phi \sigma}{k \bar{x}}\right)^2$ where ϕ is the confidence level, k is the accuracy and $\frac{\sigma}{\bar{x}}$ is the ratio of the variance to the mean of the population. From the observed field data the ratio of $\frac{\sigma}{\bar{x}}$ for the log data was found to be .284 (1.07 real time). For a confidence level of 90% = 1.64, $\left(\frac{\sigma}{\bar{\bar{x}}}\right) = .284$ and an accuracy of ±5% a sample size of 90 would be required.

The parts to be used for simulated maintenance tasks are selected on the basis of average failure rates for each part class, the number of parts of each part class and the part contribution to downtime. The number of parts per part class is multiplied by the average failure rate per 1000 hours to determine the expected number of failures per 1000 hours of equipment operation. The percent contribution of each part class to the total expected failures is then computed and the number of each type of failure for the pre-determined sample size is established. The specific parts to be selected are determined with the aid of the equipment part list and a table of random numbers.

A maintainability analysis is performed for each part selected for the evaluation. At the present time, the part is assumed to have failed in its most common failure mode. Starting with the system malfunction, a logical diagnostic procedure is followed to isolate the defective part. With each step, notations are made regarding access problems, test equipment requirement, and other information important in performing the maintenance task.

The completion of the maintainability analysis forms the basis for completing the checklists. The checklist scores provide an overall view of the design of the equipment from the standpoint of maintainability.

As described previously, the scores from the checklists are then applied to the downtime nomograph and the predicted downtime for the specific task is determined. The mean ($\bar{M}_{ct}$) and maximum (M_{max}) are calculated from the equations.

$$\bar{M}_{ct} = \frac{\sum_{1}^{N} M_{ct}}{N}$$

$$\log M_{max} = \overline{\log M_{ct}} + 1.65 \sqrt{\frac{\sum_{1}^{N} (\log M_{ct})^2 - \frac{(\sum_{1}^{N} \log M_{ct})^2}{N}}{N - 1}}$$

where M_{ct} = the corrective maintenance time per task

N = the number of simulated maintenance tasks

The validity of this technique is presently being tested. The technique was used to predict $\bar{M}_{ct}$ downtime of two equipments. Maintenance time data was recorded at operational field sites for the same equipment. Preliminary analysis of the data indicates that the maximum difference between predicted and observed values for $\bar{M}_{ct}$ was 20%.

The technique which has been developed is reflected in Appendix A of Specification MIL-M-26512B. Equations for the mean and maximum downtime expressed in paragraph 30.3.1 of the specification establish the goals to be achieved. Task selection is described in Section 40. The only significant difference between the procedures described by the specification and that developed under the contract lies in the selection of the number of simulated maintenance tasks. Table 1, Appendix A, as it is formulated, restricts the number of simulated tasks to a minimum of 52. A more rigid determination of sample size would employ the equation previously described with the associated confidence level and accuracy. Table 1 can be used to select maintenance tasks during the maintainability prediction phase. The same tasks can be used during the demonstration phase where the actual maintenance times are recorded. The actual maintenance time is used in the "verification" equations described in paragraph 40.1.4 of the Appendix. Comparison of the actual $\bar{M}$ and M_{max} with those established as the goals within the stated confidence levels determines compliance or non-compliance with the maintainability requirements.

Although the major objective of this study was to develop a prediction technique, other relationships were developed which are of interest. Mean downtime for preventive maintenance ($\bar{M}_{pt}$) may be approximated from the relationship $\bar{M}_{pt} = \frac{\bar{M}_{ct}}{1.4}$. This assumes that the mean corrective maintenance time ($\bar{M}_{ct}$) is known. A more accurate estimate can be obtained by applying the prediction technique to a group of representative preventive maintenance tasks. Another useful relationship was developed relating maintenance time data obtained from field sites in the actual operating environment and similar data obtained in a "laboratory" controlled environment. This relationship is expressed as $M_{ctf} = (M_{ctl})^{1.227}$. This relationship can be very useful in expediting maintainability testing by allowing some tests to be performed at the plant and account for degradation caused by the field maintenance environment. Caution should be exercised in the use of these relationships since it is felt that additional data and validation is required.

The prediction technique as it is presently formulated requires refinement. RADC has initiated a program to increase the quantity and quality of maintenance task time data particularly at the part and circuit level with particular emphasis on the influence of variation in circuit design on maintainability. It is anticipated that this effort will increase the confidence in the prediction technique and its accuracy in the early design stages of equipment development.

SECTION II

The use of the prediction technique discussed is dependent on sampling procedures in conjunction with transformations, regression analysis and figures of tolerance and confidence. Basically the mathematical fundamentals of the prediction exercise are as follows:

1. Selection of sample size.
2. Application of regression analysis.
3. Calculation of maintenance indices.

Both laboratory and field data indicate that downtimes for any given electronic equipment are distributed log normally (see Figure I). Since it is difficult to fully and simply analyze and examine all the characteristics of this distribution in its raw shape, a transformation of one of its variables is necessary to reduce it to more tractable form.

Let the new variables be U and V, where $U = Y$ and $V = \log_{10}X$.

where Y = frequency of occurrence of a value of downtime

X = the value of downtime

The distribution of Figure I is then transformed to the distribution of Figure II (a normal distribution) which lends itself to examination and analysis more readily. Figure II is then a log normal representation or more simply the distribution of the logarithms of downtime.

Let us assume that this distribution is representative of a universe of the log of downtimes for any given equipment. Take H samples from this universe, each of size N and compute the mean of each sample. It will be found that the means of the H samples are normally distributed with standard deviation σ_x [*1], and a mean of sample means of $\overline{\log_{Mct}}$.

$$\sigma_x = \frac{\sigma_{\log_{Mct}}}{\sqrt{N}} \qquad (1)$$

where $\sigma_{\log_{Mct}}$ = the standard deviation of the universe of log downtime

N = the number of items in a sample.

Since we are dealing with normalized quantities, a statistical area of spread may be defined for the true mean of a normal universe.

Let us see what this means.[*2] If we took many, many samples of downtimes, each of size N, the mean of each sample would not be the same. Some means would be larger than others, but percentages of all means can be located with respect to the mean of the universe with aid of the standard deviation σ_x and the concept of normality. For example, about 2/3 of all means would be within one standard deviation (σ_x) of the universe mean, and 95% of the sample means would be within 2 standard deviations ($2\ \sigma_x$) of the universe mean.

In our sample of N log downtimes we find a mean of $\overline{\log_{Mct}}$.

[*1] - For extension of the above concept see Hald "Statistical Theory with Engineering Applications", Chapter 8.

[*2] - See Waugh, "Elements of Statistical Method", Chapter 9.

$$\text{where } \overline{\log_{M_{ct}}} = \frac{\sum_{1}^{N} \log_{M_{ct}}}{N}$$

We do not know that this is the mean log downtime of our universe of log downtimes; other samples would give other means. But in our assumptions, we know that two-thirds of all these other means will be within σ_x of the mean of the universe of log downtimes. It is therefore true that the chances are 2 out of 3 that this mean ($\overline{\log_{M_{ct}}}$) is within σ_x of the mean of the universe of downtimes. Conversely it is true that the chances are 2 out of 3 that this mean of the universe is within σ_x of the means of this sample. Since then the mean of the sample is $\overline{\log}$ [illegible] the chances are 2 out of 3 that the mean of the universe $\log_{M_{ct}}$ is within σ_x of $\overline{\log_{M_{ct}}}$ or

$$\overline{\log_{M_{ct}}} \pm \sigma_x$$

Hence the true mean of the universe may be defined by a spread of standard deviations about the sample mean. In general

$$\overline{\log_{M_{ct}}} \pm \phi \, \sigma_x \qquad (2)$$

where ϕ = the confidence to be applied to the estimate, ϕ = 1 for 2/3 confidence, ϕ = 2 for 19/20 confidence.

It is possible to represent

$$\phi \, \sigma_x = k \, \overline{\log_{M_{ct}}}$$

or

$$\phi \, \frac{\sigma_{\log_{M_{ct}}}}{\sqrt{N}} = k \, \overline{\log_{M_{ct}}}$$

where k - is defined as a parameter of accuracy or spread with respect to the mean

Hence

$$N = \frac{(\phi)^2}{(k)^2} \frac{(\sigma \log_{M_{ct}})^2}{(\overline{\log_{M_{ct}}})^2} \qquad (3)$$

where N - is the number of samples necessary to the prediction exercise

Observed field data provides a basis for determining the sample size needed for a typical problem since $\frac{\sigma \log_{M_{ct}}}{\overline{\log_{M_{ct}}}}$ has been found to be = .284

$$N = \frac{(\phi)^2}{(k)^2} (.284)^2 \qquad (4)$$

Therefore merely by stipulating the spread parameters ϕ (the confidence to be applied to the spread) and k (the proportion of spread with respect to the mean), the sample size necessary for prediction of $\overline{\log M_{ct}}$ (mean log downtime) may be calculated. (The above might be restated to - to determine the sample size which will permit stating the mean with an accuracy of k (100) percent with a confidence stipulated by ϕ.)

It should be noted that the above (equation 4) sets the accuracy and confidence levels for the prediction of $\overline{\log M_{ct}}$.

Although equation (3) (the calculation of sample size) was derived on the basis of a log normal representation, it is sufficiently non-parametric in nature to be applied generally to any practical distribution (for relatively large values of N where $N \ll H$) such that

$$N = \frac{(\phi)^2}{(k)^2} \frac{(\sigma)^2}{(\bar{x})^2} \qquad (5)$$

where σ = standard deviation of the distribution

$\bar{x}$ = distribution mean

Observed field data provides a basis for determining the sample size to determine $\overline{M_{ct}}$ (mean downtime) for a typical problem since $\frac{\sigma}{\bar{x}}$ of untransformed downtime data has been found to be = 1.07.

Hence

$$N = \frac{(\phi)^2}{(k)^2} (1.07)^2 \qquad (6)$$

Therefore the accuracy and confidence of $\overline{M_{ct}}$ are also set by the sample size.

After determining the proper number of samples the prediction is implemented as in Section I and the regression equation

$$Z = \log M_{ct} = 3.54651 - .02512A - .03055B - .01093C \qquad (7)$$

is evaluated for each sample task (a simulated failure). Checklists A, B and C provide the values necessary for computation of M_{ct}. A nomograph (see Figure IIIO presents the regression equation in a convenient form and

$$\frac{\sum_{1}^{N} M_{ct}}{N} = \overline{M_{ct}} \qquad (8)$$

defines the figure of <u>mean downtime</u>.

The prediction of equipment maintainability must also include the determination of the 95th percentile (that value below which 95% of the all downtimes lie). In order to define this characteristic most fully, let us consider a normal representation. Define the mean of the log normal representation as M (log x) = log ϵ. ϵ does not denote the mean of the variable x, hence merely taking the antilog of the mean of a log normal representation <u>will not yield</u> the mean of the variable. The mean of x ($\bar{x}$) may be denoted as

$$\bar{x} = \text{antilog } (\log \epsilon + 1.1513\sigma^2) \text{ (see Hald's} \qquad (9)$$

(Statistical Theory with Engineering Applications for proof)

The median of x (x^1) may however be found by taking the antilog of the mean of the log normal representation.

$$x^1 = \text{antilog } (\log \epsilon) = x^1 = \epsilon$$

Reference is made to Figure IV. The figure shows a histogram of a normally distributed representation of log x values. Utilizing the concept of normality that 47.5% of all elements belong to the interval ($\log \epsilon - 1.96\sigma < \log x < \log \epsilon$) and 47.5% to the interval ($\log \epsilon < \log x < \log \epsilon + 1.96\sigma$) where σ is the standard deviation of the log normal representation. (note both intervals are same width).

If this distribution is transformed (Figure V) from a log representation to its original form, and if the corresponding elements are considered, the two intervals <u>still holding each 47.5%</u> of the elements are modified to

$$\left(\frac{\epsilon}{1+\alpha} < x < \epsilon\right) \text{ and } (\epsilon < x < \epsilon\,(1 + \alpha)\,)$$

where $10^{1.96\sigma} = 1 + \alpha$

If σ is relatively large the size of the two intervals differ markedly (i.e., 47.5% of the population are squeezed together in a small interval to the left of the median and another 47.5% of the population are scattered over a comparatively large interval to the right ot the median). It is these characteristics along which allow the 95th percentile to be calculated as

CONDITIONS PERTAINING TO EQUATION (11) SHOULD READ:

WHERE

$$\left\{ \begin{array}{l} \log \epsilon = \overline{\log M_{ct}} \\ \log X = \log M_{ct} \\ \sigma = \sigma_{\log M_{ct}} \end{array} \right\}$$

$$M_{max} = \text{antilog}\ (\overline{\log_{M_{ct}}} + 1.645\ \sigma_{\log_{M_{ct}}}) \qquad (11)$$

$$\text{where} \left\{ \begin{array}{l} \log \epsilon = \overline{\log_{M_{ct}}} \\ \log x = \log_{M_{ct}} \\ \sigma\ (\log x) = \sigma \end{array} \right\}$$

$$\overline{\log_{M_{ct}}} = \frac{\sum_{1}^{N} \log_{M_{ct}}}{N} \qquad (12)$$

$$\sigma \log_{M_{ct}} = \sqrt{\frac{\sum_{1}^{N} (\log_{M_{ct}})^2 - \frac{(\sum_{1}^{N} \log_{M_{ct}})^2}{N}}{N - 1}} \qquad (13)$$

The probability that when maintenance action is taken because of equipment failure, the system will be restored to a satisfactory operating condition in a given period of time may be given as

$$P_r = \frac{1}{\sqrt{2\pi}} \int_{-}^{\mu} \epsilon^{\frac{-\mu^2}{2}}\ d\mu \qquad (14)$$

$$\text{where} \quad \mu = \frac{\log M_{ct} - \overline{\log M_{ct}}}{\sigma_{\log_{M_{ct}}}}$$

The probability P_r may be determined also from tables of the cumulative normal distribution available in most handbooks of tables.

Maintainability is demonstrated in a manner similar to its prediction.

1. A sample number is chosen consistant with the required accuracy and confidence, (this number, however, must be at least 50), utilizing equations (3) or (5).

2. Appropriate tasks (N) (simulated failures) are chosen in the same manner as was done during the phase of prediction.

3. The downtime associated with each task is measured and a mean downtime for all N is calculated.

4. Values of $\overline{\log M_{ct}}$, and $\sigma_{\log_{M_{ct}}}$ are calculated from the data.

5. Equations are utilized to determined the measured M_{max}.

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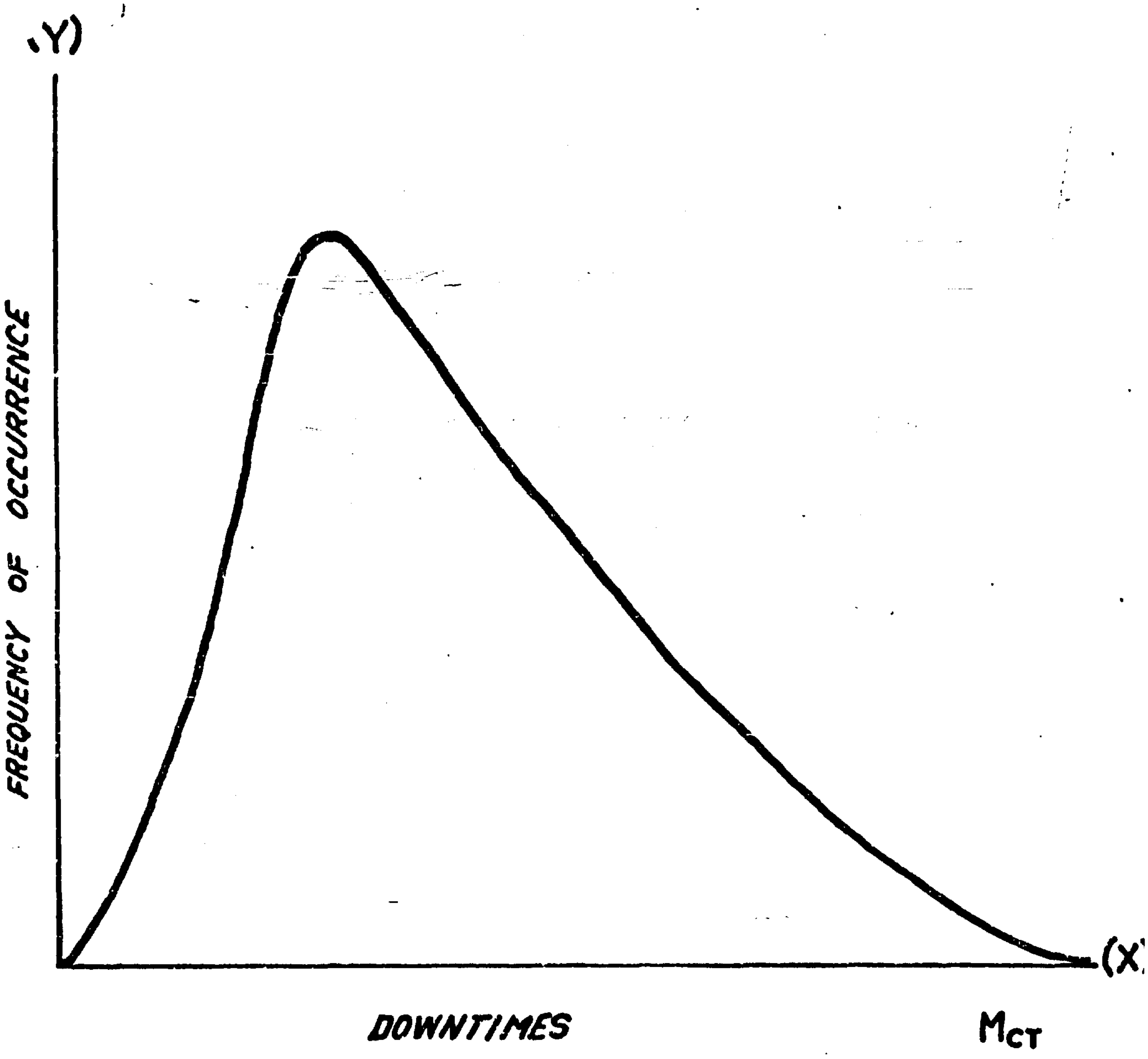
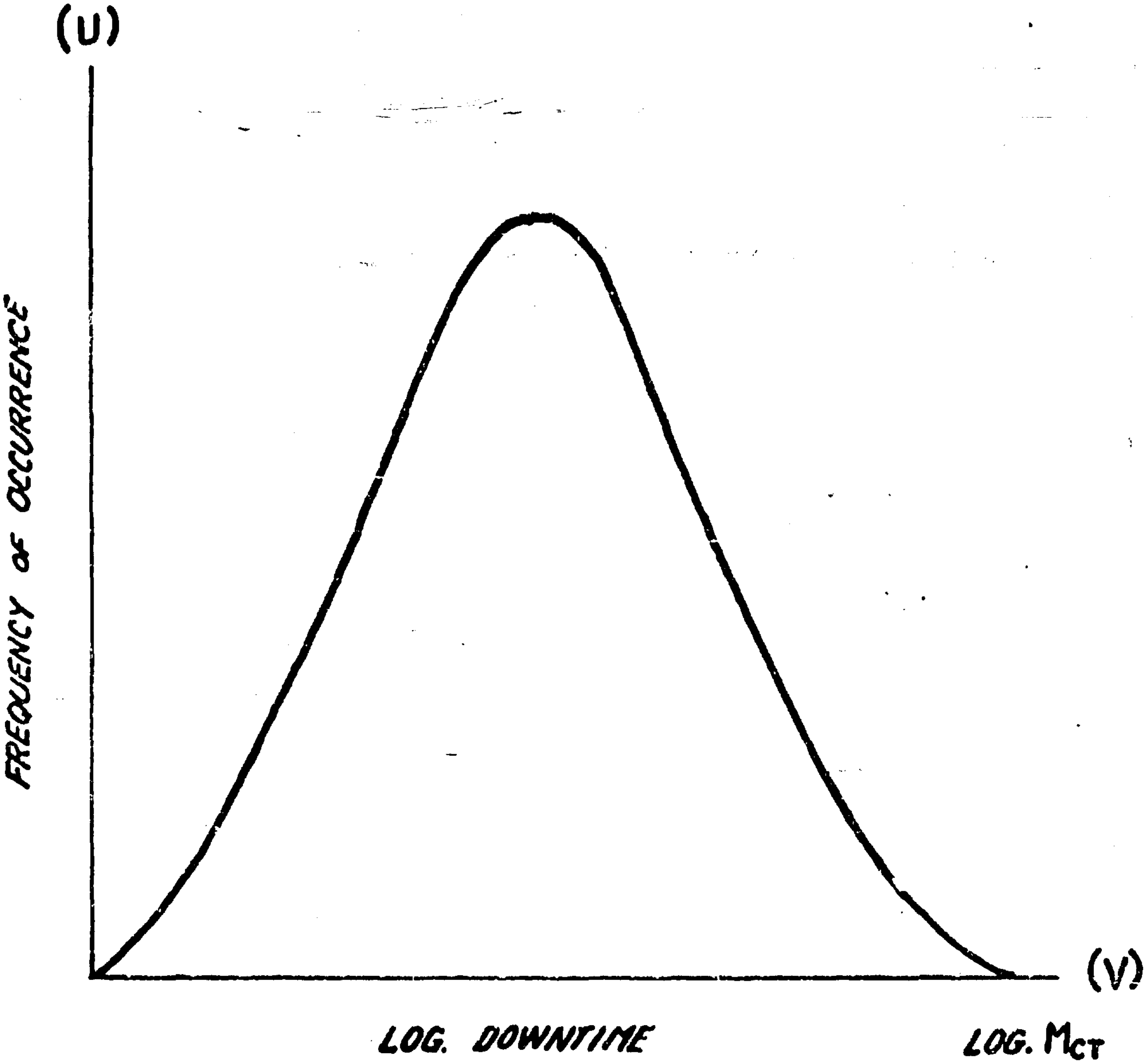


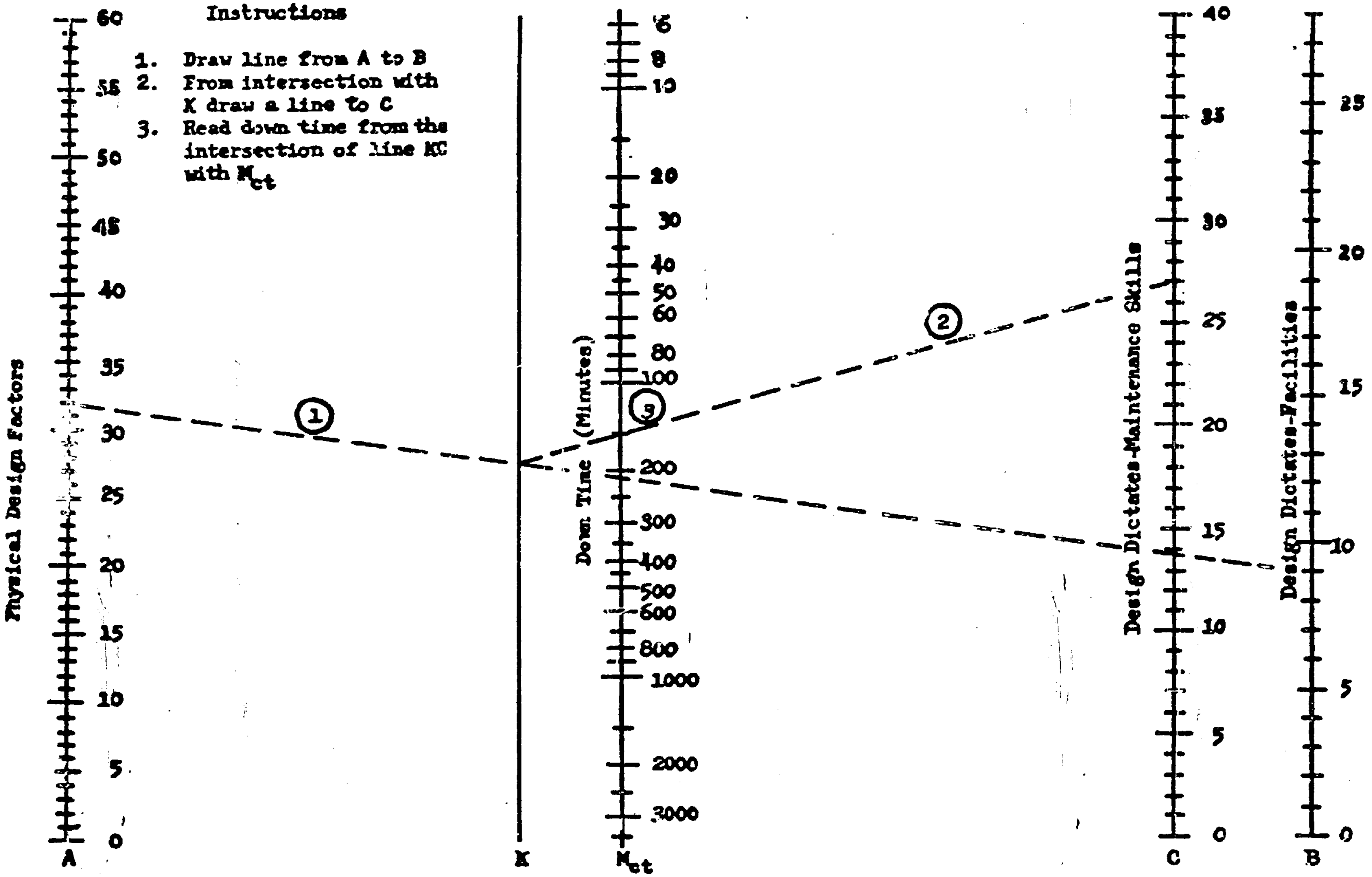
M_{CT} = DOWNTIME

FIG. I



M_{CT} = DOWNTIME

FIG. II



Instructions

1. Draw line from A to B
2. From intersection with K draw a line to C
3. Read down time from the intersection of line KC with M_{ct}

FIGURE III NOMOGRAPH - DOWN TIME

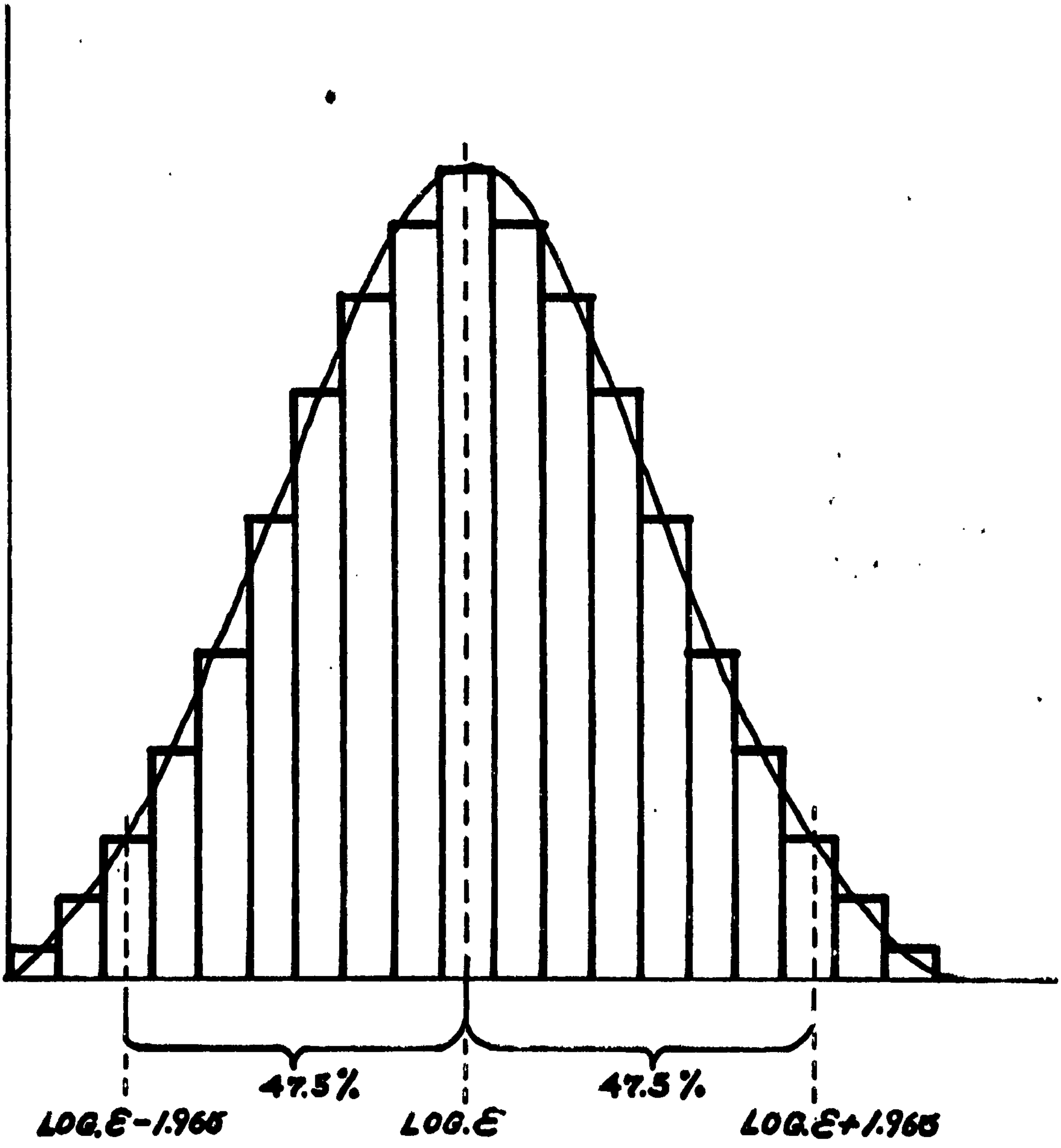


FIG. IV

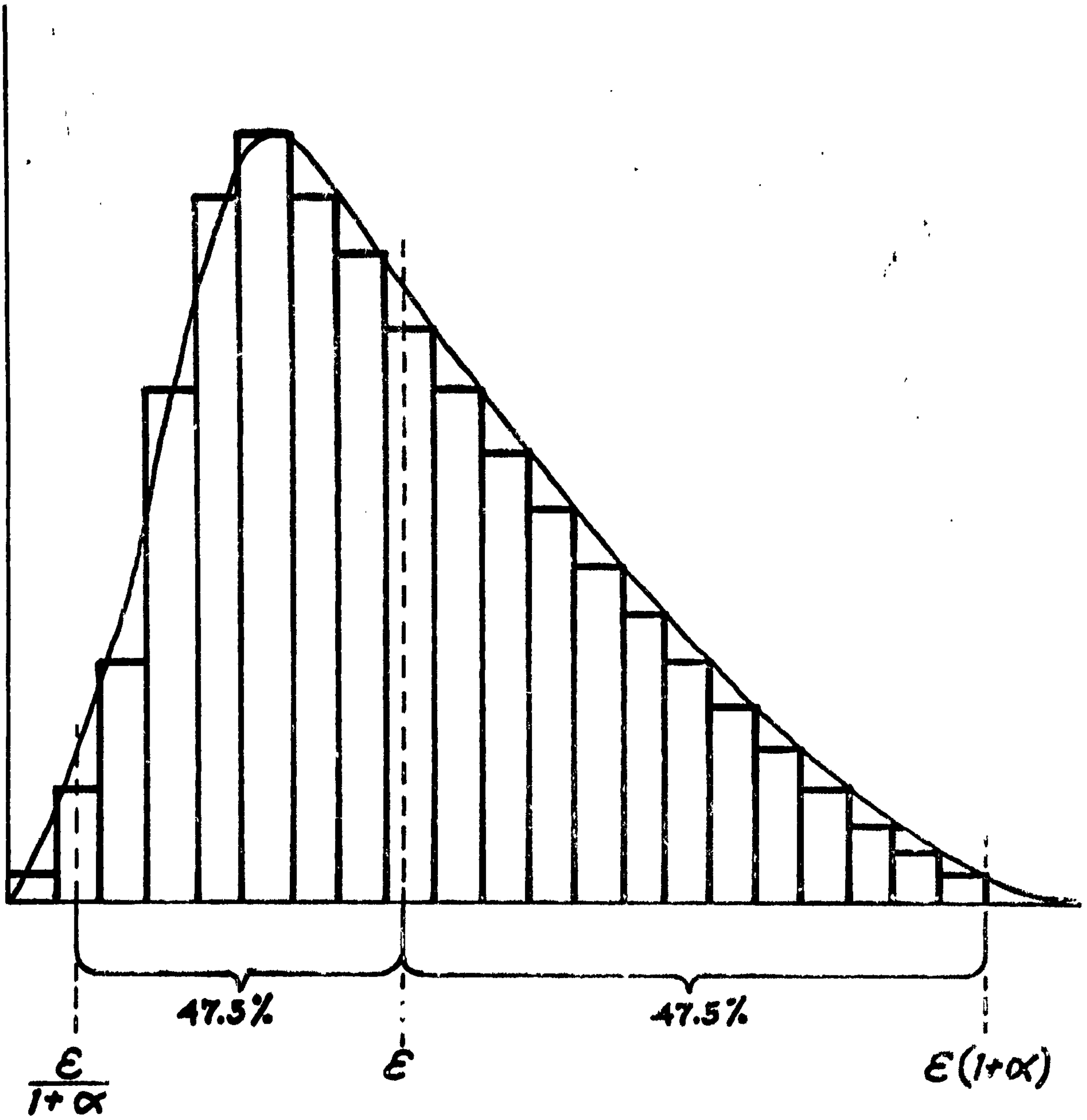

47.5%
47.5%
$\frac{\varepsilon}{1+\alpha}$
ε
$\varepsilon(1+\alpha)$

FIG. V

SUPPORT SYSTEM ANALYSIS

by

W. J. Arnold - S. M. Laster

Special Projects Operation
General Electric Company

Presented at
Maintainability Conference
12-13 March 1963

Electronics Systems Division
Lawrence G. Hanscom Field
Bedford, Massachusetts

SUPPORT SYSTEM ANALYSIS

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SPECIAL PROJECTS OPERATION

GENERAL ELECTRIC COMPANY

SUMMARY:

This paper describes a general analytic model that has been developed for use in support systems analysis. The paper outlines the basic logic of this model, and describes the application of the model to the problem of selecting an optimum support system.

ACKNOWLEDGEMENT:

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INTRODUCTION:

The design of a support system for the maintenance of large-scale electronic systems should be approached in the same systematic manner used in designing the hardware system itself. Unfortunately, the engineering decisions on a given support system design are often made by several individuals or groups without considering the numerous interrelating effects. Spare parts are sometimes selected by use-quantity without considering reliability failure rates or the detailed maintenance concept. The maintenance concept is sometimes established on the basis of speed or tailored to fit into a given system, without regard to spare parts cost or system over-all availability. The omission of such considerations in the selection of a given support system element is not deliberate. The problem arises from lack of emphasis on early planning by an engineering group designing the over-all support system and establishing trade-offs among the many parameters that must be considered.

The purpose of this paper is to enumerate some of the many considerations involved in a typical support system design and to develop analytical models which may be used for actually determining the trade-offs required by the typical system described. By postulating different support configurations, and determining the net effectiveness of each, it is then possible to compare the configurations and make a selection based on the desired criterion.

SUPPORT SYSTEM DESIGN CONSIDERATIONS:

Let us begin by describing the type of system we have in mind for this typical analysis. The system could be a large ground electronics network for communications, missile guidance, detection, etc., and would cover a continental area. It would consist of many sites, either manned or unmanned; and the sites might be interrelated. With a general description such as this, the model will, of course, be general in nature and will become specific to a given system by virtue of the numbers placed on the various interacting parameters.

The next question, then, is what are the parameters being considered? For this area, it is convenient to divide the analysis into two categories: Maintenance Availability and Supply Availability.

Maintenance Availability covers the following areas: (1) equipment performance from a reliability standpoint, (2) the time periods between either automatic or manual tests, (3) the time required for repair crew travel upon detection of a failure, (4) the time required to locate the cause of failure and to repair, (5) the time required to obtain the necessary spare parts after identification of the failed replaceable item, and (6) the efficiency of each equipment test (namely, the probability of the test detecting a failure).

The maintenance availability factor, by itself, makes the assumption that the replacement unit to repair the system is actually available for use at the time of the detected failure. The factor of transportation to acquire this available unit is, however, included in the maintenance availability areas as mentioned above. The assumption of immediate availability of spare replacement items can, of course, be made with an unlimited quantity of spare units. The magnitude of the "unlimited" is dependent upon the over-all system size and complexity. Such a situation is normally prohibitive from a cost standpoint and consequently a second grouping of items to be considered in the Support System Analysis is Supply Availability.

The Supply Availability considers such items as: (1) the number of spare modules for the complete system, (2) the number of repair benches to maintain these spare modules in working order, (3) the number of repairmen and the amount of time required to find and repair the malfunctioning component part in the spare module, (4) the number of items per unit time anticipated at the repair point, (5) the transportation time from the point of failure to the repair facility, and then back to the operable module storage area, (6) the time required, if any, awaiting replacement parts, and (7) the scheduled working periods of repairmen - for example, it may be desirable to have only a single shift with provisions for emergencies.

No doubt there are other considerations for both maintenance and supply availability, and these could be included in a similar analysis if the particular system in question possessed these additional considerations as significant parameters.

In designing an over-all support system, both maintenance availability and supply availability must be treated. The over-all support system availability may be expressed as the product of the supply and maintenance availabilities - i.e.,

Eq. (1) $$A = A_M A_S$$

where

A_M = Maintenance Availability

A_S = Supply Availability

MAINTENANCE AVAILABILITY:

Ground military electronic systems generally have the characteristic that some failures can be tolerated if their occurrence is not too frequent and if the resultant downtime, is not too long. Failure repair to the piece-part level usually involves long time periods for both the location and actual change of the failed item. This would result in excessive system downtime if replacement of the failed part were required to return the system to operation. As excessive downtime is unacceptable, the maintenance concept with respect to returning the system to satisfactory operation is that of module replacement, where the module is of the plug-in printed-wire board type. When a failure is detected at a site, it is localized to a module that is then removed and replaced with a spare. There may be many modules of a given type at a given site and modules of the same type are interchangeable. Modules are considered as being of the same type even though an electrical parameter adjustment may be necessary. There are many types of modules in a given site. It is recognized, that keeping the number of module types as low as possible will have a significant effect on the over-all support system problem. This is an equipment design problem, however, and is not treated directly in this support system analysis. The model can be utilized to show the effect of reducing the number of modules by changing this normally fixed parameter in the support system analysis.

Two types of tests are postulated for determining whether or not the site has failed. Test 1 is a periodic, comprehensive test which detects any failure in the site; that is, the efficiency of Test 1 with respect to detecting a failure is unity. Normally, Test 1 would be manually initiated and monitored. Test 2 is a continuously-monitoring test which detects a fraction of the site failure - its efficiency is usually less than unity. Through the efficiency value in the analytical mode, either test may be considered to be the only test, or any mix may be postulated.

In the determination of maintenance availability, it has been assumed that the maintenance personnel who perform the periodic Test 1 do not service the failures detected by Test 2. It is further assumed that when a failure is detected by the continuous test, Test 2, a repairman is available to begin the service. These assumptions have been made for analytical convenience and the consequences of their denial should be investigated. This investigation is beyond the intended scope of this paper.

The availability associated with Test 1 is considered first. In this instance, the downtime associated with a failure detected by Test 1 contains the following elements:

(1) A calculated time period during which a failure existed but was not detected (and here consideration is given to the efficiency of Test 2)

(2) The time to detect, remove all failed modules, and obtain replacement modules.

The equations derived assume that the site is operational during the time period required to perform the test itself if failures do not exist. In the event that the equipment must be taken out of operation to perform Test 1, then the time to perform the test may be added directly.

The total site failure rate is λ and λ_1 is defined as that portion of the total site failures which is not detected by the continuous Test 2 or:

Eq. 2 $\lambda_1 = (1 - P_2) \lambda$ where

P_2 = the efficiency of Test 2 in failure detection.

The average downtime per Test 1 cycle $E (+_0)$ may be expressed as:

Eq. 3
$$E (+_D) = (R_1 \lambda_1 + 1) t_1 + \left\{ \frac{\lambda_1 T_1 - 1}{\lambda_1} \right\} \left\{ 1 - \varepsilon^{-\lambda_1 t_1} \right\}$$ where

R_1 = average replacement time of a module including fault localization, removal and replacement by a spare module

$+_1$ = scheduled period of time between the periodic Test 1

T_1 = downtime caused by transportation when replacing a failure discovered by Test 1

ε = Base of Naperian Log

Eq. 3 is derived in the appendix.

The transportation time (T_1) takes on special values with different maintenance concept supply configurations. For example:

(a) If spare modules are located at the site itself or are carried there by a crew performing Test 1, then $T_1 = 0$.

(b) If spare modules are located at a remote supply point, but can be sent in answer to a call, then $T_1 = T_4$ where T_4 is the travel time from the supply point to the site.

(c) If spare modules are located at a central supply point but communications are not available, then $T_1 = 2T_4$.

The transportation time can also be used to incorporate delays other than obtaining spares. If the results of Test 1 are remotely indicated, T_1 should also include the *travel delay time (T_3) of the repairman to the site. In the instance where performance of Test 1 removes the equipment from operational status, the total test time T_6 would be added to the expression for $E_1\ (+_D)$ (equation 3.)

The average uptime of the complete Test 1 cycle as derived in the appendix is:

Eq. 4 $$E_1\ (+_u) = \frac{1}{\lambda_1}\ (1 - \varepsilon^{-\lambda t_1})$$ when the equipment is operational during the test itself.

The site availability with respect to Test 1 is A_1 and may be expressed as:

Eq. 5 $$A_1 = \frac{E\ (+_u)}{E\ (+_u) + E\ (+_d)}$$ where equations (2), (3), and (4) give the required substitutions.

Test 2 would be an automatic type of test by either a remote or on-site control device. The indication of a fault is displayed at a manned station where immediate action can be initiated. The typical Test 2 is performed while the equipment is fully operational and does not possess unity efficiency in failure detection. (λ_2) is defined as that portion of the total site failure which will be detected by Test 2.

Eq. 6 $$\lambda_2 = P_2 \lambda$$

The downtimes associated with Test 2 are as follows:

(1) The travel time of a repairman from home base to the site, (T_3)

(2) The time to localize, remove, and replace the failed module and the time to obtain the replacement module, (R_2)

(3) The time to obtain the necessary replacement spare modules, (T_2)

(4) The average downtime per failure detected by Test 2 is:

Eq. 7 $$E_2(+_D) = R_2 + T_2 + T_3$$

The average uptime may be expressed as:

Eq. 8 $$E_2\ (+_u) = \frac{1}{\lambda_2}$$

The site availability with respect to Test 2 then is:

Eq. 9 $$A_2 = \frac{E_2(+_u)}{E_2(+_u) + E_2(+_D)}$$

* communication and administrative delay included.

Eq. 10 $$= \frac{1}{1 + \lambda_2(R_2 + T_2 + T_3)}$$

As previously mentioned, the situation of the repairman not being at home base has not been considered.

The over-all maintenance availability of the site is given as:

Eq. 11 $$A_M = A_1 \cdot A_2$$

A major factor affecting the Maintenance Availability is the number of maintenance teams required for Test 2 and repair teams for Test 1. For convenience the two teams for Test 1 and Test 2 are treated as independent, and the demand for service by these teams is assumed to be non-conflicting.

Let: N_1 = number of teams required to perform Test 1 for all sites.

An expression for N_1 is straightforward with the assumption of independence between the teams, and may be expressed as:

Eq. 12 $$N_1 = \frac{V}{\xi +_1}$$ where

V = total number of sites in the system.

ξ = mean number of site tests (Test 1) performed by a team in a unit period of time and is a function of the travel time between sites, the duty cycle of the test team, as well as the actual time to perform each test and replace any detected failures.

An additional complicating factor must be included in ξ when spare parts for replacing failed modules are not immediately available. For the calculations in this paper, assumptions have been made for values of ξ . More detailed expressions are necessary and should be pursued in future work.

N_2 = number of "line" repair teams per support area required to implement Test 2.

The estimation of N_2 is more tenuous because of the waiting-line situation arising from the rundown distribution of equipment failures. The estimate has been made using a 25% utilization factor for the repair teams. The estimate of manning requirements on this basis for Test 2 is that N_2 = the smallest integer such that:

Eq. 13 $$4\lambda_2 h\ (2T_2 + R_2) \leq N_2$$ where

h=number of sensor sites serviced by a <u>support area</u> where a <u>support area</u> is the home base of the "line" repairman.

R_2 = average replacement time of a module whose failure is detected by Test 2 and includes fault localization, removal and replacement of a module. $4\lambda_2$ represents the 25% utilization factor in the equation and $(2T_2 + R_2)$ represents the time expended for each failure.

It is recognized that both manning estimates should receive further attention analytically.

SUPPLY AVAILABILITY

The Supply Availability (A_s) is the probability that a site is not inoperable for want of a replacement module at its normal storage point. The normal storage point is that established by the maintenance concept covered in the system maintenance availability. The supply availability of a site then is taken as the joint availability of all module types.

$A_s = \pi_i \Delta_i$ where

Δ_i = supply availability of module type i

The supply availability of a module type depends upon its failure rate, inventory level, and time delays between its failure and return to the ready inventory. The time delays, in turn, appear from four sources:

(a) Pipeline delays caused by transport from single site to repair shop and transport from the repair shop to the supply point (T).

(b) Waiting time in the repair shop for a repair bench to be free to accept the repair.

(c) Waiting time for a repairman to be free to accept a repair.

(d) Actual repair time.

In contrast to the maintenance availability, where the required equations are amenable to manual computation, the supply availability computations are highly interactive and repetitive, making their programing on a computer essential. The program inputs are the equipment parameters.

β_1 = failure rate of a given module type

N_i = the average repair time for a given module type

C_i = the cost of a given module type

λ = the site failure rate

The configuration parameters

r - the number of sites using a single supply point

s - the number of sites using a single repair shop

T - defined above

The equations used in the computer calculations involving the above parameters to calculate A_i and the cost trade-off's are stated and derived in the appendix. A_i consists of two prime factors:

$$A_i = \left(\text{Probability of zero spares shortage}\right) + \text{Conditional probability that, given a spare shortage, it will not be required during the shortage period.}$$

We have thus far confined the analysis to the parameters associated with maintaining the equipment in operational status. In reality, however, the ultimate in any supply configuration is strongly influenced by cost and hence this must be included in the analysis.

The approach used in the selection of the spare quantities is to have the program initially compute the site supply availability with zero inventory of spare modules. It next computes the ratio of change in site availability to module cost for the first purchase on each module type and selects the module type having the highest ratio for inclusion into spares inventory. The new availability inventory cost and item selection are computed and printed. The program next computes the ratio of change in site availability to module cost for the first purchase of each module type not previously selected and for the next purchase of each type previously included. The module type having the highest ratio is added to inventory, and the new availability, inventory cost, and item selection are computed and printed. The inventory selection is continued until arbitrarily stopped at a given level or availability or a given inventory cost. The output is a table of increasing site availability versus inventory cost, and the associated inventory item identification. Example shown in table 3.

It must be emphasized that the selection of one or many module types for spares is strongly dependent upon previous selections made; and, if a spares listing is made up with this technique, a review of all items below a deleted item must be made.

The repair cycle includes a waiting time for the unavailability of a repairman and this effect must be included. M is defined as the number of shop repairmen and the group of shop repairmen are treated as an M-channel waiting-line situation in which the arrival rate is the total arrival rate seen by the benches ($S\lambda$), and the service rate is the actual repair time spent in fixing a module (μ_a). From this model, a value for mean waiting time prior to actual service, but subsequent to waiting for a bench, may be found for adjusting the total bench service rate (μ). This procedure is an approximation because μ is considered the mean rate of an exponential distribution in the sparing model, but the adjustment to μ destroys the exponentiality. However, no other recourse is evident. In summary the procedure is to compute:

Eq. 14
$$E(W) = \frac{\rho^M}{(M-1) \cdot \mu_a (M-\rho)^2} \qquad \frac{1}{\sum_{n-0}^{M-1} \frac{\rho^n}{n!} + \frac{\rho^M M}{M!\,(M-\rho)}}$$

where $\rho = \frac{S\lambda}{\mu_a}$

This equation as derived in the appendix gives the average wait for a repair. The machine computation input is

$$\mu = \frac{\mu_a}{1 + \mu_a E(W)}$$

Typical Support System Analysis Calculations:

In the present section several support configurations are postulated, and the parametric values characterizing the configurations are summarized. An analysis of these configurations in regard to site availability and the cost of support will be presented in the following section. It is felt that the range of configurations considered is sufficiently broad to represent many of the major support possibilities for the system. It should be stressed, however, that these configurations are for illustrative purposes only and that the input values used are extremely gross estimates.

Equipment Breakdown

Two methods for dividing the site equipment into spare assemblies were used. The first considers a group of 10 circuit cards, occupying a tray in a 19-inch equipment rack, as the spared item. From preliminary equipment diagrams a set of 20 such "modules" plus several antennas, meters, etc., were selected, and cost and reliability estimates were made for each. We designate this set as Equipment List A.

The second approach was to consider a printed circuit board as the spared item. A figure of 28 to 30 circuit card types was selected and the site equipment considered to have a total of some 170 cards. This set of equipment is designated as Equipment List B.

Costs were estimated in the range of $100 to $250 per circuit card, and MTTF's were judged, in general, to be greater than 20,000 hours.

Site Mean-Time-To-Failure (MTTF)

Three values were used for the MTTF of the site: 140, 420, and 840 hours. This will provide an indication of the advantage if any of redesigning the equipment for an MTBF improvement of a site.

Test 2 Efficiency (p_2)

The Test 2 check-out efficiency (p_2) was estimated to be 95%, on the assumption that a simulated signal will be applied at the inputs of the initial electronic stages, with normal processing and reporting channels used for response. Parametric variation of the test efficiency was not included.

Module Repair Facility

The repair characteristics of both modules, List A, and boards, List B, were judged to be such that their repair can be performed on a general purpose, non-automatic repair bench using standard test equipment. Each module in Equipment List A was, therefore, assigned to one bench class; similarly, when Equipment List B was used, each board was assigned to a single bench class. The mean repair time, μ_a, was taken to be 1 hour in either case.

In-line Repair Time (R_1 and R_2)

The mean replacement time (i.e., fault localization, replacement, and checkout) was estimated to be 35 minutes for modules in List A, and 75 minutes for items in List B - i.e.,

$$R_1 = R_2 = \begin{cases} 35 \text{ minutes for List A} \\ 75 \text{ minutes for List B} \end{cases}$$

R_1 and R_2 will normally be equal. The 5% of the total failures not detected by Test 2 will usually be similar in nature to the remaining 95%. Provision is made in the model, however, to allow for variations.

POSTULATED CONFIGURATIONS

For the purpose of this analysis, the overall system is assumed to consist of 40 sites, formed into 4 groups of 10 sites each. A support center in each group is located at a mean distance of some 500 or 600 miles from the sites in its group. It is assumed that the sites may also be divided into smaller groups of 4 sites each, such that an intermediate location at a mean distance of some 250 miles from each of the four sites, could be used for support purposes.

On these assumptions, the seven support configurations shown in Table 1 were postulated.

In each configuration, the module (or board) repair facility is assumed to be located at the support centers: hence s, the number of sites per repair facility, is always 10. It is also assumed that when the supply point is not located at the site - namely, for configurations 5, 6, and 7 - each "line" repair team and each periodic test team carries a complement of spares (one spare of each type). Thus the values of T_2 in Table 1 represent the one-way transportation time from the support area to the site; and the maintenance transportation time for Test 1, T_1, is assigned the value of 1/2 hour, since Test 1 is performed in-line.

A word should be added regarding the values of T, the repair cycle transportation time, in Table 1. The normal one-way module transportation, packaging, and handling time between the repair facility and remote areas is estimated to be 125 hours. Thus for configurations 1, 2, 3, 5, and 6, which involve round-trips, 2 x 125 hours was used for T. However, this time is reduced in configuration 4, since the transportation of the module can be accomplished by the repair team returning to the regional center, thus eliminating delays due to administrative, packaging, etc., procedures.

COST ESTIMATES

The following cost estimates are based on a 5-year operating period for a system. Only cost factors subject to variation within the support configurations considered are included. For example, the cost of operating the repair facility is constant for each configuration, and is therefore not included.

(1) Cost of a "line" repair team (C_1)

(a) When support area is at site, C_1 = \$210,000.

Table 1

POSTULATED SUPPORT CONFIGURATIONS

	Location of Supply Point	Location of Support Area	Mode of Transportation Between Site and Support Area	Sites per Supply Point (r)	Sites per Support Area (h)	Repair cycle Transportation Time (T)	Maintenance Transportation Time for Test 2 (T_2)
#1	site	site	- -	1	1	250 hrs.	1/2 hr.
#2	site	intermediate location	helicopter	1	4	250 hrs.	5 hrs.
#3	site	intermediate location	truck	1	4	250 hrs.	12 hrs.
#4	site	regional center	truck	1	10	125 hrs.	24 hrs.
#5	intermediate location	intermediate location	helicopter	4	4	250 hrs.	5 hrs.
#6	intermediate location	intermediate location	truck	4	4	250 hrs.	12 hrs.
#7	support center	support center	truck	10	10	21 hrs.	24 hrs.

- personnel (2 positions, manned at ratio of 2.5 men per position: 5 men) = $190, 000
- test equipment (initial investment) = $10, 000
- test equipment (operating and maintenance) = $10, 000

(b) When support area is at intermediate location, and truck transportation is used, C_1 = $420, 000

- personnel (2 positions, manned at ratio of 5 men per position: 10 men) = $380, 000
- vehicle (initial investment, operating, and replacement) = $20, 000
- test equipment (initial investment) = $10, 000
- test equipment (operating and maintenance) = $10, 000

(c) When support area is at intermediate location, and helicopter transportation is used C_1 = $1, 240, 000

- personnel (same as above) = $380, 000
- test equipment (initial investment) = $10, 000
- test equipment (operating and maintenance) = $10, 000
- helicopter (initial investment) = $250, 000
- helicopter (operating, maintenance, and new) = $590, 000

(d) When support area is at regional center, C_1 = $430, 000

- Same as for (b), except that vehicle cost is $30, 000 rather than $20, 000

(2) Cost of a periodic test team (C_2)

C_2 = $174, 000

- personnel (3 positions, manned at ratio of 1 man per position: 3 men) = $114, 000
- vehicle (initial investment, operating, and replacement) = $30, 000
- test equipment (initial, operating and maintenance) = $30, 000

(3) Cost of spares complement (C_3)

(a) For equipment List A, C_3 = $34, 000

(b) For equipment List B, C_3 = $5, 000

(4) One-way transportation cost per module (C_4) (site to repair facility)

(a) For Equipment List A, $C_4 = \$25$

(b) For Equipment List B, $C_4 = \$10$

SYSTEM ESTIMATES

The primary measure of effectiveness of a support system is the availability of the "line" equipment being supported. Since a given availability can usually be attained in a variety of ways, it is apparent that the cost of achieving the given availability provides a criterion for choosing between alternate ways. In the present section, we choose several availability levels for the sites, and then determine the particular configuration that minimizes the cost of support. The required availability of the individual sites can be established only from the analysis of the overall system, and may be high to low depending on the system interconnection redundancy characteristics. Hence, three exemplary levels of required site availability were chosen, 0.85, 0.92, and 0.98.

Seven support configurations were postulated in Table 1. It will be convenient, at this point, to enlarge the characterization of a configuration in the following way. For each configuration in Table 1 we also specify a MTTF, and Equipment List, and a required availability. Since there are three possible MTTF values (140, 420, and 840 hours), two Equipment Lists (A and B), and three required site availabilities (.85, .92, and .98), we thereby generate 18 new configurations for each original configuration, or a total of 126 configurations. Designate each of these 126 configurations as a simple configuration.

We observe that the parametric values for each simple configuration are fixed, except for two parameters: the spares level at supply points, and the periodicity of Test 1. Hence, there are also only two cost variables for any simple configuration: the investment in spares, and the investment in periodic tests. Now, the periodicity of tests, t_1, clearly varies inversely with the number of Test 1 teams (see equation (10)). Using the maintenance availability model, we then have a direct relationship between A_M and the number of crews (and hence the cost of periodic testing). Similarly, the availability model establishes the relation between A_S and the investment in spares. It is then relatively simple to determine the particular combination of testing and spares investment that minimizes their combined cost.

It should be noted that such a combination may not exist, in that the required availability might not be attainable for a particular configuration. Thus, when

Eq. 15

$$\frac{\bar{A}}{A_2} \quad \text{or} \quad \frac{\bar{A}}{A_1} > 1$$

(where $\bar{A}$ is the required availability), the required availability is clearly not obtainable. In such cases, we designate the configuration as insoluble.*

With the configurations that are not insoluble, we may unambiguously compute all the support costs associated with each configuration (exclusive of those costs that are not variable across configurations**). The choice of the best configuration is then simply a matter of picking the configuration with the lowest cost or acceptable trade off between cost and availability.

Table 2 lists the one hundred twenty-six simple configurations, with a summary of the resulting availability and cost.

The computer program was utilized to provide spare parts information starting from a zero spares inventory for a typical Table 2 calculation of .98 availability and an MTBF of 420 hours. The termination point is the achievement of .98 availability. Table 4 shows such a list.

A typical cost analysis for the .98 and 420 hour calculation is shown in Table 5 and shows the total 5 year costs for 40 sites.

CONCLUSIONS:

With the types of information as shown in Table 2 a realistic evaluation and selection can be made with respect to the optimum support system configuration. Table 3 shows the best summary configurations and a summary such as this would provide the basis for system selection. It may be noted that a cost improvement of approximately $200,000 per site over a five year period would be achieved if a reliability improvement program was successful in increasing the site MTBF from 140 hours to 840 hours.*** This improvement would of course be less the cost of the improvement effort. The calculations show that a .98 availability is impossible with the given conditions when a site MTBF is only 140 hours.

As an after the fact analysis the worth of the Support System Analysis Concept is significantly diminished as compared to the situation where it is used as a design tool from the initiation of any program. Tools similar to this are used in the basic equipment system design - why shouldn't they be used for the support system design?

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* For computational purposes, the conditions of insolubility were actually somewhat more stringent. The maximum A_s computed was .996; and the maximum number of periodic teams considered for the system was 12 (resulting in a periodicity of 187 hours). Thus a configuration was insoluble whenever

$$\frac{\overline{A}}{A_2} > .996\ \overline{\overline{A}}_1$$

where $\overline{\overline{A}}_1$ represented the value of A_1 for t_1 = 187 hours.

** Non-variable costs could, of course, also be computed; however, they are irrelevant to our purpose.

*** or 420 hours to 840 hours in the case of .98 availability.

Table 2
SUPPORT CONFIGURATION DATA SUMMARY

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Location of Supply Point	Location of Support Area	Mode of Transportation Between Site and Support Area	Sites Per Supply Point (r)	Sites Per Support Area (n)	Repair Cycle Transportation Time (T)	Maintenance Transportation Time For Test 2 (T_2)	Equipment List	Site M. T. T. F.	Required Availability (A)	Maintenance Availability (Am)	Test 1 Periodicity (t_1)	No. of Periodic Test Crews For System	Supply Availability (As)	$ Supply Point Inventory Per Site	No. of in Line Crews Per Site	Total Support Costs (Investment +5 yr. ops)
Site	Site	—	1	1	250 hrs	1/2 hrs	A	140	.85	.899	560	4	.945	39,000	1.00	282,143
									.92	.929	373	6	.911	34,000	1.00	285,893
									.98	-	-	-	--	--	--	--
								420	.85	.934	1120	2	.910	27,100	1.00	251,064
									.92	.934	1120	2	.985	33,500	1.00	257,464
									.98	.981	280	8	.979	50,700	1.00	300,914
								840	.85	.996	1120	2	.853	9,900	1.00	228,910
									.92	.996	1120	2	.923	21,250	1.00	240,260
									.98	.996	1120	2	.983	31,650	1.00	250,660
Site	Intermediate Location	Helicopter	1	4	250 hrs	5 hrs	A	140	.85	.902	373	6	.942	38,600	0.5	700,443
									.92	.926	224	10	.914	35,000	0.5	714,393
									.98	-	-	-	--	--	--	--
								420	.85	.924	1120	2	.920	27,300	0.5	661,264
									.92	.924	1120	2	.995	43,300	0.5	677,264
									.98	-	-	-	--	--	--	--
								840	.85	.993	1120	2	.853	9,900	0.25	328,910
									.92	.993	1120	2	.924	21,350	0.25	340,360
									.98	.996	1120	2	.984	31,750	0.25	350,760
Site	Intermediate Location	Truck	1	4	250 hrs	12 hrs	A	140	.85	.876	280	8	.970	50,500	0.75	416,193
									.92	-	-	-	--	--	--	--
									.98	-	-	-	--	--	--	--
								420	.85	.910	1120	2	.934	29,200	1.00	458,474
									.92	.940	560	4	.978	33,100	1.00	475,814
									.98	-	-	-	--	--	--	--
								840	.85	.995	1120	2	.854	10,000	0.25	124,010
									.92	.995	1120	2	.924	21,350	0.25	135,360
									.98	.995	1120	2	.985	31,850	0.25	145,860
Site	Regional Center	Truck	1	10	125 hrs	24 hrs	A	140	.85	-	-	-	--	--	--	--
									.92	-	-	-	--	--	--	--
									.98	-	-	-	--	--	--	--
								420	.85	.887	1120	2	.959	26,100	1.00	613,457
									.92	.926	373	6	.993	33,100	1.00	635,957
									.98	-	-	-	--	--	--	--
								840	.85	.994	1120	2	.855	0	0.10	51,800
									.92	.994	1120	2	.926	10,450	0.10	62,330
									.98	.994	1120	2	.986	29,600	0.10	81,480

Table 2 (Cont.)

1 Location of Supply Point	2 Location of Support Area	3 Mode of Transportation Between Site and Support Area	4 Sites Per Supply Point (r)	5 Sites Per Support Area (h)	6 Repair Cycle Transportation Time (T)	7 Maintenance Transportation Time For Test 2 (T_2)	8 Equipment List	9 Site M.T.T.F.	10 Required Availability (A)	11 Maintenance Availability (Am)	12 Test 1 Periodicity (t_1)	13 No. of Periodic Test Crews For System	14 Supply Availability (As)	15 $ Supply Point Inventory Per Site	16 No. of in Line Crews Per Site	17 Total Support Costs (Investment +5 yr. ops)
Intermediate Location	Intermediate Location	Helicopter	4	4	250 hrs	5 hrs	A	140	.85	.902	373	6	.942	67,000	0.50	750,993
									.92	-	-	-	--	--	--	--
									.98	-	-	-	--	--	--	--
								420	.85	.924	1120	2	.920	7,550	0.50	660,214
									.92	.924	1120	2	995	16,125	0.50	668,789
									.98	-	-	-	--	--	--	--
								840	.85	.996	1120	2	.853	2,900	0.25	331,954
									.92	.996	1120	2	.924	5,775	0.25	334,829
									.98	.996	1120	2	.984	8,325	0.25	337,379
Intermediate Location	Intermediate Location	Truck	4	4	250 hrs	12 hrs	A	140	.85	.862	373	6	.986	22,500	0.75	409,993
									.92	-	-	-	--	--	--	--
									.98	-	-	-	--	--	--	--
								420	.85	.910	1120	2	.934	8,125	1.00	486,789
									.92	.940	560	4	.978	10,825	1.00	499,939
									98	-	-	-	--	--	--	--
								840	.85	.995	1120	2	.854	2,937	0.25	127,147
									.92	.995	1120	2	.924	5,775	0.25	129,985
									.98	.995	1120	2	.985	8,375	0.25	132,585
Regional Center	Regional Center	Truck	10	10	21 hrs	24 hrs	A	140	.85	-	-	-	--	--	--	--
									.92	-	-	-	--	--	--	--
									.98	-	-	-	--	--	--	--
								420	.85	.887	1120	2	.959	327	1.80	845,977
									.92	.926	373	6	.993	2,875	1.80	869,425
									.98	-	-	-	--	--	--	--
								840	.85	.994	1120	2	.855	0	0.10	57,750
									.92	.994	1120	2	.926	0	0.10	57,750
									.98	.994	1120	2	.986	945	0.10	58,695
Site	Site	—	1	1	250 hrs	1/2 hrs	B	140	.85	.895	560	4	.950	5,300	1.00	239,057
									.92	.925	373	6	.994	7,075	1.00	249,582
									.98	-	-	-	--	--	--	--
								420	.85	.932	1120	2	.912	2,350	1.00	223,186
									.92	.932	1120	2	.947	4,800	1.00	225,636
									.98	.983	224	10	.997	5,625	1.00	261,461
								840	.85	.996	1120	2	.853	450	1.00	219,304
									.92	.996	1120	2	.923	1,310	1.00	220,164
									.98	.996	1120	2	.983	3,815	1.00	222,669

Table 2 (Cont.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Location of Supply Point	Location of Support Area	Mode of Transportation Between Site and Support Area	Sites Per Supply Point (r)	Sites Per Support Area (h)	Repair Cycle Transportation Time (T)	Maintenance Transportation Time For Test 2 (T_2)	Equipment List	Site M. T. T. F.	Required Availability (A)	Maintenance Availability (Am)	Test 1 Periodicity (t_1)	No. of Periodic Test Crews For System	Supply Availability (As)	$ Supply Point Inventory Per Site	No. of in Line Crews Per Site	Total Support Costs (Investment +5 yr. ops)
Site	Intermediate Location	Helicopter	1	4	250 hrs	5 hrs	B	140	.85	.869	560	4	.978	5,850	0.50	649,607
									.92	.921	224	10	.998	8,675	0.50	678,682
									.98	-	-	-	--	--	--	--
								420	.85	.923	1120	2	.921	2,560	0.50	633.396
									.92	.923	1120	2	997	5,625	0.50	636,461
									.98	-	-	-	--	--	--	--
								840	.85	.996	1120	2	853	450	0.25	319,304
									.92	.996	1120	2	924	1,320	0.25	320,174
									.98	.996	1120	2	.984	3,850	0.25	322,704
Site	Intermediate Location	Truck	1	4	250 hrs	12 hrs	B	140	.85	.859	373	6	990	6,575	0.75	350,332
									.92	-	-	-	--	--	--	--
									.98	-	-	-	--	--	--	--
								420	.85	.909	1120	2	.935	2,900	1.00	433.736
									.92	.939	560	4	.978	4,425	1.00	444.011
									.98	-	-	-	--	--	--	--
								840	.85	.995	1120	2	854	465	0.25	114,319
									.92	.995	1120	2	.924	1,320	0.25	115,174
									.98	.995	1120	2	.985	3.910	0.25	117,764
Site	Regional Center	Truck	1	10	125 hrs	24 hrs	B	140	.85	-	-	-	--	--	--	--
									.92	-	-	-	--	--	--	--
									.98	-	-	-	--	--	--	--
								420	.85	.885	1120	2	.960	2,500	1.80	786,293
									.92	.925	373	6	.994	4,675	1.80	805,968
									.98	-	-	-	--	--	--	--
								840	.85	.994	1120	2	.855	0	0.10	51.802
									.92	.994	1120	2	.926	460	0.10	52,262
									.98	.994	1120	2	.986	3,000	0.10	54,802
Intermediate Location	Intermediate Location	Helicopter	4	4	250 hrs	5 hrs	B	140	.85	.869	560	4	.978	2,082	0.50	651,739
									.92	.922	224	10	.998	2,881	0.50	683,887
									.98	-	-	-	--	--	--	--
								420	.85	.923	1120	2	.921	802	0.50	635,838
									.92	.923	1120	2	.997	1,756	0.50	636,792
									.98	-	-	-	--	--	--	--
								840	.85	.996	1120	2	.853	156	0.25	321,860
									.92	.996	1120	2	.924	394	0.25	322,198
									.98	.996	1120	2	.984	1,090	0.25	322,894

Table 2 (Cont.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Location of Supply Point	Location of Support Area	Mode of Transportation Between Site and Support Area	Sites Per Supply Point (r)	Sites Per Support Area (h)	Repair Cycle Transportation Time (T)	Maintenance Transportation Time For Test 2 (T_2)	Equipment List	Site M.T.T.F.	Required Availability (A)	Maintenance Availability (Am)	Test 1 Periodicity (t_1)	No. of Periodic Test Crews For System	Supply Availability (As)	$ Supply Point Inventory Per Site	No. of in Line Crews Per Site	Total Support Costs (Investment +5 yr. ops)
Intermediate Location	Intermediate Location	Truck	4	4	250 hrs	12 hrs	B	140	.85	.898	373	6	.990	2,531	0.75	358,888
									.92	-	-	-	--	--	--	--
									.98	-	-	-	--	--	--	--
								420	.85	.909	1120	2	.935	931	1.00	438,467
									.92	.939	560	4	.978	1,071	1.00	440,057
									.95	-	-	-	--	--	--	--
								840	.85	.995	1120	2	.854	104	0.25	116,908
									.92	.995	1120	2	.924	394	0.25	117,198
									.98	.995	1120	2	.985	1,125	0.25	117,929
Regional Center	Regional Center	Truck	10	10	21 hrs	24 hrs	B	140	.85	-	-	-	--	--	--	--
									.92	-	-	-	--	--	--	--
									.98	-	-	-	--	--	--	--
								420	.85	.886	1120	2	.960	17	1.80	793,467
									.92	.925	373	6	.994	290	1.80	814,640
									.98	-	-	-	--	--	--	--
								840	.85	.994	1120	2	.855	0	0.10	53,950
									.92	.994	1120	2	.926	0	0.10	53,950
									.98	.994	1120	2	.986	45	0.10	53,995

Table 3

BEST CONFIGURATION

Availability	MTTF	Location of Supply Point	Location of Support Area	Mode of Transportation Between Single Site and Support Area	Total No. of Periodic Test Crews	Equipment List	Maintenance Availability A_m	Supply Avail. A_s	Total Cost/Site (5 yr)
.85	140	Single Site	Single Site	———	4	B	.895	.950	$239,057
	420	Single Site	Single Site	———	2	B	.932	.912	223,186
	840	Single Site	Regional Location	Truck	2	B	.994	.885	51,802
.92	140	Single Site	Single Site	———	6	B	.925	.994	249,582
	420	Single Site	Single Site	———	2	B	.932	.987	225,636
	840	Single Site	Regional Location	Truck	2	B	.994	.926	52,262
.98	140	*							
	420	Single Site	Single Site	———	10	B	.983	.997	261,461
	840	Regional Location	Regional Location	Truck	2	B	.994	.986	53,995

*All configurations insoluble for this value.

B = circuit board replacement

Table 4

RECOMMENDED SPARES FOR SITE SUPPLY POINT (IN-LINE SPARING)

(Availability = 0.98, MTTF = 420 hrs.)

Spared Item	Cumulative Cost	Single Site Supply Availability
	--	.5443
1 KC F/F	$ 250	.6650
Low Speed Gate	350	.6919
High Speed Gate	450	.7198
Radiation Detector	500	.7298
64 KC F/F	750	.7769
Amplifier	900	.7957
A/D Convert	1050	.8150
Regulator - Power Supply	1200	.8325
Filter-info	1300	.8426
Timer	1350	.8467
Antenna	1450	.8544
XFMR	1550	.8614
1 KC F/F	1800	.8787
Diff	1925	.8863
Logic	2050	.8940
Power Supply - Filter/Rectifier	2150	.8994
Regulator - Power Supply	2250	.9048
Timer	2400	.9130
F/W Rectifier	2500	.9182
Preamplifier	2600	.9235
5 MC F/F	2900	.9347
Filter-info	3050	.9401
Timer	3300	.9488
Antenna	3350	.9502
Bhang Meter	3650	.9590
Blocking OSC	3750	.9618
Shaper	3850	.9645
1 MC F/F	4150	.9723
1 Shot MV	4325	.9762
Comparator	4500	.9802
Comparator	4675	.9841
Delay	4875	.9885
Sensor	5025	.9914
OSC	5275	.9934
64 KC F/F	5525	.9953
Comparator	5625	.9961

Table 5

COST ANALYSIS FOR SAMPLE CONFIGURATION *

(Availability = 0.98, MTTF = 420 Hours)

	Item	Initial Investment Costs		Operating Costs			Total 5 Year Costs (40 Sites)
				Annual		5 Year	
		Item	Total	Item	Total	Total	
Line Repair Team	Test Equipment	400,000					
	Personnel			1,520,000			
	Test Equipment Maintenance			80,000	1,600,000		
	Total		400,000			8,000,000	8,400,000
Periodic Test Team	Vehicle	90,000					
	Test Equipment	150,000					
	Personnel			228,000			
	Vehicle Op.			44,000			
	Test Equipment Maintenance			30,000	302,000		
	Total		240,000			1,510,000	1,750,000
Supply Point Sparing	Spares	225,000					
	Total		225,000				225,000
Transportation of Modules	Handling and Transportation			16,688	16,688		
	Total					83,440	83,440
				Total Annual Operating	1,918,688		
	Total		865,000			9,593,440	10,458,440

*Item 8 - Table 3

LIST OF SYMBOLS

A - Overall Support System Availability

A_1 - Site availability with respect to Test 1

A_2 - Site availability with respect to Test 2

Ai - Availability of a given module type when needed

A_M - Maintenance Availability

A_S - Supply Availability

C_1 - Cost of a "line" repair team

C_2 - Cost of a periodic test team

C_3 - Cost of spares complement

C_4 - One-way transportation cost per module (site to repair facility)

Ci - Cost of a given module type

$E_1(+_D)$ - Average down time per Test 1 cycle

$E_1(+_u)$ - Average up time per Test 1 cycle

$E_2(+_D)$ - Average downtime for Test 2 detected failures

$E_2(+_u)$ - Average up time for Test 2

$E(\omega)$ - Average wait for a repair

M - Number of shop repairmen

h - Sites per support area

N_1 - Number of teams required to perform Test 1 for all sites

Ni - Average repair time for a given module type

N_2 - Number of "line" repair teams per support area required to implement Test 2 repairs

LIST OF SYMBOLS (cont'd)

r - Number of sites using a single supply point

R_1 - Average replacement time of a module including fault localization, removal and replacement by a spare module for Test 1 detected failures

R_2 - Same as R_1 except for Test 2 related failures

S - Number of sites using a single repair shop

T - Pipeline delays caused by transport from site to repair shop and transport from the repair shop to the supply point

t_1 - Scheduled period of time between periodic Test 1

T_1 - Downtime caused by transportation when replacing a failure detected by Test 1

T_2 - The travel time of a repairman from home base to the site for Test 2 detected failures

T_3 - Travel time of the repairman to the site when Test 1 detected failures are remotely indicated

T_4 - Travel time from the supply point to the site

T_6 - Time to perform Test 1 - necessary when Test 1 requires sites to be non-operating

V - Total number of sites in the system

βi - Failure rate of a given module type

ε - Base of Naperian Log

ξ - Mean number of site tests (Test 1) performed by a team in a unit period of time

λ - Site failure rate

λ_1 - Site failure rate not detected by Test 2

LIST OF SYMBOLS (concluded)

λ_2 - Site failure rate detected by Test 2

μ - Average overall repair time

μ_a - Average repair time for module repair

APPENDIX I

METHODOLOGY AND MODEL STRUCTURE

TABLE OF CONTENTS

1. Introduction
2. Supply availability
    - 2.1 Background
    - 2.2 The derivation of p(j;i)
    - 2.3 The derivation of Δ_{ix}
    - 2.4 Supply availability and module sparing
3. Maintenance availability
    - 3.1 The derivation of A_1
    - 3.2 A_2 and A_M
4. Site availability
5. Summary of parameters and equations
    - 5.1 Input parameters
    - 5.2 Supply availability equations
    - 5.3 Maintenance availability equations
    - 5.4 System availability equations

1. Introduction

This appendix describes the mathematical analysis and models used in the parametric study of the support system. The major purpose of the analysis is to determine the availability of the site, where availability is defined as the probability that, at any random point in time, the system is in an operable state. It was found convenient to divide the analysis into two parts. The first part develops a model for determining what is called "supply availability" - namely the probability that a site is not down (i.e., inoperable) because of supply shortages. The second part (section 3) provides a model for determining "maintenance availability," which is defined as the conditional probability that the system is operable, given that the supply availability is 1.0. As will be shown (section 4), the overall availability of the system is then simply the product of its supply and maintenance availabilities.

2. Supply availability

2.1 Background

We assume that the site is made up of n modules, which are replaceable (in-line) and are repaired at some maintenance or repair installation. These modules, in turn, are grouped into a number of module types such that each module belonging to a given type, i, is interchangeable with any other module belonging to that type, but with no module belonging to another type. It is also assumed that the site is operable if and only if each module comprising it is operable. Hence, if we define the supply availability of the system, A_s, as the probability that the system is not down because of supply shortages, and define the supply availability of module type i, Δ_i, as the probability that no in-line module of class i is down because of supply shortages, it follows that

$$(1) \quad A_s = \prod_{i=1}^{t} \Delta_i$$

where t is the number of module classes comprising the system.

In addition, it is assumed that, for each site, there is one, and only one, supply point (which may or may not be located at the site) at which spare modules are placed. Similarly, each supply point has one, and only one, repair shop that repairs its failed modules. No restriction is made as to the number of sites using a single supply point.

Now, if we define the "supply phase" of a module as the movement of a module from the time it is removed from the in-line system to the time it leaves the supply point (for return to a site), the following sequence of events, occurring during the phase, may be enumerated:

(1) The module is transported from the site to the repair shop.

(2) The module is in a queue, awaiting repair, at the repair shop.

(3) The module is repaired on some bench at the repair shop.

(4) The module is transported from the repair shop to the supply point.

(5) The module is at the supply point, awaiting a call for use in some in-line system.*

During events (1) through (4) the module is inaccessible to any call for in-line replacement, and is hence designated as "non-serviceable." Event (5) thus constitutes the only portion of the supply phase in which the module is said to be "serviceable."

By definition, any module belonging, say, to type i may be replaced by any other module belonging to that type. Now, assume that this interchangeability extends across systems- specifically, to each single site using the same supply point. Hence, each of these systems draws on the same stock of spares for any type i module failure, and we may unambiguously assign all spares used by this group of systems to the supply point. Accordingly, the analysis of the supply phase revolves around the movement of modules about the supply point; at the conclusion of any phase, a module may be located at a different single site than the one it originated from, while it always passes through and is associated with, a single supply point.**

The analysis of supply availability now proceeds as follows:

(1) Consider the modules, of type i, that pass through a single supply point (i.e., the spares assigned to the supply point plus the in-line modules of the sites using that supply point). Let J be a random variable representing the number of these modules that are non-serviceable at some point in time, and let p (j;i) be the probability density function of J. Our first task is to derive p (j;i).

(2) Given p (j;i), we next derive Δ_{ix}, the supply availability of module type i, where x is the number of type i spares assigned to a supply point.

(3) Given Δ_{ix}, we finally derive a decision mechanism for sequentially choosing spares, such that each choice provides the particular spare that maximizes the incremental change in the system's availability per unit investment.

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* - Obviously, if the supply point is separated from the single site, the module must still be transported from the supply point to the site before it can be installed. However, this will hardly take place before the in-line module it replaces has failed and been identified. The transportation time from the supply point to the sensor site is therefore not considered part of the supply phase, but is included as part of the downtime involved in maintenance availability.

** - It would be possible, of course, to allow modules to be exchanged between supply points (for example, by re-routing modules leaving the repair shop). However, we have elected to ignore this possibility.

2.2 The derivation of p (j;i)

Let

r = number of single sites using a supply point

n_i = number of in use modules belonging to type i

β_i = failure rate of a type i module

The total rate (designated α_i) at which type i modules fail and enter the supply phase from the r systems is then

(1) $\alpha_i = rn_i\beta_i$

We assume that the failure generation is a Poisson process and that α_i is constant.

Now, let J be a random variable representing the number of modules of class i that are non-serviceable; and let

T = "transportation" time:
the time from the module's removal from the in-line equipment to its arrival at the repair shop (event 1), plus the time from the completion of repair at the repair shop to the module's arrival at the supply point (event 4). T is assumed constant.

Q = "queue" time:
the time spent by a module in the repair shop, awaiting repair (event 2), plus the time required for bench repair (event 3).

X = random variable representing the number of modules in transport.

Y = random variable representing the number of modules in the repair queue. J is of course equal to X + Y; and the probability, p (j;i), that J = j (any non-negative integer) for type i is the joint probability that X = x and Y = y, taken over all combinations of x + y = j (where x and y are non-negative integers).

We observe that, under steady-state conditions, a Poisson input to a queue results in a Poisson output, and that the input and output rates are the same. Hence, since the entry of modules to the supply phase is Poisson with rate α_i, their entry into events 2, 3, and 4 - and into the composite events represented by T and Q - is also Poisson with rate α_i. We also note that, given Poisson inputs for a sequence of queues, the number of objects in the sequence may be found by convoluting the number in each sequence. *
Thus, if

f(x) = probability that X = x

g(y) = probability that Y = y

it follows that

(2) $p\ (j;i) = f(j) * g\ (j)$

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* - See R. R. P. Jackson: "Random Queueing Processes with Phase-Type Service"; Royal Statistical Society Journal, series B, volume 18, 1956, pp. 129-132.

Since the transportation time, T, is constant with a Poisson arrival distribution, the probability that X = x is simply

$$(3) \quad f(x) = e^{-\alpha_i T} \quad \frac{(\alpha_i T)^x}{x!}$$

The probability that Y = y may be found as follows. Let

c = number of repair channels (benches) that can service a module

δ_i = arrival rate at the repair shop for all modules using the particular set of repair channels used by module class i

μ = repair rate

(The repair time itself is assumed to be exponentially distributed)

$$\rho = \frac{\delta_i}{\mu}$$

Suppose that there are a total of n modules in the repair queue (i.e., awaiting repair and in repair). The probability that any one of these modules is from a given supply point and is of type i is

$$\gamma = \frac{\alpha_i}{\delta_i}$$

Hence the conditional probability, h (y| n), that there are y modules from a single supply point and of type i, given a total of n in queue, is

$$(4) \quad h\,(y\,|\,n) = \binom{n}{y} \gamma^y \, (1 - \gamma)^{n-y}$$

Now, the probability, b(n), that there are a total of n modules in the repair queue is*

$$(5) \quad b(n) = \frac{\rho^n}{n!} \; b\,(o) \qquad o \leq n \leq c$$

$$\frac{\rho^n}{c^{n-c} \; c!} \; b\,(o) \qquad n \geq c$$

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* - See, e.g., Goode and Machol: System Engineering; 1957, N.Y.; pp 344-6.

where:

$$p(n) = \frac{1}{\sum_{i=o}^{c-1} \frac{\rho^{i}}{n!} + \frac{\rho^{c}}{(c-1)\,!\,(c-\rho)}}$$

The probability that Y = y, g(y), is then

$$(6) \quad g(y) = \sum_{n=y}^{\infty} b(n)\ h(y \mid n)$$

and, by equations (2), (3), (4), and (6), we have

$$(7) \quad p(j;i) = f(j) * \sum_{n=j}^{\infty} b(n)\ h(j \mid n)$$

$$= \sum_{k=o}^{j} \rho^{-\alpha_i T} \frac{(\alpha_i T)^k}{k!} \sum_{n=j-k}^{\infty} h\ (j-k \mid n)\ b(n)$$

2.3 The deviation of Δ_{ix}

We have derived b(j;i), the probability that there are j non-serviceable modules. We are now interested in finding the supply availability of module type i, Δ_{ix}, which is defined as:

> the probability that a site has no in-line modules of type i down because of supply shortages (given x spares of type i assigned to a supply point).

If we let

$\Delta_{ix,j}$ = the conditional probability of no supply shortage in module type i at a site, given x spares and given that there are j non-serviceable modules of type i,

it follows that

$$(8) \quad \Delta_{ix} = \sum_{j=o}^{\infty} \Delta_{ix,j}\ b(i;j)$$

Now, so long as the number of non-serviceable modules, j, is no greater than the number of spares, x, no supply shortage exists at any site serviced by the supply point. When the number of non-serviceable modules is greater than $x + (r-1)n_i$

(i.e., the total number of modules remaining is less than the number required for any system), a supply shortage necessarily exists at every site. Hence

$$(9) \quad \Delta_{ix,\,y} = \begin{cases} 1 & \text{when } j \leq x \\ o & \text{when } j > x + (r-1)n_i \end{cases}$$

Consider the case when neither of the conditions listed in equation (9) exists; that is, the case when $x < j \leq x + (r-1)n$. The number of modules short in all the sites supported by a supply point is then j-x; and $\Delta_{ix,y}$ represents the probability that o modules out of the j-x modules that are short are from a single site. This probability may be viewed as a term of the hypergeometric distribution thus: We have a population of nr elements (the number of in-line modules in r systems). This population consists of j-x "short" modules and nr - (j-x) operable modules. A group of n elements (the number of in-line modules in a single site) is chosen at random; and we inquire about the probability that none of the n elements chosen is short. This probability is

$$(10) \quad \Delta_{ix,j} = \frac{\binom{nr - (j-x)}{n}}{\binom{nr}{n}} \qquad \text{for } x \leq j \leq x + (r-1)n$$

From equations (8), (9), and (10), we thus have

$$(11) \quad \Delta_{ix} = \sum_{j=o}^{x} b(j;i) + \sum_{j=x+1}^{x+(r-1)n} b(j;i) \frac{\binom{nr - (j-x)}{n}}{\binom{nr}{n}}$$

2.4 Supply availability and module sparing

We now wish to specify a routine for building up a spares inventory in terms of two criteria: the cost of spares, and the supply availability resulting from different spare levels. We first consider the supply availability of a site when there are no spares at all. We then purchase, as our first spare, the particular module that will secure the largest increase in availability per dollar. The second spare (which may or may not be in the same i-class) is similarly chosen, namely, as that module which secures the largest gain in availability per dollar, given that the first spare purchase has been made. And so on, for each successive spare purchase.

We remind the reader (see equation (1)) that the supply availability of the system, A_s, is

$$(12) \quad A_s = \prod_{i=1}^{t} \Delta_i$$

(where t = number of module classes comprising the site)

Let:

c_i = unit cost of type i module

$(A_s)_m$ = supply availability of system, given m spares (of all types)

Δ_{iy} = Δ_i, given y spares of type i

(a) <u>The choice of the first spare</u>

When there are no spares, A_s is simply

$$(A_s)_o = \prod_{i=1}^{t} \Delta_{io}$$

Assume that the first spare chosen is from class $*$. The change in A_s, ΔA_s, per unit cost is then

$$\Delta A_s \text{ per unit cost} = \frac{(A_s)_1 - (A_s)_o}{c_*}$$

where:

$$(A_s)_1 = \Delta_{10} \cdot \Delta_{20} \cdots \Delta_{*-1,0} \cdot \Delta_{*1} \Delta_{*+1,0} \cdots \Delta_{to}$$

$$= \frac{\Delta_{*o}}{\Delta_{*o}} \Delta_{10} \Delta_{20} \cdots \Delta_{*-1,0} \Delta_{*1} \Delta_{*+1,0} \cdots \Delta_{to}$$

$$= (A_s)_o \cdot \frac{\Delta_{*1}}{\Delta_{*o}}$$

Hence

$$(13) \quad \Delta A_s \text{ per unit cost} = \frac{1}{c_*} \left\{ (A_s)_o \frac{\Delta_{*1}}{\Delta_{*o}} - (A_s)_o \right\}$$

$$= \frac{1}{c_*} \left(\frac{\Delta_{*1} - \Delta_{*o}}{\Delta_{*o}} \right) (A_s)_o$$

Accordingly, ΔA_s per unit cost is greatest when $\left(\frac{\Delta_{*1} - \Delta_{*o}}{\Delta_{*o}\ c_*}\right)$ is greatest. The first module chosen, therefore, will be that module of class i such that the ratio

$$(14) \qquad \frac{\Delta_{i1} - \Delta_{io}}{\Delta_{io}\ c_i}$$

is at least as great as the comparable ratio for any other module type.

(b) The choice of the n^{th} spare

Assume that n-1 spares have been chosen and that the value of $(A_s)_{n-1}$ is known. By specifying a rule for finding the n^{th} spare, we will thereby have established our general method for choosing spares.

The n-1 spares already chosen are:

α_1 type 1 modules
α_2 type 2 modules
$\vdots$
α_t type t modules

where $\alpha_1 + \alpha_2 + \ldots + \alpha_t = n-1$, and each α_i is some integer between 0 and n-1.

The choices open for the n^{th} spare are thus:

$(\alpha_1 + 1)^{st}$ type 1 module
$(\alpha_2 + 1)^{st}$ type 2 module
$\vdots$
$(\alpha_t + 1)^{st}$ type t module

Now, if a type $\neq$ module is chosen, the change in A_s per unit cost is

$$(15) \quad = \frac{(A_s)_n - (A_s)_{n-1}}{c_{\neq}}$$

$$= \frac{1}{c_{\neq}} \left\{ \left[\frac{(A_s)_{n-1} \quad \Delta_{\neq,\alpha_{\neq}+1}}{\Delta_{\neq\alpha_{\neq}}} - (A_s)_{n-1} \right] \right\}$$

$$= \frac{(A_s)_n}{c_{\neq}} \left(\frac{\Delta_{\neq,\alpha_{\neq}+1} - \Delta_{\neq\alpha_{\neq}}}{\Delta_{\neq\alpha_{\neq}}} \right)$$

Thus our n^{th} choice is for the module of type i such that the ratio

$$(16) \quad \frac{\Delta_{i,\,a_i+1} - \Delta_{i\,a_i}}{\Delta_{i\,a_i} \quad c_i}$$

is as great as that of any other module.

3. Maintenance availability

The maintenance availability of the single site (A_M) is defined as the conditional probability that the site is operable, given that the supply availability is 1.0.

As before, we assume that the generation of failures in the system is a Poisson process with a constant rate. In addition, we assume that two distinct failure detection tests are applied to the system:

Test 1: A periodic test that detects all failures, where:

t_1 = scheduled interval between tests (i.e., the duration of time from the system's passing of the test to the next application of the test)

R_1 = "replacement" time for a failure detected by test 1 (where replacement covers the time required to isolate the failure down to the module level, the remove and replace time, and the repair verification time)

T_1 = "transportation" time associated with a failure detected by test 1 - namely, the time required for the repair crew to reach the in-line equipment (if it were not present there during the test), and the time required to secure a spare module from the supply point.

Test 2: A continuous test that only detects a certain portion of the failures, where:

p_2 = proportion of failures detected by test 2

R_2 = "replacement" time for a failure detected by test 2

T_2 = "transportation" time associated with a failure detected by test 2

Let:

λ = failure rate of site

λ_1 = type 1 failure rate, where a type - 1 failure is a failure that is not detectable by test 2 and, hence, is only detectable by test 1

λ_2 = type 2 failure rate, where a type - 2 failure is a failure that is detectable by test 2. *

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* - Since, by hypothesis, test 2 is continuous, all type 2 failures are, in fact, detected by test 2 although they are capable of being detected by test 1 as well.

If follows then that

$$\lambda_1 = (1 - p_2)\lambda$$

$$\lambda_2 = p_2 \lambda$$

Let A_1 and A_2 represent the maintenance availability in regard to type - 1 and type 2 failures, respectively. We then have

(17) $A_M = A_1 \cdot A_2$

3.1 The derivation of A_1

Assume that the site passes test 1 at time $t = 0$. Test 1 will next be applied at time $t = t_1$. If a failure is detected at t_1, a certain amount of time will be required for the replacement and transportation of modules before the system is operable again. Designate this time t_2, and let n = number of type 1 failures in t_1. Then*

(18) $t_2 = n R_1 + T_1$

Let τ be the point in time at which the first failure occurs. Then the total downtime, t_D, consists of t_2 plus the time from the occurrence of the first failure i.e.,

(19) $t_D = (t_1 - \tau) + nR_1 + T_1$

where τ and n are distributed functions. The up-time is simply τ. The availability under Test 1 is

(20) $$A_1 = \frac{E(t_u)}{E(t_u) + E(t_D)}$$

where E ( ) is an expectation.

For $\tau > t_1$ the up-time is t_1, as the test cycle repeats; hence

$$E(t_u) = \int_0^{t_1} \tau\lambda_1 e^{-\lambda_1 \tau} d\tau + t_1 \int_{t_1}^{\infty} \lambda_1 e^{-\lambda_1 \tau} d\tau$$

$$= \frac{1}{\lambda_1} \left\{ 1 - e^{-\lambda_1 t_1} (\lambda_1 t_1 + 1) + \lambda_1 t_1 e^{-\lambda_1 t_1} \right\}$$

---

* - Equation (18) is only approximate, since the generation of additional failures during t_2 is ignored. When $t_1 >> t_2$, these additional failures are of course negligible.

$$(21) \quad E(t_u) = \frac{1}{\lambda_1}\left(1 - e^{-\lambda_1 t_1}\right)$$

$$E(t_D) = E(t_1 - \tau) + E(T_1) + E(nR_1)$$

$$= E(t_1 - \tau) + E(T_1) + R_1 E(n)$$

The failures are Poisson-distributed; hence

$$(22) \quad E(n) = \lambda_1 t_1$$

$$E(t_1 - \tau) = \int_0^{t_1} (t_1 - \tau)\, \lambda_1 e^{-\lambda_1 \tau}\, d\tau$$

$$= t_1 \int_0^{t_1} \lambda_1 e^{-\lambda_1 \tau}\, d\tau - \int_0^{t_1} \lambda_1 \tau e^{-\lambda_1 \tau}\, d\tau$$

$$= t_1 \left(1 - e^{-\lambda_1 t_1}\right) - \frac{1}{\lambda_1} \left\{1 - e^{-\lambda_1 t_1} (\lambda_1 t_1 + 1)\right\}$$

$$(23) \quad E(t_1 - \tau) = t_1 - \frac{1}{\lambda_1} + \frac{e^{-\lambda_1 t_1}}{\lambda_1}$$

The constant T_1 appears only if any failure has occurred. Hence,

$$(24) \quad E(T_1) = \left(1 - e^{-\lambda_1 t_1}\right) T_1$$

Then

$$E(t_D) = t_1 - \frac{1}{\lambda_1} + \frac{e^{-\lambda_1 t_1}}{\lambda_1} + \left(1 - e^{-\lambda_1 t_1}\right) T_1 + \lambda_1 t_1 R_1$$

(25) $$E(t_D) = (R_1\lambda_1 + 1)\, t_1 + \frac{(\lambda_1 T_1 - 1)}{\lambda_1} \left(1 - e^{-\lambda_1 t_1}\right)$$

Equations (20), (21), and (25) define the maintenance availability under Test 1.

3.2 A_2 and A_M

The derivation of A_2 follows immediately from its definition: namely,

$$A_2 = \frac{\text{mean uptime}}{\text{mean uptime + mean downtime}}$$

(26) $$= \frac{\frac{1}{\lambda_2}}{\frac{1}{\lambda_2} + R_2 + T_2}$$

A_M is then found by taking the product of A_1 and A_2 (see equation (17)).

4. Site availability

A site is available if it satisfied two conditions:

(1) The site is not down because of supply shortages. We designate this condition as event A.

(2) The site is not down because of maintenance factors (e.g., undetected failures, repair, fault isolation, etc.). We designate this condition as event B.

Hence, if the availability, A, of the system is the probability that the system is available, it follows that

$$A = P \left\{ A \text{ and } B \right\} = P \left\{ A \right\} \cdot P \left\{ B \mid A \right\}$$

Pr $\left\{ A \right\}$ is of course the supply availability, A_s, and Pr $\left\{ B \mid A \right\}$ is the maintenance availability, A_M, derived above. Thus we have

(27) $$A = A_s A_M$$

5. Summary of parameters and equations

The following is a summary of the parameters and equations used in the availability models. These have been rearranged to conform to the order in which computations were actually made.

The equations for supply availability were programmed for the IBM 7090. Those for the maintenance availability were not, since computations for maintenance availability were simple enough to be handled on a desk calculator.

5.1 Input parameters

Given a total of t module types comprising a site, the following parameters are associated with module type i ($i = 1, 2, \ldots, t$):

1. n_i = number of modules (from a site) belonging to type i
2. a_i = normalized failure rate of a type i module

   i.e., $\frac{\text{Failure rate of a class i module}}{\text{Failure rate of site}}$
3. b_i = normalized failure rate of all modules (from a site) using the set of repair channels used by module type i
4. c_i = unit cost of a type i module

The following input parameters are associated with all module types:

5. $\frac{1}{\lambda}$ = MTTF of the site per supply point
6. r = number of sites using a single supply point
7. s = number of sites using a single repair shop
8. c = number of repair channels (benches) that can service a module
9. μ = repair rate per bench
10. T = "transportation" time for supply phase - i.e., the time from the removal of module from site to its arrival at the repair shop, plus the time from the completion of repair to the module's arrival at the supply point
11. t_1 = scheduled interval of time between test 1
12. R_1 = maintenance "replacement" time for test 1
13. T_1 = maintenance "transportation" time for test 1
14. p_2 = proportion of failures detected by test 2
15. R_2 = maintenance "replacement" time for test 2
16. T_2 = maintenance "transportation" time for test 2

Parameters 1. through 10. constitute the input parameters for the (IBM 7090) supply availability model. Parameters 5. and 11. through 16. are the input parameters for the maintenance availability model.

5.2 Supply availability equations

Let:

β_i = failure rate of a type i module

α_i = rate at which type i modules (from the r sites using a single supply point) enter the supply phase

δ_i = arrival rate at the repair shop for all modules (from the s sites using a repair shop) using the set of repair channels used by module type i.

Then

$\beta_i = \lambda \,.\, a_i$

$\alpha_i = r\, n_i \beta_i$

$\delta_i = \lambda\, s\, b_i$

Let:

p(j;i) = probability density function that J (the number of non-serviceable modules of type i from the r sites using a supply point) = j.

Then

$$p(j;i) = e^{-\alpha_i T} \sum_{n=o}^{\infty} b(n)\, e^{-\gamma_i n_i} \left(\frac{\alpha_i T + \gamma_i n_i \;{}^{j}}{j!} \right)$$

where:

$$b(n) = \begin{cases} \dfrac{\rho^n}{n!}\, p(o) & o \leq n \leq c \\[2ex] \dfrac{\rho^n}{c^{n-c}\, c!}\, p(o) & n \geq c \end{cases}$$

$$p(o) = \frac{1}{\displaystyle\sum_{i=o}^{c-1} \frac{\rho^i}{n!} + \frac{\rho^c}{(c-1)\,!\,(c-\rho)}}$$

$$\rho = \frac{\delta_i}{\mu}$$

$$\gamma_i = \frac{a_i}{\delta_i}$$

Let:

Δ_{ix} = supply availability of type i, given x_i spares for the supply point

Then

$$\Delta_{ix} = \sum_{j=o}^{x_i} p(j;i) + \sum_{j=x_i+1}^{x_i+(r-1)n_i} p(j;i) \frac{\binom{n_i r - j + x_i}{n_i}}{\binom{n_i r}{n_i}}$$

The computational routine for choosing spares proceeds as follows.

Let:

$(A_s)_k$ = Supply availability of the system for k spares per supply point

$(C)_k$ = Spares investment for k spares

$$\omega_{iy} = \frac{\Delta_{i,\,y+1} - \Delta_{i,y}}{\Delta_{iy} \cdot c_i} \qquad \text{where: } i = 1, 2, \ldots, t \quad y = 0, 1, 2, \ldots$$

<u>Step 0</u>:

$$(A_s)_o = \prod_{i=1}^{t} \Delta_{io}$$

$$(C)_o = o$$

<u>Step 1:</u>

Consider set $\Omega_o = \left\{\omega_{10}, \omega_{20}, \ldots, \omega_{to}\right\}$

Choose the largest element of Ω_o (If there are several largest elements, choose any <u>one</u>)

Suppose $\omega_{\epsilon',o}$ is the element chosen

Then:

$$(A_s)_1 = (A_s)_o \frac{\Delta_{\varepsilon' 1}}{\Delta_{\varepsilon' o}}$$

$$(C)_1 = c_{\varepsilon'}$$

Step 2:

Consider set Ω_1, where Ω_1 is the same as Ω_o except that $\omega_{\varepsilon' o}$ is replaced by $\omega_{\varepsilon' 1}$

Choose the largest element of Ω_1.

Suppose $\omega_{\varepsilon'' a}$ is the element chosen

(the index a, in this case, is either 0 or 1 depending on whether or not $\varepsilon' = \varepsilon''$)

Then:

$$(A_s)_2 = (A_s)_1 \frac{\Delta_{\varepsilon'', a+1}}{\Delta_{\varepsilon'', a}}$$

$$(C)_2 = c_{\varepsilon'} + c_{\varepsilon''}$$

Step n:

Consider set Ω_{n-1}, where Ω_{n-1} is the same as Ω_{n-2} except that the element chosen for the $(n-1)^{st}$ choice, say, $\omega_{\varepsilon^{(n-1)}, a}$, is replaced by $\omega_{\varepsilon^{(n-1)}, a+1}$

Choose the largest element of Ω_n; say it is $\omega_{\varepsilon^{(n)}, a}$

Then:

$$(A_s)_n = (A_s)_{n-1} \frac{\Delta_{\varepsilon^{(n)}, a+1}}{\Delta_{\varepsilon^{(n)}, a}}$$

$$(C)_n = c_{\varepsilon'} + c_{\varepsilon''} + \ldots + c_{\varepsilon^{(n)}}$$

5.3 Maintenance availability equations

The maintenance availability of the site, A_M, is

$$A_M = A_1 \cdot A_2$$

where:

$$A_1 = \frac{\frac{1}{\lambda_1}\left(1 - e^{-\lambda_1 t_1}\right)}{\frac{1}{\lambda_1}\left(1 - e^{-\lambda_1 t_1}\right) + \left(R_1\lambda_1 + 1\right) t_1 + \frac{(\lambda_1 T_1 - 1)}{\lambda_1}\left(1 - e^{-\lambda_1 t_1}\right)}$$

$$A_2 = \frac{1}{1 + \lambda_2 (R_2 + T_2)}$$

$$\lambda_1 = (1 - p_2)\lambda$$

$$\lambda_2 = p_2 \lambda$$

5.4 System availability equation

The overall availability of the site, A, is

$$A = A_s A_M$$

Table 2 (Cont.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Location of Supply Point	Location of Support Area	Mode of Transportation Between Site and Support Area	Sites Per Supply Point (r)	Sites Per Support Area (h)	Repair Cycle Transportation Time . (T)	Maintenance Transportation Time For Test 2 (T_2)	Equipment List	Site M.T.T.F.	Required Availability (A)	Maintenance Availability (Am)	Test 1 Periodicity (t_1)	No. of Periodic Test Crews For System	Supply Availability (As)	$ Supply Point Inventory Per Site	No. of in Line Crews Per Site	Total Support Costs (Investment +5 yr. ops)
Intermediate Location	Intermediate Location	Helicopter	4	4	250 hrs	5 hrs	A	140	.85	.902	373	6	942	67,000	0.50	750,993
									.92	-	-	-	--	--	--	--
									.98	-	-	-	--	--	--	--
								420	.85	.924	1120	2	.920	7,550	0.50	660,214
									.92	.924	1120	2	.995	16,125	0.50	668,780
									.98	-	-	-	--	--	--	--
								840	.85	.996	1120	2	.853	2,900	0.25	331,954
									.92	.996	1120	2	.924	5,775	0.25	334,829
									.98	.996	1120	2	.984	8,325	0.25	337,379
Intermediate Location	Intermediate Location	Truck	4	4	250 hrs	12 hrs	A	140	.85	.862	373	6	.986	22,500	0.75	400,993
									.92	-	-	-	--	--	--	--
									.98	-	-	-	--	--	--	--
								420	.85	.910	1120	2	.934	8,125	1.00	486,789
									.92	.940	560	4	.978	10,825	1.00	489,939
									.98	-	-	-	--	--	--	--
								840	.85	.995	1120	2	.854	2,937	0.25	127,147
									.92	.995	1120	2	.924	5,775	0.25	129,985
									.98	.995	1120	2	.985	8,375	0.25	132,585
Regional Center	Regional Center	Truck	10	10	21 hrs	24 hrs	A	140	.85	-	-	-	--	--	--	--
									.92	-	-	-	--	--	--	--
									.98	-	-	-	--	--	--	--
								420	.85	.887	1120	2	.959	327	1.80	845,977
									.92	.926	373	6	.983	2,875	1.80	869,425
									.98	-	-	-	--	--	--	--
								840	.85	.994	1120	2	.855	0	0.10	57,750
									.92	.994	1120	2	.926	0	0.10	57,750
									.98	.994	1120	2	.986	945	0.10	58,095
Site	Site	—	1	1	250 hrs	1/2 hrs	B	140	.85	.895	560	4	.950	5,300	1.00	239,057
									.92	.925	373	6	.994	7,075	1.00	240,582
									.98	-	-	-	--	--	--	--
								420	.85	.932	1120	2	.912	2,350	1.00	223,186
									.92	.932	1120	2	.987	4,800	1.00	225,636
									.98	.983	224	10	.997	5,625	1.00	261,461
								840	.85	.996	1120	2	.853	450	1.00	219,304
									.92	.996	1120	2	.923	1,310	1.00	220,164
									.98	.996	1120	2	.983	3,815	1.00	222,660

Table 2 (Cont.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Location of Supply Point	Location of Support Area	Mode of Transportation Between Site and Support Area	Sites Per Supply Point (r)	Sites Per Support Area (h)	Repair Cycle Transportation Time (T)	Maintenance Transportation Time For Test 2 (T_2)	Equipment List	Site M.T.T.F.	Required Availability (A)	Maintenance Availability (Am)	Test 1 Periodicity (t_1)	No. of Periodic Test Crews For System	Supply Availability (As)	$ Supply Point Inventory Per Site	No. of in Line Crews Per Site	Total Support Costs (Investment +5 yr. ops)
Intermediate Location	Intermediate Location	Truck	4	4	250 hrs	12 hrs	B	140	.85	.898	373	6	.990	2,531	0.75	358 888
									.92	-		-	--	--	--	--
									.98	-	-	-	--	--	--	--
								420	.85	.909	1120	2	.935	931	1.00	438.467
									.92	.939	560	4	.978	1,071	1.00	440 057
									.98	-	-	-	--	--	--	--
								840	.85	.995	1120	2	.854	104	0.25	116,908
									.92	.995	1120	2	.924	394	0.25	117.198
									.98	.995	1120	2	.985	1,125	0.25	117,929
Regional Center	Regional Center	Truck	10	10	21 hrs	24 hrs	B	140	.85	-	-	-	--	--	--	--
									.92	-	-	-	--	--	--	--
									.98	-	-	-	--	--	--	--
								420	.85	.886	1120	2	.960	17	1.80	793,467
									.92	.925	373	6	.994	280	1.80	814,640
									.98	-	-	-	--	--	--	--
								840	.85	.994	1120	2	.855	0	0.10	53,950
									.92	.994	1120	2	.926	0	0.10	53,950
									.98	.994	1120	2	.986	45	0.10	53,995

TECHNIQUE FOR ESTABLISHING
RELIABILITY - MAINTAINABILITY CRITERIA
FOR THE
EUROPEAN MEDITERRANEAN COMMUNICATION SYSTEM

by

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SUMMARY

This paper presents a technique for establishing the following reliability-maintainability criteria: 1) MTBF levels to be included in procurement specifications which enable the proper selection of equipments to meet a pre-established system availability, 2) calculation of system availability based upon the specific equipments selected, and 3) monitoring and analysis of field operational data on the communication system to determine the degree of success achieved in system availability.

Phase I concerns the development of criteria for establishing MTBF's that will be required of specific equipment types to be selected for the communication system. The criteria are predicated on the maximum number of voice channel outage hours that can be tolerated in the longest transmission path in order to achieve a pre-established system availability. The MTBF's will be used by Quality Assurance in procurement specifications as the minimum MTBF that is acceptable for specific equipments.

After final selection of the equipments that will comprise the communication system has been completed, it is necessary to insure that the pre-established system availability can still be achieved. This is accomplished in Phase II of the technique. The primary effort during this phase is the detailed calculation of channel outage hours based on the equipment selected in Phase I. Factors such as, propagation outage hours, manual or automatic switching of subassemblies/equipments, etc. are included in calculating channel outage hours.

The final phase of the technique involves the monitoring and analysis of field operation data on the communication system to determine if the calculated system availability is actually being achieved.

PHASE I - DEVELOPMENT OF CRITERIA FOR ESTABLISHING EQUIPMENT MTBF'S

The European-Mediterranean Tropospheric Scatter Communication System is a network which will provide intracontinental communications for the United States Air Force. This communication system is to be capable of continuous operation within the specified performance limits with a minimum system availability of 99.9% per year. System availability is defined as, "the fraction of the total desired operating time that the system is actually operable". Since the total desired operating time is continuous, the yearly availability fraction is 0.999, and conversely the yearly unavailability of the system is 0.001. The total system hours of outage in one year based on its unavailability fraction cannot exceed (.001) (8760) = 8.76 hours, if the minimum system availability of 99.9% is to be maintained.

The system outage of 8.76 hours is divided into two components: 1) that due to equipment failures, and 2) that caused by adverse fading in the received signal level. Adverse fading in the received signal level which results in system transmission outage is hereafter referred to as propagation outage. The propagation outage per channel per year was determined by path loss calculations in the longest transmission path of a channel at 4.0 hours. In reality, the exact amount of propagation outage hours per year can not be known until sufficient operational data, over a predetermined time interval, have been recorded and analyzed. In order to provide a safety margin in the amount of system outage caused by adverse propagation effects, the 4.0 hours were increased to an estimated 4.76 hours, resulting in a maximum allowable amount of equipment outage of (8.76-4.76) = 4.0 hours.

At present a total of sixty (60) voice channels is provided for in the EUR-MED System. Based on 60 voice channels and the equipment outage per year of 4.0 hours, the maximum amount of total channel outage cannot exceed (4.0) (60) = 240 hours per year. A criterion for the development of equipment MTBF's, therefore, has been established by setting the 240 channel outage hours as the maximum that can be incurred by any combination of equipments used in the longest transmission path of the EUR-MED System. Figure 1, Humosa to Karamursel Channel Transmission Path, shows the equipment types used in the longest channel transmission path which originates at Humosa and terminates at Karamursel. To reiterate, MTBF's developed for equipments employed between Humosa and Karamursel when combined cannot exceed 240 channel outage hours, if the minimum system availability of 99.9% is to be maintained. Figure 1 also shows that redundant equipments, subassemblies, etc. are employed in the system for improvement of reliability. Few formulae seem to be available for calculating the availability of a system based on the parameter of both reliability and maintainability. Federal Electric Corporation has developed and utilizes formulae for evaluating the availability of equipment where repair facilities must be considered along with reliability. These formulae assumes that an equipments' Mean-Time-Between-Failure (MTBF), Mean-Time-To-Repair (MTTR), failure rate (λ) and repair rate (M) are constant and follow the Poisson Law.

The different types of equipments employed in the EUR-MED System consists of: 1) frequency-division multiplex, 2) tropospheric communications, 3) line-of-sight communications, and 4) power equipment which is composed of diesel generators and motor generators. MTBF's must be established for each of the four equipment categories listed above. These MTBF's do not include the effects of propagation system outage hours, but are based solely on the maximum number of voice channel hours of outage expected at a stated confidence level. Phases II and III of this technique include propagation system outage hours in calculating the amount of voice channel outage hours. As such, the first equipment MTBF's to be established will concern itself with the multiplex equipment, the second with the tropospheric equipment, and so on.

a. Multiplex Equipment MTBF's

The multiplex equipment consists of the following two or three major units, depending on the particular type of station in the voice channel transmission path: 1) a voice channel unit consists of sixty (60) separate voice channel assemblies, 2) a group channel unit consists of five (5) separate group assemblies, each group assembly carrying 12 voice channels, and 3) a super-group channel unit consists of one (1) super-group assembly, carrying 5 group and 6 voice channel assemblies.

If the multiplex equipment consists of 1), 2), and 3) above (a B1 multiplex equipment, see Figure 1) it would be made up of sixty (60) voice channels, five (5) groups, and one (1) super-group, for a total of sixty-six (66) assemblies. If the multiplex equipment consists of 2) and 3) above (a B2 multiplex equipment, see Figure 1) it would be made of five (5) groups and one (1) super-group, for a total of six (6) assemblies. Each of the five group assemblies of each multiplex equipment is in an active parallel arrangement with a group assembly in another multiplex equipment. The super-group assembly is also in an active parallel arrangement with another super-group assembly. Each assembly in both B1 and B2 multiplex equipment is assumed to have an equal failure rate in the development of multiplex MTBF's. It should be noted, that during actual field operation of these assemblies the failure rates exhibited would not be equal. In the development of multiplex equipment MTBF's, however, this effect is not serious. Even if these assemblies should exhibit a substantial difference in failure rates, their combined effect still would not seriously alter the equipment MTBF's that are developed. Having established that a constant failure rate for the assemblies will be used in this analysis, a repair time for the multiplex equipment is required. Based on field operational data on other multiplex equipments, it was determined that it would take five minutes to patch in a standby voice channel assembly in the event of a failure in the voice channel unit.

For a given Mean-Time-Between-Failure (MTBF) of the multiplex equipment, the failure rate of a voice channel assembly, group assembly and super-group assembly is developed as follows:

$$\sum_{L=1}^{66} \lambda_i = \lambda_{MUX}$$

where:

$$\lambda_i = \lambda_2 = \lambda_3 = \ldots\ldots \lambda_{66}$$

$$\lambda_i = \frac{\lambda_{MUX}}{66}$$

λ_i = the failure rate of a voice channel assembly or a group assembly or a super-group assembly.

λ_{MUX} = the failure rate of the multiplex equipment equal to $\frac{1}{MTBF}$.

(1) Voice Channel - The probability of 0, 1, 2, 3 . . . . . r failures of a voice channel in a time t can be computed by

$$P_{(r)} = \frac{e^{-\lambda i t} \quad \lambda i t^{\,r}}{r!}$$

Since there is more than one (1) voice channel assembly, it is necessary to determine the probability distribution of failure representing the sum of the probability distributions of failure of each voice channel assembly. This is determined as follows:[1]

$$P_{(R)} = \frac{e^{-t\sum_{i=i}^{N} \lambda i} \left[t \sum_{i=i}^{N} \lambda i \right]^{R}}{R!}$$

where:

$P_{(R)}$ = the probability of R failures in all the voice channel assemblies in time t

t = the time period concerned = one year = 8760 hours

$\sum_{L=1}^{N} \lambda i$ = the sum of the failure rates of the voice channels from the 1st to the Nth

N = the number of voice channel assemblies

Derivation of the above formula can be seen in the following where we have a random variable r whose probability distribution is:

$$P_{(r)} = e^{-\lambda t} \quad (\lambda t)^{r}$$

and: λ and t are the parameters of the physical process that generates r.

Now we have a group of other random variables r_i ($i=1,2,3,--N$) which are identically distributed, that is:

$$P_i(r_i) = \frac{e^{-\lambda t} \quad (\lambda_i t)^{ri}}{r_i!}$$

and we wish to find the probability distribution for the sum of the N random variables r_i, that is, we wish to find $P_{(R)}$, where:

$$R = r_1 + r_2 + r_3 --- r_N$$

There is a basic theorum that states that the moment generating function of the sum of a set of independent variables is equal to the product of their individual moment generating functions. The Poisson probability distribution is:

$$e^{-\lambda_1 t\,(1+s)} \quad e^{-\lambda_2 t\,(1+s)} \quad e^{-\lambda_3 t\,(1+s)} \quad \text{----} \quad e^{-\lambda_N t\,(1+s)} = e^{-t \sum_{i=i}^{N} \lambda_i \,(1+s)}$$

but this is the moment generating function of the Poisson probability distribution and the probability distribution can be computed by the following equation:

$$P_{(R)} = \frac{e^{-t \sum_{i=i}^{N} \lambda_i} \left[t \sum_{i=i}^{N} \lambda_i \right]^R}{R!}$$

Since it requires a fixed five minutes to patch a failed voice channel assembly, the maximum number of voice channel minutes of outage is readily determined by calculating the maximum number of voice channel assembly failures expected and multiplying this value by five minutes.

Based on field operational data the MTBF of a typical multiplex equipment should fall within the range of 100 hours to 800 hours. Using this MTBF parameter, the maximum amount of voice channel outage hours was calculated in increments of 100 hours. An example of these calculations is presented below where the multiplex MTBF is 500 hours.

$MTBF_{MUX-BI}$ = 500

$MTBF_i$ = 500 (66) = 33000

λ_i = $.3030303 \times 10^{-4}$

N = 480 voice channel assemblies in the system

$$\sum_{i=1}^{N} \lambda_i = 480\,\lambda_i = .01454545$$

t = 8760 hours

$$P_R = \frac{e^{-t \sum_{i=1}^{N} \lambda_i} \left[t \sum_{i=1}^{N} \lambda_i \right]^R}{R!} = e^{-127.41818} \; \frac{(127.41818)^R}{R!}$$

Using the normal probability distribution as an approximation of the Poisson Probability Distribution

α = 4 = confidence level of .99994

np = 127.41818

$np + \alpha \sqrt{np}$ = 127.41818 + 4 (11.2879) = 172.57

Therefore, we would expect no more than 173 operational random voice channel assembly failures at a probability level of .99994. With a fixed five minutes to patch a failed voice channel assembly, the maximum number of voice channel hours of outage expected due to the failure of voice channel assemblies is 5/60 (173)= 14.42 hours. These values are underlined in Table I which shows the maximum number of voice channel assembly failures expected at the given probability level and the associated number of voice channel hours of outage expected for different $\text{MTBF}_{\text{MUX-BI}}$'s of the multiplex equipment.

MTBF_{MUX} (B_I)	MTBF_i	Maximum Number of Voice Channel Assembly Failures Expected	Probability Level	Maximum Number of Voice Channel Hours of Outage Expected
100	6,600	739	.99994	61.59
200	13,200	390	.99994	32.50
300	19,800	271	.99994	22.58
400	26,400	210	.99994	17.50
500	33,000	173	.99994	14.42
600	39,600	148	.99994	12.34
700	46,200	130	.99994	10.84
800	52,800	116	.99994	9.67

Table I. Maximum Number of Voice Channel Hours of Outage Expected for Different Voice Channel Assembly MTBF's

(2) Multiplex Group or Super-Group MTBF's - The MTBF of a group or super-group assembly in active parallel with another group or super-group assembly respectively, is given by[2]

$$\text{MTBF}_c = \frac{3\lambda_p + M}{2\lambda_p^2}$$

where:

λ_p = the failure rate of a group or super-group assembly path

M = the repair rate of a group or super-group assembly path

A repair rate (M) of one per hour was used as an estimate of the true M. This was based on an analysis of DEWLine data which concerned thirty-five (35) corrective maintenance repair times on fifty-seven (57) multiplex equipments (Lenkurt 45BXT2 multiplex in the AN/FRC-45). The results of this analysis indicated a repair rate of 1.02 per hour (MTTR = 58.6 minutes). The reliability of the group or super-group assembly complex is given by[3]

$$R = \frac{S_1 e^{S_2 t} - S_2 e^{S_1 t}}{S_1 - S_2}$$

where:

$$S_1 = \frac{-(3\lambda_p + M) + \sqrt{\lambda_p^{2} + 6\lambda_p M + M^{2}}}{2}$$

$$S_2 = \frac{-(3\lambda_p + M) - \sqrt{\lambda_p^{2} + 6\lambda_p M + M^{2}}}{2}$$

t = the time period = 8760 hours

Since the repair rate (M) is many times larger than the failure rate ($M \gg \lambda_p$), the group or super-group assembly complex has an approximately constant failure rate (λ_c) given by

$$\lambda_c = \frac{2\lambda_p^{2}}{3\lambda_p + M}$$

Now the probability of 0, 1, 2, 3..... r failures in a time t of a group or super-group assembly complex can be computed by:

$$P_{(r)} = \frac{e^{-\lambda_c t} \quad {\lambda_c t}^{r}}{r!}$$

The Poisson probability law can be used to determine the maximum number of failures expected in all the group or super-group assembly complexes at any desired confidence level.

Queueing theory was used to determine the number of voice channel hours of outage due to the failure(s) of the group or super-group assembly complexes.[4] The expected proportion of the operating time (d) that each group or super-group assembly path would be waiting in a failed state while the technician was repairing the parallel group or super-group assembly path respectively, was computed by:

$$d = \frac{K^{2}}{1 + 2K + 2K^{2}}$$

where:

$$K = \frac{MTTR_p}{MTBF_p}$$

$MTTR_p$ = the Mean-Time-To-Repair a group or super-group assembly path = 1/M

Multiplying d by the sum of: 1) the product of the number of group assemblies in the system, the number of voice channels affected by a group assembly failure, and the calendar operating time concerned, and 2) the product of the number of super-group assemblies in the system, the number of voice channels affected by a super-group assembly failure, and the calendar operating time concerned, the voice channel hours of outage due to the failure(s) of the group and super-group assembly complexes is determined.

Because queueing theory gives a measure of the expected voice channel hours of outage, it was decided to be conservative during this Phase of the technique and increase the $MTTR_p$ from 1.0 to 2.0 hours. This would give a measure of the maximum expected voice channel hours of outage of the group and super-group assembly complexes.

An example of these calculations is presented below where the MTBF of the multiplex equipment is shown as 500 hours.

$$MTBF_{MUX-B2} = 500$$

$$MTBF_i = 500\ (66) = 33{,}000$$

$$\lambda_i = .3030303 \times 10^{-4}$$

$$M = 1.0$$

$$MTBF_c = \frac{3\lambda_p + M}{2\lambda_p^{\ 2}} = \frac{1.000090909}{.1836547291 \times 10^{-8}} = 544{,}549{,}500$$

$$R_c = \frac{S_1 e^{\ S_2 t} - S_2 e^{\ S_1 t}}{S_1 - S_2}$$

where:

$$S_1 = \frac{-\ (3\lambda_p + M) + \ \lambda_p^{\ 2} + 6\lambda_p\ M + M^2}{2}$$

$$S_2 = \frac{-\ (3\lambda_p + M) + \ \lambda_p^{\ 2} \quad 6\lambda_p\ M + M^2}{2}$$

$$S_1 = \frac{-(1.000090909) + 1.000090905}{2} = -.2 \times 10^{-8}$$

$$S_2 = \frac{-2.000181814}{2} = -1.000090907$$

$$t = 8760 \text{ hours}$$

$$S_1 e^{\ S_2 t} = .0 \times 10^{-10}$$

$$S_2 e^{\ S_1 t} = -1.000090907 e^{\ -.00017520}$$

$$R_c = \frac{1.000090907 e^{\ -.00001752}}{1.000090905} = .999983$$

$$\lambda_c = \frac{.000000001836547291}{1.000090909} = .1836380347 \times 10^{-8}$$

Group Assemblies

N = 140 group assembly complexes in the system

$R_{cs} = R_c^{140} = .99776$ = the reliability of all the group assembly complexes in the system

$$\sum_{i=1}^{N} \lambda_c = .257093248 \times 10^{-6}$$

t = 8760 hours

$$P_{(R)} = \frac{e^{-t \sum_{i=1}^{N} \lambda_c} \left[t \sum_{i=1}^{N} \lambda_c \right]^R}{R!} = e^{-.0022521368} \frac{(.0022521368)^R}{R!}$$

$P_{(o)} = .997750$

$P_{(i)} = .002247$

$P_{(o)} + P_{(1)} = .999997$

We would expect no more than 1 operational random group assembly complex failure at a probability level of .999997.

$MTBF_p = 33,000$

$MTTR_p = 2.0$

$$K = \frac{MTTR_p}{MTBF_p} = \frac{2.0}{33,000.} = .6060606 \times 10^{-4}$$

$$d = \frac{K^2}{1 + 2K + 2K^2} = \frac{.3673094581 \times 10^{-8}}{1.000121219} = .3672699386 \times 10^{-8}$$

t = 8760 hours

Each group assembly contains 12 voice channels. There are 280 group assemblies in the system.

The maximum expected voice channel hours of outage due to the failure of the group assembly complexes is (8760) (12) (280) $(.3672699 \times 10^{-8})$ = .1081 hours. This value is underlined in the Table 2 which represents the maximum number of group assembly complex failures expected at the given probability level and the associated maximum number of voice channel hours of outage expected for different $MTBF_{MUX}$'s of the Multiplex Equipment.

$MTBF_{MUX}$ (B_1)	Equivalent $MTBF_{MUX}$ (B_2)	$MTBF_p$	$MTBF_c$	R_c	Maximum Number of Group Assembly Failures Expected	Probability Level	Maximum Number of Voice Channel Hours of Outage Expected	R_{cs}
100	1,100	6,600	21,789,900	.999599	2	.99997	2.70	.94552
200	2,200	13,200	87,139,800	.999895	1	.99990	0.68	.98540
300	3,300	19,800	196,049,700	.999912	1	.99998	0.30	.99385
400	4,400	26,400	391,773,142	.999973	1	.99999	0.17	.99632
500	5,500	33,000	544,549,500	.999983	1	.99999+	0.11	.99776
600	6,600	39,600	784,140,201	.999989	1	.99999+	0.08	.99846
700	7,700	46,200	1,000,064,935	.999991	1	.99999+	0.06	.99874
800	8,800	52,800	1,250,07 ,020	.999993	1	.99999+	0.05	.99910

Table 2. Maximum Number of Voice Channel Hours of Outage Expected for Different Group Assembly MTBF's

Super-Group Assemblies

N = 28 super-group assembly complexes in the system

$R_{cs} = R_c^{28} = .99955$ = the reliability of all the super-group assembly complexes in the system.

$$\sum_{i=1}^{N} \lambda_c = 28\lambda_c = .51418649716 \times 10^{-7}$$

t = 8760 hours

$$P_{(R)} = \frac{e^{-t \sum_{i=1}^{N} \lambda_c} \left[t \sum_{i=1}^{N} \lambda_c \right]^R}{R!} = e^{-.000450427371} \cdot \frac{(.000450427371)^R}{R!}$$

$P_{(o)} = .999549$

$P_{(1)} = .000450$

$P_{(o)} + P_{(1)} = .999999$

We would expect no more than 1 operational random super-group assembly complex failure at a probability level of .999999.

$MTBF_p = 33,000$

$MTTR_p = 2.0$

$$K = \frac{MTTR_p}{MTBF_p} = \frac{2.0}{33000.} = .6060606 \times 10^{-4}$$

$$d = \frac{K^2}{1 + 2K + 2K^2} = \frac{.3673094581 \times 10^{-8}}{1.000121219} = .3672699386 \times 10^{-8}$$

t = 8760 hours

Each super-group assembly contains 60 voice channels. There are 56 super-group assemblies in the system.

The maximum number of voice channel hours of outage expected due to the failure of the super-group assembly complexes is 8760 (60) (56) $(.3672699 \times 10^{-8})$ = .1081. This value is underlined in Table 3 which represents the maximum number of super-group assembly complex failures expected at the given probability level and the associated maximum number of voice channel hours of outage expected for different $MTBF_{MUX}$'s of the Multiplex Equipment.

$MTBF_{MUX}$ (B_1)	Equivalent $MTBF_{MUX}$ (B_2)	$MTBF_p$	$MTBF_c$	R_c	Maximum Number of Group Assembly Failures Expected	Probability Level	Maximum Number of Voice Channel Hours of Outage Expected	R_{cs}
100	1,100	6,600	21,789,900	.999599	1	.99993	2.70	.98886
200	2,200	13,200	37,139,800	.999895	1	.99999	0.68	.99706
300	3,300	19,800	196,049,700	.999912	1	.99999+	0.30	.99876
400	4,400	26,400	391,773,142	.999973	1	.99999+	0.17	.99926
500	5,500	33,000	544,549,500	.999983	1	.99999+	0.11	.99955
600	6,600	39,600	784,140,201	.999989	1	.99999+	0.08	.99969
700	7,700	46,200	1,000,064,935	.999991	1	.99999+	0.06	.99974
800	8,800	52,800	1,250,071,020	.999993	1	.99999+	0.05	.99980

Table 3. Maximum Number of Voice Channel Hours of Outage Expected for Different Super-Group Assembly MTBF's

b. Tropospheric Equipment MTBF's

The tropospheric communication complex consists of two active parallel paths; each path consisting of one transmitter in series with two receivers in an active parallel arrangement for quadruple diversity reception (see Figure 1). The formula determining the MTBF of the two receivers in one path is given by:

$$\mathrm{MTBF}_{RC} = \frac{3\lambda_R + M}{2\lambda_R^2}$$

where:

λ_R = the failure rate of one receiver

M = the repair rate of the receiver

Based on similar DEWDrop data consisting of forty-three (43) corrective maintenance repair times on two tropo-transmitters and four tropo receivers (AN/FRC-47V), a repair rate of 1.64 per hour (MTTR = 36 minutes) was computed. This technique uses a more conservative estimate of one per hour for the repair rate (M) of the tropo equipment.

The MTBF of one transmitter-receiver path (one transmitter in series with two receivers in parallel) is given by:

$$\mathrm{MTBF}_{TRP} = \frac{1}{\lambda_T + \lambda_{RC}}$$

where:

T = Transmitter

R = Receiver

P = Path

C = Complex

Since the MTBF_{RC} of the receiver complex is many times greater than the MTBF_T of the transmitter in series with it, the MTBF_{TRP} of the transmitter-receiver path is for practical purposes dependent on the MTBF_T of the transmitter alone. For example, if the MTBF_T of the transmitter is equal to 750 hours and the MTBF_R of each receiver is equal to 750 hours, the MTBF_{TRP} of the transmitter-receiver path is 748 hours. If the MTBF_R of each receiver is reduced to 500 hours, the MTBF_{TRP} of the transmitter-receiver path becomes 745.5 hours. Therefore, it can be seen that a significant change in the MTBF_R of the receiver has a negligible effect on the MTBF_{TRP} of the transmitter-receiver path. Based on similar White Alice data consisting of sixty-four (64) corrective maintenance failures on 38 continuously operating 10 KW amplifiers, an MTBF of 855 hours was computed; therefore, an MTBF of 750 hours for a tropo-transmitter is reasonable.

The $MTBF_{TRC}$ of the transmitter-receiver complex is given by:

$$MTBF_{TRC} = \frac{3\lambda_{TRP} + M}{2\lambda_{TRP}^{2}}$$

The reliability of the transmitter-receiver complex is given by:

$$R_{TRC} = \frac{S_1 \, e^{S_2 t} - S_2 e^{S_1 t}}{S_1 - S_2}$$

where:

$$S_1 = \frac{-(3\lambda_{TRP} + M) + \sqrt{\lambda_{TRP}^{2} + 6\lambda_{TRP} M + M^{2}}}{2}$$

$$S_2 = \frac{-(3\lambda_{TRP} + M) + \sqrt{\lambda_{TRP}^{2} + 6\lambda_{TRP} M + M^{2}}}{2}$$

t = the time period = 8760 hours

Since the repair rate (M) is many times larger than the failure rate ($M \gg \lambda_{TRP}$), the transmitter-receiver complex has an approximately constant failure rate (λ_{TRC}) given by:

$$\lambda_{TRC} = \frac{2\lambda_{TRP}^{2}}{3\lambda_{TRP} + M}$$

Now the probability of 0, 1, 2, 3 .... r failures in a time t of a transmitter-receiver complex can be computed by:

$$P_{(r)} = \frac{e^{-\lambda_{TRC} t} \left[\lambda_{TRC} t\right]^{r}}{r!}$$

and the Poisson probability law can be used to determine the maximum number of failures expected in all the transmitter-receiver complexes at any desired confidence level.

Queueing theory was used to determine the number of voice channel hours of outage due to the failure of the transmitter-receiver complex. The expected proportion of the operating time (d) that each transmitter-receiver path would be waiting in a failed state while the technician was repairing the parallel transmitter-receiver path was computed.

$$d = \frac{K^2}{1 + 2K + 2K^2}$$

where:

$$K = \frac{MTTR_{TRP}}{MTBF_{TRP}}$$

Multiplying d by the product of: 1) the calendar operating time concerned; 2) the numbers of transmitter-receiver paths in the system; and 3) the number of voice channels affected by a failure, the voice channel hours of outage due to the failures of the tropo equipment is determined. Queueing theory as applied here gives a measure of the expected voice channel hours of outage; as such, it was decided to increase the $MTTR_{TRP}$ from 1.0 hours to 2.0 hours in this phase of the technique. This would give a measure of the maximum expected voice channel hours of outage of the tropo transmitter-receiver complexes.

Based on field operational data the MTBF of a typical tropospheric transmitter-receiver complex should fall within the range of 400 to 1100 hours. Using this MTBF parameter, the maximum amount of voice channel outage hours was calculated in increments of 100 hours. An example of these calculations is presented below where the MTBF of the receiver is 750 hours.

Receivers

$MTBF_R = 750$

$\lambda_R = .001333333$

$M = 1.0$

$$MTBF_{RC} = \frac{3\lambda_R + M}{2\lambda_R^2} = \frac{1.003999999}{.00000355555555} = 282,375 \text{ hours}$$

Transmitter-Receiver Path

$$MTBF_{TRP} = \frac{1}{\frac{1}{750} + \frac{1}{282,375}} = 748.013247$$

$$MTBF_{TRC} = \frac{3\lambda_{TRP} + M}{2\lambda_{TRP}^2} = \frac{1.004010624}{.0000035744} = 280,889 \text{ hours}$$

$$R_C = \frac{S_1 e^{S_2 t} - S_2 e^{S_1 t}}{S_1 - S_2}$$

where:

$$S_1 = \frac{-(3\lambda_{TRP} + M) + \sqrt{\lambda_{TRP}^2 + 6\lambda_{TRP} M + M^2}}{2}$$

$$S_2 = \frac{-(3\lambda_{TRP} + M) - \sqrt{\lambda_{TRP}^2 + 6\lambda_{TRP} M + M^2}}{2}$$

$t = 8760$ hours

$M = 1.0$

and:

$$S_1 e^{S_2 t} = .0 \times 10^{-10}$$

$$S_2 e^{S_1 t} = -1.004007064e^{-.03118122}$$

$$R_{TRC} = \frac{1.004007064}{1.004003504} e^{-.03118122} = .9696308$$

$$\lambda_{TRC} = \frac{.0000035744}{1.004010624} = .35601216905 \times 10^{-5}$$

$N = 18$ Tropo transmitter-receiver complexes in the system.

$R_{TRCS} = R_{TRC}18 = .56919$ = the reliability of all the tropo transmitter-receiver complexes in the system.

$$\sum_{i=1}^{N} \lambda_{TRC} = 18\lambda_{TRC} = .6408219042 \times 10^{-4}$$

$t = 8760$ hours

$$P_{(R)} = \frac{e^{-t\sum_{i=1}^{N}\lambda_{TRC}} \left[t\sum_{i=1}^{N}\lambda_{TRC}\right]^R}{R!} = e^{-.561359988} \frac{(.561359988)^R}{R!}$$

$P_{(o)} = .570433$

$P_{(1)} = .320218$

$P_{(2)} = .089879$

$P_{(3)} = .016818$

$P_{(4)} = .002360$

$P_{(5)} = .000265$

$$\sum_{R=0}^{5} P_{(R)} = .999973$$

Therefore, we would expect no more than 5 operational random tropo transmitter-receiver complex failures at a probability level of .999973.

$MTBF_{TRP} = 748.013247$

$MTTR_{TRP} = 2.0$

$$K = \frac{MTTR_{TRP}}{MTBF_{TRP}} = \frac{2.0}{748.013247} = .00267374944$$

$$d = \frac{K^2}{1 + 2K + 2K^2} = \frac{.71489361 \times 10^{-5}}{1.0054904776} = .7109899354 \times 10^{-5}$$

Each tropo transmitter-receiver path carried 60 voice channels. There are 36 tropo transmitter-receiver paths in the system. The maximum number of voice channel hours of outage expected due to the failure of the tropo transmitter-receiver complexes is (8760) (60) (36) $(.710989935 \times 10^{-5})$ = 134.54. This value is underlined in Table 4 which represents the maximum number of tropo transmitter-receiver complex failures expected at the given probability level and the associated maximum number of voice channel hours of outage expected for different $MTBF_{TRP}$'s of the tropo transmitter-receiver path.

c. Line of Sight Equipment MTBF's

There are two line-of-sight (LOS) transmitters and two line-of-sight (LOS) receivers, each in an active parallel arrangement. The $MTBF_C$ of the two transmitters or two receivers is given by:

$$MTBF_C = \frac{3\lambda_p + M}{2\lambda_p^2}$$

where:

λ_p = the failure rate of a transmitter path or a receiver path

M = the repair rate of a transmitter or a receiver

The reliability of an LOS transmitter complex is given by:

$$R_C = \frac{S_1 e^{S_2 t} - S_2 e^{S_1 t}}{S_1 - S_2}$$

where:

$$S_1 = \frac{-(3\lambda_p + M) + \sqrt{\lambda_p^2 + 6\lambda_p M + M^2}}{2}$$

$MTBF_T$	$MTBF_{TRP}$	$MTBF_{TRC}$	R_{TRC}	Maximum Number of Tropo Transmitter-Receiver Complex Failures	Probability Level	Maximum Number of Voice Channel Hours of Outage Expected	R_{TRCS}
400	399.4341	80,373	.896729	9	.999956	469.66	.14057
500	499.1162	125,307	.932486	7	.999948	301.40	.28415
600	598.7278	180,135	.952547	6	.999962	209.73	.41682
700	698.2690	244,837	.964903	5	.999942	154.32	.52566
750	748.0132	280,889	.969308	5	.999973	134.54	.56919
800	797.7399	319,391	.972958	5	.999986	118.33	.61051
900	897.1405	403,760	.978553	4	.999945	93.61	.67689
1000	996.4711	497,972	.982570	4	.999979	75.92	.72869
1100	1095.7315	601,955	.985573	4	.999991	62.81	.76983

Table 4. Maximum Number of Voice Channel Hours of Outage Expected for Different Tropo Transmitter-Receiver MTBF's

$$S_2 = \frac{-(3\lambda_p + M) - \sqrt{\lambda_p^2 + 6\lambda_p M + M^2}}{2}$$

t = the time period = 8760 hours

Using a repair rate (M) of one per hour as in the previous equipment (tropo) and considering the fact that the repair rate is many times greater than the failure rate $(M \quad \lambda_p)$, it is assumed that the LOS transmitter or receiver complex has an approximately constant failure rate which is given by:

$$\lambda_C = \frac{2\lambda_p^2}{3\lambda_p + M}$$

Now the probability of 0, 1, 2, 3 ..... r failures in a time t, of an LOS transmitter or receiver complex can be computed by:

$$P_{(r)} = \frac{e^{-\lambda_c t} \left[\lambda_c t\right]^r}{r!}$$

and the Poisson probability law can be used to determine the maximum number of failures expected in all the LOS transmitter and receiver complexes in the system. Voice channel hours of outage due to the failures of the LOS transmitter and receiver complexes was computed using the queueing theory as applied in the previous equipments.

Based on field operational data the MTBF of a typical line-of-sight equipment should fall within the range of 500 to 3000 hours. Using this MTBF parameter, the maximum amount of voice channel outage hours was calculated in increments of 500 hours. An example of these calculations is presented below where the MTBF of line-of-sight complex is 2000 hours.

$$\mathrm{MTBF}_p = 2000 = \frac{1}{\lambda_p}$$

M = 1 per hour

$$\mathrm{MTBF}_c = \frac{3\lambda_p + M}{2\lambda_p^2} = \frac{1.0015}{.0000005} = 2{,}003{,}000$$

$$R_c = \frac{S_1 e^{S_2 t} - S_2 e^{S_1 t}}{S_1 - S_2}$$

where:

$$S_1 = \frac{-(3\lambda_p + M) + \sqrt{\lambda_p^2 + 6\lambda_p M + M^2}}{2}$$

$$S_2 = \frac{-(3\lambda_p + M) - \sqrt{\lambda_p^2 + 6\lambda_p M + M^2}}{2}$$

$t = 8760$ hours

$M = 1.0$

and:

$$S_1 e^{S_2 t} = .0 \times 10^{-10}$$

$$S_2 e^{S_1 t} = -1.0014995\ e^{-.00437562}$$

$$R_c = \frac{1.0014995}{1.00149900}\ e^{-.00437562} = .995646$$

$$\lambda_c = \frac{.0000005}{1.0015} = .4992511232 \times 10^{-6}$$

$N = 4$ line-of-sight equipment complexes

$R_{cs} = R_c^4 = .982697$ = the reliability of all the line-of-sight equipment complexes in the system

$$\sum_{i=1}^{N} \lambda_c = 4\lambda_c = .19970044928 \times 10^{-5}$$

$t = 8760$ hours

$$P_{(R)} = \frac{e^{-t \sum_{i=1}^{N} \lambda_c} \left[t \sum_{i=1}^{N} \lambda_c \right]^R}{R!} \cdot = e^{-.017493759}\ \frac{(.017493759)^R}{R!}$$

$P_{(o)} = .982659$

$P_{(1)} = .017190$

$P_{(2)} = .000150$

$P_{(o)} + P_{(1)} + P_{(2)} = .999999$

We would expect no more than 2 operational random line-of-sight equipment complex failures at a probability level of .999999.

$MTBF_p = 2000$

$MTTR_p = 2.0$

$$K = \frac{MTTR_p}{MTBF_p} = \frac{2.0}{2000} = .001$$

$$d = \frac{K^2}{1 + 2K + 2K^2} = \frac{.000001}{1.002002} = .998002 \times 10^{-6}$$

Each LOS transmitter or receiver path carries 60 voice channels. There are 8 LOS equipment paths in the system. The maximum number of voice channel hours of outage expected due to the failure of the LOS transmitter and receiver complexes is (8760) (60) (8) ($.998002 \times 10^{-6}$) = 4.1964. This value is underlined in Table 5 which represents the maximum number of LOS transmitter and receiver complex failures expected at the given probability level and the maximum number of voice channel hours of outage expected for different $MTBF_p$'s of the LOS transmitter and receiver complexes.

d. Power Equipment

The power equipment at each station consists of four (4) diesel generators (DG) with one no-break motor generator (NBMG) supplying power to everything except the tropo transmitter. The four DG's are arranged in two pairs, each pair serving two tropo transmitters. In the event of failure, one DG is sufficient to provide the total tropo transmitter power. One of the pairs also supplies the power to operate an electric motor that drives the NBMG with automatic switching to the other pair should a failure occur in the DG supplying the power to the NBMG.

One DG from each pair supplies the base power. The two remaining are on a reserve status. Part of the time one of the two in reserve will not be capable of operation. This would be due to corrective maintenance repair or a preventive maintenance routine.

There are two DG's operating at each of the ten stations or twenty continuously operating DG's in the system. Based on similar DEWLine data on one hundred twenty-one (121) diesel generators, forty-four (44) corrective maintenance failures were reported, thirty-two (32) in the diesels and twelve (12) in the generators, giving an $MTBF_{DG}$ of 22,044 hours.

Using an $MTBF_{DG}$ of 15,000 hours per DG, the probability of 0, 1, 2, 3 ..... r failures in a time t of a DG can be computed using:

$$P_{(r)} = \frac{e^{-\lambda_{DG}t} \left[\lambda_{DG}t\right]^r}{r!}$$

$MTBF_p$	$MTBF_c$	R_c	Maximum Number of LOS Equipment Failures Expected	Probability Level	Maximum Number of Voice Channel Hours of Outage Expected	R_{cs}
500	125,750	.932716	4	.999988	66.75	.756828
1000	501,500	.983119	2	.999946	16.76	.934166
1500	1,127,250	.992264	2	.999995	7.46	.969413
2000	2,003,000	.995646	2	.999999	4.20	.982697
2500	3,128,750	.997211	1	.999935	2.69	.988890
3000	4,504,500	.998060	1	.999959	1.87	.992262

Table 5. Maximum Number of Voice Channel Hours of Outage Expected for Different LOS Transmitter-Receiver MTBF's

and the Poisson probability law can be used to determine the maximum number of failures expected in all the DG's at any desired confidence level.

Based on field operational data it would take a maximum of fifteen seconds to restore power using a reserve diesel generator and another equal amount of time until the tropo transmitter was back in operation; in effect a path outage of thirty seconds per DG failure. However, if at the time of a DG failure quadruple diversity existed in both directions in the tropo equipment, there is no system outage time accrued. Assuming an impossibly low figure of merit of each tropo transmitter-receiver path and that a failure would have to occur in one or more of the four tropo transmitter-receiver paths within a three hour time period before the reserve DG was powering the two tropo transmitters, the reliability of the four tropo transmitter-receiver paths for a given DG failure can be computed by:

$$R = e^{-4\lambda_{TRP} t}$$

where:

λ_{TRP} = the failure rate of a tropo transmitter-receiver path

t = the time period considered, equal to three hours

Knowing the maximum number of failure expected in all the DG's (computed previously) we can determine by using the binomial probability law, the maximum number of DG failures expected when one or more of the tropo transmitter-receiver paths is in a failed state for any desired confidence level. The product of: 1) the maximum number of DG failures expected when one or more of the tropo transmitter-receiver path is in a failed state; and 2) the maximum, one-half minute outage time per DG failure; and 3) the 60 voice channels affected by each DG failure is the voice channel minutes of outage due to the failures of the DGs. This is a conservative estimate of the voice channel minutes of outage since there are certain combinations of dual diversity and quadruple diversity in which a DG failure will not result in voice channel outage.

There is one NBMG at each of the eleven (11) stations or eleven continuously operating NBMG's in the system. Based on the previously mentioned DEWLine data, twelve (12) corrective maintenance failures were reported on the generator giving an $MTBF_G$ of 81,000 hours. The reliability of the electric motor is considered to be at least as good as that of the generator. Using an $MTBF_{NBMG}$ of 30,000 hours for each no-break motor generator, the probability of 0, 1, 2, 3 ..... r failures in a time t of a NBMG can be computed by:

$$P_{(r)} = \frac{e^{-\lambda_{NBMG} t} \left[\lambda_{NBMG} t\right]^{r}}{r!}$$

and the Poisson probability law can be used to determine the maximum number of failures expected in all the NBMG's at any desired confidence level. Based on operational data it would take an average of one minute maximum to restore power by by-passing the NBMG and supplying power directly from an operating DG. The product of: 1) the maximum number of NBMG failures that can occur; 2) the maximum average of one minute outage time per NBMG failure; and 3) the 60 voice channels affected by each failure is the voice channel minutes of outage due to the failures of the NBMG. This is a conservative estimate since several stations have a diesel motor as a backup to the electric motor driving the NBMG.

The sum of the voice channel minutes of outage due to the failures of the DG's and NBMG's converted to hours is the voice channel hours of outage caused by the power equipment.

For example, if the MTBF's of the diesel generator is 15,000 hours and the motor generator is 30,000 hours, the maximum number of voice channel hours of outage is calculated as follows:

Diesel Generators

$MTBF_{DG} = 15,000$

$t = 8760$ hours

$$\lambda_{DG} = \frac{1}{15,000} = .666667 \times 10^{-4}$$

N = 20 operating diesel generators in the system

$$\sum_{i=1}^{N} \lambda_{DG} = 20\ \lambda_{DG} = .00133333333$$

$$P_{(R)} = \frac{e^{-t \sum\limits_{i=1}^{N}} \left[t \sum\limits_{i=1}^{N} \lambda_{DG} \right]^{R}}{R!} = \frac{e^{-11.68} \quad (11.68)^{R}}{R!}$$

Using the Normal Probability Distribtuion as an approximation of the Poisson Probability Distribution

$\alpha = 4 =$ confidence level of .99994

$np = 11.68$

$np + \alpha \sqrt{np}$

$11.68 + 4\ (3.4176) = 25.35$

We would expect no more than 26 operational random diesel generator failures at a probability level of .99994

$MTBF_{TRP} = 399.4341$

$t = 3$ hours

$$R_{4TRP} = e^{-4\ \lambda_{TRP} t} = e^{-.03004249} = .970405$$

$N = 26$

$q = .970405$

$1-q = p = .029595$

$P_{(R)} = C_r^N \; p^r \; q^{N-r}$

$$\sum_{r=o}^{s} C_r^{26} \; (.029595)^r \; (.970405)^{26-r} \geq .9999$$

s = 5 at a probability level of .999907

We would expect no more than five DG failures to occur when one or more of the tropo transmitter-receiver paths is in a failed state at a probability level of .999907.

Outage time of 30 seconds for each of 5 DG failures for each of 60 voice channels. 30 x 5 = 150 system seconds of outage = 2.5 system minutes = 2.5 voice channel hours of outage.

<u>No-Break Motor Generator</u>

$MTBF_{NBMG} = 30{,}000$ hours

t = 8760 hours

$$\lambda_{NBMG} = \frac{1}{30{,}000} = .3333333 \times 10^{-4}$$

N = 11 operating no-break motor generators in the system

$$\sum_{i=1}^{N} \lambda_{NBMG} = 11 \; \lambda_{NBMG} = .000366666666$$

$$P_{(R)} = \frac{e^{-t \sum_{i=1}^{N} \lambda_{NBMG}} \left[t \sum_{i=1}^{N} \lambda_{NBMG} \right]^R}{R!} = \frac{e^{-3.212} \; (3.212)^R}{R!}$$

$$\sum_{r=o}^{12} P_{(R)} = .999992$$

We would expect no more than 12 operational random no-break motor generator failures at a probability level of .999992.

Outage time of 1 minute per failure in each of 60 voice channels 1 x 12 = 12 system minutes of outage = 12 voice channel hours of outage. The voice channel hours of outage caused by failure of the power equipment is 12 + 2.5 = 14.5 hours.

e. EUR-MED Equipment Procurement Tables

The preceding paragraphs concern the development of equipment MTBF's based on the maximum amount of 240 voice channel hours of outage. Tables 6 to 11 show, for the EUR-MED System, the maximum expected voice channel hours of outage per year for several MTBF's of the multiplex equipment, tropo equipment, line-of-sight equipment, and one set of MTBF's for the power equipment. Examination of these tables show different combinations of MTBF's are required for an expected voice channel outage of 240 hours.

In using these tables the minimum equipment MTBF's required for a specified maximum amount of voice channel hours of outage can be determined. These minimum MTBF's are used by Quality Assurance in procurement of specific equipment as the degree of reliability required for the minimum EUR-MED system availability of 99.9%.

PHASE II - TECHNIQUE FOR CALCULATING CHANNEL OUTAGE HOURS

After final selection of the equipments that will comprise the EUR-MED System has been completed, it is necessary to insure that the pre-established system availability of 99.9% can still be achieved. This is accomplished in Phase II of the technique. The primary effort during this phase is the calculation of channel outage hours utilizing the selected equipments. Factors such as, propagation outage hours, manual or automatic switching of subassemblies/equipments, etc. are included in calculating channel outage hours. The final selection of equipments in the EUR-MED System at this time, however, has not been completed since the multiplex equipment has not been procured. For this discussion of the channel outage calculation technique an example of the Big Rally II Communication System is presented. These two communication system types are very similar, in that, they both utilize the same types of equipments, (e.g., multiplex, tropo, etc.). The channelling plan of the Big Rally II System is shown as Figure 2. It can be seen in this figure (2) that the majority of voice channels originate at Station ID and terminate at various stations in the system. In the following example, only the availability calculation of channel number 6 is presented, although all Big Rally II channel availabilities would be calculated in the same manner.

In order to calculate the availability of channel 6, an equivalent representation of its signal path from point of origin to terminus had to be developed. To accomplish this, the equipments employed in providing channel 6 were analyzed to determine the signal path through their subassemblies. If the signal path was in <u>series</u> with all the parts used in the subassembly, then the entire subassembly was represented as a block. On the other hand, if the parts used in the subassembly provided a parallel path for the channel signal, then the parts were segregated into two blocks, each block in parallel with the other, but still representing a series signal path for channel 6. This method of segregating parts in subassemblies, is continued until the entire signal path of channel 6, from its point of origin to terminus, is shown as a series and parallel block configuration. The block configuration for channel 6 is shown as Figure 3. The availability calculated for channel 6 is a function of the Mean-Time-Between-Failure (MTBF) and Mean-Time-To-Repair (MTTR) for each block shown in Figure 3. MTBF and MTTR values, therefore, were determined for each block.

VOICE CHANNEL HOURS OF OUTAGE
FOR DIFFERENT MTBF'S OF THE EQUIPMENT IN THE EUR-MED TROPO SYSTEM*

TABLE 6

LOS MTBF = 500

		Tropo Equipment (MTBF)								
		400	500	600	700	750	800	900	1000	1100
Multiplex Equipment (MTBF)	100	618	450	358	303	283	267	242	224	211
	200	585	417	325	269	250	233	209	191	178
	300	574	406	314	259	239	223	198	180	167
	400	569	400	309	253	234	217	193	175	162
	500	566	397	306	250	230	214	190	172	159
	600	563	395	303	248	228	212	187	170	157
	700	562	394	302	247	227	211	186	168	155
	800	561	392	301	245	276	209	185	167	154

TABLE 7

LOS. MTBF = 1000

		Tropo Equipment (MTBF)								
		400	500	600	700	750	800	900	1000	1100
Multiplex Equipment (MTBF)	100	568	400	308	253	233	217	192	174	161
	200	535	367	275	219	200	183	159	141	128
	300	524	356	264	209	189	173	148	130	117
	400	519	351	259	203	184	167	143	125	112
	500	516	347	256	200	180	164	140	122	109
	600	513	345	253	198	178	162	137	120	107
	700	512	344	252	197	177	161	136	118	105
	800	511	342	251	195	176	159	135	117	104

* Power Outage Included
MTBF of each no-break motor generator is 30,000 hours
MTBF of each diesel generator is 15,000 hours

VOICE CHANNEL HOURS OF OUTAGE
FOR DIFFERENT MTBF'S OF THE EQUIPMENT IN THE EUR-MED TROPO* (Cont.)

TABLE 8

LOS. MTBF = 1500

	Tropo Equipment (MTBF)								
Multiplex Equipment (MTBF)	400	500	600	700	750	800	900	1000	1100
100	559	390	299	243	224	207	183	165	152
200	525	357	266	210	190	174	149	132	119
300	515	347	255	199	180	163	139	121	108
400	509	341	250	194	174	158	133	116	103
500	506	338	246	191	171	155	130	113	99
600	504	336	244	189	169	153	128	110	97
700	503	334	243	187	167	151	127	109	96
800	501	333	241	186	166	150	125	108	95

TABLE 9

LOS. MTBF = 2000

	Tropo Equipment (MTBF)								
Multiplex Equipment (MTBF)	400	500	600	700	750	800	900	1000	1100
100	555	387	295	240	220	204	179	162	149
200	522	354	262	207	187	171	146	128	115
300	512	343	252	196	176	160	135	118	105
400	506	338	246	191	171	155	130	112	99
500	503	335	243	188	168	152	127	109	96
600	501	333	241	186	166	150	125	107	94
700	499	331	239	184	164	148	123	106	92
800	498	330	238	183	163	147	122	104	91

* Power Outage Included
MTBF of each no-break motor generator is 30,000 hours
MTBF of each diesel generator is 15,000 hours

VOICE CHANNEL HOURS OF OUTAGE
FOR DIFFERENT MTBF'S OF THE EQUIPMENT IN THE EUR-MED TROPO SYSTEM* (Cont.)

TABLE 10

LOS, MTBF = 2500

		Tropo Equipment (MTBF)								
		400	500	600	700	750	800	900	1000	1100
	100	554	386	294	239	219	203	178	160	147
	200	521	352	261	205	186	169	145	127	114
	300	510	342	250	195	175	159	134	116	103
Multiplex Equipment (MTBF)	400	505	336	245	189	170	153	129	111	98
	500	501	333	242	186	166	150	125	108	95
	600	499	331	239	184	164	148	123	106	92
	700	498	330	238	182	163	146	122	104	91
	800	497	328	237	181	161	145	121	103	90

TABLE 11

LOS, MTBF = 3000

		Tropo Equipment (MTBF)								
		400	500	600	700	750	800	900	1000	1100
	100	553	385	293	238	218	202	177	159	146
	200	520	352	260	205	185	169	144	126	113
	300	509	341	249	194	174	158	133	115	102
Multiplex Equipment (MTBF)	400	504	336	244	189	169	153	128	110	97
	500	501	332	241	185	166	149	125	107	94
	600	499	330	239	183	163	147	122	105	92
	700	497	329	237	182	162	146	121	103	90
	800	496	328	236	180	161	144	120	102	89

* Power Outage Included
MTBF of each no-break motor generator is 30,000 hours
MTBF of each diesel generator is 15,000 hours

a. Mean-Time-Between-Failure (MTBF)

The Mean-Time-Between-Failure (MTBF) for each block was determined from two sources of data: 1) field operational data from identical equipments, and 2) MTBF's calculated using part failure rates and methods outlined in the RADC Notebook TR-58-111, 31 December 1961, Section 8.

Field operational data used in calculating block MTBF's covered a period of one year of continuous operation. These MTBF's were calculated using the expression: (operating population) (operating time)/number of interruptions. This expression assumes that the times-between-interruptions are exponentially distributed. An interruption of service is a catastrophic chance failure which occurs during normal operation.

The block MTBF's that were calculated using the TR-58-111 method are also predicated on the catastrophic chance type of part failure. The MTBF of a block using this method is determined by: 1) calculating the failure rate for each part whose independent failure would cause the loss of the signal path of channel 6 based on the electrical and thermal stresses to which the part is subjected; 2) summing the failure rates for all such parts employed in a block; and 3) taking the reciprocal of the sum of the part failure rates to determine the MTBF.

Stated in mathematical form, assuming N parts in a given block, the failure rate of the block becomes:

$$\lambda_T = \sum_{i=1}^{i=N} (\lambda_P + \lambda_M + \lambda_E)_i$$

where:

λ_T = total failure rate for the block under study while it is functioning under specified operational circuit and environmental conditions.

λ_P = conventional part quality in terms of a nominal or quiescent failure rate.

λ_M = failure rate term accounting for an increased or decreased failure probability arising from circuit application (electrical stress).

λ_E = failure rate term accounting for an increased or decreased failure probability arising from environmental (primarily thermal) effects.

From the total block failure rate (λ_T), the block MTBF is calculated. This MTBF is simply the reciprocal of the total failure rate, as follows:

$$\text{Block MTBF} = 1/\lambda_T$$

b. Mean-Time-To-Repair (MTTR)

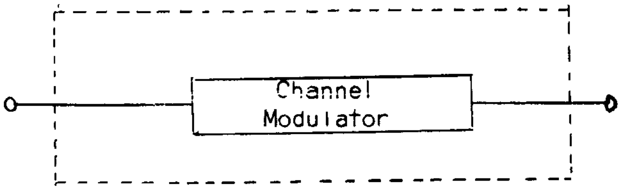
The Mean-Time-To-Repair (MTTR) for each block was determined from two sources of data, as follows: 1) field operational data from identical equipments, and 2) engineering estimates from the equipment manufacturer.

The MTTR value is defined as "the time required to locate, isolate, disassemble, interchange, reassemble, align and checkout a malfunction". It does not include any time incurred while waiting for replacement parts that are not immediately available or any other non-related repair factors. The repair rate (μ) is the reciprocal of the Mean-Time-To-Repair and is the number of repairs that could be accomplished in the unit measure of time. In contrast to the failure rate (λ), the repair rate (μ) has no significant operational meaning, but is just used to simplify statistical formulae.

c. Calculation of Channel 6 Availability

The availability of channel 6 is calculated using standard laws of probability theory. In using the standard laws of probability, the channel 6 block configuration shown as Figure 3, is segmented into portions. Each portion representing a specific amount of channel 6 availability, or conversely, channel 6 unavailability (i.e., downtime).

To clearly illustrate the technique used in segmenting the signal path into portions and the formulae used to calculate channel 6 availability, the following three examples are presented. Consider first a block such as the channel modulator in the MC-50 Equipment shown in Figure 3 and repeated here for convenience. This block represents a portion of the signal path of channel 6 and is called a simple element.



A Simple Element

The expected proportion of continuous operating time that channel 6 is not operating (i.e., downtime, d) due to the failure of this simple element is calculated by:[5]

$$d = \frac{\lambda}{\lambda + \mu} = \frac{MTTR}{MTBF + MTTR}$$

where:

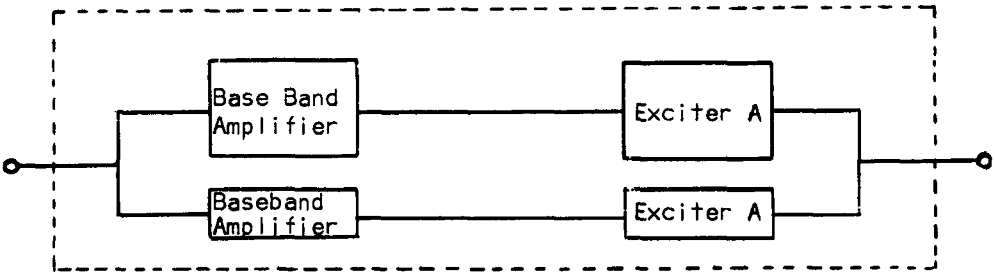
λ is the element constant failure rate and is equal to 1/MTBF

μ is the element constant repair rate and is equal to 1/MTTR

MTBF is the Mean-Time-Between-Failure

MTTR is the Mean-Time-To-Repair

Consider next, a number of blocks in which the signal path is a simple series-parallel configuration of blocks. An example of this condition occurs in Figure 3 where the signal path of channel 6 enters the baseband amplifiers of the MC-50 equipment and traverses through a portion of the AN/MRC-85 Exciter Equipment to the point where automatic switching of exciters is available. The configuration of these blocks is called a complex element and is presented below.



A Complex Element

The expected proportion of continuous operating time that channel 6 is not operating (i.e., downtime, d) due to the failure of this complex element is calculated by:

$$d = \frac{2K^2}{1 + 2K + 2K^2}$$

where:

K is the ratio of λ/μ

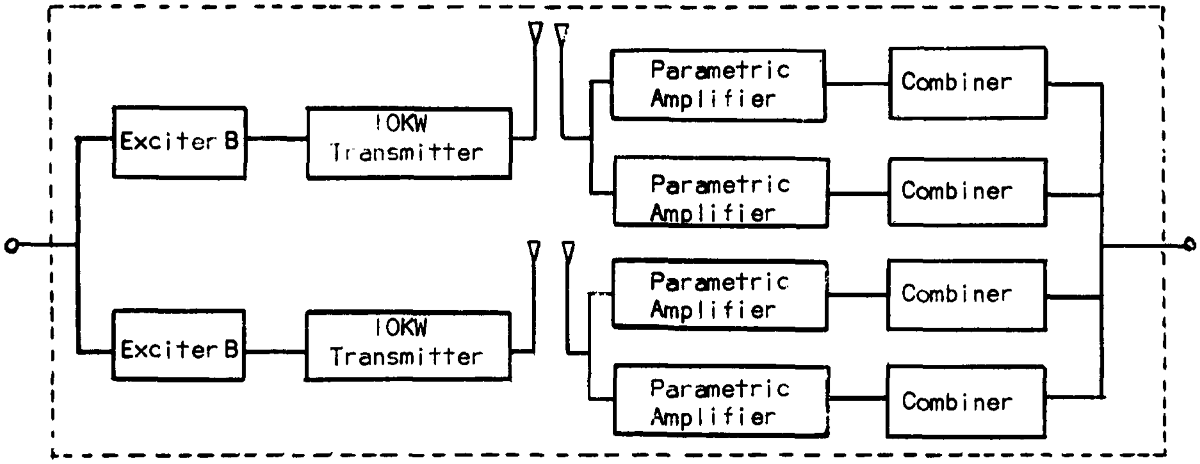
λ = the constant failure rate of the base-band amplifier (BBA) and the Exciter A (EA) in series with it
$= \lambda_{BBA} + \lambda_{EA}$

μ = the constant repair rate of the base-band amplifier and the Exciter A in series with it
$$= \frac{\lambda}{\frac{\lambda_{BBA}}{\mu_{BBA}} + \frac{\lambda_{EA}}{\mu_{EA}}}$$

There is one repair crew
The two blocks are identical

The downtime (d) is the expected proportion of the time that a repair crew will be repairing a failed Base-Band Amplifier or Exciter when the other Base-Band Amplifier or Exciter is in a failed condition. In other words, d is equal to the time that both channel paths are inoperable.

The following example is composed of a number of blocks in a very complex configuration.



A Very Complex Element

This very complex element is found in the AN/MRC-85 Equipment where automatic switching of exciters is available, and ends at the combiner output of the signal path in the quadruple diversity receivers.

The expected proportion of continuous operating time that channel 6 is not operating (i.e., downtime, d) due to the failure of this very complex element is calculated in the following paragraphs.

The failure rate (λ_R) and the expected repair rate (μ_R) of the receiver (R) which consists of one parametric amplifier (PA) in series with its combiner (C), is calculated as follows:

$$\lambda_R = \lambda_{PA} + \lambda_C$$

$$\mu_R = \frac{\lambda_R}{\frac{\lambda_{PA}}{\mu_{PA}} + \frac{\lambda_C}{\mu_C}}$$

The expected proportion of continuous operating time that channel 6 is not operating (i.e., downtime, d) due to the failure of this very complex element is calculated by the following steps:

Step 1

The failure rate (λ_R) and the repair rate (μ_R) of the receiver (R) consisting of one parametric amplifier (PA) in series with its combiner (C), is:

$$\lambda_R = \lambda_{PA} + \lambda_C$$

$$\mu_R = \frac{\lambda_R}{\frac{\lambda_{PA}}{\mu_{PA}} + \frac{\lambda_C}{\mu_C}}$$

Step 2

The failure rate (λ_{2R}) and repair rate (μ_{2R}) of two receivers in parallel 3 is:

$$\lambda_{2R} = \frac{2\lambda_R^2}{\mu_R}$$

$$\mu_{2R} = \frac{\lambda_{2R}\ (1-d)}{d}$$

where:

$$d = \frac{2K^2}{1 + 2K + 2K^2}$$

and:

K is the ratio of λ_R/μ_R

λ_R is the constant failure rate of one receiver

μ_R is the constant repair rate of the receiver.

Step 3

The failure rate (λ) and repair rate (μ) of one Exciter B, the 10 KW transmitter and the two parallel receivers in series with each of them is:

$$\lambda = \lambda_{EB} + \lambda_T + \lambda_{2R}$$

$$\mu = \frac{\lambda}{\frac{\lambda_{EB}}{\mu_{EB}} + \frac{\lambda_T}{\mu_T} + \frac{\lambda_{2R}}{\mu_{2R}}}$$

Step 4

The expected proportion of continuous operating time that channel 6 is not operating (i.e., downtime, d) due to the failure of this very complex element is:

$$d = \frac{2K^2}{1 + 2K + 2K^2}$$

where:

$K = \lambda/\mu$

λ = the failure rate of one Exciter B, the 10KW Transmitter and the two parallel receivers in series with them.

μ = the repair rate of one Exciter B, the 10KW Transmitter and the two parallel receivers in series with them.

The preceding example illustrated how the signal path of channel 6, composed of simple, complex or verycomplex elements, is reduced to a series arrangement of elements, and the technique for determining the channel downtime assignable to each element.

The expected propagation outages between the stations in the signal path of channel 6 were provided by the Big Rally II Engineering Project Office. Outage due to power failures and outage incurred by manual switching between subassemblies are also included in the availability calculations.

The availability of channel 6 is the product of the availabilities of the elements in the signal path and is computed using the following formula.

$$\text{Channel 6 Availability (CA-6)} = \left[\prod_{i=1}^{N} (1-d_i)\right] \left(1-P_o\right)\left(1-PE_o\right)$$

where:

(CA-6) is the proportion of the total desired operating time that channel 6 is operable.

N is the number of elements in the signal path of channel 6.

d_i is the proportion of the total desired operating time that the ith element in channel 6 is inoperable.

P_o is the expected propagation outage between the stations in the signal path of channel 6.

PE_o is the expected outage due to power failures in the signal path of channel 6.

Table 12 shows the availability calculations for channel 6. As seen in this table (12) the availability calculated for channel 6 is:

$$Acp = \prod_{i=1}^{100} (1-di) = 0.99882 \text{ or } 99.88\%$$

PHASE III - MONITORING AND ANALYSES OF FIELD SYSTEM OPERATIONAL DATA

The final phase of this technique involves the monitoring of field operational data on the EUR-MED System to determine if the calculated system availability is actually being achieved. In order to accomplish this objective, a field failure reporting system is required. It is planned that the EUR-MED System will utilize a standard failure reporting form. A preliminary version of this form, the Site Outage and Discrepancy Report, is shown as Figure 4. The specific entries that will be used to monitor and analyze the EUR-MED System availability in this report will be block numbers 3, 10, and 11. Block 3 indicates the specific voice channel circuit. Block 10 indicates the exact time that the voice channel service was interrupted and block 11 indicates the exact time the voice channel service was restored. Other blocks in the failure report form permit monitoring and evaluation of MTBF's and MTTR's of the equipments, subassemblies, etc. In addition, high failure rates of specific parts, high cost parts, non-standard parts, etc. are also obtained from the data shown in the reporting form.

Since the equipment in the EUR-MED System operate continuously (24 hours a day) no equipment operational time logs are necessary. Therefore, the formula used to calculate the EUR-MED System Availability (A) is:

$$A = \frac{CT - \sum_{i=1}^{N} Ci\ ti}{CT} \times 100\%$$

where:

C = the number of channels in the system

T = the calendar time involved = one year

Ci = the number of channels incapacitated during the ith failure

ti = the length of time the channels were incapacitated during the ith failure

N = the number of failures that occurred in the time T

TABLE 12

AVAILABILITY OF THE COMMUNICATION PATH OF CHANNEL SIX FROM STATION ID TO STATION IGC

Transmit Path

STATION	BLOCK	$10^5 d$	AVAILABILITY (1-d)
ID	Channel Modulator	.20855	.9999979145
	Channel Carrier Supply (1)	.30581	.9999969419
	Master Oscillator (1)	.10142	.9999989858
	Harmonic Generator (1)	.54794	.9999945206
	Power Supply P-3 (1)	.77820	.9999922180
	Power Supply P-4 (1)	.44843	.9999955157
	Sinewave Supply (1)	.07722	.9999992278
	Signal Tone Generator (1)	.01760	.9999998240
	Group Modulator	.27174	.9999972826
	Alarm Indicator (1)	.24814	.9999975186
	Monitor and Alarm Panel (1)	.91323	.9999908677
	Alarm Sensor (1)	.01670	.9999998330
	Terminal Board (1)	.00060	.9999999940
	H.F. Connector (1)	.00100	.9999999900
	Baseband Amp., Exciter A Baseband Amp., Exciter A	.00118	.9999999882
ID-IR	Exciter B, 10KW Trans., Two Receivers (Parametric Amp., Combiner) Exciter B, 10KW Trans., Two Receivers (Parametric Amp., Combiner)	.21306	.9999978694
IR	Baseband O.W. Amplifier Baseband O.W. Amplifier Baseband O.W. Amplifier Baseband O.W. Amplifier	.20999	.9999979001
	Bandpass Filter	.00740	.9999999260
	Lowpass Filter	.00200	.9999999800

(1) Common to both the Transmit and Receiver Path

TABLE 12 (Continued)

STATION	BLOCK	10^5d	AVAILABILITY (1-d)
IR (Continued)	Exciter A Exciter A	.00116	.9999999884
IR-IC	Exciter B., 10KW Trans., Two Receivers (Parametric Amp., Combiner) Exciter B., 10KW Trans., Two Receivers (Parametric Amp., Combiner)	.21306	.9999978694
IC	Baseband O.W. Amplifier Baseband O.W. Amplifier Baseband O.W. Amplifier Baseband O.W. Amplifier	.20999	.9999979001
	16 db Pad	.00030	.9999999970
	H.F. Connector (1)	.00100	.9999999900
	Terminal Board (1)	.00060	.9999999940
	Alarm Sensor (1)	.01670	.9999998330
	Monitor and Alarm Panel (1)	.91323	.9999908677
	Alarm Indicator (1)	.24814	.9999975186
	Group Demodulator	.32895	.9999967105
	Signal Tone Generator (1)	.01760	.9999998240
	Sinewave Supply (1)	.07722	.9999992278
	Power Supply P-3 (1)	.77820	.9999922180
	Power Supply P-4 (1)	.44843	.9999955157
	Harmonic Generator (1)	.54794	.9999945206
	Master Oscillator (1)	.10142	.9999989858
	Channel Carrier Supply (1)	.30581	.9999969419
	Channel Demodulator	.72463	.9999927537
	23 db Pad	.00040	.9999999960
	Channel Modulator	.14330	.9999985670
	Carrier Frequency Supply (1)	1.87217	.9999812783

(1) Common to both the Transmit and Receive Path

TABLE 12 (Continued)

STATION	BLOCK	$10^5 d$	AVAILABILITY (1-d)
IC (Continued)	Subgroup Modulator	.14701	.9999985299
	Power Supply (1)	1.19832	.9999880168
	Transmit Circuit	.22392	.9999977608
	Voltage Regulator Voltage Regulator	.00003	.9999999997
	Transformer, Power Supply, Transmitter Transformer, Power Supply, Transmitter	1.84011	.9999815989
IGC	R.F. Tuner and Converter, 1KW Trans., Bandpass Filter R.F. Tuner and Converter, 1KW Trans., Bandpass Filter	.01242	.9999998758
	Bandpass Filter, Amp. Converter, I.F. Amp., Lim. Disc. AFC, Power Supply, Bandpass Filter, Amp. Converter, I.F. Amp., Lim. Disc. AFC, Power Supply	17.65420	.9998234580
	Pre-Amp., Noise Amp., Shaper Detector, Pilot Tone Detector Pre-Amp., Noise Amp., Shaper Detector, Pilot Tone Detector	.00000+	.9999999999
	AFC Squelch	.02510	.9999997490
	Logic	.05050	.9999994950
	Combiner	.10160	.9999989840
	Post Amplifier	.04450	.9999995550
	Combiner Power Supply	.33430	.9999966570
	Baseband Amplifier Rec.	1.00000	.9999900000
	Receive Circuit	.52876	.9999947124
	Power Supply (1)	1.19832	.9999880168
	Subgroup Demodulator	.13464	.9999986536
	Carrier Frequency Supply (1)	1.37217	.9999812783
	Channel Demodulator	.21196	.9999978804

(1) Common to both the Transmit and Receive Path

TABLE 12 (Continued)

STATION	BLOCK	$10^5 d$	AVAILABILITY (1-d)
1D-1GC	Equivalent Power Equipment Series (1)	4.44473	.9999555527
	Equivalent Propagation Outage Series (1)	51.54922	.9994845078
	Receive Path		
1GC	Channel Modulator	.14330	.9999985670
	Subgroup Modulator	.14701	.9999985299
	Transmit Circuit	.22392	.9999977608
	Voltage Regulator Voltage Regulator	.00003	.9999999997
	Transformer, Power Supply, Transmitter Transformer, Power Supply, Transmitter	1.84011	.9999815989
	R.F. Tuner and Converter, 1KW Trans., Bandpass Filter R.F. Tuner and Converter, 1KW Trans. Bandpass Filter	.01242	.9999998758
1C	Bandpass Filter, Amp. Converter I.F. Amp., Lim. Disc. AFC, Power Supply, Bandpass Filter, Amp. Converter, I.F. Amp., Lim. Disc. AFC, Power Supply	17.65420	.9998234580
	Pre-Amp., Noise Amp., Shaper Detector, Pilot Tone Detector Pre-Amp., Noise Amp., Shaper Detector, Pilot Tone Detector	.00000+	.9999999999
	AFC Squelch	.02510	.9999997490
	Logic	.05050	.9999994950
	Combiner	.10160	.9999989840
	Post Amplifier	.04450	.9999995550

(1) Common to both the Transmit and Receive Path

TABLE 12 (Continued)

STATION	BLOCK	10^5d	AVAILABILITY (1-d)
IC (Continued)	Combiner Power Supply	.33430	.9999966570
	Baseband Amplifier Rec.	1.00000	.9999900000
	Receive Circuit	.52876	.9999947124
	Subgroup Demodulator	.13464	.9999986536
	Channel Demodulator	.21196	.9999978804
	23 db Pad	.00040	.9999999960
	Channel Modulator	.20855	.9999979145
	Group Modulator	.27174	.9999972826
	Baseband Amp., Exciter A Baseband Amp., Exciter A	.00118	.9999999882
IC-IR	Exciter B, 10KW Trans., Two Receivers (Parametric Amp., Combiner) Exciter B, 10KW Trans., Two Receivers (Parametric Amp., Combiner)	.21306	.9999978694
IR	Baseband O.W. Amplifier Baseband O.W. Amplifier Baseband O.W. Amplifier Baseband O.W. Amplifier	.20999	.9999979001
	Bandpass Filter	.00740	.9999999260
	Lowpass Filter	.00200	.9999999800
	Exciter A Exciter A	.00116	.9999999884
IR-ID	Exciter B, 10KW Trans., Two Receivers (Parametric Amp., Combiner) Exciter B, 10KW Trans., Two Receivers (Parametric Amp., Combiner)	.21306	.9999978694

TABLE 12 (Continued)

STATION	BLOCK	10^5d	AVAILABILITY (1-d)
ID	Baseband O.W. Amplifier	.20999	.9999979001
	Baseband O.W. Amplifier		
	Baseband O.W. Amplifier		
	Baseband O.W. Amplifier		
	16 db Pad	.00030	.9999999970
	Group Demodulator	.32895	.9999967105
	Channel Demodulator	.72463	.9999927537

Transmit or Receive Path Availability*

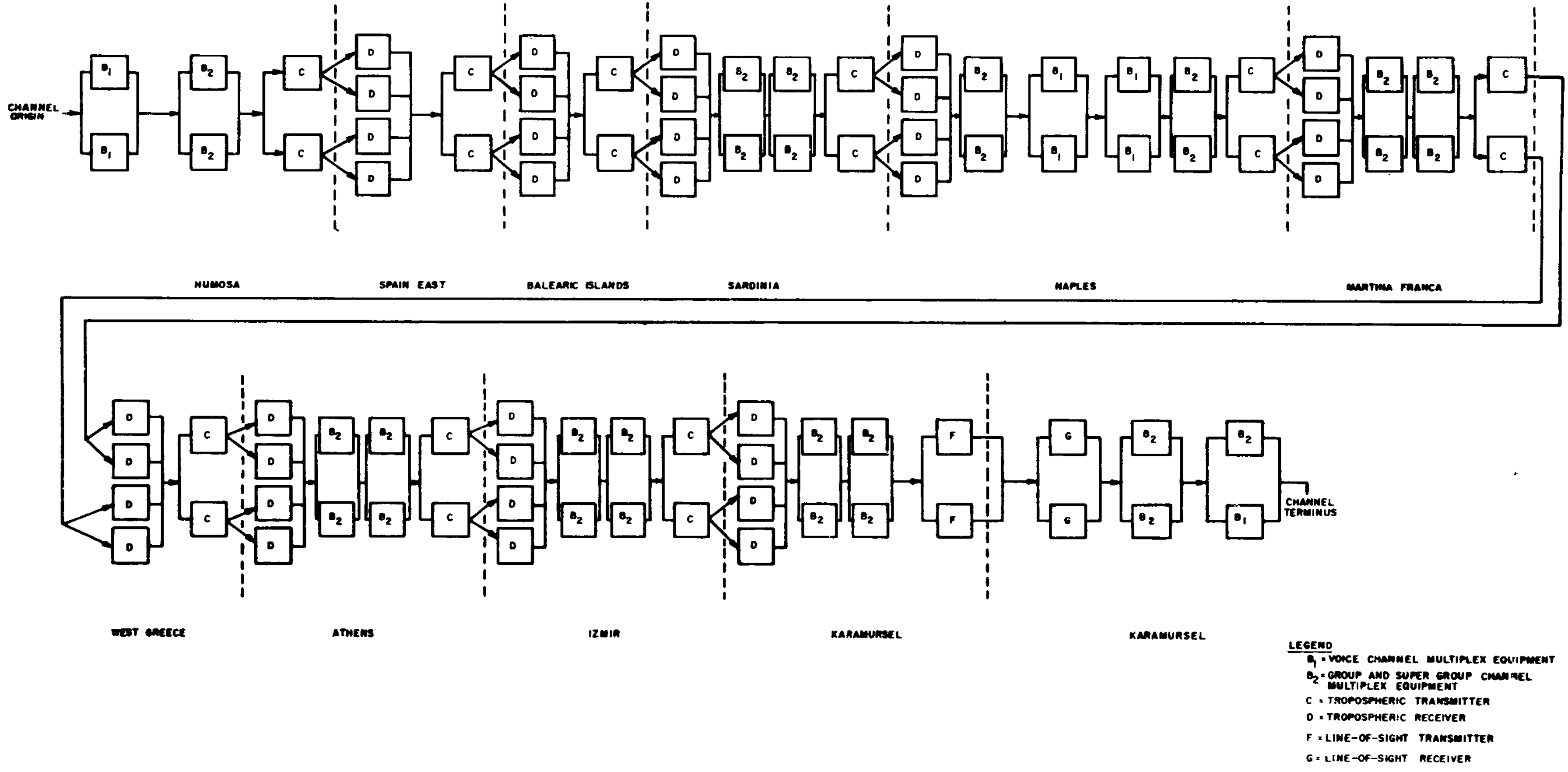
$$A_T \text{ or } A_R = \left[\prod_{i=1}^{59} (1-d_i)\right] (1-P_O)(1-P_{EO}) = .9990703258$$

Communication Path Availability

$$A_{CP} = \left[\prod_{i=1}^{100} (1-d_i)\right] (1-P_O)(1-P_{EO}) = .9988221229$$

*Includes that which is common to both the Transmit and Receive Path

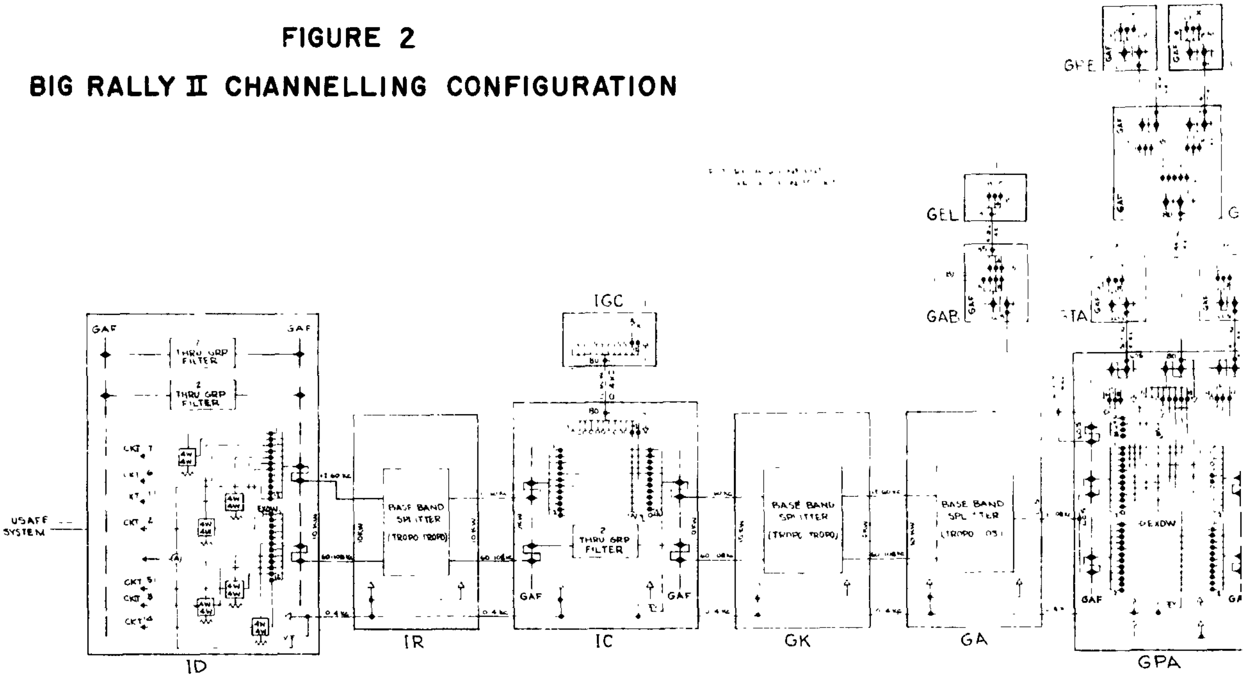
FIGURE I
HUMOSA TO KARAMURSEL
CHANNEL TRANSMISSION PATH



LEGEND
B_1 = VOICE CHANNEL MULTIPLEX EQUIPMENT
B_2 = GROUP AND SUPER GROUP CHANNEL MULTIPLEX EQUIPMENT
C = TROPOSPHERIC TRANSMITTER
D = TROPOSPHERIC RECEIVER
F = LINE-OF-SIGHT TRANSMITTER
G = LINE-OF-SIGHT RECEIVER

FIGURE 2

BIG RALLY II CHANNELLING CONFIGURATION



CHANNEL GROUP
ASSIGNMENTS

ID GPA
ID IC
IC-IGC
IC-GPA
GPA-GAB
GPA GTA
GPA-GHO
GPA GIM
GAB GEL
IR GROUP GHO GPE
GHO GAG
GPA-TID
GPA TKG
TID TIL
TIL-TKG
TKG TDY
TKG TAL
TKG-TEF
TKG TKR
TKR-TIZ
TDY TD
TDY TMA
TMA TER

NOTES

1 THIS DRAWING IS IN ACCORDANCE WITH BR II ROUTING MAP (ISSUE 1) FOR ITALY AND GREECE AND PER PROPOSED TMP(WEST) FOR TURKEY

2 CIRCLED NUMBERS REPRESENT CIRCUITS INTERCONNECTING BR II VOICE FREQUENCY CHANNELS WITH INCOMING USAFE SYSTEM

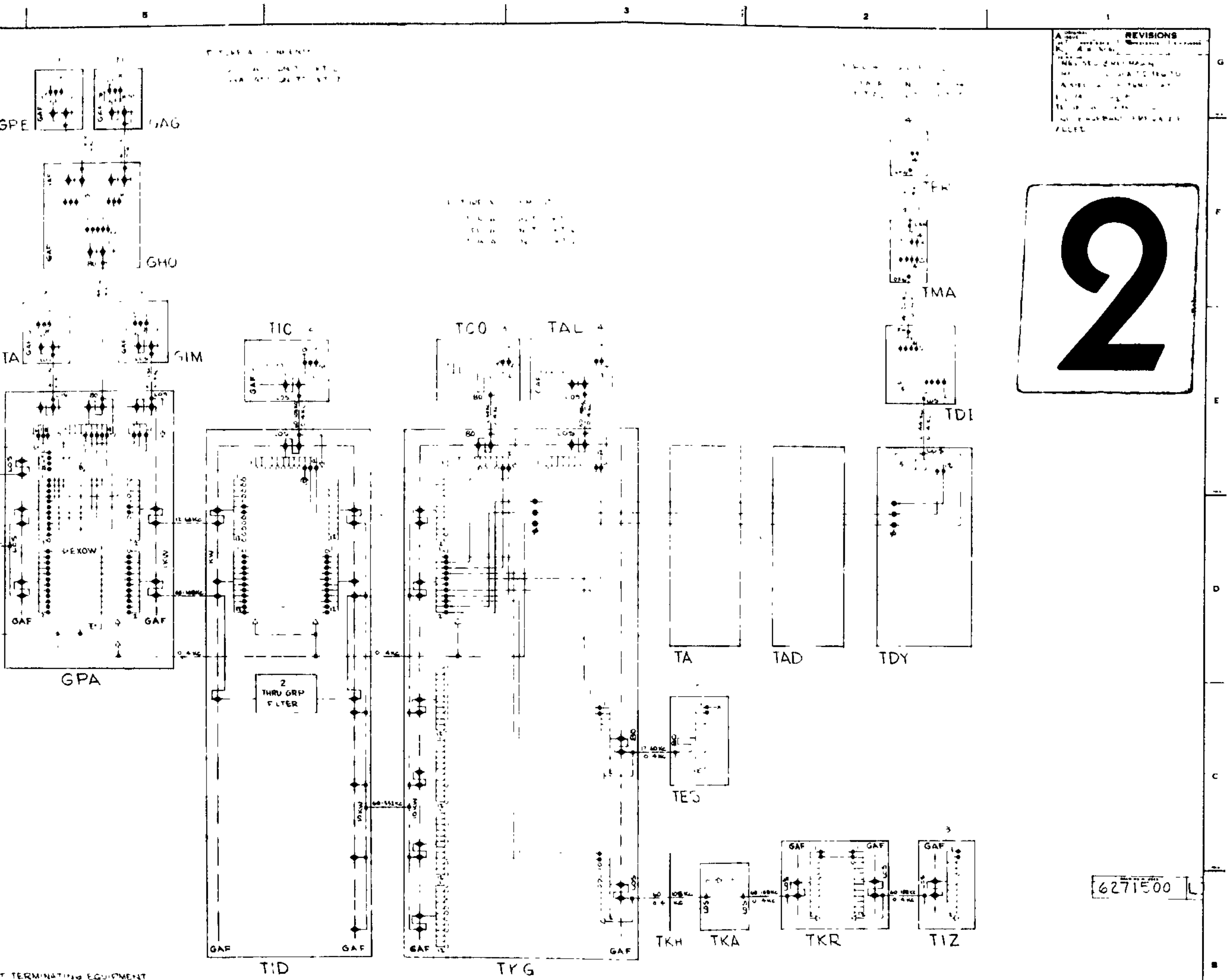
3 CIRCLED LETTERS REPRESENT TECHNICAL CONTROL CIRCUITS FOR CIRCUIT LAYOUT SEE DWG #6271835 Ⓐ
DWG #6271837 Ⓑ
DWG #6271838 Ⓒ
DWG #6271836 Ⓓ

4 THE INDICATED FREQUENCIES REPRESENT MULTIPLEX AND ORDER WIRE BASEBAND FREQUENCY SPECTRUM

5 RADIO EQUIPMENT IDENTIFICATION
10KW = AN/MRC 85 (10KW) LINK TO TKG WILL USE AN/FRC 39A(V) (10KW)
1KW = AN/MRC-85(1KW)
80 = AN/MRC 80
35 = AN/TRC 35
LOS = 8 KMC LINE OF SIGHT RADIO EQUIPMENT

LEGEND

⊥⊥⊥⊥⊥⊥	CHANNEL GROUP
⫯	ONE CHANNEL MODEM
●	ONE CHANNEL WITH CIRCUIT TERMINATING EQUIPMENT
x	CIRCUIT TERMINATION
↑	ORDER WIRE TERMINATION
◆	GROUP TERMINATION
GAF	GROUP ACCESS FRAME
Φ	CONNECTING SYSTEM (IT IS ASSUMED THAT THE USAF CAN MAKE THREE CHANNELS AVAILABLE BETWEEN TKG - TDY FOR BR II CIRCUIT REQUIREMENTS)
⊥	PATCHING CAPABILITY



T TERMINATING EQUIPMENT

N

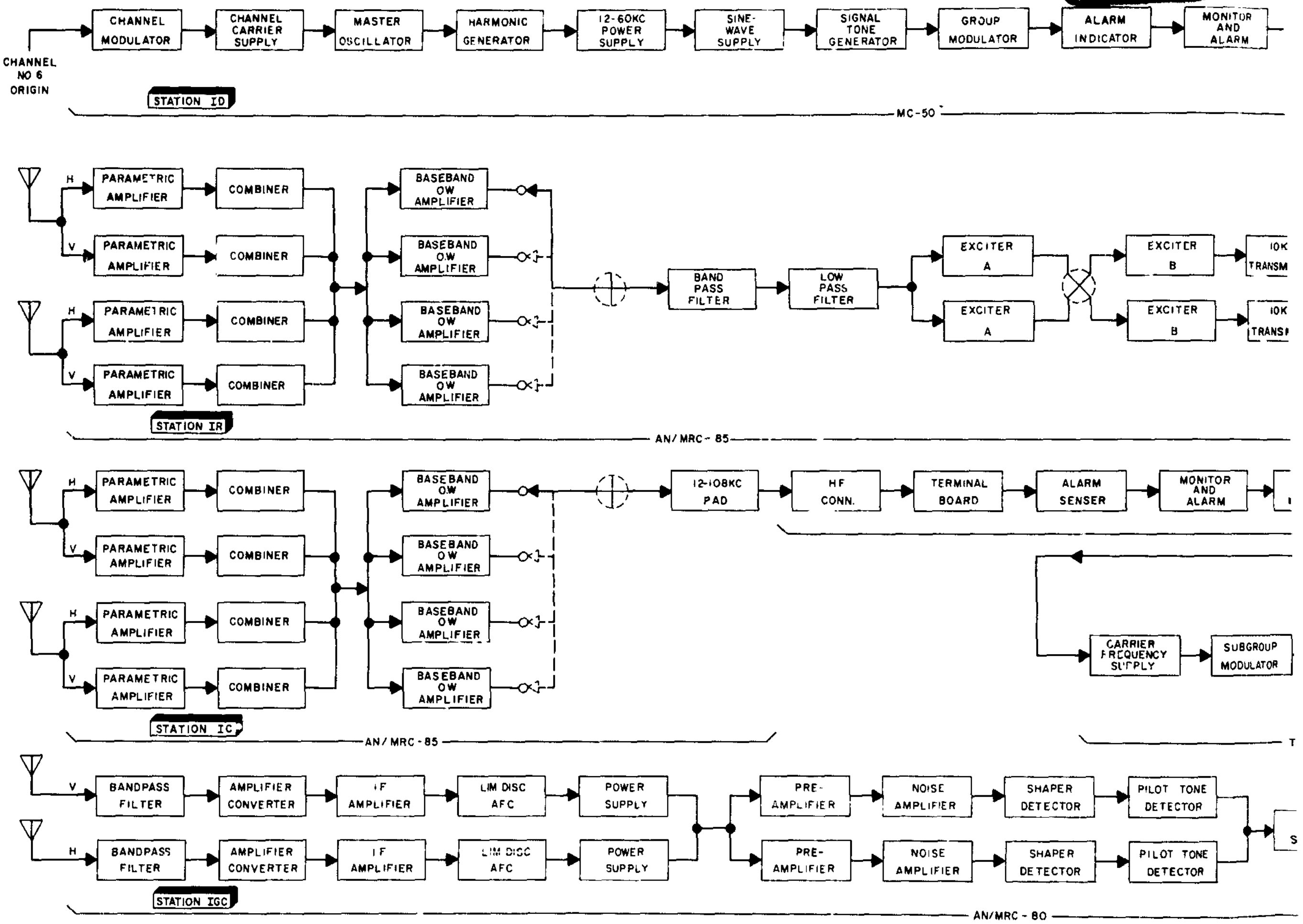
ASSUMED THAT THE USAF
S AVAILABLE BETWEEN
DIT REQUIREMENTS)

SERVICE
Federal Electric Corporation
Paramus New Jersey U.S.A.

BIG RALLY II
CHANNELLING
CONFIGURATION

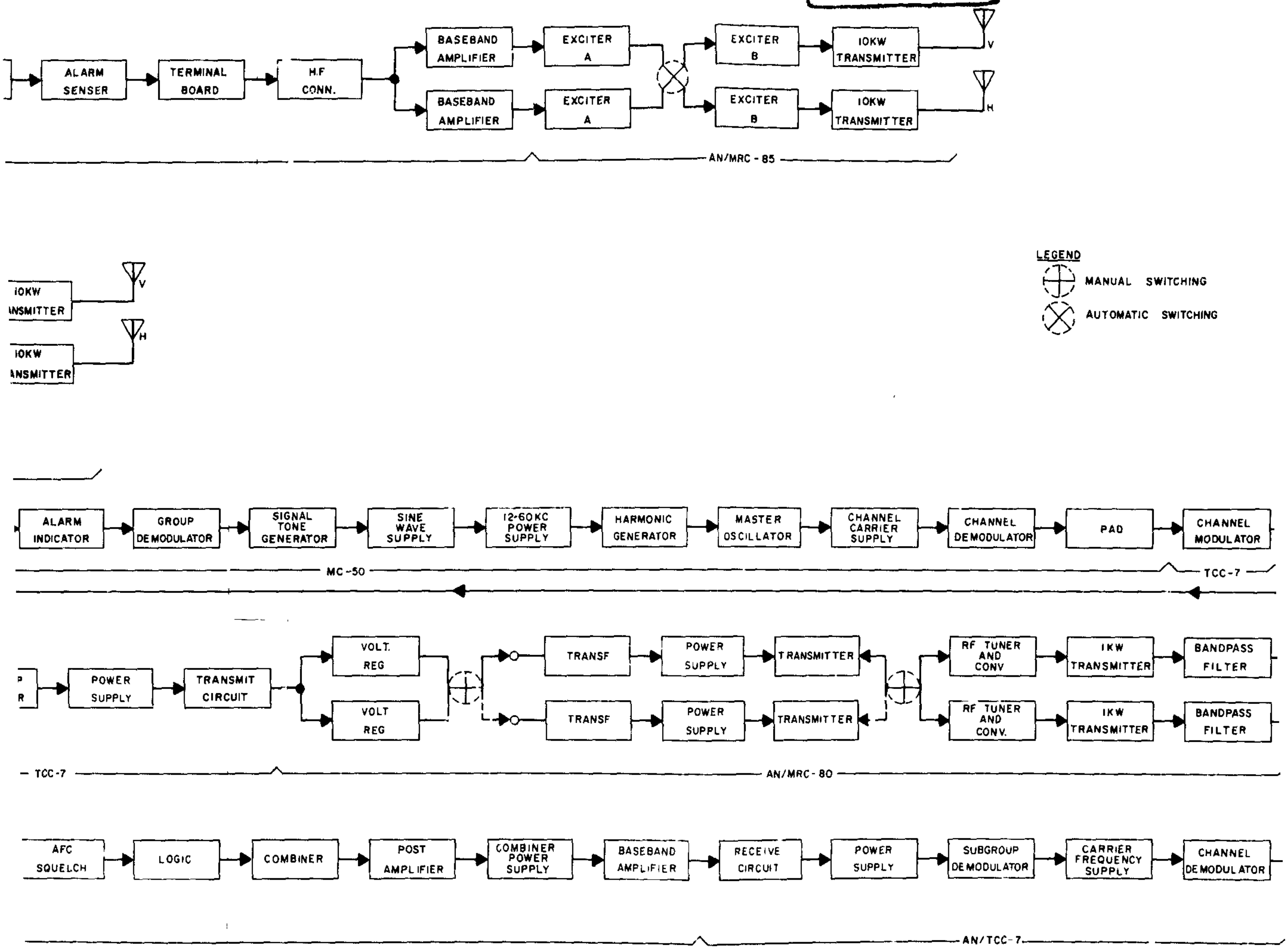
H 6271500 L

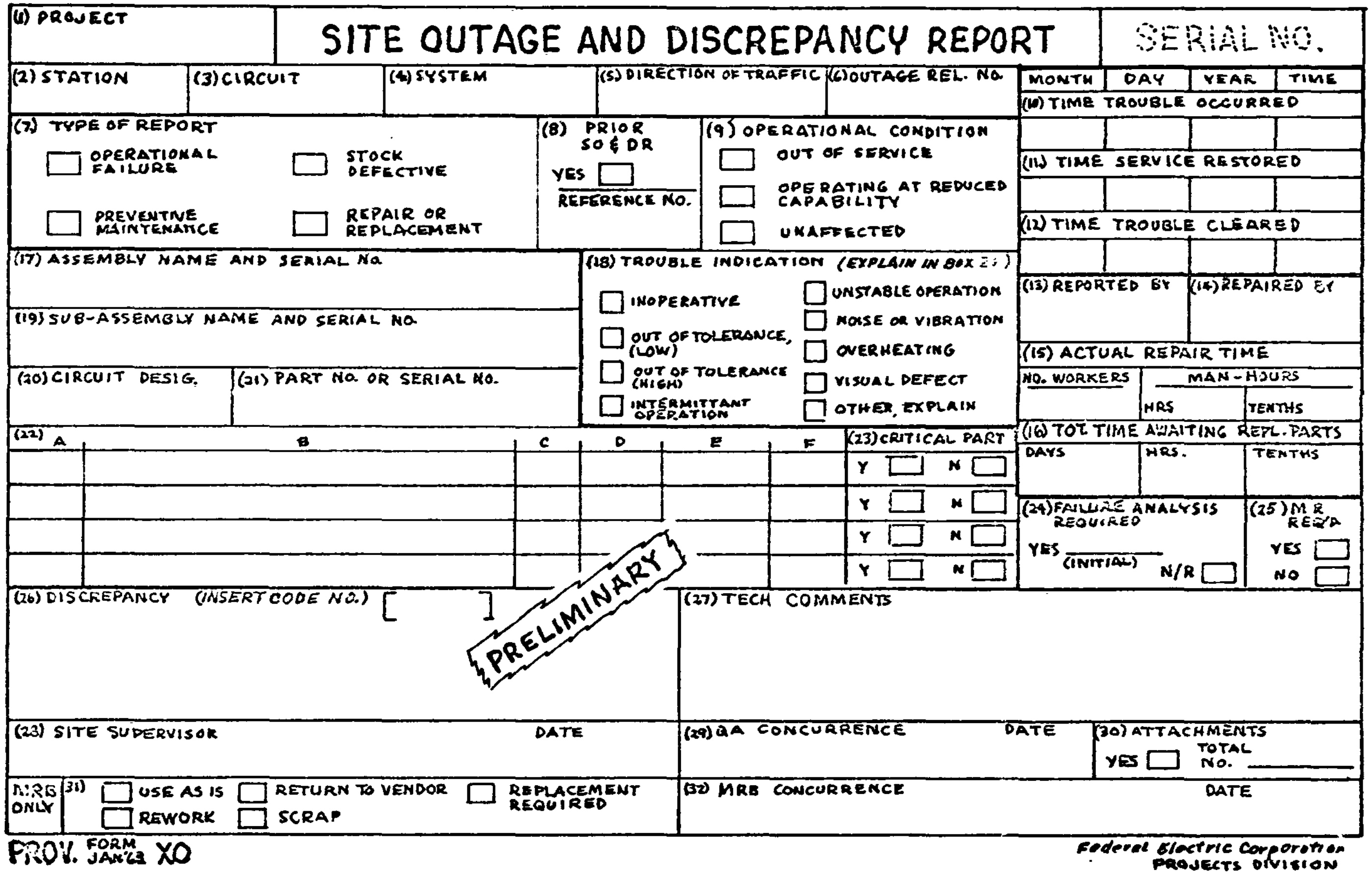
EQUIP


CHANNEL NO 6 ORIGIN
CHANNEL MODULATOR
CHANNEL CARRIER SUPPLY
MASTER OSCILLATOR
HARMONIC GENERATOR
12-60KC POWER SUPPLY
SINE-WAVE SUPPLY
SIGNAL TONE GENERATOR
GROUP MODULATOR
ALARM INDICATOR
MONITOR AND ALARM
STATION ID
MC-50
H
V
PARAMETRIC AMPLIFIER
COMBINER
BASEBAND OW AMPLIFIER
BAND PASS FILTER
LOW PASS FILTER
EXCITER A
EXCITER B
10K TRANSM
10K TRANS
STATION IR
AN/MRC-85
12-108KC PAD
HF CONN.
TERMINAL BOARD
ALARM SENSER
MONITOR AND ALARM
CARRIER FREQUENCY SUPPLY
SUBGROUP MODULATOR
STATION IC
AN/MRC-85
T
BANDPASS FILTER
AMPLIFIER CONVERTER
IF AMPLIFIER
LIM DISC AFC
POWER SUPPLY
PRE-AMPLIFIER
NOISE AMPLIFIER
SHAPER DETECTOR
PILOT TONE DETECTOR
S
STATION IGC
AN/MRC-80

2

FIGURE 3
CHANNEL NO.6
UIPMENT BLOCK SCHEMATIC
OF THE
TRANSMIT PATH





(1) PROJECT

SITE OUTAGE AND DISCREPANCY REPORT

SERIAL NO.

(2) STATION
(3) CIRCUIT
(4) SYSTEM
(5) DIRECTION OF TRAFFIC
(6) OUTAGE REL. NO.

MONTH	DAY	YEAR	TIME
(10) TIME TROUBLE OCCURRED			
(11) TIME SERVICE RESTORED			
(12) TIME TROUBLE CLEARED			

(7) TYPE OF REPORT
☐ OPERATIONAL FAILURE
☐ STOCK DEFECTIVE
☐ PREVENTIVE MAINTENANCE
☐ REPAIR OR REPLACEMENT

(8) PRIOR SO & DR
YES ☐
REFERENCE NO.

(9) OPERATIONAL CONDITION
☐ OUT OF SERVICE
☐ OPERATING AT REDUCED CAPABILITY
☐ UNAFFECTED

(17) ASSEMBLY NAME AND SERIAL NO.

(19) SUB-ASSEMBLY NAME AND SERIAL NO.

(20) CIRCUIT DESIG.
(21) PART NO. OR SERIAL NO.

(18) TROUBLE INDICATION (EXPLAIN IN BOX 27)
☐ INOPERATIVE
☐ OUT OF TOLERANCE, (LOW)
☐ OUT OF TOLERANCE (HIGH)
☐ INTERMITTANT OPERATION
☐ UNSTABLE OPERATION
☐ NOISE OR VIBRATION
☐ OVERHEATING
☐ VISUAL DEFECT
☐ OTHER, EXPLAIN

(13) REPORTED BY
(14) REPAIRED BY

(15) ACTUAL REPAIR TIME

NO. WORKERS	MAN-HOURS	
	HRS	TENTHS

(16) TOT. TIME AWAITING REPL. PARTS

DAYS	HRS.	TENTHS

(22) A	B	C	D	E	F	(23) CRITICAL PART
						Y ☐ N ☐
						Y ☐ N ☐
						Y ☐ N ☐
						Y ☐ N ☐

(24) FAILURE ANALYSIS REQUIRED
YES ______ (INITIAL)
N/R ☐

(25) M R REQ'D
YES ☐
NO ☐

(26) DISCREPANCY (INSERT CODE NO.) [ ]

PRELIMINARY

(27) TECH COMMENTS

(23) SITE SUPERVISOR DATE

(29) QA CONCURRENCE DATE

(30) ATTACHMENTS
YES ☐ TOTAL NO. ______

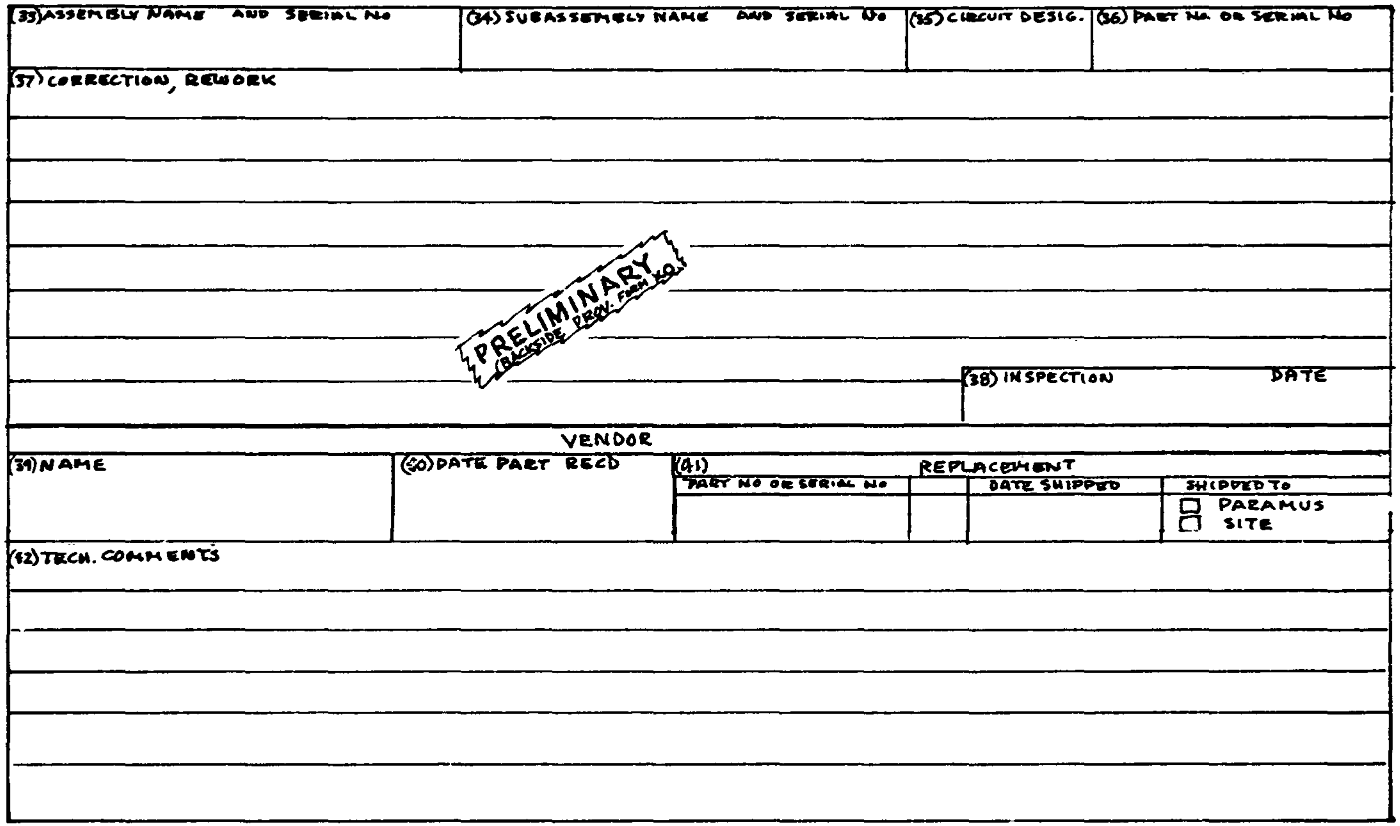
MRB ONLY (31)
☐ USE AS IS
☐ REWORK
☐ RETURN TO VENDOR
☐ SCRAP
☐ REPLACEMENT REQUIRED

(32) MRB CONCURRENCE DATE

PROV. FORM JAN'63 XO

Federal Electric Corporation
PROJECTS DIVISION

Figure 4 Preliminary Site Outage and Discrepancy Report (Front)



(33) ASSEMBLY NAME AND SERIAL No

(34) SUBASSEMBLY NAME AND SERIAL No

(35) CIRCUIT DESIG.

(36) PART No OR SERIAL No

(37) CORRECTION, REWORK

PRELIMINARY (BACKSIDE PROV. FORM XO.)

(38) INSPECTION DATE

VENDOR

(39) NAME

(40) DATE PART RECD

(41) REPLACEMENT

PART NO OR SERIAL NO

DATE SHIPPED

SHIPPED TO

☐ PARAMUS

☐ SITE

(42) TECH. COMMENTS

Figure 4 (Continued) Preliminary Site Outage and Discrepancy Report (Back)

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1) An Introduction to Probability Theory and Its Applications by William Feller, Volume I, Second Edition, Pg. 270-272.

2) Reliability of Some Two Unit Redundant Systems, by Epstein and Hosford in Sixth National Symposium on Reliability and Quality Control.

3) Reliability of Parallel Systems with Repair and Switching, by S. G. Kneale in Seventh National Symposium on Reliability and Quality Control.

4) The Assignment of Workers in Servicing Automatic Machines, by Docent Conny Palm in the Journal of Industrial Engineering, Jan-Feb. 1958, Volume 9, No. I.

5) RADC Reliability Notebook, TR-58-111, 31 December 1961, Section 9.

RELIABILITY AND AVAILABILITY OF SOME REDUNDANT SYSTEMS

by

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Presented at
Maintainability Conference
12-13 March 1963

Electronic Systems Division
Laurence G. Hanscom Field
Bedford, Massachusetts

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Great Neck, New York

SUMMARY

The use of redundancy with provision for rapid repair and replacement of components can greatly increase the reliability and availability of a system. The systems considered in this paper make use of standby redundancy (instantaneous replacement) with and without capabilities for the individual components. The basic system considered has two components in series and another in standby which is capable of replacing either of the series components should one of them fail. The reliability and availability of this system, with and without repair, are derived. From these mathematical models the expressions for the reliability and availability of a system of n components in series with k redundant or spare components are derived. The improvements due to repair and redundancy are discussed. Some properties of the exponential distribution are derived and discussed in order to facilitate the derivation of the redundancy formulas.

INTRODUCTION

System reliability will be defined as the probability that the system performs its specified function for a specified period of time. Availability will be the probability of the system functioning at a particular time regardless of the previous history of the system. A redundant system is one which employs more than the minimum required number of components to perform its function. Thus, a system with standby or spare components is considered to be redundant. The redundant units are not turned on until they are needed due to a failure. The time to replace or switch components will be considered negligible or instantaneous and the probability of a switching or sensing failure will be taken to be zero.

The systems will be composed of units having a constant failure rate and thus having an exponential failure density function. The mathematical models for repairable systems are based upon a constant rate of repair. Thus, the probability of repair during a particular time interval will also follow an exponential distribution. Repairs on failed components begin immediately after they fail and upon completion of repair the units are immediately returned to operation, if needed, or to the standby state. A system will be considered off or in a failed state when it is not performing its function and during this period all non-failed components will be turned off. It is also assumed that component failures only occur while operating and not while in standby. Thus, no component will be in operation unless it is operable (not failed) and is necessary for system operation. At the beginning of operation all units are either operating or operable.

1. PROPERTIES OF THE EXPONENTIAL DISTRIBUTION - The exponential or Poisson process which describes the random failure laws for electronic equipment has many interesting properties. One that is important for the discussion to follow is the so-called property of "lack of memory." Basically, this property implies that the reliability of a system obeying this process is not dependent on the length of time the system or any of its components has been operating but only on the state of the system at the time of interest. Thus, given that a system of n series units is operating at time t and regardless of the length of time each unit has been operating, the probability that the system survives the period of time from t to t + Δt, for any Δt, is the same as the probability of an identical new system being turned on and operating without failure for time Δt. Also, it can be stated that if the system is operating at time t its expected time to failure measured from that point is the same as the expected time to failure of a new system at the onset of operation. A brief proof of these statements will now be given.

Consider n units where the operation of each is necessary for the system to function. Let each unit have a constant failure rate λ_i, $i = 1, \ldots, n$. Thus, each unit has a failure density function given by

$$f_i(t) = \lambda_i \exp(-\lambda_i t) \tag{1}$$

and a probability of survival (reliability)

$$R_i(t) = \exp(-\lambda_i t) \tag{2}$$

where the units are new when put into operation at t = 0. The reliability of this system is

$$R(t) = \exp(-\sum_{i=1}^{n} \lambda_i t) \tag{3}$$

and its failure rate is

$$\sum_{i=1}^{n} \lambda_i,$$

and thus its expected time to failured (measured from t = 0) or MTBF is

$$M = 1/\sum_{i=1}^{n} \lambda_i. \tag{4}$$

Now assume that a system has been running and we have been replacing failures with new units. Then if the system is operating at time t, a situation might occur where the ith unit was put into the system new at time t_i where $0 \le t_i \le t$ for all $i = 1, \ldots, n$. At time t the ith unit will have operated for a period of $t - t_i$ hours. The probability that a unit which is new at t_i will last to time t is $\exp[-\lambda_i(t - t_i)]$, and the probability that all units (where the ith is new at t_i) will operate till t is

$$R(t) = \exp[-\lambda_1(t-t_1)] \cdot \exp[-\lambda_2(t-t_2)] \ldots \exp[-\lambda_n(t-t_n)] \tag{5}$$

$$R(t) = \exp\left[-\sum_{i=1}^{n} \lambda_i (t - t_i)\right].$$

The instantaneous failure rate at time t, given that the system is operating then, and with the above conditions holding is,

$$h(t) = -\frac{dR(t)}{dt} / R(t) = \sum_{i=1}^{n} \lambda_i \tag{6}$$

which is the same failure rate as when the system was new. Now, the probability of the system failing during the interval t to T, $(T \ge t)$, given that the system is operating at time t, is

$$G(T) = \int_t^T -\frac{dR(t)}{dt}\, dt / R(t) = 1 - \exp\left[-\sum_{i=1}^{n} \lambda_i (T - t)\right]. \tag{7}$$

It is important to note that the t_i, or the times of the original unit failures and replacements no longer appear, (the system is independent of its past failures). Now, letting $\Delta t = T - t$ our new "starting" time is $T = t$ or $\Delta t = 0$ and the probability that the system does not fail during time Δt is given by

$$R(\Delta t) = \exp\left[\left(-\sum_{i=1}^{n} \lambda_i\right) \Delta t\right]. \tag{8}$$

This quantity depends only on the time interval Δt measured from the point of interest t, (when the system was operating) and is independent of any past failures or history. Thus, the reliability of the system and of a "new" system are the same. It can also be seen that the expected time till the system fails, measured from time t, and given that the system was operating then is

$$M = 1 / \sum_{i=1}^{n} \lambda_i$$

This is the same as the expected time to failure of the system with new components.

It has previously been shown (Ref. A) that the reliability of a system requiring one unit to operate and having k units in standby is given by the Poisson distribution and is

$$R(t) = \exp(-\lambda t) \sum_{j=0}^{k} (\lambda t)^j / j! ,\tag{9}$$

where λ is the failure rate of each unit and only one unit operates at any time. The mean-time-to-failure of such a system is $k/\lambda = km$ where m is the MTBF of a single unit.

2. RELIABILITY - NON-REPAIRABLE SYSTEM

2.1 The Basic System - Consider three identical units with constant failure rate λ, where two are needed for system operation and the other is in standby (spare). The spare will replace either of the first two units should one of them fail.

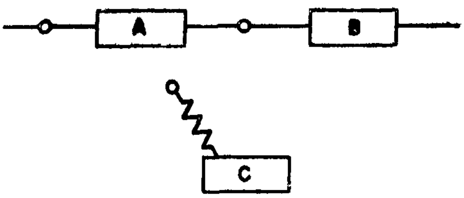

Fig. 1 Basic System

The system begins operation with units A and B operating and unit C in standby. The system will fail when two units have failed. The system will operate successfully till time t if; (1) both units A and B survive till time t, or (2) one of the units, A and B (say B), fails at time $t_1 < t$ but the remaining unit A survives till t and unit C operates for a period t_2 where $t_1 + t_2 = t$. These two events, both insuring success, can be described as operation of units A and B until time t_1 when one unit fails, where $0 \leq t_1 \leq t$, and successful operation of the non-failed unit and the spare for a period of time t_2, where $0 \leq t_2 \leq t$ and $t_1 + t_2 = t$. The possibility of both A and B failing at exactly the same time is omitted since this event has probability zero.

The reliability of the system from time 0 to time t_1 is given by

$$R_1(t_1) = \exp(-2\lambda t_1) \text{ where } 0 \leq t_1 \leq t. \tag{10}$$

The reliability function describing the system when a unit has failed at time t_1 and is replaced is

$$R_2(t_2) = \exp(-2\lambda t_2) \text{ where } 0 \leq t_2 \leq t, \quad t_1 + t_2 = t. \tag{11}$$

$R_1(t_1)$ is just the reliability of 2 units in series. $R_2(t_2)$ follows from the fact that at time t_1 when one unit fails, the non-failed unit has a probability of survival for time t_2 of exp ($-\lambda t_2$) which is the same as that of the spare unit. The corresponding failure density functions are

$$f_1(t_1) = 2\lambda \exp(-2\lambda t_1),\ 0 \leq t_1 \leq t \tag{12}$$

and

$$f_2(t_2) = 2\lambda \exp(-2\lambda t_2),\ 0 \leq t_1 \leq t_2,\ t_1 + t_2 = t. \tag{13}$$

The joint density function for failure during time t will be

$$\varphi(t) = \varphi(t_1, t_2) = f_1(t_1)\, f_2(t_2) \tag{14}$$

since the probabilities of failure in either time interval (t_1 or t_2) are independent. Thus

$$\varphi(t_1, t_2) = 4\lambda^2 \exp(-2\lambda t_1 - 2\lambda t_2),$$

$$0 \leq t_1 \leq t,\ 0 \leq t_2 \leq t,\quad t_1 + t_2 = t. \tag{15}$$

The probability of system failure during time t is given by:

$$Q(t) = \int_{t_2=0}^{t} \int_{t_1=0}^{t-t_2} \varphi(t_1, t_2)\, dt_1\, dt_2 \tag{16}$$

or

$$Q(t) = 1 - \exp(-2\lambda t) - 2\lambda t \exp(-2\lambda t). \tag{17}$$

The probability of system survival to time t is

$$R(t) = 1 - Q(t) = \exp(-2\lambda t) + 2\lambda t \exp(-2\lambda t). \tag{18}$$

This result may be arrived at in a purely logical manner by first considering a system having one unit operating and one in standby. The reliability of that system is given by (9) where K = 1. Expression (18) may be obtained from (9) by replacing λ by 2λ. This follows since whenever this system is operating it has failure rate 2λ, while the other system has failure rate λ when it is operating and the standby procedure is the same.

The mean-time-to-system failure (MTTF) of a system is given by (Ref. B),

$$M = \int_0^\infty -t\frac{dR(t)}{dt}\, dt = \int_0^\infty R(t)\, dt. \tag{19}$$

For the "basic" system it becomes

$$M = 1/\lambda = m, \tag{20}$$

where m is the MTBF of a single unit. The MTTF of two units in series without a spare is m/2, and by using only one spare the expected life of the system is doubled. Thus, a 50% increase in equipment complexity gives a 100% increase in MTTF.

A commonly used redundant system is shown on the left in Figure 2. This system has 2 units operating till one of them fails and then the system operates with 2 identical units which are in standby. The system on the right is an equivalent system with regards to reliability which is given by (9) where the failure rate is 2λ and $n = 1$.

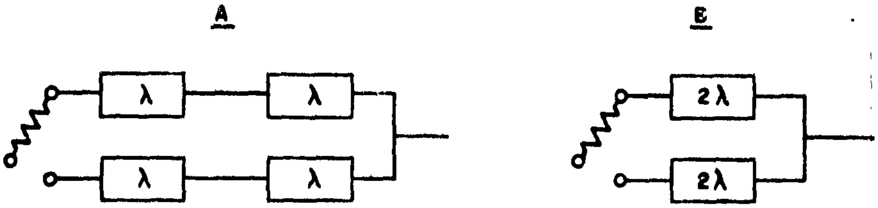

Fig. 2 Equivalent Reliability

Thus,

$$R(t) = \exp(-2\lambda\ t) + 2\lambda\ t \exp(-2\lambda\ t)$$

However, this system only has the same reliability as the "basic" system which performs the same function and uses only 3 units instead of 4. This is so since both the system above and the basic system have a failure rate of 2λ when operating. Thus, by using what may be a slightly more complicated switching system, the resulting reliability is the same with only 75% of the complexity.

The reliability of the 3-unit system where $\lambda_a \neq \lambda_b \neq \lambda_c$ can be obtained in a similar manner using joint density functions. In this case, the system reliability is

$$R(t) = P_a(t)\ [P_b(t_1) \times P_c(t-t_1)] + P_b(t)\ [P_a(t_2) \times P_c(t-t_2)] \tag{21}$$
$$\cdot\ P_a(t)\ P_b(t),$$

where $0 \leq t_1 \leq t$, $0 \leq t_2 \leq t$, and where $P_b(t_1) \times P_c(t-t_1)$ is the probability that unit B survives for time t_1 and unit C (the spare) lasts from t_1 to t. This probability is given by:

$$P_b(t_1) \times P_c(t-t_1) = 1 - \int_{t_1'=0}^{t} \int_{t_1=0}^{t-t_1'} \lambda_b \exp(-\lambda_b t_1)\, \lambda_c \exp(-\lambda_c t_1')\, dt_1 dt_1'$$

$$= 1/(\lambda_c - \lambda_b)\ [\lambda_c \exp(-\lambda_b t) - \lambda_b \exp(-\lambda_c t)] \qquad (22)$$

where $P_b(t) = \exp(-\lambda_b t)$ etc. The third term in (21) accounts for the possibility that both units A and B last till time t. After evaluating $P_a(t_2) \times P_c(t-t_2)$ the system reliability becomes

$$\begin{aligned} R(t) = {} & [\lambda_c/(\lambda_c - \lambda_b) + \lambda_c/(\lambda_c - \lambda_a)] \exp[-(\lambda_a + \lambda_b)t] \\ & + [\lambda_b/(\lambda_b - \lambda_c)] \exp[-(\lambda_a + \lambda_c)t] \\ & + [\lambda_a/(\lambda_a - \lambda_c)] \exp[-(\lambda_b + \lambda_c)t] - \exp[-(\lambda_a + \lambda_b)t] . \qquad (23) \end{aligned}$$

It can be shown that it does not matter which unit is used as the spare.

2.2 n Units in Series With One Spare

The results and techniques of the previous section can be generalized to the case of n identical units functioning in series with another unit as a spare. Again, the lack of memory property, which states that at time t, when the first failure occurs the remaining n-1 operating units behave as though they are all new, is the main point in the development. In this case whenever the system is operating it has failure rate $n\lambda$. The failure density functions are:

$$f_1(t_1) = n\lambda \exp(-n\lambda t_1),\quad f_2(t_2) = n\lambda \exp(-n\lambda t_2)$$

where

$$0 \leq t_1 \leq t,\ 0 \leq t_2 \leq t,\ \text{and } t_1 + t_2 = t.$$

Proceeding as before the reliability of this n + 1 unit system is given by

$$R(t) = \exp(-n\lambda t)\ [1 + n\lambda t] . \qquad (24)$$

The system MTTF will be

$$M = 2/n\lambda = 2m/n, \qquad (25)$$

where m is the MTBF of a single unit and n is the number of units in series. Without a spare the expected time to failure would be m/n and by using only one spare for n units the expected life of the system can be doubled.

2.3 n Units in Series with K Spares

The reliability of a system with n = 1 and k spares in standby is given by (9) and the reliability for n units in series and 1 spare is given by

(24). The general result can be obtained by considering these equations. The system is shown in Figure 3.

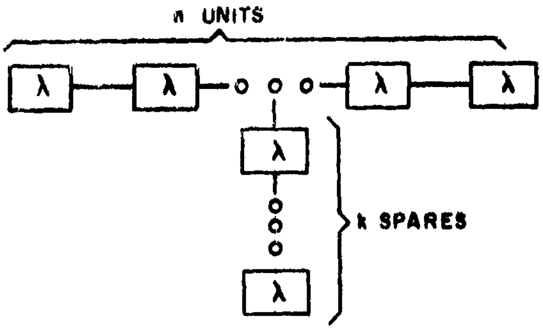

Fig. 3 n Units in Series with k Spares

In this system, whenever a failure occurs, the failed unit is replaced by a spare. Thus, it is necessary that k+1 units fail before the system will fail. At the time of any failure the surviving units are as good as new. At any time the system is operating it has a failure rate of $n\lambda$ and its probability of survival for a period T from that time is $\exp(-n\lambda T)$. The reliability for this system can be found by obtaining the joint density function of the k variables $t_1, t_2, \ldots, t_k$ such that $t_1 + t_2 + \ldots + t_k = t$. The t_i are the failure times for the k failures which can occur without causing the system to fail. Once the joint density function is obtained R(t) can be derived by k integrations of the type done in section 2.1. However, the result is obtained directly, in view of the previous discussions, by replacing λ by $n\lambda$ in (9). The reliability of this n + k unit system is given by:

$$R(t) = \sum_{j=o}^{k} (n\lambda t)^j/_{j!} \; [\exp(-n\lambda t)] . \qquad (26)$$

The expected time to system failure will be

$$M = k/n\lambda = km/n. \qquad (27)$$

which is k times the MTTF of n units in series without any standby units. Thus, the addition of each spare increases the MTTF by m/n.

3. Reliability of Some Repairable Systems

In some redundant systems it is possible to repair a failed unit while the redundant or spare unit is operating. If repairs are completed before the redundant unit fails the system is restored to its initial state and will be as good as a new system. The system may be kept operating for a comparatively long time if the repair rates are high enough. The systems considered will have components having constant failure rate λ and constant repair rate u.

3.1 The Basic System

The system in Figure 1 with the addition of repair capability is considered first. Units A and B operate until one of them fails at which time it is replaced by the spare and repairs are begun on the failed unit. This process continues until two units are simultaneously failed and thus the system has failed. The spare unit only operates when it is necessary for system operation. We are interested in the probability of system survival (no system failure) till time t.

At any particular time the system can be in one of only 3 possible "states." These states shall be defined as follows:

State 2 - two units are operating and a good unit is in standby,

State 1 - two units are operating and the third has failed and is being repaired,

State 0 - two units, and thus the system, have failed.

After the system has been operating for a while the 3 units will lose their identity and the system will have undergone a number of transitions between the various states. One the system enters state 0 it remains in that state. Difference equations will be used to obtain the mathematical model describing these transitions.

Let $P_i(t)$, $i = 0, 1, 2$, be the probability that the system is in state i at time t. When the system is operating, it has a failure rate of 2λ and the probability of one of the two units failing in a small interval Δt is $2\lambda\ \Delta t$. The probability of a unit coming out of repair is $u\Delta t$. The second order terms in Δt (i.e., terms of the form $h(\Delta t)$ such that $h/\Delta t \rightarrow 0$ as $\Delta t \rightarrow 0$) are neglected and thus the possibility of a unit both failing and being repaired in Δt is neglected.

To be in state 2 at time $t + \Delta t$ the system could have been in state 2 at time t and did not experience any failures during Δt, or it could have been in state 1 at time t and the failed unit came out of repair during Δt while neither of the operating units failed. To be in state 1 at $t + \Delta t$ the system could have been in state 2 at t and had one unit fail during Δt or it could have been in state 1 at time t and experienced neither a failure or repair during Δt. Neither state 2 nor state 1 can be reached from state 0 once that state is reached the system has failed. To be in state 0 at $t + \Delta t$ the system could have been in state 2 at time t and suffered two failures, the probability of which is a 2nd order term in Δt and will be neglected, or it could have been in state 1 at time t and suffered a failure during Δt while no repairs were completed, or it could have been in state 0 at t with nothing more happening.

The system will be operating if it is in state 2 or state 1 and the system reliability is given by:

$$R(t) = P_2(t) + P_1(t) = 1 - P_0(t)$$

$$\text{where } P_0(t) + P_1(t) + P_2(t) = 1. \qquad (28)$$

If all components are initially in good condition the initial conditions are

$$P_0(0) = P_1(0) = 0 \quad P_2(0) = 1.$$

The difference equations describing the transitions are:

$$P_2(t+\Delta t) = P_2(t)\ (1-2\lambda\Delta t) + P_1(t)\ u\ \Delta t(1-2\ \lambda\Delta t) \qquad (29a)$$

$$P_1(t+\Delta t) = P_2(t)\ (2\lambda\Delta t) + P_1(t)\ (1-u\ \Delta t)\ (1-2\ \lambda\Delta t) \qquad (29b)$$

$$P_0(t+\Delta t) = P_1(t)\ (1-u\Delta t)\ (2\lambda\Delta t) + P_0(t). \qquad (29c)$$

Now subtract $P_2(t)$ from both sides of (a), divide both sides by Δt, and take the limit as $\Delta t \to 0$ (and perform similar operations on (b) and (c)) and the following differential equations result:

$$\frac{dP_2(t)}{dt} = -2\lambda\ P_2(t) + uP_1(t) \qquad (30a)$$

$$\frac{dP_1(t)}{dt} = 2\lambda\ P_2(t) - (2\lambda + u)\ P_1(t) \qquad (30b)$$

$$\frac{dP_0(t)}{dt} = 2\lambda\ P_1(t). \qquad (30c)$$

It should be noted that the omission of second order terms in Δt was not really necessary as they would have disappeared as a result of the limiting process.

The differential equations can be solved by the use of Laplace transforms. Let the Laplace transform of $P_i(t) = p_i(s)$ and that of $R(t) = r(s)$. The transform of $dP_i(t)/dt$ is given by; $sp_i(s) - P_i(0)$. Thus

$$r(s) = p_1(s) + p_2(s) \qquad (31)$$

$$-up_1(s) + (s + 2\lambda)\ p_2(s) = 1 \qquad (32a)$$

$$(s + 2\lambda + u)\ p_1(s) - 2\lambda\ p_2(s) = 0. \qquad (32b)$$

Solving for p_1 (s) and p_2 (s) gives:

$$p_1(s) = \frac{2\lambda}{s^2 + (4\lambda + u)\, s + 4\lambda^2}, \quad p_2(s) = \frac{s + 2\lambda + u}{s^2 + (4\lambda + u)\, s + 4\lambda^2} \tag{33}$$

and thus,

$$r(s) = \frac{s + 4\lambda + u}{s^2 + (4\lambda + u)\, s + 4\lambda^2} . \tag{34}$$

R(t) can be found after some algebraic manipulations and with a table of inverse Laplace transforms to be

$$R(t) = 1/(a-b)\ [a \exp(-bt) - b \exp(-at)] , \tag{35}$$

where $a = \frac{(4\lambda + u) + (8u\lambda + u^2)^{\frac{1}{2}}}{2}$ and $b = \frac{(4\lambda + u) - (8u\lambda + u^2)^{\frac{1}{2}}}{2}$

This result could have been obtained upon consideration of the reliability of a 2 unit system where one unit operates and one is in standby (ref. c). By replacing λ by 2λ in the reliability function for the 2 unit system the formula for reliability of the 3 unit system, which has two units operating and one in standby, can be obtained. This would be a logical conclusion even without the above mathematical derivation. At any time the 3 unit system is operating it has failure rate 2λ, rather than λ for the 2 unit system and no more than one unit can be in a failed state at any time for either system.

The MTTF of the 3 unit system is given by

$$M = \int_0^\infty R(t)dt = 1/\lambda + u/4\ \lambda^2 = m + m^2/4r \tag{36}$$

where $m = 1/\lambda$ is the MTBF of each unit and $r = 1/u$ is the average time to repair a single unit. Comparison of this result with that for the same system without repair capabilities shows that repair increases the MTTF by $m^2/4r$. The increase in MTTF due to both redundancy and repair is $m/2 + m^2/4r$.

3.2 N Units in Series - One Spare

For a system with n identical and repairable units in series and one in standby there can be no more than one unit in a failed state at any time since n units are needed for operation. If two units are simultaneously in a failed state the system is said to have failed. Whenever this system is operating it will have failure rate $n\lambda$. At most one unit is being repaired at any time the system is operating. Again there will only be three possible states for the system; state 2, n units operating and an operable spare;

state 1, n units operating and one in a failed state; state 0, two units and thus the system has failed. The mathematical formulation of the difference equations is identical with that given above for a system with two units in series and one spare. All that need be done is replace 2λ by $n\lambda$ in the difference equations (29). The reliability of the n + 1 unit system is

$$R(t) = 1/(a-b) \ [a \exp(-bt) - b \exp(-at)] \qquad (36)$$

where $a = \frac{(2n\lambda + u) + (4un\lambda + u^2)^{1/2}}{2}$ and $b = \frac{(2n\lambda + u) - (4un\lambda + u^2)^{1/2}}{2}$.

Inspection of a and b shows they are both positive so that $R(\infty) = 0$.

The mean time to system failure is

$$M = 2m/n + m^2/n^2 r \qquad (37)$$

The MTTF for a system of n units in series is m/n, for the same system with k spares and no repair it is km/n, and with repair it becomes, (1 spare), $(2m/n) + (m^2/n^2 r)$. Thus, an increase in reliability can either be achieved by increasing the amount of redundancy or by designing the system so that failed units can be repaired while the standbys are in use. The method employed depends on the type of system, weight and space requirements and the feasibility of making repairs.

4. Availability of Some Repairable Systems

In some systems continuous operation may be desired but not mandatory. If the system is off due to a failure it may be repaired and restored to operation. What is usually important in this case is the percentage of time the system is operating and the probability of the system being operational at a particular time.

4.1 The Basic System

A 3 unit system with 2 units operating and one spare is considered as the basic system. The probability A(t) that the system is operating at time t regardless of past system failures or repairs is desired. When two units, and thus the system, are in a failed state the third unit is turned off so there are never more than two units in a failed state at any time. The three possible system states are:

State 2 - two units are operating and the other is operable,
State 1 - two units are operating and the other is being repaired,
State 0 - no units are operating, but one is operable

If two units are operating the probability of one of them failing in Δt is $2\lambda\Delta t$; similarly if two units are failed the probability of repairing one of them in Δt is $2u\Delta t$ while if only one is failed the probability of repairing it in Δt is $u\Delta t$. The difference equations describing the possible transitions (neglecting some 2nd order terms in Δt) are:

$$P_2(t+\Delta t) = P_2(t)(1-2\lambda\Delta t) + P_1(t)(1-2\lambda\Delta t)\,u\Delta t \tag{38a}$$

$$P_1(t+\Delta t) = P_2(t)(2\lambda\Delta t) + P_1(t)(1-2\lambda\Delta t)(1-u\Delta t) + P_0(t)(2u\Delta t) \tag{38b}$$

$$P_0(t+\Delta t) = P_1(t)(2\lambda\Delta t)(1-u\Delta t) + P_0(t)(1-2u\Delta t). \tag{38c}$$

Performing the same type of limiting process as before the following differential equations are obtained:

$$\frac{dP_2(t)}{dt} = -2\lambda P_2(t) + uP_1(t) \tag{39a}$$

$$\frac{dP_1(t)}{dt} = 2\lambda P_2(t) - (u+2\lambda)P_1(t) + 2uP_0(t) \tag{39b}$$

$$\frac{dP_0(t)}{dt} = 2\lambda P_1(t) - 2uP_0(t). \tag{39c}$$

The system will be available if it is either in state 2 or state 1. Thus, system availability is given by:

$$A(t) = P_2(t) + P_1(t) = 1 - P_0(t), \tag{40}$$

where

$$P_0(t) + P_1(t) + P_2(t) = 1, \tag{41}$$

and

$$P_0(0) = P_1(0) = 0,\ P_2(0) = 1.$$

Using Laplace transforms where $L[P_i(t)] = p_i(s)$, $i = 0, 1, 2$, gives the following set of equations:

$$(s+2\lambda)\,p_2(s) - up_1(s) = 1 \tag{42a}$$

$$-2\lambda p_2(s) + (s+u+2\lambda)\,p_1(s) - 2up_0(s) = 0 \tag{42b}$$

$$-2\lambda p_1(s) + (s+2u)\,p_0(s) = 0. \tag{42c}$$

Solving for $p_o(s)$ by determinants gives:

$$p_o(s) = \frac{4\lambda^2}{s\,[s^2 + s(3u+4\lambda) + (4\lambda^2 + 4\lambda u + 2u^2)]},$$

The inverse transform is found to be:

$$P_0(t) = \frac{4\lambda^2}{4\lambda^2 + 2u^2 + 4\lambda u} + \frac{4\lambda^2}{ab(a-b)}[b \exp(at) - a \exp(bt)]$$

The system availability is:

$$A(t) = \frac{4\lambda u + 2u^2}{4\lambda^2 + 4\lambda u + 2u^2} + \frac{4\lambda^2}{ab(a-b)}[a \exp(bt) - b \exp(at)] \quad (43)$$

where;

$$a = [-(4\lambda + 3u) + (u^2 + 8\lambda u)^{1/2}]/2$$

and

$$b = [-(4\lambda + 3u) - (u^2 + 8\lambda u)^{1/2}]/2 .$$

This result for the three unit system (two operating and one spare) is the same as would be obtained by substituting 2λ for λ in the expression for availability (ref. D). The limiting or steady state availability, $\bar{A}$, (sometimes called efficiency) is the value of A(t) as t approaches infinity. Since a and b are both positive quantities $\bar{A}$ becomes:

$$\bar{A} = \frac{4\lambda u + 2u^2}{4\lambda^2 + 4\lambda u + 2u^2} = \frac{4mr + 2m^2}{4r^2 + 4mr + 2m^2}, \quad (44)$$

where $r = 1/u$ is the average time to repair a single unit. If $m = 10r$, which is conservative, then $\bar{A} = 60/61$. For two units in series, without a spare, the corresponding availability would only be $(m/m + 2r) = 5/6$.

4.2 n Units in Series - One Spare

The techniques and results of the previous section can be generalized. The availability of a system consisting of n units operating in series with one spare can be obtained by replacing 2λ by $n\lambda$ in expression (43). Hence:

$$A(t) = \frac{2n\lambda u + 2u^2}{n^2\lambda^2 + 2u^2 + 2n\lambda u} + \frac{n^2\lambda^2}{ab(a-b)}[a \exp(bt) - b \exp(at)] \quad (45)$$

where

$$a = \frac{-(2n\lambda + 3u) + (u^2 + 4n\lambda u)^{1/2}}{2}, \quad b = \frac{-(2n\lambda + 3u) - (u^2 + 4n\lambda u)^{1/2}}{2}.$$

The limiting availability is

$$\bar{A} = \frac{2n\lambda u + 2u^2}{n^2\lambda^2 + 2u^2 + 2n\lambda u} = \frac{2nmr + 2m^2}{n^2r^2 + 2m^2 + 2nmr}. \quad (46)$$

The limiting availability of n series units without a spare is $u/(u + n\lambda)$. If $u = 10\lambda$ and $n = 10$ then the addition of the spare gives 1.6 times the availability of a non-spared system.

CONCLUSIONS

It is generally believed that the application of redundancy in electronic equipment will at least double its size and weight. In practice, however, many sub-assemblies or units are found to be identical in complex electronic equipment. For these cases this paper has shown that standby redundancy can be judiciously employed to achieve a high degree of reliability and availability without the penalty of drastically increasing size and weight. A typical example may be found in digital to analog conversion equipment. In such systems many circuits or channels are repeated in order to handle all the signals involved. By providing extra channels in standby the reliability and availability of the equipment can be greatly enhanced. Similar applications can be found in digital computer equipment. In effect, this provides an efficient means of making trade-offs between system reliability and complexity.

The following chart summarizes the results of this paper.

Series Units	Standby Units	Repair	Reliability (MTTF)	Availability ($\bar{A}$)
2	0	no	$m/2$	*
2	1	no	m	*
n	0	no	m/n	*
n	1	no	$2m/n$	*
n	k	no	km/n	*
2	0	yes	$m/2$	$m/(m + 2r)$
2	1	yes	$m + m^2/4r$	$(4mr + 2m^2)/(4mr + 4r^2 + 2m^2)$
n	0	yes	m/n	$m/(m + nr)$
n	1	yes	$2m/n + m^2/n^2r$	$(2nmr + 2m^2)/(n^2r^2 + 2m^2 + 2mnr)$

MTTF = Mean Time to First System Failure

$\bar{A}$ = Steady State Availability or efficiency

m = MTBF of each component

r = Average time to repair a component

*** The availability of a non-repairable system is essentially zero since once it fails the system remains in a failed state.**

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OPTIMIZING ELECTRONIC WEAPON SYSTEM EFFECTIVENESS

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SUMMARY

Weapon system effectiveness may be defined as the ratio of the statistically determined probable number of target area hits to the maximum possible number of target area hits, within a specified time after a command to fire has been issued, for a system operating in a prescribed manner with a specified maintenance policy.

Weapons system effectiveness is optimized by "trading-off" between the constituent reliability, maintainability and accuracy parameters of the system. A most important relationship and vehicle for this optimization is the availability ratio. It is within this ratio that the analytic model relating maintenance and reliability is established.

In this paper, a derivation of a probabilistic model for a relatively uncomplicated, but nevertheless realistic, electronic weapon system is presented with emphasis on the basic mathematical techniques involved. The resulting model is then discussed in the light of its role as a major factor in the determination of weapon system effectiveness and a practical approach to an estimate of mean-time-to-repair is presented.

A method for optimizing the effectiveness is then discussed for the conditions when system accuracy is independent of time, and when system accuracy is a function of time between data inputs or calibrations.

INTRODUCTION

The success of any electronic weapons system is reflected in:

- first, its ability to react successfully within an allowable time limit from a command-to-fire, and

- second, its ability to control the accuracy of the weapon, with a given probability of operating to within a specified system "error," or "miss-distance."

A major parameter in determining a system's ability to react successfully is its "availability," or state of readiness, when the command-to-fire is given, where system availability, or readiness probability, is the ratio of the average time spent in a "ready" and/or "near-ready" state to the total average system time, over an operational maintenance cycle. Consequently, it is not only necessary to consider the reliability and accuracy of the equipment in optimizing system effectiveness but its maintainability as well, since such parameters as mean-time-to-repair (or replace) contribute significantly in the determination of an availability ratio.

Projection of the effectiveness of an electronic weapon system, therefore, involves the joint consideration of the system's availability, the probability of its successful survival throughout the period of time required to complete its mission, and the probability of operating to within specified accuracy limits.

System effectiveness is optimized by "trading-off" between the constituent parameters of the system. Since these reliability, maintainability, and accuracy factors are implicitly established by many of the early design and development decisions involved in specifying a system, including such considerations as circuit derating, parts procurement levels, and field maintenance philosophy, the establishment of a system effectiveness model permits optimization of this characteristic.

SYSTEM AVAILABILITY CONCEPTS

The availability of a system is described as the probability of having a system in an operating condition and in a ready state when a demand is made. If the condition of operationality is modified to assume that the probabilities of having undetectable failures and large error accuracy degradations are negligible and that the system is always unavailable while undergoing a replacement-type repair or an interrogation, then a reasonable approximation of the availability model can be derived.

a. Basic Requirement

One of the most important requirements on which the following analysis is based, is that the failure rate of the system is constant. Essentially, this means that the times-between-failure of the system are exponentially distributed. For the system under discussion it has been statistically determined from field operating time and failure data that the failure rate is constant.

b. Transition Probability Transients

It can be shown for the system under analysis that the transient effects of starting a new system soon die down and the transition probabilities become constant after a relatively short number of standby interrogation cycles via the technique of the Markov chain applied to an ergodic process. However, another explanation from the physical (or intuitive) point of view will be made in the following section when the system equations are derived.

DERIVATION OF A SYSTEM AVAILABILITY MODEL

a. Definition of System Availability

By definition of A we can write the following ratio:

$$A = \frac{\left[\text{Expected (or avg.) total time that a system is operational (working) and ready (known to be working)}\right]}{\left[\text{Total time in use}\right]}$$

(1) The above expression for A is simply the statistical definition of probability which states that the probability that an state will occur is the total time the state does occur over the amount of time that all possible states occur.

b. Interrogation System

The basis for determining whether a system is good is the interrogation system.

(1) For the perfect interrogation system it is known at the end of the interrogation whether the system is ready to enter the next standby period in working order or the system requires maintenance action.

(2) If the interrogation system is less than perfect, then there is a probability designated as "a" that the interrogation system will call a working or good system bad (i.e. ; a false alarm probability exists) and a probability (1-d) that it will accept a nonworking or failed system as being good. It follows, that "d" is the probability of detecting a "failed" system.

c. Determining the Probability of a System Entering the $(n+1)^{st}$ Cycle in a Working or "Good" Condition

The first quantity required in the derivation of an availability model is the probability that a system will enter an interrogation in a good and ready condition. This follows from the definition of the Availability ratio which is the total time a system is good and ready over the total time the system exists.

(1) A cycle is defined as the total time span between the start of succeeding scheduled equipment interrogations, symbolized as T.

(2) The following boundary conditions were used to generate this model in order to simplify its form and promote the understanding

of the technique.

(a) All repairs are perfect.

(b) After a repair has been made another interrogation is performed, but no more than two interrogations are performed during any one cycle.* T_i and T_r are the times to interrogate and repair, respectively.

(c) A system failure can occur during any interrogation, but as limited in the preceding ground rule, the second consecutive repair of the system will not be interrogated. This rule is also applicable to repairs fostered by one or more false alarms.

(d) The system failure rates in the standby portion of the cycle are considerably lower than the system failure rates in the interrogation portion of the cycle; $\lambda_s << \lambda_i$.

(e) The time spent in standby is considerably longer than the sum of the times required to effect two repairs and conduct two interrogations.

(f) Means are not available to determine if a system is working while in standby.

(3) The probability of entering $(n+1)^{st}$ cycle both good (working) and ready (known working) is schematically represented by the flow diagrams of figures (1) and (2).

(a) Figure (1) shows the flow of all possible states the equipment can take while entering good and leaving good. For simplicity all of the transition states which would allow the equipment to enter the next cycle bad have been left out.

(b) Figure (2) shows the flow of all possible states th equipment can take while entering bad (not working) and leaving good.

(c) The transition probabilities for state-to-state traverse are shown and these factors will be combined to derive the system equation. It should be noted that the probability of effecting a repair $P[M]$ is unity as stated in the ground rules. A good system (working) known to be good is represented by G_G and a good system thought to be bad (nonworking) is represented by G_B. A bad system known to be bad is B_B.

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* For a practical model the number of interrogations allowed per cycle can be quite large, but a decision will have to be made as to when the next cycle must start.

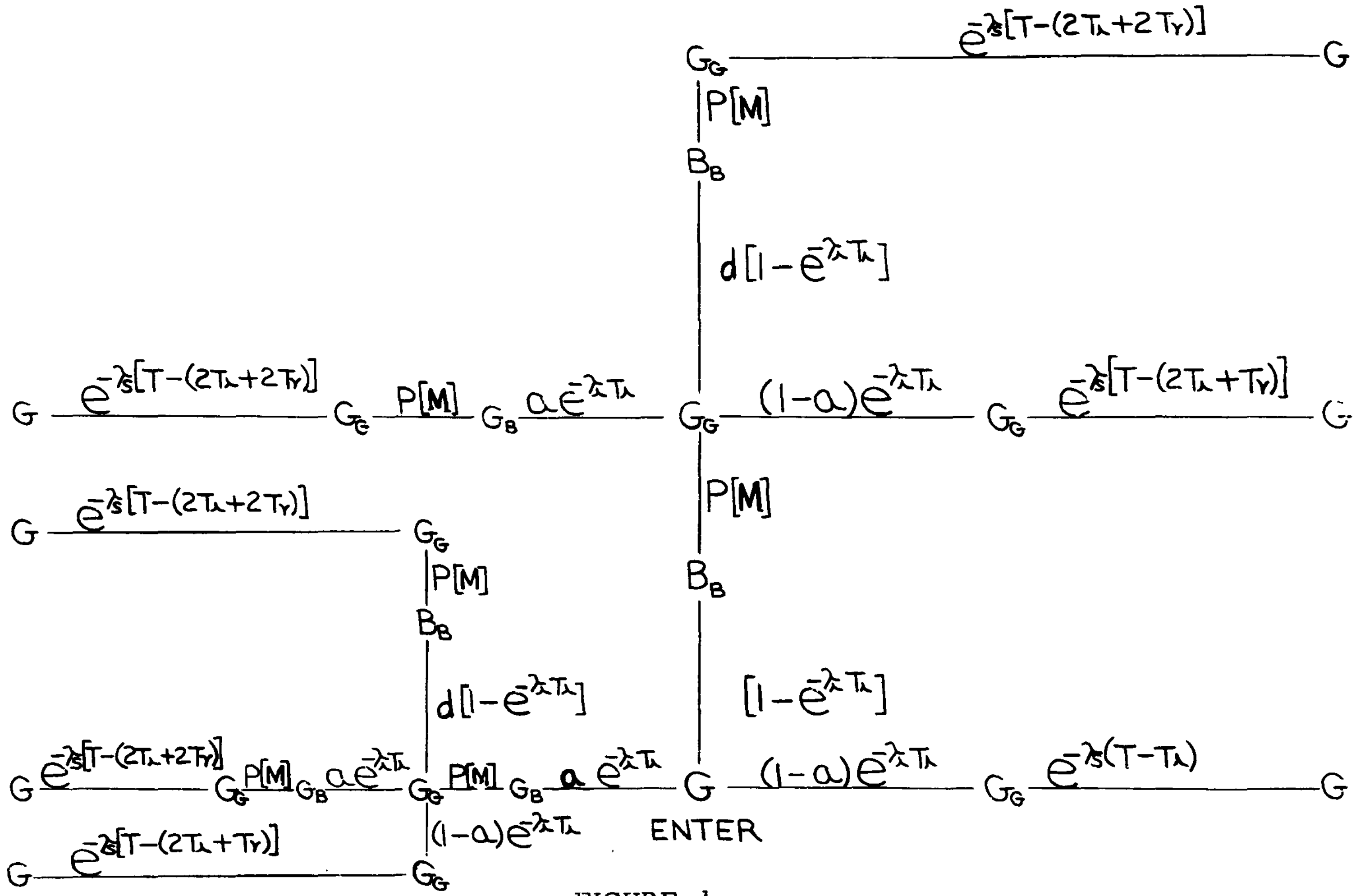

FIGURE 1

FLOW DIAGRAM - ENTER CYCLE GOOD, LEAVE CYCLE GOOD

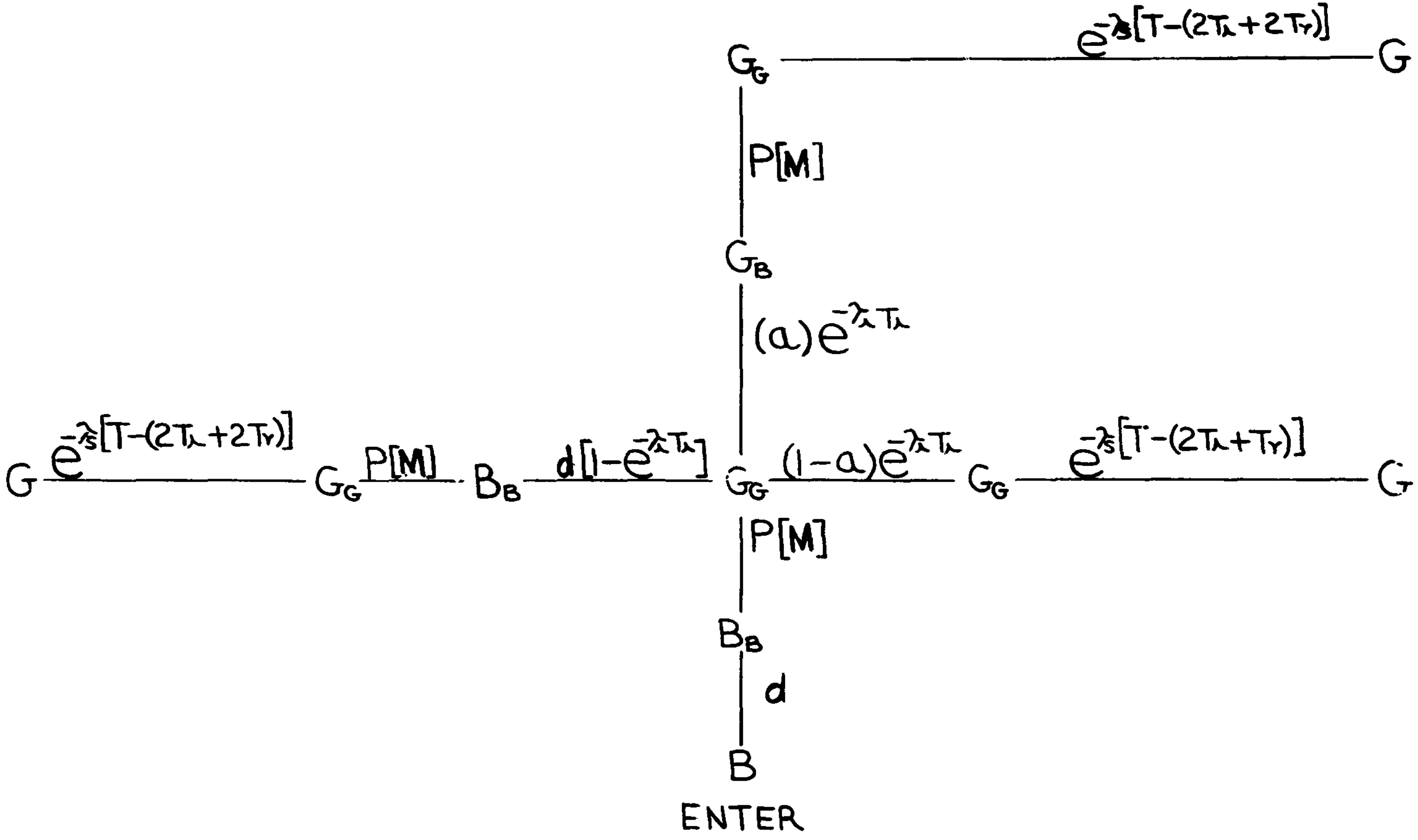

FIGURE 2

FLOW DIAGRAM - ENTER CYCLE BAD, LEAVE CYCLE GOOD

(4) The probability of entering the $(n+1)^{st}$ cycle good is:

$$
\begin{aligned}
P_G(n+1) = {} & P_G(n)(1-\alpha)e^{-\lambda T_\lambda}\, e^{-\lambda_s(T-T_\lambda)} + \\
& P_G(n)\, d\,(1-e^{-\lambda T_\lambda})(1-\alpha)\, e^{-\lambda T_\lambda}\, e^{-\lambda_s[T-(2T_\lambda+T_r)]} + \\
& P_G(n)\, d^2(1-e^{-\lambda T_\lambda})^2\, e^{-\lambda_s[T-(2T_\lambda+2T_r)]} + \\
& P_G(n)\, d\,(1-e^{-\lambda T_\lambda})\alpha e^{-\lambda T_\lambda}\, e^{-\lambda_s[T-(2T_\lambda+2T_r)]} + \\
& P_G(n)\alpha e^{-\lambda T_\lambda}\, d(1-e^{-\lambda T_\lambda})\, e^{-\lambda_s[T-(2T_\lambda+2T_r)]} + \\
& P_G(n)\alpha e^{-\lambda T_\lambda}(1-\alpha)\, e^{-\lambda T_\lambda}\, e^{-\lambda_s[T-(2T_\lambda+T_r)]} + \\
& P_G(n)\alpha^2(e^{-\lambda T_\lambda})^2\, e^{-\lambda_s[T-(2T_\lambda+2T_r)]} + \\
& (1-P_G(n))\, d\,(1-\alpha)e^{-\lambda T_\lambda}\, e^{-\lambda_s[T-(2T_\lambda+T_r)]} + \\
& (1-P_G(n))\, d\,\alpha e^{-\lambda T_\lambda}\, e^{-\lambda_s[T-(2T_\lambda+2T_r)]} + \\
& (1-P_G(n))\, d^2(1-e^{-\lambda T_\lambda})\, e^{-\lambda_s[T-(2T_\lambda+2T_r)]}
\end{aligned}
$$

(a) Obviously it is seen that each term is merely the product of the individual transition probabilities (which are independent) and the sum of all of the transitions which result in a working system at the start of the $(n+1)^{st}$ cycle. P_G is the probability of being good.

(b) If we note that the entire weapon system and its maintenance-reliability performance is a random process and also note that we have constant failure rates and that the time to repair a system is an overall weapon system average, then it is reasonable to expect the ensemble (or statistical) average probability of being good is equal to the single (or time) system average probability of being good. This, of course, is the definition of an ergodic random process and means that the transition probabilities stabilize after a finite number of transitions. For this system it can be verified using Markov chains that the probabilities stabilize after a few transitions.

(c) In relating the preceding discussion to the derivation of an expression for entering the $(n+1)^{st}$ cycle in a working condition we have reasoned that the transition probability between cycles is equal, hence the relationship between $P_G(n+1)$ and $P_G(n)$ is:

$$P_G(n+1) = P_G(n), \text{ where } n \gg 3.$$

The expression in sub-section 4) can now be algebraically solved for $P_G(n)$.

(d) The probability that a system is good is:

$$P_G = \frac{d\, e^{-\lambda_s[T-(T_Y+2T_\lambda)]}\left[(1-\alpha)e^{-\lambda T_\lambda} + \left[\alpha e^{-\lambda T_\lambda} + d(1-e^{-\lambda T_\lambda})\right] e^{\lambda_s T_Y}\right]}{1 - e^{-\lambda T_\lambda} e^{-\lambda_s(T-T_\lambda)} \left\{ \begin{array}{l} (1-\alpha) + d\, e^{-\lambda T_\lambda} e^{-\lambda_s(T_\lambda+T_Y)} + \\ \alpha e^{-\lambda T_\lambda} - d^2(1-e^{-\lambda T_\lambda}) \end{array} \right\}}$$

d. System Availability

The system availability for this particular system is the sum of the average time spent in a working condition in standby over the average time/cycle which is T. An expression for the expected or average good standby time/cycle must now be derived:

(1) Derivation of an Expression for the Average Good Standby Time/Cycle.

(a) There are two possible ways a system which enters a standby period in a working or good condition can end the standby period:

1. The system can fail before the period is complete and the average working time given that the system will fail and the distribution of times-to-failure for the system is exponential is:

$$\overline{T}_{s_1} = \int_0^{T_s} \frac{t\lambda_s e^{-\lambda_s t}}{1-e^{-\lambda_s T_s}}\, dt = \frac{1 - e^{-\lambda_s T_s} - \lambda_s T_s e^{-\lambda_s T_s}}{\lambda_s - \lambda_s e^{-\lambda_s T_s}}$$

2. The system will survive the standby period:

$$\overline{T}_{s_2} = T_s$$

3. The probabilities that a system will survive or fail during the standby period are:

$$P[\text{Failure}] = 1 - e^{-\lambda_s T_s}$$

$$P[\text{Survival}] = e^{-\lambda_s T_s}$$

4. Now it follows that the average good time is:

$$\overline{T}_s = P[\text{Failure}]\overline{T}_{s_1} + P[\text{Survival}]\overline{T}_{s_2} \therefore \overline{T}_s = (1-e^{-\lambda_s T_s})/\lambda_s$$

(b) The T_s used in this derivation is only a variable of integration since there are several standby periods possible due to the fact that all repairs and subsequent interrogations after the first scheduled interrogation reduce the effective length of the standby period. Incidentally, it directly reduces the availability as will be seen in the ensuing derivation.

(c) The expression for the availability ratio is merely the sum of the average good time for each different length of standby period, multiplied by the probability of entering that particular period with a working system. The expression can be picked off from the flow diagrams shown in figures (1) and (2). P_G has been previously derived.

$$A = \frac{1}{T}\left\{\begin{array}{l} P_G(1-\alpha)e^{-\lambda T_\lambda}\left(1-e^{-\lambda_s(T-T_\lambda)}\right)/\lambda_s + \\ \left[P_G(1-e^{-\lambda T_\lambda})+(1-P_G)\right]d(1-\alpha)e^{-\lambda T_\lambda}\left(1-e^{-\lambda_s[T-(2T_\lambda+T_\gamma)]}\right)/\lambda_s + \\ \left[\begin{array}{l} P_G\left(\begin{array}{l} d^2(1-e^{-\lambda T_\lambda})^2+2\alpha d(1-e^{-\lambda T_\lambda})e^{-\lambda T_\lambda}+ \\ \alpha^2 e^{-2\lambda T_\lambda}+(1-\alpha)\alpha e^{-2\lambda T_\lambda} \end{array}\right)+ \\ (1-P_G)\left[d^2(1-e^{-\lambda T_\lambda})+d\alpha e^{-\lambda T_\lambda}\right] \end{array}\right]\frac{\left(1-e^{-\lambda_s[T-2(T_\lambda+T_\gamma)]}\right)}{\lambda_s} \end{array}\right\}$$

In order to retain some order of simplicity the expression previously derived for P_G has not been substituted.

OPTIMIZATION OF THE AVAILABILITY RATIO

Optimization of the availability ratio is the first step in the optimization of weapons system effectiveness. Of course, it might be asked against what variable or variables do we optimize. If we were concerned only with determining the effective scheduled time between interrogations the problem would be relatively simple since we would then only need to take $\partial A / \partial T$ and set the resulting expression to zero. We would then solve for T. However, this is not the case. We are, in fact, interested in solving for T, but it turns out that the value of T_r is partially dependent or a function of T. In the following portion of this section, one technique of achieving availability optimization will be presented.

a. What is Tr?

Tr as now defined is the average time-to-repair, averaged over a large number of repairs for a system which has been operating with a specified time-between-interrogations, a specified number of service channels, and a specified logistic (inventory of replacements) picture.

(1) We have previously stated that the failure rate during interrogation (λ_λ) is greater than the failure rate during standby (λ_s).

(2) If we assume that our inventory of spares is inexhaustible and that a pool of men capable of making the necessary replacement-type repairs is similarly inexhaustible, then the optimum availability is derived by a simple differentiation and Tr is not a f(T).

(3) Our system, however, is bounded by the condition that both the pool of spares and men are limited. Therefore, Tr is a f(T).

b. The Variation of Tr as an f (T)

In order to understand this process, the following picture of T_r variation is presented:

(1) If the time-between-interrogations, T, is large, then most of the failures occur during the standby period. Since these failures are undetectable until the interrogation has been completed, it follows that there can be long periods of undetectable down time. The net result of an interrogation schedule of this type is to lower availability and limit service requests.

(2) If T is very small, then the great majority of failures must occur during interrogation and therefore we will not have periods during which the system is thought good but is really bad. The result of this

schedule is to radically increase the number of failures (hence, the number of service calls and replacements) and heavily overload the service and logistic facilities. The result of this operating condition is two-fold:

(a) First, the value of T_r increases, because the number of replacements required has a good chance of exceeding the inventory, and this will result in long delays which average into the value of T_r.

(b) Second, the percent down time due to the increased ratio of interrogation time to time between interrogations directly lowers the availability ratio.

(3) A typical graph (normalized) of T vs Tr (figure (3)) shows that the situation begins to blow up as T approaches zero. This problem has been analyzed mathematically in many textbooks on queueing theory where the average rate of arrivals exceeds the average service rate. Although the queue can become infinite an average waiting time does exist in the theoretical limit. However, what would happen in this case is that as more systems await servicing, the arrival rate will decrease and a queue limit of less than the total population will develop. The resulting T_r will be large and of course the availability will be small.

c. Optimization Methodology

(1) The system equation for P_G and A should be developed noting that T_r is really the expected value of some f(T) or $E(f(T)) \equiv T_r$.

(2) Based upon knowledge of the service facility, the inventory levels and system operating reliability, a curve or model* can be developed for T_r.

(3) Then a curve or model of A can be derived and the optimum can be picked off a graph of T vs A or solved by differentiating with respect to T. In any event, an estimate of T optimum will have been made. See figure (4).

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* Models which are closely applicable can be found throughout the recent O-R literature and textbooks.

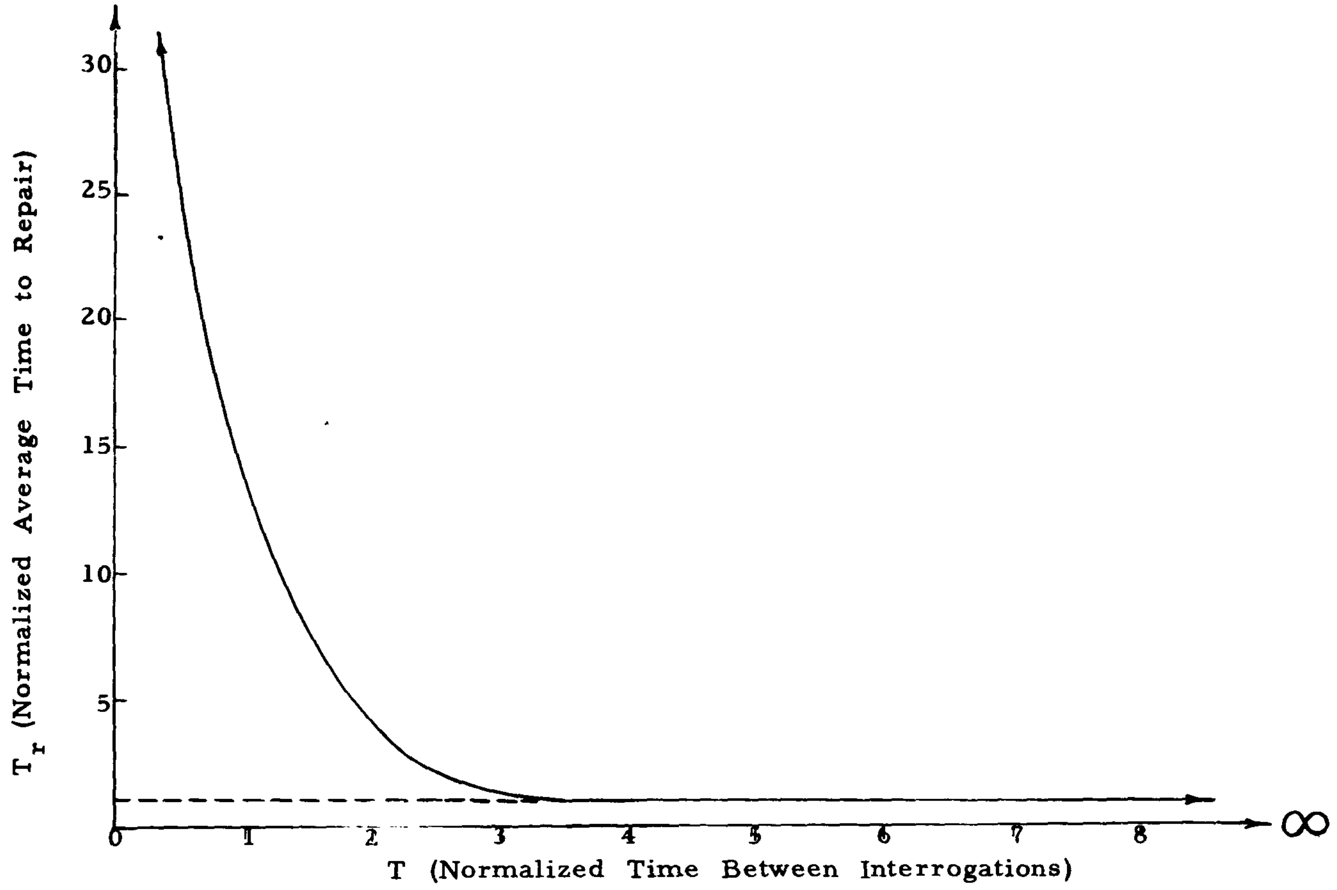

FIGURE 3

AVERAGE TIME TO REPAIR VS. TIME BETWEEN INTERROGATIONS

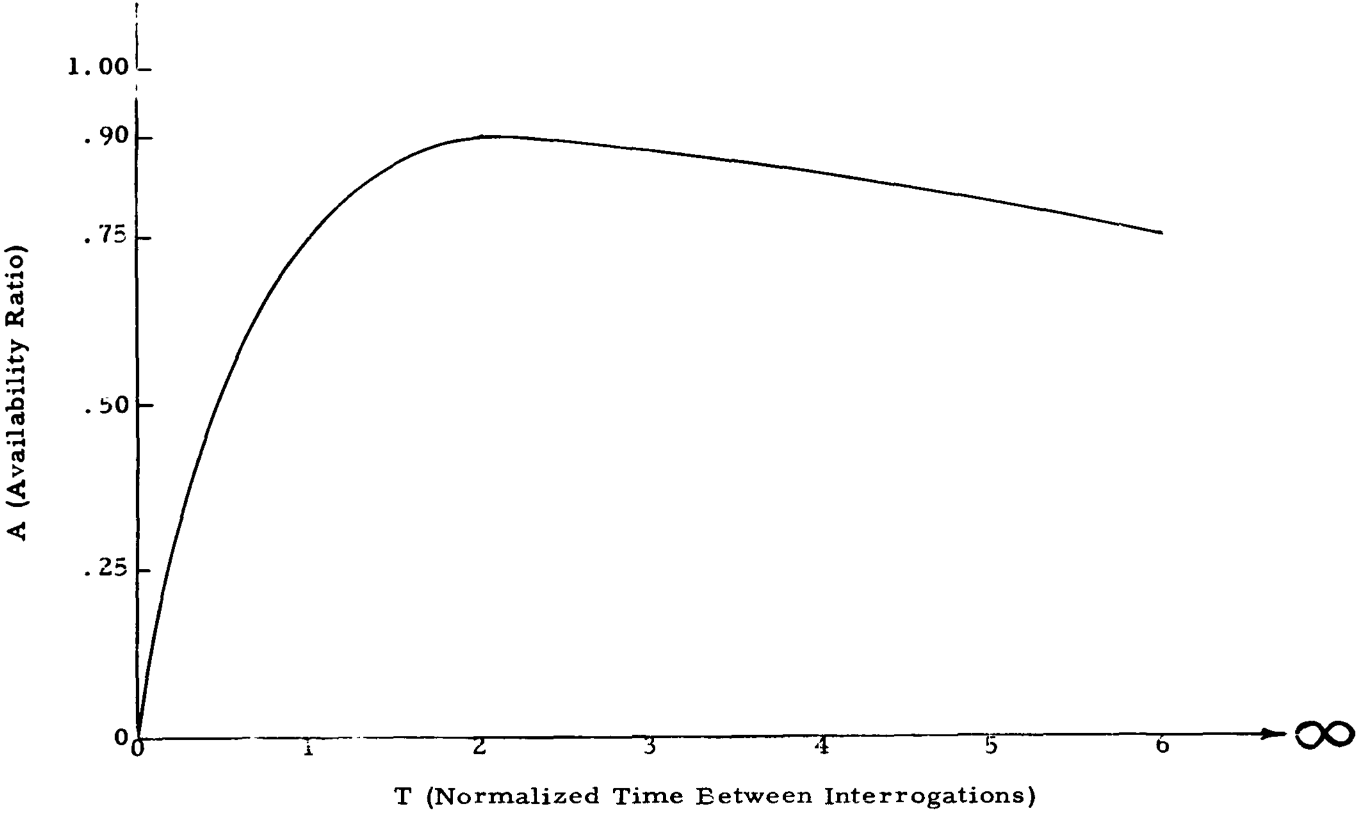

FIGURE 4

AVAILABILITY RATIO VS. TIME BETWEEN INTERROGATIONS

OPTIMIZATION OF ELECTRONIC WEAPONS SYSTEM EFFECTIVENESS

Weapons system effectiveness is optimized by "trading-off" between the constituent reliability, maintainability, and accuracy parameters of the system. Up to this point we have discussed the optimization of availability as a function of reliability and maintainability.

a. System Accuracy

System accuracy is a function of component accuracies which are statistical in nature. Thus, the distributions of the down range miss-distance (X) and the cross range miss-distance (Y) are both Normal with zero mean. In general, these distributions for X and Y are independent, so that if we define our system accuracy as the radial miss-distance from the target (ρ), and assume that the variances of X and Y are equal, then the distribution of ρ is a Rayleigh distribution with a standard deviation of σ .

(1) The Rayleigh distribution is represented by the following expression:

$$P(\rho) = \frac{\rho}{\sigma^2} e^{-\frac{\rho^2}{2\sigma^2}} , \quad 0 \leq \rho < \infty$$

(2) System accuracy is usually specified in terms of its Circle of Equal Probability (CEP). This Circle of Equal Probability is defined as the radius of a circle, centered about a target point, which has a 50% probability of encompassing the weapon system's strike point.

(3) The probability that an error ρ lies within a circle of radius r is obtained by integration as follows:

$$P_A(\rho \leq r) = \int_0^r \frac{\rho}{\sigma^2} e^{-\frac{\rho^2}{2\sigma^2}} d\rho = 1 - e^{-\frac{r^2}{2\sigma^2}}$$

where: P_A is the system accuracy probability (cumulative error distribution), and r is the allowable radial error (miss-distance).

(4) If we let $P_A (\rho \leq r) = 0.5$ (the 50 percent probability point), then we can solve for the specific radius r_{CEP} , called the CEP radius, for the system:

$$P_A(\rho \leq r_{CEP}) = 1 - e^{-\frac{r_{CEP}^2}{2\sigma^2}} = 0.5,$$

and $r_{CEP} = 1.177\sigma$.

(5) Consequently, the accuracy probability $P_A\ (\rho \leq r)$ can be stated in terms of system CEP radius for any miss distance r as:

$$P_A\,(\rho \leq r) = 1 - e^{-\left(\frac{0.832r}{r_{CEP}}\right)^2}$$

b. System Effectiveness

If the system accuracy function is modified to reflect the availability of the system under consideration, an expression for the average system effectiveness emerges:

$$\eta_s(\rho \leq r) = A \cdot R_f R_c P_A$$

where: R_c is the countdown reliability, and
R_f is the flight reliability

(1) If the system accuracy is independent of the time between interrogations (T), then the expression for the average system effectiveness (η_s) as stated above is merely a function of the availability ratio (A) and is optimized when A is optimized.

(2) If during the interrogation certain characteristics are either checked or "set-in" that contribute effectively (plus or minus) to the value of system CEP and these characteristics are also a function of time between interrogations, then the optimization technique described for the weapons system effectiveness in paragraph (1) of this section cannot be strictly applied.

Since the desired criteria is to maximize the number of weapon system "strikes" rather than to optimize system readiness, the optimization model previously derived for system availability is no longer self-sufficient.

The procedure for this case is outlined below:

(a) Generate a function for "available" systems vs. time between interrogations (T) by computing system availability for each maintenance interval to be considered.

(b) Generate a function for system CEP vs. time between interrogations by considering the effects of lengthened maintenance intervals on the degradation of component accuracies and their statistical distribution functions.

(c) Select the conditions for optimum system effectiveness by maximizing η_S for a specified miss-distance, as a function of maintenance cycle time T. A typical curve of η_S vs. T for a system where the accuracy degrades with T is shown as illustrated in figure (5).

c. Minimum Assurance - A Final Measure of the Optimized Weapons System Effectiveness

The "average" optimum number of systems strikes expected within r miss-distance of the target can be established by multiplying the optimum η_S by the total system population. The characteristics of this average strongly imply that it is the mean of a Poisson distribution. Therefore, it can now be determined how many system strikes will be within r miss-distance of the target, for 95% of the time. The "minimum" optimum value of weapons system effectiveness is then obtained when the minimum number of hits is divided by the system population.

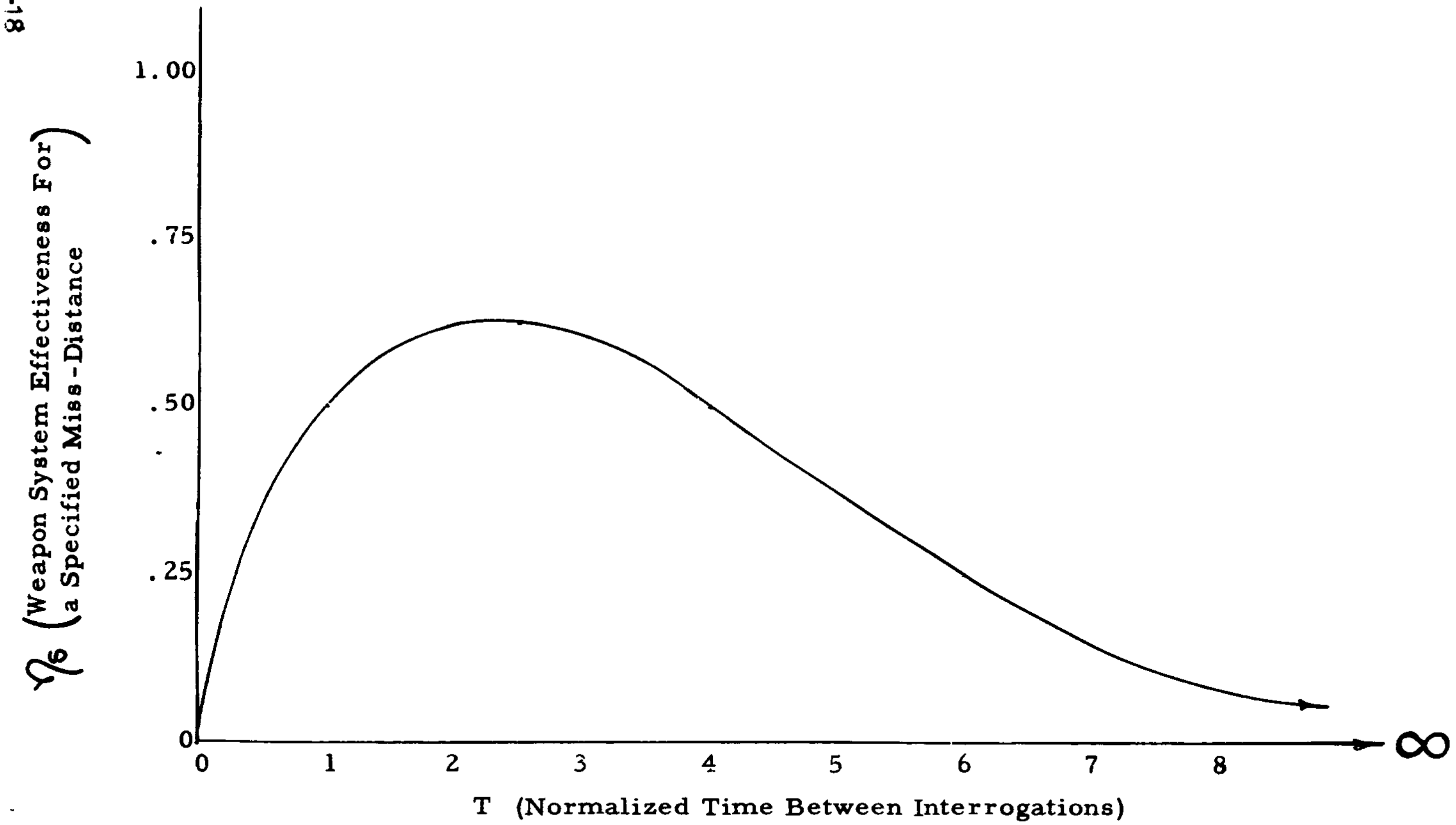

FIGURE 5

WEAPON SYSTEM EFFECTIVENESS FOR A SPECIFIED MISS-DISTANCE VS. TIME BETWEEN INTERROGATIONS

CONCLUSIONS

The methods described in this paper are basic. They can be applied to many situations concerning the effectiveness of any large population of "demand" systems. For an electronic weapons system the final measure of its effectiveness is the system's ability to respond to an alert and destroy at least the acceptable minimum number of targets a large percentage of the time.

a. Applications of Results

The following applications of this technique can be utilized:

(1) Two or more differently conceived weapons systems can be measured on a common ground (economics excluded here, but the economic questions can also be introduced) and the most effective weapons system can be selected.

(2) The parameters which enter into the measure of effectiveness can be changed and the net improvement or degradation can be measured making it relatively simple to choose the most promising paths of weapons system improvement. Such considerations as system or subsystem redundancy can be evaluated in terms of the total effect upon depot workload and spares levels, as well as reliability improvement, and the net effect on weapon system effectiveness can be properly determined.

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HUMAN FACTORS AND MAINTAINABILITY

by

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Presented at
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The definition of maintainability in the maintainability specification Mil-M-26512B tells us that "Maintainability is the characteristics, both qualitative and quantitative, of material design and installation which make it possible to meet operational objectives with a minimum expenditure of maintenance effort (manpower, personnel skill, test equipment, technical data, maintenance support, and facilities) under operational environmental conditions in which scheduled and unscheduled maintenance will be performed." This makes it seem that maintainability is basically equipment-oriented; however we must remember that both the prime equipment and the support equipment are designed to be operated and maintained by man. If systems are to be easily and efficiently maintained by man it is essential that human capabilities and limitations be considered in system design. Thus, in a sense, we can say that maintainability is human oriented; -- that human factor considerations are of paramount importance in achieving maintainability. It is my purpose here today to discuss some of the important human factor considerations involved in design for maintainability. My remarks will briefly cover the following:

a. Human factors considerations in the design of equipment.

b. Some implication of the number and skill level of maintenance personnel.

c. Maintenance aids, including maintenance data publications.

d. Maintainability tradeoffs.

I will also mention some of the human factors data available for use by design engineers and will refer briefly to some research that is producing human factors engineering data for maintainability.

First, we will look at some maintainability factors in the design of equipment, or more specifically, some human engineering principles which improve maintainability. These principles are based on physical body measurements, physical strength, sensory and memory limitations, physical endurance, and other human factors information.

When we think of maintainability, what is usually the first thing to come to mind? Probably it is accessibility — accessibility of test points, adjusting screws, components, and parts. This aspect of maintainability is more obvious than most. In repairing equipment, if one or more parts must be removed to reach a certain part for replacement, the total down time is increased. Also, if access openings are poorly placed or so small the maintenance man has difficulty in seeing his work area to make adjustments or to remove parts, increased maintenance down time will result. These facts about accessibility may seem so obvious as to need no discussion; however this is one maintainability principle that is still violated, often without cause — the end result being the waste of thousands of maintenance hours and possibly requiring a costly modification program. Its importance cannot be stressed too strongly.

Some other design factors affecting maintainability are: circuit simplicity, marking and color-coding of parts and modules, interchangeability of modules, keying of connectors, and location and readability of dials and other indicators. Maintenance time can often be saved by attention to these factors. Color-coding of wires and components and stamping of identifying information on sections of the chassis can significantly reduce maintenance time. Attention to circuit simplicity and standardization should reduce not only the time to isolate a malfunction but also the amount of training needed by technicians.

Lack of attention to these maintainability factors not only can and often does lead to increased down time in finding and correcting malfunctions, but also may degrade reliability by inviting human error in the course of maintenance operations. Reliability degrading errors such as: (a) improper wiring, (b) bent or damaged plugs, (c) inaccurate adjustments, (d) skipping a checkout step, (e) replacing wrong component and (f) reversing cables, to name but a few, can often be avoided by proper equipment design. The fact that approximately 40% — 50% of the costly failures in our missile programs can be traced to personnel errors of this sort, attests to the critical nature of the human factor in maintenance and equipment design.

The human engineering design factors for maintainability which I have mentioned so far do not begin to exhaust the array of human factor considerations in design for maintainability. Extensive descriptions of these and other aspects of maintainability design are available in two technical reports: WADC TR 56-218, "Guide to Design of Electronic Equipment for Maintainability" (Ref 2) and ASD TR 61-381, "Guide to Design of Mechanical Equipment for Maintainability" (Ref 1). Design data from these guides and from other sources of human engineering data are being gradually included in the "HIAD" series (AFSCM's 80-1, 80-3, 80-5, 80-6, and 80-8) where they are possibly more convenient for use by design engineers.

The data used in designing working spaces and access openings for equipment is based on anthropological measurements of the human body, including arm reach and hand size. In other aspects of equipment design, the data is based on limitations of man's memory, sensory abilities, problem-solving ability, and other human factors.

The Behavioral Sciences Laboratory at Wright-Patterson Air Force Base has research in progress which will add to the store of human factors information applicable to maintainability. Results from these studies will be incorporated into technical reports, military standards, and Air Force design guides and handbooks. The Human Engineering Branch of the Behavioral Sciences Laboratory is presently studying space requirements for optimum use of various maintenance tools. Studies have been done to find out limitations in man's arm reach, and his ability to perform when encumbered by a space suit; and investigations of the problems of space maintenance are also in progress.

There are tradeoffs which can be made between various maintainability factors in the design of equipment. For example, if it is not possible to give the desired accessibility to some parts, special tools may be furnished for removing them. If it is not possible to have interchangeable modules or simplified wiring, a clear, legible and efficient system of marking parts, circuits, and modules may compensate. In practice it will be found that design for maintainability is often compromised because of other considerations such as performance requirements or cost. For example, it may be necessary to locate a certain item in such a way that two other parts must be removed to replace it. To locate every major part or assembly so it is easily accessible could lead to an extremely complex wiring system or considerable waste of space.

Design engineers responsible for making the final decisions on design tradeoffs should weigh carefully all the design factors before rejecting good maintainability features. Special care must be taken to avoid placing parts in locations where hours are required to remove and replace them, or in having circuitry with unnecessary complexity, thus requiring more skilled man-hours in fault isolation. One additional caution for the design engineer and maintainability engineer in designing system equipment lies in modifications to original designs. If relocation of parts or wiring is considered, the proposed changes must be carefully analyzed to see if maintainability will be affected. Will parts having the higher failure probabilities be more accessible? Will relocation of a part block access to another part or to test or servicing points for periodic maintenance, calibration, or troubleshooting? Will each chassis be stamped with the changed location of parts and accesses? And here is an important one: will every reference to any affected part or circuit in the Technical Orders be checked to see that it is correct in every respect? Incorrect diagrams, instructions and parts numbers are a cause of many lost man-hours in maintenance.

It is probably unnecessary to mention that design for maintainability should come early in system design, long before the construction of any hardware. The longer we wait to get maintainability in the system, the more probable that it will not receive consideration. If it becomes necessary to modify a system to improve maintainability after the system is in the field, the cost will be many times what it would have been in the design phase.

The factors I have discussed to this point are those usually considered maintainability factors — chiefly factors affecting equipment design. There are several other related factors, however, that interest us greatly because of their effect upon system maintainability. These are such things as the skill and training of personnel, the test and support equipment used, and the area of maintenance aids, including maintenance data publications.

A study was recently completed by Republic Aviation Corporation (Ref 3), based on questionnaires and interviews with 2, 300 technicians and supervisors involved in Air Force maintenance activities. Results showed that the quality of technical data varied considerably between weapon systems, and that in general there is much room for improvement in presenting technical information to the technicians. One implication of the findings is that much costly down time could be eliminated by making information easier to find and easier to follow. Other maintenance aids such as special check lists, charts and color-coded diagrams, are often time savers, especially if they can reduce unnecessary tests and lengthy searches through the technical orders.

The design engineer usually does not make decisions about the background and skills of the crew who will maintain the system when it is operational. He must keep in mind, however, that the system must be designed so it can be maintained by the using command personnel who will be assigned to it. Another thing to remember is that prediction of down times should be based on maintenance by the type and number of technicians who will be assigned to the system; and demonstration of maintainability, based on time to restore equipment to normal operation, should be accomplished with technicians similar in experience, skills and training to the men who will ultimately maintain it. Use of technicians in the demonstration and test who have superior skills would indicate a higher level of maintainability than actually exists.

The test and support equipment used may have a marked effect on total down time. Of course the decision as to how automatic and mechanized the test and support equipment should be is usually made early in the planning stage. These decisions may be based on economic considerations, availability of skilled manpower, complexity of the system, spares to be available, and other factors.

It is probably unnecessary to justify to you the need to consider maintainability in equipment design. If anyone should doubt the importance of a maintainability program, he needs only to listen to the people who use the equipment. I recently conducted a study of human errors in the operation of electronic checkout equipment which took me to ten field organizations using and maintaining five completely different weapon systems. I interviewed supervisors and administered questionnaires to scores of technicians, gathering much information about errors and difficulties the technicians experienced as well as their opinions and suggestions for improvement of the maintenance system. There were many reports of parts and check points hard to reach. One technician reported that to replace a certain transformer on a Tacan unit, it was necessary to remove the entire front of the unit, disconnecting other wiring and parts, requiring about two hours. If the transformer had been easily accessible, ten minutes would probably have been adequate. Also removing and replacing the front panel often resulted in other malfunctions or required circuit adjustments. A large percent of all technicians in this study felt that better technical data, diagrams and check lists would speed up maintenance. Much of the equipment in these systems did not have adequate handles for lifting, had inadequately marked access openings and parts locations on chassis. Although final analysis of all the information from these technicians has not been made, it seems safe to say that more attention to maintainability in these systems would have saved thousands of man-hours and greatly reduced the so called "human error" problem.

This feedback from people who are using and maintaining Air Force equipment, some of it with a high degree of built-in maintainability and some barely maintainable, adds support to my comments during the past few minutes. Maintainability factors are important in the design of prime equipment and support equipment, and human factors data found in maintainability guides and in design handbooks can be an invaluable aid in the design of maintainable equipment.

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DESIGN MAINTAINABILITY ASSURANCE FOR THE AN/TSQ-47 SYSTEM

by

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SUMMARY

Recent research efforts have resulted in the development of techniques to implement the requirements of Maintainability Specification MIL-M-26512B. This paper describes the application of the basic concepts of this document during various phases of the AN/TSQ-47 program.

A maintainability program was initiated to implement the system specification for maintainability. This program provides for training, orientation, and control of subcontractor efforts. The program also provides a systematic approach for design review and documentation of the state-of-the-art of existing and newly designed hardware. Human engineering, reliability and logistical studies provide supporting documentation. Engineering support, essential in the achievement of maintainability, is featured as a system parameter; it is provided through concise and objective design guidelines.

Application of maintainability design checklists provides essential ingredients leading to predicted indices at the subsystem and system level. Investigation of problem areas during application of the checklists is illustrated. Preliminary empirical data and design scoring of maintainability factors is presented. Verification of derived numerics is carried out during subsystem and system tests to provide documentation for subsequent system design improvements. Subsequent considerations are given for the remainder of the program.

INTRODUCTION

It was expressly brought to the speakers attention that this presentation on "Designing Maintainability into the AN/TSQ-47 System Hardware" should not be philosophical. Voltaire once stated: "When he who hears doesn't know what he who speaks means, and when he who speaks doesn't know what he himself means, that is philosophy." Thus it is the speakers intention to dispense with philosophy and bring to light the factual criteria utilized in establishing the maintainability program for the AN/TSQ-47 system, beginning with the scope of the program and ending with resultant conclusions.

a. Scope of the Maintainability Program

System specification MIL-A-27919, with Amendment No. 1, establishes that the maintainability program shall be strictly limited to the detection, identification analysis, and reporting of problem areas at the system, subsystem, and major component level. A major component is defined as a complete set, such as a radar set, a communications set, a teletypewriter, an indicator, etc.

The program shall not concern itself with the individual circuit elements of such sets without submitting adequate technical justification to, and obtaining prior approval of, the cognizant engineering agency. It shall not be permitted to impede or delay the design, fabrication, test, or delivery of the AN/TSQ-47 system, nor shall its recommendations be considered sufficient grounds for engineering changes in the system or equipment specifications.

b. Applicable Documents

(1) Specifications - Maintainability requirements are contained in the following documents:

MIL-A-27919	Military Specification, Air Traffic Control and Communications System AN/TSQ-47[1]
MIL-M-26512B	Military Specification, Maintainability Requirements for Aerospace Systems and Equipment[2]
WS-Q47-19	General Requirement Specifications, Air Traffic Control/Communications System AN/TSQ-47[3]

Paragraph 3.5.2.7 of MIL-A-27919 states the requirements for the maintainability program.

(2) Special Instructions - In addition to the above requirements, special instructions have been issued by the 482-L System Program Office, requesting that initial maintainability analysis data be submitted concurrently with equipment design approval data.

SYSTEM DESCRIPTION

To delineate clearly the problems confronted by the Program Management Office of the AN/TSQ-47 program in establishing a meaningful maintainability program, it is necessary to describe briefly the AN/TSQ-47 system components and their complexity. Figure 1 shows a typical deployment of the subsystems that make up the AN/TSQ-47 system.

a. Subsystems and Major Components

(1) AN/TPS-35 Air Search Radar Set - This subsystem contains the following equipment:

a) Radar Equipment AN/UPS-1 - This is an off-the-shelf equipment that has been in existence a number of years, modified to incorporate Electronic Counter Counter-Measures (ECCM).

b) IFF (Identification Friend or Foe) Equipment - This is Government Furnished Equipment.

c) Microwave Relay Link - This is a modified version of the Motorola FRQ-11 system. (Also included is a coaxial link.)

d) Communications Equipment - This consists of ultra-high-frequency and very-high-frequency transmitter-receivers. In addition, the intershelter communications equipment RACEP (Random Access Correlation Extended Performance) is a major element of communications.

e) Power Sources - These consist of 2 to 20 kw gas turbine generators and miscellaneous equipment.

f) Junction Boxes - These are utilized for interconnection of power and signal distribution.

g) Air Conditioner - This unit maintains the shelter at an acceptable temperature and humidity.

All of the above units are integrated in an S141 type shelter.

(2) AN/TSW-5 IFR (Instrument Flight Rules) Shelter (RAPCON - Radar Approach Control) - This is the main center for landing aircraft under poor visibility conditions. Equipment contained within the shelter consists of:

a) IFF Equipment - This is Government Furnished Equipment.

b) Microwave Relay Link - This is a modified version of the FRQ-11 Motorola system (including a coaxial link).

c) Intershelter Communications - This is achieved via the RACEP equipment.

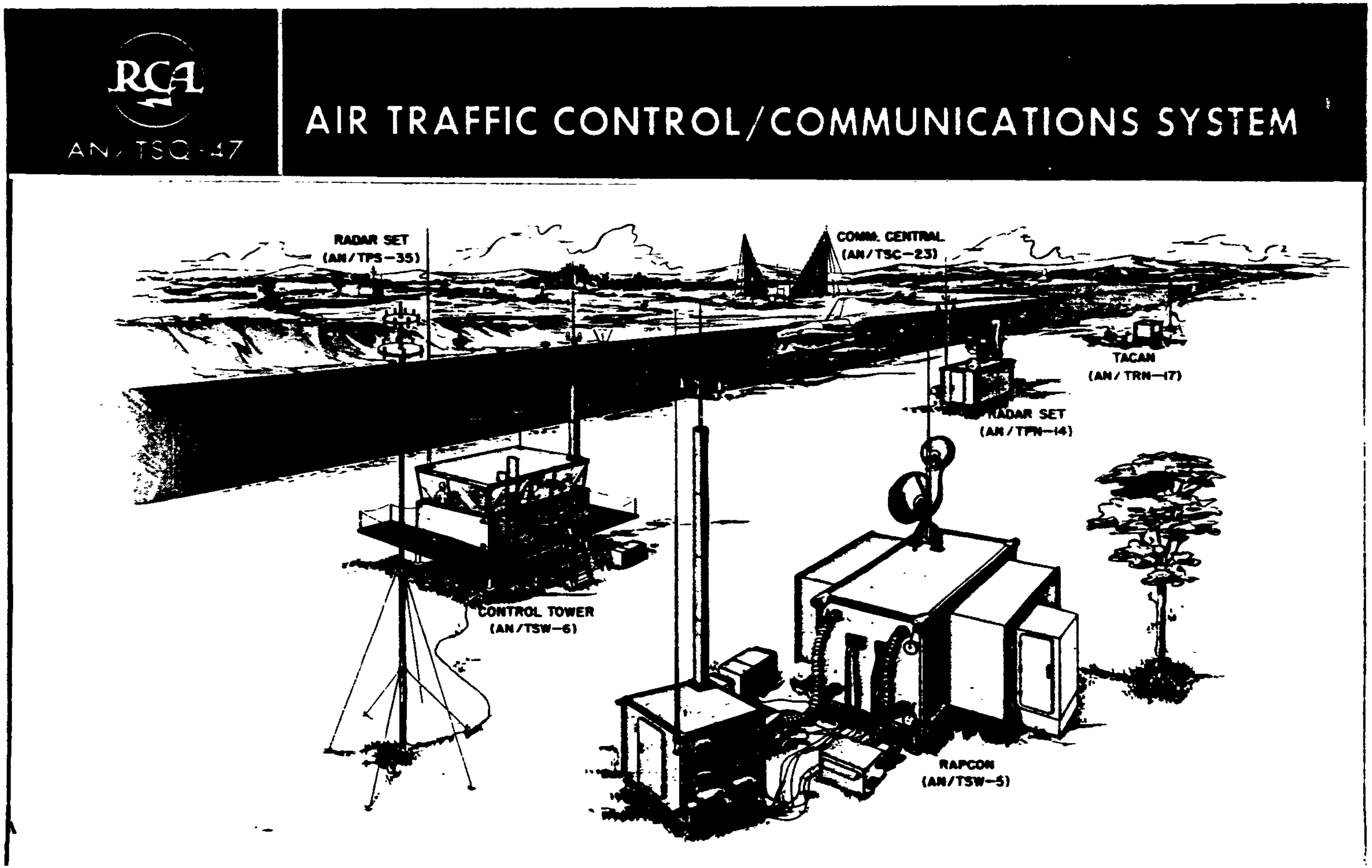

RCA
AN/TSQ-47
AIR TRAFFIC CONTROL/COMMUNICATIONS SYSTEM
RADAR SET (AN/TPS-35)
COMM. CENTRAL (AN/TSC-23)
TACAN (AN/TRN-17)
RADAR SET (AN/TPN-14)
CONTROL TOWER (AN/TSW-6)
RAPCON (AN/TSW-5)

Figure 1

d) Audio Equipment - This consists of mikes, headsets, and distribution panels.

e) Numerous Display and Control Panels (indicators and projectors are examples).

f) Power Sources - These are made up of 4 to 20 kw gas turbine generators and miscellaneous equipment meters, panels, etc.)

g) Junction Boxes - These distribute power and signal sources.

h) A light gun to signal landing aircraft.

i) Air Conditioner - This unit maintains temperature and humidity within the specially constructed shelter, which is motorized to extend wings for additional space requirements.

(3) AGA (Air-Ground-Air) Communications Shelter - This is an annex to the AN/TSW-5 RAPCON shelter. Contained within this shelter are the following:

a) Communications gear consisting of high-frequency, very-high-frequency, and ultra-high frequency transmitter-receiver equipment and intershelter communications gear (RACEP).

b) A self-contained 28-volt d-c power supply.

c) Various junction boxes for distribution of power and signals.

d) An Air Conditioner to maintain an acceptable environment within the shelter.

(4) AN/TSC-23 Air Traffic Control Communications Center Shelter - This unit provides world-wide communications via voice and teletype. Coded or uncoded information may be transmitted. Housed within the shelter are:

a) Teletype equipment consisting of frequency-shift keyers, control panels, jack panels, crypto, and teletypewriter.

b) Communications equipment consists of a high-frequency radio receiver and transmitter, and intershelter communications equipment (RACEP). An electric typewriter is used to duplicate messages.

c) Audio equipment, such as headsets, landlines, and microphones.

d) Power sources for this shelter are 3 to 20 kw turbine generators and special power supplies.

e) An air conditioner maintains the proper environment within the shelter, a modified S141 type.

(5) AN/TSW-6 VFR (Visual Flight Rules) Shelter (Flight Control Towers) - This subsystem provides communications for flight control under good visibility conditions and for taxiing aircraft to parking areas. Contained in this newly designed shelter are the following equipments:

a) High-frequency, very-high-frequency, and ultra-high frequency receiver-transmitter and intershelter communications equipment (RACEP).

b) Audio equipment

c) Display and control panels

d) Direction finder (DF) and indicator, which is remoted from the TRN-17.

e) Power supplies consist of 2 to 20 kw gas turbine generators and a 28-volt d-c power supply.

f) Junction Boxes for distribution of power and signal sources.

g) Light gun and wind measuring equipment.

h) An air conditioner for maintaining an adequate environment within the shelter.

(6) AN/TPN-14 Precision Approach Radar Set - This subsystem utilizes the following equipment:

a) Modified version of the field-proven AN/TPN-8 Radar Set.

b) Microwave equipment link utilizing the modified version of the Motorola FRQ-11 system.

c) Communications equipment consisting of very-high-frequency and ultra-high-frequency gear and intershelter communications gear (RACEP).

d) Audio equipment such as that contained in other subsystems.

e) Power sources are 2 to 20 kw gas turbine generators and special power supplies.

f) Junction Boxes for routing power and signal lines.

g) An Air Conditioner to provide the required environment within this modified S141 Shelter.

(7) AN/TRN-17 Beacon Transponder - This subsystem is utilized as a navigational aid for approaching aircraft, and is Government Furnished Equipment modified to operate with:

a) 20-kw gas turbine generator

b) Static converter (60-cycle operation)

c) Air conditioner for maintaining proper environment.

The navigational equipment consists of a transponder, monitor, and control unit.

b. Air Traffic Control Mission Concepts

Air Traffic Control/Communications System AN/TSQ-47 will be used by the Air Force Systems Command mobile squadron to support the operation commands on emergency military missions and to support civil authorities during disaster and emergencies. The following specific missions may be expected in support of the operational commands:

a) Support of a newly acquired advanced air base under combat conditions.

b) Temporary replacement or supplement to a fixed facility.

c) Training and mobility exercises.

c. Maintainability Factors

Before beginning the technical discussion it is worthwhile to state a generally accepted definition for maintainability: "The combined qualitative and quantitative characteristics of material design and installation which enable the accomplishment of operational objectives with the minimum expenditures including manpower, personnel skill, test equipment, technical data, and facilities under operational environmental conditions in which scheduled and unscheduled maintenance will be performed."

Maintainability factors can then be defined as a group of factors and/or environmental features which affect the performance of maintenance on electronic equipment. Some examples required by the equipment specifications are:

a) Test points for essential waveforms.

b) High-voltage interlocks and external indicator devices.

c) Circuit protectors with status indicators on front panels.

d) Ground straps for each rack for earthing.

e) All components to be readily accessible for tune-up operation and routine maintenance.

f) Units requiring assembly and disassembly during maintenance to be secured with captive screws.

g) Pattern charts of circuit functions located conveniently for rapid testing.

MAINTAINABILITY CONSIDERATIONS

As has been indicated, maintainability requirements for the AN/TSQ-47 system are specified in MIL-A-27919. Paragraph 3. 5. 2. 7 of the specification provides that maintainability specification MIL-M-26512B will be used as a guide to carry out analyses of systems and subsystems. The maintainability objectives for the AN/TSQ-47 are stated in general qualitative terms. The specifications establish a means for determination of the state-of-the-art of equipments to be used in the system without reference to a specific maintainability numerical as a design goal.

a. Specification References

Applicable portions of specification MIL-A-27919 are referenced as follows:

(1) Maintainability Principles - Paragraph 3. 8. 3 of the specification outlines general design considerations. Included are such factors as (1) minimum complexity of maintenance, (2) design for accessibility, and (3) design for rapid and positive equipment fault recognition.

(2) Maintainability Characteristics - Paragraph 3. 1. 4 states that maintainability characteristics of equipment shall be determined. Factors to be considered shall include Mean Time Between Failures, Mean Time To Repair, and Mean Time for Scheduled Maintenance.

(3) System Compatibility Factors - Paragraph 3. 2. 5 essentially states that major problem areas be determined during the analysis.

(4) Plan for Demonstration of Maintainability - A method for determining and establishing quantitative requirements for active maintenance downtime and for establishing tests are presented in Appendix A of the specification.

(5) Maintainability Requirements for Design Changes - Paragraph 3. 2. 7 states that additional evaluation will be made whenever design changes are made for product improvement.

(6) Maintainability Definitions and Maintainability terms are defined in Paragraph 6.3. Included are Active Corrective Downtime, Availability, and Maintenance Task. Appropriate symbols are given for each term.

b. Maintainability Requirements

General maintainability requirements for design and fabrication of equipment used in the AN/TSQ-47 system are outlined in applicable RCA specifications or "work statements". These work statements are issued by the Program Management Office to the various subcontractors. Maintainability tasks to be accomplished are set out in detail. In summary the tasks include the following:

(1) Maintainability Control - A maintainability program will be developed and implemented in accordance with applicable portions of MIL-M-26512B. New or modified equipment will be designed to the applicable portions of this specification.

(2) Maintainability Analysis Information - Maintainability data is to be provided on both existing and newly designed equipment at the initial stages of contract award. Requirements include general supporting information, maintainability policy and how the program will be implemented, documented mean downtime estimates, and problem areas.

(3) Maintainability Rating - Simulated maintenance tasks are to be scored using the checklists given in RADC-TDR-62-156.[4] Scoring is to be carried out through use of the given criteria. Qualified engineering personnel will perform the scoring.

c. Data Flow

The overall maintainability plan for the AN/TSQ-47 system is depicted in Figure 2. It can be seen that the program provides for a systematic approach to the flow and control of maintenance data throughout the development phases. Liaison with the System Project Office provides for decision-making capabilities on a timely basis. Essential data input is derived from equipment subcontractors for final analysis by the product assurance office. Where necessary, feedback loops are provided for corrective action, monitoring, and guidance in support of the subcontractor's program. Such groups as Human Engineering, Design Engineering, Aerospace Ground Equipment, and Personnel Subsystems, contribute essential data input for the final analyses.

(1) Data Acquisition - Essential data input for the subsystem analysis is derived from subcontractor reporting. Specific data requirements for maintainability analysis are shown in Figure 3. Under "Maintainability Analysis", specific numerics on newly designed modified, and existing equipment are provided. Maintainability rating data provides the basis for a theoretical evaluation of equipment through the application of

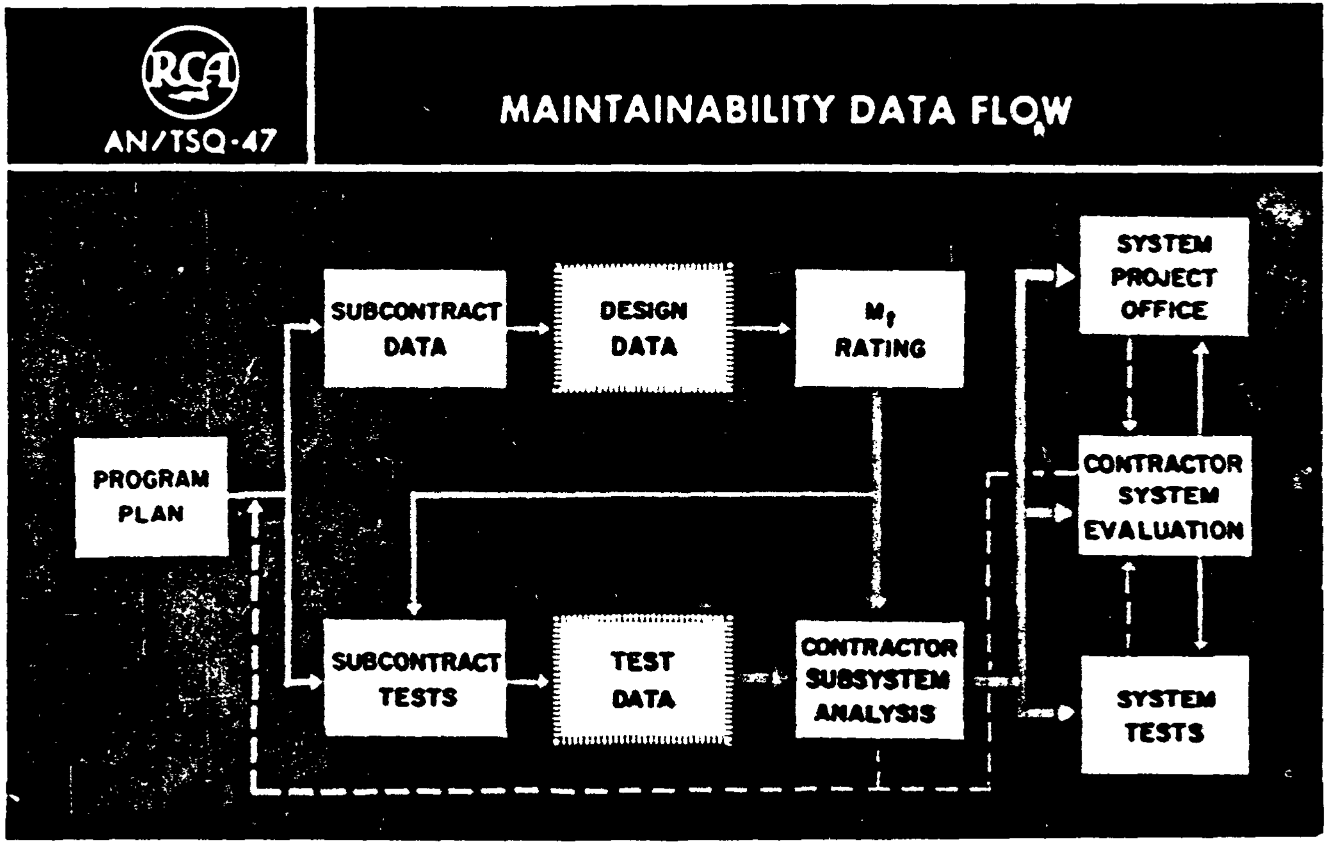
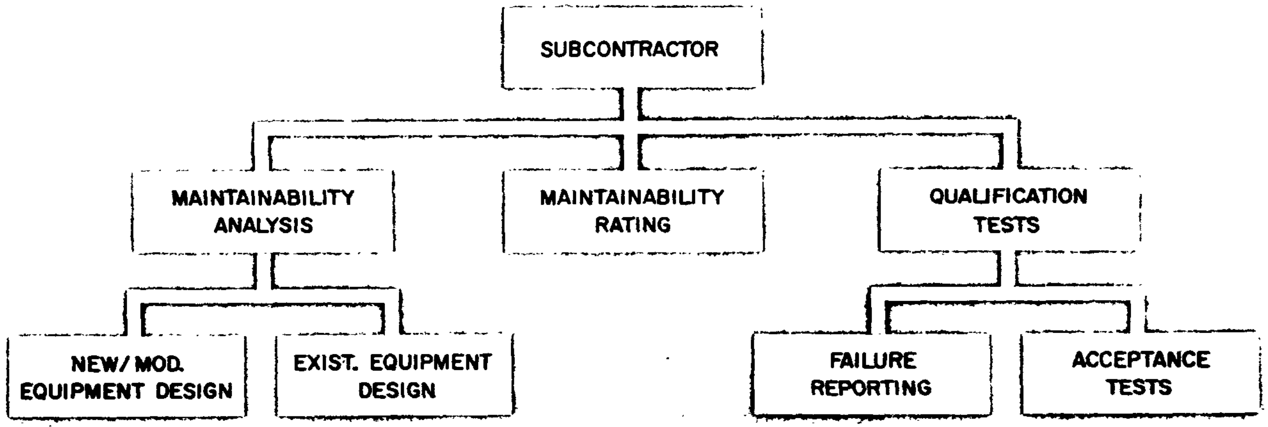

RCA
AN/TSQ-47
MAINTAINABILITY DATA FLOW
PROGRAM PLAN
SUBCONTRACT DATA
DESIGN DATA
M_t RATING
SUBCONTRACT TESTS
TEST DATA
CONTRACTOR SUBSYSTEM ANALYSIS
SYSTEM PROJECT OFFICE
CONTRACTOR SYSTEM EVALUATION
SYSTEM TESTS

Figure 2

AN/TSQ-47

SUBCONTRACT MAINTAINABILITY DATA FLOW



SUBCONTRACTOR

MAINTAINABILITY ANALYSIS

MAINTAINABILITY RATING

QUALIFICATION TESTS

NEW/MOD. EQUIPMENT DESIGN

EXIST. EQUIPMENT DESIGN

FAILURE REPORTING

ACCEPTANCE TESTS

Figure 3

the maintainability prediction technique previously referenced. Results of qualification and acceptance tests are reported in terms of maintenance time required to accomplish specific maintenance tasks resulting from actual equipment failures during operational tests. System engineering documentation provides supporting and supplementary input for subsequent analysis.

(2) Data Application - Maintainability numerics based on empirical and predicted data provided the essential ingredients for the construction of subsystem and system profiles. Such information constitutes basic decision-making data for the determination of design requirements for future systems. Submissions are also prepared as part of the design approval cycle on equipments and shelter interface. At this point, problem areas and recommendations are initially made. These recommendations are modified and expanded in the final phases of the project.

d. <u>Design Review</u>

Maintainability design review is carried out in conjunction with design approval action and as part of the prediction steps. Basic consideration is given to general maintainability features. A number of these features, expressed as design criteria for maintainability, are shown in Figure 4. To carry out the design review, certain technical information is necessary.

DRAWERS AND RACKS -- PULL-OUT FEATURES

COMPONENTS AND CIRCUITS -- PROTECTIVE DEVICES

ACCESSIBILITY -- HUMAN FACTORS

SELF-TEST FEATURES -- BUILT-IN TEST EQUIPMENT

PACKAGING CONCEPTS -- EASE OF REMOVAL

CONNECTORS -- QUICK-RELEASE FEATURES

TEST POINTS -- AVAILABILITY AND ACCESS

ADJUSTMENTS -- MINIMIZE REQUIREMENTS

Figure 4. Maintainability Design Criteria

(1) Technical Data - Technical data consists of the following:

a) Equipment physical construction and profiles.

b) Equipment block diagrams, schematics, and signal flow charts.

c) Equipment operating theory and characteristics.

d) Maintenance philosophy, operating procedures, and maintenance instructions.

(2) Major Problem Areas - In the design review, particular attention is given to major maintenance problem areas which may have significant effect on the system mission. For design approval, the worse case situation is taken to highlight these problem areas. The format illustrated in Figure 5, is used for this purpose. The resulting predicted maintenance time provides an indication of the maximum anticipated maintenance time to perform a maintenance task within the shelter interface; that is, the time to isolate a malfunction within the shelter to a specific location and replace the defective equipment.

e. Maintenance Analysis Data

Maintenance data from field evaluation, tests, and past experience provide documented time information. Since a major portion of the AN/TSQ-47 system utilizes equipment having operational background, this data constitutes an important and major input for establishing maintainability profiles and for design approval submission. As may be seen from Figure 5, documentation of major problem areas is required for proper analysis.

f. Qualification and Acceptance Tests

Information derived from qualification and acceptance tests provides important data for verification of initial maintainability evaluations. Supplementary information reflecting such maintenance concepts as technician requirements and spares provisioning may find useful application during final system analysis. Data to be reported includes the following:

(1) Failed component or part identification.

(2) Operate time of unit from which component or part was taken.

(3) Failure symptom.

(4) Cause of failure.

(5) Corrective action taken.

Additional data is provided through test records submitted during and after completion of the tests. Figure 6 indicates the flow paths for test data.

MAINTAINABILITY CONTROL

a. Evaluation and Control Procedures

It is desirable that a systematic and uniform approach be established and carried out during the program. Further, since the system consists of newly designed as well as existing equipment, it was necessary that maintainability criteria be developed for the program in the initial phases of development. Supporting documentation to the specifications and the program

DESIGN FEATURES		CHECKLIST SCORE	NO. OF PROBLEM AREAS	ENVIRONMENTAL AND SPECIAL PROBLEM REMARKS
A1	Access (Ext.)			
A2	Fasteners (Ext.)			
A3	Fasteners (Int.)			
A4	Access (Int.)			
A5	Packaging			
A6	Units - Parts			
A7	Displays			
A8	Fault Indicators			
A9	Test Points (Avail.)			
A10	Test Points (Ident.)			
A11	Labeling			
A12	Adjustments			
A13	Testing (In Circuit)			
A14	Protective Devices			
A15	Safety (Personnel)			
	TOTAL			

Figure 5. Physical Design Checklist

RCA AN/TSQ-47

MAINTAINABILITY TEST PROGRAM

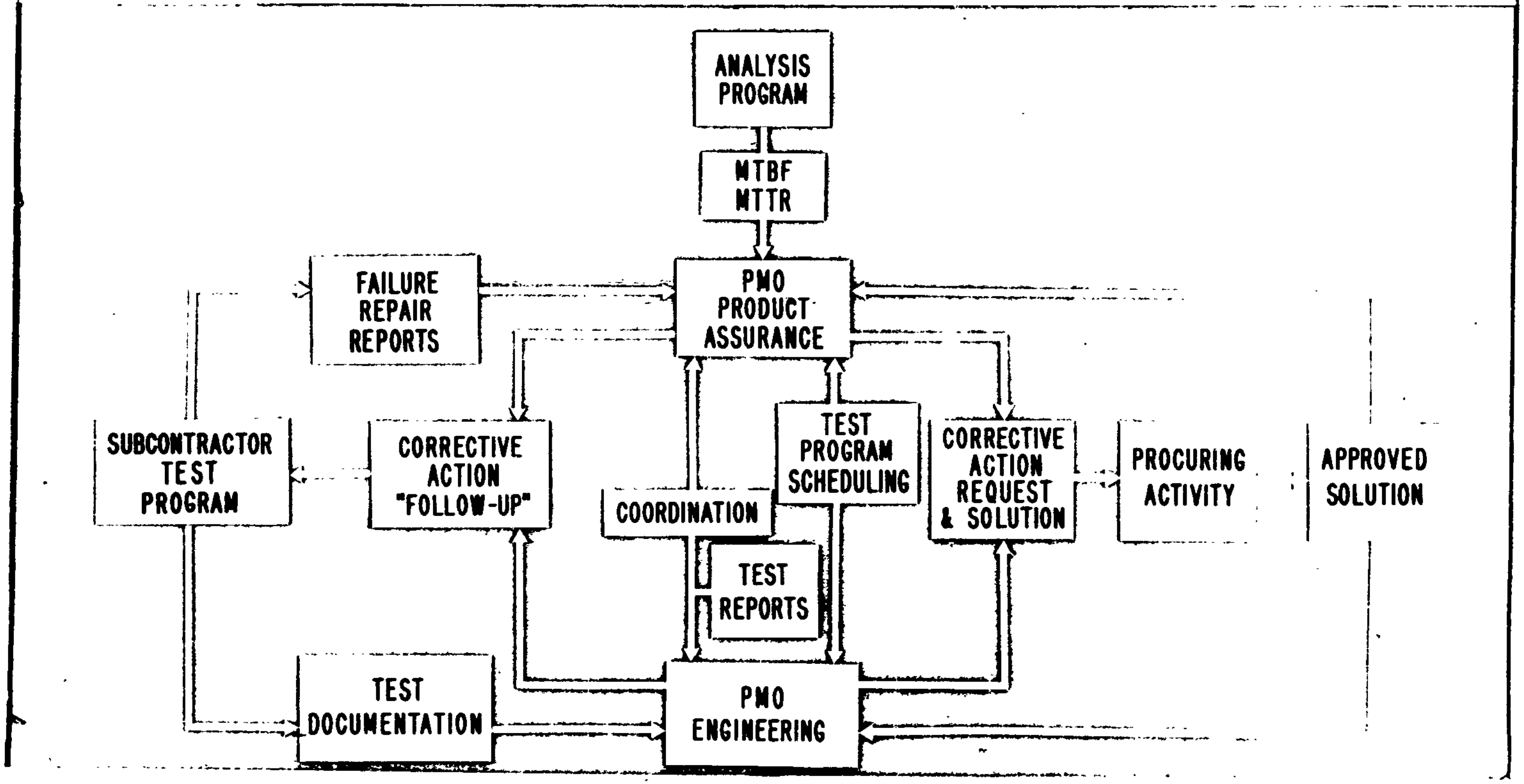


Figure 6

plan has been accomplished through the issuance of a maintainability guideline.[5] This document serves two purposes: (1) uniform procedures for data reporting and analysis are provided to subcontractor and other cognizant activities and (2) maintainability design criteria are formulated for engineering guidance. In summary these guidelines present the information described below.

(1) Principles and Application - Basic concepts and leading particulars pertaining to the prediction technique are explained. The method for applying these techniques are detailed.

(2) Prediction Procedure - Steps leading to scoring and calculating appropriate indices are outlined. Mathematical formulas required for the determination of these indices are given.

(3) Scoring Checklists - Criteria for evaluating maintainability design features are given. Each checklist question is explained to enable a qualified engineer to score the checklists. Checklist A, Physical Design, Checklist B, Design Dictates-Facilities, and Checklist C, Design Dictates-Maintenance Skills, are presented.

(4) Maintainability Design Guidelines - Maintainability factors important to design are outlined. These factors have been found to have significant influence on equipment maintenance time.

(5) Terms and Definitions - Terms important to maintainability measurement are presented and defined. These terms are consistent with usage in government and industry.

(6) Failure and Repair Reporting - Procedures for data acquisition during qualification and acceptance testing are detailed. Means are provided for collecting essential equipment data during equipment tests.

b. <u>Development of the Program Plan</u>

The applicable documents previously discussed, and the RCA AN/TSQ-47 System Proposal were utilized to construct the Maintainability Program Plan. Careful attention was given to the time phasing of contract elements, since equipment delivery was scheduled 12 months from the contract date of award. Development of the program plan was based on the following premises:

a) Maintainability was not to impede or delay the design, fabrication, test, or delivery of the system.

b) Recommendations could be given but not necessarily implemented on this program.

c) A recommended program covering future USAF Category II and III tests, to follow acceptance tests, would be outlined.

(1) With this background, it was possible to construct the program outline by considering the following question. "How can RCA provide the System Project Office with an effective and timely program within the time scheduling requirements of the contract?"

(2) Product Assurance Plan, Section B - Maintainability will be investigated quantitatively in order to evaluate problem areas and recommend solutions to the procuring activity. The program plan contains the following sections:[6]

- I. Maintainability Prediction
  - A. Completion of checklists A, B, and C of RADC-TDR-62-156.
  - B. Initial calculation of M_T.
  - C. Reliability and Maintainability Status Report -day reporting interval).
- II. System Evaluation at time of Design Approval.
  - A. Correlation of maintainability principles with manpower cost and input of M_T.
  - B. Statement of maintainability problem areas with preliminary recommendations.
  - C. Updating of maintainability analyses to be included in 90-day status reports.
- III. Final Recommendations
- IV. Plan for USAF Category II/III Tests of the AN/TSQ-47.
  - A. System Maintainability Demonstration.
  - B. System Maintainability Evaluation.

c. Implementation of Plan

Since the program involves numerous subcontractors it was necessary to devise a method of control. Control was established for audit of both overall product assurance and maintainability analysis.

(1) Product Assurance Program Audit, Section H - The Product Assurance Office for the AN/TSQ-47 system is responsible for auditing subcontractors for the system, susbystems, and major components, previouslydescribed, for the following activities and in accordance with the contract and applicable specifications:

a) Reliability

b) Maintainability

c) Standardization

d) Quality assurance

e) Design assurance

f) Failure data collection and analysis

g) Audit check list preparation

(2) Audit Checklist - Expanding on b) and e) of the above list, product assurance audit checklists were developed. Figure 7 illustrates the various areas reflecting the overall subcontractor maintainability program. A similar checklist, shown in Figure 8, was developed to evaluate the progress of the subcontract maintainability analysis.

(3) Audit Scheduling - An audit schedule was developed to cover three periods during the contract:

a) Prior to fabrication in order to orient subcontractors on the requirements of the work statement, specifications, and contract, as well as an initial audit of facilities and the capability of meeting these requirements.

b) During test to evaluate ease in troubleshooting and repair of equipment and as a follow-up audit.

c) Final audit prior to delivery of hardware to observe acceptance tests and final inspection of equipment.

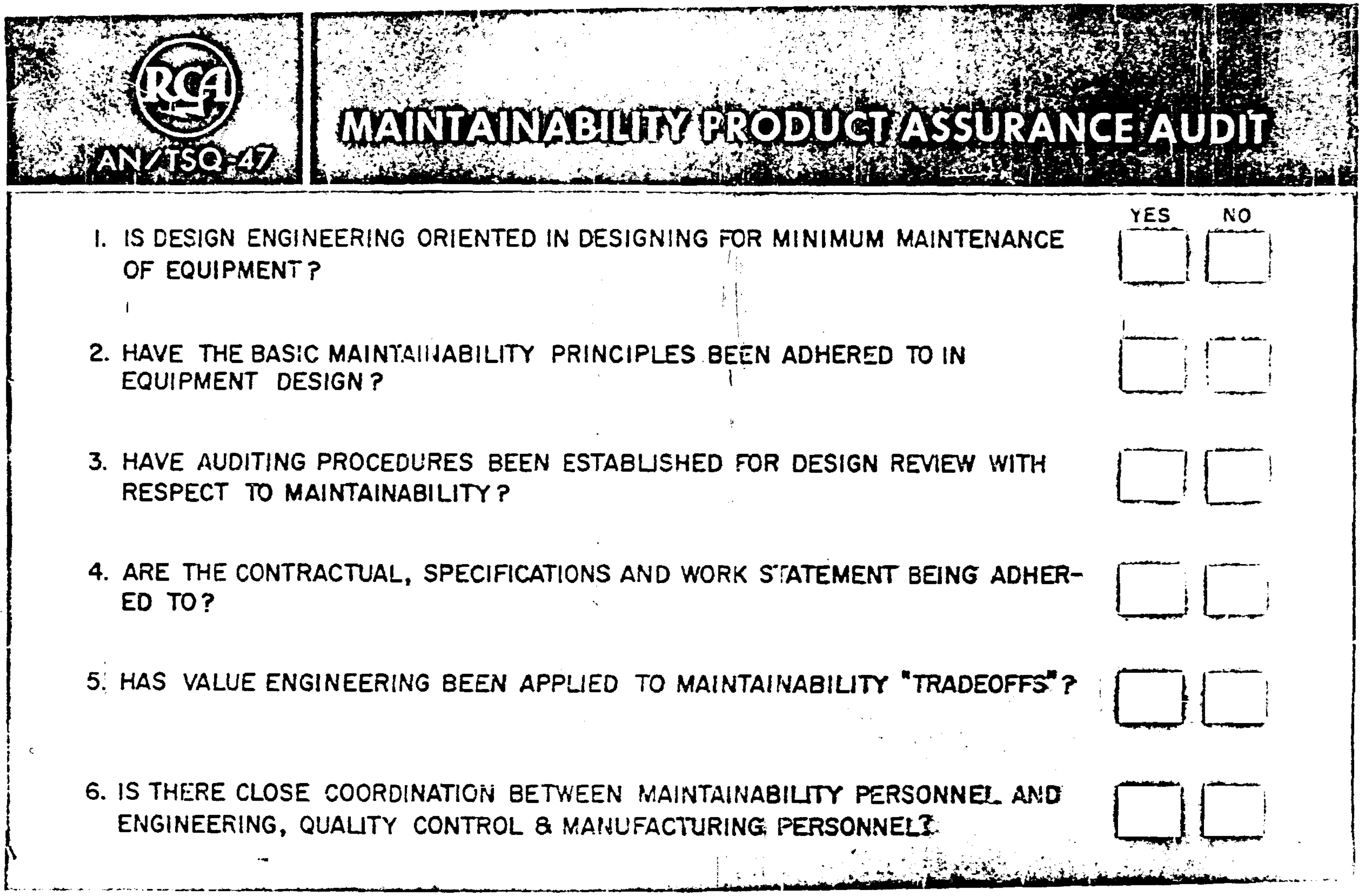
SUPPORTING ACTIVITIES

In order that an effective maintainability program may be carried out, certain vital technical data must be available on a timely basis. Data pertaining to equipment reliability, personnel technical requirements, and design data must be made available early in the development phases, and updated periodically during the program.

a. Reliability Data

Reliability measurements provide a direct indication of equipment maintenance requirements. Equipment failure rates and the number of parts, when translated into maintenance terms, reflect the frequency of maintenance for equipment, subsystems, and the system. In the AN/TSQ-47 program reliability data serves two important functions: (1) failure contribution of components, assemblies, etc. are determined and (2) the severity of problem areas is isolated. Additional application of reliability data may be made during final system evaluation where an overall product value is desired.

(1) Initial Analysis - Equipment failure rates are applied during the initial analysis of maintenance data to evaluate equipment and shelter interface. Through the use of reliability data, areas likely to be subjected to repeated maintenance are isolated.



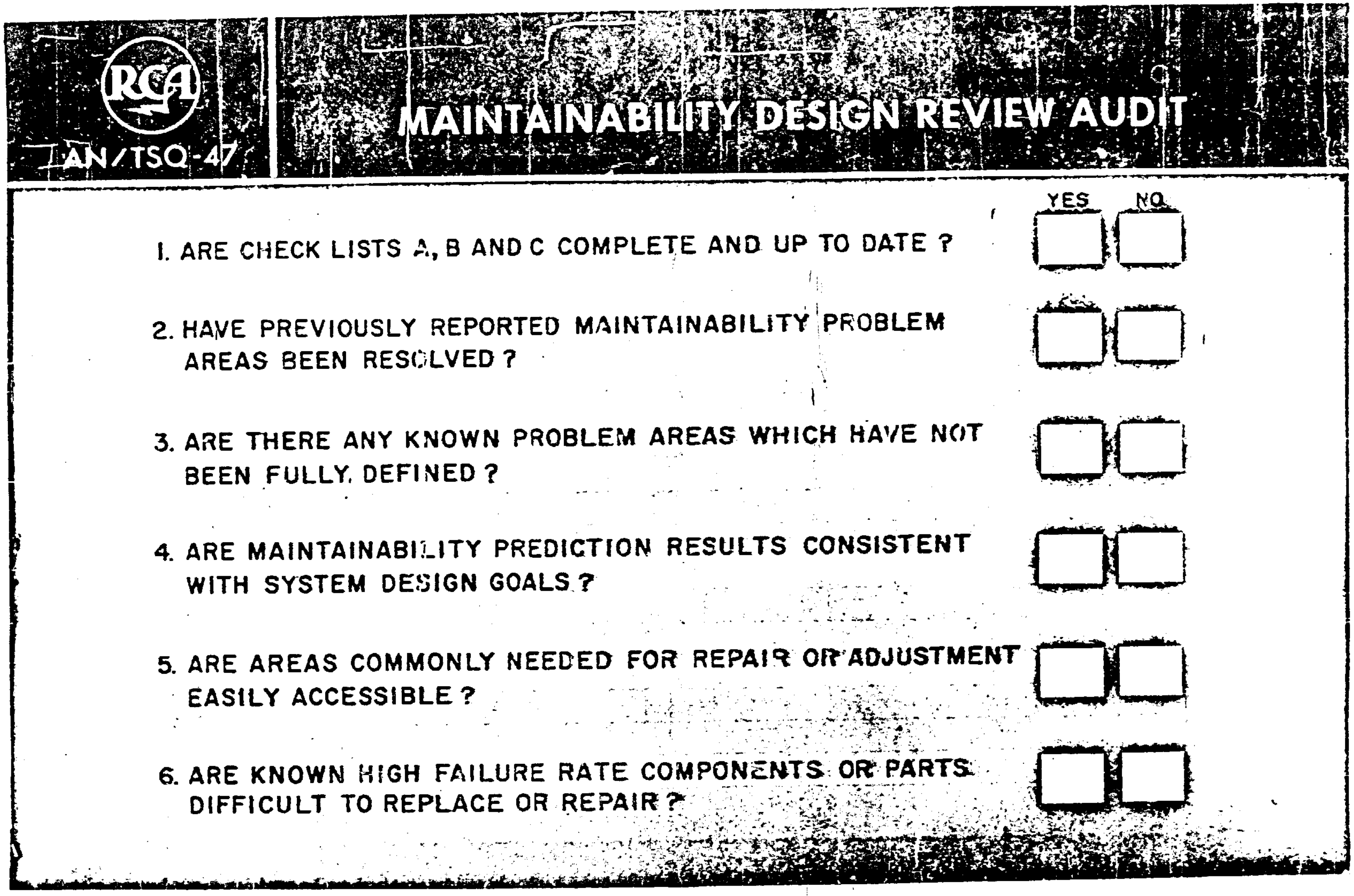
RCA

AN/TSQ-47

MAINTAINABILITY PRODUCT ASSURANCE AUDIT

	YES	NO
1. IS DESIGN ENGINEERING ORIENTED IN DESIGNING FOR MINIMUM MAINTENANCE OF EQUIPMENT?	☐	☐
2. HAVE THE BASIC MAINTAINABILITY PRINCIPLES BEEN ADHERED TO IN EQUIPMENT DESIGN?	☐	☐
3. HAVE AUDITING PROCEDURES BEEN ESTABLISHED FOR DESIGN REVIEW WITH RESPECT TO MAINTAINABILITY?	☐	☐
4. ARE THE CONTRACTUAL, SPECIFICATIONS AND WORK STATEMENT BEING ADHERED TO?	☐	☐
5. HAS VALUE ENGINEERING BEEN APPLIED TO MAINTAINABILITY "TRADEOFFS"?	☐	☐
6. IS THERE CLOSE COORDINATION BETWEEN MAINTAINABILITY PERSONNEL AND ENGINEERING, QUALITY CONTROL & MANUFACTURING PERSONNEL?	☐	☐

Figure 7



RCA

AN/TSQ-47

MAINTAINABILITY DESIGN REVIEW AUDIT

	YES	NO
1. ARE CHECK LISTS A, B AND C COMPLETE AND UP TO DATE ?	☐	☐
2. HAVE PREVIOUSLY REPORTED MAINTAINABILITY PROBLEM AREAS BEEN RESOLVED ?	☐	☐
3. ARE THERE ANY KNOWN PROBLEM AREAS WHICH HAVE NOT BEEN FULLY DEFINED ?	☐	☐
4. ARE MAINTAINABILITY PREDICTION RESULTS CONSISTENT WITH SYSTEM DESIGN GOALS ?	☐	☐
5. ARE AREAS COMMONLY NEEDED FOR REPAIR OR ADJUSTMENT EASILY ACCESSIBLE ?	☐	☐
6. ARE KNOWN HIGH FAILURE RATE COMPONENTS OR PARTS DIFFICULT TO REPLACE OR REPAIR ?	☐	☐

Figure 8

(2) Prediction - In conjunction with the scoring process and application of the prediction technique, reliability data is used to determine the failure contribution of equipment assemblies, modular units, etc. This process isolates high-density maintenance areas and establishes the need for further consideration of potential problem areas. Table 1 illustrates the procedure, utilizing basic reliability data.

Table 1. Equipment Failure Contribution

Modules (Assembly)	Complexity	Failure Rate (%/1000 Hrs)	Failure Contribution (%)
20-30 Mc IF Amplifier	128	0.31465	15.0
1.85 Mc IF Amplifier	104	0.22477	11.0
Audio Amplifier	117	0.01849	2.0
Spectrum	59	0.17579	8.0
Power amplifier	110	0.22372	11.0
Modular	47	0.10385	5.0
Guard receiver	43	0.16229	8.0
Relay	127	0.35654	17.0
Mechanical drive	11	0.05930	3.0
Oscillator	17	0.13609	7.0
Rectifier	68	0.09320	4.0
Power supply	21	0.00670	0.3
Chassis	19	0.18776	9.0
TOTAL	878	2.06315	100%

Note that the analysis indicates that the relay assembly contributes approximately 17% of the equipment failures. In contrast, the power supply contributes less than 2%. It can be expected in this instance that maintenance will be proportionately distributed. Further, this distribution will be closely allied with the number of tubes used in each case. The process may be extended to include parts in each assembly or unit to actually select the high-failure parts for scoring of maintenance tasks.

b. Logistics and Support

Logistics and support, while not a direct function of maintainability design, is an important factor in maintainability evaluation. Information relating to technical personnel, maintenance levels, and spares provisioning determines the analytical approach for maintainability evaluation. Such data is particularly important during equipment scoring for prediction purposes. In the AN/TSQ-47 program logistics and support information is available through various studies and documentation from support groups.

(1) Technical Personnel Requirements - Quantitative and qualitative data relating to technician qualification and human factors considerations establish basic premises for system analysis and scoring.[7] Through personnel subsystem documentation, such factors as maintenance technician capabilities and manning requirements are established. In the maintainability analysis process, these factors must remain constant and be stipulated for any given measurement. The average maintenance technician must be described in quantitative terms. For example, an equipment design characteristic which may not have a detrimental effect on a seven-level technician would seriously handicap a three-level technician when performing maintenance. This would be reflected in higher maintenance downtime measurements.

(2) Human Factors - Human factors requirements indirectly reflect the design considerations for maintainability. Where technical personnel needs are jeopardized by restrictions imposed by design, human factors and maintainability evaluations tend to substantiate and verify problem areas discovered on an independent basis. Actual maintenance technician requirements are outlined in the Qualitative and Quantitative Personnel Requirements Plan and in human engineering reports.[8]

c. Test Equipment and Spare Provisioning

(1) Supporting Documents - Documentation of test equipment and test procedures is given in the Aerospace Ground Equipment Plan.[9] This document is submitted in accordance with MIL-D-9412D. It outlines test equipment and test requirements for adjustment and repair of AN/TSQ-47 equipment. Test equipment requirements are presented for operational, organizational, and depot maintenance. Time to accomplish specific tasks are provided wherever practical.

(2) Basic Considerations - At this time, establishment of spares provisioning and maintenance level concepts has not been completed. Pending final decisions regarding these areas, the analysis considers requirements necessary to insure system operational capability regardless of the circumstances involved. Therefore, the analysis reflects the inherent equipment maintainability.

EQUIPMENT EVALUATION

It has been pointed out that the maintainability analysis of the AN/TSQ-47 system is concerned with the determination of indices at the black-box level. These indices are obtained from (1) documentary data based on previous equipment usage and experience and engineering estimates and (2) application of checklist scores to the prediction technique. Final analysis is made in conjunction with final system and subsystem tests. Results provide the basis for establishing system maintainability and determining recommendations for design improvements for future systems. Maintainability concepts, including level of maintenance, technician requirements, and spares provisioning are reviewed and coordinated with appropriate groups for final review and recommendations.

a. Maintainability Analysis Procedure

The objective of the maintainability analysis is to determine the average active downtime for each equipment in the AN/TSQ-47 system. The term active downtime is used to signify that such contingencies as awaiting supply action and administrational functions are not included in the evaluation. Average downtime is expressed in terms of average corrective tasks and average preventive tasks.

(1) Maintenance Indices

(a) Corrective Downtime - Corrective downtime is associated with the occurrence of true random failures and, therefore, is a function of reliability. It is the time required to diagnose and correct an equipment malfunction resulting from such failure. Corrective downtime may be expressed as follows:

$$\overline{M}_{ct} = \frac{M_{ct}}{N_c} = \text{average corrective downtime per task,}$$

where M_{ct} = total corrective downtime for all tasks under consideration,

N_c = number of corrective tasks based on occurrence of true random failures.

(b) Preventive Downtime - Preventive downtime measures the requirements for retaining an equipment at a specified performance level. Preventive maintenance may or may not occur during an operational period. Preventive downtime may be determined as follows:

$$\overline{M}_{pt} = \frac{M_{pt}}{N_p}$$

where M_{pt} = total downtime for all tasks under consideration,

N_p = number of preventive tasks.

In practice preventive tasks often involve actions to achieve optimum equipment performance and to forestall or prevent equipment degradation. Where maintainability has been effectively designed into equipment, preventive maintenance capabilities are substantially improved. Scheduling for performance checkouts and adjustments may be adjusted to meet specific mission requirements.

(c) System Availability - Equipment availability may be determined by considering reliability and maintainability numerics. Availability is expressed by the following formula:

$$A_i = \frac{MTBF}{MTBF + \overline{M}_T} = \text{inherent availability}$$

where $MTBF = \frac{1}{\lambda_t}$ = mean time between failures,

λ_t = total equipment failure rate,

$\overline{M}_T$ = average total downtime for corrective and preventive maintenance tasks.

System availability is a probability function expressing the degree of certainty for satisfactory operation in a given time period. It is most useful for such planning purposes as establishing mission requirements, subsystem utilization, etc.

(2) Subcontractor Reports - As was shown in Figure 2, maintenance indices are provided by the contractor. This data consists of corrective and preventive time estimates for newly designed modified, and existing equipments. The data is reviewed and summary information is submitted to the System Project Office with any problem areas and recommendations for design changes. Questions regarding the nature of the data, integration and clarification are referred to the subcontractor and/or to the cognizant subsystem engineer. Where scoring data is in suitable form, maintenance indices are developed for subsequent system analysis.

(3) Maintainability Prediction - Principles and procedures developed in RADC-TDR-156 are used to evaluate maintainability design features of each equipment. This evaluation provides a quantitative evaluation of the inherent maintainability of the equipment based on the maintenance level established by appropriate concepts for the AN/TSQ-47 system. This prediction is accomplished by scoring the three checklists for maintainability design factors. These factors are:

a) Physical Design (Checklist A) - Access, types of fasteners, packaging test points, and visual displays are among the factors considered.

AN/TSQ-47

MAINTAINABILITY DESIGN FEATURES

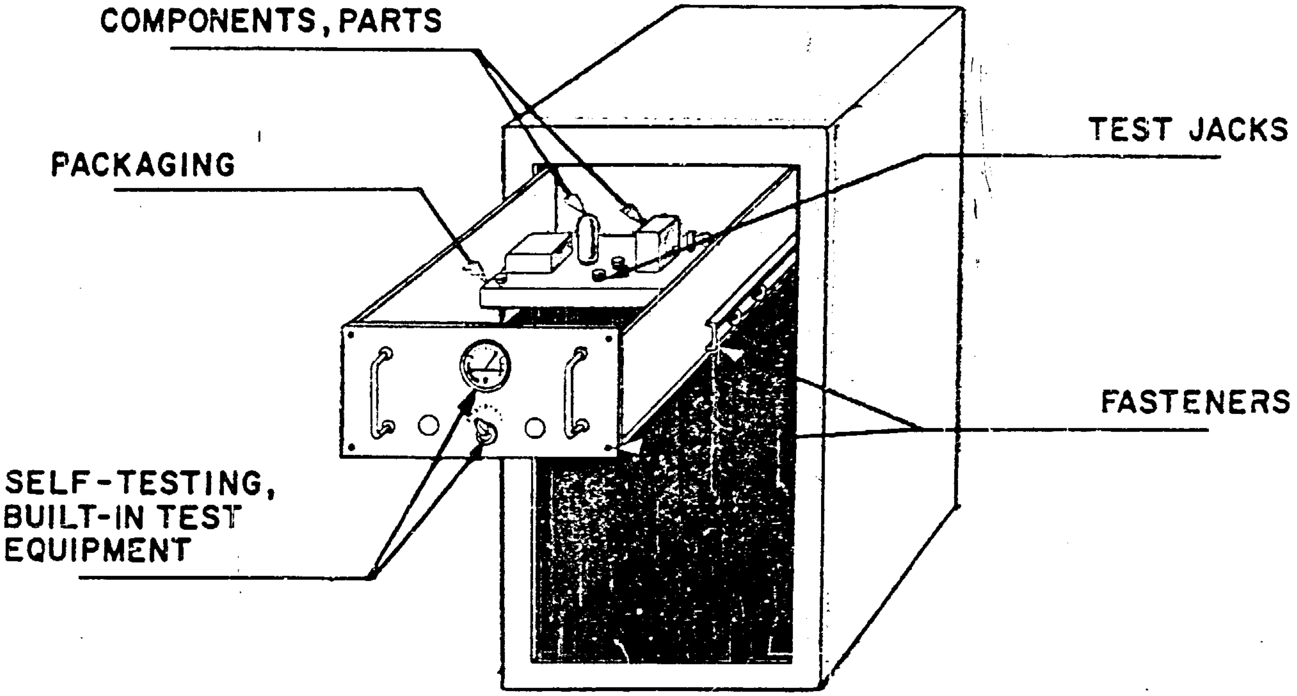


Figure 9

b) Design Dictates - Facilities (Checklist B) - Design requirements for test equipment, special connectors, technical assistance, and physical equipment arrangement are scored.

c) Design Dictates - Maintenance Skills (Checklist C) - The checklist considers the design requirements for physical strength, logical analysis, and memory.

(4) Scoring - The prediction technique provides that certain criteria be used to score each question (Checklist A has 15 questions, Checklist B has 7 questions, and Checklist C has 10 questions). These criteria are applied to the equipment design as reflected in specifications, physical layouts, and other pertinent documentary data. Each checklist question is given a score between 0 and 4 depending on the degree to which the equipment design meets a specific maintainability factor (checklist question). Figure 9 illustrates a number of design factors presented in Checklist A. Note that such maintainability design features as built-in monitoring devices, quick-release fasteners, modular construction, and accessibility enhance the maintainability capability of the equipment. Scoring may be carried out on a sufficient number of tasks to establish a statistical validity to determine average maintenance time.

b. Preliminary Findings

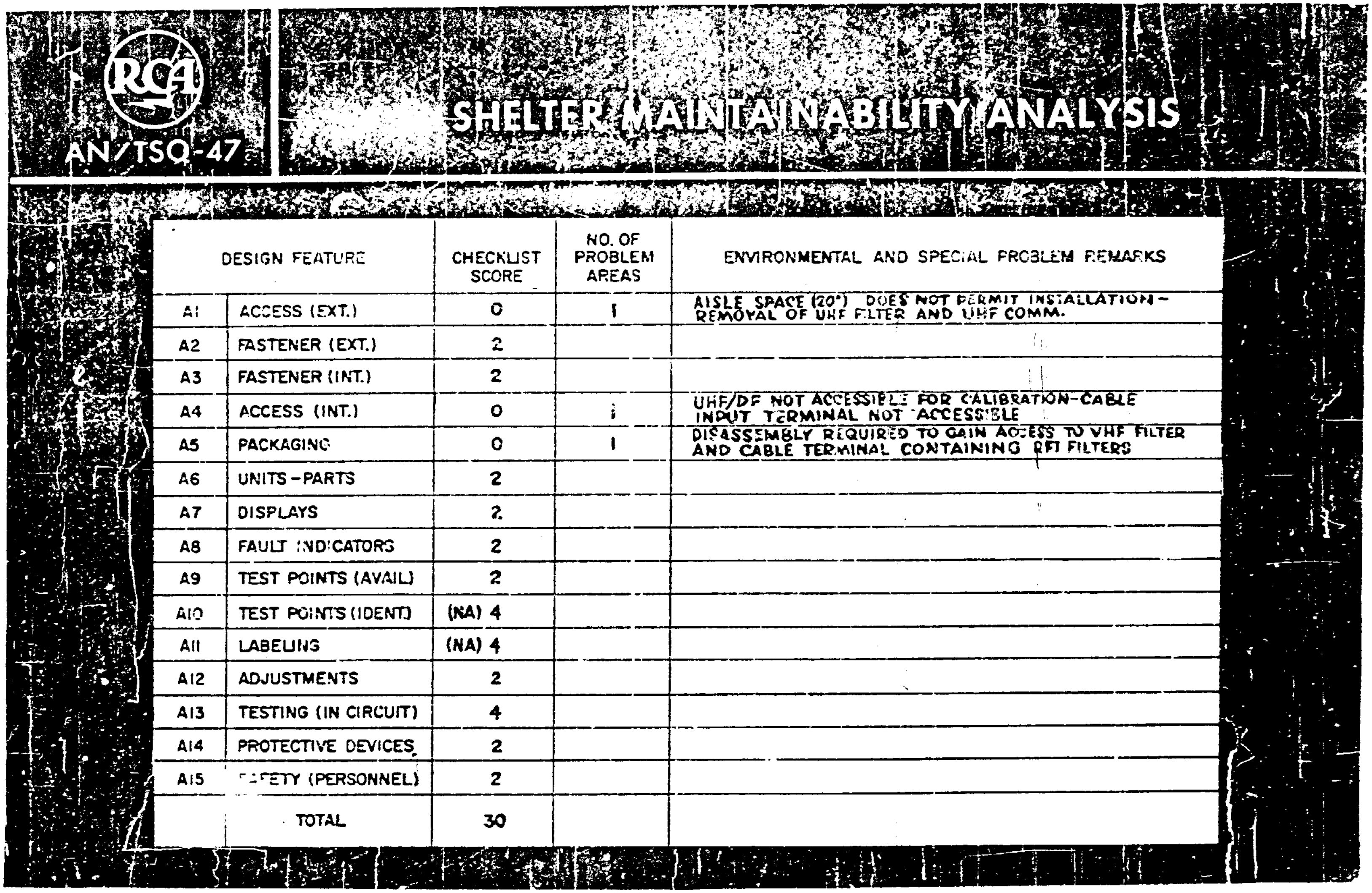
Final determination of the maintainability characteristics of the AN/TSQ-47 system will be possible at the completion of Category II and III tests. These tests will be performed under actual end-use conditions. At this time the full implication of the design principles and maintenance concepts will be realized. To provide an insight into the anticipated maintainability capabilities and major problems resulting from the integration and use of equipment programmed for each system, a number of preliminary findings are presented here.

(1) Subsystem Maintainability - Subsystem analysis considers the interface relationships of shelter equipment and the shelter. Through the analysis it is possible to establish the time requirements for maintenance as related to subsystem malfunction detection, symptom diagnosis, and replacement of defective equipment. To highlight problem areas the analysis is based on the worse case situation. Scoring is predicted on this criteria. Table 2 summarizes the analysis and major problem areas for a number of subsystems. The maintenance times shown indicate, more realistically, the maximum anticipated downtime, including preventive and corrective tasks, rather than average values.

(2) Scoring Results - In Figure 10 the actual scoring of Checklist A is presented. A score of zero reflects the worse case condition with the major problem summarized where applicable. Where a particular checklist question does not apply, that is the factor does not constitute a requirement in the maintenance scoring, "NA" is noted and a score of 4 is given. In those instances where insufficient data is available to score a particular question, "NS" is noted and an average question score is determined. In subsequent analysis NS scores are recorded where information becomes available.

Table 2. Preliminary Maintainability Evaluation, AN/TSQ-47 System

SYSTEM	CHECKLIST SCORE			$\overline{M}_T$ ESTIMATE (Hr)	MAJOR PROBLEM AREAS
	A	B	C		
Shelter 1	32	12	8	2.9	Signal entrance cable not accessible for subsystem tests. Confined packaging of equipment in shelter reduced maintenance capability.
Shelter 2	30	12	3	3.2	UHF Filter, VHF Communications, and cable input terminal not accessible for removal.
Shelter 3	45	20	23	1.3	No major problem areas. Indicator requires mobility for ease of access.
Shelter 4	32	17	16	1.7	Accessibility to receiver inadequate. No interlock safety devices provided on antenna pedestal.



SHELTER MAINTAINABILITY ANALYSIS

DESIGN FEATURE		CHECKLIST SCORE	NO. OF PROBLEM AREAS	ENVIRONMENTAL AND SPECIAL PROBLEM REMARKS
A1	ACCESS (EXT.)	0	1	AISLE SPACE (20") DOES NOT PERMIT INSTALLATION-REMOVAL OF UHF FILTER AND UHF COMM.
A2	FASTENER (EXT.)	2		
A3	FASTENER (INT.)	2		
A4	ACCESS (INT.)	0	1	UHF/DF NOT ACCESSIBLE FOR CALIBRATION-CABLE INPUT TERMINAL NOT ACCESSIBLE
A5	PACKAGING	0	1	DISASSEMBLY REQUIRED TO GAIN ACCESS TO VHF FILTER AND CABLE TERMINAL CONTAINING RFI FILTERS
A6	UNITS-PARTS	2		
A7	DISPLAYS	2		
A8	FAULT INDICATORS	2		
A9	TEST POINTS (AVAIL)	2		
A10	TEST POINTS (IDENT)	(NA) 4		
A11	LABELING	(NA) 4		
A12	ADJUSTMENTS	2		
A13	TESTING (IN CIRCUIT)	4		
A14	PROTECTIVE DEVICES	2		
A15	SAFETY (PERSONNEL)	2		
	TOTAL	30		

Figure 10

CONCLUSIONS

It has been the purpose of this paper to describe briefly the AN/TSQ-47 maintainability requirements and their implementation. In accordance with the system specification, a maintainability program was initiated detailing the analysis to be accomplished. Military Specification MIL-M-26512B was used as a basic guide to outline the steps to be carried out during the program. A maintainability guideline was prepared outlining subcontractor responsibilities, method of data analysis, criteria, essential terms and definitions, and data reporting procedures. Maintainability design considerations affecting maintenance time were outlined in this document. Finally, the basic steps to be used in the application of the maintainability technique were illustrated.

a. Status and Accomplishment

As part of the design approval cycle, analyses of equipment and subsystems have been carried out. Supporting the analyses are subcontractor reports submitted in accordance with data reporting requirements. Scoring and empirical data is currently being prepared for the determination of applicable indices for the system. Essential tasks accomplished to date are described below.

(1) Shelter Evaluation - A majority of the subsystem shelter interfaces have been evaluated and scored and preliminary downtime estimates have been calculated for worse-case conditions. Recommendations have been proposed as part of the design approval submissions. For example, it has been recommended that operator unattended equipment in the control tower be housed in a separate accessible shelter beneath the tower. This arrangement will make equipment accessible for maintenance and provide greater operator movement in the tower.

(2) Maintainability Prediction - Maintainability prediction for a number of equipments has been completed. Tasks were selected, and scored and downtime estimates were determined for the prediction. Problem areas were investigated and recommended solutions were submitted as part of the design approval cycle.

b. Future Needs

Within the scope and time scheduling of the AN/TSQ-47 system, the maintainability program has effectively achieved its primary objective, i. e., to analyze and report design problem areas. It has provided the necessary guidance to establish the state-of-the-art of off-the-shelf equipment predominantely used in the system. The maintainability evaluation has provided the Air Force with the necessary maintainability improvements for future procurements. For future planning the following suggestions are recommended:

a) Establish Air Force and contractor policies affecting spares provisioning, maintenance levels, and technical personnel requirements prior to system design.

b) Develop liaison with all cognizant groups at the initial phase of the program that will continue throughout all phases.

c) Establish maintainability requirements in terms of specific tasks to be accomplished within the framework of contractual needs, time scheduling, and costs at the time of contract award.

References

1. "Military Specification, Air Traffic Control and Communications System AN/TSQ-47", MIL-A-27919 (USAF), Amendment No. 2, Air Force Office of Aerospace Research, dated 1 March 1962.

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5. "Maintainability Analysis Guidelines for the AN/TSQ-47 Program", RCA-ACCD, Burlington, Mass., dated 21 December 1962.

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7. "Qualitative and Quantitative Personnel Requirements Information, Air Traffic Control/Communications System AN/TSQ-47", CR-62-548-16, RCA-ACCD, Burlington, Mass., dated 15 December 1962.

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SPACECRAFT MAINTAINABILITY & RELIABILITY

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SPACECRAFT MAINTAINABILITY & RELIABILITY

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SUMMARY

The techniques and controls used to assure spacecraft mission success through maintainability in product assurance programs is discussed. The old maintainability concepts for weapon systems and their inadequacy for manned spacecraft will be reviewed briefly. The maintainability concepts for manned lunar spacecraft which assure the maintenance of all system functions during the mission will be examined. These concepts will permit achievement of mission success which approaches 100% with hardware having an inherent reliability of only 90% to 95%. The method whereby a step-by-step integration of these maintainability concepts into the design analysis and review and subsequent extension into the test and redesign activities for verification will be discussed in detail.

PREFACE

Maintainability and reliability must be brought together through a program that treats reliability as the sum of design and quality, and maintainability as the effective consideration of the man-machine relationship.

Reliability (R) is the probability of performing, without failure, a specified function under given conditions for a specified period of time. Reliability is a measure of the time stability of a product's performance and is expressed as the sum of design and quality.

Maintainability (M) is that quality of the combined features of equipment, design, and installation which facilitates the accomplishment of inspection, test, servicing, repair, and overhaul with minimum time, skill, and resources in the planned maintenance environment. Quantitatively, it is the probability that, when specified maintenance or replacement action is taken, the system can be restored to a satisfactory operational condition in a given period of time.

The concept that brings these elements together is the Product Assurance program; a concept that provides optimum employment of design, quality, and maintenance to assure the maximum probability of mission success (S_m).

$$\text{Thus,} \quad S_m = R + M$$

INTRODUCTION

Manned spaceflight demands a first-flight success probability of 88 to 95 percent; the requirement for crew survival approaches 100 percent. These requirements are much higher than the achievements of comparable systems in the past, even after years of improvement (Figure 1).

Conversely, increases in the capability and complexity of equipment have caused the burden of maintenance to increase at an even greater rate. Thus, increasingly complex maintenance must be performed on increasingly complicated equipment to enable it to operate for longer periods of time.

Developments in equipment have been forced into miniaturization by our propulsion capabilities. Miniaturization, with reductions in equipment weight and size with thousands, even tens of thousands, of components packed into minimal space, is not susceptible to maintenance, and yet equipment must be maintained. Further, maintenance of the manned space vehicles will have to be performed while the vehicles are on missions, remote from earthbound facilities.

Mission success depends on (1) quality of design, (2) quality of manufacture, and (3) quality of maintenance. Man in the system augments basic reliability through in-mission maintenance, if the equipment is designed and arranged to exploit this capability. The design and arrangement of equipment, and the provision of spares and tools, must be conducted on the basis of trade-offs between maintainability and reliability; a system of low reliability requires more maintenance, and vice versa.

Mission success probability is involved in the trade-off of apportioned reliability, required maintainability, and the associated factors of cost, crew ability, weight, and redundancy. As has been pointed out, a system of low reliability would perform adequately if subjected to extensive maintenance. A high degree of Maintainability would be required to permit this extensive maintenance - i.e., great quantities of spares, a large inventory of tools, and large factors of access. On the other hand, a system of high inherent reliability would require little or no maintenance, and therefore, a lower Maintainability apportionment. Mission success determinants are shown in Figure 2.

It should be noted that high reliability and high maintainability are costly, both in dollar value, and otherwise. Optimum choice of a maintainability level involves the realistic assessment of such things as: the state-of-the-art, the level of reliability that the system may reasonably be expected to maintain, and the quantity of maintenance required, either between failures or to prevent failure, during the mission.

These considerations indicate the degree of maintainability that must be provided for some specific mission success probability. A certain level of in-mission maintenance, determined by a maintainability requirement, provides a two-fold cost reduction, through reliability within the state-of-the-art, and maintainability within reasonable weight and volume.

The product of the assessment is an improvement of life characteristics that can be accomplished in the following three ways (see Figure 3):
(1) Use of redundant components, (2) Through maintenance replacement of failed components automatically or physically, (3) Periodic servicing.

Reliability and maintainability are major design factors, but their achievement is not a factor of design, alone. If this was the case, then the problem would be solved after completion of system design. However, the problem continues through production, delivery, installation, and operation. Consequently, the usual method has been to seek maintainability, and thus reliability, during system operation. Because the improvement program are, in a sense, maintenance, they should also be planned and designed into the systems at the beginning.

A more effective approach to the problem is through a Product Assurance program that establishes the organization, plans, and procedures to assure that equipments are designed to achieve the required level of reliability, maintainability, and performance, and that these qualities are maintained throughout production and operation. Unless there are dramatic break throughs, there will be no significant upgrading of system reliability; it will not be adequate for extended manned space flight in the near future. In-mission maintenance sill be necessary to assure mission success.

MAINTAINABILITY APPROACH

Let us reiterate the classical definition of reliability concerning something doing what it's supposed to, where and when it's wanted to. It is to this end that reliability must be maintained. Maintenance is the act of assuring mission success, and maintainability is the provision for it (see Figure 4).

Replacement of components raises reliability to an amount equal to, or slightly above, the wearout failure probability. During a mission, there are specific periods when the various prime equipments must operate, and other periods when the equipments are not needed. Since time is required to accomplish maintenance, the required operating time of the prime equipment is also a criterion.

A maintenance operation consists of detection, identification, isolation, and application of the corrective measures necessary to restore or maintain equipment in an operating condition. The degree of mechanization to be utilized in accomplishing all or part of the maintenance operation requires consideration of the human factor, as well as the practical limits of design, reliability, and quality.

Mission success is the final measure of the proficiency of design, the quality of materials and manufacture, and the adequacy of maintenance. Although design and quality are carried through into equipment operation, maintenance or lack of maintenance, is the only factor that can modify the affects of design and quality after launch. In turn, maintainability is a measure of the degree to which maintenance can be accomplished.

The reliability, quality provisions, and potential maintainability of a design are subject to analysis and, because they are so closely related, are adjunctive. Analysis for these qualities can best be accomplished in relation to mission phase, and further broken down into separate equipment items, their functions, the overall affects of failure, and the corrective design action to be taken in order to make the equipment as reliable as possible within cost limitations. Having established levels of reliability and quality, analysis for maintenance and maintainability then becomes the prime determinant of continued mission effectiveness and success.

Necessity for New Approach

Manned space efforts to date have consisted of earth orbital flights of relatively short duration. Projected programs include long term space exploration with space depots, resupply points, rescue craft, and maintenance station. Perhaps eventually, the "corner gas station" will exist in space, and in-flight maintenance will be a problem of little magnitude.

For the next few years, however, man's contribution to mission success, after launch from earth, will be limited to those functions contained within the spacecraft, as supported by earth facilities for communications, tracking, trajectory prediction, and telemetric analysis of equipment performance.

Implementation of New Concepts

In the approach to application of an integrated Product Assurance program, two general divisions of the total effort may be made. One is primarily associated with engineering; the other with quality control, and manufacturing or producibility. This division in no way implies that the two efforts are sequential in time. Both must be an integrated activity beginning with initial design and continuing through to the final phase of production. Close coordination, both formal and informal, must be effected between all concerned units. Informal coordination is a function of the organisational structure, character of personnel, motivation, and training. Formal coordination, final evaluation, and direction of the concerned activities must be accomplished through program management and a design review board vested with sufficient authority to implement the recommendations contained in the analyses of reliability, maintainability, quality control, producibility, operability, safety, and value.

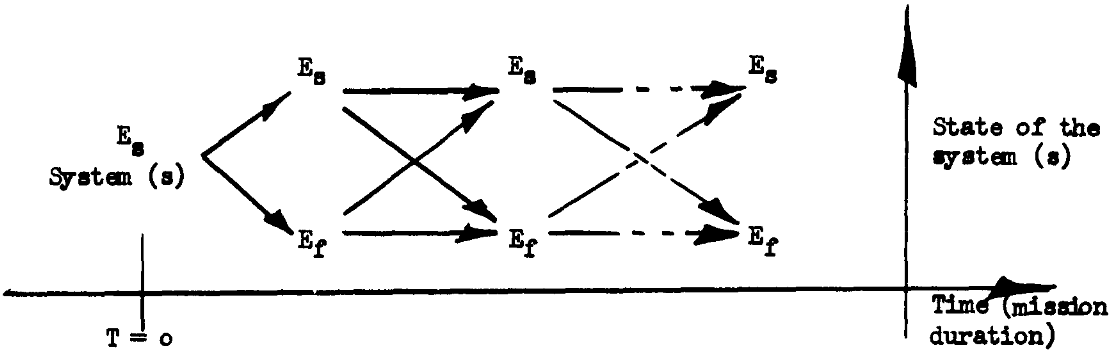
With this type of product assurance program, the necessary design margins are established, and controls are initiated to maintain the required ultimate mean strength, and to limit variance of the produced hardware. The cost and calender payoff comes especially in the fields of analysis and testing - qualification and verification. Overall product integrity is achieved with a considerable reduction in cost (see Figure 5).

TIME CONSIDERATIONS

The problems of maintainability are associated with time. This includes mission duration, and the time available to perform the maintenance operations. Mission duration is measured in hours or days, while that of the future may be measured in weeks, months, and eventually, even in years. Therefore, in manned space operations with long mission durations, representative functions, such as allowable systems maintainability, standby redundancy, frequency of maintenance cycles, and efficiency of life support equipments, are fundamental to equipment survival. Redundancy is one answer to the problem of maintenance, since failure of individual units, and combinations of units, often results in a degradation of system performance, rather than complete mission failure. For example, if two power supplies are employed, the failure of either one will degrade the system output capability, but the significance of the failure can be regarded as a system performance compromise, rather than as a mission failure.

Operational modes for a manned space vehicle of the near future will probably include launch, orbit, ejection from orbit, a trans-spatial phase, orbit and/or landing upon the intended celestial body, and a return flight. These modes may be followed by direct reentry, and after touchdown, final communications requirements. Assuming that the launch and orbital phases are successful, the operational sequences associated with mission success are dependent upon design for maintainability. Figure 6 illustrates mission success as a function of maintained reliability for the system. At the present time, the representative reliability requirement for the operational phases of a manned space vehicle may be estimated by assuming operational life requirements ranging from 500 hours to perhaps 10,000 hours for all the systems of the aerospace vehicle.

Assuming a successful launch operation, the operational sequence associated with mission success is dependent upon crew operations and the supplies at hand. As an example, let us assume a 10,000 hour operational requirement, and study the mission success as a function of ζ, where ζ represents the periodic maintenance for an attended system. The probability equations of a maintained system are derived from the following state/space diagram, where the system operational state (E_s) and inoperational state (E_f) are the transfer functions with respect to system operating time (T).



When the operational life requirement is 10,000 hours, with an anticipated maintenance cycle equal to $\zeta = \frac{1}{20}, \frac{1}{10}$, and $\frac{2}{5}$ of the 10,000 hours operational requirement, the maintained system reliability, as a function of system operating time is shown in Figure 6.

The calculated reliabilities associated with the depicted mission time shown in the illustration are based on the analyses given below.

When the systems are operating at time (T), the probability that service or periodic maintenance will be required before time (T + h) is $\theta h + O(h)$; if the systems are being serviced or repaired at time (T), the probability that the service time will terminate before time (T + h) and be restored to the correct operating state is $\zeta h + O(h)$, since the systems under consideration can be in one of the two possible stages at time (T) - the operational state (E_s) or the inoperative state (E_f).

The state of the systems at time (T) can be described by two parameters, θ and ζ. The state associated with the passage of the events from E_s to E_s and E_s to E_f is represented by parameter θ.

When the event of the system starts at E_{si} at time (T_i), the waiting time up to the first passage through E_{fj} at time (T_j, $T_j > T_i$), can be described by the exponential probability distribution:

$$R(t) = e^{-\theta T}$$

because the likelihood of system malfunction increases with mission time without maintenance. When maintenance is an integral part of the manned operations of the spacecraft, parameter ζ, associated with the passage from E_f to E_s will also have a probability distribution to describe the maintenance tasks.

Analyses indicate that parameter ζ, associated with the passage from E_f to E_s, is best described by the exponential probability distribution, $P_r(t) = e^{-\zeta T}$, so that the delayed passage from E_f to E_s at time (T) may be investigated in greater detail.

The probability for any system of the spacecraft to remain operating successfully during the time interval (T, T + h) with maintenance is:

$$P_{ss}(T + h) = (1 - \theta h)\ P_{ss}(T) + \zeta h\ P_{sf}(T) + O(h)$$

Since P_{ij} is the probability that if the system is in state (E_i), it will be in E_j T time-units later, the reliability level of any system is represented by the linear differential equation given below.

$$P_{ss}'(T) = -\ \theta\ P_{ss}(t) + \zeta\ P_{sf}(T)$$

Solutions:

$$P_{ss}(t) + P_{sf}(t) = 1,\ P_{sf}(t) = 1 - P_{ss}(t),\ P_{ss}'(t) = \theta\ P_{ss}(t) +$$

$$\zeta\ [1 - P_{ss}(t)]\ ;\quad P_{ss}'(t) = -\ \theta\ P_{ss}(t) + \zeta - \zeta\ P_{ss}(t)$$

Therefore: $P_{ss}(t) = -\ (\theta + \zeta)\ P_{ss}(t) + \zeta$

So that: $P_{ss}(t) = \zeta + ce^{-(\theta + \zeta)}\ t/\theta + b/\zeta$

But: $P_{ss}(0) = 1$ and $c = 0$

Therefore: $P_{ss}(t) = \dfrac{\zeta + \theta e}{\theta + \zeta}$

Design Analysis

Maintenance demands on the time and ability of the crew must be correlated with other performance requirements and considered in the design analysis. A preliminary configuration is then established which has redundancy and alternate modes, considering man in the loop as necessary for override functions, switching activities, and assumption of automatic functions that are within the capabilities of the crew. This increases the reliability of the spacecraft, but places additional requirements on the in-mission flight crew. These requirements must be considered, together with the normal flight crew operational functions, by constructing a flight time line event chart (Figure 7) which includes all spacecraft and subsystem functions, and individual activities which must be performed for each spacecraft operation.

MAINTAINABILITY DESIGN CONCEPTS

The amount of maintenance the astronaut is capable of performing during the mission is the major consideration, and is the factor used to make determinations of automatic versus manual maintenance, or determinations of redundancy versus weight, complexity, or criticality. These determinations, in turn, define the design goals for maintainability.

Having established maintainability goals, the designer then breaks them down into specific design problems based on the analyses shown in Figure 8. As the analysis breaks down the maintainability requirements into individual design problems, some trade-offs are required. Features having a primary function in performance must be evaluated in terms of maintainability, and conversely, maintenance features must be evaluated in terms of reliability, performance, producibility, and other design goals (see Figures 9, 10, 11, and 12).

These same requirements for designed maintainability apply equally to ground equipment and to mission equipment. On the ground, the degree of system readiness, and the amount of system wearout, is governed by the length of checkout operations and by the amount of system exercising during checkout.

As maintenance begins on the ground, and the level of in-mission maintenance is partially determined by the degree of readiness and systems wearout at the time of liftoff, ground equipment must also be designed for ease of maintenance by providing adequate checkpoints, easy accessibility of components, marking and color coding of parts, and human engineering of displays and controls. Improvements in maintainability can be obtained by designing the support equipment to increase the accuracy, speed, and reliability of the maintenance operations. Efficient automatic checkout equipment reduces troubleshooting time, and therefore, reduces the total maintenance time. The rapid and efficient performance of in-mission maintenance is even more dependent upon this designed maintainability - the provision of color coding, check-points, accessibility, and compact, easily-stored technical materials and information for the maintenance operations.

Maintainability is a characteristic of design, and must be accomplished in design, or in design-related processes. Design for maintainability, then, must have the following major aspects: Man's role in maintenance must be considered as an integral part of the system. The design must be based upon maintenance performance specifications that provide the designer an understanding of, and some degree of control over, the participation of man in this system. The design must provide those structural features that are necessary to allow and facilitate this participation. Access provisions, work clearances, test, and service points are examples of maintainability design areas. The design must also dictate the critical characteristics of supplementary equipment, job aids, and job supports which are vital and integral to the participation. Finally, the design must anticipate and compensate for variations in this participation. The design must make further compensations for in-mission maintenance, where the astronaut must use and maintain the equipment at the same time. Design for in-mission maintainability must make considerable allowances for the limitations imposed upon the astronaut by the environmental envelope which imposes the necessity that he wear a space suit, or limits his ability to use tools in a weightless condition.

Application

Replacement is the most common type of repair. It can be accomplished in many ways, ranging from active redundancy, through completely automatic and/or manual switching of redundant inventory, to manual replacement at all equipment levels. When redundancy is used, it can amount to as much as a 30 percent increase in total system weight. It is also necessary to increase the payload weight so that other maintenance subsystems can be carried. Naturally, this increase can be minimized by component selection and stringent quality control and testing requirements.

Component failures usually result from deterioration due to manufacturing imperfections, therefore, these faults can be detected by monitoring the performance of the components, and, through testing, accurately determining those components truly susceptible to failure. Redundancy in storage spares can then be minimized, and through the efforts of the human subsystem, the in-mission reliability maintained at a high level.

Prediction and Measurement

Mission reliability can be predicted as the proportion of time that either the human or the hardware systems operate within tolerance when exposed to proper inputs. Human subsystem reliability coefficients can be mathematically treated, together with hardware coefficients. However, some measure of the variability of human performance in the intended design is required to accomplish this condition.

Human performance for the intended design can be measured, under controlled conditions, to yield the statistics necessary to develop the reliability coefficients, through the use of full scale mock-ups. These mock-ups bear little hardware realism, but if designed with care, they can be psychologically meaningful enough to run human subjects through them with confidence. Given adequate statistical and experimental control, research can use these mock-ups to optimize the design before drawing release, and thus achieve high human reliability.

An equation for predicting total maintenance time is an important step toward determining an ideal predictor of maintainability. The next logical steps are to increase the number of standard replacement times available, and to validate and refine the technique by using it for predictions on systems other than the one on which it was developed. The ability to use a system or component at the time desired to perform the required function is a primary goal of all operations aboard a spacecraft. Within certain limitations, such equipment may deteriorate, and yet permit performance of a desired task, or continuation of a task, or all of an intended mission. Performance within such limitations can be defined as effective, and effectiveness is defined as a degree of real success of the actual mission, compared to the achievements planned for the mission. Some of the levels of effectiveness are: task accomplishment within the required time, task accomplishment, but over a longer period of time, task failure, but accomplishment of remaining mission, and malfunction and mission failure, but crew survival. Zero effectiveness would be at the level of complete mission failure with loss of the crew.

Given adequate treatment, maintainability can be treated as reliability, or in a similar manner. Since reliability and maintainability are becoming equally important characteristics, it is essential that they be accorded similar treatment. As with reliability, some yardstick for the measurement of maintainability is needed. It is essential that some numerical requirement be ultimately established, otherwise, it would be no more useful to require that equipment be maintainable than to require that an automobile be fast. The words "fast" and "maintainable" can mean many things to many people. Unfortunately, it is unlikely that many of these people would be in complete agreement if each were permitted to supply his own interpretation. This requirement for assigning numeric value as a measure of maintainability goes even further. If we are to assign a value, the characteristic of maintainability must be measureable and demonstrable. The ability to state a numerical requirement is of little value if it is not possible to subsequently determine whether or not this requirement has been met. This characteristic of maintainability must be predictable, or it would be most difficult for a contractor to propose production of a piece of equipment when he is unable to estimate, in advance, his ability to provide the required levels of maintainability. Presently, the parameter which shows the greatest promise as an adequate measure of maintainability is time - the time required to restore equipment to operating conditions following a failure. Time may be a satisfactory choice, in that it can be treated quantitatively, measured, and to some extent, predicted. However, time is not the only conceivable unit of measurement, and in fact, may not be the most satisfactory. For, while measured performance times may reflect something wrong in the performance of a certain maintenance task, the time measurements, along, cannot indicate the root of the problem, or the answer to the problem.

RELIABILITY THROUGH MAINTENANCE

Reliability figures for space equipment are critically dependent on an exact number of operations, or hours of use, when operating close to design operating life. Sensitivity of reliability figures to duration of operation is highly magnified in equipment which is designed for such factors as optimum packaging and power consumption. As an example, let us assume a vehicle in earth parking orbit: A failure has occurred in the communications link to the earth base, just prior to ejection from orbit. The many obvious ways in which this could affect the mission must be considered against the possibility of (1) continuing the mission without use of this equipment, (2) increasing the time in orbit by performing maintenance before proceeding, thereby jeopardizing the reliability of other systems, (3) postponing the maintenance to another phase of the mission, (4) continuing the mission, but omitting the phases of the mission made hazardous by the malfunction of this equipment, (5) aborting the mission, or (6) some other combination of the many available choices.

The probability of various failures and their importance to the mission must be considered in early mission programming. With this information we can evaluate the requirements for spares, maintenance equipment, skills, and training needed for the crew. Man's optimum use in space can be obtained only if the mission program logic contains all of these factors, in addition to the various system and goal interrelationships.

Although equipment might not be guaranteed against failure during the required operating period, it can be so constructed that after a failure, it can be quickly restored to the required operating condition. Success in this direction would improve the overall ability of the equipment to perform the function for which it was designed, since it would be available for use for a greater proportion of time. The major products of maintainability can be defined as follows:

Operational Readiness	The probability that the system will be ready to perform when called upon to do so.
Mission Reliability	The conditional probability that the system will continue to perform satisfactorily for the duration of the mission, given that it was in satisfactory operating condition at the beginning of the mission.
Design Adequacy	The conditional probability that the system is able to accomplish its mission, given that it is operating properly.

Using these definitions and others, maintainability requirements can be imposed, and a Product Assurance program maintained. A desired maintainability characteristic can be assured in the product through the use of adequate specifications and design techniques for maintainability.

The Human Element

Maintainability deals not only with time and the availability of spares, but with scientific psychology, physiology, and psycho-dynamics. Thus, a major influence on the time required to repair equipments is the ability or the attitude of the astronaut on extended space missions. There may also be problems of perception, attention, or of reason itself. The long term effect of journeys into the far reaches of space is naturally a subject on which we are almost totally lacking in data.

Training and experience have a considerable effect on lowering the troubleshooting time on a given piece of equipment, and can, in time, compensate, to a considerable degree, for a lack of design for maintainability. Consider however, the time saved during the training cycle if the equipment is designed for maintainability in the beginning.

VERIFICATION

The test program provides a means of verifying the results of the design phase - the degree to which reliability and maintainability have been incorporated into the system. The test program should not be considered as merely a test of the hardware; it is really a test of systems and subsystems. Man is considered a subsystem, so the testing must include the human/hardware relationships.

To correlate the capabilities of design and man, and the interface problems involved, extensive simulation techniques should be utilised. Simulation has two purposes. One is to provide verification of design; the other is to provide crew training. Simulation is the best means, short of an actual mission, of approximating mission conditions, including the element of time.

Equipment utilised for simulation may range from the subsystem level to a replica of the spacecraft. Program costs and schedules will determine the extent of the simulation program. Obviously, more useful data will be obtained if the simulation closely approximates the conditions and equipment to be encountered in the actual mission. It may be necessary to use procedure trainers representing a particular system and so arranged as to be similar to the spacecraft installation. In any event, simulation must provide opportunity for the crew to operate, adjust, and repair the subsystems as they would in flight. Means will be provided to introduce failures into the system which require crew action to maintain or restore system functions. This provides a measure of the adequacy of detection systems, and of the ability of the crew to function as intended. If the test is conducted over an appreciable time period and correlated with other crew responsibilities, it establishes an indication of the practicability of crew assignments and answers questions concerning whether or not the crew has been overloaded. Finally, it establishes a tool to check design and maintenance analyses relative to the maintainability and repairability of equipment - the accessibility of components, ease of adjustment or repair, and the time and effort involved in replacement of modules.

In-Flight Maintainability Considerations

At this point in the discussion, especially with awareness of the state-of-the-art, it is obvious that reliability, per se, is not assurance of mission success. Success is achieved only through the factors associated with the maintenance of system functions. There are special considerations to be given to design and other preparations for in-mission maintenance (Fig.13); operation problems and parameters must be taken into consideration. Every procedure must be thoroughly validated before it is incorporated into maintenance instructions. Every conceivable requirement for inspection and handling of emergency conditions must be thought of, and procedures developed for them. Consideration must be given to providing the maintenance system with adequate procedures for determining that the system has been repaired and is again ready for use. Special thought must be given to compression and condensation of technical data, without reduction in its usefulness. Replacement parts and components must be adequately identified in a uniform manner. Repair information must be either completely displayed on the equipment, or provided completely in the technical data; not mixed between the two. A system of logical relationships on part names and numbers should be established. Required tools must be kept to a minimum and should either be common hand tools, or, if experience dictates, hand tools designed especially for use by man wearing a space suit. Equipment must be designed so that connectors can be easily distinguished. Cables must be of a length that reaches to one point only. If hardware mixup is still possible, different types of receptacles must be used. Interchangeability should be developed to a high degree; modules containing set patterns of various components that, when connected in different ways, perform different functions, would greatly simplify in-mission maintenance. In conjunction with this, of course, the maintenance technical data would contain specific instructions for connecting a universal module to perform a given function.

Because maintainability, operability, and reliability, although not synonymous terms, are closely allied, they can best be performed by closely coordinated effort within one completely responsible organization. To be most effective, maintenance engineering, reliability, human engineering, and the other factors of maintainability - i.e., operations analysis, should be performed concurrently and cooperatively with truly effective liaison with equipment designers.

Just as we at the Space & Information Systems Division of North American are utilizing design reliability analysis and design reliability review, so then, do we anticipate the need for design maintainability analysis and review. As with our reliability engineering efforts, we recognize that these maintainability groups must be project oriented and endowed with the authority to review design drawings and develop models, to effect these as necessary to insure maintainability of the final product. We recognize that for in-mission maintenance, design must be oriented for maintenance, especially in the weightlessness of space where there are problems of perception, size and mass comparison, strength, and facility, that require special attention.

We also recognized that, management-wise, the current real problems of maintainability are a general lack of respect for professional competence between design groups and others - i.e., reliability, maintainability, and value. There is also a problem of communications; many specialist groups assume their functions to be esoteric and, therefore, deliberately minimize their contact with other groups. The level of effort, and degree of success in liaison and communication between groups is, to a great extent, based on personal rapport rather than project policy, and, due to the lack of methods for adequately specifying and demonstrating maintainability, it is looked upon as only a fringe benefit. Obviously for the man in space, maintainability is the prime requisite. Upon this maintainability and the determination and demonstration of it, can be based our only assurances of long-mission success in the near future.

CONCLUSION

Maintainability must be applied to all systems, including the human one. For the equipment, our term is Product Assurance; assuring that equipment can be repaired, and maintained in operation. For the human subsystem, maintainability becomes meaningful in the terms of sustenance and protection - accessory comforts and basic life support. The degree to which man can be utilized in space will depend primarily on how his performance enhances probability of mission success. Man's complete effort and concentration will be required to assure success in these early stages of the space program.

Although man may function under adverse conditions, his performance may be impaired, or it may even decline to a state of worthlessness. The maintenance of optimum performance in an undesirable environment may exhaust the energy of an individual, resulting in subsequent performance deficiency due to the cumulative effects of stress. Thus, with man in the system, and considered as a subsystem, it is to be considered that mission success is the sum of reliability and maintainability. A decrease in man's effectiveness could result from an overall deterioration of system efficiency, thus, maintainability includes the requirement for maintenance of the human subsystem. To fully utilize man's capabilities requires a system designed for maintainability, and the present state-of-the-art in reliability requires that man exercise his capability of maintenance to the fullest. The degrading affects of time and environment can be countered only by optimum design for reliability and maintainability.

$$S_m = R + M$$

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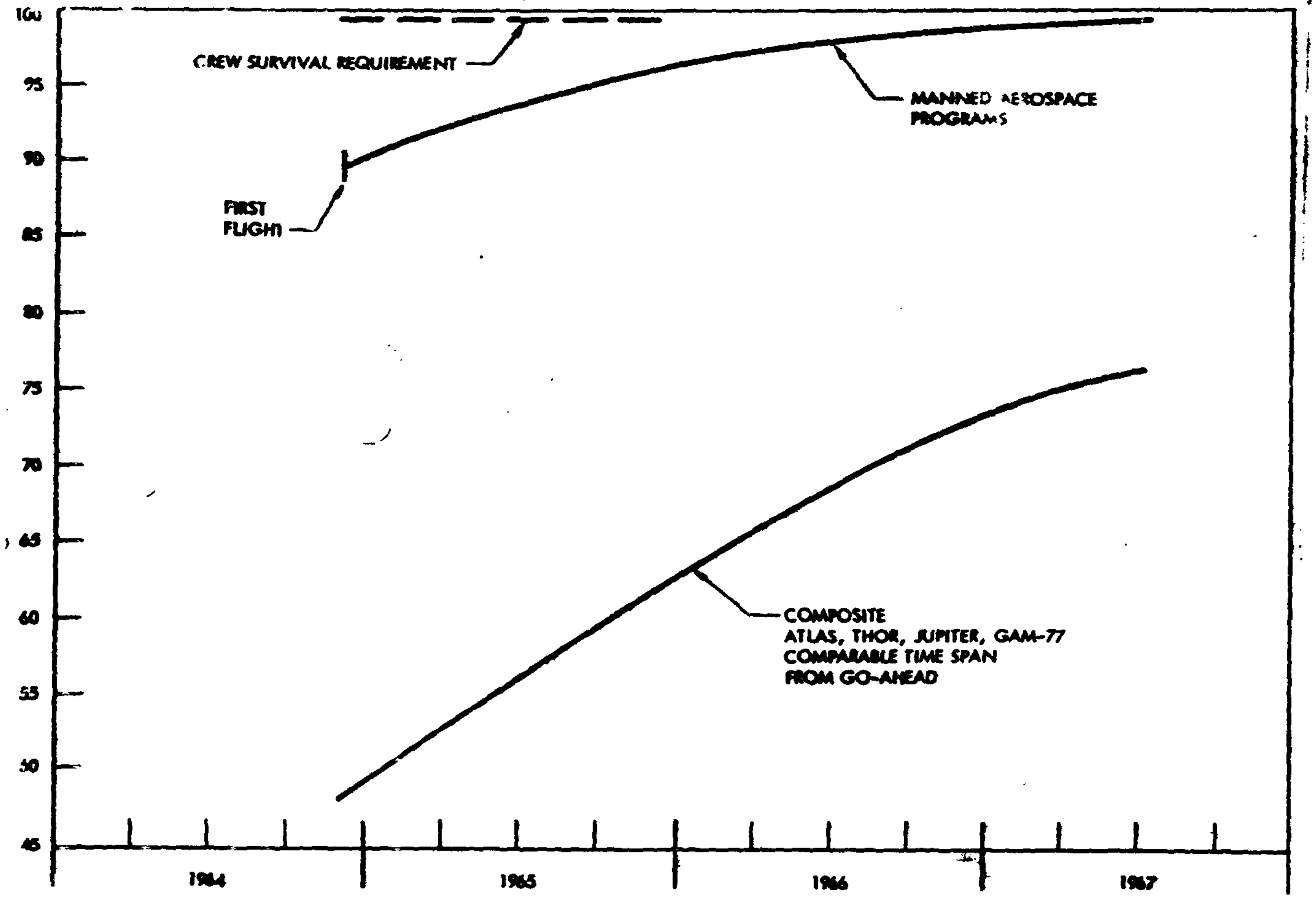

Figure 1. Aerospace Reliability Requirements

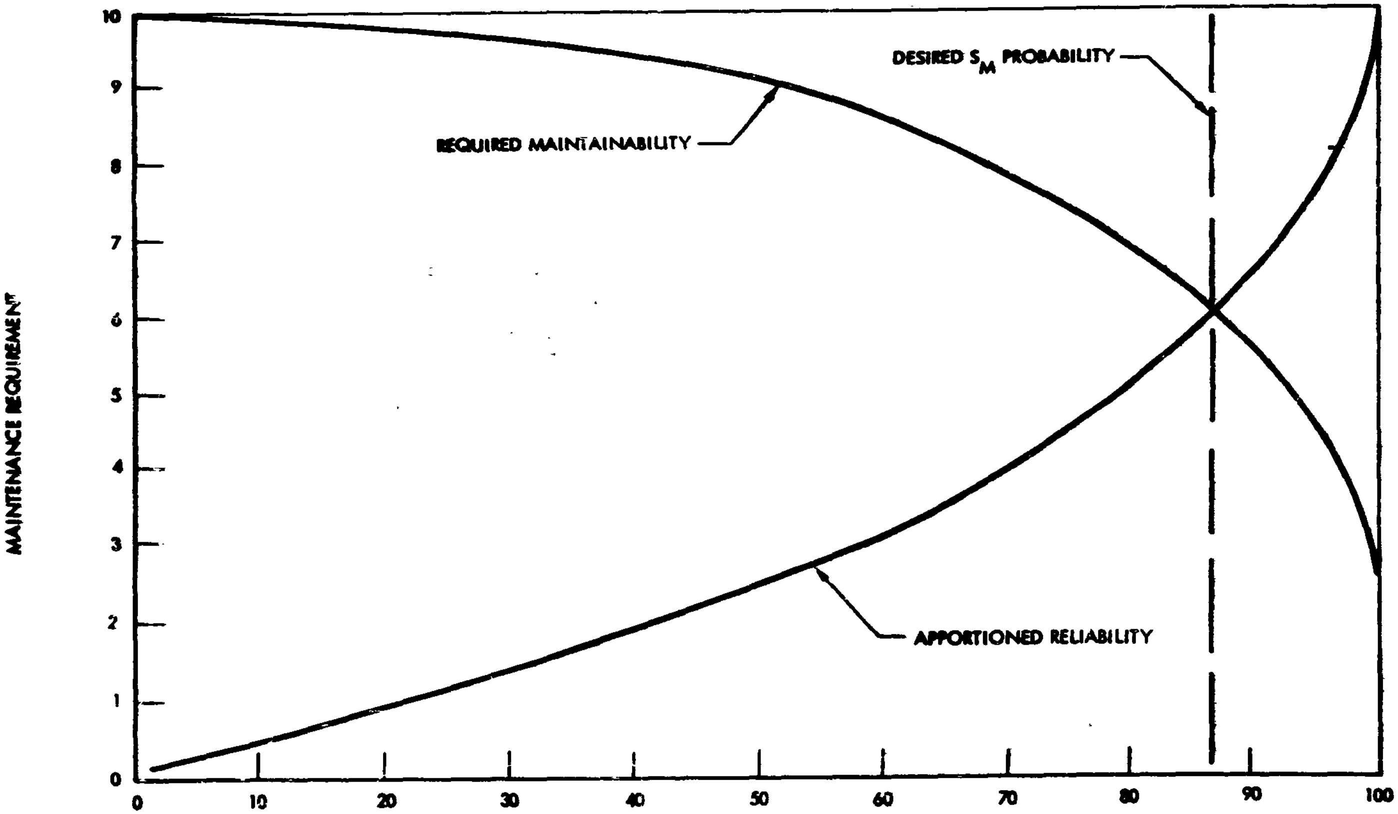

Figure 2. Mission Success Determinants

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IVA-17

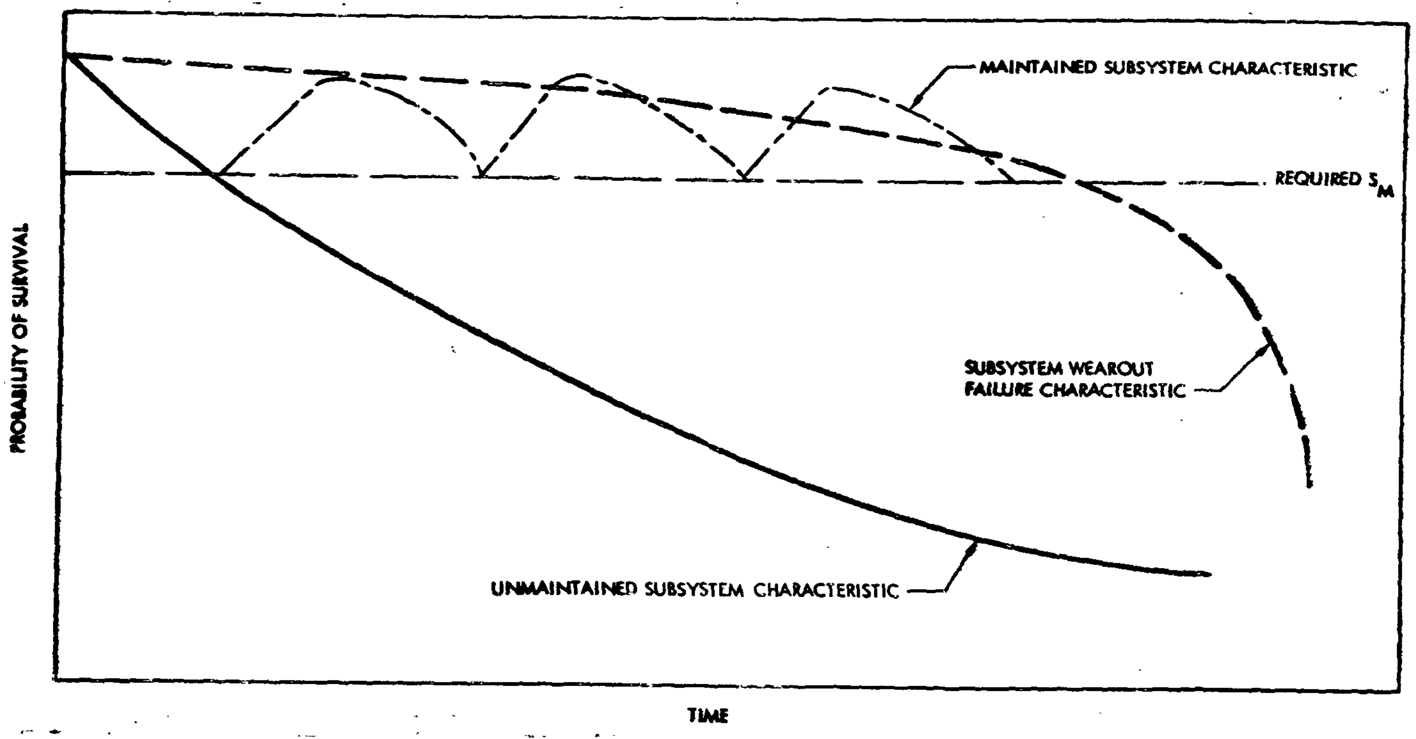

Figure 3. Life Characteristic Curves

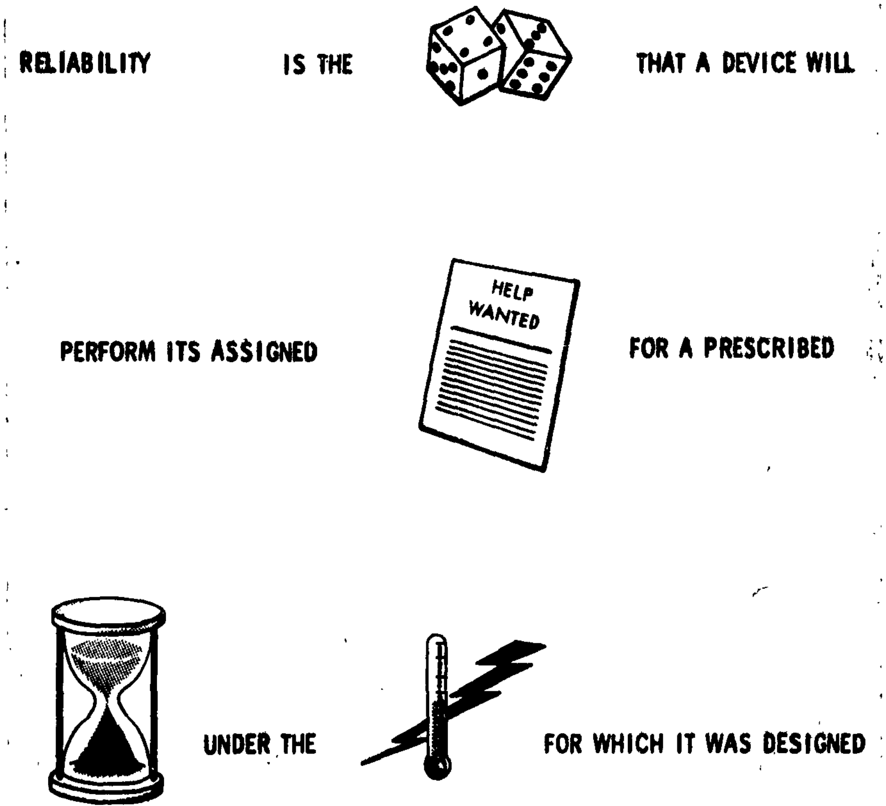

Figure 4. Classical Reliability Definition

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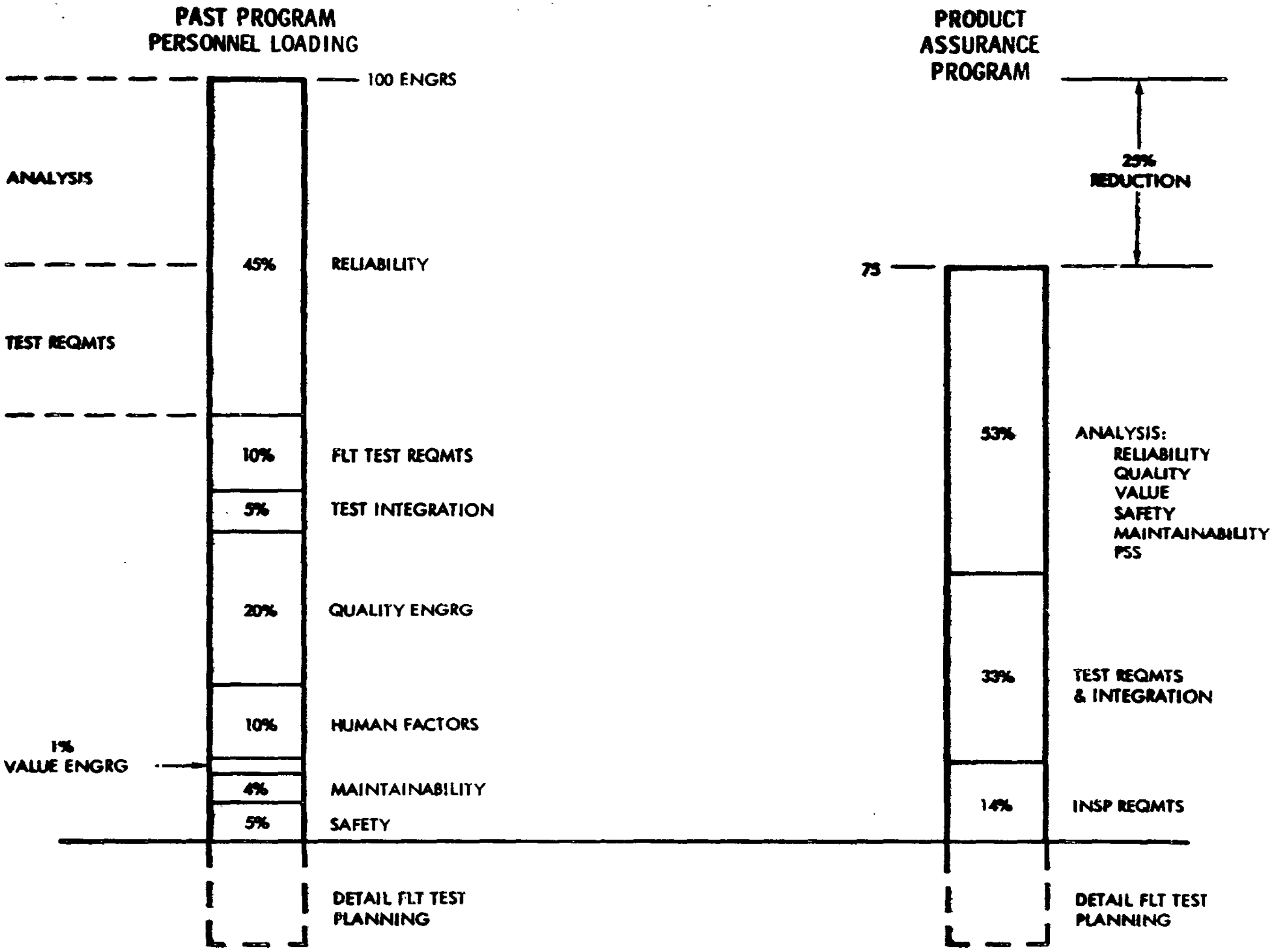

Figure 5. Product Assurance Payoff

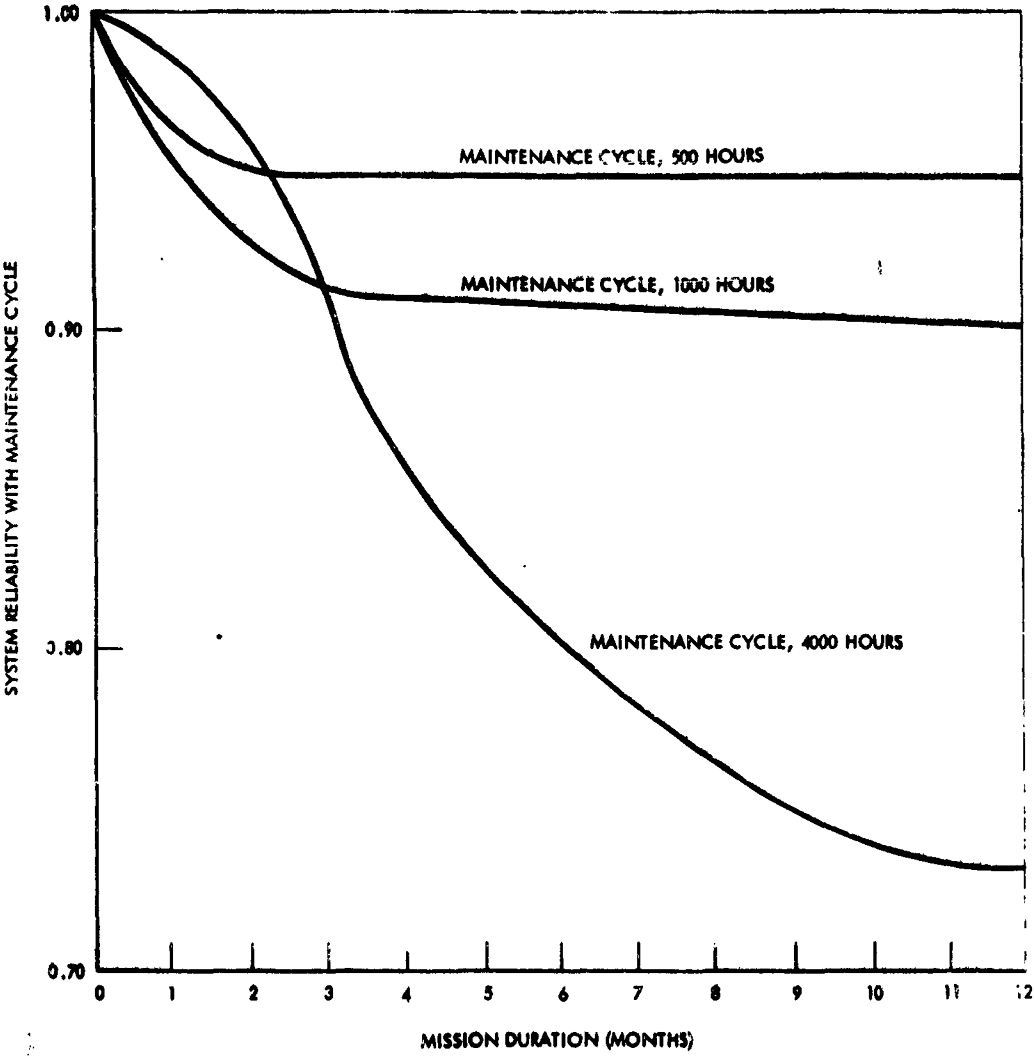

Figure 6. Mission Success

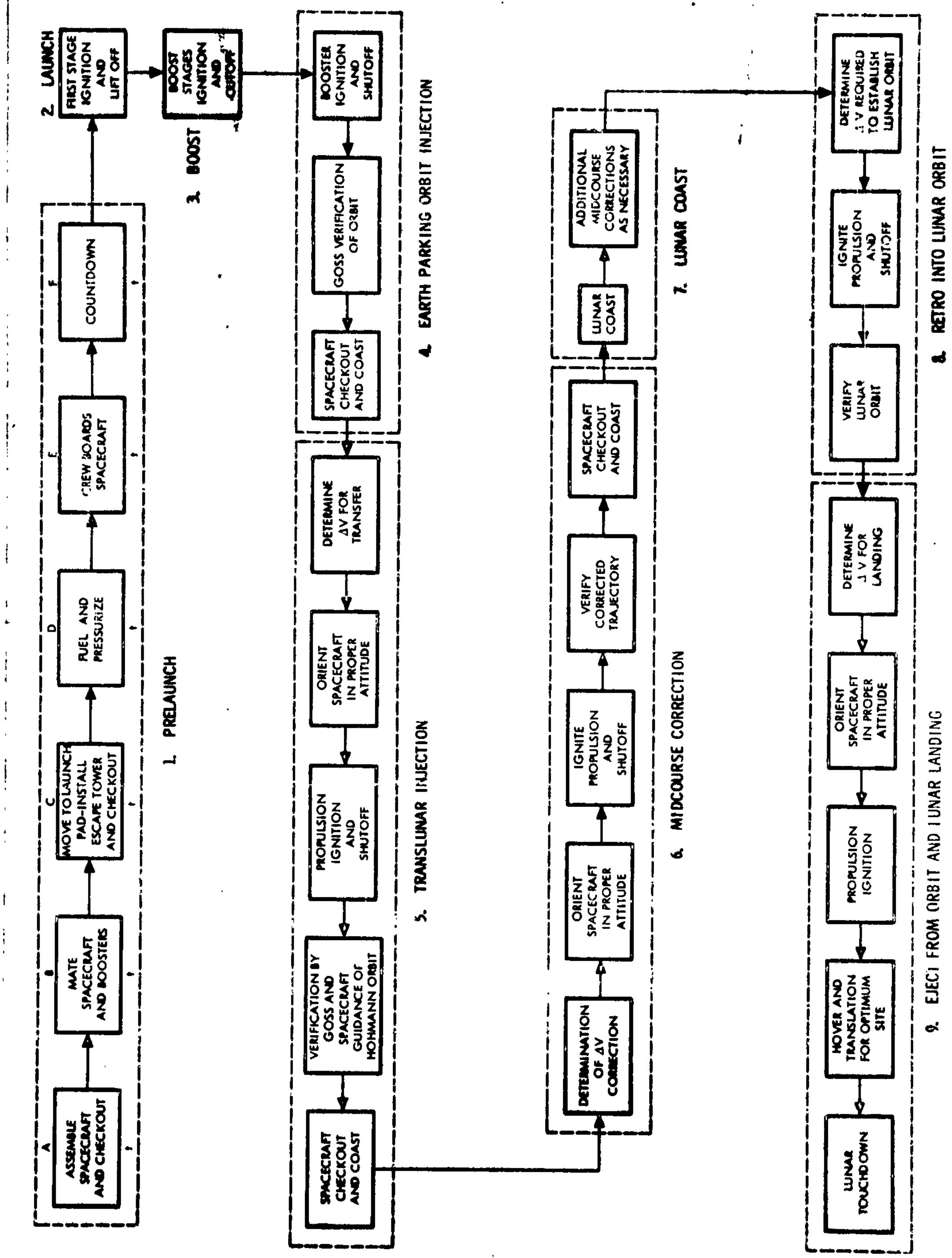

Figure 7. Flight Time Line Event Chart

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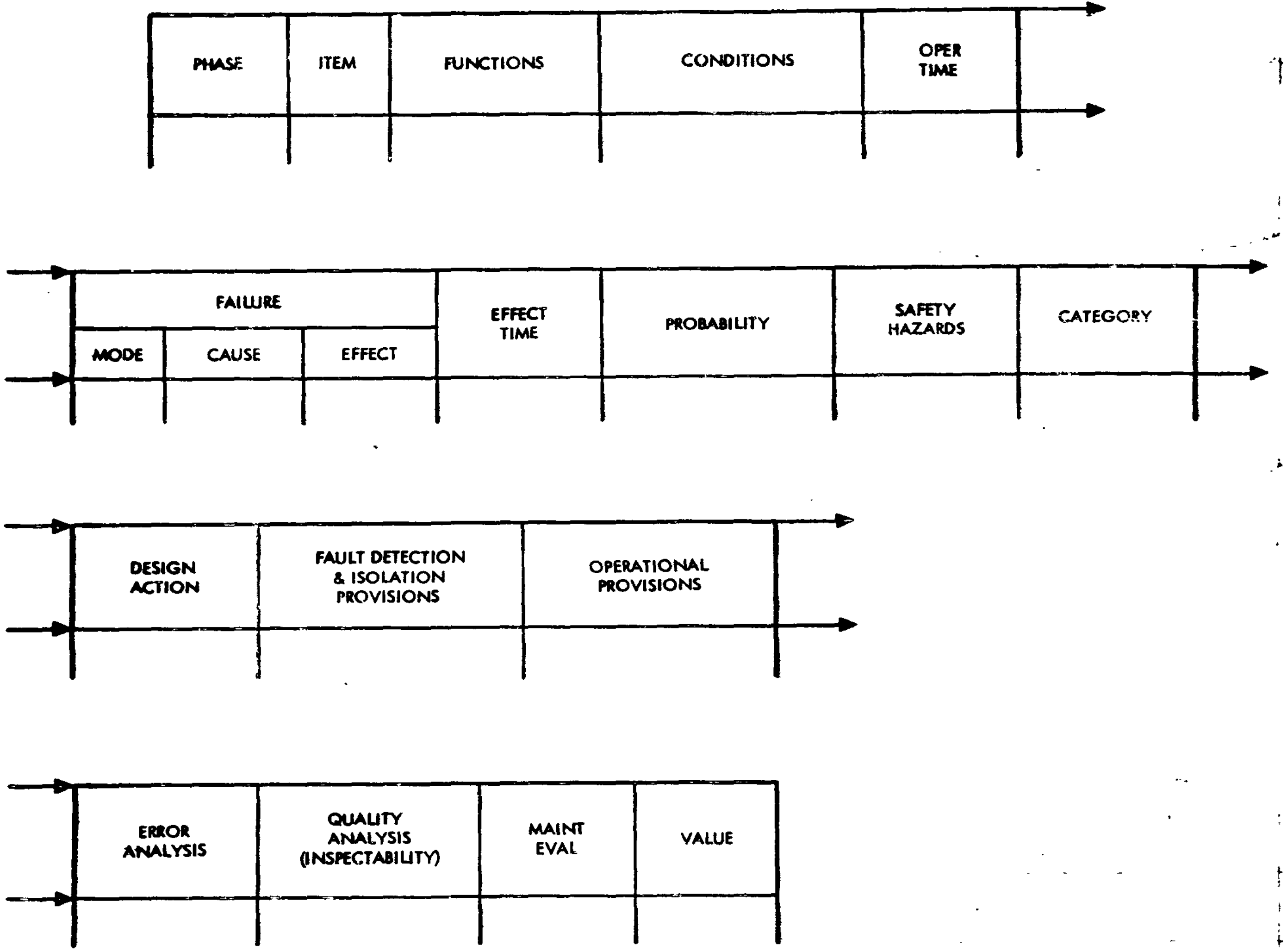
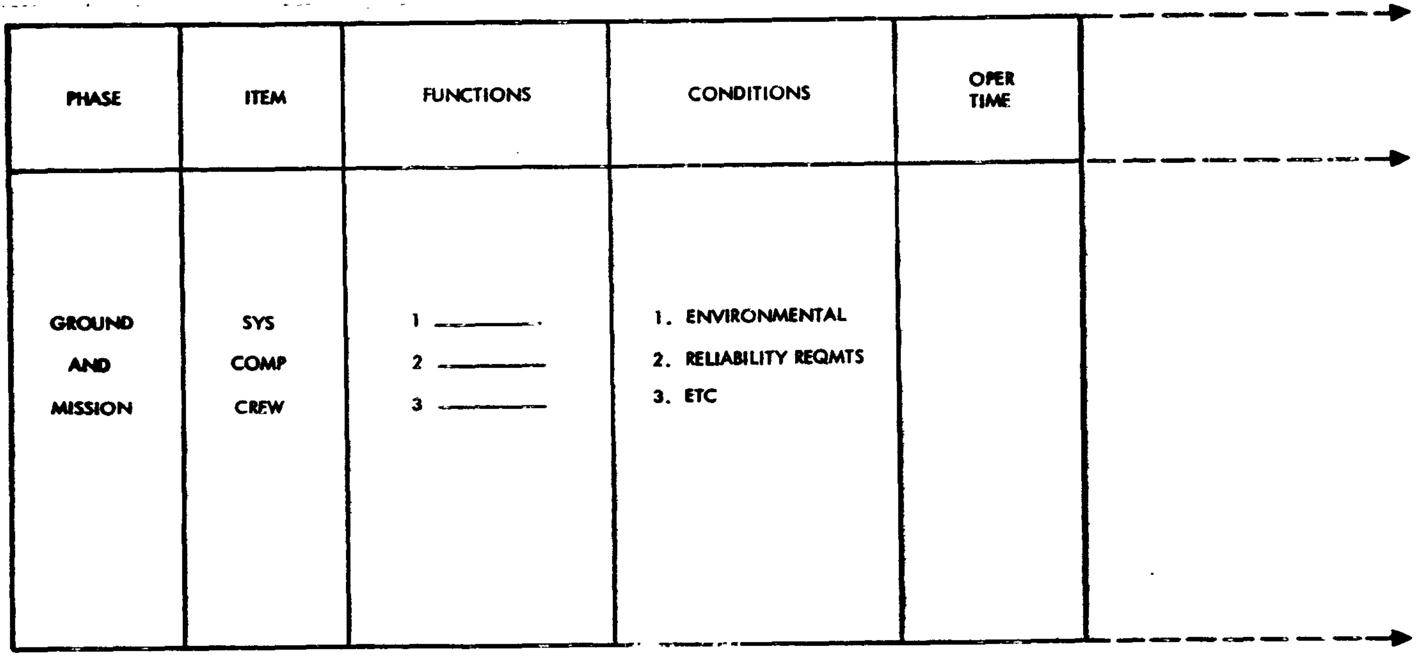


Figure 8. Design Analyses



TIME LINE STUDY OF PHASES AND FUNCTIONS TO DETERMINE SIGNIFICANT AREAS FOR ANALYSIS

ESTABLISHES IMPORTANT FUNCTIONS

Figure 9. Equipment - Function Time Flow

FAILURE			EFFECT TIME	PROBABILITY	SAFETY HAZARDS	CATEGORY
MODE	CAUSE	EFFECT				
		ON MISSION SYSTEM ITEM, OTHER SYSTEM CREW, ETC		0.999 OR HIGH LOW, OR NEG		CRITICAL MAJOR MINOR

- ESTABLISHES IMPORTANT EQUIPMENT CHARACTERISTICS FOR TEST AND INSPECTION

Figure 10. Failure Cause - Effect

IVC-25

CATEGORY	DESIGN ACTION	FAULT DETECTION AND ISOLATION PROVISIONS	OPERATIONAL PROVISIONS
CRITICAL MAJOR MINOR	1 ELIMINATE MODE 2 FAIL-SAFE PROVISION 3 MINIMIZE EFFECT 4 MINIMIZE PROBABILITY (REDUNDANCY, PARTS IMPROVEMENT, SPECIAL CHECKOUT OR INSPECTION, ETC)		AUTOMATIC ABORT REMOVE AND REPLACE CREW TAKEOVER ETC

- ANALYSIS ESTABLISHES LOGICAL BASIS
  FOR DESIGN IMPROVEMENT
  FOR OPERATIONAL MEASURES

Figure 11. Prevention and Protection

WORK LOAD ANALYSIS	QUALITY ANALYSIS	MAINTENANCE EVALUATION	VALUE
GROUND AND MISSION	INSPECTABILITY PROCESS AND METHODS EVAL TOLERANCE REQUIREMENTS ETC	ACCESSIBILITY REPLACEABILITY REPAIRABILITY ETC	

Figure 12. Provision and Evaluation

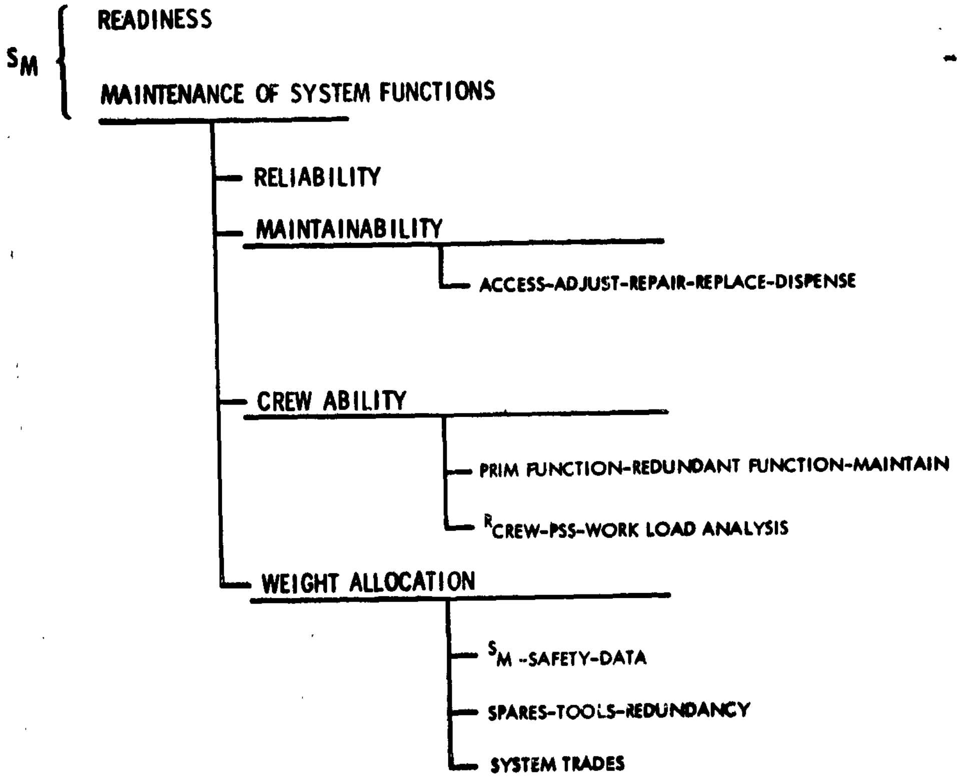


Figure 13. R & S_M

CUSTOMER REQUIREMENTS FOR MAINTAINABILITY (M) CHARACTERISTICS IN AIR FORCE SYSTEMS AND EQUIPMENT

by

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Presented at
Maintainability Conference
12-13 March 1963

Electronic Systems Division
Laurence G. Hanscom Field
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SUMMARY

It is the position of the Air Force Logistic Command and the using commands that the present day world situation and the urgent need to obtain maximum defense for each dollar and for each manhour spent, dictates that the military services and Industry work together as a team for the common good of our national defense and the economy of our country. It has been established that the operational capability and effectiveness of our equipment is being reduced by unnecessary downtime for maintenance. Also, that funds, manpower and logistic resources are being expended to perform maintenance that could have been avoided by designing and building good maintainability characteristics into all equipment during the initial design phase. Hundreds of millions of dollars are being expended annually for retrofit modifications to redesign equipment so that it can be effectively maintained and supported with resources that are available to the operating units.

MAXIMUM DEFENSE FOR EACH DOLLAR

The present day world situation and the urgent need to obtain maximum defense for each dollar and for each manhour spent, dictates that the military services and Industry work together as a team for the common good of the defense and economy of our country. To achieve these objectives, we must improve our communication and coordination. We must develop a better understanding of current and potential problems that cause unnecessary downtime of our equipment or result in the unnecessary expenditure of vital manpower, funds and materiel resources. In this regard, the program for improved systems and equipment maintainability covers an area where our joint efforts can pay unlimited dividends. Unfortunately, many people in Industry and the Air Force are not aware that the capability and effectiveness of our forces is being reduced by unnecessary downtime for maintenance, and that we are expending funds and manpower resources to do work that could have been avoided by early recognition of important logistic requirements during initial design of all systems and equipment. If the procurement agency, contractor and design engineer do not know or fully understand the customer's requirements, capabilities and limitations, the probabilities are high that the end product will not contain all required characteristics. Failure on the part of the service and Industry to identify and define all vital systems and equipment design requirements and characteristics is resulting in the delivery of systems and equipment that are not maintainable at the three levels of maintenance; i.e., organizational, field and depot, with available personnel, funds and materiel resources. As a result, mission capability is being degraded through unnecessary equipment downtime for maintenance. This forces the Air Force to expend critical funds, manpower and materiel resources that could have been avoided through effective planning and coordination during the conceptual and early design phases.

EDUCATION

During the past 36 months I have talked with many people, both in Industry and in the Air Force, concerning the importance of designing and building good maintainability characteristics into all systems and equipment. The reaction of various people to this vital program is very interesting. I find that most people can be placed in one of two groups. The group an individual falls in usually depends on his background, experience and interest displayed in achieving maximum operational effectiveness at minimum cost.

a. PRO

Among the first group are those who have spent considerable time in the field where they were immediately responsible for or directly concerned with the maintenance of first line equipment. Also among this group are management people who have refused to accept the contension of some that greatly increased systems and equipment downtime for maintenance, and high logistic support costs are inherent with present day systems and equipment. This first group of people is very cognizant of the urgent need for an effective maintainability program, and are doing everything possible to support it. They are highly encouraged to know that top level management in Industry and the Air Force are beginning to give attention to this important area.

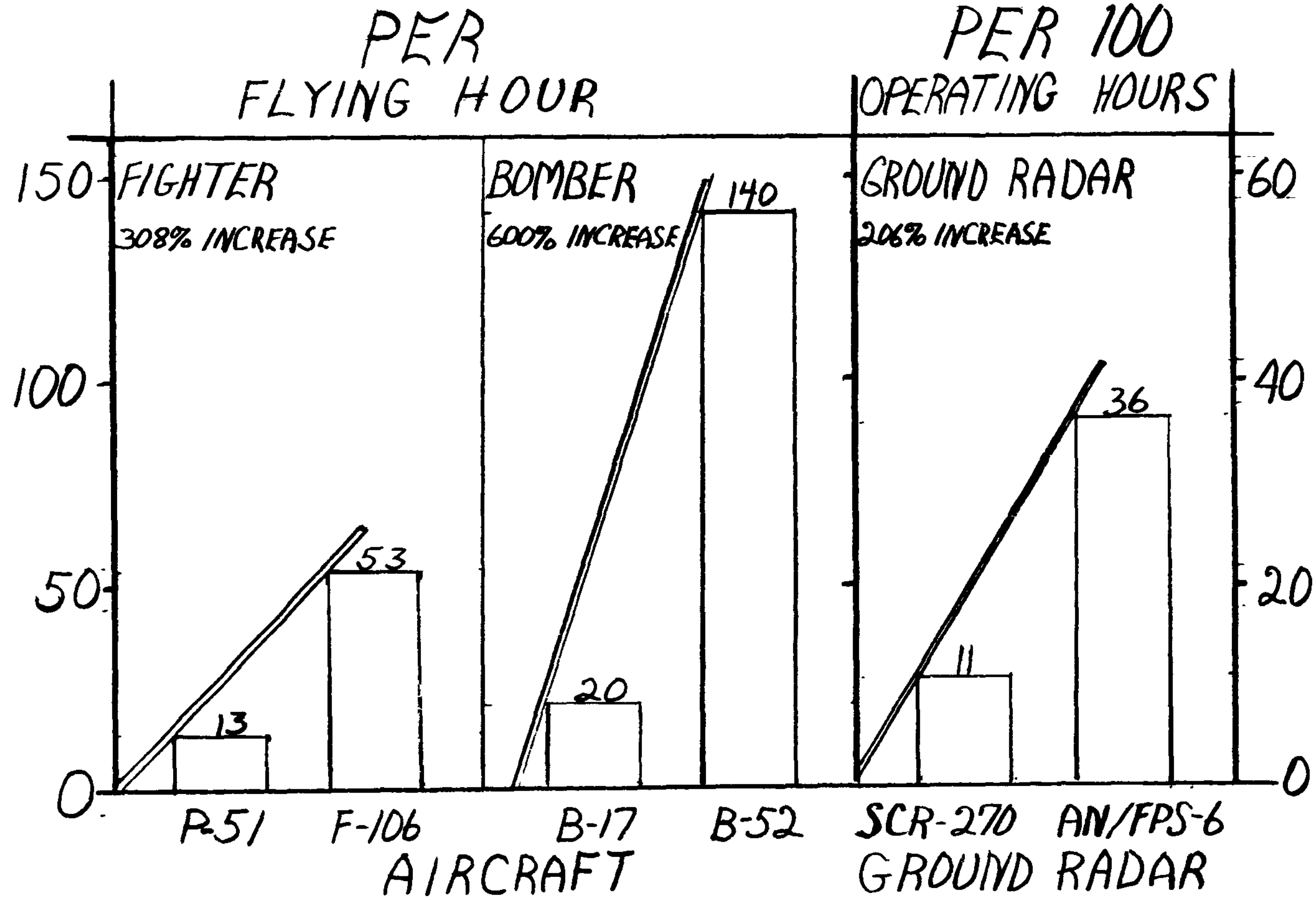
b. CON

The second group consist primarily of those people who have little or no knowledge of logistics or logistic requirements. They have not been exposed to field operations and do not know the customer, his requirements, limitations or capabilities. They do not realize that the Air Force mission is being degraded by unnecessary systems and equipment downtime for maintenance. Furthermore, they are unaware that the maintenance manhours per flying hour or operating hour in the case of equipment and non-air borne systems, has increased 2 to 7 times over what it was for comparable equipment during World War II. (REFER TO MAINTENANCE MANHOUR TREND CHART)

c. EXAMPLE

The famous World War II P-51 required approximately 13 maintenance manhour per flying hour. Today, the F-106 requires approximately 50 maintenance manhours per flying hour, or an increase of 308% over the World War II P-51. In the bomber class, it is interesting to note that the B-17 required approximately

MAINTENANCE MANHOURS



20 maintenance manhours per flying hour. Currently, the B-52 requires approximately 140 maintenance manhours per flying hour, or an increase of 600% over the B-17. In the non-airborne equipment area, we note that the World War II SCR-270 ground radar set required approximately 11 maintenance manhours per 100 operating hours. Current AFM 66-1 maintenance data indicates that the AN/APS-6 radar requires approximately 36 maintenance manhours per 100 operating hours, or 206% increase over the World War II SCR-270.

CAUSE FACTORS

You may be interested to know that a high percentage of this increased downtime for all of this equipment is due to unscheduled maintenance of electronic equipment. Adequate test points, modular design and proper accessability would greatly reduce the downtime and increase the operational availability of the equipment. From these examples, it is apparent that something must be done to reduce this rapidly increasing trend in maintenance per operating hour or flying hour and systems equipment downtime for maintenance. We are rapidly exceeding our maintenance capability and the availability of personnel, skills, funds and logistic rescources to accomplish the maintenance workload.

EQUIPMENT AND COMPLEXITY

It is reasonable to assume that a portion of this increased workload is due to increased complexity of our systems and equipment. However, in most cases, the ratio between the increase in systems and equipment complexity and the increase in maintenance manhours per flying hour or operating hour is completely out of proportion.

COST OF MAINTENANCE vs COST OF EQUIPMENT

Another indication of the increasing requirement for improved maintainability characteristics can be found in information compiled by NSIA and the DOD. The NSIA has established that even though the American people and the military services have been showing increased concern in research and development aspects of our national defense program, the dollars spent for maintenance each year have far exceeded the dollars spent for research and development of new systems and equipment and pure science. The Department of Defense figures indicate that we are currently spending approximately 25 million dollars per day for all types of maintenance. During recent years this cost has been increasing each year at the rate of approximately one million dollars per day. Until recently, this represented approximately 25% of the total defense budget. Also, it was interesting to note that the cost of maintenance exceeded by far the cost for procurement of new systems and equipment, including their associated development costs.

a. EXAMPLE

Using the above information, we may make a comparison of what would happen if you as an equipment buyer and operator experienced a similar situation where the cost for maintenance of your automobile, television set, refrigerator or washing machine exceeded the amortized cost of your equipment by 500 to 1,000%. If the annual maintenance costs for your automobile, television set, refrigerator or washing machine exceeded 50% of the annual amortized equipment costs, you would be most unhappy. You would probably register a strong complaint with the manufacturer or his local sales representative. If he would not, or could not do anything about the excessive equipment downtime and maintenance cost, you would probably refuse to buy the same product again. By refusing to buy his product, you would force the manufacturer of competitive products to consider, during initial design, the customers requirement for reliability and maintainability, as well as performance. Yet within the service, we continue to buy equipment that cannot be effectively maintained or supported until we spend millions of dollars for modifications to redesign it. I think it is about time we start giving recognition to the contractors and design engineers that design and build good reliability and maintainability characteristics into their equipment, as well as performance.

THE THREE LEGS OF THE STOOL

Designing equipment with outstanding performance characteristics and ignoring the requirement for reliability and maintainability, is like building a stool with one leg. You must design and build at least three legs on the stool for it to serve its purpose. The only way you can eliminate the requirement for a third leg is to design and build the reliability leg so broad that it spans the arc between the reliability leg and the maintainability leg. This takes time, is limited by the state of art and usually is not economically advisable.

a. INITIAL DESIGN COST vs REDESIGN COST

Let us assume we fail or refuse to recognize the requirement for the reliability and maintainability legs on the stool, and after we deliver it to the customer, he soon recognizes that he cannot use the stool. He has two choices. Number 1, junk it. Number 2, redesign it to provide for the two legs that should have been included during initial design. However, when he gets the bill for redesigning the stool to provide for the maintainability and reliability legs, he finds that the cost for redesigning or modifying the stool was 1,000 times what it would have been to include the two additional legs during initial design. A study of the cost for modifications to achieve equipment reliability and maintainability indicate that the ratio of cost for initial design vs redesign is approximately 1 to 1,000. Therefore, it becomes very important that we identify all design requirements early whereby they can be included in the initial design.

b. COST FOR RETROFIT MODIFICATIONS

Annually the Air Force spends hundreds of millions of dollars for modifications that are necessary to reduce systems and equipment downtime for maintenance and to redesign the equipment so that it will be maintainable at the three levels of maintenance. (DISCUSS COST AND PROBLEMS RESULTING FROM THE TCTO BACKLOG)

c. ATTITUDE OF THE CUSTOMER

It is very difficult to convince our maintenance personnel in the field that Industry, AFSC and AFLC have done everything possible to design their equipment so that it can be effectively supported, maintained and operated. This is especially true in those cases where the technician knows that they are being required to spend hundreds of manhours to gain access to high failure items that could be inspected, removed or replaced in a matter of minutes if they had been properly located or adequate test points provided. On various occasions I have heard technical personnel in the field express the view that designers must deliverately design Air Force equipment so that it will be difficult to maintain. These people cannot understand how a brilliant design engineer can design a complex system or item of equipment that will perform miracles and yet not give due consideration to the requirement to perform maintenance in the field. These people cannot understand why the design engineer does not recognize that when the reliability of equipment has been degraded through use, the inherent reliability can be restored only through proper maintenance.

d. NEED FOR BETTER COMMUNICATION AND CONTRACTUAL COURAGE

I must admit that for many years I shared this view with our technicians and other personnel. However, as a result of considerable study and discussion with design engineers, I am of the opinion that the basic cause for disregarding maintainability requirements during initial design of our systems/equipment results from the lack of contractual requirements and ineffective communication between the customer and the design engineer concerning logistic requirements. In most instances, the design engineer is not acquainted with operating problems experienced in the field. He is not sufficiently familiar with the capability and limitations of the mechanic. In many instances he has not been appraised of the operational requirements for short turn around time and minimum downtime for maintenance. His efforts are therefore primarily concentrated on performance characteristics of the equipment. As a result, he designs a piece of equipment with outstanding performance characteristics that cannot be effectively maintained or supported.

e. AIR FORCE RESPONSIBILITY

The Air Force has an important responsibility in this area. During the conceptual phase, we must give thought to logistic requirements along with operational and performance requirements. We must develop realistic maintenance concepts based on the mission, the geographical areas and climatic conditions where the equipment will be maintained. If the operational mission of the equipment dictates that maintenance be performed in a rice paddy during the monsoon season, then we should apprise the contractor and the designer of this fact. We must advise the contractor of all requirements both logistic and operational that demand consideration during initial design. We must apprise the contractor of our maintainability requirements at the three levels of maintenance, the Air Force Base Self Sufficiency Policy, maximum maintenance downtime limitations, the requirement for maximum standardization and interchangeability of parts, the requirement for minimum peculiar AGE, tools and special skills, etc. It is unreasonable to expect the design engineer to read our minds. Since most design engineers have not been exposed to sustained field operations, we cannot expect him to know the specific problems and requirements of the field. He does not appreciate the difference in environment of his air conditioned work room and the hot dessert or ice covered ramp or cite where the equipment will be serviced and maintained.

f. A STEP THAT WOULD HELP

It would appear that Industry could make great progress in this area by supporting the design engineer with highly qualified and experienced technicians who know from experience the requirements for equipment maintainability characteristics. These technicians could provide an invaluable input to the design engineer. They could be effectively utilized throughout the design and development to include Category II and III Test Programs. Since our greatest concern in this area is downtime of equipment and associated costs, these technicians could greatly assist the engineer in arriving at reliability and maintainability trade of decisions. The contractors technical representatives and field service personnel should be an ideal source to obtain these people, provided they have had sufficient field experience. This action would relieve the engineer of many time consuming details and permit him to devote more time to pure engineering work.

THE CUSTOMERS' POSITION

From what has been said it should be quite evident that the Air Force Logistic Command and the using commands are quite concerned over the rapidly increasing trend in maintenance workload and the resultant downtime of our equipment. Also, we are highly concerned about the increasing cost involved in supporting this increased maintenance workload. We must take positive action now to reverse this rapidly increasing trend. If we cannot reverse the trend, we must flatten it out. Any way you approach the problem, common sense dictates that Industry and the military services must jointly develop and implement a maintainability (M) program that will result in the delivery of systems and equipment that can be effectively maintained, supported and operated with the limited funds, personnel and materiel resources that are available to the Air Force Logistic Command and the using commands.

CLOSING REMARKS

In closing I would like to briefly discuss some examples of poor maintainability in electronic systems. These examples should give you an idea why many of our people in the field contend that our systems acquisition people and Industry are not too concerned about the maintenance workload that is imposed on them, or the associated costs and downtime of their equipment.

a. EXAMPLES

1. (For discussion during presentation.)
2.
3.
4.

From these examples and from what I have said, it should be apparent that the Air Force Logistic Command in our dual role of providing world wide logistic support for all Air Force materiel and as a using command have no choice but to demand that all systems and equipment be designed initially so that it can be effectively maintained at the three levels of maintenance.

MAINTAINABILITY DESIGN OF THE NUDETS SYSTEM

by

William B. Johnson

General Electric Company
Defense Systems Department
Syracuse, New York

Presented at
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SUMMARY

From the more than forty (40) existing definitions of maintainability, a simplified version is stated along with a brief synopsis of the history of maintainability programs and today's requirement for the maintainability engineer.

The NUDETS System maintainability program is defined beginning with the origination of customer specifications followed by the step-by-step series of events that transpires until the time of customer equipment acceptance. The maintainability engineer's role is shown in a typical program such as the one applied to the NUDETS system and covers the phases of pre-design, development, manufacturing, testing, and installation/customer acceptance.

The equipment pre-design and development phase takes into consideration factors such as the equipment configuration, the environment, type of maintenance to be performed, the facilities and test equipment available and the capabilities of personnel required to perform this maintenance. As back-up material for these phases, the guide lines for design as stated in MIL-M-26512 and AFSC Manual 80-5 are listed for use as references.

In the manufacturing, test and installation/customer acceptance phases, a maintainability measurement program is outlined. This program measures the impact of the maintainability effort on the overall system and shows how to translate these measurements into tangible improvements to the system. A maintainability checklist is described in order to acquaint the audience with a means of determining the existence of maintainability features in the various sub-divisions of the equipment. The advantages, disadvantages and best use of the checklist is also pointed out. In addition, such things as designed features that affect equipment downtime on displays, controls and external accessibility are covered.

Since maintainability evaluation and reporting is a new and challenging field, it is shown how the more detailed and well defined the information regarding data collection and methods of analysis, the greater the value of maintainability realized. In conclusion, guides to successful maintain-

ability designs are listed for references in designing future programs.

INTRODUCTION

Maintainability means many things to many people. To a wife it means maintaining her in the style that she would like to become accustomed. To the small child it means Dad's ability to repair the numerous toys that are frequently broken. To industry it can mean one of over forty (40) different definitions that are listed in various publications. One EIA guide lists a total of 27. Maintainability to the Defense Systems Department of the General Electric Company means the generation, monitoring, and measurement of the combined features and characteristics of equipment design that facilitates the ease, rapidity, economy and accuracy with which maintenance operations can be performed by personnel of average skills under specified environmental and usage conditions.

Maintainability is not new to industry; it has been known by many names throughout history. Repairability and serviceability were popular terms during the early 50's. At that time, many companies had large advertising campaigns stressing these features. Some campaigns were in conjunction with reliability features. It is interesting to note that when the effort to improve reliability was first initiated, many hoped that equipment reliability could be improved to the degree that the need for maintenance activity would be practically eliminated. However, the growth in equipment complexity soon shattered this hope and although the search for further reliability improvement continues, it is unwise to plan future systems on the assumption that some miracle will suddenly achieve the ethereal goal of absolute reliability.

Faced with these problems, military and commercial customers must pay increased attention to the new technology of designing for maintainability. This technique too is not new to the design engineer nor to industry. Good engineers have always designed their equipment with an eye to maintaining it. When today's maintainability programs were new, it was often said that if the design engineer did his job well, there would be no need for the maintainability engineer. This is probably true under ideal conditions; however, the complexity of the systems and specifications of today and the usual crash programs encountered, do not allow time, nor do most companies have the staff of design engineers that can give the maintainability portion of design the detailed attention that is required to assure a truly maintainable product. Therefore, today there is an increased demand for a specialist to work with the designer beginning with the initial stages of equipment concept design and ending with the users acceptance of the end product.

In between the alpha and omega of design phases, we think in terms of pre-design, development, manufacturing, testing, and installation/customer acceptance efforts. At each stage the maintainability engineer has a never-ending job to do. The importance of acquiring maintainability aid at the earliest possible time in a development program cannot be stressed too often. Designing after-the-fact can only increase design and production costs. Besides the costs in terms of dollars and cents, it is not unlikely that the cost could include lives lost or missions failed.

PRE-DESIGN PHASE

In a typical program such as the one the General Electric Company applied to the NUDETS system, the conception of the maintainability program began with the system proposal work. Keeping in mind the prime objective of our Maintainability program which is to increase the useability and hence the availability of the equipment, sleeves were rolled up and the work began. At this stage, which will henceforth be referred to as Pre-design Phase; ground work was laid in conjunction with various other engineering functions that ended in a maintainability concept. To accomplish this end the system was defined in order to determine the design necessary to adequately manufacture, test, repair, install, and maintain the required equipment. Logistics requirements and limitations pertaining to maintenance were also considered along with environment criteria, test equipment, and tool availability.

In addition, some time was spent during Pre-design in detailed contract negotiations of maintainability tasks. The degree of application of maintainability principles to the system design parameters were determined and accomplished after coordination meetings between the contractor and the customer. Particular attention was paid to degree of compliance with MIL-M-26512A. The Maintainability Program then developed was based on MIL-M-26512A. Plans were also made to demonstrate maintainability features and accomplishments. The maintainability engineers output derived from the negotiations during the Pre-design Phase consisted of the following inputs to the program plan: MTTR, MTBF goals, work statements, milestones, manpower estimates, preliminary maintainability checklists, and availability equipment specifications.

To sum up the Maintainability engineer's effort during the Pre-design Phase, it was a time of defining the system and customer requirements, negotiating maintainability tasks and submitting inputs to the program plan. The plan included information defining the company's anticipated maintainability goals and a method for achieving and demonstrating that the maintainability goals have been met.

DEVELOPMENT PHASE

During the Development Phase close liaison was maintained between maintainability engineering and other functions such as design, reliability and value engineering, human factors, quality control, drafting, spare parts production, field and sub-contractor support. Maintainability engineers were made available for consultation and assistance to the equipment design engineers. This assistance, thus acted as an aid to the design engineer in order to assure compliance with maintainability requirements without compromising the technical performance of the equipment.

In the case of sub-contractor activity on the NUDETS system, a preliminary maintainability checklist was submitted with the equipment specs. Under General Electric's direction a maintainability program was implemented by each associate contractor. The role of the General Electric Company then became one of coordination in order to achieve an integrated overall maintainability program

The work at this time took into consideration factors such as equipment configuration, environment, type of maintenance to be performed facilities, and test equipment available and the capabilities of personnel required to perform this maintenance. As back-up material for these efforts some of the more important guide lines for design, as stated in MIL-M-26512A and AFSC 80-5 and 6 were used as references in designing electronic equipment Examples of these guide lines are:

[illegible] Design to minimize the complexity of maintenance tasks.
(2) Design for rapid and positive recognition of equipment malfunction or marginal performance.
(3) Design to require minimum maintenance skills and training.
(4) Design for optimum accessibility in all systems requiring maintenance, inspection removal or replacement.
(5) Design for maximum safety of personnel performing tasks.
(6) Design for a minimum number and type of spare parts and assemblies.

Similar guide lines were used to derive up-dated maintainability check lists. Provisions were then made to assure that the latest maintainability design checklists were provided for the use of each design engineer. These checklists, combined with the maintainability engineers experience and consultation efforts, were an excellent means of assuring compliance with the maintainability program plan. However, you must remember that the design engineer still has complete charge of the approval of the end product therefore, many trade offs were realized before the end product was a reality. As a result of this factor, considerable time was spent with Design Engineering at the early stages of this phase in order to negotiate these design trade-offs on both in-house and purchased equipment. Where trade-offs are involved, there are many problems that arise in this area. For instance in considering sub-contractors, many factors such as the economics, the timing, the techniques used etc., have to be analyzed before accepting a sub-contractor or an off-the-shelf item. In cases like this maintainability is bound to suffer somewhat due to the necessity of weighing the best interests of the job against some compromise reached in the selection of a particular company or product.

Another trade-off situation that comes to mind is the problem connected with the availability figures associated with commercial equipment that must be combined with the in-house equipment being designed. One could make the assumption that if a system is designed from the beginning by one company that has a Maintainability/Reliability, hence Availability Program, then you realize a relatively high figure of performance. But if you have to purchase equipment from an outside company that has no M/R program, you usually realize a lower figure of performance. This can be especially true when purchasing some commercial off-the-shelf equipment that must be combined with military equipment. The main problem in this case is getting a company to redesign a feature that is recognized as non-maintainable or one that has a definitely low MTTR figure. As stated before, once an item is designed, a great deal of time, effort, and cost is involved in order to redesign. Therefore, the Maintainability engineer must use all of his design experience and tact in order to resolve these areas to the best compromise possible. If per chance it cannot be done, then this information must be presented to the contracting office so that everyone is aware of the reason behind the lower Availability figure applied to the overall system.

At this time it should be noted that equipment design characteristics are always evaluated for conformance to maintainability principles to assure that they are within other system design parameters prior to making any design trade-offs affecting operational or logistics requirements. Once again it is most important to design maintainability features into the equipment at the initial development stages; that is why the Development Phase is by far the most important phase of any Maintainability program. The availability of the system will be assured if the correct features are designed into the system at this time.

The development Phase then was a time of close design cooperation between maintainability and other engineering functions both in-house and with sub-contractors. This action was necessary to assure the introduction of maintainability features into the equipment at the initial stage of design. MIL-M-26512A and AFSC 80-5 and 6 were used to make certain that best engineering practices were incorporated. Preliminary checklists were generated, utilized, and signed off to confirm compliance with program plans. Informal design reviews are held with cognizant personnel. Where necessary, recommendations and corrective actions were processed as a result of these endeavors.

MANUFACTURING PHASE

Assessment of the achievements of the maintainability program is a necessary and integral part of the overall program. In the manufacturing phase the actual measurement program began. The goal was, of course, to measure the impact of the maintainability effort on the overall system and translate these measurements into tangible improvements to the system. At this stage formal design review procedures were utilized to realize this end. Formal design reviews in this case means combined customer/contractor equipment or system design reviews. During the Development Phase many company internal design reviews were held as well as informal meetings with the customer and sub-contractors, but it is not until this Phase of Design that all of the customers, consultants, contractors, and sub-contractors assemble to thrash out their differences on the more or less completed assemblies.

The formal design reviews in this case were held, once drafting had completed preliminary drawings and prior to design finalization and released to manufacturing. These design reviews were held in conjunction with each individual piece of equipment, such as the sensors, computer, console, etc. In preparation for the review, the maintainability engineer prepared an up-dated checklist which applied specifically to the latest design of the equipment in question. This checklist accomplished a quantitative appraisal of compliance with maintainability requirements. The design review checklist was tailored to consider all echelons of maintenance. The prime consideration was to minimize system downtime. Additional emphasis was placed on control of fault recognition, fault isolation, repairable features, and repair verification.

The following information shows an example of checklist categories for one type of equipment: All items were rated from 1 to 4.

(1) Packaging
Equipment is of modular construction for easy unit replacement.

(2) Labeling
Parts and controls clearly and accurately labeled.

(3) Latches and Fasteners
Latches and/or fasteners are captive, need no special tools and require only a fraction of a turn to release.

(4) Accessibility
Access adequate for visual and manipulative tasks.

(5) Cables and Connectors
All cables routed so they cannot be pinched by doors, lids, etc.

(6) Operation and Fault Detection
Task accomplishment requires minimum test equipment.

(7) Adjustments
Required adjustments kept to a minimum.

(8) Test Points
Exposed test point provided for outputs and/or inputs of each major unit.

(9) Tools, Jigs, and Adaptors
Special tool requirements kept to a minimum.

The advantage of a checklist is that it allowed experienced design oriented engineers to go through the electrical and mechanical features of the design and evaluate each and every item. Here working in conjunction with the reliability engineers preliminary functional analysis we were able to determine, in the case of electrical circuits for example, the components or printed circuit card assemblies with the lowest MTBF. With this information an analysis of the mechanical construction plus the diagnostic time determined up-dated MTTR figures. Recommendations for improvement were then initiated where necessary.

In addition to the checklist and guide lines for best engineering design practices, the maintainability engineer was also concerned with design features that are unique to specific portions of the equipment. While there are close correlations between these areas, there are nevertheless published lists that allow the engineer to specifically analyze particular features of each piece of equipment. These data are always up-dated to reflect advances in maintainability technology and changes in design configurations.

The following design data illustrates some of the features that affect downtime on specific portions of equipment:

a. Design features affecting equipment downtime on displays and controls.

(1) Locate all displays used in system checkout so they can be observed from one position.

(2) Use auditory signals to supplement tele-lights for displays not constantly watched when changes in indications must be noted immediately.

b. Design features affecting equipment downtime on external accessibility.

(1) Use hinged door for physical access in lieu of cover plate with screws.

(2) If units must be pulled out frequently from installed positions, mount them on roll-out racks, slides, or hinges.

(3) Locate test points in an accessible location, unimpeded by other parts of the equipment.

In conjunction with the Design Review effort, the Maintainability engineers were also engaged in factory follow-up activities. These activities consisted of periodic factory inspections and consultations with Quality Control and Reliability personnel. Numerous constructive suggestions were received from the man closest to the problem - the factory foreman. The factory follow-up activities resulted in additional improvements to the equipment design and/or verification of the existing design criteria.

The manufacturing Phase may then be summed up as follows: The assessment of the achievements of the maintainability program began at this time in the form of formal design reviews held prior to the finalization of design and the total release of drawings to manufacturing. Through the use of maintainability checklists, portions of actual hardware were appraised in conjunction with mechanical drawings and schematics. Recommendations for improvement or corrective actions were then initiated where necessary. During the actual manufacturing process factory follow-up activities allowed the maintainability engineer to verify the latest design criteria.

TEST & INSTALLATION PHASE

The first phases of the program previously discussed were basically concerned with evaluating design features that cause downtime and affect maintainability primarily from a hardware sense. Design features are the portion that the design and maintainability engineer can influence. Since design features are only partly responsible for the length of time a piece of equipment is in an unsatisfactory operating condition, it is reasonable to investigate and allow for additional causes of downtime consumption primarily from a software sense; the part a maintainability engineer cannot necessarily influence. In a typical program, the test and installation acceptance phase involves these additional causes.

In this light, the support practices are a very important factor of downtime consumption on systems having a strict availability requirement. The problem of which technique to use in gathering meaningful data from these practices can get to be an involved process. For example, a poorly designed system could be made operational and data thus masked by a highly technical and efficient maintenance group that engaged in non-reporting redesign activities as a part of their function. Data gathered from this group would be meaningless. By the same token to try to determine with accuracy the intrinsic maintainability of equipment by observing only the events of maintenance would be misleading also. To realize realistic figures, it would probably require the exclusion of such factors as maintenance support policies, human factors, environment and many other important situations that determine availability. Many of these situations which certainly should be considered are difficult to measure.

There are also many time elements that enter into availability predictions. For instance, system downtime can be subdivided into logistic, repair, and final test time, while system repair time can be subdivided into the following maintenance events:

(1) Preparation
(2) Malfunction Verification
(3) Fault Location
(4) Part Procurement
(5) Repair
(6) Final Testing

The time required to perform each of these distinct categories varies from zero to several hours depending on numerous characteristics of the equipment and maintenance events. Fault location is by far the principal contributor to system repair time. If diagnostic time is to be minimized, it is necessary to consider human factors elements and then design the equipment to facilitate quick, accurate and positive actions by the technician. The most important human factor element in this case, that would increase equipment availability, would be to thoroughly train the technician trouble shooter. His ability holds the key to this most important time element.

Some feel that time and motion studies for MTTR measurements may be another solution to the problem of accurate data collections. While time and motion studies work quite well in factory assembly evaluations, it is sometimes impractical to use this approach on maintenance events. To be able to enumerate all possible motions which would take place in any maintenance task would be a formidable task. Moreover, the impracticability of this approach is compounded by the tenuous nature of the relationship between the frequency of occurrence of the motions and the characteristics of the system. Time, money, and manpower in most cases limits the collecttion of data in this manner.

On the other hand, proper data must be collected via some efficient method. With proper data, the frequency of occurrence of repairing certain equipment can be predicted fairly accurately. The illustrations previously given showed some of the problems involved. In spite of these problems, the situation is not hopeless. Experience has shown that in order to collect proper data, you must first allow the proper testing time both in the factory and in the field. In both cases, insist on accurately filled-out failure reports. If these methods are followed, realistic equipment failure rates can be determined for use in further evaluations. The test and installation acceptance phase should accomplish this end.

At the time of this writing, the NUDETS equipment is in the factory test and installation phase. Data is being collected from some equipment in operation at the site and from some factory testing. Mean-time-to-repair predictions, based on the assumption that all spares, test equipment and experienced personnel are on location during a malfunction, have been completed. The final functional analyses which would point out weak points in the system have just been completed also. Therefore, it is only possible to point out the method to be used in the field for data collection and the evaluation required to determine the realization of maintainability goals.

During the test and installation phase the equipment is checked out, operated and tested. As a result of operating the equipment all failures should be properly recorded and fed back to Reliability and Maintainability personnel. Little data of course would be gathered if the system operates in a flawless manner. You would require a period of years to get a true picture of the problem. On the other hand, if failure simulations are scheduled, the equivalent of accelerated life testing in a non-destructive manner would be accomplished.

Failure simulation in this case means to plan, through the use of Reliabilities functional analysis, tests for each one of the system functions. These tests would consist of determining components to be evaluated, using sampling methods called for in MIL-M-26152B and then rendering certain relays, diodes, power supplies, etc., inoperative. At this point, record the length of time that it takes qualified personnel to locate, repair, test, and return the system to normal operation. With sufficient data of this type plots and accurate predictions can be made on the MTBF and MTTR features of the system. If the equipment is measured under field environmental conditions, the test will be more realistic.

The key to this phase of system design then is to allow for sufficient time to test the equipment in environmental conditions in order to collect an accurate picture of the equipment capabilities. The longer the test cycle, or the more complete the failure simulations and the more complete and accurate the data, the more realistic the distribution curve and hence the more realistic the predictions.

To complete the picture, the maintainability program must take into consideration the problems of spares, logistics, and maintenance organizations. The proper test equipment with sufficient repair tools and spare parts must also be allowed for. In addition, qualified personnel must be made available and provided with up-to-date technical manuals. When all of these facets are in place, true maintainability/availability can be realized.

GUIDES TO SUCCESSFUL MAINTAINABILITY DESIGN

In conclusion, to sum up the highlights of the Maintainability Design of the NUDETS System, the following points, which are recommended for any program, are contributing to a successful NUDETS maintainability program:

(1) Determine maintenance requirements imposed by system operating conditions.

(2) Consider logistics requirements, maintenance organizations, and support personnel limitations.

(3) Translate system requirements into definite maintainability specifications.

(4) Prepare and continually up-date checklist to assure compliance with all maintainability features through numerical prediction techniques.

(5) Design maintainability features into equipment at earliest phase to prevent costly redesign.

(6) Follow best design practices per AFSC 80-5/6 and MIL-M-26512B.

(7) Plan for early data collection and analysis.

(8) Work closely with design engineering and other functions.

(9) Participate in design reviews, recommend and follow up corrective action.

(10) Perform periodic factory inspections in order to verify latest design criteria.

(11) Demonstrate achievement of established goals through controlled maintainability tests.

(12) Procure complete and accurate failure data under field environmental conditions for realistic analysis and field follow-up efforts.

(13) Provide adequate reporting of progress made in maintainability development to cognizant authorities.

RESUMES

William J. Arnold
General Electric Company
Syracuse, New York

Mr. Arnold is a Project Engineer in the Reliability Engineering Group, Defense Systems Department, General Electric Company, Syracuse, New York. In this position he has been responsible for all standards activity with respect to equipment reliability, evaluation reliability testing techniques - processes with respect to reliability, reliability documentation including project requirements. He has also been responsible for reliability vendor reviews and establishing overall project reliability programs, and is currently Project Engineer for reliability on the 477L System (NUDETS), a nuclear detection system.

Mr. Arnold joined the General Electric Company in 1956 after graduating from the University of Rhode Island with a BSEE, and is an alumnus of General Electric's Advanced Engineering Program completing the Creative Engineering branch of this program. While a member of the program, experience was gained in the design and evaluation of semiconductor devices, design of temperature measuring devices for automatic measurement, development of laboratory techniques for electronic tube evaluation without any tube modification and contributions to the development of techniques for particle measurements as well as experience in the design and evaluation of industrial equipment.

Subsequently in 1958, Mr. Arnold joined the Reliability Engineering Group of the General Electric Heavy Military Department, located in Syracuse, where his responsibilities included the development of technical and administrative procedures for standard parts and project data book, the establishment of project standards for reliable design, the establishment of circuit testing techniques to predict and insure reliable design, and the investigation of advanced techniques for reliability design improvement.

In 1961, Mr. Arnold was appointed to his present position of Project Engineer, Reliability Engineering.

Mr. Arnold is a member of the following professional societies:

Professional Engineer N. Y. S.
Associate Member AIEE
Member IRE
Member IRE Group on Reliability and Quality Control

JAMES R. BARTON
Major USAF

Served three and one half years during World War II as Aircraft Maintenance Officer and Technical Inspector - Squadron and Group level respectively.

BSEE - 1947 - Auburn University, Auburn Alabama

Electrical Engineer - three and one half years - 1947-1950

Recalled to service (USAF) 1950. Served 1950-1955 with Tactical Air Command, squadron, group, and wing level. Served 1955-1958 with Strategic Air Command in positions of:

Flight Line Maintenance Office

Quality Control

Standardization

Maintenance Control

Chief of Maintenance

Chief of Maintenance Task Force

Commander Periodic Maintenance Squadron

Division Aircraft Maintenance Office

Air Force Institute of Technology Graduate Program 1958-1960

MSEE - University of New Hampshire - 1960 - Thesis Subject: Design of Simplified and Economical Characteristic Curve Tracer for Transistors.

Assigned ESD (CCDD) 1960

Chief Equipment Engineering Branch
(Reliability, Maintainability, AGE)

Chief Reliability Division
(Reliability, Maintainability)

Deputy Chief Personnel Subsystem/Reliability Branch
(Reliability, Maintainability)

Chief Engineering Requirements Division

James R. Barton (Cont'd)

<u>MEMBER</u>

IRE

PGRQC - Professional Group on Reliability
and Quality Control

Tau Beta Pi - National Honorary Society
for Engineers

Eta Kappa Pi - National Honorary Society
for Electrical Engineers

AFSC Reliability Task Force

AFSC Maintainability Task Force

ROBERT L. BIDWELL

Manager, Value Analysis Administration

Martin Company
Division of Martin Marietta Corporation
Orlando, Florida

Robert L. Bidwell, Manager of Value Analysis Administration at Martin, is a U. S. Army veteran (Lt. Colonel, ret.) whose service spans a quarter of a century with the Air Corps, Quartermaster Corps and Ordnance Corps. More than half of this service has been directed toward industrial efforts, providing him with a rich and varied background for the responsibilities which he assumed at Martin in May 1961.

Bidwell launched his Army career in 1936 as a Private and rose to the rank of Lt. Colonel. Assignments during those years covered the broad spectrum of Administration and Procurement. They ranged from Commander of maintenance and supply depot operation in New Guinea during World War II to Staff Officer of manpower and operating budgets for all Ordnance Procurement Offices in Washington for four years.

For seven years with the San Francisco Ordnance Procurement District, Colonel Bidwell served in such capacities as Executive Officer, Contracting Officer, War Manpower Representative, Labor and Deferment Officer, and later, -- for three years, acted as advisor to the Netherlands Government on building, maintenance and organization of a Supply and Maintenance Depot System.

Prior to his appointment with Martin, Bidwell organized and operated a Branch Office of the Birmingham Ordnance District which was responsible for some $400 million in contracts. As Commander of this post, he had overall responsibility for the quality of material contracted and released to the Army, Navy, and Air Force as well as administration of all assigned contracts.

Joining Martin shortly after his retirement from active service, Bidwell assumed managership of the company's Value Analysis Program which has contributed more than $18,000,000 in operating cost reductions during the past year.

Martin, as a leading exponent of Value Analysis in action, has attracted nation-wide interest in its program. Explanation of this program by Mr. Bidwell and his staff has been presented to widely diversified audiences including the Department of Defense, the Army, Navy, and Air Force, American Management Association, and a host of manufacturing and civic organizations.

F. W. Bucher, Chief, Logistics Engineering

Autonetics, North American

Mr. Bucher joined Autonetics in 1954 as a research engineer in the Inertial Navigation System Test Unit. His responsibilities during the first four years included development of special test instrumentation equipment for laboratory, field and flight testing of inertial navigation systems. His work included development of laboratory test procedures and factory process specifications, as well as associated operation and maintenance instruction manuals. During the last year in the System Test Group Mr. Bucher served in the capacity of Engineering Supervisor.

During the next two years Mr. Bucher was supervisor of the Systems Engineering Unit in the Inertial Navigation Project Engineering Section with responsibility for conducting special studies and investigations of special systems problems as well as development of Engineering documents such as Technical descriptions, model specifications, and program reports.

Mr. Bucher joined the Inertial Navigation Logistics division in 1960 to serve as Group Leader of the Logistics Engineering Group which was being started. During this period an organization was developed which was oriented to approach the problems of maintenance, support and maintainability from a quantitative viewpoint. In mid-1962 Mr. Bucher assumed responsibilities for the Logistics Engineering and Technical Publication Section in the capacity of Chief.

Mr. Bucher received a B.S. in physics from Wheaton College, a B. S. in electrical engineering from Illinois Institute of Technology and a M.S. in electrical engineering from the University of Southern California. He is a member of Tau Beta Pi and Etta Kappa Nu.

S. R. Calabro

President, Electronics Reliability Corporation

S. R. Calabro is a graduate of City College of New York with a Bachelor's Degree in electrical engineering.

He is also a licensed Professional Engineer in Pennsylvania. He has lectured on quality control at Rutgers University and other institutions.

He was the Director of the Product Assurance Division, International Electric Corporation, Paramus, New Jersey. In this capacity, he was responsible for all reliability and quality control activity, the scope of which necessitated the generation of many new concepts in order to achieve specified reliability goals.

For eleven years he was the Manager and Director of Quality Control and Reliability for the International Telephone and Telegraph Corporation.

He has also had extensive experience during World War II as a Signal Corps officer in procurement and inspection activities.

He is presently the President of the Electronics Reliability Corp., at 666 Fifth Avenue, New York City which firm specializes in Reliability and Maintainability Engineering.

He is a member of the American Society for Quality Control, the American Ordnance Association and has lectured at meetings of the American Management Association and symposiums held on various occasions by Industry and Government Agencies.

He is the author of "Reliability Principles and Practices" published by McGraw-Hill.

JAMES H. S. CHIN

ENGINEERING SECTION HEAD
Surface Armament Division, Sperry Gyroscope Company

EDUCATION: BSEE, University of Michigan, 1950
MSEE, University of Michigan, 1951

EXPERIENCE: 1951 to Present, Sperry Gyroscope Company

Mr. Chin came to Sperry in 1951 as an assistant project engineer working on circuit design and system development work on fire control radars. He spent the following years in system development work on Naval tracking and missile guidance radars, and in November 1957 was promoted to senior engineer. The group redundancy technique which has been successfully applied to Naval Tracking Radar was a result of Mr. Chin's work during this period. In 1961 he was appointed to his present position as engineering section head for mathematical analysis in the Reliability Engineering Department.

PROFESSIONAL ACTIVITIES: Etta Kappa Nu, Member IRE, Vice Chairman of the IRE Professional Group on Reliability and Quality Control Metropolitan New York Chapter. He has presented numerous papers at WESCON and IRE conventions and as guest speaker, he lectured at the Cornell University Industrial Seminar; the ASQC symposium at the University of Rochester, and at the Annual meeting of the Operational Research Society of America, all in the area of reliability.

JEROME E. HOROWITZ

Mr. Horowitz is a graduate of the University of Rhode Island with a B.S. in chemical engineering. In addition, he has taken courses at Brown University and various Service Schools.

He is presently employed as a Staff Reliability and Maintainability Engineer by the Directorate of Technical Services, ESD, L G Hanscom Fld. Prior to joining the Air Force he served as Supervisor for Eastern New England Area of the U.S. Army Signal Supply Agency, Phila., Pa. and in addition, prepared special staff studies for the Office of the Chief Signal Officer. He is a registered Professional Engineer and a member of the American Society for Quality Control and the National Society of Professional Engineers.

JOHN JENORIKI

John Jenoriki is a Senior Engineer in the Equipment and Systems Evaluation Branch, C&E Department, of Federal Electric Corporation* the Service Associate of ITT, Paramus, New Jersey and has been with the company since 1956. He is presently serving as project engineer responsible for the Reliability-Maintainability prediction aspects of the Big Rally II and European Mediterranean Tropo Communication Systems. Mr. Jenoriki is also engaged in the determination of techniques for predicting the reliability of electronic equipment during the early (pre-design) stage.

Past responsibilities have included such project as: (1) DASH Weapon System Reliability Study (a destroyer based unmanned helicopter that is remotely controlled); (2) Systems Integration Studies consisting of reliability studies of special items such as Power Amplifier Klystrons, Planar Triode, 416B/6280, Magnetrons, T-R Tube 6322, etc.; (3) Engineering editing of the monthly DEWLine Reliability Report to the 4601st USAF Support Wing; and (4) Systems Engineering for various projects involving radar profile readings and calculations of path loss, channel noise, etc. in accordance with CCIR and CCITT.

Mr. Jenoriki's experience in the field of reliability and maintainability prediction includes the application of prediction methods such as: (1) electrical/electronic TR-59-416-1, TR-1100, and RADC TR-58-111; (2) mechanical and electro-mechanical, RCA-176; (3) part failure distributions and predictions using the exponential, weibull, etc. in conjunction with failure modes; catastrophic, degradation, etc. He has field experience in Radar, Communication, Telephone, Telegraph and has been responsible for the operation and maintenance of these equipments at DEWLine Sites.

He is a graduate of Capitol Radio Engineering Institute in Electronic Engineering. He also attended Radar, Communication and Navigational schools conducted by Federal Electric Corporation. He is an associate member of American Institute of Electrical Engineers, a senior member of Capitol Radio Engineering Institute Association, and a member of Electronic Industries Association.

*Now with Computer Applications, Inc.

W. B. JOHNSON

Mr. Johnson attended the University of Hawaii, University of Pittsburgh, and Syracuse University. His major subjects were Electrical and Industrial Engineering. He also completed a course on Electronic Packaging for Design Engineers at the University of California.

Since joining the General Electric Company in 1948, he has worked as an Electro-Mechanical Designer and Project Engineer with the Specialty, Television Receiver and Defense Systems Departments. Mr. Johnson has wide experience in the electronic design and packaging of oscilloscopes, signal generators, AM-FM radios, television receivers, electronic system evaluators, and transistor pellet mount machinery. He has done considerable work in the areas of oscillator radiation, printed circuit board development, dip soldering, spark gaps, heat analysis, packaging, console design, and micro-miniaturization.

On assignment with the Defense Systems Department in the Design Standards area, he utilized his past experience in providing consultation in the electronic packaging area and in evaluating design practices utilized within the General Electric Co. In addition, while working on the Apollo Support Program, he reviewed specifications and design practices utilized by various NASA centers and subcontractors. A report consisting of an implementation plan to consolidate all common specifications and practices resulted from this effort.

Mr. Johnson is presently responsible for maintainability engineering within the Defense Systems Department and NUDETS Project.

Mr. Johnson is a member of the American Rocket Society and the Syracuse General Electric Engineers Association.

JEROME KLION

Jerome Klion received his BA in Mathematics-Physics from Syracuse University in 1957 and is presently working toward his Masters Degree in Electronic Engineering from the same institution. He has been a member of the Reliability Techniques Group of the Rome Air Development Center, Griffiss Air Force Base, New York since 1957. There he has conducted investigations relevant to the development of new techniques for improving, predicting, and verifying the reliability of ground electronic equipment. He is the author of several papers on reliability presented and published at national symposia. He is a member of the IRE and Professional Group on Reliability and Quality Control of the IRE.

S.M. Laster
General Electric Company
Syracuse, New York

Mr. Laster is an operations analyst in the Defense Systems Department of the General Electric Company, and is presently a group leader in the systems engineering unit of that department's Nuclear Detection Subsection.

At General Electric he has also worked on operations analysis studies for the Atlas guidance system, advanced guidance systems projects, communications studies, and mobile ballistic missiles studies.

Before joining the General Electric Company, Mr. Laster had worked at the Harvard Business School, on Air Force Logistic studies, and at Harbridge House, Boston, Massachusetts. Mr. Laster received an AB from Harvard College in philosophy and mathematics, and is doing graduate work at Syracuse University in mathematics.

FRANK D. MAZZOLA

Frank D. Mazzola received his BS Degree in Electrical Engineering from Rensselaer Polytechnic Institute in 1952. Since graduation he has been employed at the Rome Air Development Center, Griffiss Air Force Base, New York, where his duties have been concerned chiefly with general and special purpose test equipment and maintainability techniques. In 1959 he became leader of a new Maintainability Group organized within the Applied Research Laboratory and has since planned and supervised study and development of techniques for maintainability prediction, measurement and improvement. He is the author of several papers and, as a member of certain USAF committees, has contributed to various official publications in the maintainability area.

IRWIN NATHAN

Irwin Nathan is a Senior Systems Engineer in the Reliability Section, Arma Division, American Bosch Arma Corporation. He received an M.E. degree from Stevens Institute of Technology, and M.E.E. and M.I.E. degrees from New York University where he is presently working towards an Sc. D. degree in Operations Research. He is currently responsible for the technical direction of the activities of the Systems Evaluation Group of the Section, including generation of system reliability estimates as predicted from system configuration, design, and usage projections, and as computed from failure and operating time data. In addition, he is responsible for designing statistical reliability tests and the application of "state-of-the-art" O-R techniques for solution of maintainability, availability, and logistic problems.

Prior to joining the Reliability Section he was engaged in the design, development and application of inertial components for use in the Arma Inertial Guidance System for the Atlas ICBM and the Arma Subminiature Gyro Compass. Previously, he was an R&D Electronics Engineer at Bendix Aviation Corporation and at Reeves Instrument Corporation where he worked on fire control systems.

Mr. Nathan is a member of the New York State Society of Professional Engineers. His other professional activities include a presentation on the statistical analysis of reliability field data, to be given at the 1963 IEEE International Convention.

LOUIS T. POPE

Louis T. Pope was born in 1919. He served as an aerial navigator in the United States Air Force in both World War II and the Korean conflict. Prior to 1943, he worked as an electronic maintenance technician and foreman. He received the B.A. degree from Texas Christian University in 1955 and the M.A. and Ph.D. degrees from the University of Houston in 1959 and 1961. Dr. Pope has been employed as a Research Psychologist with the 6570th Aerospace Medical Research Laboratories since May 1959, and is assigned to the Maintenance Design Section. He has recently completed studies on human monitoring behavior and on electronic checkout equipment. He has made presentations on the subject of maintainability before several military and industry groups.

F. G. REBER, JR.

Mr. Reber pursued his undergraduate work at Drexel Institute of Technology, Pacific University and Temple University toward an AB in Physics.

Mr. Reber's early training with RCA included a Management Training Program he attended in Company headquarters, Camden, N.J.

Mr. Reber became associated with Philco Corporation in 1951, performing technical electronic work on prototype radars. He then joined Eckert-Mauchly (presently a Division of Sperry-Rand) and built specialized test equipment for various computer circuits.

In 1953 he joined RCA and was involved in the test program for the AN/ARC-21; later supervising a production program for AN/ARC-21 product improvement.

From 1955 to 1960 Mr. Reber worked as a test process engineer developing specialized test equipment for computer and high-speed memory testing.

In 1960, he entered product assurance in product operations of the Electronic Data Processing Division. This included planning, design, and prototype evaluation phases of engineering projects.

Early in 1960, Mr. Reber was given the responsibility for product evaluation in the product assurance section of Aerospace Communications and Control Division.

In 1962, Mr. Reber was selected to administrate the Product Assurance activities of the AN/TSQ-47 System Program. This involved setting up a complete program for reliability, maintainability, quality control, failure data collection, analysis and standardization for this system. Presently, Mr. Reber is Administrator, Product Assurance for the AN/TSQ-47 Program Management Office.

STANLEY A. ROSENTHAL

Stanley A. Rosenthal, Head, Reliability Section, Arma Division, American Bosch Arma Corporation, received his B.E.E. degree from City College of New York and his M.E.E. degree from New York University, where he has been pursuing post-graduate studies toward a doctoral program in control systems and simulation techniques. He is currently responsible for the administration and technical direction of all Arma Division reliability activities, including the reliability program for the Atlas Missile Guidance System. Previously he was responsible for systems reliability analysis for an inertial bombing-navigation system, for the Sperry Gyroscope Company, after being engaged in the systems engineering effort on this equipment. Prior to joining Sperry, he was concerned with the application, utilization, and performance of industrial electronic control equipment, for the General Electric Company.

During this time, for a period of over five years, he also served as an adjunct member of the electrical engineering faculty at Cooper Union School of Engineering.

Mr. Rosenthal is a member of Tau Beta Pi, Eta Kappa Nu, Institute of Radio Engineers, American Society for Quality Control, Operations Research Society of America, American Astronautical Society, and is a New York State Licensed Professional Engineer. He is the author of several papers on system reliability aspects and reliability programs, presented at national meetings and symposia of the IRE/PGMIL, IRE/PGRQC, and SAE, and is a contributor to the IRE-ASQC Reliability Training Text.

Richard B. Schwartz

Richard B. Schwartz is a Senior Statistician in the Equipment and Systems Evaluation Branch, C & E Department of Federal Electric Corporation, the Service Associate of ITT, Paramus, New Jersey and has been with the company since March 1959. His duties involve the research, development and application of statistical methods used in predicting and measuring the reliability and maintainability of electronic equipment and systems. He is responsible for the mathematical and statistical approach used in the availability prediction of systems such as Big Rally II and the EUR-MED Tropo Communication System. Mr. Schwartz established the statistical criteria for the Navy Service Failure Analysis Program. The aim of this program is the improvement in electronic equipment performance through reliability and maintainability analysis of field operational data.

He was also responsible for the development of spare parts provisioning formulas, for the 465L Materiel Control Program, which would determine the number of spares required so that, at a specified probability level, the proper spare part would be available to effect a required repair. Mr. Schwartz developed the statistical approach used in isolating and identifying reliability and maintainability problems on the DEWLine.

He received his B.B.A. degree in Statistics from the City College of New York and is presently working there toward his M.B.A. in Statistics which he expects to receive in 1964. He is a member of the American Statistical Association and the American Society for Quality Control.

W. K. Warner - Director, Reliability Department
Space & Information Systems Division
North American Aviation, Inc.

Mr. Warner has 21 years aircraft and missile engineering experience of increasing responsibility, the last twelve years of which have been with S&ID. His current assignment as Director of Reliability Department places him in ultimate charge of all reliability efforts for S&ID of North American Aviation. Under his direction, the S&ID Reliability Department was ranked by the U.S. Air Force as one of the best in the Nation, and the Department has been recommended as a model to other companies by NASA.

His background also includes heading up Standards Engineering, Human Factors Engineering, Flight Test Analysis. In the past, he was engineering group leader and assistant project engineer with Douglas Aircraft, and chief engineer for Piper Aircraft Company and Aviation Maintenance Corporation.

His educational background includes mechanical engineering at the University of Kansas.

STUART A. WEISBERG

Mr. Weisberg is an associate engineer in the Reliability Department, Surface Armament Division, Sperry Gryroscope Company where he has been employed since June 1962. He is engaged in various theoretical studies concerning redundancy and availability, the construction of mathematical models, and reliability prediction techniques. His previous experience was with the Raytheon Company from September 1960 as a systems analyst concerned with the B-58 Doppler Radar, and from June 1961 to September 1961 in a reliability department where he was engaged in a preventive maintenance study. From June 1959 to September 1959 he was employed as an analyst and computor programmer by the General Electric Company.

Mr. Weisberg received the Bachelor of Science degree in Applied Mathematics from the Polytechnic Institute of Brooklyn in 1959. He was a full time student at the Polytechnic graduate school from 1960 to 1962 and is now attending on a part time basis. He has completed the course requirements for the P.H.D. in Mathematics. While in graduate school he held a Teaching Fellowship and taught courses in differential and integral calculus. He is now engaged as a part-time instructor by the Vocational Education and Extension Board of Nassau County, New York and teaches graduate level mathematics courses. Mr. Weisberg is a member of the IRE and it's PGRQC.