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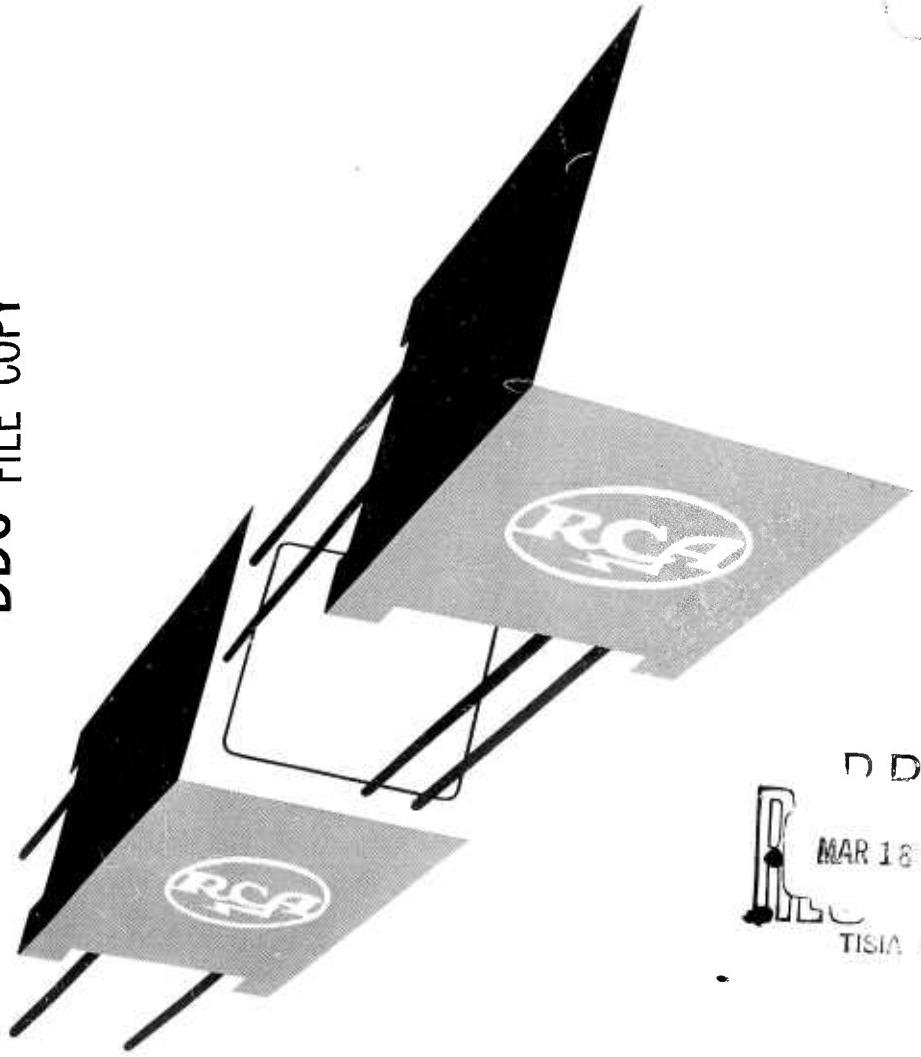

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MICRO-MODULE EQUIPMENT MAINTENANCE AND LOGISTICS PROGRAM

PREDICTION OF LOGISTICS AND MAINTENANCE DEMAND PARAMETERS

PERIOD COVERED—1 APRIL 1962 THROUGH 30 JUNE 1962.
SIGNAL CORPS CONTRACT DA-36-039-SC-85980

SURFACE COMMUNICATIONS DIVISION
DEFENSE ELECTRONIC PRODUCTS
RADIO CORPORATION OF AMERICA
CAMDEN, NEW JERSEY

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The purpose of this program is to achieve an optimum balance between Maintenance and Logistics on one hand and Equipment Performance on the other for a given state of operational readiness.

(9) FINAL REPORT 1 Apr - 30 June 62

VOLUME III

(6)

MICRO-MODULE EQUIPMENT MAINTENANCE AND LOGISTICS PROGRAM

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(15)

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TABLE OF CONTENTS

SECTION		PAGE
I	Introduction	1-1
	1.1 General Discussion	1-1
	1.2 Approach	1-1
	1.3 Prediction of Demand Variables	1-1
II	Reliability	2-1
	2.1 Failure Rate Determination	2-1
	2.1.1 Micro-Modules and Their Components	2-1
	2.1.1.1 Element Test Data	2-2
	2.1.1.2 Element Failure Rates	2-3
	2.1.1.3 Micro-Module Test Data	2-7
	2.1.1.4 Micro-Module Failure Rates	2-7
	2.1.1.5 Correlation of Element and Micro-Module Failure Rate Data	2-8
	2.1.2 Standard Part Failure Rates	2-9
	2.1.3 Prediction Techniques	2-10
	2.1.3.1 Micro-Modules	2-11
	2.1.3.2 Standard Parts	2-13
	2.2 Factors Involved in Prediction of Task Frequency and Item Usage Rates	2-13
	2.2.1 Secondary Failure Rate	2-14
	2.2.2 Wear-Out Failure Pattern	2-14
	2.2.3 Accidental Failures	2-15
	2.2.4 Faulty Maintenance Rates	2-15
	2.2.5 Supply Line Failure Rates	2-15
III	Maintenance Analysis Techniques	3-1
	3.1 Introduction to the Hypothetical Maintenance Model	3-1
	3.1.1 Description of the Hypothetical Maintenance Model	3-1

TABLE OF CONTENTS (Continued)

SECTION			PAGE
	3.1.1.1	Equipment	3-1
	3.1.1.2	Assembly	3-1
	3.1.1.3	Subassembly	3-4
	3.1.1.4	Module Board	3-4
	3.1.1.5	Micro-Module	3-4
3.2	Maintenance Task		
3.2.1	Transformation of Equipment Maintenance Tasks into Economic Elements		3-4
	3.2.1.1	Determination of Maintenance Tasks	3-4
	3.2.1.2	Economic and Operational Elements Associated with Maintenance Actions	3-7
	3.2.1.3	Application of Hypothetical Maintenance Model	3-9
	3.2.1.4	Definition of Maintenance Task	3-11
	3.2.1.5	Sampling Techniques Applicable for Reduction of Maintenance Analysis Effort	3-12
	3.2.1.6	Prediction of Maintenance Task	3-14
3.2.2	Characteristics of Maintenance Task		3-16
	3.2.2.1	Maintenance Task Symbols and Related Symptoms	3-15
	3.2.2.2	Frequency of Maintenance Task	3-16
	3.2.2.3	Maintenance Task Time	3-17
	3.2.2.4	Tools and Test Equipment Requirements	3-18
	3.2.2.5	Skill Levels Affecting Maintenance Task	3-22
3.3	Human Factors Aspects of Maintainability in Design		3-23
3.3.1	Equipment Development		3-23
3.3.2	Human Factors Tasks		3-24
3.3.3	Integrated Approach to Human Factors in Equipment Design		3-24
3.3.4	General Maintainability Requirements		3-25
3.4	Steady-State Personnel Requirements		3-25

TABLE OF CONTENTS (Continued)

SECTION				PAGE
IV	Provisioning Identification Documentation			4-1
	4.1	Parts Provisioning Breakdown		4-1
		4.1.1	Manufacturer's Part Number and Name	4-2
		4.1.2	Prices	4-2
		4.1.3	Lead Time	4-2
	4.2	Critical Items		4-2
	4.3	Failure Rate Affecting Provisioning		4-2
	4.4	Federal Stock Number		4-2
	4.5	Spares		4-2
V	Logistic Considerations			5-1
	5.1	General		5-1
	5.2	Support Problem		5-1
	5.3	Characteristics of the System		5-3
		5.3.1	Reporting Ratio	5-3
		5.3.2	System Configuration Arrival Rates	5-4
	5.4	Logistic Analysis		5-5
		5.4.1	General	5-5
		5.4.2	Transportation Requirements	5-6
		5.4.3	Administrative Requirements	5-6
		5.4.4	System Delays	5-6
		5.4.5	Effects of Priorities	5-7
	5.5	Delays		5-8
		5.5.1	Transportation Delay Rate	5-8
		5.5.2	Administrative Delay Rate	5-17
			5.5.2.1 First Echelon	5-17
			5.5.2.2 Second Echelon	5-17
			5.5.2.3 Higher Echelons	5-18
			5.5.2.4 Error in Assignment of Administrative Task Times	5-18
			5.5.2.5 Other Possible Delays	5-19
		5.5.3	Packing Delays	5-19

TABLE OF CONTENTS (Continued)

SECTION		PAGE
5.6	Peacetime-Wartime Comparisons	5-19
5.6.1	Logistics	5-19
5.6.1.1	Operational Readiness	5-20
5.6.1.2	Failure Rate	5-20
5.6.1.3	Arrival Rate	5-21
5.6.1.4	Repair Rate	5-21
5.6.1.5	Transportation Time	5-21
5.6.1.6	Administration Time	5-21
5.6.1.7	Mean Waiting Time	5-21
5.6.1.8	Number of Echelons	5-21
5.6.1.9	Condemnation Rate	5-21
5.6.1.10	Maintenance Float	5-22
5.6.2	Cost Analysis	5-22
5.7	Field Application	5-22
5.7.1	Physical Constraints of Inventory	5-22
5.7.2	Equipment Density/Use	5-26
5.7.2.1	Density	5-26
5.7.2.2	Distribution	5-26
5.7.2.3	Deployment	5-26
5.7.2.4	Operating Time	5-27
5.7.2.5	Operator Utilization	5-27
5.7.2.6	Nature of Mission	5-27
5.7.3	Summary	5-27
VI	Demand Rates	6-1
6.1	General	6-1
6.2	Failure Rate (Primary)	6-1
6.3	Condemnation Rate	6-2
6.4	Casualty Rate	6-3
6.5	Usage Rate	6-3
6.6	Arrival Rate	6-3

TABLE OF CONTENTS (Continued)

SECTION		PAGE
VII	Training Approach	7-1
	7.1 General	7-1
	7.2 Failure Symptoms - Maintenance Task	7-2
	7.2.1 Definitions	7-2
	7.2.2 Example	7-3
	7.3 Advantages and Limitations	7-4
	7.3.1 Advantages	7-4
	7.3.2 Limitations	7-5
	7.3.2.1 Training Manuals	7-5
	7.3.2.2 Skill Level	7-5
	7.4 Training Outline	7-6
	7.5 Training Cost	7-6
	7.6 Field Training	7-7
	7.6.1 Problem Defined	7-7
	7.6.2 Programmed Instruction	7-7
	7.6.3 Audio-Visual Devices	7-8
VIII	Determination of System Data and Constraints	8-1
	8.1 General	8-1
	8.1.1 Sources	8-1
	8.1.2 Costs	8-1
	8.2 Specific Notes	8-2
	8.2.1 Downtime and Other Constraints	8-2
	8.2.2 Effects of Costs on Resulting Maintenance System	8-2
IX	Glossary of Terms	9-1
X	Glossary of Symbols	10-1
XI	Bibliography	11-1

ILLUSTRATIONS

FIGURE	TITLE	PAGE
2-1	XM-13 Binary Divider	2-12
3-1	Hypothetical Micro-Module Construction	3-2
3-2	Equipment Subassembly Location Scheme	3-3
3-3	Equipment Sub-subassembly Location Scheme	3-5
3-4	Modulc Board. Micro-Module Location Scheme	3-6
3-5	Maintenance Task Breakdown into Economic Elemcnts	3-10
3-6	Method of Achieving Maintainability in the Design Sequence	3-26
5-1	Examples of Abstract and Field Configurations (Model Logic)	5-2
5-2	Signal Maintenance Channels - Battle Group	5-11
5-3	Signal Maintenance Channels - Infantry Division	5-12
5-4	Illustration of Equipment Dispersion	5-13

TABLES

TABLE	TITLE	PAGE
5-1	Peacetime to Wartime Logistic Parameter Changes	5-23
5-2	Cost Characteristics of Wheel Vehicle Modes	5-24

SECTION I

INTRODUCTION

This volume contains detailed techniques for estimating necessary maintenance, logistic, and cost parameters relevant to logistic and maintenance support system planning. Its intent is to develop for personnel charged with the responsibility of estimating design and logistic parameters, techniques which may be easily and reliably applied.

1.1 GENERAL DISCUSSION

Although prediction methodology exists in various isolated technical areas, at present there is no central source available which ties together all the prediction elements common to the maintenance and logistic planning problem.

In Volumes I and II, respectively, are indicated (1) basic data requirements as dictated by the decision problem and (2) the form in which the required data should be collected and documented. This volume indicates preliminary techniques for estimating and/or predicting the magnitude of the parameters germane to maintenance and logistic planning.

It is anticipated, with the growing awareness of military planners of the need for more accurate prediction methodology of parameters which effect both logistic and tactical thinking, that the prediction methodology presented herein will be modified and improved in time. This is especially true in the identification of cost elements.

An ameliorating factor, however, may be the degree of accuracy demanded in estimating a logistic or design parameter.

1.2 APPROACH

The method of exposition followed in this volume has been to present first the requirements for estimation or prediction of the parameter in question in terms of a discussion, and second, by the detailed methodology recommended for this purpose, providing the required estimations with sufficient accuracy that the tool will be capable of producing usable results.

Generally, the prediction models recommended in this volume are based on required accuracy as determined from the logical structure of the problem involved.

1.3 PREDICTION OF DEMAND VARIABLES

In any problem in Logistics there are a multitude of variables which influence the decision-making problem. The variables of the problem which act independently are

here called demand variables, and/or parameters in some instances. (Although a difference exists between these terms, they may be taken as synonymous in this context.) These variables take on the demand characteristics in that they make demands on thc logistic support system; also, they are handled through (generally) normal administrative demand protocol.

In the following brief discussion, it is intended to convey a synopsis of how the individual parameters are used in problem solution.

The Operational Readiness Mathematical Model has provisions for relating the following general types of data:

Inputs

(1) R = Operational Readiness Level.

(2) N = Total number of units (same type) in the support system.

(3) λ = Failure rate of a unit.

(4) μ = Repair rate of a unit (failure).

(5) τ = Time delay (transportation, administration, spares).

Outputs

(1) M = Number of echelons (maintenance).

(2) r = Repair channels.

(3) L = Maintenance float in support system.

The logic of the mathematical representation of the support system is such that any of the parameters listed above may be considered as either an input or output variable. However, in view of the predictive aspects of certain of these parameters, a delineation between input and output parameters can be made. An examination of these parameters reveals the following:

(1) Input Parameters

(a) R = Five operational readiness levels are being considered - 0.99, 0.95, 0.90, 0.80, 0.50. Model processing will be performed for each of these values.

(b) N = Tactical equipment requirements throughout the support system will be provided for each equipment type.

(c) λ = Failure rates of equipments will be predicted.

(d) μ = Repair rates of equipments will be predicted.

(e) τ = Delay rates due to transportation, administration, and spares availability are also of a predictive type.

(f) M = Number of echelons may also be specified or may be an output parameter. M = 1, 2, 3, 4, 5, or 6 may be considered.

(2) Output Parameters

(a) r = Repair channels per maintenance echelon.

(b) L = Quantities of equipments in float at each echelon designated to carry float.

(c) M = Number of echelons may be input; see above.

The input parameters above are the demand parameters. In the subsequent discussion, all required estimations are related to the input parameters, with the exception of estimation of physical constraints imposed either by design or tactical feasibility.

SECTION II

RELIABILITY

The rate of demand for maintenance is a direct function of the inherent reliability of an equipment and the operational environment to which it is subjected. Relation of these factors to a prediction technique has been accomplished through the interpretation of large quantities of data on tests of components, and the results of field usage of these components. The resulting techniques for prediction have been applied successfully to the determination of demands for spares, maintenance, test equipment, and other support parameters, except those failures due to accidental damage or combat casualty.

In this application, two areas of reliability must be considered. Initially, the inherent capability of an equipment to meet its required reliability goals; and secondly, the effects of the operational and maintenance environment on this inherent reliability. These two areas are considered concurrently in the development of failure rates for application. The extrapolation from one to the other has been accomplished by mathematical manipulation of the test data analyzed.

2.1 FAILURE RATE DETERMINATION

Table of failure rates are based on the available component test data. It must be emphasized that these rates predict only what are commonly called random catastrophic failures . This failure classification applies to those failures which occur after all efforts have been made to eliminate design defects and unsound parts, and before any unforeseen wear-out phenomena have time to appear. Primary random, maintenance-induced, and poor workmanship-induced failures are not covered by this technique. To predict these classes of failures properly, it is necessary to extend further the basic prediction technique through reasonable practices. This extension process necessitates a review of historical performance data in order to develop a satisfactory modifying factor.

Test data are presently available on micro-module components to a limited extent and, in a comprehensive form, on conventional components through a number of tables of failure rates. Tables for the latter components can be found in RCA's technical report TR 59-416-1 and other industry and military documents. Descriptions of the techniques for application of these rates are presented in the following paragraphs.

2.1.1 MICRO-MODULES AND THEIR COMPONENTS

To provide a means of relating the environmental effects on micro-modules, a technique for reliability prediction must be developed. For convenience, the development of this technique has followed the basic pattern used in the development of techniques for the

prediction of conventional component inherent reliability. The technique is of the following format.

(1) Review test data on elements and micro-modules. A review of live test data on elements and micro-modules for the complete developmental processes is conducted to establish failure rates for these units.

(2) Relate test data to reliability prediction techniques by element analysis. Element test data are analyzed to establish a relationship between various thermal and electrical stresses and corresponding failure rates.

(3) Analyze micro-module test data to establish reliability relationships between element analysis and packaged unit (micro-module) analysis. Test data on packaged unit tests will be analyzed to determine if a relationship exists between the application of the element analysis results and the micro-module test data available.

(4) Analyze reliability improvement trends through the developmental processes. The improvement in element and micro-module test results over the developmental period leads to extensions of the derived failure rate figures to reflect micro-module reliability during the period of program implementation.

(5) Determine an appropriate set of reliability numerics for the general micro-module configurations. A formal technique for utilizing the failure rate estimates derived under the previous steps has been developed for application to the mathematical support model.

2.1.1.1 Element Test Data

Element test data have been accumulated throughout the duration of the micro-module program. Numerous micro-element testing phases have produced, as of January 1962, more than 32 million element hours of testing. These tests were run under accelerated conditions of high electrical stresses and ambient temperatures up to 200° C. Following are brief descriptions of several types of microelements subjected to testing.

2.1.1.1.1 Precision Multi-layer Ceramic Capacitors

No failures, either degradational or catastrophic, occurred after 1,732,000 unit hours of testing the multi-layer ceramic capacitors. These tests were conducted at twice rated voltage and at 85° C ambient temperature.

2.1.1.1.2 General-Purpose Multi-layer Ceramic Capacitors

During life testing on this type of unit, one degradational failure occurred after 1,355,000 unit hours of testing. This testing was performed at twice rated voltage and at 85° C ambient temperature.

2.1.1.1.3 Solid Tantalum Capacitors

The tests on the solid tantalum capacitors have completed 2,103,000 unit hours at rated voltage and 85° C ambient temperature. The units suffered four failures, three catastrophic and one degradational.

2.1.1.1.4 Microelement Cermet Resistors

Cermet microelement resistors were tested at temperatures of 70° C or higher, and at full rated power. No failures occurred after 2,759,000 unit hours of testing.

2.1.1.1.5 Microelement Inductors

Mieroelement inductors, made with ferrite and carbonyl iron cores, have accumulated 1,440,000 unit hours of testing without failure. Test were conducted at 80° C and 125° C ambient temperatures.

2.1.1.1.6 Microelement Diodes

The microelement diodes suffered five failures after completing 1,240,000 unit hours of storage life testing at 175° C.

2.1.1.1.7 Microelement Transistors

All the mircoelement transistor units were placed on storage life test at 200° C ambient temperature for a total of 2,360,000 Unit hours, resulting in five failures.

2.1.1.2 Element Failure Rates

The process of relating accelerated test results to thermal and electrical conditions normally encountered must be applied to the test data available. Through use of acceleration factors, the observed failure rates can be converted to meaningful figures.

Acquisition of these acceleration factors in itself requires a study of test data of varying types for each of the microelements under test. Test conditions must be of several temperatures and stress conditions to permit plotting and extrapolation to the normally encountered conditions.

Since the micro-module program has been of relatively short duration for the accumulation of sufficient test data, it is necessary to refer to acceleration factors for various military standard components. These factors have been emphasized in both industry and military prediction guides in the process of developing tables of failure rates. Such failure rate tables have been developed for those elements discussed in Section 2.1.1.1 and are included below.

The element test data were translated to tabular form by the application of acceleration factors, presented in a RCA predictive guide, to the basic element life test data presented in Section 2.1.1.1.

MICRO-ELEMENT INDUCTOR

Applicable to Grade 3 Class 0 of Mil-C-1530A

Temperature	Failure Rate
0 - 60°C	0.025
65°C	0.045
75°C	0.180
85°C	0.450

Failure Rate is determined by the following:

$$\lambda = 0.05\, k\, \lambda_T$$

where λ = the actual failure rate

k = number of terminations

λ_T = appropriate failure rate from the above table

Precision Multilayer Ceramic Capacitors

Ambient Temp.	Stress Ratio 0.1	0.2	0.4	0.6	0.8	1.0
25°C	0.0001	0.0001	0.0001	0.0001	0.0004	0.0009
35°C	0.0001	0.0001	0.0001	0.0003	0.0006	0.0012
45°C	0.0001	0.0001	0.0001	0.0004	0.0009	0.0017
55°C	0.0001	0.0001	0.0001	0.0005	0.0013	0.0025
65°C	0.0001	0.0001	0.0003	0.0007	0.0019	0.0036
75°C	0.0001	0.0001	0.0003	0.0012	0.0026	0.0051
85°C	0.0001	0.0001	0.0004	0.0016	0.0036	0.0073

General Purpose Multi-Layer Ceramic Capacitors

Stress Ratio

Ambient Temp.	0.1	0.2	0.4	0.6	0.8	1.0
25°C	0.0002	0.0002	0.0002	0.0002	0.0006	0.0011
35°C	0.0002	0.0002	0.0002	0.0004	0.0007	0.0015
45°C	0.0002	0.0002	0.0002	0.0006	0.0011	0.0022
55°C	0.0002	0.0002	0.0002	0.0007	0.0017	0.0031
65°C	0.0002	0.0002	0.0004	0.0009	0.0024	0.0046
75°C	0.0002	0.0002	0.0004	0.0015	0.0033	0.0065
85°C	0.0002	0.0002	0.0006	0.0020	0.0046	0.0093

Solid Tantalum Capacitors

Stress Ratio

Ambient Temp.	0.1	0.2	0.4	0.6	0.8	1.0
25°C	0.001	0.001	0.004	0.011	0.034	0.060
35°C	0.001	0.002	0.004	0.013	0.039	0.070
45°C	0.001	0.002	0.005	0.015	0.048	0.084
55°C	0.002	0.002	0.005	0.018	0.057	0.101
65°C	0.002	0.003	0.007	0.022	0.069	0.124
75°C	0.002	0.003	0.009	0.028	0.085	0.153
85°C	0.003	0.004	0.011	0.035	0.107	0.189

Micro-Element Cermet Resistors

Stress Ratio

Ambient Temp.	0.1	0.2	0.4	0.6	0.8	1.0
25°C	0.006	0.007	0.008	0.010	0.013	0.018
35°C	0.007	0.008	0.009	0.012	0.015	0.021
45°C	0.008	0.008	0.010	0.013	0.018	0.024
55°C	0.009	0.010	0.012	0.015	0.020	0.028
65°C	0.010	0.011	0.013	0.017	0.023	0.033
75°C	0.011	0.012	0.015	0.020	0.027	0.041
85°C	0.012	0.014	0.017	0.023	0.032	0.048

DIODE

Stress Ratio

T_k	0.1	0.2	0.4	0.6	0.8	1.0
0	0.05	0.06	0.10	0.17	0.28	0.48
0.1	0.05	0.06	0.10	0.17	0.47	
0.2	0.05	0.06	0.10	0.35		
0.3	0.05	0.06	0.13			
0.4	0.05	0.06	0.32			
0.5	0.05	0.06				
0.6	0.05	0.11				
0.7	0.05	0.26				
0.8	0.09					
0.9	0.20					
1.0	0.48					

TRANSISTOR

Stress Ratio

T_k	0.1	0.2	0.4	0.6	0.8	1.0
0	0.02	0.03	0.05	0.08	0.12	0.21
0.1	0.02	0.03	0.05	0.08	0.21	
0.2	0.02	0.03	0.05	0.15		
0.3	0.02	0.03	0.06			
0.4	0.02	0.03	0.14			
0.5	0.02	0.03				
0.6	0.02	0.05				
0.7	0.02	0.11				
0.8	0.04					
0.9	0.09					
1.0	0.21					

T_K = normalized temperature = $(T_A - T_S)/(T_F - T_S)$

where T_A = actual temperature

T_S = temperature of start of part derating

T_F = temperature (maximum) for part derating

Normalized temperatures are provided for semiconductor devices because derating curves differ among distinct transistor or diode types as to the temperature at the start of derating, T_s, and the maximum temperature for part derating, T_f. For example, a general-purpose silicon diode may show linear derating from 25° C at maximum power to 125° C at zero power, where as a general-purpose germanium diode may show linear derating from 25° C at maximum power to 85° C at zero power.

2.1.1.3 Micro-Module Test Data

During the micro-module program, module performance has been monitored from a failure rate viewpoint through extensive "life" testing of modules. The effects of integration of various element types into functional circuits is evident by the results of tests performed under four tasks of this program. Operating time for these modules is given in element hours and converted to a representative module configuration by considering eleven elements per module. As of June 1962 these test data have been obtained.

Task 7	1960 Test Units	34,950,000 element hours
Task 25A	PRC-51	1,579,900 element hours
Task 25B	Micropac	11,078,900 element hours
Task 36-1	Preproduction	1,589,000 element hours
		49,197,800 element hours

Dividing this by eleven elements per module, the total module hours of operating time equals 4,472,527.

Fourteen failures occurred during this testing. It should be noted, however, that these failures represent a true random failure summation. Precautions were taken to investigate thoroughly every failure which occurred for possible deletion from the countable quantity. This practice is quite normal in that it permits the censoring of data which are a direct consequence of such factors as faulty workmanship and aecidental failures, and is geared to reflect the true operational capability of the items being tested.

2.1.1.4 Micro-Module Failure Rates

The operating time and failures as presented in the preceding section forms the basis for the calculation of micro-module failure rates. The numerics are initially used as follows, for an estimate of the MTBF.

$$\text{MTBF} = \frac{\text{Total Operating Times}}{\text{Total failures}} = \frac{4{,}472{,}527}{17} = 263{,}089 \text{ hours.}$$

Failure rate is then expressed as the reciprocal of this MTBF and given in terms of %/1000 hours.

$$\text{Failure Rate } (\lambda) = 1/\text{MTBF} = 1/263{,}089 = 0.380\%/1000 \text{ hours.}$$

This same expression can be converted to other failure rate indicators as follows:

$$0.380\%/1000 \text{ hours} = 0.0038 \text{ parts}/1000 \text{ hours} = 0.0000038 \text{ parts/hour.}$$

2.1.1.5 Correlation of Element and Micro-Module Failure Rate Data

The data presented reflect both digital and communication type micro-module performance. They further illustrate the effects of testing on an element basis as well as on the integrated circuit. A simple comparison of the element data and the micro-module data would serve to illustrate the degree of correlation which is present. Recalling that micro-module test data indicated a failure rate of 0.038%/1000 hours, consider a similar module constructed of the elements for which failure rates are presented. A table such as the following would be developed. Failure rates are taken from appropriate tables at temperatures of 75°C and stress ratios of 0.5 for resistors and capacitors. Transistors and diodes are taken at 0.1 stress ratio and a value of $T_k = 0.8$. The stress ratio figures taken most closely represent actual operating conditions during the testing process.

Parts usage is reflected as the average number of transistors, diodes, etc., in modules tested. Failure rates are then taken from the tables developed in Section 2.1.1.2.

Part Type	Usage	Failure Rate/Part	Total Failure Rate
Transistors	1.5	0.038%/1000 hours	0.057%/1000 hours
Diodes	2.0	0.086%/1000 hours	0.172%/1000 hours
Resistors	5.0	0.0175%/1000 hours	0.0875%/1000 hours
Ceramic Capacitors	1.5	0.0008%/1000 hours	0.0012%/1000 hours
Coil	0.4	0.180%/1000 hours	0.072%/1000 hours
Tantalum Capacitors	0.6	0.015%/1000 hours	0.009%/1000 hours
			0.4187%/1000 hours

The degree of significance of the data presented is immediately evident in the comparison between 0.380%/1000 hours derived by micro-module test data, and 0.419%/1000 hours derived by element test data.

This very close comparison leads to the conclusion that element test data, as extrapolated in the form of the tables of failure rates, provides a suitable base from which to perform reliability predictions. It should be borne in mind, though, that data are

rather limited and represent some very early developmental testing. Consequently, the tables presented must continually be updated, revised, and tested.

2.1.2 STANDARD PART FAILURE RATES

The development of failure rates for standard military parts has been the result of lengthy analysis of accumulated representative test data. The results have led to firmly established prediction techniques and the tabular representation of anticipated performance through temperature and stress matrices. Tables have been developed to relate failure rates for any thermal or electrical environment to which an equipment might be exposed.

Some of the major specifications which are applicable under the prediction techniques are:

Electron Tubes	-MIL-E-1D
Semiconductors	-MIL-E-1D
Resistors	-MIL-E-11C
	MIL-R-93B
	MIL-R-10509D
	MIL-R-11804C
	MIL-R-11804C
	MIL-R-19
Capacitors	-MIL-C-25
	MIL-C-5
	MIL-C-3965
Transformers	-MIL-T-27
	MIL-C-15305A

The numerics associated with part performance characteristics are presented in many industry and military documents as guides for reliability prediction. Of these, RCA has contributed substantially in the form of its technical report TR-1100 and the subsequent revision TR-59-416-1, "Reliability Stress Analysis for Electronic Equipment." The latter report is present in an expanded and updated version in "Reliability Notebook Supplement 1" from the Rome Air Development Center.

The reference documents provide the necessary documentation which will be used in the failure rate prediction processes.

2.1.3 PREDICTION TECHNIQUES

In consideration of the various requirements for reliability estimates, several techniques can be adopted. Requirements for reliability estimates exist in the areas of:

(1) An estimate of equipment mean time to failure for the purposes of:

(a) evaluating an equipment's (in a preliminary design stage) capability of meeting contractual requirements.

(b) determining the need of redundant applications.

(c) allocating reliability requirements to various subassemblies.

(2) Prediction of final design reliability for capability of meeting contractual requirements.

(3) Prediction of subassembly, module, and part failure rates for the determination of spares requirements and maintenance requirements.

Fulfilling these requirements can be accomplished through the use of two techniques for failure rate prediction. A parts count analysis or a detailed stress analysis may be employed as required.

Parts count analysis represents a technique whereby all components of a similar type are grouped and counted, and are assigned a failure rate which represents a typical operating condition for each part type. The failure rates are then summed on an assembly board or equipment basis as required. Its application is principally in the early design or systems design phase of contracts.

Detailed stress analysis are performed during the final stages of design and reflect the actual electrical and thermal environment to which the equipment will be subjected. To accomplish this goal, engineering analysis must be performed on each circuit to determine voltage, power, or electromechanical stresses which will be imposed on the various parts by nature of the circuit design. The ratio of the stresses applied to the stresses permitted provides a measure of this evaluation.

Similarly, analysis of the thermal conditions imposed on the parts as influenced by cooling air supply (volume and temperature), case materials, relative locations of parts, overall dissipation of the circuits, and types of finishes must be performed to effectively relate the ambient temperature of each part in the equipment.

The combination of electrical stress and part temperature results in a failure rate representative of the inherent reliability of the part. Individual part failure rates are

then summed on an assembly, board, or equipment basis as required. The summing procedure forms the foundation of prediction of usage rates of parts and the maintenance task requirements (see Reference 1).

2.1.3.1 Micro-Modules

A micro-module in itself must be considered as the smallest replaceable item, or, more simply, a part in itself. However, by nature of the content of each micro-module, a significant difference in failure rate is possible from one type to another. Since, at present (encompassing change capabilities), the component parts of the micro-module are basically standard parts in a different packaging configuration, the standard technique of summing failure rates to determine total micro-module failure rate will hold. This total rate then serves as the starting point for assembly, board, or equipment failure rate determination.

These failure rates can be determined through each of the methods, parts count or detailed analysis, suggested previously. To illustrate the processes, a sample micro-module, the XM-13 Binary Divider (Figure 2-1) has been selected. For the parts count prediction, certain assumptions must be made here; however, more exact information would be available in application. These assumptions are as follows:

(1) Average stress ratios on resistors = 0.5

(2) Average stress ratios on capacitors = 0.2

(3) Average stress ratios on diodes = 0.5

(4) Average stress ratios on transistors = 0.5

(5) Temperature will be 50° C and T_K for diodes and transistors = 0.2

For the detailed analysis of the circuit, the following stresses were calculated. Note here that minimal stress conditions are reflected as 0.1 since failure rates are believed to show no significant difference at stresses less than that condition.

One assumption must be made here, as well, for operating temperature. This is assumed to be 50° C, identical to that chosen for the parts count illustration.

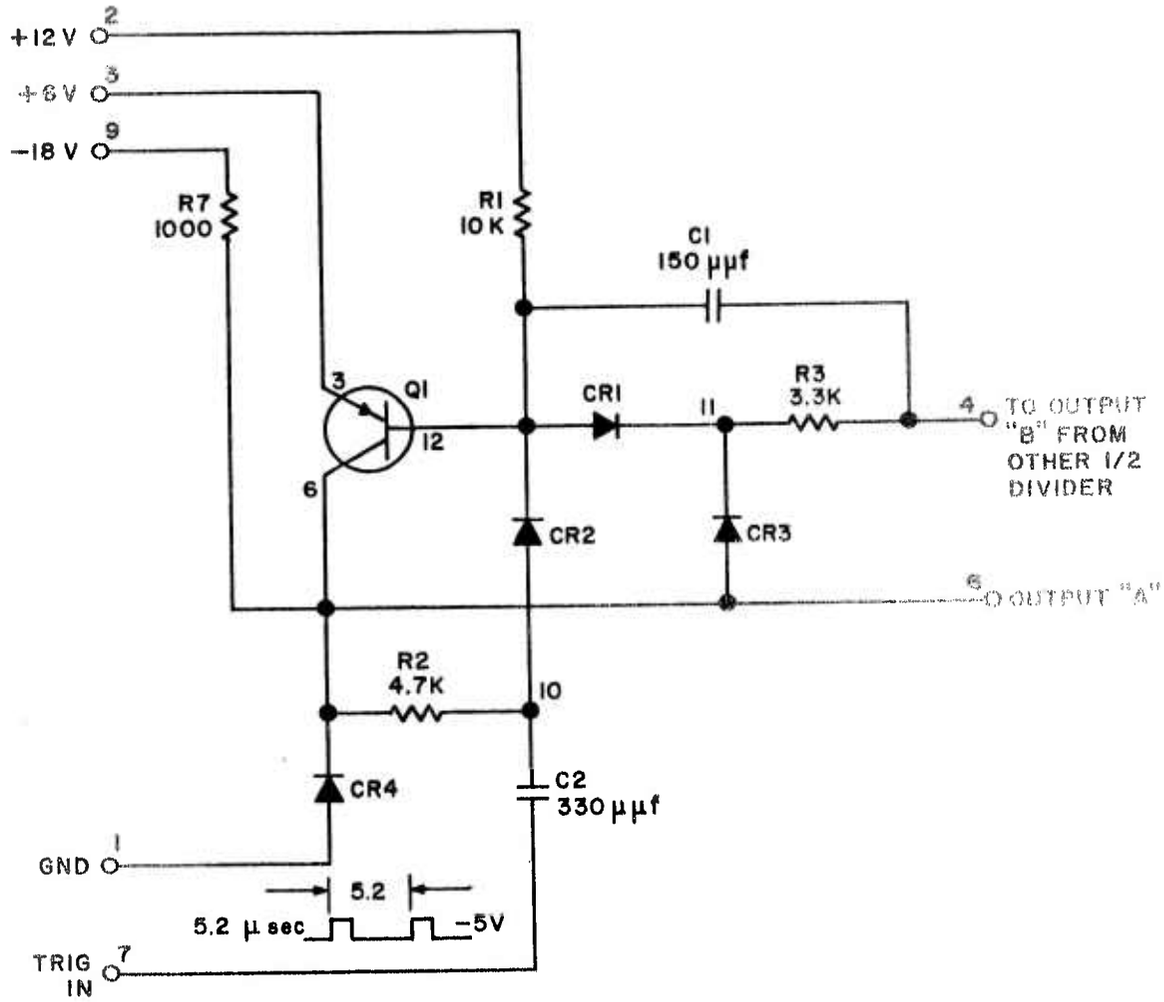


Figure 2-1. XM-13 Binary Divider

The following comparison results:

Part Type		Part Count Failure Rate	Detailed Analyses Failure Rate
Diode	- CR 1,2,3	0.303%/1000 hr	0.142%/1000 hr
	CR4	0.101%/1000 hr	0.063%/1000 hr
Rcsistors	- R 1,2,3	0.0375%/1000 hr	0.0249%/1000 hr
	R 7	0.0125%/1000 hr	0.0141%/1000 hr
Capacitors	- C 1,2	0.00028%/1000 hr	0.00028%/1000 hr
Transistor	- Q 1	0.099%/1000 hr	0.036%/1000 hr
Total		0.55328%/1000 hr	0.28028%/1000 hr

CR 1,2,3 = 0.1, CR 4 = 0.2

R 1,2,3 = 0.1, R 7 = 0.6

C 1, C2 = 0.1

Q1 = 0.3

2.1.3.2 Standard Parts

As pointed out in the description of micro-module failure rate calculations, the technique is one of considering each element as a distinct part. Standard parts in this respect are themselves the lowest breakdown point. Evaluation of stress conditions must be made in conjunction with their associated circuit components whether these be other parts or micro-modules. Detailed analyses must reflect the dependency of these parts on each other.

The analysis approach to standard parts is as described previously. The failure rate summation process follows.

2.2 FACTORS INVOLVED IN PREDICTION OF TASK FREQUENCY AND ITEM USAGE RATES

Failure rates of parts do not alone determine usage of parts or requirements for replacements. The failure rate tables presented above provide a means of predicting random failures. Below are listed some other failure-producing factors which must be considered in predicting arrival and/or usage rates.

(1) Secondary failures - those which occur as a direct result of a primary failure (sometimes called dependent or associated failures).

(2) Wear-out failures - those which occur due to "normal" wear and which, after a certain age or total duration of operation, cause failure rate to increase with time.

(3) Accidental failures - those which are induced through careless or improper procedures.

(4) Faulty maintenance rates - items condemned as a consequence of damage incurred during maintenance, or of faulty diagnosis.

(5) Supply line failures - failures which occur while in transit, in storage, or as a result of handling or storage of parts, boards, or assemblies.

(6) Combat casualties - loss or damage as a consequence of military action.

Condemnation rates, as applied to each of these sources of failures, constitute a major input, since usage can come about only through loss or condemnation.

2.2.1 SECONDARY FAILURE RATE

This failure rate depends on the failure modes of items providing input to or receiving output from the item under study. Thorough engineering analysis can lead to the determination of the conditions of failure of each part type which would result in associated failures. Micro-modules tend to reduce the magnitude of this problem by combining in a single throw-away element the circuit elements most likely to fail jointly, one as a consequence of the other. Generally, good design will hold this factor to a neglibible level so that it need not be considered.

Effective design reviews will provide further checks for electrical isolation of components, and proper safeguards.

2.2.2 WEAR-OUT FAILURE PATTERN

Wear-out implies a failure rate that increases with time (total or operating) at some point. Thus, it must be described as a curve rather than a single number. It is usually relevant only in its role in preventive maintenance; otherwise the average rate is adequate for most purposes. Where there is an established preventive maintenance policy and where the effect of preventive maintenance on downtime is different from that of corrective maintenance, separate average "failure" or maintenance rates for preventive and corrective maintenance are adequate. Where no policy exists, the curve may be used to help develop one. Maintenance analysis and actual practice are the sources of the necessary information.

2.2.3 ACCIDENTAL FAILURES

This includes both damage due to misuse and mishandling by the user. Techniques for estimating the quantities of the failures would, of necessity, be based on use of historical data which may be unavailable. Effective human factors engineering in design can do much to preclude this type of failure.

2.2.4 FAULTY MAINTENANCE RATES

These rates depend on the skills (both technical knowledge and manual dexterity) of the maintenance man as well as on the equipment, jigs, and fixtures available, and the comprehensiveness and convenience of the maintenance manuals. Past experience with similar equipment and maintenance personnel offer sources of estimates. In practical experience, good design of operating equipment and of test equipment, etc., combined with effective training, can keep these rates at a low level.

2.2.5 SUPPLY LINE FAILURE RATES

Present specifications reflect an anticipated storage of components, making this factor readily adaptable to the prediction processes. However, failures due to handling are less easily predicted and experience generally provides the best source of estimates either separate from or combined with actual storage (aging) failure rates. Handling discipline and packing are major determinants of these rates and can be strongly influenced by the effectiveness of control of these functions.

SECTION III

MAINTENANCE ANALYSIS TECHNIQUES

3.1 INTRODUCTION TO THE HYPOTHETICAL MAINTENANCE MODEL

In order to discuss and illustrate the various aspects of maintenance more easily, and to obtain basic information in a meaningful and countable manner, it is desirable to develop a maintenance model. The model can then be used as a basis for the manipulation of the relevant parameters described in the following sections. A flexible model adaptable to different configurations as may be needed in the future is required. On this basis, a hypothetical model appears best suited. This hypothetical model could then be physically expanded or reduced to conform closely to the actual equipment anticipated or produced. Furthermore, a hypothetical model, illustrated in sketch form, can serve to clarify the symbology used in the text.

3.1.1 DESCRIPTION OF THE HYPOTHETICAL MAINTENANCE MODEL

The hypothetical model chosen uses five levels of assembly. The number of levels may be increased by making the system model a subsystem of a larger system, or decreased by making a lower level of assembly serve as a system. Assignment of reference designations corresponding to physical locations will follow the pattern established in MIL-STD-16C, dated 4 December 1961, except that for further simplification, assemblies within assemblies will be called subassemblies; assemblies within subassemblies will be called boards; and micro-modules on the boards will be called micro-modules (rather than parts as in MIL-STD-16C). The purpose of this simplification is to avoid possible confusion which might occur by isolating a micro-module by the letters A1A9A1A15 instead of by A1S9B1M15. This system of nomenclature is explained in the following sections.

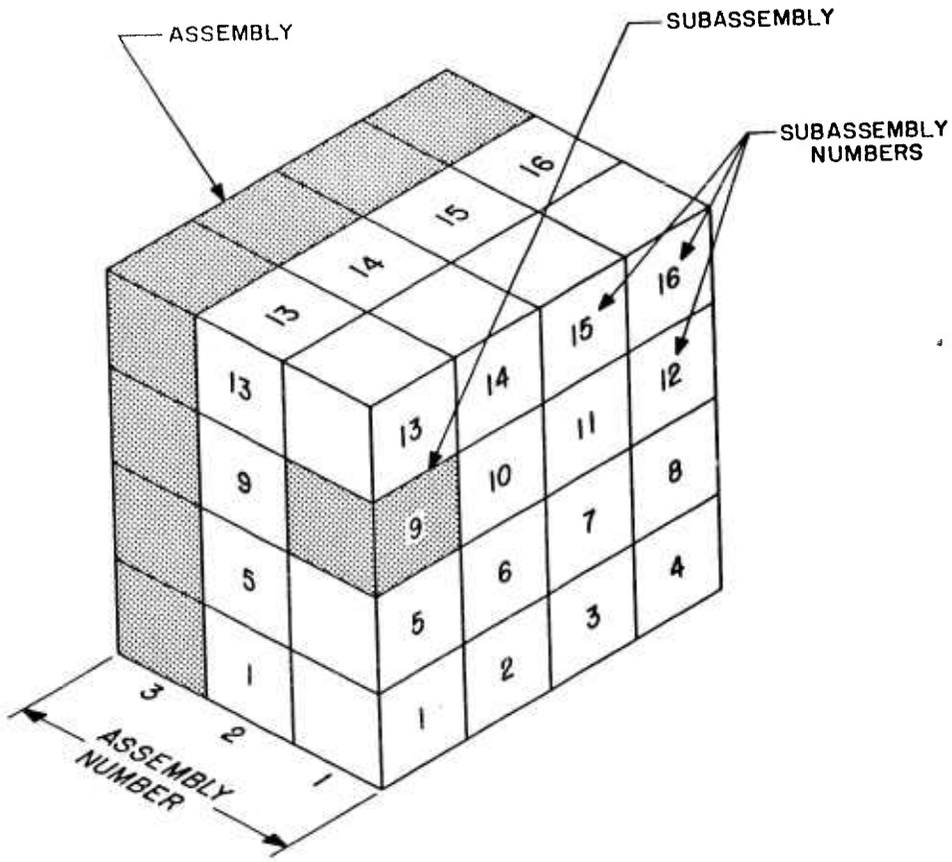
3.1.1.1 Equipment

Construction of the hypothetical model is shown in Figure 3-1. The entire piece of equipment may be divided into three major sections called assemblies. Each assembly is given a number. The three assemblies may then be designated as A1, A2, A3.

3.1.1.2 Assembly

Figure 3-2 represents the assemblies removed from the equipment shown in Figure 3-1. The assemblies plug into the bottom plane of the equipment. Each assembly consists of subassemblies which plug into the back plane of the assembly. Each subassembly in an assembly has a different reference number assigned to it, always starting with the number 1. The subassemblies in the assemblies are numbered as shown in Figure 3-1. Identification of a subassembly then would consist of the number of the

EQUIPMENT CONSISTING OF 3 ASSEMBLIES



A3 LOCATES DARKENED ASSEMBLY
A1S9 LOCATES DARKENED SUBASSEMBLY

Figure 3-1. Hypothetical Micro-Module Construction

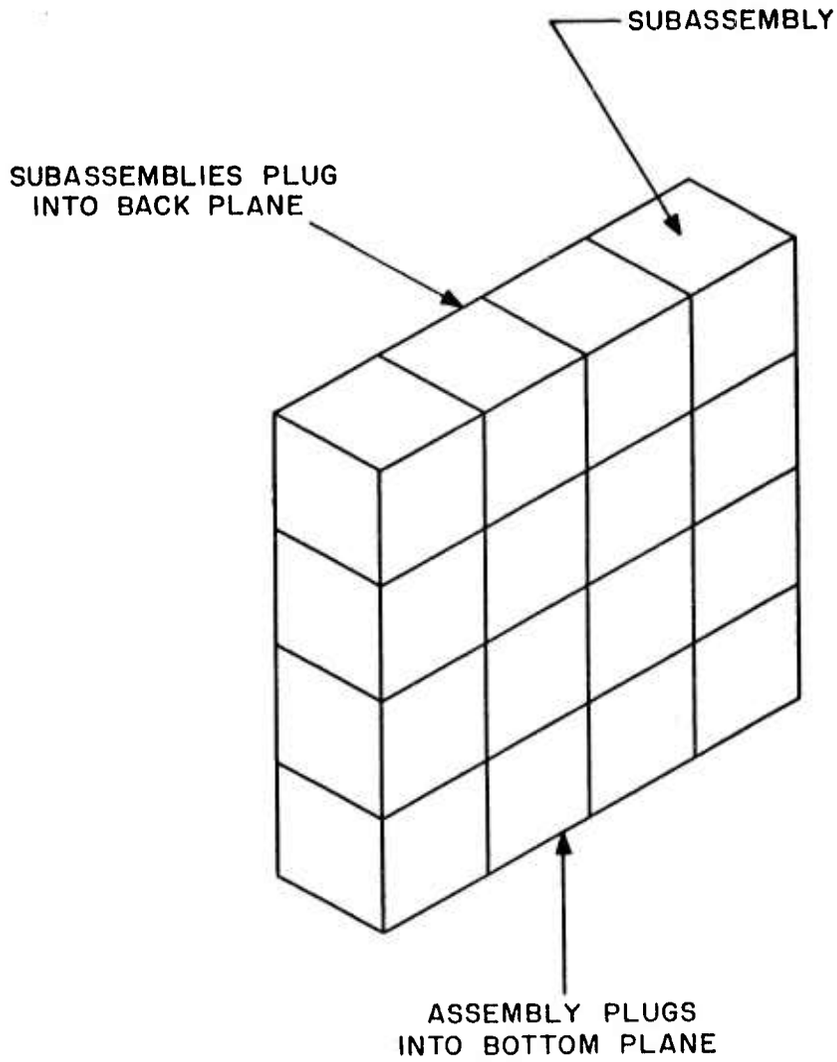


Figure 3-2. Equipment Subassembly Location Scheme

assembly containing the subassembly and the number of the subassembly. The illustration Figure 3-1 shows that the darkened subassembly may be designated as A1S9.

3.1.1.3 Subassembly

When one of the subassemblies shown as a cube in Figure 3-2 is removed and examined, it appears as shown in Figure 3-3. The subassemblies plug into the back plane of the assemblies. Each subassembly consists of module boards which plug into the subassembly. Each module board on a subassembly is numbered starting with the number 1, as shown in Figure 3-3. Identification of a module board consists of identifying the subassembly as described in the preceding paragraph plus the number of the module board. The illustration (Figure 3-3) shows that the darkened module board may thus be identified as A1S9B3.

3.1.1.4 Module Board

A module board removed from the subassembly would appear as shown in Figure 3-4. The module boards plug into the subassemblies. Each module board contains micro-modules soldered into the back plane of the module board. Each micro-module on a board is numbered starting with 1. Identification of a micro-module anywhere on the equipment consists of identifying the assembly, subassembly, and module board and then adding the number of the micro-module. Figure 3-3 shows a darkened micro-module which may be identified as A1S9B1M15.

3.1.1.5 Micro-Module

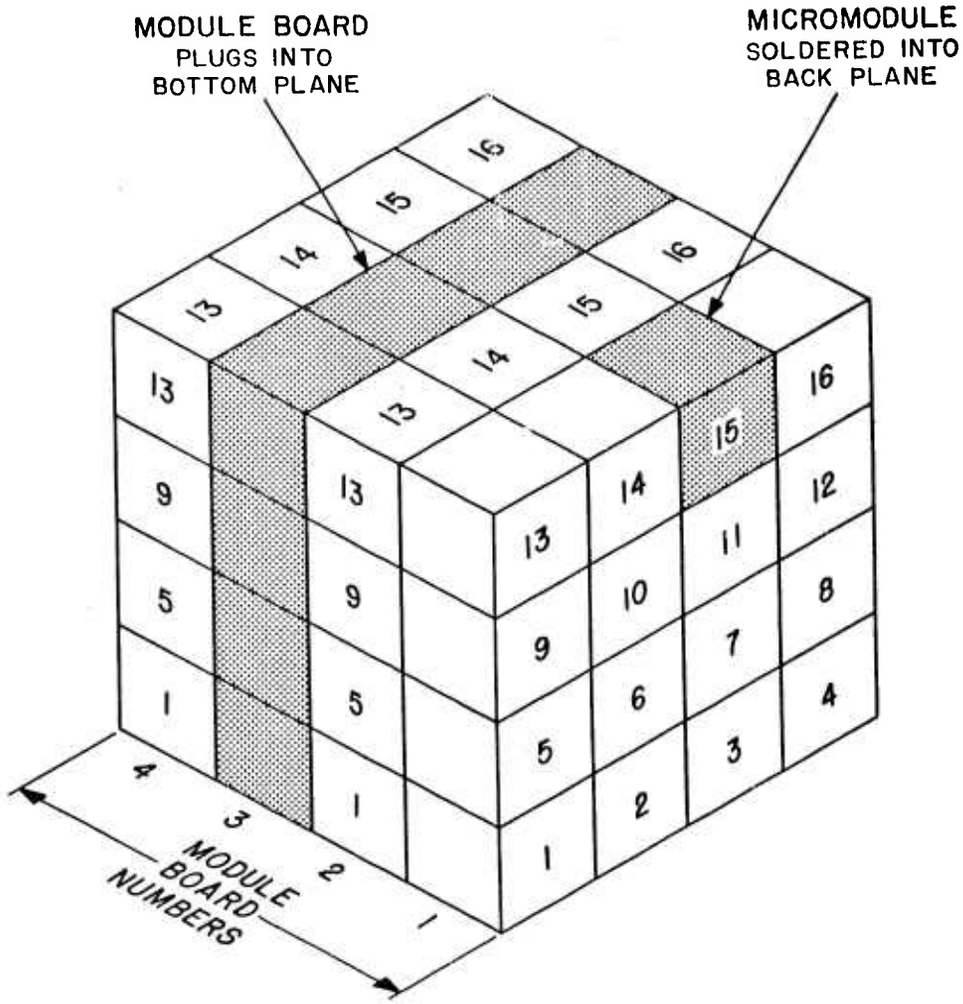
The micro-module is the last assembly level and is not repairable. The micro-module consists of micro-elements comprising one or more circuits in an encapsulated form with projecting pins which are soldered to the board's printed wiring. Under MIL-SPEC-16C, the subassemblies, module boards, and micro-modules would all be designated by letter A's, and the micro-module referenced in the preceding paragraph would be identified as A1A9A1A15. In actual military equipment, the designations making repeated use of the letter A will be used, but in this section of the final report, the A, S, B, and M designators will be used for clarity.

3.2 MAINTENANCE TASK

3.2.1 TRANSFORMATION OF EQUIPMENT MAINTENANCE TASKS INTO ECONOMIC ELEMENTS.

3.2.1.1 Determination of Maintenance Tasks

The ability to predict the occurrence and frequency of a maintenance task associated with a given equipment is of fundamental importance to the allocation of maintenance tasks to echelons throughout a support system. The concept of a maintenance task,



SUBASSEMBLY PREVIOUSLY LOCATED BY AIS9
AIS9B3 LOCATES DARKENED MODULE BOARD
AIS9BI$\overline{M}$I5 LOCATES DARKENED MICROMODULE

Figure 3-3. Equipment Sub-subassembly Location Scheme

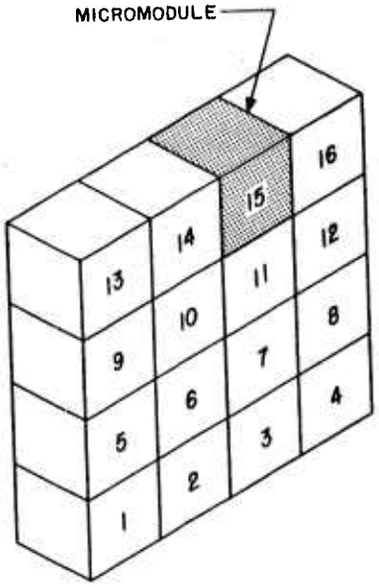


Figure 3-4. Module Board. Micro-Module Location Scheme

therefore, must be very explicit and definitive, and possess the necessary quantitative characteristics that will actually give a firm basis to the allocation process. Pursuant to this understanding, the following material has been developed.

For purposes of clarity, a differentiation is made between a basic maintenance task and a common maintenance task.

Definition I. A common maintenance task is any set of necessary sequential maintenance actions associated with a single failure.

Definition II. A basic maintenance task is defined as the necessary sequence of all identifiable maintenance actions required for repair of a failed end item equipment. Therefore, it comprises the complete set of common maintenance tasks associated with the same failure.

The term necessary excludes, by definition, superfluous maintenance actions. The term "sequence" or "sequential," by definition, means the juxtaposition of maintenance actions that must be performed in order, working from the failed part upward.

The term identifiable is defined as any maintenance action which possesses clear economic significance, maintenance skill significance, or which may significantly violate military operational requirements.

With any end item equipment there is a limited number of basic maintenance tasks: specifically, $\sum_i m_i = N$, where m_i is the number of different failure modes of the *ith* part.

Essentially then, a basic maintenance task corresponds to a series of economic or skill significant steps associated with a complete sequence of maintenance actions.

The basic maintenance task is divided into common maintenance tasks which are performed by personnel differing in skill or differing in the echelon to which they are assigned. Economic and technical factors determine the dividing lines.

3.2.1.2 Economic and Operational Elements Associated with Maintenance Actions

In the process of performing the sequence of maintenance actions, the necessary steps in the sequence followed may be differentiated in the following ways:

(1) Going from one level of assembly to another; i.e., from assembly to subassembly to printed board to micro-module, or printed board to parts, or vice versa.

(2) Requirements for different and/or additional measurement and/or sensitivity characteristics in test equipment (i.e., different type of test equipments) in following sequential repair procedure.

(3) Requirements for different and/or additional tools for making accessible test points and/or removal or replacement at a lower level of assembly.

It should be noted that, in some instances, when spares are available, the isolation routine will reach a stage involving replacement of suspect plug-in units on a trial basis rather than making further measurement.

(4) Significantly different knowledge and/or experience and/or training in interpretation of test results and/or dexterity characteristics in following the sequential procedure.

(5) Logistic and/or military constraints and/or operational requirements violated as evaluated at each possible echelon of maintenance; i.e., packing requirements, volume, weight, etc.

(6) Time requirements in performing succeeding step, if there exists a difference in time magnitudes.

(7) Number of personnel required to perform succeeding measurement, etc.

All items above either have economic ramifications and/or are consistent or inconsistent with imposed logistic and military constraints.

A complete maintenance analysis will require the generation of all basic maintenance tasks associated with the equipment being analyzed. Common maintenance tasks, as required, may be generated from the basic maintenance tasks already established.

The total possible number of maintenance tasks is the sum, for all items at the lowest level of assembly, of the number of failure modes times the number of levels of assembly. However, in practice it is rarely necessary to generate in detail all basic maintenance tasks, since many will lose uniqueness of identity at the part or micro-module level of assembly.

There are four distinct steps in developing equipment maintenance tasks. These steps are derived from the structure of the maintenance task allocation problem in conjunction with the physical maintenance action sequence in the failure isolation routine (see Section VII of Volume I and Section V of Volume IV).

Whether one works from the part up to the system failure symptom, or in the reverse direction, is dictated by the expediency of the approach based on the design configuration of the equipment being analyzed.

Step 1. Determination of points of failure symptom manifestation for each failure mode: first, a failure occurs and manifests itself as a malfunction at the system level. It also produces symptoms, deviations from normal performance, in some of the lower levels of assembly. Some of these symptoms can be detected at "test points". The first phase of development of a basic maintenance task, therefore, consists of examining the system from the bottom up, starting at part level in the input stages of the system, and determining the particular effects at points produced by significantly likely input or performance deviations.

Step 2. Determination of feasible economic breakpoints in the basic maintenance task: this step involves breaking the routine into common maintenance tasks at points in the routine according to the economic dicta developed above.

These two steps constitute development of the basic maintenance task.

Step 3. Determination of common failure mode symptom points: numerous basic maintenance tasks will lose uniqueness of identity of symptom as the level of assembly increases. These common symptom points are listed. The result of this step will be the generation of groups of common maintenance tasks capable of sharing tools or test equipment with other maintenance tasks.

The foregoing steps are illustrated in Figure 3-5.

Step 4. Generation of feasible allocatable maintenance tasks: from all the common symptom maintenance tasks developed in Step 3, failure rates are estimated and appended to the respective task.

3.2.1.3 Application of Hypothetical Maintenance Model

The hypothetical model previously described illustrates the concept of how the various sections of the equipment fit together. With this concept in mind, consider an equipment consisting of three assemblies, each of which contains four subassemblies, each of which consists of five module boards, each of which contains thirty micro-modules. Every part of the equipment may be uniquely identified as follows:

1	Equipment (Unit) designated as U1	
3	Assemblies designated as A1, A2, A3	
12	Subassemblies	A1S1, A1S2, A1S3, A1S4 A2S1, A2S2, A2S3, A2S4 A3S1, A3S2, A3S3, A3S4
60	Module boards	A1S1B1, A1S1B2, A1S1B3, A1S1B4, A1S1B5 A1S2B1, ... A1S3B1, ... A1S4B1, ... A2S1B1, A2S1B2, A2S1B3, ... A3S4B1, ... A3S4B5
1800	Micro-Modules	A1S1B1$\overline{M}$1, A1S1B1$\overline{M}$2, ... A1S1B1$\overline{M}$30 . . . A3S4B5$\overline{M}$1, ... A3S4B5$\overline{M}$30

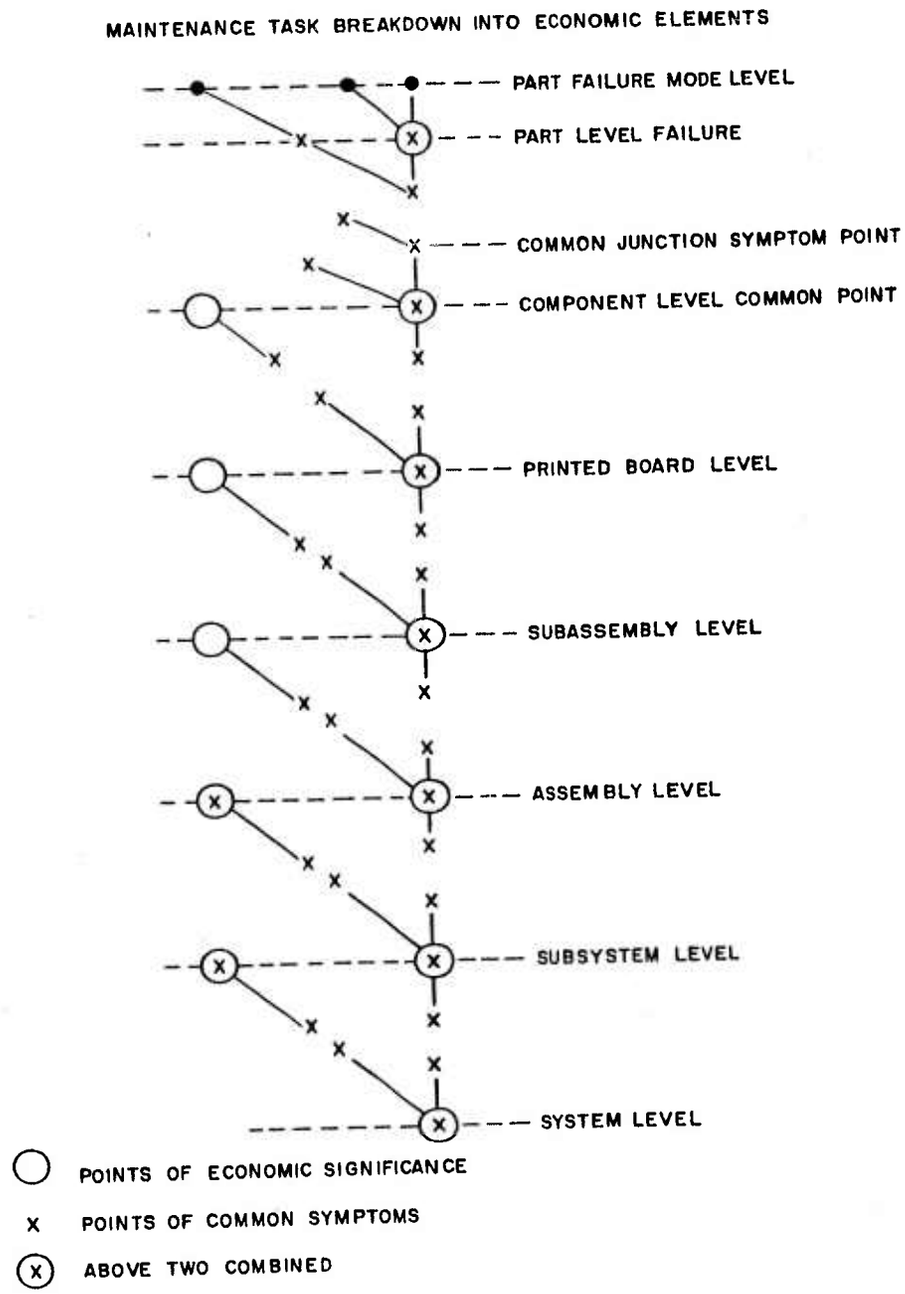


Figure 3-5. Maintenance Task Breakdown into Economic Elements

In order to repair an equipment or any section of the equipment, the malfunctioning part, or an assembly containing the malfunctioning part, must be isolated. Sometimes fault isolation is accomplished without test equipment; other times a minimum of test equipment is required; and at still other times, extensive test equipment may be required. Staying within the bounds of the illustrative example set up in this section, assume that any one of six failure symptoms would identify assembly A1 as malfunctioning. In order to manipulate symptoms, test equipment, skill levels and echelons, each of the above symptoms would have to be associated with one or more maintenance tasks. The maintenance task to be performed, therefore, depends on the cause of the malfunction as exhibited by the applicable failure symptom(s). The test equipments or skilled personnel needed to find the symptoms required to isolate the defective element may not be at one location. The isolation effort may be divided among different people, different test equipment, different echelons, and therefore different tasks in some cases. This concept leads to the definition of the maintenance task.

3.2.1.4 Definition of Maintenance Task

A maintenance task consists of a series of actions on an item at a particular level of assembly, usually prescribed, performed by an individual or a fixed team having particular skills and equipment. This series of actions, with respect to the given level of assembly, terminates in one of the following:

(1) Return of the item to proper operation

(2) Scrapping the item as non-repairable

(3) Forewarding the item for further maintenance to a team which is either equipped and/or more skilled.

Each significantly different mode of failure* in the next lower level of assembly constitutes a maintenance task.

The ways in which the symptoms are analyzed will constitute maintenance tasks. A meter reading is a sub-task. Seeing whether or not a light is on or off is a sub-task. The performance of each of these actions consitutes a maintenance sub-task. Several sub-tasks combined may be considered a task provided they include disposition of the item. If the result of one or more observations determines that the item cannot be repaired at the echelon where these observations are made, this action also constitutes a maintenance task even though no repair action has taken place.

*A significantly different failure mode is one which differs from each other mode by at least one identifying symptom. See below for further discussion and definition.

When, in addition to the analysis of symptoms and the isolation of the faulty section, that section is repaired (usually by removing and replacing the removed section with an operational section) and checked out, the foregoing also will be defined as a maintenance task.

3.2.1.5 Sampling Techniques Applicable for Reduction of Maintenance Analysis Effort

3.2.1.5.1 General

Useful approximations of the input requirements on repair rates, failure rates, etc., can be obtained by sampling techniques; for example, test equipment and skill requirements are needed only in terms of total number of demands and average usage per demand in order echelons and shop TO&E's.

Naturally, more complete data are required to determine inventory quantities of the less common items whose failure frequency estimates would have large statistical errors. However, in most instances, these data are obtainable with adequate accuracy from parts counts and other failure rate techniques.

3.2.1.5.2 Sampling

Sampling is practical only on relatively large systems in which the sample will be small (less than half) relative to the total number of parts. Sampling errors can be predicted by means of classical statistical techniques.

Specifically, a maintenance analysis of a sample of lowest level of assembly items, carried up to the highest level, can provide the estimates of the frequency and average duration of maintenance tasks according to test equipment and skill level required. Thus, for example, a micro-module included in the sample would be analyzed to provide:

(1) Modes of failure in the micro-module as caused by failure of the basic elements in their various modes of failure.

(2) Inputs which could have the same effect on module outputs as its own failure modes, to determine if additional tests are required for isolation of failed modules.

Sampling on a part-to-system maintenance analysis can function effectively as follows:

(1) List parts (lowest level of assembly items) in any convenient order along with location(s), quantities, and failure rates (preferably by failure mode).

(2) Take a sample of parts which will account for an estimated combined failure of λ_s (sample failure rate) out of an estimated total failure rate of the equipment λ. The probability of selecting a specific part (circuit symbol, not part number) should be in proportion to its estimated failure rate. One means of accomplishing this is to add failure rates entering the subtotal on each line, then, using a table of random numbers to make the selections. This, in turn, can be accomplished in two ways.

(a) Draw random numbers with number of digits equal to that in λ. Study the part whose subtotal is next above the number selected. Continue selecting parts until λ_s has been met. Ignore numbers greater than λ.

(b) Based on average failure rate per part, estimate the number of parts required to provide λ_s. Divide λ by this number to obtain an average "space" between parts. Multiply this value by two to obtain an upper limit to random numbers considered. Draw random numbers of the appropriate number of digits, adding and recording subtotals until λ_s has been reached. Study parts whose subtotals are next higher than those obtained from the random numbers. If additional parts are required to obtain a satisfactory λ_s, method (1) may be used.

If a few parts make relatively large contributions to the failure rate and/or present unusually difficult problems in failure isolation, all these parts should be treated separately (or, at least have a higher sampling rate than the others) and removed from the sampling population.

Values of total failure rates, and equipment and personnel requirements obtained from the sample, can be multiplied by λ/λ_s to obtain an estimate of values for the whole system. Sampling errors can be estimated by standard techniques assuming exponential distribution of MTBF, TRR, etc.

Data for demand on inventory due to part failure can be derived from parts counts:

$$\text{demand} = \lambda \phi b N$$

where

λ = failure rate

ϕ = operating rate (proportion of time operated)

b = number per equipment

N = number of equipments in system

Predictions concerning the demand which will arise at each echelon may be estimated from sample maintenance analyses. From knowledge of the kinds of inputs and outputs the item should have, test equipment required for isolation is implied. The test equipment, in turn, implies maintenance at a particular echelon.

The full maintenance task cannot be practically developed from this analysis since all the tests in the isolation process cannot be considered without doing a complete analysis. However, the magnitude of the other elements of the isolation phase of the task can be estimated, as well as that of the other associated tasks involved in the isolation.

3.2.1.6 Prediction of Maintenance Task

The maintenance tasks for a specific equipment will be predicted as follows:

A. Starting with the smallest part of the equipment (usually the micro-module), the failure modes of the part will be determined, and the failure symptoms produced by the various failure modes on the next higher assembly will be recorded as failure symptoms associated with the particular part (micro-module).

B. The failure modes of the assembly will then be determined and the symptoms produced on the next higher assembly will be recorded as failure symptoms associated with the particular lower assembly.

C. In like manner, the process will continue until a set of symptoms is derived for the end item equipment. At the end item equipment level, a set of symptoms will be obtained which will enable a maintenance man to isolate troubles to successively lower levels of assembly.

D. The methods used to isolate the trouble by the use of the symptoms which have been identified as failure symptoms, will form the basis for establishing maintenance tasks.

E. Based on failure symptoms associated with various levels of assembly, test equipment, and maintenance skills, the maintenance tasks will be defined and assigned maintenance task symbols which will be associated with the physical location of the assembly in the end item.

3.2.2 CHARACTERISTICS OF MAINTENANCE TASK

The characteristics of the maintenance task as described in the following sections will be referenced to the equipment described in Section 3.2.1.3 (1800 micro-module concept).

3.2.2.1 Maintenance Task Symbols and Related Symptoms

In the definition of the maintenance task, reference was made to the symbol associated with the maintenance task. This symbol will be called the maintenance task symbol. Associated with each maintenance task symbol is one or more identifying failure symptoms. An identifying symptom is a parameter measurement or performance characteristic which has been found, in combination with certain other identifying symptoms, to identify unambiguously the defective next lower level of assembly. Specific symptoms are selected as identifying symptoms because of their relative ease and simplicity of measurement. A particular symptom may be produced by one or more malfunctioning parts. Therefore, at the higher levels of an equipment, different failures could produce the same symptoms. Each of these failure modes implies and is associated with a maintenance task on a one-to-one basis. Each mode is identifiable in terms of measurable effects on inputs to and outputs from the item under consideration. Maintenance task symbols will be assigned by designating the physical location of the level of assembly under consideration and then adding to that designation letters and numbers representing the significantly different failure mode which the assembly can show. The way the assignment is associated with the location is illustrated in Section 3.2.1 which discusses the definition of the maintenance task. If a module board could have 15 possible failure modes, caused by any number of micro-modules, and the board location was U1A3S2B4, then the modes and symptoms caused in the subassembly could be identified as:

Tasks (Modes of Board Failure)	Symptoms of Subassembly
U1A3S2B4T1	U1A3SZY1,2,3,4
U1A3S2B4T2	U1A3SZY1,2,3,5
U1A3S2B4T3	U1A3SZY2,4,7
U1A3S2B4T4	U1A3SZY2,4,7,9
.	.
.	.
.	.
U1A3S2B4T15	U1A3SZY11

At this point, it is appropriate to mention that a number of symptoms may be required to isolate, unambiguously, a malfunctioning part, just as a malfunctioning part is capable of producing several symptoms at different parts of a circuit. To illustrate the requirement whereby two or more symptoms may be required to identify the malfunctioning micro-module on a board, assume the following:

	Symptom		Test Point
Failure of $\overline{M}30T_2$ produces	Y1	at	Pin 3
	Y2	at	Pin 4
	Y3	at	Pin 7
Failure of $\overline{M}25T_1$ produces	Y1	at	Pin 3
	Y2	at	Pin 4
	Y4	at	Pin 8
Failure of $\overline{M}27T_1$ produces	Y1	at	Pin 3
	Y4	at	Pin 8
	Y3	at	Pin 7

In the foregoing example, any one of the symptoms produced by micro-module $\overline{M}30$, failing in its mode, T_2, is also produced by the malfunction of either micro-module $\overline{M}25$, failing in its mode, T_1, or $\overline{M}27$, failing in its mode, T_1, so that at least two symptoms are required to identify micro-module $\overline{M}30$ which has failed in mode T_2.

3.2.2.2 Frequency of Maintenance Task

A maintenance task must be performed as a result of a failure of some part of an equipment. How often a particular maintenance task must be performed depends on how often certain parts fail; in this case, those parts which necessitate the performance of the maintenance task in question. Each of the parts in the system has an assigned failure rate adjusted for thermal and electrical stresses encountered by the part in the circuit used. (Failure Rate Determination is discussed in Section 2.1.) By knowing the parts which cause the symptoms requiring the performance of the maintenance task, and using the assigned failure rates of those parts responsible for requiring the maintenance task, the frequeney of the maintenance task may be determined as the sum of the failure rates involved. Just as failure rate of an equipment is estimated by assessing the failure rates of all the parts of the equipment, so may a failure rate be associated with a maintenance task. Translation of a failure rate of an equipment to "Mean Time Between Failures" is equivalent to determing "Frequency of Occurrence of Failures." Therefore, the frequency of occurrence of a maintenance task will be directly related to the failure rate of the parts which result in the requirement of the maintenance task.

It should be mentioned that some items do not have constant failure rates but, instead, have wearout characteristics which may or may not be known. An example is the grease or oil used to lubricate a blower motor. In many cases like this, recommended

preventive maintenance is employed, i.e., oiling the motor every 30 days. Other examples of such preventive maintenance are: installing new brushes on motors after the old ones have worn down to a prescribed length; cleaning the dust filters at prescribed time intervals; installing new tubes after emission has been reduced to a known value; taking meter readings at prescribed intervals to detect slow degradation of signals; adjusting operating controls for maximum efficiency at frequent intervals; and calibrating test equipment at fixed intervals. Preventive maintenance tasks will be indicated using the same numbering system as described in the maintenance task section (3.1), except that whereas the letter T denotes a maintenance task and Y denotes a failure sympton, P will denote a Preventive Maintenance Task.

3.2.2.3 Maintenance Task Time

The three major divisions of the maintenance task as previously defined involve isolation of a fault, removal and replacement of the next lower assembly containing the fault, and checkout of the section containing the replaced item to verify that the fault has been corrected. Throughout the rest of this volume the three divisions will be called isolate, R & R, and checkout for the sake of brevity. The symbol for a maintenance task previously used is U1A1T1 which is the symbol describing the isolation of a fault to assembly A1, R & R of A1, and checkout of the unit containing the replaced A1 when the failure mode of U1 is described by T1.

The time to complete the maintenance task is the sum of the times to isolate the faulty item, remove and replace, and check out the replaced item when all three actions are performed. In some cases, the maintenance task will be an attempt to isolate the faulty item by looking for designated symptoms. If the designated symptoms are not present, the equipment (subassembly, etc.) will be forwarded to another echelon for maintenance. The time to remove and replace a defective assembly can generally be estimated accurately by an experienced engineer with or without direct recourse to experience on similar equipment. When this cannot be done, the equipment may be stripped down and re-assembled for time study, and reliable remove-and-replace times established subject to limitations discussed below.

The checkout time also is easily obtained by estimating the actions involved in setting up test equipment and performing the specification tests as for isolation. For greater accuracy, a time study may also be used to determine checkout time subject to limitations discussed below.

The most accurate, but at the same time, expensive and time-consuming way to determine the isolate time would be to perform a motion and time study observation of personnel performing the different sub-tasks in the isolation process for the various failure modes. Even then, as in any study of individuals, the accuracy would be high only for those people whose training, aptitude, etc., are similar to those in the sample. The test itself will provide some estimate of possible statistical errors. An alternate

to the above method would be a paper analysis of the motion and time study procedure based on assembly drawings and schematics, making a paper simulation.

A third method for obtaining the isolate time would be based on engineering judgement. In this method an engineer familiar with the circuit would make estimates, based on his own judgement, on how long it would take to isolate different levels of assembly from observable symptoms.

New equipment which resembles older equipment having case histories available may be assigned the same values for isolate time as the older equipment. Depending on how closely the new equipment resembles the older equipment, mechanically and electrically, so will the accuracy of the predictions vary.

The last method mentioned here for predicting maintenance task time is based on indices explained in the Phase IV Progress Report of the Maintainability Prediction Technique, RADC-TDR-62-156, Contract AF30(602)-2057, prepared for Rome Air Development Center, Air Force System Command, United States Air Force, Griffis Air Force Base, Rome, New York, and prepared by Government Services, RCA Service Company, a Division of Radio Corporation of America, Cherry Hill, New Jersey.

3.2.2.4 Tools and Test Equipment Requirements

3.2.2.4.1 General

The tools and test equipment required to perform the maintenance task will be determined when the maintenance task is analyzed. At the time the end product equipment is designed, some thought is given (usually) to the maintenance concept and the type of test equipment that will be required to maintain the equipment. Establishment of requirements for special test equipment depends on the quantity of equipment being produced, the complexity of the end product equipment, how adaptable troubleshooting this end product would be to automation, and other revelant factors. Special test equipment is defined as that which is peculiar to an equipment and is not readily obtainable from normal sources due to its specialized nature. When special test equipment is needed to perform a maintenance task, no other test equipment will serve the purpose. Special test equipment also affects the distribution of maintenance tasks. Assuming good design, the more specialized a piece of test equipment is, the easier it is to locate a fault, and easily locatable faults require less training of maintenance personnel. However, the generally higher cost of special test equipment plus its restriction of use to the equipment for which it was designed, limits its acceptability by the purchasing agency. The essential special test equipment is accepted reluctantly. Nonessential test equipment may greatly reduce isolate and checkout times; however, it is usually rejected on the grounds of cost and limited use. Viewed in the light of the overall objectives relative to cost, operational readiness, etc., the decisions may be made on a rational economic basis.

Determination of the measurements required to perform the maintenance task is the first step in establishing equipment requirements. These measurements, in turn, imply certain measuring elements which may be obtained individually as items of standard equipment or combined in an item of special test equipment. The choice between standard and special test equipment can be made on an economic basis. For minor items, it may be necessary to analyze the whole system for each alternative, comparing results for these alternatives. Standard tools and test equipment are those which are readily procurable as "off the shelf" items and which are common to the repair of many equipments.

The actual test equipment specified is selected on the basis of that piece of test equipment which will be capable of making the most measurements (or supplying the most inputs) required for various maintenance tasks with the required degree of accuracy, magnitude and stability. The test equipment is not selected on the basis of the absolute minimum requirement to perform each individual maintenance task as this approach would be impractical. For example, if a continuity check constituted a maintenance task, a flashlight bulb and battery or a fifteen dollar ohmmeter would suffice as the test equipment; but common sense dictates that if a good multi-meter has to be used for certain accurate measurements, another cheaper meter should not be ordered in addition just to make measurements requiring less accuracy. What is implied here is that the overall maintenance actions should be kept in mind rather than the blind application of test equipment based solely on each individual maintenance task.

The manner in which test equipment and tools will be associated with a maintenance task is shown in the chart included in Section 3.2.2.3. The test equipment will be coded using the letters of the alphabet. Single letters will denote standard test equipment and double letters will denote special test equipment. Although no tools are shown in the chart, the same method that is used for test equipment will be used for tools. The actual form used (shown in Volume 2) has divisions so that the test equipment used at different echelons is associated with the tasks (or sub-tasks) performed at one or more echelons.

As the test equipment and tools are shown in coded form on the Maintenance Task Form, an additional form relating the code to the actual equipment is used to identify the tools and test equipment and to present other data useful in provisioning.

3.2.2.4.2 Special Test Equipment

Special test equipment is test equipment designed especially for use with a particular end item or a very limited group of end items. It usually simplifies maintenance, as compared to using only standard equipment, by requiring less time for the isolation of a fault and for checkout of an item after it has been repaired. However, the cost of special test equipment limits its use. Other factors against wide-spread use of special test equipment are: the use is limited to one type of equipment; its failure may

inhibit repair of the item for which it was designed because no one at the particular echelon knows how to test the end item without the special test equipment; and when the end item becomes obsolete, so does the special test equipment.

As the design of an operating equipment progresses, a maintenance concept develops in the minds of the men who design and debug the engineering models. After a prototype has been built, certain testing techniques are developed by personnel concerned about how testing will occur in the factory during production. At various times, then, some segments of the manufacturer's personnel are concerned with how to find, fix, and repair an equipment when it malfunctions. To conserve time, increase production, and permit the use of low-skill factory personnel, special test equipment is designed. The type of special test equipment designed for factory use generally is not suitable for use with the military, as the test equipment is designed for small sections of the overall production run and deals with a much higher volume than would be encountered in the field. However, the circuits used to obtain the rapid testing procedures required at the factory are often adaptable to field use in the form of special test equipment. In trying to decide whether or not special test equipment for an end item equipment should be procured, the obvious question is if the special test equipment is really worth the time, design effort, and cost. In order to consider the above factor realistically, the complexity of the special test equipment to be built must be defined. It may be economically feasible to design and manufacture special test equipment up to a certain degree of complexity but not worth while beyond that degree.

In order to determine how complex the special test equipment should be made before the cost and time savings exceed the benefits obtained from the special test equipment, the following method is proposed:

(1) Determine the time it would take to perform the various maintenance tasks using only standard test equipment.

(2) Determine the time it would take to perform the various maintenance tasks using special test equipment of incremental degrees of complexity. Varying degrees of complexity of the special tools and test equipment would be determined by analyzing what would be needed to simplify the maintenance task and how complex it would be to design the test equipment to meet the need. Examples follow:

(a) Assume an equipment consisting of micro-modules mounted on module boards which plug into jacks that are inter-connected by wires. Using only standard test equipment, the maintenance man has to make a test involving three pins on a module board. The probes or test leads have to be touched to some part of the circuitry directly connected with the pins involved. This operation can become extremely difficult and, in some cases, impossible. When it is

impossible, some special test equipment or fixture is designed to alleviate the condition. The impossible situation which mandates special test equipment is not of concern here, but rather instances of where a choice of equipment does exist.

(b) When it is extremely difficult for the maintenance man to make the above measurements, an aid in the form of a special socket connector with test points on it could be designed so that when the module board is removed from the equipment and plugged into the special aid which in turn is plugged into the equipment, a set of tcst points corresponding to the pins on the module becomes available to the maintenance man.

(c) The above principle could be extended to a patch card arrangement where the module board is laid on the bench and patched into the equipment, thereby enabling the maintenance man to work on the board away from the congested eonfines of the equipment.

(d) Extending thc above principle still further, measuring devices could be incorporated into the patch card so that the module board would be connected to the equipment through the measuring devices and interlocked switching could be incorporatcd to monitor the signals on different pins.

(e) The above procedures show how successive levels of complexity of special test equipment can be built up and cost associated with the different levels.

(f) The savings in time achieved by using the successive levels of special test equipment can also be established as well as the overall time saved when compared to not using any special test equipment at all.

(3) By analyzing the cost and time figures associated with special test equipment, an optimum configuration of how much and what kind of special test equipment is needed can be determined.

Most of the direct cost of special test equipment are relatively easy to establish. It consists, first, of design and development costs, which are relatively independent of the quantity ordered. The second major group of costs is manufacturing costs which are more nearly proportional to the number of equipments ordered although there may be some economics in quantity production. Third are support costs for the equipment which include spare parts inventories (depends on whether parts are common to other equipments or are "special"), specialized training required for maintenance and other elcments which embody some "set-up" type costs and some costs depending on the

number of test equipment in the field. These costs can be determined in the same manner as costs related to operating equipment.

The effects of special test equipment on other costs are frequently indirect. The major influences are on time and skill required for a particular maintenance task. The special test equipment reduces both skill and/or time required for performance of a particular task as compared to standard equipment. This appears as cost saving in reduction in number and/or skill required by a particular shop and/or reduction in float and other inventory costs because of decreased downtime, a consequence of lower time-to-repair. The marginal approach to costing is appropriate here. Methods and approximations are discussed in Volume IV.

3.2.2.5 Skill Levels Affecting Maintenance Task

In the definition of the maintenance task, it was shown that a maintenance task could involve only one echelon but possibly more than a single maintenance man. It was implied that the different maintenance men would have different skills or skill levels. A maintenance man at the organizational level would proceed as far as he could in isolating the trouble in a malfunctioning unit and if he could not find the trouble, the unit would be sent to the next echelon. At the next echelon, another maintenance man, usually with a higher skill rating, would proceed in his attempt to isolate the trouble using more advanced techniques and test equipment than the maintenance man at the first echelon. In the mathematical model, the assignment of skill levels to the various echelons of maintenance is one of the outputs. Therefore, the various skill levels involved in performing the different sub-tasks of a maintenance task must be known as input to the model. In the maintenance task form included in Volume II, provisions are made for including the skill level requirements in the same manner as task equipment requirements. The skill level required for each phase of the maintenance task is associated with the complete maintenance task in the manner shown on the chart in Section 3.2.2.3 of this volume. The skill levels shown will correspond to existing methods of classification (MOS numbers) used by the Electronics Command.

Skill levels will be grouped into categories in accordance with complexity. Complexity will be determined from the description of the various maintenance tasks and the dexterity, logic, and experience estimated as required to perform the task. Present military occupational specialty numbers indicate a branch, specialization in the branch, and skill level in a broad sense. The skill level required in connection with the concept presented here is associated with specific maintenance tasks on one piece of equipment. The time that it takes to achieve a certain skill level as implied in this concept must also be established. As time elements are associated with skill level training, the skill levels themselves will have to be further divided into subdivisions. Refering again to maintenance tasks as the basis for establishing and assigning skill levels, it may be seen that a sequence of maintenance tasks may involve progressive measurements, all of which are dependent upon previous measurements. Assume

that there are three different maintenance tasks, all of which require measurements which are made using a voltmeter. The first task involves making six voltage measurements. The second requires making four additional voltage measurements, and the third requires measuring an additional five voltages. All the above tasks involve low degrees of experience, logic, and dexterity and would be classified as skill level 1. If it takes 15 minutes to train a man from scratch for the third maintenance task, he is automatically being trained to perform the first two tasks because the latter measurements are never made before the previous ones, since they are not significant unless the previous ones have been made. As the above tasks are related to each other insofar as they must be learned in progressive sequence, a group letter will be assigned to designate the relationship. Therefore, all the three related maintenance tasks previously described would be classified as Skill Level 1, Group A, or briefly, 1A. However, the time given to train a man for each of the tasks will be given as though the man actually did start from scratch. In this way, as a breakoff point is determined for any group of related tasks, the task for which the longest "time to train" is indicated will be the time it takes to train for the skill level to perform all the tasks involved in the group selected. Different groups of related skill levels will appear as 1B, 1C, 2A, 2B, etc.

The skill level required will depend both on the test equipment and on how it will be used. In general, go-no-go readings will require less skill than quantitative readings. Direct readings will require less skill than those obtained by adjusting to obtain a specific meter reading. This, in turn, generally requires less skill than those concerned with obtaining particular oscilloscope forms, etc. Using this common sense approach to ranking and grouping various tasks, practical skill grades can be defined, preferably coincident with existing grades.

3.3 HUMAN FACTOR ASPECTS OF MAINTAINABILITY IN DESIGN

3.3.1 EQUIPMENT DEVELOPMENT

The trend in electronic equipment is toward increased complexity. However, the trend of the military is toward:

(1) Active downtime restriction,

(2) Decreased skill level requirements,

(3) Fewer manning personnel;

(4) Lower cost

yet, while maintaining increased logistical system effectiveness - the bulwark of operational command success.

The onus of resolving this apparent conflict falls on the Equipment Development Team and their ability to evaluate the factors of design and the important tradeoffs; e.g., availability (maintainability-reliability) on the one hand, vs cost constraints, physical design limitations, and the given mission specifications on the other hand.

3.3.2 HUMAN FACTORS TASKS

Human Factors Engineering is the "name applied to that branch of modern technology which deals with ways of designing machines, operations, and work environments so that they match human capacities and limitations."

A Human Factors Engineer working in conjunction with Development Engineers throughout the design cycle is able to promote the effectiveness of the operator's and electronic maintenance man's performance through his basic knowledge in the psychological-physiological parameters which affect the total equipment operation.

In general, the "human individual as a factor in design" calls for a continuous decision-making process to optimize human performance in terms of cost, mission, and logistical systems on the individual. This reduction of burden and, hence, improvement of performance and minimization of human-initiated failure, is a major responsibility of the Human Factors Engineer.

3.3.3 INTEGRATED APPROACH TO HUMAN FACTORS IN EQUIPMENT DESIGN

A comprehensive Human Factors Analysis starts with an overview of the system, noting contractual specifications - cost, performance, maintenance downtime restrictions, etc. - which are imposed by the issuing organization. These factors are then traded off with current design principles and the realism dictated by the physical characteristics of the equipment and its specifications.

There are eight equipment design stages:

(1) Preliminary analysis

(2) Determination of electrical stages by block diagram

(3) System and subsystem development

(4) Circuit specifications

(5) Component specifications

(6) Layout and final construction of a prototype

(7) Revision and correction of the prototype for production, and

(8) Production.

In the first stages the Development Engineers are concerned with getting the system to operate, while the Human Factors Engineer as part of the team is concerned with:

(1) Emphasizing and assigning responsibility for "design in" of maintainability.

(2) Collecting pertinent maintenance structure and anthropometric information from the using organization directed at determining the maintenance levels; type of personnel available at these levels (their age, experience, etc.); and facilities available among the different levels (work environment, tools and test equipment, power supplies, spare parts, etc.).

(3) Performing a checkout to see if the equipment is actually maintainable by the using organization, by investigating whether the user is able to perform all the maintenance action required of him.

3.3.4 GENERAL MAINTAINABILITY REQUIREMENTS

Micro-module equipment will be designed with the following characteristics. The system/equipment maintainability characteristics will be such that ease and economy in all maintenance functions are achieved. Maintainability characteristics will be engineered, designed, and built into the system and equipment, and the special facilities required. The system/equipment should incorporate features and have characteristics that will enable the preservation or restoration of the operational performance and mission capability with a minimum amount of maintenance resources. The combined features and characteristics of the equipment design and the technical data should be such as to permit the accomplishment of maintenance by maintenance personnel under the prescribed environmental conditions in which the system/equipment will be maintained. The maintenance functions should be determined and identified during the initial stages of design and engineering.

Figure 3-6 is a flow diagram showing the major human engineering inputs during the major steps in the design sequence to achieve optimum maintainability aspects of the micro-module equipment.

3.4 STEADY-STATE PERSONNEL REQUIREMENTS

The allocation of skill levels and maintenance personnel to each echelon is a function of the maintenance analysis. To maintain a steady state of qualified personnel in his echelon, the commanding officer must be aware of the fluctuations in personnel.

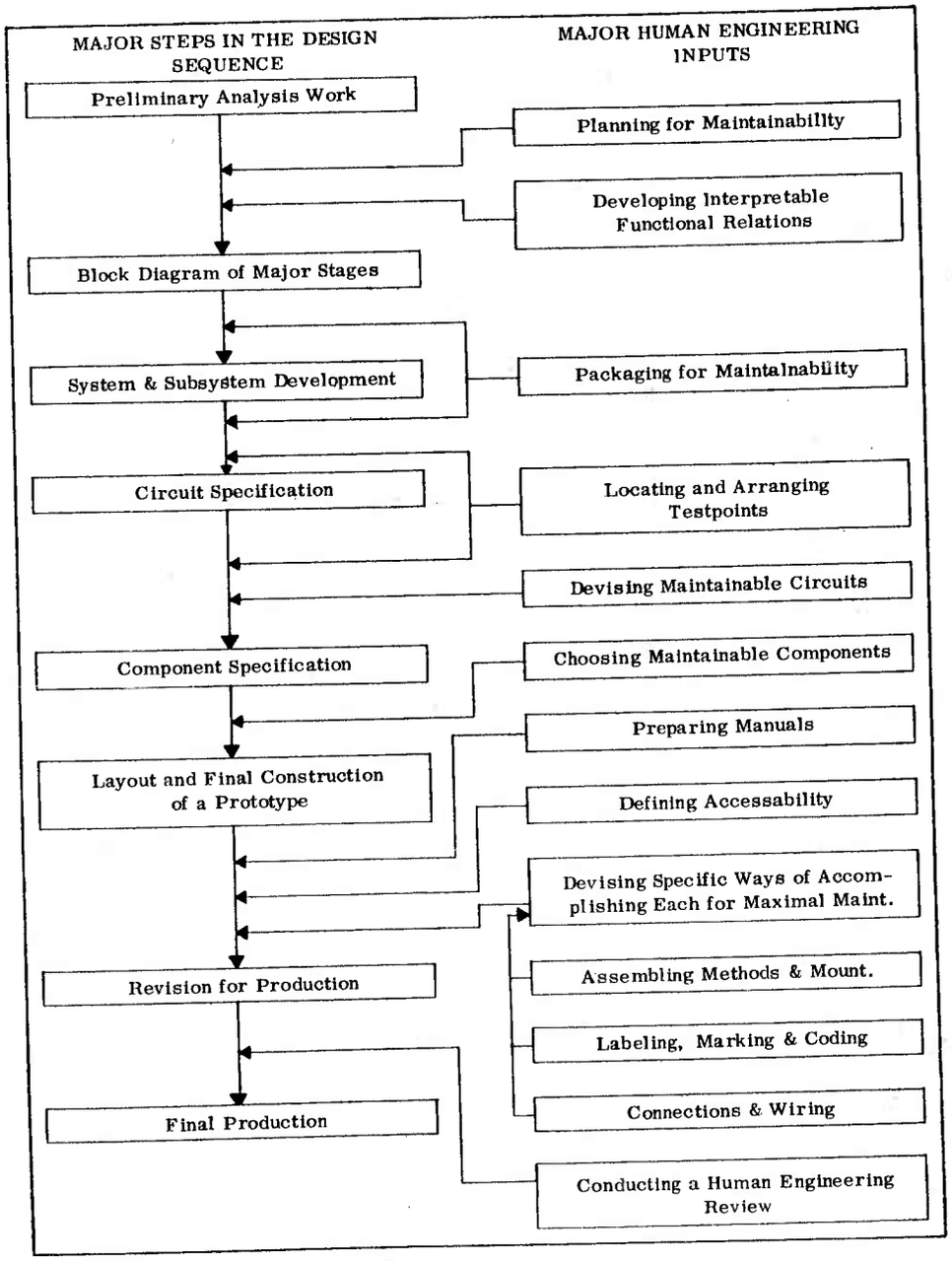
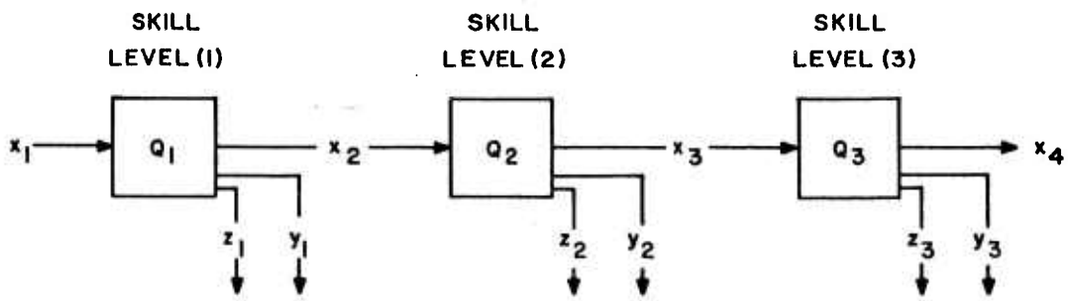


Figure 3-6. Method of Achieving Maintainability in the Design Sequence

The following discussion is a mathematical treatment of this problem.

The personnel system will be based on three distinct maintenance capability levels (skill levels); however, the concept may be extended to include a larger number of different skill levels.

The maintenance personnel system may be envisaged as a flow system of the form depicted below.



where:

Q_i = Number of Maintenance Personnel Required of Skill Level i.

x_i = Influx of Maintenance Personnel to the *ith* Skill Level Per Unit Time.

y_i = Resignations of Personnel of the *ith* Skill Level Per Unit Time.

z_i = Net Internal Transfers of Duty Assignments from *ith* Skill Level Per Unit Time.

To_i = Minimum Time in *ith* Skill Level for Promotion to (i+1)*st* Skill Level.

In order to achieve a steady-state personnel skill level system (the proper number of maintenance personnel of the *ith* skill level = Q_i), it is clear that:

$$x_i = x_2 + y_1 + z_1$$

$$x_2 = x_3 + y_2 + z_2$$

$$x_3 = y_3 + z_3 \qquad x_4 \text{ assumed } = 0$$

Substituting for x_2 and x_3 to solve x_1 in terms of y_i and z_i; x_1, x_2 and x_3 become:

$$x_1 = \sum_{i=1}^{3} y_i + \sum_{i=1}^{3} z_i$$

$$x_2 = \sum_{i=2}^{3} y_i + \sum_{i=2}^{3} z_i$$

$$x_3 = \sum_{i=3} y_i + \sum_{i=3} z_i$$

From these "per organization" rates, "per man" rates can be developed as follows:

$\Gamma_{xi} = x_{i+1}/Q_i$ = Men entering skill level i per man already in it.

$q_{yi} = y_i/Q_i$ = Men resigning from skill level i per man already in it.

$q_{zi} = z_i/Q_i$ = Men transferred from skill level i per man already in it.

These values can be established independently of any particular Q_i. In order to ensure a sufficient quantity of maintenance personnel in the ith skill level, the following equalities

$$Q_1 (q_{y1} + q_{z1} + \Gamma_{x1}) = x_1$$

$$Q_2 (q_{y2} + q_{z2} + \Gamma_{x2}) = \Gamma_{x1} Q_1$$

$$Q_3 (q_{y3} + q_{z3}) = \Gamma_{x2} Q_2$$

can be manipulated to yield:

$$\frac{Q_2}{Q_1} \leq \frac{\Gamma_{x1}}{q_{y2} + q_{z2} + \Gamma_{x2}}$$

$$\frac{Q_3}{Q_2} \leq \frac{\Gamma_{x2}}{q_{y3} + q_{z3}}$$

$$\frac{Q_3}{Q_1} \leq \frac{\Gamma_{x1} \; \Gamma_{x2}}{(q_{y2} + q_{z2} + \Gamma_{x2}) \; (q_{y3} + q_{z3})}$$

A further necessary but not obvious consideration is the time required of maintenance personnel to be in-grade prior to promotion.

If the rate of influx of personnel to the *ith* skill level is x_i and the time in-grade prior to promotion is To_1, then the mean number of personnel <u>not</u> available for promotion is

$x_1 \; To_1$; whereas

the number quantity available for promotion is

$Q_i - x_i \, To_i$

If Γ'_{xi} represents the number of promotions per unit time per available promotable personnel, then the identity exists

$$\Gamma'_{xi} \; (Q_i - x_i \, To_i) = \Gamma_{xi} Q_i = x_{i+1}$$

or

$$\Gamma'_{xi} = \frac{\Gamma_{xi} Q_i}{Q_i - x_i \, To_i}$$

The minimum ratios of the Q_i's that must be maintained in terms of this new notation become, when translated into inequalities.

$$\left[Q_2 (q_{y2} + q_{z2} + \Gamma_{z2}) + x_1 \, To_1 \; \Gamma'_{x1} / \Gamma'_{x1} \right] \leq Q_1$$

$$\left[Q_3 (q_{y3} + Q_{z3}) + x_2 \, To_2 \; \Gamma'_{x2} / \Gamma'_{x2} \right. \leq Q_2$$

These inequalities bring to light the explicit relationship of To_i in the personnel assignment problem. It is also necessary to recognize that initially the quantity of personnel in each skill level having satisfied the necessary in-grade time requirements is:

$$(Q_i - x_i \, To_i) = \Gamma_{xi} Q_i / \Gamma'_{xi}$$

SECTION IV
PROVISIONING IDENTIFICATION DOCUMENTATION

Basic to all provisioning being done for or by any branch of military service is the requirement that the items being provided for are precisely identified, and all pertinent information concerning purchasing of said items is accurately documented.

The importance of the precise identification lies in the requisite ability to reorder quantities of the same item at a later date and perhaps competitively.

The other documentation required pertains either to multiple use of the item considered in more than major equipment or is referenced to some requirement concerning repurchase of the item.

Through appropriate coding of information requirements indicated above, it is a matter of extension to have print-outs of the required identification coding and purchasing information reproduced, as a matter of course, with provisioning dictated by the optimal allocation of maintenance tasks throughout the support system.

In the data requirements discussed below, there exists necessary and sufficient information to conduct provisioning on an equipment type basis. By extending into the present steady-state provisioning conducted by the Army, it is possible to provision within the broad spectrum of army equipment having common items.

The data requirements discussed in this section generally do not fall into the conventional statistical prediction category. However, it is appropriate that the conventional and/or standard media of generating and documenting these requirements be developed, since otherwise a hiatus between theory and the practicality of implementation would exist.

Based on information capable of being supplied by the contractor, decisions are made by the military procuring agency concerning many part quantities to buy in order to support a given equipment type. Pursuant to this end, this section discusses information that can be supplied by the contractor and techniques for documenting information.

4.1 PARTS PROVISIONING BREAKDOWN

Primary concern of procurement is a convenient way to physically separate an equipment into sections; the sections separated into subsections; the subsections separated into the next smaller division, etc., until the smallest purchasable part or section is reached. Each item in any such breakdown must have a specific nomenclature and an identification number.

4.1.1 MANUFACTURER'S PART NUMBER AND NAME

Each section in such a breakdown is assigned a number and name at the time the equipment is designed. The number corresponds to the physical breakdown of the equipment in terms of indenture. The number of decimals in the number indicates the indenture or level of assembly breakdown. In the Summary Sheet described in Volume II, Section 4, the equipment is separated into its component subsections. This technique may be utilized to achieve the parts breakdown including the manufacturer's assigned number and nomenclature.

4.1.2 PRICES

The price paid for an item usually depends on quantity purchased, and the quantity of items purchased is influenced by the price of the item. The actual quantity to be purchased, in turn, would depend on anticipated usage, cost of reorder, cost of holding purchased stock and sundry other factors. These problems can be handled and explicitly solved when the inventory problem is isolated. However, for the present program purposes, this is not feasible. Instead, the position that will be assumed here is to produce a cost estimate of each item and estimate reasonable anticipated potential variation; for purposes herein described, the cost estimate is based on a particular equipment design time phase (prototype). The estimate cost, therefore, will be on the high side (as opposed to manufacture of production lots). The estimate of variation would be established based on a known variable cost factor established at the time prototype prices are established. Therefore, the price indicated on the Summary Sheet described in Volume II, Section 4, should be the price obtained from the manufacturer's pricing department for parts used in the prototype equipment. If this information is not available at the time, an estimated price will be given. The Summary Sheet will indicate whether the price is estimated or based on prototype equipment parts.

4.1.3 LEAD TIME

The time between the placement of an order and delivery of the part ordered is of importance at the time of initial purchase and subsequent reordering. Some parts are complex in nature so that manufacturing the part takes a long time. Other items are in such low demand that they are manufactured infrequently, necessitating adequate advance notice so that a run may be introduced at the appropriate time in a production facility. It is the object of the military logistic system to have all the required spare parts on hand to support an equipment at the time the equipment is issued for field use. In order to initiate purchase orders for items which will take a long time for delivery, the lead time for each item must be known. This lead time is measured from the time the item(s) is requested from the producer or manufacturer of the item to the time of physical delivery to the designated procuring agency. The lead time for the parts described in the parts breakdown list will be obtained from the manufacturer's purchasing department and will be entered on the master tabulation sheet described in Volume II, Section IV.

4.2 CRITICAL ITEMS

The failure of some items in an equipment may cause the equipment to be inoperable, whereas the failure of other items allow the equipment to perform its operational task as well as if the items had not failed. Examples of the above would be the case of the power amplifier tube in a transmitter failing and causing the transmitter to be inoperative. However, if the pilot light serving to show that the equipment was "on" failed, it would not affect the operation of the transmitter. The effect of the failure of an item on the equipment will be indicated by proper notation on the master tabulation sheet described in Volume II.

4.3 FAILURE RATE AFFECTING PROVISIONING

The failure rate of each part, along with other considerations, such as lead time, quantity in use, etc., is used to determine the quantity of spare parts to be purchased. Therefore, the failure rate, as described in Section 2.1 of this Volume, will be included on the master tabulation sheet described in Volume II.

4.4 FEDERAL STOCK NUMBER

The federal stock number is the tie-in between different manufacturers of identical items. It also provides the common terminology for provisioning within the military. As such it is vital information. Contractors would be required to review parts used in new designs and designate existing Federal Stock numbers for parts already classified in the supply system. In the case of micro-modules, it is doubtful that any Federal Stock Numbers have been assigned. In future equipments the Federal Stock Numbers of parts previously used by the manufacturer(s) will be on file for use when provisioning information is documented.

4.5 SPARES

Spares policy is derived through application of the mathematical model. A result of optimization is specification of quantities and locations for inventories at all echelons.

The inputs required to the inventory elements of the model are as follows:

(1) Demand - derived from usage rate calculation (see Frequency of Maintenance Task, Section 3.2.2.2).

(2) Unit Acquisition Cost - cost as received at inventory point includes purchase price (except set-up charges) handling and shipping costs. (Ordering costs, set-up charges are assumed to be inevitable if there is demand.) Accounting and handling costs may be estimated from weighted averages of depot costs or from costs in equivalent civilian functions.

(3) Time for Delivery - items can, in general, be classed according to size, weight, and/or any other characteristics which determine feasible means of transport, such as man, jeep, trucks, and helicopters of various sizes, etc. For each class of transport, availability and velocity can be estimated and related to deployment to provide this data. (See section 5.5.1 for further discussion.) The critical elements in any such predictions which have major effect on not only the average time, but also the variability, lie not in the actual transport time, but in the administrative delays, wait for available transport, etc. and, of course, the loss or destruction of a depot due to enemy action. For most of these factors, priorities and other administrative policies under control of the Commanding Officer are major determinants. Sources of this information consist of policy directives and orders issued and interviews with field officers.

(4) Interest - "interest" charges on funds tied up in inventory are relevant on items periodically reordered from sources outside the government. However, they are irrelevant in instances in which the equipment is initially provisioned "for life". In this case, local inventory policies merely determine the distribution of quantities among the various storage points, but do not affect total inventory.

(5) Other Holding Costs - where mobility of a stock of parts is of concern, the weight and/or size of a part will have a "cost" associated with it. Where there are fixed weight and/or volume constraints not to be exceeded, these constraints may be expressed directly, and mathematical programming (e.g. linear programming) techniques may be used to determine the optimum mix. Alternatively, costs of space and weight can be varied until the economic optimum inventory is of the appropriate size and weight. Where there are no positive limits on size and weight, vehicular amortization and operating costs per useful unit capacity of volume or weight can be used to provide an estimate.

SECTION V

LOGISTIC CONSIDERATIONS

5.1 GENERAL

It is recognized that a logical model, formed to represent the complex behavior of a physical system, must be predicated on assumptions which reflect the nature and behavior of that system. The Generalized Operational Readiness Mathematical Model relates a single system performance characteristic - operational readiness - to the major support system parameters, and is predicated upon a particular equipment's design characteristics.

The major objective of this section, and all other sections pertaining to the area of Logistics, will be to specify (and subsequently predict) those elements of logistics that relate to the Operational Readiness of the total system. To do this will embody a technique, compatible with wartime and peacetime environments, realistically describing the physical support system between M echelons of maintenance activity.

5.2 SUPPORT PROBLEM

To every change in the physical configuration of the support environment because of tactics, there corresponds a change in the logistical configuration of the system. However, of all the functional parameters (failure rates, arrival rates, repair rates, delay rates, etc.), only the delays due to transportation losses are variable with respect to configuration dimensions.

The field configuration of the M-Echelon Model corresponds analogously to the disposition of tactical units in the field. This configuration consists of a description of the logistical lines of flow of operable and/or inoperable pieces of equipment between certain elements (maintenance elements) of the tactical field units. The system is made up of maintenance echelons which are symmetrically disposed, and are formed on the basis of maintenance capability levels.

Figure 5-1 illustrates a typical arrangement of the field support arrangement, in combination with the mathematical analog of the support problem. (Note: This diagram is intended only to indicate the model logic and the approach to the problem, rather than imply the appearance of the best solution.)

At the top of the figure, L_i designates the total maintenance float assigned to a station in the ith maintenance echelon. Upon an arrival of a failed unit at the ith echelon, when available, a unit of maintenance float from the ith echelon is immediately sent to the $(i - 1)^{st}$ echelon, leaving the ith echelon with one less unit of available maintenance float and one more unit in for repair. When it enters a service channel, either the

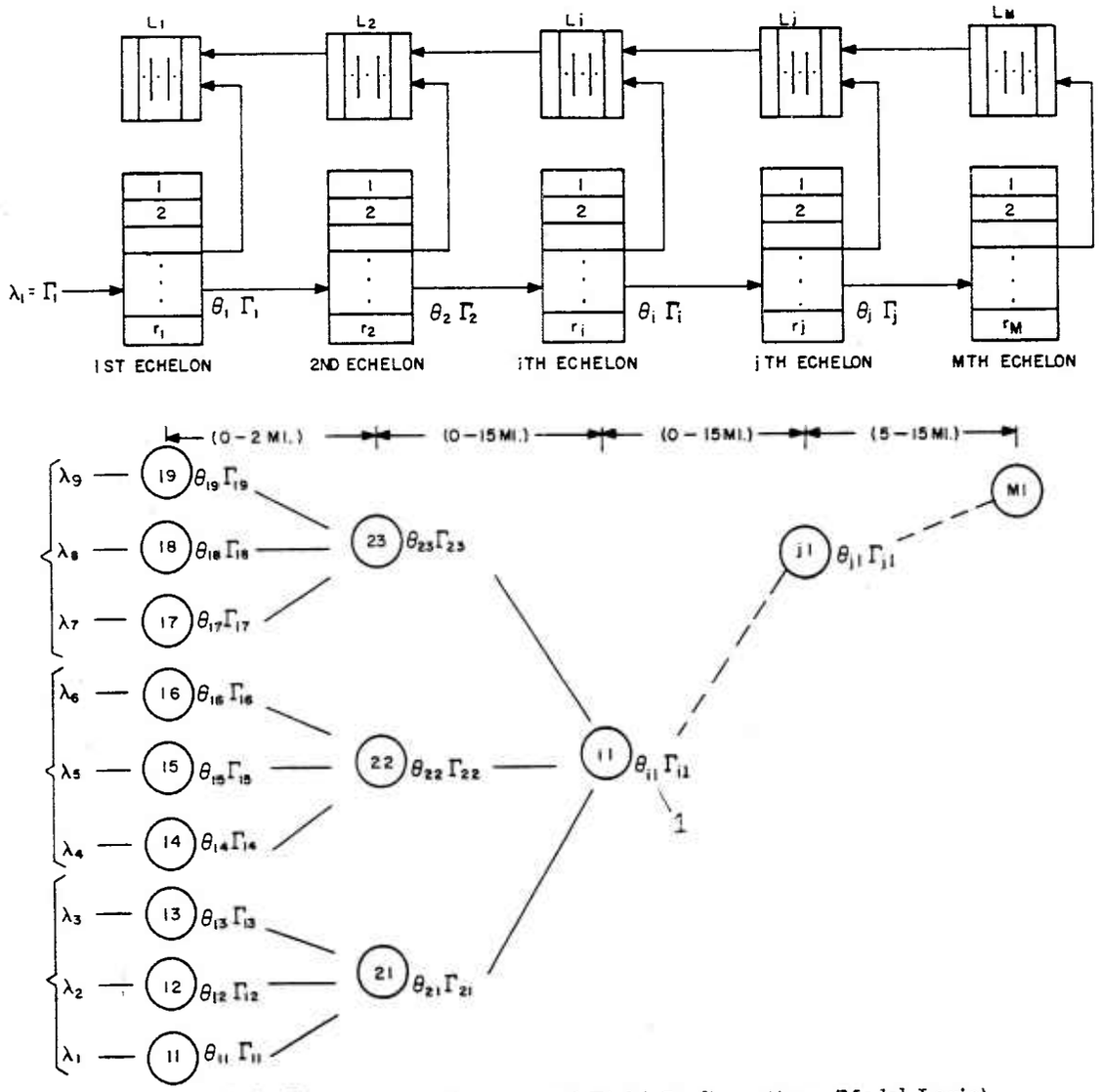


Figure 5-1. Examples of Abstract and Field Configurations (Model Logic)

failed unit is repaired and returned to its available maintenance float or the decision is made that the unit cannot be repaired there. In the latter event, the unit goes to the $(i + 1)st$ echelon, which in turns sends a unit of float down to the ith echelon (if one is available). If necessary, this cycle would continue up to, but not beyond, the last (Mth) echelon. (Note: This is the end of the sequence, with the inability to repair at the Mth echelon implying the necessity of salvage.)

5.3 CHARACTERISTICS OF THE SYSTEM

The total arrival rate (failure rate) of failed units going into the first echelon is the summation of failure rates of all failed units going into all first-echelon shops. (Note: The failure rate (λ) of any one equipment is equal to the arrival rate (Γ) of that equipment into a particular first echelon shop.)

Not all failed units arriving at a particular echelon can be repaired there. A certain percentage of equipment failures will be repaired at the first-echelon shop and the remainder sent to the second echelon. The percentage of those being sent to the second echelon (Θ_1) multiplied by the number arriving at the first echelon is the arrival rate at the second echelon.

Similarly, third echelon shops receive a percentage (Θ_2) of those equipments arriving in second echelon shops (Γ_2). This gives rise to the general relation of arrival rate to the ith echelon.

$$\Gamma_i = \Theta_{i-1} \Gamma_{i-1}$$

Figure 4-3 depicts an arrangement with a 3:1 reporting ratio. This is, however, an arbitrary choice for illustrative purposes only. An appropriate reporting ratio will have an influence on the overall cost of the system as explained in the following remarks.

5.3.1 REPORTING RATIO

Reporting ratio (n:1) is defined as the number (n_i) of shops at the ith echelon, which report forward. (Note: At the first echelon n_o represents equipment units rather than shops, which are supported by each shop.)

The most obvious advantage of considering any configuration with $n > 1$ is that it permits a reduction in cost by a centralization of maintenance effort; i.e., fewer pieces of tools and test equipment and less personnel are needed when many units of equipment are repaired at one point rather than at n points.

Considering the other extreme, then, implies letting n be as large as possible, or $n_o = N$, the total number of equipments. This approach, however, causes the cost due to transportation to increase, as n approaches N (for relatively large N), to the point where

it nullifies the savings due to centralization. This result is merely a consequence of the geometry of the problem.

One of the more involved ramifications of the physical descriptions of the military environment, is the large number of possible field configurations as related to combinations of reporting ratios. Each reporting ratio scheme will have a certain impact on logistic cost input by virtue of its relationships with arrival rates, transportation time delays, etc.

5.3.2 SYSTEM CONFIGURATION ARRIVAL RATES

Let the reporting ratio for a given logistics support system by

$$M_1/M_2 = n_1 \qquad M_1 = M_2 n_1$$

$$M_2/M_3 = n_2 \qquad \text{then} \qquad M_2 = M_3 n_2$$

$$M_3/M_4 = n_3 \qquad M_3 = M_4 n_3$$

$$M_4/M_5 = n_4 \qquad M_4 = M_5 n_4$$

and let n_o designate the operational units at each of the M_1 first-echelon stations.

The arrival rate at each succeeding maintenance shop, given Γ_1, will be

2nd $\qquad \Gamma_1 n_1 \Theta_1 = \Gamma_2$

3rd $\qquad \Gamma_1 (n_1 n_2)(\Theta_1 \Theta_2) = \Gamma_3$

4th $\qquad \Gamma_1 (n_1 n_2 n_3)(\Theta_1 \Theta_2 \Theta_3) = \Gamma_4$

.

.

.

M*th* $\qquad \Gamma_1 \left(\prod_{i=1}^{M-1} n_i \right) \left(\prod_{i=1}^{M-1} \Theta_i \right) = \Gamma_k$

With conditions $n_i \geq 1$ and $\Theta_i \leq 1$, it is seen that $(\Pi n_i \times \Pi \Theta_i)$ can be greater than unity, which implies a net arrival rate at a shop in a higher echelon greater than that at a shop in the preceding maintenance echelon.

A more extensive development of the reporting ratio concept is given elsewhere in the report (see Section 4.7 of Volume I).

In addition to the various choices of reporting ratio schemes, there exist other considerations possessing alternatives that affect operational readiness.

The concept of model discipline will have a bearing on operational readiness, whereby discipline is defined as the specific handling instructions for failed and/or repaired equipment.

Consider two cases:

> Case I. Requiring that a failed unit must be physically received at a given upper echelon before maintenance float will be released.
>
> Case II. Utilization of nearest available maintenance float in the system prior to turn-in of failed unit.

In Case I there is always the loss in time required to transport the failed units in addition to a like amount of time to transport the replacement, with its resultant effect on maintenance float levels.

Case II eliminates some of the transportation time losses that otherwise reduce operational readiness; however, there would be a need for closer controls to prevent stockpiling, etc.

5.4 LOGISTIC ANALYSIS

5.4.1 GENERAL

The maintenance function and logistics are inextricably related, with the consequence that the success of the maintenance function depends heavily on the smooth operation of the logistical elements of the system. The striet definition of logistics is "that branch of military art which embraces the details of the transport, quartering, and supply of troops." The present problem of logistics will modify this definition to the extent that troops will be replaced by military equipments, and the transport and supply phases only will be used.

The purpose of Section 5.4 is to (1) indicate what the logistical elements are, and (2) show the relevancy of an analysis of these elements to the problem of maintenance support.

5.4.2 TRANSPORTATION REQUIREMENTS

In general, the personnel charged with the responsibility of, and trained in, maintenance, are distinct from the users of the equipment. Also, for reasons of tactics, the location of maintenance facilities will be removed from the site of most equipment failures. Therefore, no repair action can begin until the failed item is transferred from the point of failure to the point of repair. This procedure requires that there be some form of transportation at (or near) the points of failure. Hence, transportation facilities must be an integral part of the entire maintenance-logistics system (see Section 5.5.1).

Of the many types of transport modes that play various roles in the Army's overall transportation mission, it is concluded that the typical military wheeled vehicle as found in a company-size unit, namely, 1/4-ton, 3/4-ton, and 2-1/2-ton trucks can provide the necessary transportation support in the field environment under study.

5.4.3 ADMINISTRATIVE REQUIREMENTS

In conjunction with the physical flow of equipment through the transportation lines between echelons, there are several actions which will normally take place.

(1) At the first and/or second echelons, a work request will be initiated (811 Form).

(2) Higher echelons, on receipt of equipment, will probably tag them for identification.

(3) Higher echelons, on receipt of equipment, will log them in, thus keeping track of work to be performed.

These actions are designed to offer some control within the system as pieces of equipment flow through the system. In addition to accounting for the whereabouts of equipment, the work order actually aids the repairman by indicating what is wrong.

The specific procedures used in performing these administrative actions will vary with local commander policies. However, they should be considered essential elements of any system, and the time delays involved should be about the same regardless of local procedures.

5.4.4 SYSTEM DELAYS

When speaking about delays in the system we are speaking of the major time factors that consume equipments in the logistic system such that the equipments are not available for operation. These major time elements are recognized and identified as:

(1) Transportation time required between the (i - 1)*st* and i*th* maintenance echelon, with the time required for flow in either direction as equal.

(2) Administrative time, which essentially consists of processing of equipment at each echelon for accountability purposes.

(3) Parts outage time caused by a demand for parts not available.

(4) Repair time delays which develop while equipment is in for repair or awaiting repairs.

With estimates of each of these delay time factors, together with knowledge of the failure characteristics of the equipment, it is possible to calculate the Operational Readiness of the logistics system having these factor characteristics.

Of particular interest, the transportation delay time and administrative delay time can also be utilized in a model to determine suitable quantities of maintenance float at each operating echelon.

5.4.5 EFFECTS OF PRIORITIES

In the light of remarks made in Section 5.4.2, three basic transport structures are possible:

(1) Available transportation is used.

(2) The maintenance facility is assigned vehicles as required to fill the need.

(3) The maintenance facility itself is mobile.

When available transportation is used, the ratio of Mean Transport Time (MTT) to MTBF is normally sufficiently large so that use of transport facilities for one failure will rarely impair the availability of facilities for another failure. If the maintenance requirements are given top priority, a situation probably dependent upon national state, etc., then other users of the transport facilities are delayed accordingly. When maintenance does not have top priority, the consequence is the same as if the MTT were longer.

At an extreme where the maintenance requirements would have very low priority, their flow would generally depend on how closely the maintenance demand for transport matched the need of other functions having higher priorities than the maintenance function. In this case, the proximity of the maintenance facility to other organizational centers will have considerable effect on the MTT. This contingency might imply, for example, that in considering Peacetime-Wartime transitions, the higher delay rate due mainly to the lower priority of maintenance during these periods may be compensated

for by locating maintenance shops in physical proximity to some high priority functions, as Ration Breakdown, Headquarters, etc. Otherwise, the delays in waiting for transport could become serious.

When the maintenance facility is assigned vehicles for maintenance transport at high priority, queueing problems arise and/or there will be, in general, poor utilization of these vehicles. When MTBF is very low relative to MTT, vehicles are used inefficiently; when it is high, queues for vehicles may develop.

5.5 DELAYS

5.5.1 TRANSPORTATION DELAY RATE

The necessary input for the model is the average or mean transport time between each pair of adjacent echelons. To predict this, the only basic requirement is to have some knowledge of the spatial relationships of the various levels of maintenance and the modes of transport that will be available. The relationship of distance and speed will then yield the required time value.

At this writing, the mean transport time between echelons, say one and two, in 1968 cannot be validly stated. To do so would erroneously imply some prior knowledge of the tactical deployment of Army field troops in the future. But by assuming present-day configuration constraints, it can very readily be shown how to arrive at the desired parameter factors, given the two necessary parameters of distance and speed.

For illustrative purposes, the vehicle modes have been tied down to just three vehicle types, which can be expected to fill all transportation requirements. The following average speeds of these modes (miles per hour) are assumed.

Vehicle	Speed	
	Peacetime	Wartime
1/4-Ton	30	40
3/4-Ton	30	20
2-1/2 Ton	20	10

It is recognized that in many instances there may be no vehicle movement; namely, the equipment will be hand-carried to a maintenance shop. This occurrence will be particularly true at the operating levels (first two echelons) where the distances are often too small to warrant use of a truck. Here also, the nature, size, and weight of the equipment will affect this possibility.

It is believed, however, that by considering average structure dimensions; e.g., two miles distance at the operating level, the case of nonvehicular transportation can be eliminated without too much loss of generality.

The problem then reduces to assigning average or expected distances between echelons. There first must be an organization with a well-defined mission. Based on established Army doctrine involving tactics, etc., this organization should be given general areas of responsibility interms of distances that must be covered when employed in the field. Within these guidelines the responsible commander (s) must appropriately locate each facility of the command, including the maintenance facilities.

From this point, the distances may be estimated by:

(1) Dividing the total area supported into sub-areas corresponding to the sub-units of the organization according to its TOE. (Note: The dimensions of these sub-areas would also be specified by Army doctrine.)

(2) Assuming that the facilities are all centrally and symmetrically oriented within these sub-areas.

(3) Identifying distinct levels (echelons) of maintenance within this framework.

(4) Then obtaining the average distance between each of these levels (the maximum distance may be safer).

The mean transport time T_{ti} between echelons i and i + 1 will then be given by

$$T_{ti} = d_i/30 \quad \text{(Peace)}$$

$$= d_i/20 \quad \text{(War)}$$

provided all transportation requirements are met with either a 1/4-ton or 3/4-ton truck; or in any event by

$$T_{ti} = d_i/\bar{v}$$

where

d_i = the average (or maximum) distance between echelons i and i + 1 in miles.

$\bar{v}$ = the average speed of the mode of transport in miles per hour.

T_{ti} = Mean Transport Time (MTT) in hours.

In practice, there may be structures having dimensions substantially less than fifteen miles. Therefore, it may be desirable to convert the time from hours to minutes by the factor 60. The transport times in that case would be

Modes	T_{ti}	
	Peacetime	Wartime
1/4 & 3/4-Ton	$2d_i$	$3d_i$
2-1/2-Ton	$3d_i$	$6d_i$

with the mean time T_{ti} in minutes.

If an idealized deployment of a battle group and an infantry division in the field is considered with respect to field frontages and depths, and the present "normal" maintenance channels, Figures 5-2 and 5-3 are evolved. (It must be noted that the drawings are purely schematic with the figures representing generalized guidelines. Variable tactical considerations would dictate the actual configuration in a particular case.) The figures do not show all signal maintenance channels in the battle group, but it does indicate "type" channels that would be utilized.

The required input related to appropriate transport structures and reporting ratios is in terms of unit cost and unit time of transport between echelons. It is here that the information obtained from field application considerations is applied. The concept of reporting ratio has been defined as the number of stations at an echelon supported by each station at the next higher echelon. Increasing the reporting ratio at an echelon permits savings through centralization of maintenance efforts.

Associated with each ratio is a transport cost factor which actually serves as a constraint to the choice of an optimum ratio configuration; i.e., as the ratios increase, so will the transport costs, eventually reaching a point where they offset the savings gained by centralization.

The relevant factors of the tactical field use of the equipment entered on Form 6.1.6 could be used to specify the environment which will determine both transport times and cost.

Consider the following two general cases (see Figure 5-4):

(1) Equipments employed are approximately equally spaced on a straight line.

(2) Equipments are dispersed more or less uniformly within some bounded area.

For practical purposes, all cases can be treated as one or the other of the above.

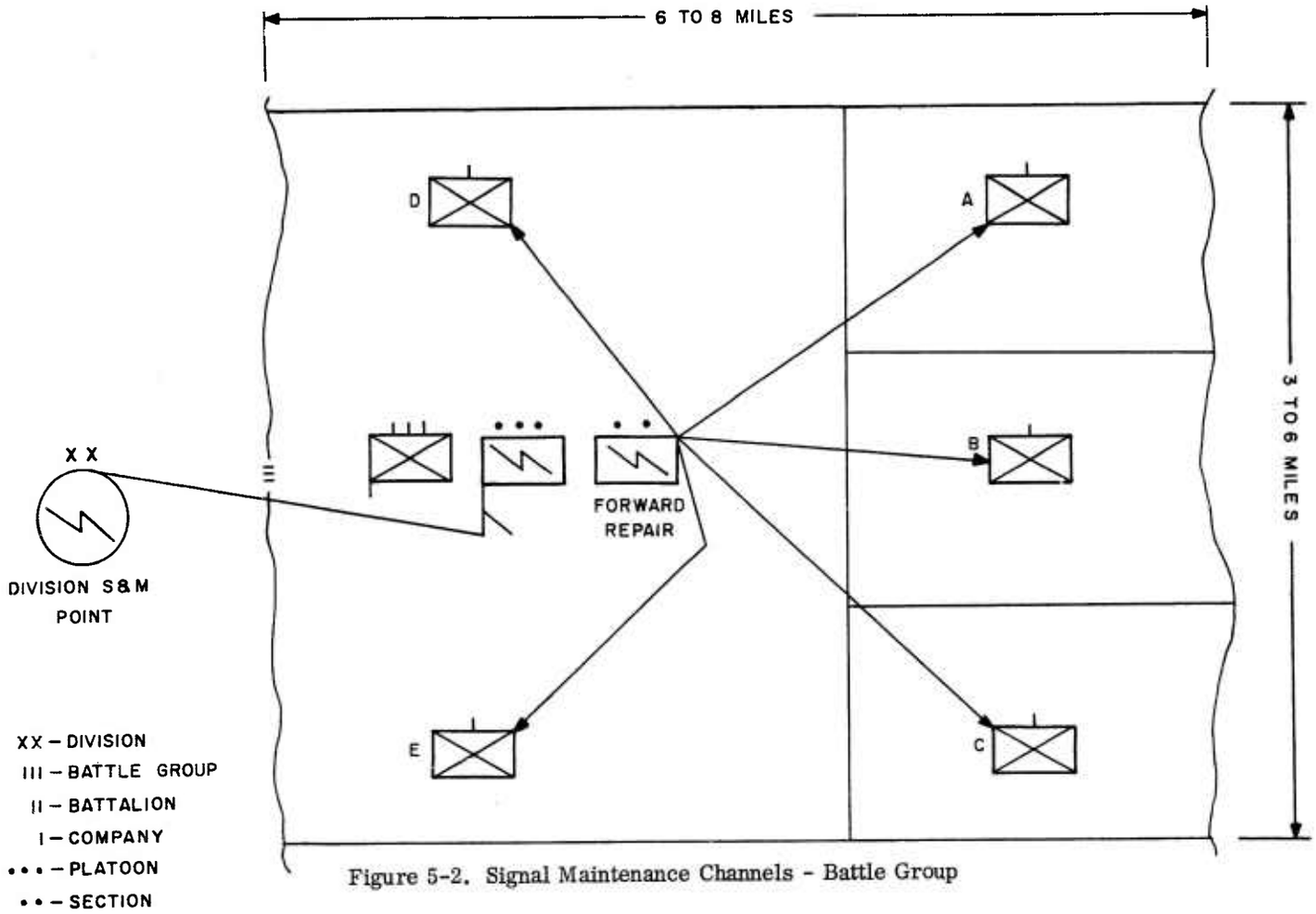
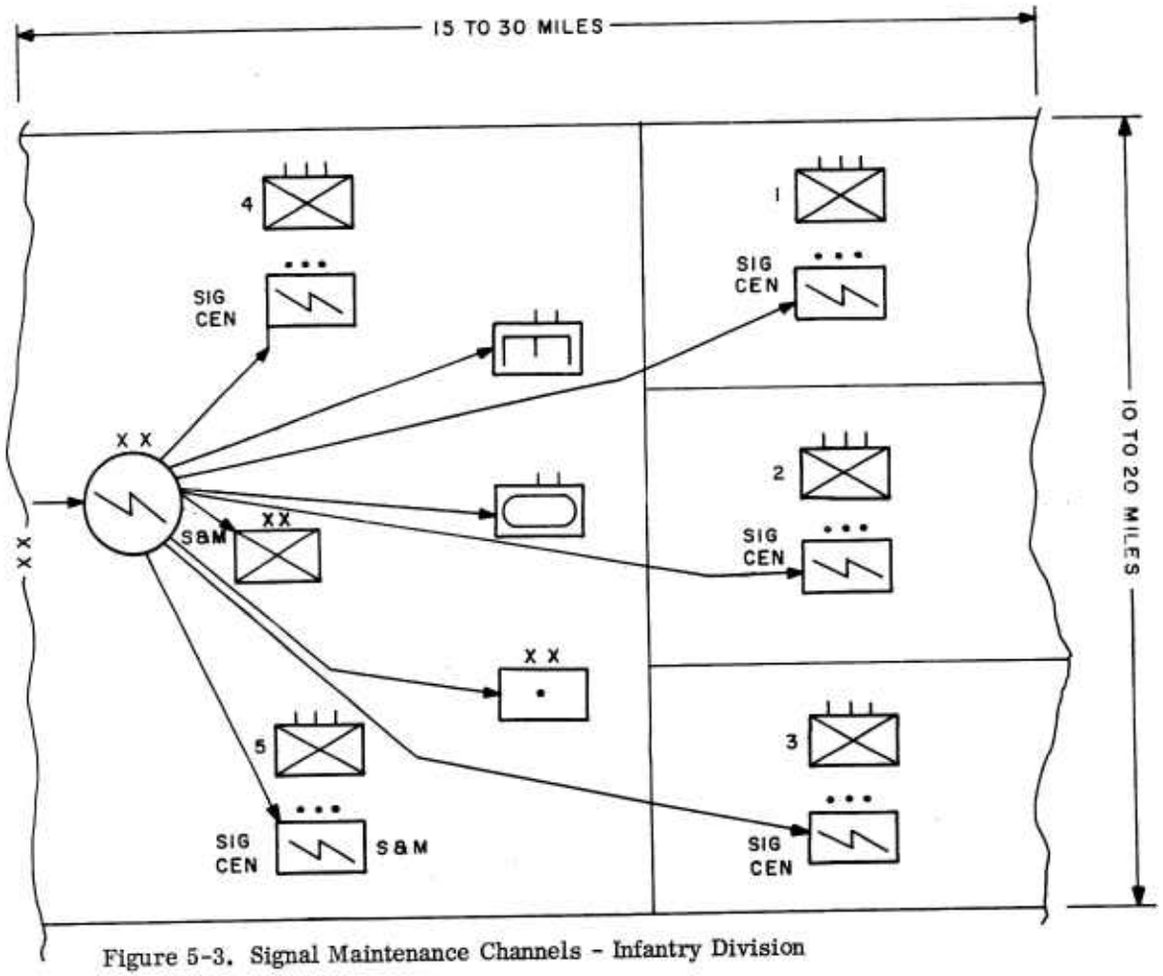
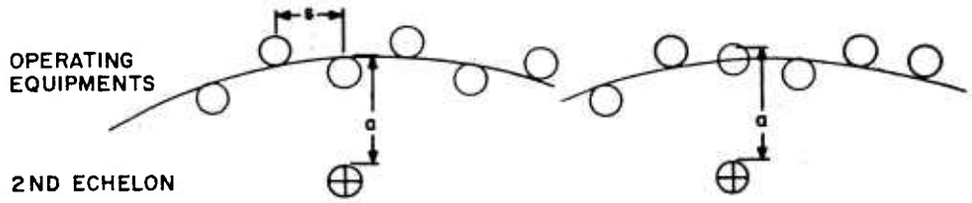


Figure 5-2. Signal Maintenance Channels - Battle Group

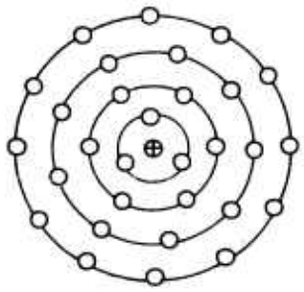


XX – DIVISION
III – BATTLE GROUP
II – BATTALION
I – COMPANY
• • • – PLATOON
• • – SECTION

Figure 5-3. Signal Maintenance Channels - Infantry Division



CASE I



CASE II

Figure 5-4. Illustration of Equipment Dispersion

The objective here is to develop the average distances to be traveled with different reporting ratios, given tactical use information.

For Case 1.

d = distance front-to-rear between echelons under consideration.

s = spacing between equipments along the line.

n = reporting ratio.

For any fixed set of these variables, the one-way distance from a maintenance shop to the farthest removed equipment is obtainable using Pythagoras' relation

$$D(n) = \sqrt{d^2 + \left(\frac{n-1}{2}\right)^2 s^2}$$

The transport cost of the system will not depend on this maximum distance, but rather on the average distance of all units in the system. Hence

$$\bar{D}(n) = \begin{cases} 2/n \sum_{i=1}^{n/2} \sqrt{d^2 + \frac{(2i-1)^2 s^2}{4}} & \text{n even} \\ d/n + 2/n \sum_{i=1}^{(n-1)/2} \sqrt{d^2 + i^2 s^2} & \text{n odd} \end{cases}$$

Case 2 does not lend itself to as precise a treatment. What can be done is to consider an area approximation approach; i.e., by assuming the field area to be a circularly bounded area, and considering the density of the dispersed equipments to be uniform, the average distance of the equipments from the supporting shop can be established, assuming the shop is located at the center of the area.

An approximation to uniform distribution can be obtained by assuming that units are uniformly distributed along concentric circles at equal increments of radius (r_1) with the supporting shop at the center and with 3, 6, 9, 12, . . ., 3k in successive circles.

Then the number of units in a system of concentric circles would be

$$n = 3 \sum_{i=1}^{k} i = 3\left[\frac{k(k+1)}{2}\right] = 1.5k(k+1)$$

Now the distance that each unit is from the shop depends upon the circle with which it is associated. Since the *kth* circle is k units from the center, the total distance, D(k), of all units from the maintenance shop is given by

$$D(k) = 3 \sum_{i=1}^{k} i^2 = 0.5\, k(k+1)\,(2k+1)$$

The average distance $\bar{D}(k)$ would then be

$$\bar{D}(k) = \left[3 \sum_{i=1}^{k} i^2 \right] \Big/ \left[3 \sum_{i=1}^{k} i \right] = \frac{0.5k(k+1)\,(2k+1)}{1.5k(k+1)} = \frac{2k+1}{3}$$

This average distance factor, a function of the number of concentric circles (k), must be converted to distance units by multiplying it by the radius (r_1) of the innermost circle. The value of r_1 bears the following relation:

$$r_1 = 1/k\sqrt{A^*/\pi}$$

where A* is the total field area and k, the number of concentric circles as fixed by the number of equipments. The average distance relation would take this new form

$$\bar{D}(k) = \left[1/(3k) + 2/3\right]\sqrt{A^*/\pi}$$

Note: One obvious restriction to this approach as described above is that it assumes an integral number (k) of concentric circles as fixed by the number (n) of equipments, whereas in fact only a very limited choice of equipment quantities will yield an integral k. This problem may be obviated by interpolation, without a significant loss in the approximation.

These distances in Cases 1 and 2 may be converted to times by inverse rate factors of pertinent transport modes. For cost conversion, use the cost per unit distance data given in this volume, (Section 5.6.3).

Remarks

(1) The transport time will be highly variable during wartime, due to its heavy dependence on tactical requirements. This highly fluctuating logistic support system during wartime is somewhat contrary to the steady-state requirements of the model (see Section 5.6 Wartime-Peacetime Comparisons).

(2) The transport times represent strictly on-the-road times; and do not account for any loss in time resulting from unavailability of transport.

The transportation time delay is a function of distance and speed, i.e., $T^* = f(d, v)$; therefore, the errors associated with the predicted time values are due to any errors in these two independent variables. To evaluate the errors involved, the following relationships hold.

$$T^* = \frac{d}{v}$$

$$\Delta T^* \approx \frac{\partial T^*}{\partial d_o} \Delta d + \frac{\partial T^*}{\partial v_o} \Delta v$$

$$\Delta T^* \approx \frac{1}{v_o} \Delta d - \frac{d_1}{v_o^2} \Delta v$$

where

$$\Delta x = x_o - x$$

and percent error is:

$$\frac{\Delta T^*}{T^*} \approx \frac{\Delta d}{d} - \frac{\Delta v}{v}$$

Since the estimate, x_o, can be either larger or smaller than the true value, x, Δx can be either positive or negative.

The second relation above for ΔT^* is the total error in terms of the predicted values of the independent variables and their expected errors. The units for this quantity will depend on consistent use of units for d and v.

The magnitude of this error will be independent of the type of organization, and any other characteristics relative to the tactical configurations involved. It will be subject only to the magnitudes of Δd and Δv, the errors in the estimates. Intelligent estimates of the bounds of these errors can be made, and are given below, provided the estimations are made in strict conformity to the techniques described above:

(Note: d_o and v_o are estimated values of the variables.)

$$|\Delta d| \leq 0.25d$$

$$|\Delta v| \leq 0.33v$$

where d and v are the "true" values of the variable.

Thus

$$\left|\frac{\Delta T^*}{T^*}\right| \leq 0.58$$

If errors in d and v can be assumed to be approximately normally distributed with 0 means and $\delta_{d_o} = 0.08d$ (from $3\delta = 0.25$), and $\delta_{v_o} = 0.11v$, then $\delta_{T_o*} = 0.14T$.

5.5.2 ADMINISTRATIVE DELAY RATE

The major administrative tasks were identified in Section 5.4.3. It will not be necessary to consider any analytical derivation of these time delays due to their relatively simple nature. The purpose here is to define more completely these administrative actions.

5.5.2.1 First Echelon

The first echelon is the actual user or operator of equipment and hence little involved in administrative actions. Generally, this echelon will try to remove a failed equipment to the next echelon as rapidly as possible. However, some intelligence must be conveyed to this next echelon, either written or oral, indicating the symptoms of the failure, etc. and/or to just request repair. If a replacement equipment is obtained immediately, then no further control is necessary. In the case of no replacement, some sort of receipt should be used to account for the absence of equipments at the echelon.

5.5.2.2 Second Echelon

At the second echelon incoming equipment must undergo the following processing:

(1) Identify owner and issue receipt if necessary.

(2) Check maintenance float for replacement.

(3) Review work request.

(4) Tag equipment.

(5) Log equipment into ledger.

With the Case I model discipline all the above actions are appropriate. With Case II discipline, (1) and (2) would not apply. Now if the equipment is repaired, then it is either returned to the user with necessary entries on the original work request, or placed into the maintenance float, this also being influenced by model discipline.

5.5.2.3 Higher Echelons

For equipment sent to higher echelons, the administrative tasks in general duplicate themselves. As such, the order of magnitude of the delays should be essentially the same.

5.5.2.4 Error in Assignment of Administrative Task Time

In the assignment of administrative task times, errors can arise in two ways.

(1) An omission of one or more procedures which occur somewhere in the system.

(2) The durations assigned to tasks can be in error.

Thorough knowledge of the operating procedures of the organization will make the first error source negligible.

In assigning durations to the performance of administrative tasks, there are two potential sources of error. First, the basic time allocated to the task can be incorrect, again due to insufficient knowledge of the task requirements and/or personnel efficiencies. Second, there will be an inherent variability in task duration because of various personnel performing the tasks at different times.

Analysis of the nature of these tasks, together with the sources leading to errors, produces the estimate that the error in the predicted administrative delay time Δt_{Ai} should not exceed three minutes per task, or:

$$\Delta t_{Ai} \leq 3 \text{ minutes}$$

Total error ΔT_A for N tasks is then bounded by

$$T_A = \sum_{i=1}^{N} \left|\Delta t_{Ai}\right| \leq 3N \text{ minutes}$$

Errors in estimates of packing delays should be relatively small, due to the small number of contributing factors and their nature. Standardized procedures of packing should keep errors within the following range.

$t_p \leq 5$ minutes

5.5.2.5 Other Possible Delays

An additional situation could cause a delay that can be classed as administrative. There may be some consideration of cost, or other criterion, that dictates a policy of accumulating failed items until either (1) a fixed number of failed units is reached or (2) some fixed time has elapsed, rather than ship immediately after each failure.

In the first case, the amount of delay would depend on the failure rate, with the higher the rate of failure, the lower the accumulation delay. In the latter case, the fixed time would be the delay. It is believed that this situation is not likely to occur.

5.5.3 PACKING DELAYS

The transportation predictions are "on the road" factors and therefore exclude preparations for shipment. The time factor required in packing and unpacking of equipments between echelons should be added to the other delays. These delays would depend on

(1) Economical lot size policy.

(2) Size and nature of equipment.

5.6 PEACETIME-WARTIME COMPARISONS

5.6.1 LOGISTICS

An army's whole purpose for being is to successfully perform assigned missions during wartime, and hence the ability to obtain a desired operational readiness level during war is of main concern. It is expected that the wartime requirement will be significantly higher than the peacetime requirement.

Wartime and peacetime environment transitions will be made through changes in demand parameters. Each of the factors that undergo a transition in wartime can be estimated to reasonable approximations based either on anticipated circumstances or historical combat records. Furthermore, worst case-best case variations associated with these approximations may be made. Using the approximation as the mean value of the parameter involved, the resultant effect in operational readiness may be estimated for the worst case analysis and the remaining parameters over which control may be exercised (inventory level, replenishment rate to compensate for condemnation rate) may be manipulated to compensate for fluctuations introduced into the system.

5.6.1.1 (R) - Operational Readiness

The operational readiness requirement of equipment in tactical deployment will almost uniformly be higher than the peacetime requirement to assure a higher probability of successful mission accomplishment. However, preparedness for war may have as its consequence peacetime operational readiness far above specified requirements.

If the probability of mission success is considered as a product of operational readiness and the probability of survival $P_x(t) = R(x)\,P(t)$, where R(x) is operational readiness at time (x) and P(t) is the probability of survival given that the equipment is operational at time x, $P_x(t)$ then designates the probability that a randomly initiated mission will be successful (the time t being the minimum required operational time without failure).

It is recognized that P(t) is fixed by mission duration and equipment design.

The only recourse to improve $P_x(t)$ is to improve R(x) through logistic support, including the obvious measure of increasing working hours in maintenance shops as required.

In some cases R(x) will be the significant factor (essentially the only one): i.e., where there is a continuous link with the logistic system; however, even here $P_x(t)$ will involve a better estimate of strategic requirements.

The actual usage of the expression $P_x(t)$ must be considered as specifically related to the mission under consideration and the different potential tactical approaches. The actual establishment of a number for R(x) will depend on the mission requirements and equipment limitations. The equipment parameters and/or limitations will be available to the Operational Commander, and the choice of $P_x(t)$ and, hence R(x) will necessarily be his.

5.6.1.2 (λ) - Failure Rate

The failure rate of an equipment is predicted on inherent quality of design; thus, for all practical purposes this quantity may be considered fixed in any transition from peacetime to wartime, provided severity of operating environment does not change.

5.6.1.3 (Γ) - Arrival Rate

The arrival rate of equipment at maintenance echelons will increase due to (1) increased operational time of the equipment, and (2) increased proportion of maintenance tasks performed at the higher echelons; however, depending on equipment type and deployment, the arrival rate will decrease due to increased condemnation rates of equipment at lower echelons and lossage due to combat.

5.6.1.4 (μ_i)- Repair Rate

Average repair rates of equipments at lower echelons will increase due to mobility requirements of maintenance echelons with subsequent shifting of longer time-consuming maintenance tasks to higher echelons. The total maintenance time per failure for all echelons will increase due to the shifting of a greater portion of the maintenance tasks to higher echelons and also as a result of potentially increasing the number of echelons in the support system.

5.6.1.5 (T_{ti}) - Transportation Time

Transportation time between maintenance echelons will increase and decrease depending on deployment. The major difficulty with transportation time will be the non-stable nature of the time element, since it would depend on strategic requirements.

This time element in a wartime environment must be estimated on the basis of the anticipated mission requirements and available modes of transport.

5.6.1.6 (T_{Ai}) - Administration Time

Administrative time will be decreased per item transferred; this result will come about due to reduced control on inventory documentation.

5.6.1.7 (T_{ij}) - Mean Waiting Time

The mean waiting time for parts at a given echelon will, if decreased by increasing inventory levels, etc., improve Operational Readiness, but it is anticipated that wider fluctuation will be encountered due to lesser accuracy that may be associated with demand rates, transportation times, etc., for a specific level of operational readiness.

5.6.1.8 (M) - Number of Echelons

The number of active maintenance echelons will increase generally through anticipated overseas operations. This number in itself may become a variable quantity with deployment of equipments.

5.6.1.9 (K) - Condemnation Rate

The condemnation rate of equipment will suffer a significant increase in a transition to wartime. Specifically, this increase will be due to:

(1) Mobility requirements placed on active maintenance echelons, thereby forcing a certain amount of discarding of inoperable equipment.

(2) The type and extent of damage suffered by equipments will frequently necessitate condemnation rather than repair, especially when dealing with physical damage rather than electrical failure.

(3) Loss of equipment due to greater exigencies existing which dictate jettisioning rather than repairing equipment.

In establishing a general condemnation rate for wartime, each of the potential avenues of contribution to this rate must be evaluated and estimated. Again these factors would depend on equipment and logistic support tactical employment.

5.6.1.10 (L) - Maintenance Float

Maintenance float requirements would necessarily increase to off-set the effectively increased usage rate developed from the foregoing factors.

Table 5-1 represents a summary of the above listed parameter changes in tabular form.

5.6.2 COST ANALYSIS

The establishment of an efficient economical support system, a goal of the present study, requires that cost be a major criterion for analysis. The final allocation technique and optimization procedure will, among other things, require certain cost factors as related to physical ramifications of the problem and the consequent implications on the transport structure.

5.6.3 TRANSPORT MODES

The costs involved with military vehicles that will be considered and included here is the acquisition cost and operating cost. (Note: It should be remembered that acquisition costs represent merely the first cost to the Government at the manufacturer's plant. Additional factors are involved, such as shipping costs, storage, maintenance, and overhead.)

The variable cost factors of concern are those due to the operating cost of the vehicles. Table 5-2 gives the cost characteristics for the four modes considered as part of the maintenance function.

5.7 FIELD APPLICATION

5.7.1 PHYSICAL CONSTRAINTS OF INVENTORY

The application of micro-modularized signal equipment is to be viewed in a projected 1965-70 time frame. The question then arises, "What differences can be expected with respect to use of equipment in the field now, as compared to the projected time frame?"

TABLE 5-1

PEACETIME TO WARTIME LOGISTIC PARAMETER CHANGES

Peacetime	Wartime	Predictability	Compensation for Change
1. Operational Readiness R	Increases	Decreases	Dictated by Tactical Requirements
2. Arrival Rates Γ_i	Increase	Decreases	Dictated by Tactical Requirements
3. Repair Rates μ_i	Increase	Decreases	Dictated by Tactical Requirements
4. Administrative Delays T_{Ai}	Decrease	Decreases	Dictated by Tactical Requirements
5. Transportation Delays T_{ti}	Increase	Decreases	Dictated by Tactical Requirements
6. Maintenance Echelons M	Increase	Decreases	Dictated by Tactical Requirements
7. Part Outage Delays t_{ig}	Decrease	Decreases	Higher Supply Levels to Compensate for Fluctuations
8. Failure Rate λ	Constant	Decreases	Built into Equipment
9. Condemnation Rate K	Increases	Decreases	Increased Rate of Replenishment
10. Maintenance Float L	Increase	Decreases	None

TABLE 5-2

COST CHARACTERISTICS OF WHEEL VEHICLE MODES

	Oper.* Cost	Acquisition* Cost	Capacity (Tons Approx.)
Truck, 1/4-Ton	$0.15/mi.	$2,004	1/2
Truck, 3/4-Ton	0.17/mi.	3,993	1-1/2-2
Truck, 2-1/2-Ton	0.18/mi.	6.250	4
Shop Equipment Mtzd.			
Shop Van, 2-1/2-Ton	0.20/mi.	8,818	

The answer seems to be that the anticipated availability and use of nuclear weapons in future warfare will require increased mobility and dispersion over that required by conventional weaponry in the past.

The requirement of mobility has a very definite impact on the logistical problem. In general, it may be said that operational elements of a command (i.e., first and second echelons), should be capable of relocating from any point of operation to some other designated point, in a specified minimum time. A similar statement applies for the higher levels. Specific requirements of time would depend on the kind of unit, types of equipments used, etc.

The mobility requirement is a tactical consideration which affects many of the logistical considerations. A primary consideration is the restrictions placed upon the various elements of the total military machine with respect to mission accomplishment, after the allocation of tools, test equipment and spare parts to these elements. In particular, the use and location of on-line equipments is not arbitrary. By definition, it is at the first echelon. However, characteristics of the equipment; i.e., size, weight, portability, etc., will certainly dictate its tactical use. Additional implications of these physical characteristics is to inform operational commanders of:

(1) Number of men required to man the equipment.

(2) Type and number of vehicles required for mission accomplishment.

(3) Type and number of vehicles required for maintenance support.

*Cost estimates provided by ORDB6-TR, U. S. Army Ordnance, Aberdeen Proving Ground, Md.

In very much the same way the problem of allocating maintenance tools and equipment at the various echelons will have restrictions placed by physical constraints as a major criterion.

It is possible to consider units of different sizes as being a part of a larger unit; e.g., one infantry division has five sub-units (battle groups) plus a number of other units. As a rule, most of the units below a certain size will not be capable of operating alone. These units will not have support elements organic to their structure and thus could be autonomous only for very short periods of time. Common exceptions to this would be the small units employing guerrilla tactics, and scouting teams which are usually very far removed from the parent organization.

The operational readiness of an independently operating unit will be influenced by the allowable spares level at each echelon of maintenance. By virtue of weight and volume restrictions of necessary equipment spare packages, decisions have to be made as to the limits to be placed on spares inventories at each echelon.

These decisions are based on the following considerations:

(1) Basic load of spares. How many spares in terms of weight and volume can the front line elements carry without sacrificing required mobility?

(2) Spares Inventory. Each of the higher levels can only carry so many spares consistent with their size and weight and the units mobility requirements.

(3) Reliability. A knowledge of the equipment's reliability indicates how many spares must be carried along with the equipment so that the unit will function for some specified period.

(4) Maintainability. The ability to efficiently maintain the equipment could be a factor in cases where there is a relatively high Mean Repair Time (MTTR) and a small MTBF which would require the same additional number of equipments to last a given period of time.

(5) Personnel. Unavailability of personnel could preclude the utilization of the maximum allowable maintenance time, which would affect (4) above.

At the time of design the physical characteristics of the equipment and all required spare parts kits are determined and included in the pertinent technical publications which will accompany the equipment. On the basis of these physical characteristics and the physical constraints placed on the inventory structure by the above considerations, boundary conditions are established for the inventory policy.

5.7.2 EQUIPMENT DENSITY/USE

A number of the demand parameters of the model will vary depending on how the equipment is employed in the field. By employed in this context is not meant the actual operation of the equipment, but rather such questions as:

(1) How long do they operate?

(2) How many are in use?

(3) How close together are they, etc.?

This employment is dictated by the tactical deployment of the field troops. It is, therefore, with respect to the organization's tactical mission that the following operational uses of the equipment are considered as required information. In all the factors below, the primary source of "error" will lie in the inability to anticipate with precision, the conditions under which the equipment will be used, or the changes in organization structure which may be dictated by combat conditions.

5.7.2.1 Density

The density of the equipments tell how far apart they are in forming a portion of the physical structure. It is relevant to the assigning of feasible reporting ratios and as such is also useful in determining transport structures. This could be in terms of equipments/mile or square mile, etc. Data are obtainable from the TOE and tactical manuals and guides.

5.7.2.2 Distribution

Closely related to the density of the equipment is its distribution. This would specify the allocation of the equipments throughout the organization and could also influence reporting ratios, maintenance policy, and the general physical support structure. Example: one helmet radio per man, three PRC-25 per company, etc. Data are obtainable from TOE.

5.7.2.3 Deployment

In determining mean transport times for delay rates and reporting ratios, consideration must be given to the dispersal pattern of the equipment; i.e., are they generally located linearly along the battleline or dispersed throughout the total structure in depth behind the line? Is there a uniform distribution (even spacing) or are the units grouped with several local concentrations, (see Section 5.7.2.1 for data sources).

5.7.2.4 Operating Time

For use with failure rates, arrival rates, inventory levels, etc., the amount of time the equipment will be operating is required. Example: A continuously operating computer might need considerably more support than a piece of radio equipment operated only six hours per day. Normally expressed as fraction of total time, data must be obtained by interview of using commanders at various levels.

5.7.2.5 Operator Utilization

If the operators are not required to devote all their duty time to operation of the equipment, then these operators could perhaps be assigned some of the maintenance tasks that would otherwise fall to maintenance personnel. Data may be obtained from instruction manuals, TOE s and study of individual installations.

5.7.2.6 Nature of Mission

The mission determines all other decisions. It should be known if the mission is continuous or one requiring completion in a specified period of time. Field commanders provide the basic input to this parameter.

5.7.3 SUMMARY

The operational and tactical use of equipment in the field has a direct impact upon logistical support requirements. These requirements result from the physical constraints of the equipment and the variety of possible forms of the military environment in which the equipment is found. Given a complete a picture as possible of the expected military environment, the logistical contributions to the operational readiness problem can be evaluated.

It is not anticipated that this environment will be very different from present-day environments (i.e., present-day if there were war), except to the extent that the future use of nuclear weapons will introduce the requirement of increased mobility and dispersion.

As an example, a division front today is from ten to twenty miles, with a depth of fifteen to thirty miles. By 1965-70 these distances will probably be even greater.

To cope with this dispersion, several new concepts are being developed; namely,

(1) The MOMAR concept (Modern Mobile Army)

(2) ROAD (Reorganization of Army Division)

Although Active Army divisions are expected to begin implementation of this reorganization in 1962, the particulars of the concept are classified information. Therefore, present-day configurations may be used as a base as long as the implications of the nuclear age as noted above are incorporated.

SECTION VI

DEMAND RATES

6.1 GENERAL

Failure, easualty, condcmnation, usage and arrival rates are sometimes synonymously used, and frequently confused. Futhermore, not all users of these expressions mean the same thing. For these reasons, it is appropriate that a discussion of these terms be presented.

(1) Failure Rate: Number of failures (non-scheduled interruptions of operation) of the item per unit operational time.

(2) Condemnation Rate: Fraction of failures which are not repaired because of technical impracticality and/or economic advantage of replacement.

(3) Casualty Rate: Rate of loss of item per mission-hour per item.

(4) Usage Rage: Rate at which items must be replenished per unit time (rate at which items are replaced less the rate at which they are actually repaired) from source manufacture.

(5) Arrival Rate: The rate at which units requiring performance of particular maintenance tasks or groups of tasks arrive at a given maintenance shop, group of shops or echelon as specified.

6.2 FAILURE RATE (PRIMARY)

The primary failure rate is based on the inherent physics of the item considered, such as part failure rate and network failure rate, which is some combination of part failure rate and mutual failure effects manifested which may increase or decrease the net total part failure rate. It is the rate at which items fail when operated according to correct procedures under conditions in which it was designed to operate. As a result of equipment complexity, and all-around performance capabilities progress, the concept of "criticality of failure" has been necessitated.

For the purpose of logistic and maintenance analysis, our concern is restricted to failures having either maintenance or logistic significance. To achieve this, it is only necessary to consider three degrees of criticality in primary failures.

(1) Critical: If the equipment is inoperative in terms of primary mission.

(2) Major: Equipment performs primary mission with degradation in performance or which would cause failure of primary mission if it occurred in conjunction with a certain other major failure(s).

(3) Minor: Operation of equipment is handicapped but with no degradation of primary mission.

These degrees of criticality are equally applicable to equipment systems encompassing redundancy or simple non-redundant systems.

6.3 CONDEMNATION RATE

The condemnation rate of an item is based essentially on the economics of repair of an item in the state of failure. If in the failure, an item is invariably too costly to repair, the item possesses a condemnation rate of one; whereas, if a fraction, K, of the time the item is economically feasible to repair, then the item is said to possess a condemnation rate of K per failure. The major determinants in establishing the condemnation rate are:

(1) Failure of some single expensive part (high cost relative to total cost of item)

(2) Wearout of item

(3) Inaccessibility of the failure cause

(4) Physical damage of item.

Items (1), (2), and (3) are either measurable or predictable and are to be evaluated as a matter of course when the design undergoes maintenance analysis.

The contribution to condemnation rate -

(1) is determined by addition of failure rates of parts having this classification,

(2) is of concern for mechanical parts generally, otherwise added to the failure rate in (1),

(3) is the failure of inaccessible parts added to the failure rate obtained in (1) for those parts not already common to (1),

(4) must be determined by estimation of (a) the frequency of maintenance induced faults and (b) damage due to travel. Item (a) may be obtained in analysis of the simulated repair performed during maintenance analysis. Item (b) can be estimated by study of impact considerations of the packing design in conjunction with historical transportation records. Both (a) and (b) will capitalize on feedback information during support system performance.

6.4 CASUALTY RATE

Perhaps the most significant and least predictable factor from the standpoint of accuracy, is the equipment quantity that is lost due to battle casualty. It is appropriate that this effect be put in some compatible form for the purpose of calculating and planning compensatory devices for stability of the support system. The most meaningful way of approaching the equipment casualty status is in terms of casualties per operational mission per time unit. It is understood that the equipment does not have to fail in the conventional electronic sense to suffer a casualty.

Casualty rate then would consist of the following components:

(1) Equipment jettisoned during combat as a result of electronic failure.

(2) Equipment jettisoned during combat as a result of physical damage rendering the equipment inoperative.

(3) Equipment jettisoned during combat for the reasons of expediency.

(4) Equipment and subdivisions thereof damaged in combat and sent to maintenance.

Component (1) above is most susceptible to calculation, since equipment failure rate is readily calculable. However, an estimate of the probability that an equipment suffering failure will be returned for maintenance action is still required.

Components (1), (2), (3), and (4) will all be very closely related (a) to tactical deployment, and (b) equipment characteristics such as mobility, weight, prevailing conditions.

6.5 USAGE RATE

The term "usage rate" has several "obvious" meanings. In this report, it will be used to refer to: the steady state average quantity per unit time of particular items required from the manufacturer (or other non-military sources) for the maintenance of an equipment in satisfactory operating condition.

The usage rate for a particular item due to a particular cause is calculated by multiplying the rate of incidence of the cause (e.g., failure rate, casualty rate), times rate of exposure; (e.g., operating rate mission time), times condemnation rate for this cause. The total usage rate is the sum of the rates for all causes.

6.6 ARRIVAL RATE

This rate has significance with respect to a maintenance task arriving at a given echelon of maintenance. The actual establishment of an arrival rate is dependent on the allocation of maintenance tasks throughout the maintenance echelons.

This allocation is discussed in detail in Sections 4.7 and VII of Volume I.

The basic procedure for establishing an arrival rate for a given maintenance echelon consists of adding the rate of occurrence per unit time of all maintenance tasks allocated to that echelon. This sum is then multiplied by the operating rate of the total number of end item equipments in the field.

SECTION VII

TRAINING APPROACH

7.1 GENERAL

The maintenance and repair concept of micro-module equipment differs significantly from most other types of electronic equipment. The ability to replace the equivalent of many circuit elements by replacing a single module means that the maintenance personnel need not know the detailed theory of operation for any piece of equipment to repair it. Instead, the concept of trouble-shooting by a detailed block diagram and specific response to failure symptom-maintenance task procedure is submitted.

Another consideration is that the equipment itself (because of its small size) may be economically sent back to the last echelon for repair.

Thus, the concept of training now is based on how much skill each maintenance level requires in order to perform its assigned task.

The training for repair of more conventional types of electronic equipment is such that maintenance personnel must find and repair (or replace) the defective component at the lowest level of assembly before the unit is again operational. If the first or second maintenance echelon cannot find the defect, the unit is sent out of the area to be repaired. The result of this procedure is the unavailability of a piece of equipment, perhaps for several days. The training of personnel involved is about the same for each level.

Micro-module equipment being of a lightweight, modular type can be repaired in the field by replacement of subassemblies (e.g. boards or drawers) containing many circuit elements. This procedure sometimes allows practical application of the "brute force method". Where a full complement of spares is available, the repairman's requirement at this level of maintenance is only that he suspect which portion of the equipment is defective and replace that subassembly with a spare. However, it often is more economical to follow a routine system of tests, utilizing built-in indicators and meters or simple external test equipment. In either instance, the item at the lowest level of assembly to which the failure is isolated may be then sent to a higher echelon for repair.

At this higher echelon, the repairman does not need to know the detailed circuitry of the assembly board. By following instructions from the manual, by the use of "tracers", audio-visual devices, or by previous experience, etc., he trouble-shoots the assembly board. An assembly tester will often be available to determine if the assembly board is functioning properly.

Essentially, by use of this procedure the equipment is available for field use most of

the time. The training of the personnel at each maintenance echelon can be different, since their tasks are different. A major point is, that no matter what the complexity of a piece of micro-module equipment, the amount of training involved in maintenance and repair of such equipment is kept to a minimum.

7.1.1 KNOWLEDGE

The knowledge essential to trouble-shooting is how to trace signal flow between test points of replaceable subassemblies either as embodied in the routine prescribed in the manual or in the operator's training. What goes on within the replaceable subassembly is irrelevant to the trouble-shooter.

Quite different classes of knowledge are required to trace and test:

(1) Circuit flow from circuit diagrams

(2) Logical block relationships

(3) Functional block relationships

In micro-module equipment the number of subassemblies is small compared to conventional electronic equipment because there are many circuits contained in each subassembly.

The number of test points on a micro-module subassembly are also at a minimum because only input and output signals of either single or multiple stages are of interest. Therefore, functional block relationships are easier for the novice to learn than logical block relationships and logical block relationships are easier than circuit flow from circuit diagrams.

7.2 FAILURE SYMPTOMS-MAINTENANCE TASK

7.2.1 DEFINITIONS

The prime consideration of any military equipment is that it keep operating reliably in an average tactical situation.

In such a tactical situation the responsibility of keeping the equipment operating lies with the field maintenance man or with the operator.

Based on a preliminary analysis of the use of the "Failure Symptoms-Maintenance Task" technique.of service, it is estimated that 85% of all equipment problems can be solved at this echelon within 15 minutes by proper use of this technique.

The failure symptom is a physical description of the manner in which an equipment can fail. This description can be of a general or common form such as "no output", "no sound", "noisy", etc., providing that it is a symptom of the failure and indicates fault location within the failed equipment.

Maintenance task is defined as any one or more manipulative actions required to preclude the occurrence of a failure (preventive maintenance) or to restore an equipment to satisfactory operating condition (corrective maintenance).

There are three general distinct actions involved in the maintenance task:

(1) Locate the faulty sub-unit

(2) Remove and replace the faulty sub-unit

(3) Check out the repaired unit

The Failure Symptom-Maintenance Task technique in essence, therefore, is that for a certain type of failure exhibiting previously defined symptoms, a prescribed set of maintenance tasks is used.

7.2.2. EXAMPLE

Assume a certain type transceiver in the field is inoperative (i.e., transmitting, but not receiving) and that sparing in the field is at the sub-assembly level; then, the following routine might become established:

FAILURE SYMPTOM	MAINTENANCE SUB TASKS
Receiver apparently inoperative	Check Controls & Indicators
	If not o.k.:
	Check Power Source If still defective
	Are all connectors secure? If still defective
	Is the antenna connected? If still defective
85% of all trouble will fall in here	Replace receiver subassembly If still defective

Replace transmitter subassembly
If still defective

Replace remaining subassembly
If still defective

Send unit to higher skilled maintenance man

It is assumed that the difficulty found will be a subassembly (assume receiver subassembly). This defective subassembly will frequently be sent to specialists for repair.

FAILURE SYMPTOM	MAINTENANCE SUB-TASK
	1) Set up tests according to the prescribed routine to isolate the defective element
	2) Follow instructions in the manual (or audio-visual device) taking the appropriate voltage, resistance, and scope readings to determine defective stage.
	3) Check printed circuitry around stage.
	4) Replace micro-module
	5) Test subassembly

It is stressed again that the above is just an example and that allocation of specific failure symptoms-maintenance tasks to each echelon has yet to be assigned.

7.3 ADVANTAGES AND LIMITATIONS

7.3.1 ADVANTAGES

The advantages of the Failure Symptom-Maintenance Task technique of training as compared to the conventional type training as compared to the conventional type training are:

(1) A training course of reduced duration wherein the student is trained to use the equipment neeessary to perform tasks appropriate to his level of skill and to utilize maintenance manual effectively.

(2) The entrance requirements for this type of training would be less because the theoretical portion of the course plays only a minor role.

(3) Since the time duration is shortened, it follows that the training cost per qualified technician is less.

(4) Technicians can be readily replaced and at a minimum cost.

(5) Assurance that a man ean perform tasks within a stated time period with a specified confidence level.

7.3.2 LIMITATIONS

The limitations of the Failure Symptom-Maintenance Task technique of training is that the technician is limited in his basic knowledge of electronics and will not be trained to perform maintenance without the aid of detailed maintenance instruction manuals.

This disadvantage may be overcome by the field training program as suggested in Section 7.4, Volume II of this report. This field training program enables a technician to upgrade his abilities and responsibilities and at the same time increase his value.

7.3.2.1 Training Manuals

The training Manuals on micro-module equipment will be written with the philosophy of the Failure Symptoms-Maintenance Task technique.

Manuals will be organized by symptoms and task according to test equipment required, and thus, for each echelon, maintenance tasks which they are to perform will be grouped together.

7.3.2.2 Skill Level

A technician obtains a skill level by either completing a course on micro-module equipment, on the job training, or by other educational media. The technician's skill level may be viewed as a direct function of the number and type of courses and/or training he has completed.

The required skill levels will differ since some maintenance tasks require minimal skill while others will require varying skills.

The allocation of maintenance tasks to the different repair echelons has not been assigned; therefore, the skill levels needed at each echelon also remain undefined. However, at each echelon, the highest skill level will be at least as high as the highest at any lower level.

Once the maintenance tasks are defined and the necessary test equipment available, the skill level needed to repair can be defined. Thus the training for each echelon is

immediately retreivable when the maintenance tasks are assigned to the various echelons.

7.4 TRAINING OUTLINE

The objective of a military technician training program is to turn out technicians of adequate skills to perform specific tasks.

The type of training required is, of course, a function of the task for which the students are being trained (in this case, the maintenance task). The maintenance task itself is dependent to some extent upon the design philosophy. If maintainability considerations are employed in the design of the equipment, it is possible to simplify the maintenance task and thus simplify the training necessary.

To keep training costs at a minimum, it is necessary to train the students only for the tasks they are required to perform. It is, therefore, necessary to define clearly the maintenance tasks for which the students will be responsible.

Training will be completed in a specified maintenance task when the student has demonstrated his capability to recognize and perform maintenance tasks of a specified nature within a stated time duration with an assigned level of confidence.

7.5 TRAINING COST

It is anticipated that the formal training cost per man per week for micro-module equipment will be the same as it is on other types of electronic equipment.

The overall cost of training a qualified technician will be less because the time spent in formal training will be decreased. The decrease in training time is due to the Failure Symptom-Maintenance Task technique of training. The cost of field training (see paragraph 7.5) a technician on additional micro-module equipment is anticipated to be one-third of the cost of formal training or less, based on the following considerations:

(1) The technician will perform his normal duties while being trained at his home organization.

(2) There are no travel expenses involved.

(3) No instructors are required.

(4) Where no new test equipment is required and where the manuals are thorough, the technician need only go through the learning phase of gaining familiarity with the equipment.

However, the following additional costs must be taken into consideration:

(1) Preparing and distributing training material.

(2) Purchasing of audio-visual devices.

7.6 FIELD TRAINING

7.6.1 PROBLEM DEFINED

Once military personnel are trained on specific families of equipment, the question arises as to how further to train a man in the field.

It is possible, due to the high cost of training, that once a man adequately fulfills a given maintenance task, further opportunities for advanced training would not be made available to him, especially in view of rapid personnel turnover.

However, due to the mutability and complexity of modern electronic equipment, the field technician must keep abreast of the latest developments in his equipment in order to satisfactorily discharge his duties.

7.6.2 PROGRAMMED INSTRUCTION

A method of training the technician while he performs his duty, is with the use of programmed instructions. (It should be noted that programmed instruction can also be used in formal training.)

The general advantages of programmed instruction are:

(1) High comprehension for slow, average, and fast learners- each student can proceed at his own pace.

(2) Applicability almost anytime, anywhere; such as periods between assignments and during off-duty hours.

(3) Interest- it is similar to playing a fascinating, interesting, and challenging game.

(4) No necessity for classrooms with their inherent complex and expensive scheduling and administration and no traveling expenses.

(5) Standardized instruction- a program designed and written by trained educational and programming specialists will give the same accurate, motivating, and "designed for high transfer" information to many individuals at different times or locations.

(6) Congruence with programmed structure of the "isolate" routine embodied in the maintenance task.

Programmed instruction, like any other form of instruction, has its advantages and disadvantages. However, like conventional instruction, many of the disadvantages can be virtually eliminated and many of the advantages can be enhanced if the curriculum is analyzed and planned by educational specialists.

It should be noted again that the biggest advantage of programmed instruction is that it allows the military to train its men in the field, and at the same time it allows the technician to upgrade himself.

7.6.3 AUDIO-VISUAL DEVICES

A suggested audio-visual device for field training is an equipment that presents to an individual or a group an instructive program on 35mm slides synchronized with an audio presentation on magnetic tape.

This device can be used by technicians in learning how to perform certain duties, such as preventative maintenance, the operation of a new piece of equipment, or the failure mode maintenance task of a new equipment (or a review of an equipment he is already familiar with).

The device can be used for a variety of other applications in the field organization.

The general advantages of such a device are:

(1) Unit is self-contained; no special ability needed to operate.

(2) Complexity-technicians have to make frequent reference to charts, instructions, schematics, and other data. Because this device provides simultaneous visual and oral instructions, the interpretation and use of the presented data are greatly simplified.

(3) Personnel can easily be trained in more specialized skills.

(4) The knowledge of existing technicians can be quickly expanded and these techniques can be put to use more quickly.

It is significant to mention that audio-visual training can reduce learning time by half. It is possible for the learner to set his own pace and to repeat difficult subject matter as often as he needs to: the learner can choose his own time and place for learning. Time off from regular duties is reduced to a minimum.

SECTION VIII
DETERMINATION OF SYSTEM DATA AND CONSTRAINTS

8.1 GENERAL

8.1.1 SOURCES

Strategic and tactical factors are primary in the determination of the goals and constraints of the maintenance support system. However, such factors as detail budgets, conventional accounting practices, etc., are also of concern in the area of costs. Thus, both military and financial considerations provide inputs at a policy making or interpreting level.

8.1.2 COSTS

Cost constraints due to budget restrictions are fairly well defined in terms of the accounting procedure implied by the budget itself. Here, the details of the accounting rules are necessary for application to the optimization data.

For example, a constraint on "per period" personnel costs requires wage and salary schedules associated with various skills or grades; allowances, allotments, etc., which are to be included; Government-furnished housing, food, etc. which is applicable, including rates; etc.

Standard accounting procedures will usually provide relatively unambiguous rules for charging costs to various tasks, etc. However, these rules may be poor reflections of reality and be inappropriate for decision making in certain situations. Shared facilities and personnel offer the greatest problems in this area. Where facilities are shared, most accounting procedures call for allocating charges according to usage or according to some characteristics of the user. In reality, if a facility is required primarily for purpose A, and no additional costs are incurred because of its incidental use by B because of unavoidable "excess capacity", then no costs are chargeable to B. This and similar problems require careful study of the actual effects on the cost structure of decisions under consideration. Frequently, a less exact, but more practical approach can be developed. For example, cost relationships may be established such that their relative values are a measure of the relative importances of the factors involved. In general, costs of services or facilities not shared with other systems should be determined on a "per facility" or "per man" basis, whereas shared costs should be on a "per use" basis when practical.

8.2 SPECIFIC NOTES

8.2.1 DOWNTIME AND OTHER CONSTRAINTS

In some tactical situations frequent brief periods of downtime do little to inhibit system effectiveness whereas occasional prolonged periods can seriously hamper effectiveness. In such situations, a constraint on the amount of continuous downtime in excess of some limit, is appropriate. Similarly, in a system where there is partial redundancy such as line radar stations with a high degree of overlaps, the appropriate constraint may be in terms of the fraction of the time that two adjoining stations are down, etc.

8.2.2 EFFECTS OF COSTS ON RESULTING MAINTENANCE SYSTEM

When other constraints are easily met, relative order, transport, and holding costs determine the ordering policies and content of shop equipment and inventories. However, the measurement of these costs is indirect and the costs themselves somewhat indefinite. Fixed costs*, joint costs**, etc., present problems. In many instances, total costs are much more easily determined than the contribution of various elements to the total cost. The consequences of different allocations of these cost contributions follow certain general patterns.

Any item which is used must be transported to the first echelon either separately or as a part of a higher level of assembly repaired at a higher echelon. Thus, the relevant transport costs are those in excess of the minimum cost of delivering life-supply of spares to the first echelon. In general, the most significant of these differences is likely to arise from transport costs being on a "per trip" rather than a "per pound" basis (i.e., the trip is solely for the purpose of transporting the item), or because different modes of transport are used depending on the urgency of the need for and the size of the shipment. High cost of transport on a "per pound" basis favors repair at low levels of assembly at low echelons. High cost of transport on a "per trip" basis favors inventory policies involving ordering more than one of an item and more than one item type at a time.

Order costs have three elements:

(1) Per order

(2) Per line item

(3) Per unit item

*Costs which depend on the existence of a facility and not on the extent of its use; or the placement of an order and not on its size, etc.

**Fixed costs for facilities etc., shared by two or more elements.

Per unit item costs, are relevant only if they are different in different situations. Such differences where they exist, tend to favor larger base stock (higher reorder point) in preference to rush orders.

Per order and per line item costs, where they are significant, lead to order quantities greater than one. Where they are negligible, the order quantity will be one unless transport costs are on a "per trip" basis.

SECTION IX
GLOSSARY OF TERMS

Arrival Rate	- The rate at which units requiring performance of particular maintenance tasks or groups of tasks arrive at a given maintenance shop, group of shops or echelon as specified.
Casualty Rate	- Rate of loss of item per mission-hour per item
Condemnation Rate	- Fraction of failures which are not repaired because of technical impracticality and/or economic advantage of replacement
Echelon	- One or more maintenance shops responsible for performing certain specified maintenance tasks.
Failure Rate	- Number of failures (non-scheduled interruptions of operation) of the item per unit operational time.
Maintenance Float	- A stock of equipment used to replace those which are sent to maintenance for repair.
Maintenance Task	- 1. A series of actions on an item at a particular level of assembly usually prescribed, and performed by an individual or a fixed team having particular skills and equipment.
Maintenance Task, Common	- 2. Any set of necessary sequential maintenance actions associated with a single failure.
Maintenance Task, Basic	- 3. The necessary sequence of all identifiable maintenance actions required for reparation of a failed end item equipment down to the lowest level of assembly which is not condemned.

Mean Time Between Failures (MTBF)	- Average time per item between occurrence of failures. May be estimated by dividing operating time by the number of failures occuring during this time. It is the reciprocal of the mean failure rate.
Mean Transport Time (MTT)	- The average time required to transfer a piece(s) of equipment between two specific echelons of maintenance via the available military vehicle modes.
Operational Readiness	- The average percent of on line units which are operational at a given time when they are intended to be.
Parameter	- Any measurable characteristic of some population or universe of values.
Probability of Survival	- The probability that an equipment or system, initially operating satisfactorily, will continue to operate satisfactorily for a specified period of time, or, until a specified mission is accomplished.
Random Castastrophic Failures	- Failures which occur after all efforts have been made to eliminate design defects and unsound parts, and before any unforseen wearout phenomena have time to appear. Failures whose cause can not be determined by available means.
Redundancy	- Duplication of function such that there are two or more alternative means of performing a function:
Reliability	- The probability of adequate performance of a specified function or functions, for a specified time under specified conditions.
Repair Channel	- A maintenance man or maintenance team which follows a specified sequence of subtasks in repairing an item.

Repair Rate	- The reciprocal of the average time spent per channel in repairing an item excluding delays such as "wait for ehannel", "wait for spare part to be delivered", etc.
Reporting Ratio	- The number of equipments (shops) supported by each maintenance shop at the 2nd echelon and higher.
Spares	- Any part, module, board, subassembly, ete., kept anywhere in the supply system for the purpose of replacing a similar item because of its loss, damage, or failure.
Usage Rate	- Rate at which items must be replenished per unit time (rate at which items are replaecd less the rate at whieh they are actually repaired) from souree manufaeture.
Variable	- A quantity that may assume a succession of values that need not be distinct, but which can only assume those values that the form of the function makes possible.

SECTION X

GLOSSARY OF SYMBOLS

A - Assembly designator

A^* - Total field area

B - Board designator

b - Number of parts per equipment

d_o - Estimated value of distance

d_i - Average distance between echelons i and i + 1

$D(n)$ - The one way distance between a maintenance shop and the farthest removed equipment

$\bar{D}(n)$ - The average distance that n units are from the supporting maintenance shop

$D(k)$ - The total distance of all n units from the supporting maintenance shop when the units are displaced throughout the total area

$\bar{D}(k)$ - The average distance that n units are from the supporting maintenance shop when the units are displaced throughout the total area

h - Number of terminations

K - Condemnation rate

k - The number of r_1 units away from the maintenance shop

l - Number of parts per equipment

L - Total number of spare units (Maintenance Float)

L_i - Maintenance float assigned to i^{th} echelon

m_i - Number of different failure modes of the ith part

M - The total number of echelons

M_i - The number of shops at the ith echelon

M^{th} - The last maintenance echelon

$\overline{M}$ - Micro-Module designator

n - Reporting ratio

n_o - The number of equipments supported by each 1st echelon shop

n_i - The number of shops at the ith echelon supported by each shop at the $(i + 1)^{st}$ echelon

N - Total number of operational on-line equipments

P - Preventive Maintenance Task

$P_x(t)$ -Probability of survival given that the equipment is operational at time x

$P(t)$ - Probability that a randomly initiated mission will be sucessful

q_{yi} - Men resigning from skill level i per man already in it

q_{zi} - Men transferred from skill level i per man already in it

Q_i - Number of Maintenance Personnel required of skill level i

r - Repair channels

r_l - The distance of the nearest unit from the maintenance facility for area displacement of units

R - Operational readiness level

$R(x)$ - Operational readiness at time x

s - Spacing between equipments (shops) in the field

S - Subassembly designator

T^* - Time delay in traveling a given distance

T_A - Actual temperature

T_F - Temperature (maximum) for part derating

T_h - Normalized temperature

T_s - Temperature at start of part derating

T_i - Total delay rate

Ti - Maintenance task (mode) designator

T_{Ai} - Mean time delay due to administrative task at the ith echelon

T_{ij} - Mean waiting time for a jth part type at the ith echelon

T_{ti} - Mean transport time between echelons i and i + 1

To_i - Minimum time in i^{th} skill level for promotion to $(i + 1)^{st}$ skill level

U_1 - An equipment unit

v_o - Estimated value of speed

$\bar{v}$ - Average speed of relevant transport modes

x - True value of a variable

x_o - Estimated value of a variable

x_i - Influx of maintenance personnel to the ith skill level per unit time

y_i - Resignations of personnel of the ith skill level per unit time

Y_i - Failure Symptom

z_i - Net internal transfers of duty assignments from the ith skill level per unit time

Γ - Arrival rate

Γ_i -Arrival rate at the ith echelon

Γ'_{xi} - Number of promotions per unit time per available promotable personnel

Γ_{xi} - Men entering skill level i per man already in it

θ_i - Percentage of equipment entering the ith echelon shops that are sent to the $(i + 1)^{st}$ echelon shop

K - Condemnation rate

λ - Failure rate

λ_s - Estimate of the combined failure rate of a sample of parts

μ - Mean repair rate

μ_i - Rate at which a failed unit is repaired at the ith echelon

τ - Time delay (transportation, administration, spares)

ϕ - Usage rate (proportion of time operated)

SECTION XI
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