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Technical Note 41

EXPENDABLE MODULES AS BASES FOR DISPOSAL-AT-FAILURE MAINTENANCE

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

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FEBRUARY 1960

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R. O. Stone, P. Meissner, and K. M. Schwarz

The work described in this Report was sponsored by the Department of the Navy, Bureau of Aeronautics, now integrated into the Bureau of Naval Weapons

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FOREWORD

The work covered by this Note was performed by the National Bureau of Standards on behalf of the Department of the Navy, Bureau of Aeronautics, now integrated into the Bureau of Naval Weapons. The program was under the administration of the Electricity and Electronics Division and the technical supervision of the Engineering Electronics Section. A major objective of the program was the establishment of criteria for determining the conditions under which airborne electronic assemblies may be expended at failure rather than repaired. The criteria developed under this objective are presented in this Note.

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EXPENDABLE MODULES AS BASES FOR DISPOSAL-AT-FAILURE MAINTENANCE

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The maintenance of future electronic equipment will more than likely exceed the capabilities of existing maintenance activities if present maintenance procedures are continued. Design trends such as miniaturization, printed circuitry, encapsulation, and modular construction all point toward disposal-at-failure maintenance. Disposal-at-failure modular design would help to solve some of the future maintenance problems and would also be compatible with future design trends.

It has been suspected that disposal-at-failure maintenance would be too costly to be practical. This report compares the costs to procure, support and maintain an equipment designed with expendable modules to the costs to procure, support, and maintain a similar equipment designed with repairable modules. It was found that the total costs in either case were approximately equal. Since the cost factor is not important in the decision between expendable assembly or repairable assembly maintenance, other factors, such as improved reliability of equipment, smaller size, lighter weight, and improved maintenance, all advantages that may be gained through the use of expendable design, should be carefully studied. These advantages may be so important as to completely determine a decision in favor of expendability.

Modules of various electrical sizes (from 1 to 12 tubes) have been compared from the standpoint of total over-all procurement cost, in order to determine an optimum module size. On the basis of calculations made, it has been concluded that the optimum module which would lead to lowest over-all procurement cost and at the same time be of aid in the solution of logistic and maintenance problems would be one containing from 4 to 8 tubes. This is true for both disposal-at-failure and repairable modules.

1. INTRODUCTION

The difficulties that have arisen in the maintenance of complex electronic equipment used in modern aircraft are well known and have been described in detail both in the press and in official reports.[1,2,3,4,5,6] Disposal-at-failure maintenance has frequently been suggested as a means of surmounting some of the difficulties. This type of maintenance has not been widely accepted, however, because of the lack of guidelines for determining the limits within which it may be practiced. Guidelines specifically applicable to Bureau of Aeronautics* airborne electronic equipment are presented in this Note. It is believed that these guidelines can be applied with some modification to aircraft electronic equipment in general.

Such terms as piece part, module, assembly, FASRON, and O & R are frequently used herein. These and other terms are defined in a Glossary at the end of this paper.

2. PRESENT MAINTENANCE CONDITIONS

To become familiar with BuAer maintenance procedures and costs, NBS personnel visited approximately one-half of the BuAer maintenance activities,** as well as the Aviation

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*Now integrated into the Bureau of Naval Weapons.

**See Glossary.

Supply Office in Philadelphia and the Electronics Supply Office in Great Lakes, Illinois. Also, discussions were held with many equipment manufacturers and with staff members of various universities and government laboratories to acquire first-hand information on packaging* and other electronic design trends.

It was learned that the combat effectiveness of the military weapons is reduced because of the present maintenance and supply conditions. Many weapons are ineffective owing to electronic failures that have not been corrected. Also, large amounts of equipment are required for the maintenance of the electronic portions of the weapons.

A solution to the maintenance problem may be the use of standard plug-in modules that can be disposed of at failure rather than repaired. This type of maintenance is discussed in the following sections.

3. THE EXPENDABLE MODULE

A module is defined as a modularly dimensioned assembly. The phrase "modularly dimensioned" means that the assemblies are to be physically dimensioned in specified size increments that will permit a group of modules to be combined with a minimum of waste space. The modular dimensions must be

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*See Glossary.

selected so that modules can be grouped efficiently around those portions of the equipment which, for electrical or physical reasons, are not contained in modules. When a piece of equipment has been modularly constructed, it is referred to as "modulized."[6,7]

An expendable module is one which need not be disassembled for piece part* repair when it becomes defective; it is simply disposed of following suitable accountability procedures. Hence, this type of repair action has been designated "disposal-at-failure" maintenance. Within the Bureau of Aeronautics a disposable item would be coded "Consumable" (C) as opposed to "Repairable" (R). At the present time, most of the electronic equipment is designed to be repaired through the replacement of parts down through the smallest piece parts.

Current design trends indicate increasing use of modular construction techniques for compact, intricate electronic equipment. The subdivision of equipment into assemblies has advantages from the standpoint of design and manufacture when high part densities are required. From the standpoint of maintenance, it is essential that the equipment be divided into assemblies to permit accessibility to all parts of the equipment. Although the assemblies need not conform to any particular set of modular dimensions, there are important advantages in the use of standardized modules.

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*See Glossary.

The problem of installing an equipment in different aircraft has given rise to the integrated package concept. This involves the mounting of several different pieces of equipment on a common frame, eliminating separate cases for each piece of equipment. A common power supply may also be used. This concept could permit important savings in weight and space, although it has only limited application at the present time because of the wide variety of equipment and case sizes in use. A piece of equipment composed of modules could be integrated into a new aircraft by rearrangement of the modules to fit the available space, or the modules of several different equipment types could be grouped together. The same effect could, of course, be achieved by redesigning all of the equipment to fit each new aircraft, but the procurement, logistic, and maintenance problems would become intolerable.

Because of the advantages that are possible through the use of standardized modules, it seems reasonable to assume that future equipment will make increasing use of modular construction. Hence, the term "module" is used quite frequently in these pages, although the advantages of expendability could be realized with expendable assemblies which were not necessarily modular in form.

3.1 Advantages of Expendable Modules.

(a) Improved Reliability of Electronic Equipment: The environmental conditions in which equipment must operate are becoming more severe as new weapon systems are developed. Improved reliability may be gained by use of expendable modules that are embedded in plastic or sealed hermetically. Data as to how much the reliability of a module may be improved by embedment* or hermetic sealing has not been obtained. Most of the organizations contacted in regard to this problem felt that considerable improvement in reliability may be possible; however, they had made few actual measurements. One manufacturer of electronic systems containing encapsulated* modules felt that encapsulation had increased the mean life of the modules four times. If considerable improvement in reliability can be generally gained through embedment or hermetic sealing, designing equipment with expendable modules so protected would be a tremendous step toward more reliable electronic systems.

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*See Glossary.

Use of expendable modules would eliminate many of the factors which now contribute to the lowering of equipment reliability. At present, printed circuits, resistors, transistors, etc., may be easily damaged during repair. Replacement parts may be inferior to the original parts, resulting in lower reliability. Maintenance repairs increase the wear-out of electronic assemblies, particularly subminiature assemblies.

(b) Improved Systems Maintenance: Use of expendable modules should improve the present quality of electronic systems* maintenance. Since most technicians are in the service for a comparatively short time, it is not possible or practical to train them to be fully capable of piece-part* repair and at the same time to be fully capable of maintaining the various electronic systems, such as the navigation and communication systems. Under disposal-at-failure maintenance, the training required for piece-part repair could be considerably reduced, and more time could be spent on the operation and maintenance of electronic systems. Expendability will not solve all the maintenance problems, since much effort is devoted to systems check and test, adjustment and alignment, and the replacement of parts that would not be contained in modules. The use of

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*See Glossary.

expendable modules, however, would enable the maintenance personnel to devote a much greater portion of their efforts to these tasks.

(c) Reduction in Number of Spare Parts: The number of spare parts would be drastically reduced by use of expendable modules. A typical repairable four-tube module contains approximately 40 different parts which must be supported with spare parts. Expendable modules would need to be supported with spare modules only. Reduction in the number of different spare parts that must be supplied would greatly reduce the tasks of the Aviation Supply Office (ASO) and the Electronic Supply Office (ESO). Such reduction would also benefit the maintenance activities which often experience difficulties in obtaining necessary spare parts.

(d) Reduction in the Number of Specifications: The use of standard expendable modules may reduce the number of military specifications. At present, a specification is required for each of the parts in an assembly. Use of expendable modules would require only a single specification for a complete module.

(e) Better Storage Possibilities: Expendable modules will probably be embedded or hermetically sealed. Such protected modules should withstand long storage periods with little or no added protection. They should require considerably less storage volume than that required for repairable assemblies and spare parts, many of which are stored in individual protective containers much larger than the assemblies or parts.

(f) Usefulness under Emergency Conditions: In times of emergency, disposal-at-failure maintenance should be quite successful, provided that it has been adopted and practiced before an emergency arises. Piece-part repair of an assembly probably could not be made at the front-line level, and time would not permit such repair to be made at higher maintenance levels. Consequently, defective assemblies would often be expended, even if they were intended to be repaired. As a result, the present maintenance program would surely fail, since it and the equipment would not have been designed for such practice of unintended expendability. For this reason, disposal-at-failure maintenance may be highly successful, in that it would realistically provide for wartime conditions.

3.2 Possible Disadvantages of Expendable Modules.

(a) Decline of Technical Skills in the Military: Some members of the military maintenance organization have suggested that the use of expendable modules or assemblies would lead to a decline in the skill of the technicians, since the technicians would be deprived of valuable repair experience. It is true that a knowledge of parts and circuit details would be of less importance than it now is, but the skills required to locate faults in electronic systems would still be necessary. The services of high-level technicians would be just as important, although the emphasis in training would be shifted. Much more time would be spent in learning electronic system operation and fault location, and less time would be spent on circuit theory and parts. Present maintenance activities are generally so understaffed that a reduction in the number of skilled personnel is unlikely. The main purpose of expendability is to enable the present maintenance organization to handle a greatly increasing workload in the future through more efficient use of personnel. It is highly improbable that adoption of the expendability concept would reduce the number of skilled personnel or lower the level of technical skills.

(b) Increased Supply Burden: Most expendable modules will be so designed that a piece-part repair will be difficult or impossible; therefore, spare modules would always have to be available for correcting equipment failures. These conditions would put more stringent requirements on the supply system, particularly at remote bases or on aircraft carriers. Nevertheless, since only complete modules would be supplied, rather than the numerous different component parts now needed, the supply system should be capable of providing sufficient spare modules. The reliability of the standard expendable modules should be ascertained prior to acceptance by the military. With this knowledge of the reliability, the number of spare modules necessary for satisfactory operation of an equipment type for a known period of time could be calculated. Such calculations have been considered and are discussed in sections 4.1.1 and 4.1.3.

(c) Reduction in Failure Data: Under disposal-at-failure maintenance, no failure data on the parts in expendable modules could be obtained from field usage, since piece-part repairs would not be made. These data are important for reliability study and improvement. They possibly could be obtained by returning some of the failed modules to the manufacturer for evaluation.

Excellent field failure data for the modules themselves could no doubt be obtained. Small, inexpensive elapsed time indicators could be included in the modules so that complete failure data could be recorded. An accurate knowledge of the failure rate of the modules would be necessary for predicting and improving the reliability of electronic equipment.

(d) Excessive Cost: The belief has been frequently expressed that the cost of supplying spare expendable modules would be excessive. Controverting this belief, this study concludes that an equipment type built with expendable four to eight tube modules would cost about the same to procure, support, and maintain as would a similar equipment type built with repairable four to eight tube modules. (See sections 4.1.2, 4.1.3 and 5).

4. SUBDIVISION OF EQUIPMENT

Under the present BuAer maintenance system which is based on piece-part* repair, effective subdivision of an electronic set* and its units* plays an important part in facilitating maintainability. Under a disposal-at-failure maintenance system, effective subdivision would become even more important. The decisions made at the beginning of the design period would affect not only the maintainability and the electrical performance characteristics of the equipment, but also the logistics and the total costs of procuring and supporting the equipment.

The primary objective in subdividing a set into units is to optimize maintainability by the front-line maintenance activities. For achievement of this objective it is generally agreed that a set should be divided into functional units. Functional guidelines, however, are too broad and require much refinement. A functional unit could be a receiver, a transmitter, a synchronizer, etc., (large expensive units); or a functional unit could be a video amplifier, an afc amplifier, a horizontal sweep circuit, etc., (small inexpensive units).

A better guideline from the standpoint of maintainability may be:

> Subdivide the set into units in such a manner as to have a specified probability that an average technician under specified conditions could locate and exchange a faulty unit in a specified time.

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*See Glossary

Under this guideline, the primary subdivision of a set depends on its complexity and fault location possibilities. Generally, equipment of greater complexity will require use of larger primary units; equipment of lesser complexity will permit use of smaller primary units. This guideline may need to be modified when the systems and the weapon are being integrated or when short life components must be used. The physical size of a unit may often be determined by the available space and environmental conditions in the weapon.

Secondary subdivision, subdivision of the primary units into assemblies or modules, may often be required not only to facilitate maintenance by the front-line activities, but also to ease the burden on the supply system and the storage facilities and to reduce the total procurement costs. In the present study, efforts have been made to determine the optimum module size, in terms of number of tubes, that will permit achievement of these ends.

4.1 Determination of Optimum Module Size.

The details involved in determining an optimum module size (number of tubes) are best illustrated by means of a hypothetical example based on typical present-day conditions. Such a hypothetical example is presented later in this report (Section 4.1.3). In the hypothetical example, total procurement costs for typical modules of various electrical sizes have been calculated. Before these calculations could be made, however, two relationships had to be established: the relationship between the reliability of a module and the number of tubes in the module, and the relationship between the unit cost* of a module and the number of tubes in the module. The information needed for establishing these relationships was obtained from a study of currently available reliability prediction techniques and an analysis of equipment now in use by the Bureau of Aeronautics.

4.1.1 Mean Life of Module vs. Size of Module.

Reliability prediction has received a great deal of attention during the past few years. Means for predicting the reliability of electronic equipment have been developed and are being continuously improved.[8,9,10,11,12] Use of general failure rates for the electronic parts permits prediction of the mean life of a module within rather broad limits. For a specific piece of equipment, more precise estimates of the mean times to failure for the various assemblies may be made by use of actual parts distribution and stress level information. Further data may be derived from tests of the engineering and production prototypes of the equipment. In the present study, typical failure rates and parts distributions have been used to obtain an over-all system average. Absolute accuracy, however, is not important in determining the optimum module size (number of tubes). Relative accuracy, the reliability of a module as

*See Glossary.

a function of the number of tubes in the module, is the important consideration.

The following procedure was used in predicting the reliability of typical or average modules. This is the procedure suggested by Aeronautical Radio, Inc. (ARINC)[13] and the Advisory Group on Reliability of Electronic Equipment (AGREE).[8]

Step 1. Define the equipment explicitly and uniquely in terms of functions and boundary points.

Step 2. Specify the components within the system.

All of the components (assemblies) that form the complete system should be considered when system reliability is being predicted.

Step 3. Select the parts which affect the system unreliability.

Parts having very little effect can be disregarded. Those having a dominant effect due to their large number or high failure rate must be considered.

Step 4. Determine a failure rate for each part or class of parts used in each component of the system.

If the parts are not analyzed singly, the failure rate of the part is the failure rate of its class. Failure rate data may be obtained from references 8, 9, 10, and 11.

Step 5. Determine a preliminary figure for the failure rate of each component within the system.

Add the failure rates for all the parts in the component as determined in Step 4.

Step 6. Determine the correction factors to be used to modify the preliminary figures for the failure rate of each component.

When stresses are applied to the whole component, it is more practical to apply a single correction to the component rather than to correct the failure rate of each individual part.

Step 7. Determine the failure rate for each component.

Multiply the preliminary figure for the failure rate of each component by its correction factor as determined in Step 6.

Step 8. Determine a preliminary figure for the failure rate of the system.

Add the failure rates for all the components within the system to obtain the preliminary figure for the system failure rate.

Step 9. Determine the correction factors to be used to modify the preliminary figure for the failure rate of the system.

As in Step 6, the equipment may be subject to special stresses that have not been considered in the computation of the failure rates of the parts and components; these stresses must be considered at this stage.

Step 10. Determine the failure rate of the system.

Multiply the preliminary figure for the system failure rate by the correction factors determined in Step 9.

Step 11. Determine the predicted reliability function for the system.

The reliability function for the system is given by:

$$R(t) = e^{-t \times (\text{system failure rate})}$$

Step 12. Determine the predicted mean number of hours between system malfunctions.

The predicted mean number of hours between malfunctions, ϵ, is given by:

$$\epsilon = \frac{1}{\text{system failure rate}}$$

The above procedure, together with parts distribution information, has been used to predict the mean time between failures of typical modules of various sizes. (See Figure 1.) The information on parts distribution (the number and types of parts per vacuum tube) was obtained from our study of present airborne equipment and data from the Vitro Laboratories. The example given below shows how the reliability prediction was carried out. The example is based on a typical four-tube module or assembly. The parts listed are those which will affect the reliability of the module. The class failure rates and the correction factors were determined from an ARINC report,[13] to which the reader is directed for detailed information.

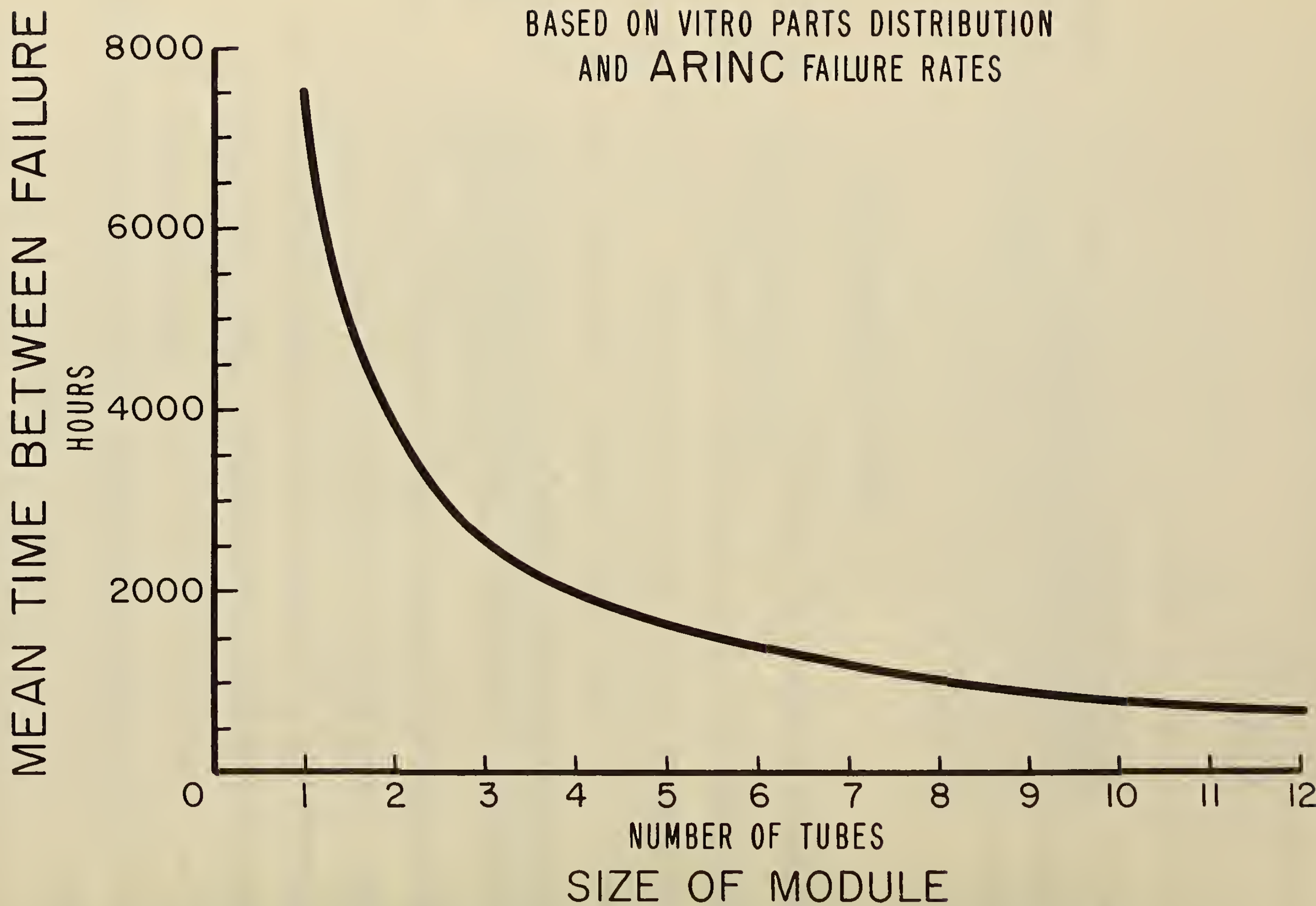

FIG. 1. MEAN LIFE OF TYPICAL MODULE VS. SIZE

No. of Parts	Type	Class Hourly Failure Rate	Failure Rate
4	Vacuum Tubes (90% rated, 100% filament)	90×10^{-6}	360×10^{-6}
11	Capacitors (80% rated)	2×10^{-6}	22×10^{-6}
16	Resistors (80% rated)	6×10^{-6}	96×10^{-6}
3	Coils	3×10^{-6}	9×10^{-6}
1	Printed Circuit	6×10^{-6}	6×10^{-6}
1	Connector	4×10^{-6}	4×10^{-6}
36			497×10^{-6}

Component tolerance: ±10%

Maximum temperature of tubes: 150°C.

Correction factor due to temperature: .85

Correction factor due to no malfunction detection: 1.2

Failure rate of module = $.85 \times 1.2 \times 497 \times 10^{-6} \approx 500 \times 10^{-6}$

Mean time between failures $\approx \dfrac{1}{500 \times 10^{-6}} \approx$ 2000 hours

4.1.2 Unit Cost of Module vs. Size of Module.

For establishing a relationship between the cost of a module and its size (number of tubes), the unit costs for representative assemblies currently used in BuAer equipment were obtained. After most of the BuAer electronic equipments of recent design were analyzed, 300 different assemblies used in 18 different equipment types were selected as representing an approximation to modularly construced assemblies. Only those assemblies that contained 10 or less tubes and were easily removable from their equipments were selected for use in this study.

The unit costs for the 300 assemblies were obtained from spare parts lists filed in BuAer equipment contracts as contract amendments, and also from the Aviation Supply Office in Philadelphia. Because design and tooling costs are included in first contracts, the latest subsequent contracts that excluded these costs were used whenever possible.

The best correlation of cost to a physical property was the cost per tube. Figure 2 is a curve showing the unit cost of assemblies versus the number of tubes in the assemblies. The vertical bars show the range of costs of assemblies versus the number of tubes. The circles indicate the average cost of the assemblies versus the number of tubes. The curve shown is the linear least-squares fit of the average costs. The correlation between the cost and the number of tubes is rather loose, with a wide dispersion in the costs for an assembly of any given size. This is to be expected, since a large number of variables have not been considered. Electrically and physically the assemblies examined differed widely. Some assemblies contained tuning elements, precision potentiometers, relays, etc.; some were encapsulated, some were plug-in, etc. The average costs of some of the assemblies may not be representative because only a few manufacturers are

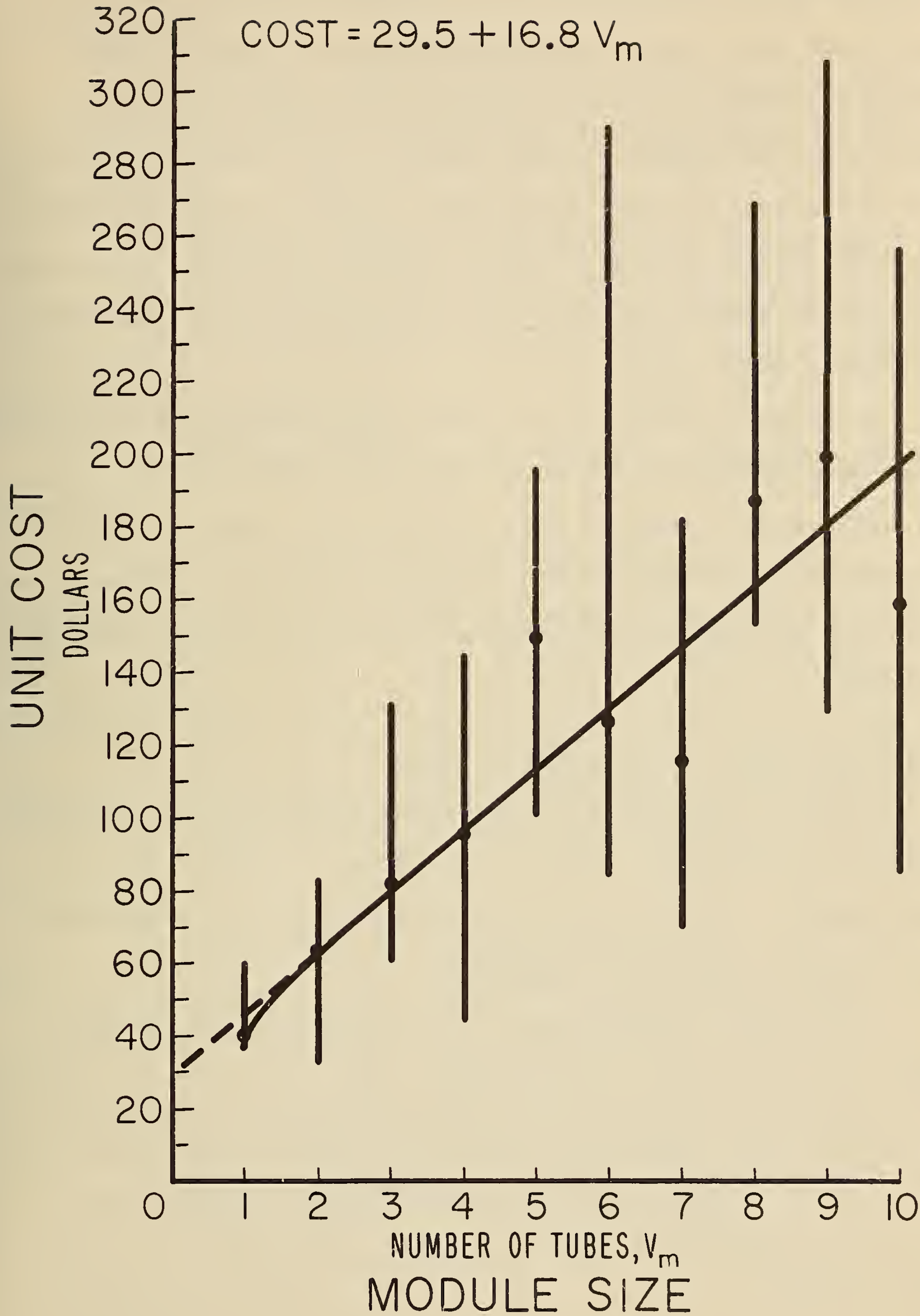

FIG. 2. MODULE UNIT COST VS. MODULE SIZE

represented; for instance, about 80% of the one-tube assemblies considered were made by one manufacturer. There is not sufficient standardization and modular design in present operational equipment to make possible the construction of an accurate curve for cost prediction; however, with the rapid movement toward standard modular design, it should be possible in the near future to construct curves for more accurately predicting unit costs.

As shown by Figure 2, it costs approximately $40 to procure a one-tube assembly, $24 more for a two-tube assembly, and approximately $17 more for each additional tube. In the absence of the actual cost or information to the contrary, this curve can be used to approximately predict the unit cost of an assembly.

4.1.3 Solution of a Typical Problem.

The data used and the conditions stated in the following problem are based as nearly as possible on present-day requirements. The solution may be considered as a solution to an actual present-day problem.

Assume that an electronic set* containing 240 tubes is required as part of a jet aircraft. The set is to be designed for disposal-at-failure maintenance. The following operational conditions are known prior to the design of the set:

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*See Glossary

1. Total of 300 sets to be installed and operated in jet aircraft.

2. Program life* for the sets to be 5 years, with an average of 400 hours of operation per year, total of 2000 hours operation.

3. Attrition rate* of aircraft is 1.5% per month.

4. For desired front-line ease of maintenance, the sets are to be divided into ten 24-tube units, each of which is assumed to be different.

5. The sets will be distributed to 20 geographical locations.

6. One bench set-up and one spare set will be required at each location for front-line maintenance; one set will be required at each of two Overhaul and Repair Depots.* This gives a total of 342 sets to initially outfit and support.

7. All spares are to be procured for life-of-type.*

8. Spares can be shifted to necessary location at any time.

9. There must be a 95% probability that sufficient spares are procured to meet requirements over the program life.

Since the attrition rate of the operating planes is 1.5% per month, the average number of sets operating in planes over the program life will be 200. Including fixed installations, the average number of sets operating will be 242. In the solution of the following problem, figures for the attrition

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*See Glossary.

rate are not required if the figure for the average number of sets operating is used. It can be shown that use of this figure is equivalent to explicitly taking account of the attrition rate.

Problem: How should the units be subdivided for achievement of optimum military value?

(a) Consider each unit to contain one 24-tube module.

A complete set will contain ten of these 24-tube modules, each module being of a different type.

Assume that the modules have equal failure rates and unit costs:

Mean time between failures (MTBF) $\approx$ 340 hours. (From Fig. 1.)

Unit cost of modules $\approx$ \$433. (From Fig. 2.)

For a 95% probability that sufficient spares are procured for the equipment, there must be a probability of $\sqrt[10]{.95}$ that sufficient spares are available for each of the 10 different module types.

$$P(s,nrt) = \sqrt[10]{.95} = .9949$$

The number of spares necessary for each module can be determined from the following equation:

$$P(s,nrt) = \sum_{m=0}^{s} e^{-nrt} \frac{(nrt)^m}{m!}$$

$P(s,nrt)$ = probability of sufficient spares
s = number of spares
$m = 0, 1, 2, 3, \ldots \ldots s$
n = average number of sets supported
r = failure rate of module = $\frac{1}{MTBF}$
t = operating time = program life in hours

Substituting appropriate values for the above quantities, this equation becomes:

$$.9949 = \sum_{m=0}^{s} e^{\frac{-242 \times 2000}{340}} \frac{\left(\frac{242 \times 2000}{340}\right)^m}{m!}$$

s = 1459 spares for each of the ten different module types.*

Knowing the number of modules in each set and the number of spares for each module, we can calculate the total procurement cost for the original and spare modules:

Total cost for spare modules = 10x1459x\$433 ≈ \$6,300,000.

Total cost for the initial quantity of modules for the 342 sets = 342x10x\$433 ≈ \$1,500,000

Total procurement cost of 24-tube modules ≈ \$7,800,000

(b) Repeating these calculations for the case in which each unit is subdivided into two 12-tube modules, we get:

MTBF for a 12-tube module ≈ 680 hours. (From Fig. 1.)

Unit cost of a 12-tube module ≈ \$231. (From Fig. 2.)

Number of spares required for each module type = 787.

Total cost for spare modules=10x2x787x\$231 ≈ \$3,600,000

Total cost for the initial quantity of modules for the 342 sets = 342x10x2x\$231 ≈ \$1,600,000

Total procurement cost of 12-tube modules ≈ \$5,200,000

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*This equation is solved by using the normal distribution approximation for P(s,nrt).

(c) These calculations have been carried out for a range of module sizes so that the size which leads to the lowest over-all procurement cost may be determined. The resulting values are tabulated in Figure 3.

Note that in Figure 3 two sets of values are given for the one-tube modules. The larger modules will generally be unique within a set because of the large number of tubes which they contain. It has been observed, however, that at the one- or two-tube level considerable repetition may occur. This is an advantage from the logistic standpoint in that fewer different module types are required. The advantage of this repetition was tested by carrying out two different calculations for the one-tube modules. In the first calculation it was assumed that each type was used only once in the equipment; in the second calculation it was assumed that each type was used twice, on the average. Thus, only one-half as many types would be required. These calculations are indicated below:

Each unit is divided into 24 one-tube modules.

Case (a): Each module is considered as unique.

Case (b): Each module is considered as used twice.

MTBF for a one-tube module $\approx$ 7500 hours. (From Fig. 1.)

Unit cost for a one-tube module $\approx$ \$40. (From Fig. 2.)

Size of Module (No. of Tubes)	Unit Cost of Modules (Dollars)	Mean Time Between Failures (Hours)	No. of Different Module Types (Units)	No. of Spares for ea Module Type (Units)	Volume of Spare Modules (Thous.of Cu. Ft.)	Cost of Initial Quan.of Modules (Millions of Dol.)	Cost of Spare Modules (Millions of Dol.)	Total Procure-ment Cost (Millions of Dol.)
24	433	340	10	1459	13.8	1.5	6.3	7.8
12	231	680	20	787	8.0	1.6	3.6	5.2
8	164	1025	30	536	6.2	1.7	2.6	4.3
6	130	1360	40	411	5.2	1.8	2.1	3.9
4	96	2000	60	304	4.2	2.0	1.8	3.8
2	64	3900	120	161	3.0	2.6	1.2	3.8
1	40	7500	240	93	2.1	3.3	0.9	4.2
1*	40	7500	120	167	1.9	3.3	0.7	4.0

* Each module type assumed to be used twice per set.

FIG. 3. COMPARISON OF VARIOUS FACTORS AS A FUNCTION OF MODULE SIZE

	(a) Each module type used only once per equipment.	(b) Each module type used twice per equipment.
Number of spares for each module type:	93	167
Total cost for spare modules:	24 x 10 x 93 x $40 = $894,000	12 x 10 x 167 x $40 = $701,600
Total cost for the initial quantity of modules for the 342 sets:	342 x 24 x 10 x $40 = $3,280,000	342 x 24 x 10 x $40 = $3,280,000
Total procurement cost for modules:	$4,200,000	$3,982,000

4.1.4 Conclusions as to Optimum Module Size.

Contrary to popular belief, it would probably be poor practice to attain an expendable modular design by simply subdividing the equipment into modules that cost less to replace than to repair. Curves of the several calculations are shown in Figure 4. These curves display some interesting information. As shown in the figure, it would cost just as much to procure the sets and spares composed of one-tube modules as it would to procure the sets and spares composed of eight-tube modules. For the electronic set under consideration, it would cost no more to expend modules containing eight tubes than to expend modules containing one tube. The lowest-cost design is that

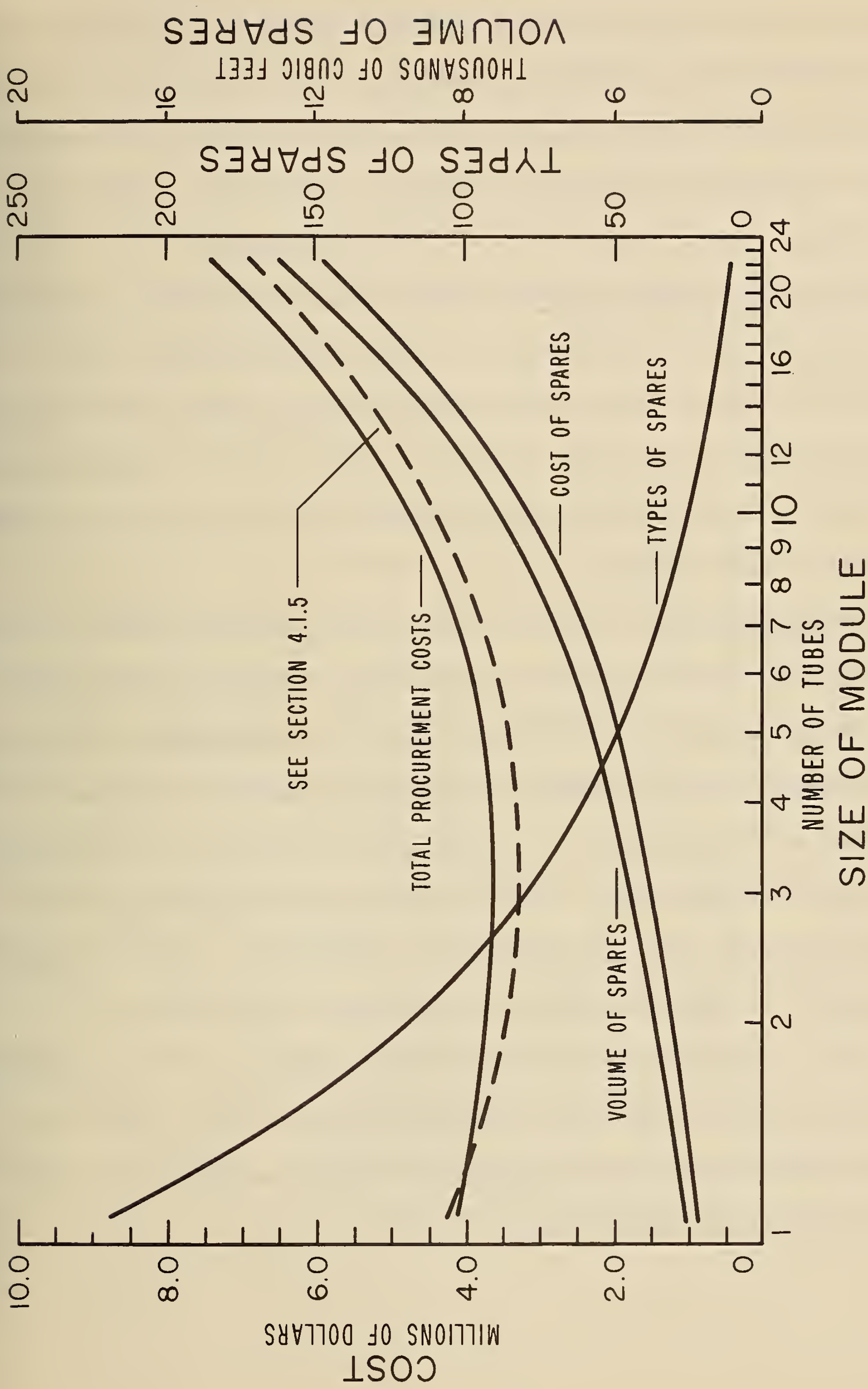

FIG. 4. VARIOUS FACTORS VS. MODULE SIZE

using modules containing between three and five tubes. The comparatively flat total-cost curve for modules containing between one and eight tubes is perhaps a fortunate condition; when the optimum module size is being determined, considerable latitude exists with respect to costs. There are, however, the following important factors to be considered.

(a) Ease of maintenance. From the maintenance viewpoint, larger modules are advantageous. It is considerably less difficult to locate a defective six or eight tube module than to locate a one or two tube module. Since ease of maintenance is the primary goal in the subdivision of equipment, it should be given the most weight.

(b) Modification. Often, after the sets and spares have been procured, the sets must be modified. Since modification of expendable modules may be impossible or difficult, replacement modules may be necessary; therefore, smaller modules would be more satisfactory. The weight to be given the modification factor is dependent upon the technical knowledge and design experience that can be used in developing and building the equipment. When an advanced equipment requiring an extension of the technical art is being considered, the modification factor should be given considerable weight. When an equipment evidencing mature design is being considered, this factor may be given less weight.

There appears to be a growing interest in deferred procurement[14] of aircraft spares, particularly when high-cost items are involved. Under a deferred procurement policy, the services would procure only enough spares for a year or so of operation. The manufacturer would be authorized to hold a small buffer stock sufficient to cover lead time. After sufficient usage* data had been accumulated and the design had become stabilized, a major procurement would be placed covering the remainder of the program. The present policy is based upon life-of-type* buying, in which efforts are made to contract for all spares at the beginning of a program.

In the case of expendable modules, deferred procurement would be advantageous, since it would prevent the scrapping of large quantities of spare modules due to modifications.

(c) Logistics. From the standpoint of logistics, several conflicting factors are evident. The types of spares (the number of line items)* increase rapidly as the size of the module is reduced. (See Fig. 4). This would suggest larger modules to minimize the number of line items controlled by supply. However, as the size of the modules increases, the storage volume of spares required goes up rapidly. (See Fig. 4). This would suggest smaller modules to minimize the storage and handling problems. In the supply system, both of these factors are important, but in front-line operation the volume of spares

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*See Glossary.

merits more serious consideration. Since improved front-line operation is the primary goal, the volume of spares should be given much more weight than the number of line items.

Included in Figure 3 are the results of repetition when one-tube modules are used. It was assumed that each of the modules was used twice. This reduces the types of spares or number of line items from 240 to 120. Due to repetition, the cost and volume of the spares was reduced by approximately 15%. The total procurement cost was reduced by very little, approximately 3%.

Designs using one-tube modules tend to be more attractive due to the benefits of repetition. However, extensive use of repetition (many identical modules throughout military equipments) would be necessary before significant advantages could be gained. Generally, a design using one-tube modules is more difficult to develop and has lower reliability, poorer maintainability, and larger size and weight than one using larger modules. These disadvantages probably outweigh the benefits that reasonably may be expected from the universal use of standard one-tube modules.

Although the solution and discussion of this typical problem does not define a particular module size, some general conclusions are possible. Small modules, one to three tubes, are unfavorable; they offer no economic advantages and have several important disadvantages. Large modules, those containing more than eight tubes, are unfavorable due to the rapid increase in total costs. The optimum expendable module size probably is in the range of four to eight tubes.

4.1.5 A General Solution for Determining the Optimum Expendable Module Size.

In the typical problem presented in section 4.1.3, one of the conditions was a 95% probability that sufficient spares were procured for the life of the program. In actual practice the number of spares procured is not determined in this manner. This condition was used in the problem to assure equal chances of having sufficient spares when comparing modules of various sizes.

At present the number of spares procured is governed by typical usage rates. Generally, the usage rates are determined by calculating the average number of spares necessary as shown by field usage reports. The usage rate of an expendable module should be approximately equal to its failure rate. By use of the failure rate to determine the average number of spare modules necessary, it is possible to obtain a general relationship between the size of the modules contained in an expendable modular equipment and the total program procurement cost of the equipment. This relationship is given by the following equation

$$C_t = \underbrace{\left[\frac{T_p}{T_t} V_e N_a}_{\text{No. of spare modules}} + \underbrace{\frac{V_e}{V_m} N_i\right]}_{\text{No. of modules initially operating}} \underbrace{\left[C_f + C_v V_m\right]}_{\text{Cost of module}} + \underbrace{\frac{V_e}{V_m}}_{\text{No. of modules to be supplied}} \underbrace{\left[C_e + \frac{T_p}{T_y} C_m\right]}_{\text{Supply costs for modules}}$$

C_t = total cost of initial modules, spare modules, and maintaining their supply.

T_p = program life in operating hours (2000 hrs).

T_t = MTBF* for typical one-tube stage, in operating hours (8000 hrs).

V_e = number of tubes in set.

N_a = average number of sets operating over program life (242).

V_m = size of module (number of tubes).

N_i = number of sets operating initially (342).

C_f = fixed cost per module ($29.5).

C_v = cost per tube of module ($16.8).

C_e = cost to establish a line item in supply system ($75).

C_m = cost per year to keep an item in supply system ($28).

T_y = operating hours per year (400).

The numbers in parenthesis represent typical values.

The above equation may be solved for the value of V_m which results in the minimum program cost:

$$V_m \text{ (for minimum program cost)} = \sqrt{\frac{N_i C_f + \frac{T_p}{T_y} C_m + C_e}{T_p N_a C_v} T_t}$$

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*See Glossary

Substituting the typical values given in parenthesis, we find that the value of V_m for minimum program cost is slightly more than 3 tubes per module.

The module size for minimum program cost is independent of the number of tubes in the set. The module size varies as the square root of the reliability level, since T_t is directly proportional to the reliability art. Future trends in the electronics field should lead to designs containing larger modules: component part and circuit reliability are continuing to improve, program lives are tending to be shorter, and attrition rates of operating equipment are becoming higher (smaller N_a in the equation).

The above equation does not include all of the costs that may in some manner be related to the module size. The cost to locate and exchange a defective module is probably a function of the size of the module. It is known that more time is required to locate a small module than to locate a large one; however, the relationship of the time to locate and exchange a defective module versus its size has not been determined. This problem has been considered in connection with the maintenance of Army missile equipment.[15] If this relationship were determined, it would be possible to convert this time function into costs in the above equation. Since the technician's time is probably more valuable than the costs incurred by the military to support him, a military value rather than costs should be established for a technician's time. In this value, the reduced down-time of aircraft due to more effective use of maintenance personnel should be considered.

The costs of the instrumentation for maintenance may be a function of the module size. Some maintenance personnel feel that a module checker to check each module individually would be necessary. The procurement and maintenance costs of a module checker would probably be a function of the module size used in the equipment. Where bench set-ups and standard test équipment are used, the instrumentation cost is almost independent of the module size. Since the type of maintenance instrumentation that may be necessary is not known, this factor has not been included in the equation.

The dashed curve in Fig. 4 shows the calculated total procurement cost for the initial modules and spares versus module size for the problem in section 4.1.3, when the general equation is used. This curve should show small differences since the probability of having sufficient spares is quite different for the two cases. However, for a large number of equipments, either of the two solutions for the optimum module size should be satisfactory.

5. COST COMPARISON OF REPAIRABLE ASSEMBLY AND EXPENDABLE ASSEMBLY MAINTENANCE SYSTEMS.

In this section, a cost comparison is made between the present maintenance system based on the use of repairable assemblies and a system based on the use of optimum expendable assemblies. Preferably, the total cost of both alternatives over the program life* should be used to permit the inclusion of fixed costs, indirect costs, and other factors such as reliability and availability.[16] However, acquisition of the information needed for such a comparison was beyond the scope of the present study. The problem is considerably simplified by concentrating on those areas in which the costs of the two systems are known to differ. This is the general approach that has been used in the comparison.

In the repair of equipment built with either repairable or expendable assemblies, the steps involved in locating a defective assembly should be essentially the same. Hence, the following discussion is concerned with the handling and disposition of a defective assembly after it has been located.

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*See Glossary.

5.1 Repair of Defective Assemblies.

Before cost differences between the repairable assembly and expendable assembly systems can be analyzed, a familiarity with the present system for repairing electronic equipment is necessary, particularly with regard to the handling of assemblies. Within the Bureau of Aeronautics there are three levels at which defective assemblies may be repaired. These levels are Squadron, FASRON*, and the Overhaul and Repair Depot.* The squadron is primarily concerned with the operation of aircraft and equipment and has very limited facilities for the repair of electronic equipment. For every few squadrons there is a FASRON (Fleet Aviation Service Squadron) which has quite complete repair facilities. The FASRON is generally located sufficiently close to the squadrons to permit use of the FASRON facilities by squadron personnel. Some squadrons, particularly those that operate in remote areas, are designated as self-supporting, and have their own facilities similar to the FASRON. Carriers have electronic shops with facilities similar to the FASRON. The O & R Depots are completely equipped for all types of maintenance and repair work. There are relatively few of them, however, and material sent to them for repair often must be packed and shipped over long distances. For efficient operation of the depots with reasonably stable workloads, a certain backlog of work is

*See Glossary

desirable; this backlog requires extra storage and handling facilities.

It has been determined that a considerable quantity of equipment is being sent to the depots for piece-part* repairs. Indications are that this quantity will increase due to the complexity of new equipment and the intricacies of modern construction techniques. Hence, the main emphasis in this study has been placed on determining the costs incurred in the repair of electronic material at the depot level. These costs include handling of the material at the originating activity, shipment to the O & R Depot, screening, storage, and repair. Figure 5 illustrates these various steps. After the item has been repaired it is returned to Supply in RFI (ready for issue)* condition, and is treated essentially as a new item. Consequently, the costs from this point on are the same whether the item is a repaired assembly or a new expendable assembly. Figure 6 illustrates the steps involved in locating and replacing a defective expendable assembly.

For the repairable case, in determining total costs over the program life of an equipment type, various costs must be considered in addition to the direct cost of making repairs. If the equipment is to be repaired only at the depot level, at least three O & R depots in different geographical areas are customarily designated as overhaul points. If the equipment

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*See Glossary.

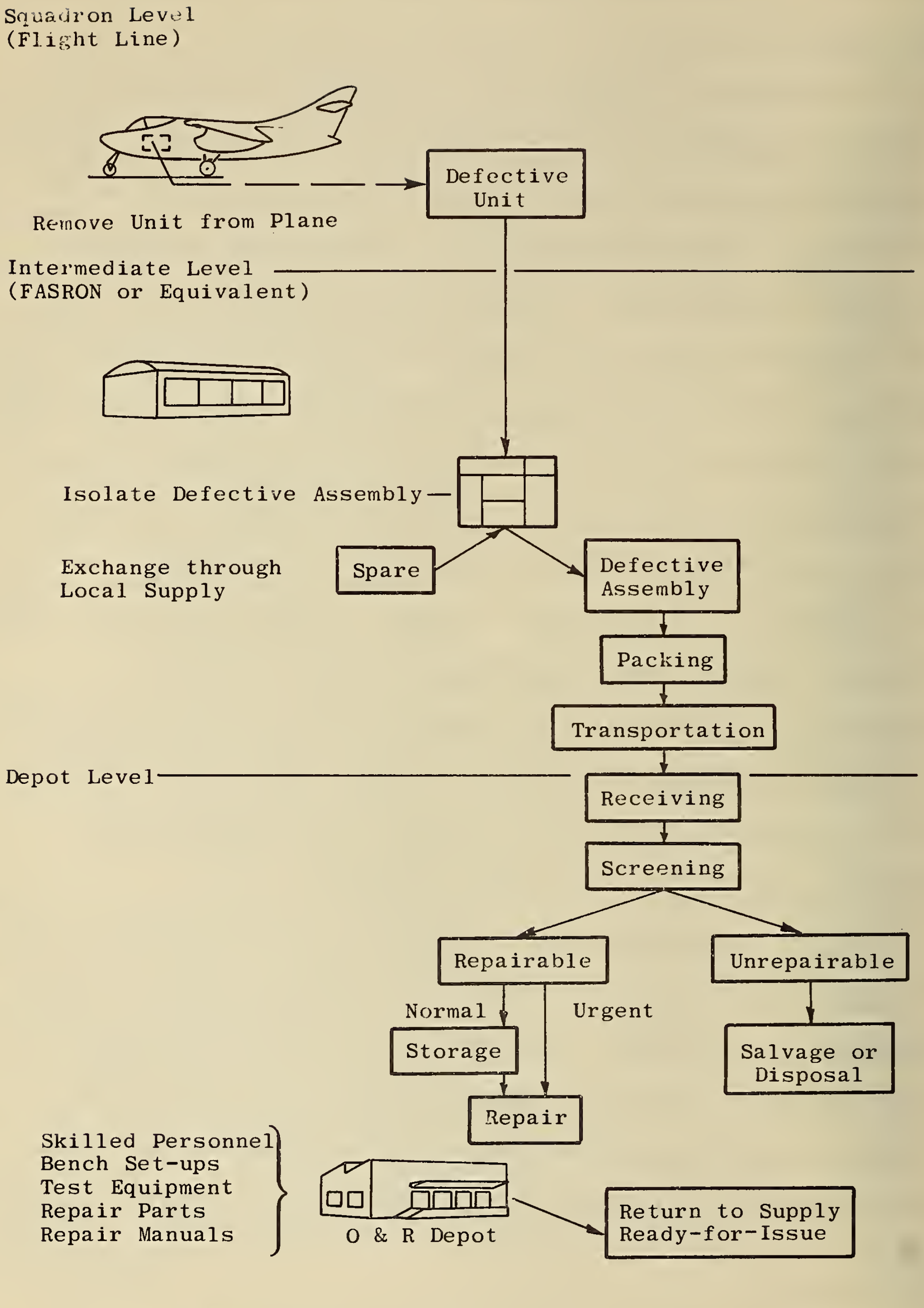

FIG. 5. MAINTENANCE SYSTEM BASED ON THE REPAIR OF ASSEMBLIES AT THE DEPOT LEVEL

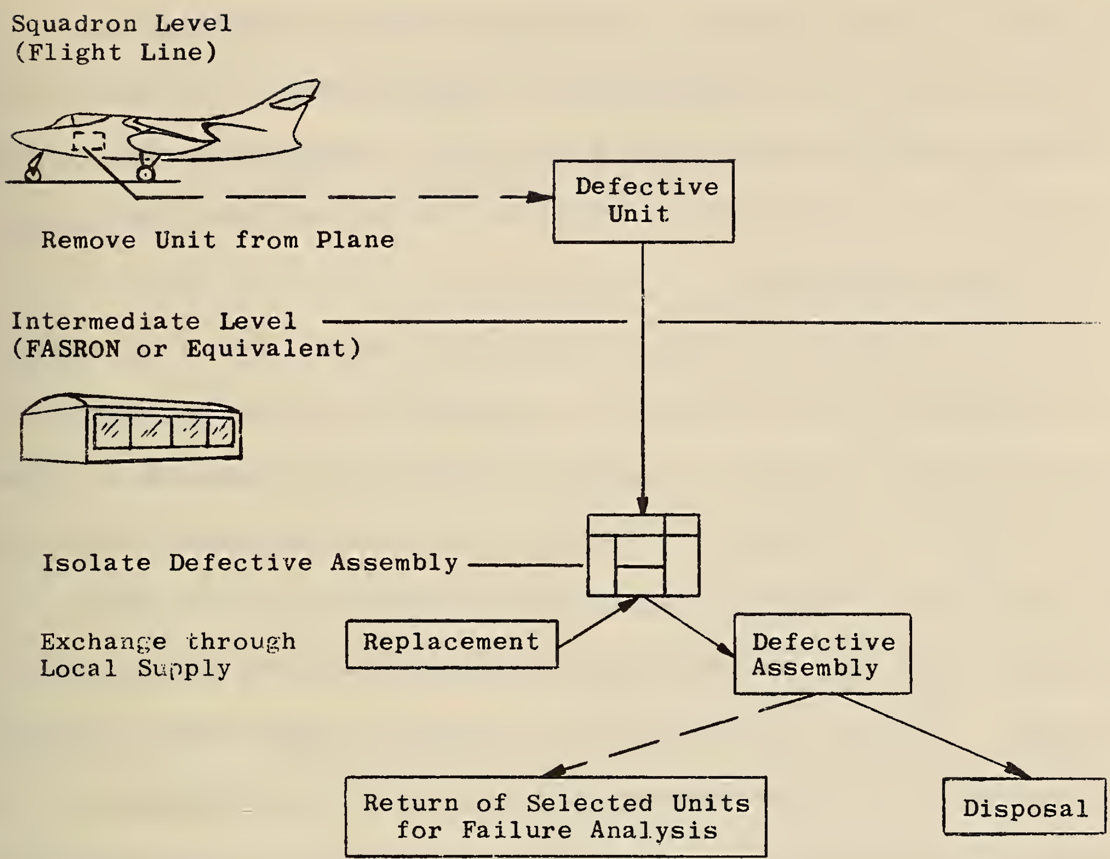

FIG. 6. MAINTENANCE SYSTEM BASED ON EXPENDABLE ASSEMBLIES

is to be used in large numbers in a variety of aircraft, then all nine O & R Depots may be designated. This means that bench set-ups and test equipment must be provided at each depot for all of the units and assemblies. In addition, a complete operating set with all of its accessories is provided for substitution checking of repaired units and for training of the repair personnel.

The training of technicians is an item of major expense. It is anticipated that the use of expendability will permit much more effective use of present maintenance personnel. The time and effort required to correct a malfunction should be greatly reduced, since it would not be necessary, in the expendable case, to perform piece-part repairs of defective assemblies. While the capability of making piece-part repairs exists at all of the maintenance levels which have been discussed, the tendency is for such repairs to be relegated to the depot level due to the pressure of more urgent duties on the front-line organizations. Consequently, for purposes of the present study, it has been assumed that the piece-part repair of assemblies is performed at the O & R depots, where the repair work is done by civilians. It has been assumed that the location and replacement of a defective assembly is essentially the same, as far as the front-line organization is concerned, whether the assembly is repairable or expendable. Hence, the value of the military technician's time is not used in determining the relative costs of the repairable and expendable cases. Civilian personnel at the O & R depots are presumed to have received technical training prior to employment, and this is reflected in the higher hourly wage rate. On-the-job training is considered as part of the overhead cost of the depot.

In order to carry out repairs on assemblies, the designated O & R Depots must have complete stocks of all "bits and pieces."* These parts must be procured, distributed, and stored, and must be requistioned as needed. Since there is always a degree of uncertainty as to what the usage* rates will be for various parts, it is unavoidable that excess stocks of some parts will be procured, while other parts may have to be reordered. Both of these situations increase the cost of maintaining stocks of spare parts. For assurance that new parts will be interchangeable with those in the original equipment, various procurement documents and lengthy specifications are required for each part.

Detailed instruction manuals with pictorial and schematic diagrams, servicing instructions, and lengthy parts lists are required to aid in the piece-part repair of assemblies. It is felt that the use of expendable assemblies would permit many of the circuits to be represented merely as block diagrams, reducing the need for schematics, and greatly simplifying the

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*See Glossary.

instruction manuals. If expendable assemblies were modified during production, or from one manufacturer to another, it would not be necessary to send out detailed change notices, so long as the performance of the assemblies remained essentially the same.

In the operation of the repairable case, a certain quantity of spare units* is necessary due to the time required to perform a repair. In addition, some of the units may be damaged beyond repair, or may be lost during shipping and handling; such losses are reflected in the system recovery rate,* which is expressed as the percentage of defective items that are restored to ready-for-issue status. Items which do not get repaired are in effect expended and must be replaced by spares. If the repair time (including handling, shipping and storage, as well as actual repair) is long, then there is a period at the beginning of a new program during which no repaired items are available, and sufficient spares must be obtained to tide the program over this period. Eventually, a "steady-state" condition is reached; however, if the repair time is a significant portion of the total program life, then this initial quantity of spares is quite important. The lower the system recovery rate, the more spares are required; if the recovery rate were zero this would correspond to the expendable case. With a low recovery rate fewer repairs are made, and the fixed costs of the repair system must be prorated

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*See Glossary.

over fewer items, leading to an increased repair cost per item.

5.2 Costs of the Repairable Assembly System.

The gathering of actual cost data has been a difficult problem. In some areas, fairly detailed data is available, while in others only rough estimates can be made. This is partly because of the variety of conditions which are encountered: shipping distances and methods vary; electronic items vary in size, weight, and complexity; procedures differ somewhat at various depots; storage time varies with system requirements; and the actual repair costs vary widely. The number of any one assembly type that is repaired may vary from a few per year to several hundred. Assemblies can fail in an endless number of ways. Repair time can vary from minutes to hours. Parts requirements can vary from simple, common items to special parts that may take weeks to obtain. Hence, any statement of repair costs must be a fairly broad average. The general problem of obtaining data on repair costs has been described in a BuSandA study,[17] which established formulas for use in determining the economic disposition (by repair or by disposal) of new and used aviation material.

The calculation of over-all costs for the repairable case is best illustrated by means of a hypothetical example.

Efforts have been made in this example to select typical values, and to use the best available cost data. The conditions selected are those that were used in the determination of the optimum module size (Section 4.1.3). These are listed below:

1. A set contains 240 tubes, grouped into ten units of 24 tubes each. Each unit is further divided into four 6-tube assemblies.* Each assembly is assumed to be different.

2. Three hundred of these sets will be installed in aircraft.

3. This equipment is to be in use for 5 years at an average of 400 hours per year, for a total of 2000 hours of operation.

4. Attrition rate for the aircraft is 1.5% per month.

5. The sets will be distributed to 20 geographical locations.

6. One bench set-up and one spare set are required at each location for front-line maintenance; one set is required at each of two O & R Depots. This gives a total of 342 sets which must be outfitted and supported initially.

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*The use of 6-tube assemblies has been chosen for this example as representing the optimum size repairable assembly for the given conditions. This can be shown by repeating the calculations for assemblies of different sizes.

7. All spares are procured for life-of-type.

8. Spares may be redistributed as needed at any time.

For calculation of the cost of maintaining the 342 sets which have been postulated, the number of sets operating at any time and the rate at which failures occur must be determined. Initially there are 300 sets installed in aircraft, but this number decreases at the rate of 1.5% per month throughout the program. This can be expressed:

$$n_i(t)^* = N_i \; e^{-at}$$

$n_i(t)$ is the number of sets in aircraft at time t.

N_i is the initial quantity of sets in aircraft, 300 in this case.

a is the value of the exponent corresponding to the specified rate of attrition, which for this case is 0.0151. (When t = 1 month, $e^{-a} = 98.5\% = .985$, $a = .0151$)

t is time in months.

The quantity of bench set-ups needed is assumed to remain constant throughout the program. For simplicity, their operating time is assumed to be equal to the operating time of the sets in the aircraft.

N_b is the number of bench sets.

The total number of sets operating at any time, t, is thus:

$$n_i(t) + N_b = N_i \; e^{-at} + N_b$$

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*This is read "n_i as a function of time."

5.2.1 Failure and Other Calculations for a 6-tube Assembly.

It is assumed that the failure rate for the assemblies is constant with respect to time, which appears to be characteristic of electronic equipment. The failures are randomly distributed, which leads to rather involved probabilistic calculations. However, for large populations these random fluctuations average out, and calculations based on average rates afford a reasonable approximation. The number of any one type of assembly that fails in a given period of time is equal to the number of equipment-hours divided by the mean life of the assembly:

$$f(t) = (\text{Equipment-hours}) \div \theta_a$$

where f(t) is the number of assemblies that have failed and θ_a is the mean life of the assembly. For the 6-tube assemblies under consideration, a mean life of 1360 hours has been calculated.

The equipment-hours can be found by taking the area under a curve of number-of-equipments versus time. This area is given by:

$$(\text{Equipment-hours}) = \int_0^t (n_i(t) + N_b)\, dt \times h_m$$

where h_m is the number of operating hours per month. In the present case, $h_m = 400 \div 12 = 33.3$ hours per month.

Evaluating the integral:

$$\int_o^t \left[n_i(t) + N_b\right] dt = \int_o^t \left[N_i\, e^{-at} + N_b\right] dt$$

$$= \int_o^t N_i\, e^{-at}\, dt + \int_o^t N_b\, dt$$

$$= N_i \left[\frac{e^{-at}}{-a}\right]_o^t + N_b\, t$$

$$= \frac{N_i}{a}\left[1 - e^{-at}\right] + N_b\, t$$

$$\text{(Equipment hours) at time } t = \left[\frac{N_i}{a}(1 - e^{-at}) + N_b\, t\right] \times h_m$$

$$f(t) = \left[\frac{N_i}{a}(1 - e^{-at}) + N_b\, t\right] \frac{h_m}{\theta_a}$$

As assemblies fail they are sent to the O & R Depot for repair. A period of time is required for completion of the repair process, which includes shipping, handling, storage, and actual repair. This time is designated T_r.

If f(t) expresses the failures as a function of time, then $f(t - T_r)$ expresses the repaired assemblies as a function of time. Since this expression does not apply for times less than T_r (no repairs are completed within a period T_r of the start of the program) the expression must be slightly modified.

This is done by multiplying the expression by the function $H(t - T_r)$, which is defined as zero for values of time less than T_r and as unity for time greater than T_r.

$$k(t) = f(t - T_r)\, H(t - T_r) \qquad H(t - T_r) = \begin{cases} 0 & \text{for } t < T_r \\ 1 & \text{for } t > T_r \end{cases}$$

where k(t) expresses the number of repaired assemblies as a function of time.

One further modification is needed, since only a portion of the defective assemblies are actually repaired. A certain percentage are screened out at the O & R Depot as unsalvageable, or disappear along the way. The proportion of the defective assemblies that are eventually restored to ready-for-issue condition is designated r_s.

r_s = system recovery rate.

Hence, the complete expression for the repaired assemblies, as a function of time, is given by:

$$k(t) = r_s\, f(t - T_r)\, H(t - T_r)$$

The number of spares needed at time t is equal to the number of failures that have occurred up to that time, minus the number of assemblies that have been repaired

s = number of spares.

$$s(t) = f(t) - k(t)$$

$$f(t) = \left[\frac{N_i}{a}(1 - e^{-at}) + N_b\, t\right]\frac{h_m}{\theta_a}$$

$$k(t) = r_s\, f(t - T_r)\, H(t - T_r)$$

$$= r_s \left[\frac{N_i}{a}\left\{1 - e^{-a(t - T_r)}\right\} + N_b(t - T_r)\right]\frac{h_m}{a}\, H(t - T_r)$$

Factoring out $\frac{h_m}{\theta_a}$ and subtracting $k(t)$ from $f(t)$:

$$s(t) = \frac{h_m}{\theta_a}\left\{\left[\frac{N_i}{a}(1 - e^{-at}) + N_b\, t\right] - r_s\left[\frac{N_i}{a}\left\{1 - e^{-a(t - T_r)}\right\} + N_b(t - T_r)\right]H(t - T_r)\right\}$$

With these expressions it is possible to determine:

(a) The number of failures that will occur.

(b) The number of defective assemblies that will be sent back for repair (assumed to equal the number of failures).

(c) The number of repairs that will be completed.

(d) The number of spares that will be consumed.

For the expendable case the number of spares consumed will be equal to the number of failures. For the repairable case, the four quantities listed above must be determined. For the hypothetical model under consideration the values selected are as follows:

N_i (initial quantity of sets in aircraft) = 300

a (attrition rate) = .0151

N_b (number of bench sets) = 42

h_m (number of equipment operating hours per month) = 33.3

θ_a (mean life of assembly) = 1360

r_s (system recovery rate of assembly) = .50

T_r (time required for repair process) = 10 months

A program life of five years, or 60 months will be considered:

t = 60 months

(a) The number of failures = $f(t)$

$$= \left[\frac{N_i}{a} (1 - e^{-at}) + N_b\, t \right] \frac{h_m}{\theta_a}$$

$$= \left[\frac{300}{0151} \left\{ 1 - e^{-(.0151)\ (60)} \right\} + (42)\ (60) \right] \frac{33.3}{1360}$$

$$= (14{,}350)\ \left(\frac{33.3}{1360}\right)$$

= 352 failures for each assembly type.

(b) The number of defective assemblies of any one type that will be sent back for repair is assumed to equal the number of failures:

Number of defective assemblies sent back for repair = 352.

(c) Because of the recovery rate of 50%, one-half of the defective assemblies will eventually be repaired:

The number of repaired assemblies = 352 x 0.5
= 176 repairs.

(d) It might at first appear that if 352 failures occurred and 176 repairs were made, the number of spares needed would simply be 352 - 176 = 176 spares. However, some of the repaired assemblies do not become available until after the 60-month period. Hence, the number of spares needed must be calculated using the equation for s(t):

The number of spares needed = s(t)

$$s(t) = \frac{h_m}{\theta_a}\left\{\left[\frac{N_i}{a}(1 - e^{-at}) + N_b\, t\right] - r_s\left[\frac{N_i}{a}\; 1 - e^{-a(t - T_r)} + N_b(t - T_r)\right] H(t - T_r)\right\}$$

The first term in square brackets is equal to 14,350 from part (a), t is 60 months and T_r is 10 months. Hence, $t > T_r$, and $H(t - T_r) = 1$.

$$s(t) = \frac{33.3}{1360}\left\{14{,}350 - 0.5\left[\frac{300}{.0151}\left\{1 - e^{-(.0151)(60-10)}\right\} + (42)(60-10)\right]\right\}$$

$$= \frac{33.3}{1360}\left\{14{,}350 - 0.5\,\left[12{,}600\right]\right\}$$

s(t) = 197 spares.

5.2.2 Processing and Repair Costs.

Having determined the number of defective assemblies that will be sent back for repair, and the number that will actually be repaired, we can calculate the costs incurred in processing and repairing these assemblies. Since the recovery rate of the assemblies under consideration is 50%, one-half of the defective assemblies will be repaired and the other half will be considered expended. It will be assumed that all of the defective assemblies reach the O & R Supply activity where they are screened to determine whether they are in repairable condition. Hence, all process costs through the screening process are incurred by all assemblies. However, only half of the assemblies incur the actual cost of repair.

The steps involved in the processing and repair of defective assemblies are listed below. Certain intermediate steps have been lumped together for convenience. Under these steps there are various types of costs, which in general can be considered as either paperwork costs or materials handling costs. The symbol F will be used for paperwork and K for materials handling. Subscripts indicate the step with which the cost is associated.

(1) Processing at the originating activity:

F_o = paperwork

K_o = materials handling

P_o = packing and marking

(2) Shipping to O & R Depot:

T = transportation cost, based on average distance, average weight, and normal mode of transportation.

(3) Receiving at the O & R supply activity:

F_r = paperwork

K_r = materials handling

(4) Screening:

S = cost to screen an item.

(5) Storage:

F_h = paperwork

K_h = materials handling

H = holding costs

(6) Transfer to O & R Shop:

F_t = paperwork

K_t = materials handling

(7) Repair:

L = labor, including overhead

B = material

(8) Return to Supply:

F_s = paperwork

K_s = materials handling

The processing costs under steps 1 through 4 (screening) are incurred by all of the defective assemblies, while the remaining steps are incurred only by the proportion actually repaired. This proportion is equal to the recovery rate. The total cost (C_r) of processing the defective assemblies may be represented thus:

C_r = (Number of defective assemblies) x (recovery rate) x (cost of steps 1 through 8) + (number of defective assemblies) x (one minus the recovery rate) x (cost of steps 1 through 4).

Using the previous notation this may be written:

$$C_r = f(t) \times r_s \times \left[F_o + K_o + P_o + T + F_r + K_r + S + F_h + K_h + H + F_t + K_t + L + B + F_s + K_s\right] + f(t) \times (1 - r_s) \times \left[F_o + K_o + P_o + T + F_r + K_r + S\right] .$$

5.2.3 Evaluation of Cost Factors

Values have been assigned to the various cost factors. Based on the 6-tube assemblies which are being considered, and the best available information which has been obtained, the following estimates have been made.

The cost of processing an assembly from the originating activity through screening at the O & R Depot is $7.33. The cost of sending an assembly through the complete repair process is $7.33 + $37.81 = $45.14.

F_o	(paperwork)	$ .07
K_o	(materials handling)	.95
P_o	(packing & marking)	2.16
T	(transportation)	2.00
F_r	(paperwork)	.73
K_r	(materials handling)	.07
S	(screening)	1.35
Costs through screening		$7.33
F_h	(paperwork)	1.69
K_h	(materials handling)	.03
H	(holding cost	1.30
F_t	(paperwork)	1.31
K_t	(materials handling)	.07
L	(labor)	20.40
B	(material)	12.00
F_s	(paperwork)	.96
K_s	(materials handling)	.05
Costs to complete repair		$37.81

It must be remembered that the above figures are obtained on the basis of the hypothetical 6-tube assembly, and that many factors are averaged in determining the various cost values. In considering a specific equipment or a proposed design, the data could probably be refined to fit actual conditions more closely.

The actual cost of repair parts has been included in the repair cost as item B; however, there are additional costs to consider in connection with the supply of these parts. These are the paperwork costs associated with purchasing and keeping track of the parts over the life of the program. It is somewhat simpler to consider these as over-all costs, rather than to prorate them over the individual parts, since it is not known how many of each part will be used, and these costs are relatively independent of the number of parts used.

Each new part that is stocked by the supply system must be procured, given a stock number, cataloged, inventoried periodically, and reordered as necessary. Thus, there are paperwork costs to be considered, in addition to the cost of the parts themselves. Some of these costs are incurred at the Aviation Supply Office (ASO) and some are incurred at the using activities (the two O & R Depots in the present case). It has been estimated that the average cost at ASO to procure a new part (generally referred to as a line item), including preparation of bids, purchase orders, etc., is $21. The cost of establishing a line item, including stock numbering, cataloging, etc., averages about $50. The cost of maintaining records, analyzing inventories, etc., averages about $23 for each year that the item is stocked.

In the case of the assemblies themselves, each type of assembly would be considered a line item whether the assembly were repairable or expendable. Hence, the cost to keep records on the assemblies would be the same for both systems. However, in the case of repairable assemblies all of the numerous different repair parts must be stocked, in addition to spare assemblies. Not all of the parts are actually new to the supply system, since many of the parts would have been used in previous equipments. In the present example, a set containing 240 tubes has been postulated, and should contain about 2400 parts, assuming average circuitry. Assuming that 10% of the parts are new, there will be 240 new parts added to the supply system for repair purposes. Presumably, the cost of the parts already in the supply system has been charged against previous equipment. The cost incurred at ASO to purchase and keep track of these 240 new items over the five-year program life can be calculated as follows:

C_{p1} = 240 new parts x ($21 to procure each part + $50 to establish each part) + 240 x $28 per year x 5 years.

= $50,640

where C_{p1} is the supply cost incurred at ASO for the 240 new parts (exclusive of the cost of the parts themselves).

In the present example, it has been assumed that the repairs will be performed at each of two O & R Depots; hence, the cost of stocking the parts at these depots must be considered. It has been estimated that a cost of about $12 is incurred for each line item that is received at an activity. Since the O & R Depots try to schedule their work 3 to 6 months in advance, they probably would reorder the necessary parts twice a year. The number of different parts ordered each time is rather a matter of conjecture, but assuming this figure to be 10%, then the number of different parts ordered each time is 10% of 2400 or 240. If orders are placed twice each year for five years, there are ten orders altogether, making a total of 10 x 240 or 2400 items that are received. The cost of receiving these items is 2400 x $12 or $28,800. Since this cost is incurred at each of two O & R Depots, this figure must be doubled:

$$C_{p2} = \$28,800 \times 2$$
$$= \$57,600$$

5.2.4 Total Costs of Repairable Assembly System.

It is now possible to arrive at the complete cost for the repairable case, with regard to those areas in which the costs differ from the expendable case. This complete cost is made up of the following items:

(1) Cost of the initial quantity of assemblies.

(2) Cost of the calculated number of spare assemblies.

(3) Cost of performing the calculated number of repairs, including the processing costs on those assemblies that are screened out as unsalvageable.

(4) Cost of stocking repair parts in the supply system.

(5) Cost of jigs, fixtures, and test equipment at the designated O & R Depots.

(6) Cost of maintenance manuals.

For the present example, these costs are evaluated as follows:

(1) Cost of assemblies for 342 initial sets:

240 tubes per set

6 tubes per assembly

240 ÷ 6 = 40 assemblies per set

342 x 40 = 13,680 assemblies for initial equipment

13,680 x $130 per assembly ≈ $1,780,000

(2) Cost of spare assemblies:

197 x 40 = 7,880 spare assemblies

7,880 x $130 per assembly ≈ $1,020,000

(3) Cost of processing and repairing defective assemblies:

The number of failures has been calculated to be 352 for each of the 40 types of assemblies.

352 x 40 = 14,080 assemblies which will be sent back for repair.

$C_r = 14{,}080 \times 0.5 \times \$45.14 + 14{,}080 \times (1-0.5) \times \$7.33$

$= 14{,}080 \times 0.5 \times (\$45.14 + \$7.33)$

$= 7{,}040 \times \$52.47$

$\approx \$370{,}000$

(4) The cost of stocking repair parts in the supply system: This has been calculated earlier:

$C_{p1} + C_{p2} = \$50{,}640 + \$57{,}600$

$\approx \$110{,}000$

(5) Cost of jigs, fixtures, prorated share of test equipment for the repair of assemblies:

$1,000 per assembly at each of two O & R Depots:

$40 \times \$1000 \times 2 = \$80{,}000$

(6) Cost of maintenance manuals:

$16,000

The costs of the repairable system are recapitulated below:

(1)	Cost of assemblies in original equipment	$1,780,000
(2)	Cost of spare assemblies	1,020,000
(3)	Cost of processing and repairing defective assemblies	370,000
(4)	Cost of stocking spare parts	110,000
(5)	Cost of depot repair set-ups	80,000
(6)	Cost of maintenance manuals	16,000
		$3,376,000

5.3 Total Costs of the Expendable Assembly System.

The cost of the repairable case may be readily compared with the expendable case, for the hypothetical example, since the number of failures has been determined, and each failure will require a replacement assembly. The number of spare assemblies is increased over the repairable case since no repairs are performed on assemblies. The cost of maintenance manuals has been reduced, though this cost cannot be eliminated entirely, since instructions are still needed for locating defective assemblies, making adjustments, and for maintaining those portions of the equipment that are not contained in expendable assemblies. The costs of the expendable case are evaluated as follows:

(1) Cost of assemblies for 342 initial sets:

13,680 assemblies at \$130 per assembly $\approx$ \$1,780,000, as before.

(2) Cost of spare assemblies:

The number of failures has been calculated to be 352 for each of the 40 types of assemblies:

352 x 40 = 14,080 failures

14,080 assemblies x \$130 per assembly $\approx$ \$1,830,000

(3) Cost of maintenance manuals:

It has been assumed that the cost of the maintenance manuals will be reduced by a factor of 4:

\$16,000 ÷ 4 = \$4,000

The costs of the expendable case are recapitulated below:

(1)	Cost of assemblies in original equipment	$1,780,000
(2)	Cost of spare assemblies	1,830,000
(3)	Cost of maintenance manuals	4,000
		$3,614,000

5.4 Conclusions as to Cost Difference.

Thus, the cost of the expendable case is $3,614,000 as compared to $3,376,000 for the repairable case, in terms of the factors that have been considered. It must be remembered that these are not the complete costs that are incurred in the support of the equipment, since many factors which were assumed to balance out have not been considered.

The small difference in costs between the expendable case and the repairable case is probably insignificant. The inaccuracies of the data and the assumptions necessary to calculate the costs preclude precise comparison. Also, there are undoubtedly significant costs for both cases that have been omitted. It is believed, however, that if more complete repair cost data were available, the difference between the expendable and repairable cases would be diminished, because most of the omissions relate to items that would add to the cost of the repairable case. It should be emphasized that the costs being considered in this study are the costs concerning only that portion of an equipment that can be modulized. The costs of procuring and maintaining those portions of an equipment that cannot be modularly designed are at least twice the costs of procuring and maintaining the modular portion. Hence, small differences in the costs of the modular portion would be insignificant when the total costs of procuring and maintaining an equipment were under consideration.

It is concluded that the costs of the expendable and repairable cases are so nearly equal that the cost factor may be eliminated as a bar to the use of expendable assemblies or modules within the optimum size of 4 to 8 tubes.

A commonly discussed ratio of maintenance costs to procurement cost is ten to one.[1] During this report no attempt was made to either substantiate or disprove this ratio. The maintenance costs considered in this report are probably a small portion of the total maintenance cost for the following reasons. First, the initial steps in the repair, namely, isolation and exchange of a defective assembly, may be much more expensive than the actual repair of the assembly. These steps are performed by military technicians. The training costs and the support costs (housing, meals, supervision, transportation, special services, recruitment, extra personnel, etc.) for these technicians add greatly to the direct labor cost. Expendability would not directly aid in reducing these costs. Second, the repair of assemblies at a depot may be much cheaper than in the field. Third, much of the total cost may be incurred in maintaining those portions of the equipment which are not contained in assemblies. Many maintenance actions do not involve repairs. Some simply involve switch settings and front-panel adjustments. Others involve routine checks and inspection of the equipment.

6. FACTORS OTHER THAN COST IN EXPENDABILITY DECISION

The following factors which cannot be converted or simply related to costs should be seriously considered in the decision between expendability and repairability. These factors all favor expendability, and with the cost factor probably eliminated as a deterrent to the practice of expendability, they may be so important as to completely determine a decision in favor of expendability.

6.1 Improved Reliability

It may be possible to achieve higher reliability with disposal-at-failure assemblies or modules than with repairable assemblies or modules. Hermetic sealing or encapsulation may be employed to improve the reliability of expendable modules. Quantitative data as to how much the reliability may be improved has not been obtained; however, several of the manufacturers of hermetically sealed or potted assemblies felt that the failure rates had been improved considerably, from 30 to 400 percent.

It is thought that performing repairs on a module lowers its inherent reliability. Replacing the parts with lower quality parts, damaging parts when soldering, handling, etc., can contribute to higher failure rates. Quantitative data as to how much the reliability may be lowered has not been obtained.

It is generally agreed that modules have nearly constant failure rates over the program life. Where this is the case it makes no difference in the reliability of an equipment whether a failed module is replaced with a new one or a used one. When wear-out is a factor, modules may have a normal failure rate, and the reliability will probably be improved by replacing a failed module with a new one rather than a repaired one.

The three factors discussed above indicate that an improvement in reliability may be possible by use of expendable rather than repairable modules. Since a comparatively small improvement in reliability offers considerable savings in the maintenance and operational costs of equipment, improved reliability may well be the most important factor in the decision between expendable or repairable design.

The savings in maintenance costs resulting from improved reliability can be evaluated in a straightforward manner by following the procedure used in the previous illustrative examples. However, the improved operational effectiveness, which is a much more important aspect, must be evaluated from a military standpoint. This aspect has been considered in studies at Redstone Arsenal,[18] and at International Business Machines, Inc.[19]

6.2 Reduction in Specifications

The use of expendable modules could lead to a reduction in the quantity of military specifications. Specifications stating the reliability, environmental, physical, and electrical requirements of the module could possibly replace the numerous specifications needed for spare parts. Although such reductions in specifications are possible, there is some question as to what the savings may be to the military. If the military should reduce or eliminate the specifications of parts, the module manufacturer would have to prepare these specifications in order to insure his meeting the module specifications.

It has been observed that many manufacturers prepare their own specifications for internal company use, above and beyond the existing military specifications. There are two main reasons for this. First, because the military specifications frequently are not sufficiently up-to-date to cover worthwhile new developments, the manufacturer must prepare his own specifications if he wishes to use the latest parts and materials. Second, in order to secure the highest quality in his equipment, the manufacturer frequently tightens the existing military specifications to restrict his suppliers to those who produce the best available parts and materials and who are known to be reliable, consistent sources. Under such circumstances, some savings might be realized by the military in the reduction of specifications.

6.3 Improved Systems Maintenance

The average military technician is not in the service long enough to become thoroughly familiar with the over-all operation of complex electronic systems, as well as the detailed functioning of circuits and parts. Yet, for rapid flight-line maintenance of aircraft, a knowledge of systems is most important and should be the primary objective in the training of flight-line technicians. The use of expendable modules would free the technicians from considerations of individual parts and circuits, and should permit a major step in the direction of improved systems maintenance. The difficulty of obtaining both detailed and over-all system maintenance has been described as follows:

> "While recognizing the practical necessity for performing the detailed maintenance functions at the using level, it should be noted that the system also suffered because of the tendency of the operational personnel to assume a general familiarity with the equipment without fully developing the detailed knowledge necessary to perform the job. In other words, a fascination with the technical aspects of the over-all system interfered with the primary maintenance objective, that of keeping the equipment operational."[15]

Piece parts repairs, if they are to be made, should not interfere with the primary mission of the front-line technicians, which is to maximize the operational readiness of aircraft. When repairs do not have to be made at the front line, there should be sufficient spare equipment to permit delaying of the repair work until a slack period, allowing time for the ordering and receipt of parts. If defective equipment is to be sent to a depot for repair, sufficient spare equipment is required to cover the period that it is out of service.

6.4 Freedom of Design

When an equipment is designed for piece-part repair, all the parts subject to failure must be accessible and removable. These requirements are not compatible with other design specifications such as small volume, light weight, resistance to humidity, shock and vibration, etc. Replacement of piece parts would not be necessary, of course, if an equipment were built with disposal-at-failure assemblies or modules; the designer would have almost complete freedom in the layout and selection of parts. In airborne equipment, lightweight, small volume, and environmental resistance are extremely important factors. Most designers of equipment agree that an expendable assembly or module may be smaller, of lighter weight, and more resistant to environment than a repairable assembly or module. Such improvements through the use of expendable modular design may be decisive factors in the choice between expendable or repairable modular design.

7. CONCLUSIONS

As mentioned in the text, the data used in the calculations were typical data. Such data cannot be considered as representing facts about any particular equipment; use of averages, estimates, and approximations were necessary to arrive at these typical values. While the approach followed in this study does not preclude certain conclusions, such conclusions should be applied with care in particular conditions. For instance, the optimum module size for equipments having short lifetimes (perhaps missile equipment) may be much larger than is indicated in (3) below; the optimum module size for equipments having long lifetimes (perhaps ground-based or shipboard equipment) may be smaller than is indicated in (3) below.

(1) Performance of piece-part repair of electronic equipment is beginning to exceed and will continue to exceed the capabilities of most of the front-line maintenance activities.

(2) Disposal-at-failure design would help to solve some of the future electronic maintenance problems, and would also be compatible with future design trends.

(3) The use of assemblies or modules (either expendable or repairable) containing from 4 to 8 tubes would lead to lowest over-all procurement cost of an aircraft equipment type for its program life and at the same time aid in the solution of logistic and maintenance problems.

(4) An aircraft equipment type built of expendable 4 to 8 tube assemblies or modules would cost about the same to procure, support, and maintain as would a similar equipment type built with repairable 4 to 8 tube assemblies or modules.

(5) The costs of the expendable and repairable cases are so nearly equal that the claim of excessive cost for the expendable case need no longer prohibit the use of expendable assemblies or modules within the optimum size of 4 to 8 tubes.

(6) The following potential advantages of expendability should be carefully studied; investigation may prove them to be preponderant in a decision for expendability.

Improved reliability of electronic equipment

Improved systems maintenance

Smaller size of equipment

Lighter weight of equipment

(7) Although the guidelines and conclusions presented in this Note pertain specifically to Bureau of Aeronautics* airborne electronic equipment, it is believed that they can be applied with some modification to aircraft electronic equipment in general.

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*Now integrated into the Bureau of Naval Weapons.

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GLOSSARY

AGREE - Advisory Group on Reliability of Electronic Equipment, Office of the Assistant Secretary of Defense (Research and Engineering)

ARINC - Aeronautical Radio, Inc.

Assembly - (See Equipment) A combination of subassemblies and parts joined together to form an element of a unit, and which performs a specific function necessary to the operation of the unit as a whole. Example: amplifier, oscillator, dynamotor, etc.

Attrition rate - The rate at which equipment or aircraft are retired from service, either because of fair wear and tear, or as the result of damage beyond repair.

Embedment - The use of a casting compound, usually a plastic resin, which permeates and encloses a device, and which hardens to form a solid, durable structure. Embedment includes both encapsulation and potting. In encapsulation the embedded device is removed from a mold, while in potting, the mold, which is usually a thin metal housing, becomes a permanent part of the structure.

Encapsulation - (See embedment)

Equipment - Aircraft electronic equipment consists of those installed electronic articles which make up the electronic configuration of an aircraft. Equipment is generally subdivided as follows: system, set, unit, assembly, subassembly, part. Explanations of these terms appear elsewhere in the Glossary.

Failure rate - The rate at which failures occur in electronic equipment, generally expressed as a function of equipment operating hours. Mathematically, the probability of failure in a small but finite interval of time following a period of failure-free operation.

FASRON - Fleet Aviation Service Squadron. The FASRON provides facilities for use by the personnel of the supported operating squadrons in the performance of intermediate-level maintenance. FASRON personnel maintain the FASRON test equipment and bench set-ups, and provide instructions and assistance.

Field Engineer - A civilian employee with an engineering degree or equivalent experience, employed by a private company and assigned under contract to a field maintenance activity for the purpose of assisting and instructing in the maintenance of specific items of electronic equipment.

Life-of-type - The period of years over which operation of a given equipment type within an authorized operating allowance is intended or can reasonably be expected.

Line item - A term used to describe entries (parts, devices, materials) as they appear on requisitions, bills of lading, and other supply documents. Each entry is considered a line item regardless of the quantity of the item.

Maintenance - Maintenance is the function of retaining material in, or restoring it to, a serviceable condition. Its phases include servicing, repair, modification, modernization, overhaul, rebuild, test, reclamation, inspection and condition determination, and the initial provisioning of support items.

Maintenance Activity - Any organization within the Bureau of Aeronautics assigned the mission, task, or functional responsibility of performing aircraft upkeep or rework.

Mean time between failures - Abbreviated MTBF. The average number of hours of operation between failures. Mathematically, the reciprocal of failure rate.

Modular - 1) Dimensioned in accordance with a set of prescribed size increments.
2) Composed of modules.

Module - A modularly dimensioned assembly.

Modulized - Designed and constructed with modules.

MTBF - Mean time between failures. (Defined above).

O & R - Overhaul and repair. (See O & R Depot)

O & R Depot - Overhaul and Repair Depot. The O & R Depot is the highest level of maintenance within the Bureau of Aeronautics and contains complete factory-type facilities and equipment. There are several O & R Depots strategically located within the Continental United States. These are fixed installations, and are staffed by civilian personnel under a military commander. The O & R Depots carry out scheduled overhaul of aircraft and perform repairs which are beyond the capabilities of the lower levels of maintenance.

Overhaul - Overhaul of equipment involves disassembly to as thorough an extent as is required to permit complete inspection, test, cleaning, adjustment, alignment, and service. Parts and portions of the equipment which are found to be unsatisfactory are restored or replaced, so that after reassembly and test, the equipment will comply with applicable specifications.

Packaging - The style of construction of electronic equipment, i.e., whether unitized, modulized, or conventional chassis.

Packing - The wrapping and crating of equipment for storage and shipment.

Part - The smallest complete entity used in the construction of equipment. Applies to all of the "bits and pieces" of which equipment is composed, including the electrical, electronic, and mechanical items and supporting hardware. Typical electronic parts are resistors, capacitors, vacuum tubes, transformers, etc. Parts are not normally susceptible to disassembly for servicing.

Piece part - Refers to the smaller electronic parts, which in general are soldered in, and are frequently inaccessible.

Program life - The period of time over which operation of a type of aircraft or equipment within an authorized operating allowance is intended or can reasonably be expected.

Ready-for-issue - Abbreviated RFI. Equipment or material which is in condition to be issued to a using organization, having been tested and inspected for compliance with all applicable specifications.

Recovery rate - The ratio of the number of defective items eventually restored to RFI condition to the number of defective items turned in for repair.

Reliability - The probability that the equipment will give satisfactory performance for a given period of time when used in the manner and for the purpose intended.

RFI - Ready-for-issue. (Defined above).

Set - (See equipment). A unit or units and necessary assemblies, subassemblies and parts connected or associated together to perform an operational function. Examples: radio receiving set, radar set, sonar set.

System - (See equipment)
1) In equipment: A combination of two or more sets, generally physically separated when in operation, and such other assemblies, subassemblies, and parts necessary to perform an operational function or functions. Examples: navigation system, communication system.
2) Conceptually: A concept or philosophy; a method of achieving an objective. Example: A system (method) of maintenance based on the use of throw-away assemblies.
3) Organizationally: The organization which gives embodiment to a prescribed concept. Example: supply system, maintenance system.

Trouble shooting - The process of locating and determining the corrective action required to rectify discrepancies or malfunctions in equipment.

Unit - (See equipment). A separate package consisting of an assembly or any combination of parts, subassemblies, and assemblies mounted together, normally capable of independent operation in a variety of situations. Examples: receiver-transmitter unit, power supply unit. Note: The unit most nearly corresponds to the notion of a "black box", having a sufficiently distinct function to permit rapid location in trouble shooting, yet small enough to be removed with reasonable effort.

Unit Cost - This term is used in procurement to refer to the purchase price of one of an item, such as a resistor or an assembly. The "item" might be an entire radar set consisting of many separate pieces, in which case the unit cost is the price of one complete radar set.

Usage rate - The rate at which spare parts and other materials are used up and must be resupplied.

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Data Processing Systems. SEAC Engineering Group. Components and Techniques. Digital Circuitry. Digital Systems. Analog Systems. Application Engineering.

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Radio Propagation Engineering. Data Reduction Instrumentation. Modulation Research. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation Obstacles Engineering. Radio-Meteorology. Lower Atmosphere Physics.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Electronic Calibration Center. Microwave Physics. Microwave Circuit Standards.

Radio Communication and Systems. Low Frequency and Very Low Frequency Research. High Frequency and Very High Frequency Research. Ultra High Frequency and Super High Frequency Research. Modulation Research. Antenna Research. Navigation Systems. Systems Analysis. Field Operations.