FOREWORD

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ABSTRACT

Increasing need for earlier estimates of manning, skills and training requirements led to the development of mathematically sophisticated techniques capable of computing and assessing requirements at every phase of system development. Current methods are largely intuitive, rely on bookkeeping procedures, and are seldom applicable at pre-hardware stages of system development. Needed was a method for making trade-offs when investigating alternatives in system design. The method presented here begins with an analysis of hardware functions and develops human requirements in terms of operational needs and service rates. Manning and skill requirements are integrated over such factors as desired operational readiness, schedules of mission frequency, various environmental demands, maintenance concepts and procedures, and training requirements. Two mathematical techniques; queuing theory and linear programming, are used to compute manning requirements and training needs. In practice, failed systems or units pile up in lines waiting for service, or else men are incompletely utilized. Queuing tables permit trade-offs between men, skill levels, sparing levels and downtime with given values for operational readiness. The Simplex algorithm permits trade-offs and optimal determination of training needs for given policies of phaseover and training cost. An advantage of the method is that its formal and mathematical structure permits objective assessment at all stages of system development.

PUBLICATION REVIEW

This technical documentary report is approved.

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LIST OF SYMBOLS

Because of the many topics and factors covered in the text and appendices, it was desirable to use particular symbols for more than one purpose. Symbols used throughout the text with the same general definition, are given below. Other symbols used only in a single section or appendix are defined in the text at their first use with a particular meaning.

1. d = average duration of each occurrence: task, operation, etc.

2. f = basic measure of frequency: frequency of task occurrence or average frequency of operations per unit of time (T); e.g., number of missions per day

3. L = number of spares (51)[1] per shop

4. N = number of equipments assigned to the organization: number of operational units (32)

5. N_o = number of equipments out of N actually capable of operating satisfactorily

6. N_d = number of equipments down (i.e., incapable of operating satisfactorily)

7. R = operational readiness (30)

8. r = number of maintenance channels (23)

9. T = time, usually an arbitrary period to be fixed at a convenient value in a particular problem (see text for particular meanings of subscripts)

10. t = time (see text for particular meaning)

11. W = Workload (67)

12. λ = failure rate (15), the reciprocal of Mean-Time-Between-Failures (MTBF)(26)

13. μ = repair rate (45), the reciprocal of Mean-Time-To-Repair (MTTR)

14. ρ = utilization factor (62)

15. ρ_A = adjusted utilization

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[1] Numbers in parentheses refer to entry numbers in the Explanation of Terms.

EXPLANATION OF TERMS

1. Allocability - The extent to which a maintenance task may practically be assigned to echelons other than the first. Depends on ease of separation of relevant hardware from the system or equipment.

2. Arrival rate - The rate at which units requiring performance of particular maintenance tasks or groups of tasks arrive at a given maintenance shop, group of shops or maintenance level as specified.

3. Black box - A discrete, physical component (sub-unit) of an operational unit to which may be identified or assigned a rate of failure and a time to repair, and which may be moved from one location to another independent of the next higher level of assembly.

4. Calendar Maintenance - Tasks which are performed regularly, being scheduled on a calendar basis; e.g., daily, weekly, monthly, etc. A type of preventive maintenance typically performed on items subject to continuous or uniform usage (e.g., BMEWS).

5. Channel - See maintenance channel.

6. Constraint - Any restriction or condition which bounds the value a variable or parameter may assume; e.g., manning must not exceed 100 men. For example, number of men available and training facilities available frequently act as constraints on the training program which can be undertaken to obtain a particular number of men with particular skills.

7. Conversion - Converting a man from one skill field to another by means of retraining.

8. Demand Rate - The average number of man-hours per time period (of maintenance) which arise from operation of the equipment or system.

9. Downtime - Time during which the operational unit or subsystem is not available for operational use because of maintenance or other factors.

10. Echelon - A maintenance level consisting of one or more maintenance shops responsible for performing certain specified maintenance tasks; e.g., organizational, field, and depot. These levels serve to break down the functions of maintenance into smaller, more manageable units, and designate responsibilities for performing tasks in different units.

11. Essential Function - A function of a system which is required for the system to accomplish its primary mission. See also Non-essential Function.

12. Exponential Distribution - A probability distribution having the form

$$P(t=T) = \frac{1}{\mu} e^{-T\mu^{-1}}, \quad \mu > 0, \; T \geq 0, \quad \text{frequency distribution}$$

$$P(t \leq T) = 1-e^{-T\mu^{-1}} \quad \text{cumulative distribution}$$

where the mean and variance are both μ^{-1}.

In this report the time between failures of equipment and time to repair failures both are assumed to be distributed exponentially.

13. Factor (in manning) - A characteristic of a system (or an equipment), its hardware, its configuration, its application, its deployment, its maintenance support philosophy, etc., whose state or value has significant effect on the skill or number of men required to man it.

14. Failure - A failure is an occurrence, either catastrophic, or gradual deterioration, which causes performance of the equipment to deviate from specified limits.

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

16. Finite Population - A fixed number of items less than infinite.

17. Frequency - The rate at which accomplishment of specific operations or duties occur. Normally refers to the total number of such events during some calendar time period.

18. Function - General description of an integrated group of equipment which performs an essential role associated with the operational unit; e.g., Fire Control, Utility Hydraulic System, Electrical System.

19. Levels of Assembly - A rough measure of the size and/or complexity of a subdivision of an equipment. Except for the lowest level of assembly, the part, each level of assembly is made up of several members of lower levels of assembly. Below are listed, from high to low level of assembly, two examples of members of various levels of assembly.

Aircraft	Radar set
Engine	Rack
Oil pump	Drawer
Cylinder assembly	Printed-wiring board assembly
Gasket	Resistor

20. Level of Protection - In reference to inventory, the probability that an item will be in stock when it is required. Depends on demand rate, sparing quantities, reorder point, and delivery time.

21. Linear Programming - A mathematical tool for finding an optimum combination among many alternatives where there are certain linear relationships among the items involved and certain limits (constraints) on the values which they may take. For details see a standard text such as Reference 3.

22. Maintainability - Ease of repairing an item given a particular combination of maintenance equipment and replacement parts and sub-assemblies. Generally measured in terms of mean-time-to-repair(MTTR)or its inverse repair rate (μ).

23. Maintenance Channel - Combination of men and equipment required to perform a particular task or groups of tasks.

24. Manning Requirements - A detailed breakdown of the manning required to meet specified operational requirements of a new weapon system.

25. Maximum Allowable Downtime - Time that a system may remain inoperative for the performance of a maintenance task.

26. Mean Time Between Failures (MTBF) - Average time per item between occurrence of failures. May be estimated by dividing operating time by the number of failures occurring during this time. It is the reciprocal of the mean failure rate (λ).

27. Mobility - A measure of how quickly the system/equipment can be relocated.

28. Non-essential Function - A function of a system or equipment which is not required for performance of its primary mission but which may enhance safety, flexibility, comfort and/or if only to a slight degree, probability of success.

29. Operational Performance - A measure of how well the system will perform its job.

30. Operational Readiness - The average percent of on-line units which are operational at a given time when they are intended to be.

31. Operational Requirements - A statement of operational readiness level required of the operational units, total operational hours, capability of the operational units during a specified period of time, and the number of missions required of the operational unit during the specified period.

32. Operational Unit - A unit of equipment which is capable of operating alone; can be assigned a mission, and is the basis for a calculation of operational readiness.

33. Operator Task - A single action or series of actions (manipulative, audio, visual, tactile, mental, etc.) required in the operation of a weapon system.

34. Parameter - A quantity to which may be assigned arbitrary values, as distinguished from a variable, which assumes only values that the form of the function makes possible. For example: the operational readiness specified. Values may be arbitrarily assigned.

35. Performance Requirements - See Operational Requirements.

36. Personnel Availability - A measure of resources of men and skills that are available outside the system to man the system.

37. Phaseover - The process of removing installations of one system from Air Force inventory and adding installations of another system. May involve modification of auxiliary equipment and facilities, and also of skills of personnel. The latter is accomplished thru special training in the new system for men with usable skills and retraining of men with surplus skills.

38. Preventive Maintenance - The care and servicing by user personnel for the purpose of maintaining equipment in satisfactory operating conditions by providing for systematic inspection and correction of incipient failures either before they occur or before they develop into a major failure. Includes scheduled calendar maintenance, scheduled usage maintenance, and scheduled per usage maintenance, which see also.

39. Primary Duty Assignment - The type of duty to which personnel are allocated during their normal on duty shift period, and which is directly connected with the operation and maintenance of the weapon system.

40. Queue - A waiting line of units which require some form of service (normally maintenance repairs).

41. Random Usage Maintenance - These tasks are performed as the need arises, as a result of the failure rate of the equipment. Sometimes referred to as corrective maintenance. Compare with Preventive Maintenance.

42. Redundancy - Duplication of function such that there are two or more alternative means of performance.

43. Reliability - The probability that an equipment or system, initially operating satisfactorily, will continue to operate satisfactorily for a specified period of time, or until a specified mission is accomplished.

44. Repair Channel - See Maintenance Channel.

45. Repair Rate - The reciprocal of the average time spent per channel in repairing an item excluding delays such as "wait for spare part to be delivered," etc.

46. Repairs - Refers to all direct physical actions required to return the item to proper working order. This includes such actions by the repairman to obtain necessary spare parts and tools.

47. Scheduled Calendar Maintenance - See Calendar Maintenance.

48. Scheduled per Usage Maintenance -Tasks which must be performed after a specific number of occurrences of some operation or action. A type of Preventive Maintenance typically performed on aircraft and other equipment requiring replenishment of energy supply (refueling) or containing items with high rate of wearout (e.g. aircraft tires)or damage (e.g. aircraft skin).

49. Scheduled Usage Maintenance - Tasks which are performed after fixed amounts of elapsed operating time. A type of Preventive Maintenance typically performed on equipment not operated uniformly per day (e.g. aircraft).

50. Skill Levels - The classification system used to rate maintenance personnel as to their relative abilities to perform maintenance.

51. Spare(s) (noun) - Systems, equipments, or black-boxes kept in reserve, unused until needed to replace a similar failed item so that there will not be a reduction of the number of operational systems of equipments. When the failed item is repaired it becomes a spare if it is not needed to provide the desired number of operational systems or equipments. Do not confuse with spare parts.

52. Spare Parts - Non-repairable items at lowest level of assembly held to replace similar items whose failure caused failure of a higher level of assembly.

53. Status Evaluation - A determination of the state that an equipment is in, i.e. operative, inoperative or standby status.

54. Subsystem - Major functional equipment or group of equipments of operational unit or support system, essential to operational completeness.

55. Support System - the maintenance personnel, equipment, spares and spare parts as organized into shops, echelons, with assigned responsibilities.

56. System Utilization Factor (ρ_s): The ratio of the total system arrival rate to the total system repair rate. For cases in which there is one operational item and one repair channel, ρ_s is equal to ρ; i.e., total failure rate of all operational items, divided by the product of the number of repair channels and the repair rate of a repair channel.

57. Task - A specific goal to be achieved given a specific stimulus. See page 8 for discussion.

58. Task Allocation - Assignment of tasks for performance at particular echelons. See also allocability.

59. Task Package - A group of tasks to be performed on an equipment or system requiring the same skill field, which are assigned to be performed sequentially in the same channel (i.e. by the same man or crew).

60. Uncontrolled Downtime - Downtime which cannot be scheduled or postponed because the item is effectively inoperable. Typically associated with failure or replenishment (e.g. refueling or replacing a worn tire). May involve a wait for the availability of a maintenance channel or of a spare part as well as actual performance of tasks required to render the item operable. Contrast with Calendar Maintenance which may be done in advance of schedule or postponed behond scheduled time without greatly impairing operability.

61. Unreadiness (U) - State of an equipment or system not being available to perform its primary mission. The complement of Operational Readiness, R (i.e. U=1-R and R=1-U).

62. Utilization (u) - The average fraction of available duty time in which each repair channel is actually engaged in making repairs. Note that utilization, u, is not necessarily the same as the system utilization factor. The difference arises from the fact that the ρ_s is based on repair channels and operational units presumed to be all operating; whereas, u must account for the operational units being down due to failure, and for spare units which may be substituted for failed operational units.

63. Utilization Factor (ρ_s): A ratio, the failure rate of an item, divided by the repair rate of the item. Queuing tables are usually based on the utilization, since it is invariant with changes in number of operational items and repair channels.

64. Variable - A quantity that may assume a succession of values that need not be distinct, but which can only assume those values that the form of the function makes possible.

65. Waiting Line - See queue.

66. Weapon System - An instrument of combat such as an air vehicle, together with all related equipment (airborne and ground), skills and supporting facilities necessary to operate the equipment.

67. Workload - Average man-hours of effort of a particular skill caused by the operation of an item or group of items when they are operated according to specified requirements.

1. INTRODUCTION

There is a pressing need for objective methods by which the engineers who design systems can be influenced by the manning (including skills and training) to be available for operational support of that system. A necessary first step toward meeting this need is the development of methods which enable engineers to compute and assess (at a very early time in the systems design) the manning and skill and training requirements for a given system design(s) with accompanying operational and maintenance concepts. This publication reports on a study to: (1) Identify significant system variables that affect the requirements for manning, skills and training; (2) Quantify the information about these variables; and (3) Develop mathematical techniques for relating these variables during the conceptual phase of system design and to compute, predict and/or control the manning and skill requirements. In addition, the techniques developed permit use of the limited early system functional information for making trade-offs between such future requirements as missions, operational readiness, manning, training, skills, maintenance and spares. These techniques and trade-offs should not only improve system design by contractors but provide data required by in-service planners who are responsible for manpower, personnel, training, maintenance, supply and related Air Force programs.

1.1 Basic Manning and Skill Identification Technique

The approach taken in this program was based on a mathematical model relating significant variables associated with manning and skill requirements: (a) task identification which determines skill; and (b) operational performance requirements. The operational requirements were: (1) R, operational readiness specified for the system -- a condition that must be satisfied; (2) capability of each operational unit to operate a total of t_o hours or d hours per mission for f missions per calendar time-unit.

In general, at any stage of development, the manning prediction is based on an estimator of information that will be available in a succeeding stage.

The task description (item a above) must be estimated based on system definition. Operational requirements (item b above) is basically the description of the system in terms of strategic requirements related to manning. In fact, item b may be used to characterize the different commands and/or systems for purposes of manning. For example, operational requirement values for various organizations might be these letting N represent number of equipments assigned to the organization:

SAC Bomber Squadron

R = .88, f = 1 mission/day, d = 6 hour mission N = 18

Intercept Squadron

R = .88, f = 8 mission/day, d = 2 hour mission N = 18

Tactical Fighter Bomber Squadron

$R = .84$, $f = 4$ mission/day, $d = 4$ hour mission $N = 18$

Minuteman Missile Wing (continuous operation of one shot silo)

$R = .97$, $f = 1$ mission/day, $d = 23.5$ hour mission $N = 50$

The operational requirements should be based on required performance capability.

In establishing operational requirements, it is desirable to differentiate between maximum, average, and required performance capability.

(a) Maximum operational requirements are difficult (if possible) to quantitatively specify.

(b) Average performance requirements are those that can be expected in a quiescent state in the usage the system experiences as the result of either training personnel or equipment exercising. Average performance may be considerably less than performance capability required.

(c) Required performance is the expected requirements under deployment conditions for which the system was designed to operate (i.e., actual mission conditions).

For some systems the mission is such that average and required performance capabilities are the same (e.g., Minuteman, SAC).

1.1.1 Manning Prediction Problems Resulting From Change

Manning prediction problems arise from change. Where changes are in details of existing systems, the problems, typically, are of the bottleneck type. Where the system itself is more or less new (for example, the ballistic missile in 1955), problems may be system-wide. Changes in applications of equipment may also cause trouble, primarily because the short time between concept and application allows little margin for adjustment in training and assignment.

1.1.2 Hardware and Applications, Analysis Essential

The foundation for the prediction of personnel requirements lies in the hardware, its associated manning and skill parameters, and its applications. It cannot lie in the mission, because the same mission may be accomplished by different hardware which requires different manning; e.g., SAC bombers vs. ICBM's. Particular performance characteristics can be modified by different hardware changes, each of which has or may have a different effect on manning. Radar performance, say, might be improved by:

a. improving the antenna, causing negligible effects on skill or manning requirements;

b. improving or adding to the electronics, perhaps causing a wide range of effects on manning and skill, depending upon the differences in components, complexity, etc.;

c. operating existing equipment at higher power, which adds to quantitative maintenance requirements (increased failures because of increased stress).

Consequently, the hardware itself must be analyzed.

Just as very different changes in hardware may be used to accomplish an identical result, so may a particular type of change in hardware be used to bring about a variety of changes in performance. For example, in aircraft, weight reduction, whether undertaken to improve climb, speed, payload, range or whatever, will depend only upon the means of change for its effect on manning. Similarly, elimination of an equipment from an aircraft as a means of weight reduction may have several effects on personnel requirements, among which may be the following:

a. If the equipment which is to be eliminated performs a nonessential function (one not required for satisfactory performance of missions), operator manning can be affected in the same ways as maintenance manning would be when the function is eliminated.

b. If the equipment which is to be eliminated performs an essential function increased skill requirements and increased workload may both be called for on the part of the operator (It is unlikely that a weight saving can be made by substituting an additional man.).

c. Where elimination of equipment increases operator stress significantly, manning may have to be increased to provide additional rest between missions, or replacement rate must be increased because of reduction in tour of duty. If these positive actions are not taken, manning problems may result from low re-enlistment rates or poor morale.

1.1.3 Problem Areas, Aids to Discovery

No simple set of rules can substitute for comprehensive analysis of a manning problem. However, there are symptoms which are frequently associated with manning problems. Among them are these:

a. Many events must take place almost simultaneously (as in the launching and tracking of a programmed multi-stage rocket);

b. Scattered dispersal (as Minutemen in solos);

c. Physical limits of materials are being approached (as skin of supersonic aircraft); and

d. Anything new in principle or application, for which the problem is only temporary until the equipment has been debugged, and/or until people become familiar with it.

1.2 Prediction

1.2.1 Prediction by Extrapolation

All scientific prediction requires extrapolation. Accurate prediction requires appropriate extrapolation, based on an understanding of causal relations.

A typical class of subsystem is likely to follow a pattern which may include the following phases:

a. Diminished requirements attributable to debugging improvements, both in the equipment design itself and in maintenance methods and equipment.

b. Increased requirements of increasing complexity, sophistication, etc., concurrent with improvement in component reliability, which itself tends to decrease requirements.

c. A leveling-off because of approach to some physical limit; e.g., sensitivity of receivers due to thermal noise in tubes in first amplifier stage.

d. Drastic change (discontinuity) resultant from major technological change.

e. After each drastic change the general pattern is repeated.

Such a pattern might be illustrated by communications electronics wherein the electron tube marks the first drastic change; semiconductors, the second. A third may be impending in the form of micro-electronics. The latter two are associated with reduction in quantitative maintenance requirements; semiconductors achieved this by virtue of their much greater reliability than tubes.

1.2.2 General Approach to Prediction

Because of the need for hardware analysis and operational performance requirements, a causal mathematical model approach was pursued for manning prediction and skill requirements.

The mathematical model relates:

a. black boxes[1] and associated repair and failure rates;

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[1] Black box as herein used is defined as a discrete, physical segment of an operational unit which possesses demand rates for the occurrence and performance of maintenance and also the characteristic of allocability. For further descriptions and discussion of this concept, see Section 3.2.2, Appendix VII and Explanation of Terms.

b. personnel;

c. spare black boxes; and

d. waiting time to make a black box available after demand.

The output of the mathematical model (waiting time) is related to the system operational requirements and through application of an algorithm allows the achievement of minimum manning for specified system operational requirements.

A summary of the technical approach taken to establish a manning technique follows. In practice, repetition of all of the broad steps given would not be required after initial accomplishment.

1.3 Summary of Manning and Skill Requirement Prediction

1.3.1 Specification of Operational Requirements

a. Specify the operational readiness (R) required of each operational unit (an equipment which is capable of operating alone and which can be assigned a mission).

b. Specify the fraction of calendar time which the operational unit must be capable of operating, or specify the number of operations per unit calendar time (f) of which it must be capable and the average duration of each operation (d).

From operational readiness we may determine the probability of having at least some specified number (say n) of N_O operational units operationally ready at a randomly selected time or, conversely, we may specify the probability that n or more units must be operationally ready at a randomly selected time, and thereby establishing R for an operational unit by using the approximation (Binomial Probability Distribution):

$$P(N_o \geq n) = \sum_{N_o=n}^{N} \frac{N!}{(N-N_o)!N_o!} R^{N_o}(1-R)^{N-N_o} , \quad 1 \geq R \geq 0 .$$

where N is the total number of equipments assigned to the organization.

1.3.2 Factors Determining Operational Readiness

Operational readiness is fixed by the following:

a. The fraction of time during which the operational unit is actually operating,

b. the fraction of time during which the unit is ready to go into operation upon command; and

c. the fraction of time that the unit is in neither state a or b, which is the time the unit or some vital part of it is either awaiting or undergoing repair.

Thus, operational readiness, R, is defined as

$$R = \frac{T-T_d}{T} = \frac{N-N_d}{N},$$

where T = total time, T_d = total downtime, N = units assigned to the organization, N_d = units down.[1]

1.3.3 Contributions to Downtime

Most downtime can be attributed to waiting for maintenance and the performance of maintenance. Maintenance may be categorized as:

a. Scheduled Calendar Maintenance, which is performed at approximately uniform time intervals. It may be performed earlier or later than the nominal time at the convenience of the organization commander. The actual performance is timed to minimize waiting for maintenance by this or other equipments. This is typically associated with equipment which undergoes continuing operation or is operated at a uniform rate; e.g., Minuteman and BMEWS.

b. Scheduled Usage Duration Maintenance, which is performed after a specific amount of operation; for example, "after 500 flying hours" or "after 10 hours at supersonic speeds." Like calendar maintenance, its time of performance is not rigidly determined: it is done at a convenient time, approximately when it is due. It is typically associated with equipment which often is used intermittently and irregularly; for example, aircraft.

c. Scheduled Per Usage Occurrence Maintenance, which is performed before or after each occurrence of particular events, such as aircraft flights and firing of guns (cleaning when fired on a flight, replacement of bullets fired). In this category fall positive maintenance actions, such as refueling.

d. Random Usage Maintenance, which is performed to remedy actual failures which are detected as a result of operation, checkout or inspection of the equipment. Occurrence is more or less random with respect to time and corrective action is generally not postponable. Consequently, it can cause downtime due to waiting for maintenance as well as for the actual maintenance itself.

These four maintenance categories exhaust all kinds of maintenance performed on an operational unit.

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[1] A method for estimating these times is covered in Section 3.

1.3.4 Data Requirements for Estimation of Downtime

To estimate the downtime of an equipment or an operational unit caused by performance of maintenance, it is necessary to know:

a. skills required to perform the maintenance tasks[1] associated with the equipment,

b. the frequency of occurrence of each type of maintenance task,

c. average time of each skill required to perform maintenance tasks.

To the extent practical, these data should be obtained for each black box in the equipment.

It is desirable to use the best available estimates of these data in predicting manning requirements. Section 2.3 describes methods of estimating these data. The choice of method depends on the detail of the information available concerning the equipments and their applications.

Accuracy in the data concerning the amount of equipment is of special importance. For example, if the preliminary operational unit's configuration requires one computer (of the RCA 301 type) and the final configuration incorporates four such computers (which have not been considered in establishing manning), a serious undermanning can be anticipated. A prediction technique which guarded against undermanning due to errors of this type, would generally cause serious overmanning.

1.3.5 Means for Affecting and Controlling Downtime

For each black box or other system subdivision for which data is obtained as in 1.3.4 above, the means by which downtime can be significantly affected, can be determined.

Possible means include:

a. Design modification to reduce failure rate (and, thus, downtime) by using more reliable parts not requiring significantly greater time to repair at a cost of additional money, weight, and/or volume.

b. Design modification to provide features to facilitate maintenance (beyond those implicit to good design) for example, automatic checkout equipment.

c. Design to provide redundant black boxes in the equipment or redundant equipment in the system (appropriate for continuously operating stationary ground equipment).

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[1] See 1.3.6 and 3.2.2 for detailed definition and discussion of "task."

d. Auxiliary equipment designed to facilitate maintenance in either testing or handling.

e. Provision of spare black boxes to permit replacement at the black box level so that repair of the black box will not normally cause downtime.

f. Provision of extra maintenance capacity (equipment and/or personnel) to allow parallel effort on a single equipment or system when simultaneously occurring tasks require the same skill. Note that safety requirements, functional interactions, or interference in access may not allow simultaneous performance of certain tasks.

1.3.6 Definition of Task

The term task is used in this report in a generic sense. It is not intended to imply a fixed degree of detail but to convey instead definition of the system in terms of work to be performed. The usefulness of the term lies in the ability to associate skill and skill workload with the task and thus a means of estimating total workload by skill.

The task is defined as: A specific goal to be achieved, given a specific stimulus. Associated with each task are three task descriptions: (1) time to achieve the goal measured from the time the stimulus is applied, (2) the frequency of occurrence of the stimulus, and (3) the number and skill distribution of personnel required to perform in the achievement of the goals.

From the viewpoint of manning, the task "maintain the operational unit" represents the highest level of abstraction. The goal is to keep the operational unit capable of operation, while the stimulus is the activation of the system. A task at this level of abstraction is of little use for computing manpower requirements. What is required is a degree of detail which will permit counting of skill workloads and personnel of a specific skill and level.

The degree of detail that tasks will be defined will depend on two factors: (1) knowledge of the hardware parameters (failure and repair rate, etc.), and (2) the level of task definition at which further useful information for manning estimation is not gained. Probably, the most efficient level of detail (efficient in the sense of time spent determining personnel required) is the black box level (see section 2.3.1). At this level the task and task descriptions are associated with a physically discrete, and removable entity of the operational unit and readily handled in a mathematical sense. In the latter case the stimulus would be failure (or recognition of failure) of the black box, and the goal would be the restoration of the black box to operational status.

Maintenance tasks can be examined to determine the organizational level at which they should be performed; for example, organizational, or depot. Some tasks may be reasonably assigned to several levels, in which case reference must be made to a maintenance philosophy imposed on the system or developed in conjunction with the manning analysis. Assignment will depend on factors such as: special equipment required, special skills required, workload on these from a typical organization (squadron) or base, and ease of sending the maintenance task to another location.

1.3.7 Personnel Trade-offs

Using the data developed above, a feasible manning schedule can be developed as a starting point for making trade-offs. A convenient starting point is the minimum manning schedule possible where the spares assignment is minimum and only necessary special equipment is available.

a. Trade-offs among downtime, personnel, special equipment, and spare black boxes can be made utilizing data developed according to the requirements above.

b. The requirements for active available manning can then be modified by adjustment factors to determine appropriate manning assignments. Adjustment factors must allow for furloughs, training, multiple shift operation, special environmental conditions, etc.

2. MANNING AND SKILL SENSITIVITY PARAMETERS

2.1 Introduction

A multitude of factors are directly or indirectly related to system manning requirements. An analysis of the significant factors[1] has been made and the results appear in Tables 1 and 2. In these tables, the description of each factor includes its identity and the measures of primary concern to manning. Each factor is mated with its relationship to personnel in a system. The measures are given below the identification of the factor. The personnel are classed in either maintenance (M) or operator (O) categories. Relations given in the tables represent rough cut effects of a change in the factor as reflected in changed manning requirements.

Factors have been selected according to their potential importance. In particular situations, any factor may loom larger than others. The magnitude of effect of a particular factor depends on the magnitude of its change.

Ease of estimation of the effects of a factor is closely related to the basic ease of measurement of the factor itself. However, in most cases, the uncertainty of an estimate stems more from the uncertainty of input data to the estimating process than from errors in the estimating process itself. Uncertainty of input is inevitable. By using these factors as guides, the degree of uncertainty is minimized through clear establishment of the type of input data that is needed. Here, the benefit lies in assuring that valuable data which is attainable will be made available.

Factors in the tables may be classified both according to their association with the equipment and to their effects on the manning requirements of the system. Table 1 contains factors relating to hardware and its applications. Table 2 contains factors relating to support equipment and organization. Some factors primarily affect the man-hours of actual labor required while others primarily affect the efficiency with which men can be used - the fraction of the time they are working productively.

In Table 1, the specific factors can be categorized as follows:

1 to 6 - Characteristics appropriate to estimation of requirements for skill and man-hours of actual labor. Apply at all levels.

7 to 9 - As applied to hardware, same as 1 to 6. As applied to personnel, characteristics of the utilization of the hardware which affect the accomplishments possible by a man in a given time.

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[1] For explicit definition of "factor" see item 13 in Explanation of Terms.

TABLE 1

EFFECT ON MANNING AND SKILL OF FACTORS IN DESIGN AND APPLICATION OF OPERATING EQUIPMENT

	Factor Measurement**		Effect on Personnel
1.	Number of Similar Items	M*	Proportional on Manning
	Count	O*	Proportional to negligible
2.	Size, Weight, Volume	M&O	Negligible. Within an order of magnitude, size per se generally has relatively little effect on manning except where heavy items must be man-handled, and where, in rare instances, tasks are dependent on size as in cleaning (important for high speed aircraft).
	Weight, Volume		
3.	Addition (or elimination) of a function, or change in means of performing an existing one: (a) new system or equipment; (b) existing equipment.	M	Changes relative demand for different skills.
	Type of hardware (electronic, mechanical...) (See also entries 4, 5, 8, 9 and 11 below.)		(b) only - May increase demand for skills required for maintenance of items whose access is worsened by new addition.
4.	Maintainability	M	On manning, proportional (as weighted by failure rate).
	Mean-time-to-repair and skill level required.	O	Negligible

*M = Maintenance; O = Operating
**The measurement of the factor is given below the factor and indented from it.

TABLE 1 (Contd)

EFFECT ON MANNING AND SKILL OF FACTORS IN DESIGN AND APPLICATION OF OPERATING EQUIPMENT

	Factor Measurement		Effect on Personnel
5.	Reliability	M	On manning, proportional (as weighted by repair times).
	Failure rate including all part or adjustment failures.		
6.	Average mission duration and frequency or, for items having continuous mission, the fraction of time at high stress.	M	Manning is proportional to duration of stress applied to equipment during the mission.
	Operating hours per hour and/or missions per hour, and proportion at each stress level (e.g., fraction of mission flown at supersonic speeds or with afterburner on or fraction of time transmitter is on).	O	Manning is proportional to negligible depending on initial efficiency in use of operators.
7.	Stress Severity	M	According to effect of stress on failure rate or on need for preventive maintenance.
	Temperature, g's (shock and vibration) (e.g., supersonic vs. subsonic flight).	O	a. Negligible where stress is on equipment. b. Negligible to proportional depending upon the extent to which the operator's ability to withstand the stress is the limiting factor to his workload.

TABLE 1 (Contd)

EFFECT ON MANNING AND SKILL OF FACTORS IN DESIGN AND APPLICATION OF OPERATING EQUIPMENT

	Factor Measurement		Effect on Personnel
8.	Climate at site (if equipment is not in controlled environment). Temperature, humidity and wind profiles. Inches of rain, inches of snow.	M	Manning increases as extremes in environment increase on equipment and thus increase failure rate. Increases as environment increases time to repair exposed items.
		O	Increases as extremes in environment reduce working hours per day, per operator.
		M&O	Where climate regularly affects relevant travel time - fog, snow, muddy roads, etc. - appropriate adjustments are required. Overtime will generally compensate for occasional delays
9.	Other environmental factors such as dust, salt spray, insects, etc. Effect on failure rate and/or working efficiency.	M&O	Increases failure rate and/or reduces repair rate according to severity (specific analysis is required).
10.	Packaging Number of levels of assembly which are plug-in.	M	Facilitates centraled repair of the lower levels of assembly, reducing manning, especially high skills. See also Table 2, entry No. 4.

TABLE 1 (Contd)

EFFECT ON MANNING AND SKILL OF FACTORS IN DESIGN AND APPLICATION OF OPERATING EQUIPMENT

	Factor **Measurement**		**Effect on Personnel**
11.	Automaticity (degree of).	M	Increases skill level and manning.
	Man-hours of effort performed by operator compared to those performed automatically; (i.e., the number of man-hours required if work were done manually instead), and/or men replaced by automatic features compared to men required and/or reduction in operator skills required. (Consider only tasks which could be performed either automatically or manually.	O	Reduces skill level and/or manning.
12.	Dispersion	M	Manning increases with increased dispersion. Rate of increase decreases the higher the echelon considered.
	Travel time between units by "practical" means of transport of maintenance man, or failed and replacement items.	O	Negligible
13.	Isolation	M	Manning increases to the point that shared facilities are not used.
	Travel time to nearest facilities which can be shared.	O	Negligible except as services can be shared (e.g., communications).

TABLE 1 (Contd)

EFFECT ON MANNING AND SKILL OF FACTORS IN DESIGN AND APPLICATION OF OPERATING EQUIPMENT

	Factor Measurement		Effect on Personnel
14.	Uniformity of mission occurrences (applied primarily to aircraft flights - ground equipment generally has "continuous" mission as used here). Coefficient of variation[1] of number of missions per T where T is maintenance time per mission.	M&O	Manning decreases with increasing uniformity because workload is more uniform and men can be utilized more efficiently.
15.	Maximum Allowable Continuous Downtime and/or Operational Readiness. Time permitted	M	Manning increases as the limit on downtime is lowered or as operational readiness requirement is increased.

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[1] Coefficient of variation (standard deviation/mean) is inversely related to uniformity. For random occurrence (Poisson events), the value is 1. For bunching (e.g., flights of several aircraft on the same combat mission event), the value is greater than 1. For spacing (e.g., patrol flights by single aircraft), the value is less than 1.

TABLE 2

EFFECT ON MANNING AND SKILL OF FACTORS IN EQUIPMENT AND ORGANIZATION FOR MAINTENANCE SUPPORT

	Factor Measurement**		Effect on Personnel
1.	Automatic Checkout Equipment (ACE) and Special Test Equipment (STE). Man-hours of effort performed by user compared to those eliminated by automatic features, and/or men replaced by automatic features compared to men required and/or reduction in operator skills required. (Consider only tasks which could be performed either automatically or manually.)	M*	Proportionately reduces manning and skill required for direct maintenance. Increases demand for high skill required to maintain ACE and STE.
2.	Shift from local to centralized maintenance when, locally, there is: (a) low utilization, (b) moderate utilization, (c) high utilization. Squadrons supported per shop.	M	a. Increases total manning slightly if local manning is not reduced. Decreases manning by large factor if local maintenance is reduced. b. Reduces manning when local manning is reduced appropriately. c. Little change if local manning is reduced appropriately.
		O*	Negligible except as operator performs maintenance.

*M = Maintenance; O = Operating

**The measurement of the factor is given below the factor and indented from it.

TABLE 2 (Contd)

EFFECT ON MANNING AND SKILL OF FACTORS IN EQUIPMENT AND ORGANIZATION FOR MAINTENANCE SUPPORT

	Factor Measurement		Effect on Personnel
3.	Logistics Delays Time between order and delivery.	M	Lessening of logistic efficiency implies lowering of operational readiness. Increases in manning necessary to compensate. Increase in skill, also may lead to more use of non-standard fixes in emergencies.
4.	Highest Level of Assembly Spared on Site (for each part of equipment). Mean-time-to-repair by replacing at that level of assembly.	M	Reduces on-site manning and, if these levels are repaired at higher echelons, often reduces skill requirements.
5.	On-site inventory of spare parts and assemblies. Level of protection against shortage.	M	Lower level of protection implies lower operational readiness unless increased manning is used to compensate.

10 to 11 - Characteristics of the system at the equipment level which affect the requirements for skill and actual man-hours of labor.

12 to 13 - Characteristics of the organization using the equipment, which affect the efficiency with which men can be used (i.e., proportion of time which men are not "idle" with respect to their duties associated with their primary AFSC).

14 to 15 - Characteristics of the use of the equipment which affect the efficiency with which men can be used.

For Table 2, the factors may be categorized as:

1 - Characteristics of maintenance equipment affecting skill and man-hours of effort required to maintain the operating and maintenance equipment.

2 - Characteristics of organization for maintenance which affect the efficiency with which men can be used.

3 to 5 - Characteristics of organization for maintenance and logistics which affect equipment downtime for repair. Manning often may be traded off with these characteristics in order to achieve a specified operational readiness.

The factors which affect the amount of actual man-hours of labor required, can be dealt with directly. Those affecting "idle" time require dealing with the interrelations of various factors which are involved in queuing problems.

2.2 Conditions of Applicability

The applicability of Tables 1 and 2 is limited as follows:

a. Relationships provide appropriate approximations wherever new systems or equipments can be viewed as consisting of hardware similar in type to that of existing systems or equipment. The accuracy of the estimate will depend, in part, upon the degree of similarity. For example, application of relationships to maintenance manning requirements on inertial navigation equipment are appropriate using other inertial navigation equipment as a basis for comparison, but not using stellar navigation equipment. Note, however, that computers in both systems might be appropriately compared. (Where novel equipments are encountered, approaches presented in Section 3.2 and in Appendix VII should be applied.)

b. The consequences of queuing must be considered as modifying all effects in the tables. General queuing effects are discussed in Sections 3.1.2.1 and 3.1.2.2. Quantitative effects can be estimated by making appropriate calculations. Tables for some situations are tabulated in Reference 5, Peck and Hazelwood, Finite Queuing Tables.

c. Manning adjustments should always be based upon personnel skill specialty codes, since reductions or increases in manning are directly related to reductions or increases in specific skill hours of work available.

2.3 Techniques for Estimating Manning and Skill Parameters

A revised system will be comprised of the following types of equipment:

a. Off-the-shelf items; i.e., equipment of types and kinds already in existence.

b. Equipment that is similar to presently existing equipment.

c. Relatively novel equipment

For each of the above types of equipment, at any time in the development cycle, information which can be utilized for the prediction of manning workload will exist.

2.3.1 Estimators of Reliability

Reliability may be based on estimators associated with the black box level, such as statistical evaluation using failures and time associated with the black box. Alternatively, the reliability of the black box may be established based on failure and time information of its components.

2.3.1.1 General Technique

The general estimation technique is as follows:

For any black box, let

n_i = number of ith type part

λ_i = failure rate of part

Then, the expected failure rate for the black box is given by

$$\lambda_{BB} = \sum_i n_i \lambda_i \ .$$

For any point in the development cycle of the black box, λ_{BB} is being estimated.

2.3.1.2 Alternative Techniques

The following alternatives are available for making estimates at the box level. They are given in order of decreasing accuracy and, thus, desirability. The selection of any specific technique for application should depend upon the type and amount of information available on the specific black box in question.

Each of estimators (a) through (h)[1] may be applied to novel equipment through function similarity, if necessary, since in general much of a new system will be comprised of existing equipments having slight modifications.

a. Reliability can be obtained from already established failure rates.

b. In the absence of black box failure rate data, λ_{BB} can be estimated from accumulated failure data; i.e.,

$$\lambda_{BB} = \frac{\text{total failures}}{\text{total operating time}}$$

c. Stress analysis can be performed. This technique is based on individual behavior of a part under working stress in the black box. Respective parts are evaluated. Individual part rates are combined according to the anticipated hardware contents of the box.

d. Parts Count can be made. This is based on average stress on a part type in the black box. All parts of the same type are presumed to have the same stress, otherwise the method is similar to (c) above.

e. In the absence of statistical information on parts, all parts can be assumed to have reliability commensurate with state-of-the-art at the time the design is made firm, otherwise the method is similar to (c).

f. Equipment can be assumed to possess same part distribution and density as similar equipment (similar function performed).

g. If state-of-the-art improvements have been incorporated in equipment, adjustment for these improvements can be made in the substitute part type; i.e., transistors for electronic tubes, etc. The same parts distribution is assumed.

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[1] For a discussion of these estimation techniques, see Reference 15.

h. An estimate of reliability based on two times the failure rate of each active part for digital circuitry and three times each active part for analog circuitry.[1]

i. In the absence of a well defined function, reliability goals (or specifications) can be given.

These goals should be given by:

(1) part failure goal,
(2) black box failure rate goal.

j. In the absence of the above information, or in conjunction with it, the contractor can provide reliability estimates of major portions of the system (and/or lower level subassembly).

(1) This would yield failure rates for all specified subsystems (and/or lower levels of assembly).

(2) Reliability could be allocated to lower levels of assembly based on subsystem reliability estimate and levels of assembly in the subsystem, which would be assumed to share in failure rate contribution on a size-proportionality basis.

2.3.2 Maintainability Estimation

The basic contributors to the maintainability of a black box are as follows:

a. status evaluation: time to determine whether or not a failure exists;

b. time to isolate the failure to the level of assembly at which the failure exists;

c. time to remove a failed black box and replace it with an available substitute.

d. time to check out the replacement in the operational unit.

Evaluation of these time elements is repeated for each level of assembly for which a remove and replace procedure is applicable.

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[1] This estimator is obtained from the observation that the active part (transistor, vacuum tube) has a failure rate approximately ten times that of passive parts (resistors, capacitors, inductors as a group). Also, there are approximately ten passive parts per active part. The factor of three is derived for analog circuitry through the observation that the parts are worked about fifty percent harder in terms of failure rate.

It is imperative that estimates be made of task time associated with each level of assembly (to the black box level). This must be done to enable determination of downtime of the operational unit, workload allocated to base maintenance, and workload allocated to other support areas - if involved.

At present, there are four prediction procedures that may be used to estimate time required for repair of a black box. These are (a) Work Sampling Analysis; (b) Statistical Evaluation; (c) Prediction Based on Level of Assembly; and (d) Prediction Based on Equipment Characteristics.

Each of these techniques have been used to estimate repair time of equipment.

The classical analysis technique (work-sampling techniques) provide the best estimate of the expected work time, where applicable (scheduled arrival-fixed duration). The generalization of work sampling -- prediction based on level of assembly -- encompasses random processes, and on face validity offers the most promise for the present purpose.

2.3.2.1 General Technique: Black Box Estimation Procedure

The task time generated by a black box may be developed in the following manner. The failure takes place at the lowest level of assembly; i.e., the part (or the throw-away item). The time contribution to the total black box repair time of the part is based on the failure rate of that part and the time necessary to isolate, remove and replace the part and to reassemble and check out the black box in which the failure is contained. The expected repair time of the task is the sum of the contributions of each part, divided by the total failure rate; illustrated,

$$\bar{t} = \frac{\Sigma \lambda_i t_i}{\Sigma \lambda_i} ,$$

wherein λ_i designates the ith part failure rate, t_i designates the time to isolate, remove and replace the failed ith part and to checkout the repair; and $\bar{t}$ designates the average task time for the black box.

If, in the above description, the replacement level of assembly is used instead of the part, the expected task time consumed down to that level of assembly should be computed. Each level of assembly must be evaluated for its contribution to downtime of the operational unit, and for the total amount of work created.

2.3.2.2 Alternate Techniques

The following alternatives are available for making repair rate estimates at the black box level. The selection of any specific technique for application should depend upon the type and amount of information available on the specific black box in question.

a. An estimate of task time from statistical data on actual operations for each level of assembly can be made. This is measured by total task time divided by the number of occurrences. (This procedure follows that of 2.3.2.1 above, applied to each level of assembly by subsystem.)

b. In the absence of the above information,

   (1) Random Task Time: Can be estimated from equipment characteristics:

      (a) Analysis of Equipment Characteristics (RCA-RADC), Reference 11; for example, see Appendix IX-A.

      or

      (b) Level of Assembly Prediction Technique (ITT-BUSHIPS), Reference 10; for example, see Appendix IX-B.

   (2) Fixed Task Time: Estimate task time using gross work sampling analysis technique. This is achieved by assigning task time to each significant task element. The task elements considered to be of significance are:

      (a) transportation time (if applicable) -- either transport of a maintenance crew to the operational unit or the transport of the operational unit to where work must be performed -- a nominal time may be assigned.

      (b) status evaluation -- determine if the operational unit is operable and check for incipient failure of subsystems -- a nominal time may be assigned.

      (c) routine supply replenishment -- refueling, loading of ammunition, etc. -- a nominal time may be assigned.

   The nominal task time assigned would be estimated using experience factors based on similar equipment and operational environment and/or existing knowledge of the equipment requirements. Where the task involves combinations of (a), (b) and (c) and/or a random duration task, the task time elements are summed; e.g., .1 hour for transportation to and from aircraft on flight line, .2 hour for fire control subsystem checkout - total time .3 hour.

c. In the absence of the above information, an estimate of task time can be made, based on the number of levels of assembly in similar equipment. This may be done using either technique. (See b (1)(a) or b (1)(b) above.)

d. In the absence of the information in (a) or (b), an estimate of task time can be made from proposed level of assembly breakdown and test and checkout features, utilizing b(1)(a) above.

e. In the absence of (d), an estimate of task time can be made from task time goals (specifications) for each level of assembly.

2.3.3 Estimation of Scheduled Maintenance

2.3.3.1 Establishment of Maintenance Schedules

Scheduled maintenance frequency is affected by three considerations:

a. The importance of the subsystem to the mission and/or flight safety of the vehicle. When failure rates are very low, the frequency of checks for safety factors are more nearly dependent on ease of performing the check than on the failure rate itself.

b. The rate of change of the probability of failure of a subsystem. There is very little accurate data concerning the relation of failure rate to time for those items whose failure probability depends on accumulative operating time. Further, it is generally easier to perform an inspection-type preventive maintenance to determine if accelerated degradation is actually taking place than it is to establish a preventive maintenance cycle analytically.

c. Ease of Performance of the Preventive Maintenance Task. Many preventive (scheduled) maintenance tasks can be performed while the operational unit is down for performance of some other necessary preventive maintenance or of corrective maintenance mandated by a failure.

Therefore, the maintenance schedules are predominantly based on intelligent guesses and/or past experience.

2.3.3.2 Techniques

In general, the following observation is valid.

In the economic sense, an optimal preventive maintenance frequency for a complex system (involving many tasks and skills) will not be easily realized. The manpower cost of theoretically predicting degradation is not justified by the possible savings in maintenance costs (at present) since ease of inspection keeps its total cost low.

One or both of the following techniques may be applied to arrive at preventive maintenance schedules and task durations:

a. Assign to a subsystem a frequency of preventive maintenance based upon similarity of existing component, black box, etc., in the existing reference system. Assign nominal task-time based on similarities to other equipment.

b. Allocate to each subsystem a total task-duration for preventive maintenance equal to the maximum total task-duration anticipated for any of the individual tasks having that specific frequency. Assume that this time will be expended for each scheduled occurrence. This will allow for scheduling of tasks at each incidence.

   This downtime would be estimated from those tasks which are non-overlapping, and which have maximum durations relative to the others. (See Appendix II; see also Appendix III for a discussion of overlapping of tasks).

3. MANNING PREDICTION

3.1 General

This section contains the sequence of steps and detailed procedures for establishing manning system requirements. The general section has been provided to acquaint the reader with the fundamental concepts involved in establishment of manning requirements.

The technique developed here, in conjunction with the system manning phaseover model developed in Section 4, will permit establishment of long-term multi-system manning requirements.

The personnel time required by a system is composed of two necessary elements: (1) Productive Time, and (2) Non-productive Time. Many factors enter into the determination of these time elements.

For all tasks required by the system, the productive time may be represented by the product of two demand rates: (1) Frequency of a task occurrence; and (2) time required per occurrence of the task.

There are two basic types of jobs or tasks required in a system -- operator and support. In some cases, the duties overlap. For each of the tasks, the demand rates may be of generally the following types:

a.	Frequency of Occurrence of Task	(1) Fixed
		(2) Random demand with a particular probability distribution
b.	Performance Time of Task	(1) Fixed duration
		(2) Random duration according to particular probability distribution

3.1.1 Productive Time

The demand characteristics of a task may be composed of the combination of any type performance time-occurrence frequency demands. It is important to recognize that work is calculable by using these demand rates. The workday of a particular operator or maintenance person may be composed of work elements of each of the above types and, in general, this very situation occurs.

Work or productive time required as a fraction of total time (T) may be ideally represented as $\frac{\lambda}{\mu} = \rho$.

λ is the rate of occurrence of the work demand per unit time, and

μ is the rate per unit time that the task is performed.

Over the period T, not all time is necessarily productive. The fraction of duty time that the person is idle is given by $1 - \rho$. Therefore, all the time spent in the period of work may be represented as (1) the time spent in which the person was actually utilized, and (2) the time in which the person was not utilized (idle time).

In general, each job assignment has the following characteristics:

a. More than one type of task assignment

b. Different combinations of demand rates -- probably all combinations indicated above

c. A priority system for performance of the tasks

d. Satisfactory level of performance criterion

Job assignments must be made in such a way that the personnel are utilized in a manner which is consistent with two general rules which follow:

a. The utilization of personnel should be less than unity (less work assigned than work capability).

b. The tasks must be scheduled in such a way that the extent of overlapping tasks is controlled to ensure the imposed level of performance.

The overlapping of tasks is controlled by assignment of tasks that can be performed simultaneously to different personnel or assignment of tasks to a single person such that there is low probability of simultaneous occurrence of two tasks. If the performance goal is taken as achievement of a specific level of operational readiness and this level is reduced, this reduction would permit more sequential performance of tasks by a single man which otherwise would require simultaneous performance.

3.1.2 Non-Productive Time

Personnel idle time results from the basic inability to schedule work in such a way that personnel are always completely utilized. Productive time-losses arise from waits for the arrival of work. Waits can occur whether the arrival pattern of work is scheduled or random. Where scheduling of work is feasible, the idle time of personnel can be minimized. Where the arrival of tasks is random, the problem becomes more complicated. Since a major portion of uncontrolled downtime of an operational unit (aircraft, missile system) occurs at random and requires random lengths of time, it is appropriate to discuss this at greater length.

3.1.2.1 Waiting Lines

Waiting lines will arise whenever the number of items which require a particular service (customers; e.g., defective equipments, aircraft to be landed) exceeds the number of servers; e.g., maintenance man, usable runways.

The utilization of the servers (maintenance man, supply personnel, etc.) is the average fraction of duty time spent by the personnel in performing tasks relevant to their primary responsibilities. Where the utilization is high, most of the personnel will be busy most of the time; therefore, tasks arriving will be subjected to waits or delays.

Where there is low utilization of maintenance personnel, increases in workload require small increases in manning compared to operations where there is high utilization. Where utilization is high, increase in manning required is approximately proportional to the increase in workload.

Where waiting time is directly related to operational readiness through downtime, a given increase in operational readiness requires a much greater increase in manning where utilization is low than where it is high; this is true because low utilization already implies low downtime attributable to waiting. Consequently, where utilization is low, spares (quickly replaced major assemblies) frequently offers the only practical means of significantly improving operational readiness.

Spare equipments, sparing at high levels of assembly, offer an alternative means of reducing downtime because of waiting for repair. This approach is most strongly indicated in concentrated groupings of systems or equipments, as in a squadron or wing of aircraft, because in these instances the investment in inventory can be small, relative to investment in operating equipment.

3.1.2.2 Definitions

To show how some of the concepts are quantitatively related, the following definitions are given:

a. Finite Population:[1] Applied to queuing situations, implies that the arrival rate is significantly affected by changes in the number of items being served or awaiting service, for numbers normally encountered.

b. Number of Channels: The number of simultaneous performances possible of the average task, or of the average task requiring a specific skill.

c. Spares: Number of spare equipments or other repairable items, such as major assemblies, which can replace all or only the defective part of a failed equipment.

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[1] See Explanation of Terms, item 16.

d. Utilization Factor (ρ): A ratio, the failure rate of an item, divided by the repair rate of the item. Queuing tables are usually based on the utilization factor (or some function thereof), since it is invariant with changes in number of operational items and repair channels.

e. System Utilization Factor (ρ_s): The ratio of the total system arrival rate to the total system repair rate. For cases in which there is one operational item and one repair channel, ρ_s is equal to ρ; i.e., total failure rate of all operational items, divided by the product of the number of repair channels and the repair rate of a repair channel.

f. Utilization (u): The average fraction of available duty time in which each repair channel is actually engaged in making repairs. Note that utilization, u, is not necessarily the same as the system utilization factor. The difference arises from the fact that the ρ_s is based on repair channels and operational units presumed to be all operating; whereas, u must account for the operational units being down due to failure, and for spare units which may be substituted for failed operational units.

g. Basic Tabular Entry (d): Average number of tasks or failed items, per channel in excess of spares which are in, or awaiting, service (repair).

Table 3 illustrates the relation among units down because of delays in maintenance and various characteristics of the repair shop. Note especially that for a given system utilization factor, the greater the number of channels, the less the average delay. (This phenomenon accounts for two of the advantages of centralized maintenance: (1) reduction in direct equipment downtime and (2) reduction in required spares per operating unit.)

For finite populations, the addition of spares not only improves system operational readiness, but also increases utilization. This is shown in Table 3. An additional channel may improve operational readiness as much as a unit of spares. For example, compare one channel at a system utilization factor of .8 with 2 channels. Note that delay is less for 2 channels with no spares than for 1 channel with a 1 unit of spares.

3.2 Identification of System Functions with Task Responsibility

3.2.1 Discussion

The initial step in establishing manning and skill requirements is identification of the physical parts of the operating unit with work to be done. From this, skill and/or work shops

TABLE 3

QUEUING RELATIONS

System Utilization Factor = .5					Spares				
Number of Channels	Number of Equipments Operating	0		1		2		4	
		d	u	d	u	d	u	d	u
1	4	.597	.425	.278	.465	.134	.483	.033	.496
2	4	.419	.396	.157	.434	.090	.477	.032	.494
System Utilization Factor = .8									
1	4	.992	.602	.662	.667	.468	.706	.206	.749
2	4	.619	.552	.397	.641	.274	.690	.098	.725
2	8	.671	.662	.486	.703	.354	.729	.201	.760

d = average number of items per channel in excess of float which are awaiting service

u = utilization

are established. For already established operational unit types; e.g., Fighter Squadron, all or most of the elements of these breakouts will already exist. For a novel unit, the following remarks will suffice for making the needed associations.

The weapon system function(s) are utilized to identify manning and skill distribution requirements for systems in the conceptual stage of development. This is consonant with current bases for manning breakouts in that function definition may be made consistent with definition of career fields, skill levels, and maintenance shops.

Each system function is identified with a subsystem of the system, or that portion of a subsystem requiring services of a specific career field and skill level. The function is identifiable with the equipment composite required for its accomplishment. Since the equipment is characterized by demand rates for operation and maintenance, this establishes a causal relationship between the function and manning and skill requirements.

Changes in a system function have an impact upon manning requirements which may be treated directly through consideration of the consequent changes in equipment demand rates. The following procedures establish the basis of the technique in some detail. It should be noted that manning requirement modifications can be related to changes in equipment design and/or operational requirements, and these can be related to function modifications.

The system is composed of functions. The function is comprised of subfunctions. The function or subfunction may be identified with a black box or group of black boxes.

a. For the present purpose, a system function may be defined as the level of equipment definition for which it is possible to specify a distribution of skills.

b. Any system function must be defined consistent with personnel career field definition.

c. A system function is identified with equipment. Each equipment is characterized by demand rates for maintenance support. This establishes the causal relationship between the system function and manning.

d. Modifications in functions are treated as reflected in hardware requirements (through demand rates).

e. Manpower per task requirement associated with a specific system function is derived from analysis of tasks associated with the equipment.

As a sample case, consider the following function breakout of an aircraft:

(1) The aircraft (operational unit) is itemized in terms of fundamental functions; e.g.,

- Fire Control System
- Propulsion System
- Armament System
- Pilot System
- Landing System
- Air Frame System
- Communications
- Navigation
- Hydraulic System
- Safety (e.g., fire extinguishers, de-icers, ejection systems)

(2) Each major function is itemized in terms of subfunctions; e.g.,

Fire Control
  Radar
  Converters - Analog-Digital
  Control Units
  Etc.

f. Establish Equipment Use Profile.

(1) Equipment Use Profile: This constitutes the objective of the system under evaluation, and necessitates evolvement of required operator personnel.

(2) The equipment profile consists of three distinct states:

(a) Pre-operation (maintenance and checkout)

(b) Mission performance (mission profile)

(c) Post-operation (maintenance and checkout)

(3) Pre-operation encompasses the functional checkout of all subsystems of the operational unit, plus integrated support functions.

(4) Mission performance encompasses the functional operation of continuous support functions and the operational unit.

(5) Operator requirements per mission (where it is discrete): Requirements are programmed along mission profile.

(6) Post-operation encompasses the functional checkout of all subsystems of operational unit and support functions.

Note: It should be noted that mission abort and training have not been explicitly included in the items above, nor is this inclusion necessary. Training requirements will not exceed operational requirements and, hence, will not require additional manning of the operational units.

Mission aborts would be included as random usage maintenance occurrence and treated accordingly.

g. The number of shifts (or crews) per operational unit can be determined from:

(1) equipment use profile

(2) position requirements

(3) procedure described in Section 3.3; et seq.

For each subfunction (through equipment identification) task performance time and schedules are established for the operational unit.

3.2.2 The Task Concept and Definition

Throughout this report, the terms task and black box are extensively used. They were defined in Chapter 1. (Sections 1.2.2 and 1.3.6.) For the purpose of further clarity, the following descriptions are given.

The fundamental building block of the manning technique is the task. Ideally, the task is identified with a black box in the operational unit and, further, the operational unit is comprised of a fixed number of black boxes.

Thus, if the operational unit is composed of black boxes, implementation of the manning technique is readily achieved. Otherwise, experience and/or ingenuity is necessary to develop hypothetical black boxes having the essential characteristics of real black boxes.

For purposes of analysis, the task is defined by a black box having the following kinds of demand rates:

a. Occurrence Demand Rates

(1) Calendar Scheduled Maintenance Demand Rate

(2) Usage Duration Maintenance Demand Rate

(3) Scheduled Per Usage Occurrence Maintenance Demand Rate

(4) Random Usage Maintenance Demand Rate

b. Performance Demand Rates

For each demand rate above, there is associated a duration of performance. This performance will require a number of personnel of a specific skill type and level. In the establishment of performance rates, it is assumed that a rate will depend on a task and not on the individual performing the task. Where random processes are involved, mean rates will be estimated based on exponential processes. It is further assumed that adequate training will be given the personnel and that the probability of an assigned man performing a task within the time estimated for the task is sufficiently high that any variance may be neglected. Given that the mean performance rate is accurate, variation from exponential processes is anticipated to involve less than 5% error in estimation of waiting time (see Section 3.10).

The black box type is defined as a single physical package, having a uniqueness by virtue of its internal logic and/or construction. It may be comprised of other black boxes.

Each combination of occurrence rate and task performance duration associated with the black box may require different skills and numbers of personnel. Since some black boxes may not be removable from the operational unit by virtue of their construction, it is desirable to add another characteristic to the black box; viz., allocability - this means whether or not the black box can be sent to another location for performance of these tasks.

The concept of allocability is of considerable importance, in that spare operable black boxes can be made available for replacement of failed black boxes with a resultant increase in the uptime of the operational unit and a concomitant decrease in personnel to achieve a specific level of operational readiness. This task concept requires a compartmentalization of the operational unit into black boxes.

In summary, the black box-task concept amounts to breaking maintenance requirements of the operational unit into reasonable work units or task packages. A "reasonable" work unit will consist of things to be done on the same occasion but which are not conveniently performed simultaneously by different people. These things-to-be-done (tasks) will require the same skill field and will require about the same level of skill. The work unit may require primarily high skill, with a few low skill elements but, typically, not the converse since the latter would lead to inefficient utilization of highly skilled personnel. The exception will arise when the workload leads to requirements for only one or two men in a particular field at a particular location. However, there will be borderline situations where there is some question as to whether a particular group of actions should be considered as one or as more than one task. Little time should be spent in making such decisions since they will almost never make a significant difference to the final result. In practice, the actions will generally be assigned to the same man even when they are considered to constitute several tasks.

Rules for recognizing and developing hypothetical black boxes and task packages are contained in Appendix VIII. Section 3.2.3 contains information for detail task scheduling.

3.2.3 Novel Tasks

In a system which incorporates considerable novelty, functions may exist that do not possess present day counterparts either in skill area or support shop layout. Where this situation exists, it will be necessary to (a) combine identified tasks, and (b) develop new skill packages (skill field).

3.2.3.1 Combining Tasks

The following set of rules encompasses the major considerations for combining tasks:

a. Combinations of tasks requiring approximately the same skill levels should be given preference.

b. Combine tasks which require the same senses or similar response actions and which are not mutually exclusive. (Probability of overlapping requirements should be less than some upper limit[1], allowing for permissible delays.)

c. Queuing effects must be considered in combining tasks which may overlap but may be delayed. Probability of excessive delay must be held to an acceptable level.

d. An essential task requiring only a small fraction of total performance time may be combined with any non-essential task which is continuous or which involves a high efficiency of manpower usage (i.e., the man is busy most of the time). For example, cooks, special services personnel, clerks, etc., may act as reserve members of the security of fire fighting forces at a station; a clerk may have special duties during an alert; etc.

e. Physical locations must be compatible - travel and/or set-up time must be considered as delays.

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[1] This limit can be set by an allocation of a permissible defect in performance, such as equipment unreadiness; e.g., probability of simultaneous demand of any two tasks equal or less than .05 for tasks of mean duration of one hour.

3.2.3.2 Development of Skill Packages

For systems comprised of functions not identifiable with existing skill fields, the following rules may be used to establish skill packages:

a. Determine tasks which must be performed, identifying by skill and timing.

b. Group tasks according to field. (Include fieldless tasks in each group.)

c. From a field, select tasks requiring highest skill level. Proceed to d.

d. Combine mutually exclusive tasks at approximately the same location. (Several such sets may exist; allocate overlaps between sets as directed below.) Proceed to e.

e. Check time utilization.

   (1) If high, combine other mutually exclusive tasks at lower skill and set aside as job package. Proceed to d (or to c if tasks in this field are exhausted).

   (2) If low, scan other tasks for this skill for those combinable but not mutually exclusive (see general rules for combinability of tasks, paragraph 3.2.3.1). Make possible combinations to the point that efficiency limit is reached or possibilities are exhausted. Where excess possibilities exist select a combination which allows convenient packaging of remaining tasks. Proceed to f.

f. Check utilization.

   (1) If high, set up as task packages. Proceed to d (or to c if tasks in this field are exhausted).

   (2) If low, check next lower skill level for possible combination, proceeding through steps d, e, and f again. When all tasks requiring this highest skill level are exhausted, repeat cycles for lower skill levels.

3.3 Establishment of Shift Schedules

Shift schedules are desirable as a reference point which both work created and workload capability can be based. The manner in which shifts are established will influence both the operational performance of the system and the manning requirements of the system. These schedules may be established as follows:

a. Operational Schedule

A unit of calendar time (probably a day) for aircraft and missile systems is divided into shifts, the ith being h_i hours in duration, and a reference point for the first shift is selected. The total number of operational hours of performance capability during the ith shift is specified. (See Table 4.)

b. Maintenance Schedule

The maintenance shift need not coincide with the operational schedule and, in fact, situations exist in which the maintenance shift may not overlap an operational shift. (See Table 5.)

3.4 Establishment of Operational Performance Requirements

The procedure developed for manning a given system is based upon the specification of required information; viz., the operational performance requirements of the system. These performance requirements can be broken out according to operating shift schedules.

3.4.1 Operational Capability

During each working shift, the system must be capable of performing its prescribed function, or operation, having a specified duration. Weighting frequency with the duration of each occurrence gives rise to a total operational capability during each shift.

3.4.2 Operational Readiness[1]

The basic system performance criterion on which the manning requirements are based is the required operational readiness of the system. This is the mean fraction of system units which are operational and is specified for each operational shift.

Based on the operational readiness specified, another performance goal can be described; namely, a requirement for at least n of the units to be ready at a randomly selected time with a specified probability.

This requirement may be approximated with the Binomial Distribution. Thus, the probability of at least n units being operational, given a total of N and a mean fraction operational, R, is expressible by:

$$P(N_o \geq n) = \sum_{N_o=n}^{N} \frac{N!}{N_o!(N-N_o)!} [R^{N_o}(1-R)^{N-N_o}]$$

where N_o is the number operational.

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[1] The concept of operational readiness is developed in Section 3.6.1.

TABLE 4

EXAMPLE OF OPERATIONAL SCHEDULE

Operational Shift	4 AM → 2 PM 1	2 PM → 9 PM 2	9 PM → 4 AM 3
Duration (hours)	10	7	7
Operational Hours Required	100	30	10

TABLE 5

EXAMPLE OF MAINTENANCE SHIFT SCHEDULE

Maintenance Shift	12 AM → 8 AM	8 AM → 4 PM	4 PM → 12 PM
Duration	8	8	8

Alternatively, we may specify $P(N_o \geq n)$, and then together with N, require a determination of R for each operational unit. Standard tables exist for determining these values; viz., Reference 6, Tables of the Binomial Probability Distribution. Table 6 below gives one form in which operational performance requirements may be designated. This table contains a breakdown of:

a. Operational Hours - capability required of all eighteen (N = 18).

b. The number of operations required during each shift. This number is different for each shift and implies a different operation duration per operation occurrence for each shift.

c. The probability of N_o or more of the (N = 18) operational units is specified for each shift. This may be allowed to vary with shift due to strategic requirements of operational units.

d. The operational readiness requirements imposed on the system. This is an alternative form of expressing (c) above.

TABLE 6

OPERATIONAL PERFORMANCE REQUIREMENTS

(N = 18 Operational Units in System)

Operational Shift	4 AM → 2 PM	2 PM → 9 PM	9 PM → 4 AM
Operational Hours Required	100	30	10
Number of Operations	25	10	5
Probability $N_o \geq n$	$\geq .95$	$\geq .95$	$\geq .75$
Operational Readiness	.75	.75	.55

3.5 Determination of Skill Workload

The total demand for personnel is most conveniently represented in terms of scheduled and random demands.

a. Scheduled Demands are: (For Mandatory Replacements, see Appendix IV)

(1) Type I: Calendar Maintenance
(2) Type II: Usage Duration Maintenance

b. Random Demands are:

(1) Type III: Scheduled Per Usage Occurrence Maintenance
(2) Type IV: Random Usage Maintenance.

All demands above must be converted into calendar time units since this is the only manning time basis having meaning. Methods of estimating work requirements for the above demand types follow.

For each type of maintenance, work time (man-hours) per operational unit, w_{ij}, will be determined for each skill, j, for each task i. The total workload per shift, W_{ij}, for the task will also be calculated. For each task, performance time, t_{ij}, for each skill is required as is the number of men of each skill type, m_{ij}. Then,

$$w_{ij} = m_{ij}t_{ij}$$

Workload is based on the number of occurrences per shift, f, on which the equipment is operated, and the time (duration of operation) per occurrence, t.

3.5.1 Determination of Scheduled Work Demands

a. Type I: Calendar Maintenance

Each calendar maintenance task will generally be associated with a status evaluation[1] of the operational unit or some element of support thereof.

$$W_{ij} = f_m w_{ij}$$

where f_m is frequency of calendar maintenance per shift (i.e., the reciprocal of the number of shifts between maintenance actions).

b. Type II: Usage Duration Maintenance

The occurrence of a usage duration maintenance task is generated on the basis of accumulative operation time of the operational unit.

Let

t = duration of time that the operational unit has operated, corresponding to each task occurrence

T = accumulative total operational time upon which the performance of the task is determined

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[1] Status refers to the state of the operational unit with respect to its being operational. See the Glossary and Appendix VII.

Then

$$W_{ij} = \frac{ft}{T} w_{ij}$$

3.5.2 Determination of Random Work Demands

a. Type III: Scheduled Per Usage Occurrence Maintenance

The work time required will be based on the number of occurrences per shift and the work time per occurrence. For each occurrence, there will be generated a specified number of tasks. Associated with each task will be an expected time to perform the task, number of personnel required and skill type of personnel.

$$W_{ij} = f w_{ij}$$

b. Type IV: Random Usage Maintenance

The expected workload is generated by three factors:

f = occurrences per shift causing operation

d = duration of operation (i.e., time operated) per occurrence

λ = failure rate

Then

$F = d\lambda f$ = expected number of failures during shift

In the above formula for F, the expected number of failures during the shift must be the product of $d\lambda f$ because failure rate, λ, is expressed as failures per operational hour. The f alone represents the number of times the system is operating per shift while the d measures the length of time the system operates each occurrence.

These failures are divided into expected work requirements of skill levels and the required number of men.

The number of hours of skill j required by the ith task (which is identified with the black box) is

$$W_{ij} = f\lambda_i d_i w_{ij}$$

where

f = the frequency of operation

λ_i = the failure rate of the ith black box

d_i = the duration of operation per occurrence

Crews must be at least large enough to provide the simultaneous specialized skill requirements for any single task that may be assigned to them. Other crews may be called upon to provide additional men having only low skill (for this task) for occasional tasks requiring an unusually large number of men acting simultaneously.

Where there is an upper limit to allowable downtime; viz., a maximum turn-around time, crew size must be sufficient to permit the job to be completed within that time through parallel effort on various independent tasks.

From the foregoing, total personnel per scheduled and random task demand is established. Any convenient form for adding task time may be used. For any given task, the number of personnel required simultaneously may be obtained by direct evaluation.

3.5.3 Total Workload Per Repair Channel

The total workload is separated into random and scheduled requirements for each work shop.

Of the total workload, let D_s and D_r represent that due to scheduled and random work demands, respectively. This workload is assumed to be shared equally by each repair channel; therefore, where there are r channels, the average time a repair channel is busy is $(D_s + D_r)/r$ and the average fraction of the time it is busy is

$$\frac{D_s + D_r}{rT}$$

which is equivalent to

$$\frac{(t_{se} + \lambda\ t_o t)N}{rT}$$

where

t_{se} = time per T a single equipment is down for preventive or corrective maintenance

t_o = the operation time accumulated on the operational unit per calendar time T

λ = failure rate of those tasks assigned to a given work shop

t = time to perform task

N = number of assigned operational units.

3.6 Operational Readiness

Up to this point, the concern has been with estimating workloads by type for a specified skill and level. Before proceeding, it is necessary to explore in detail what operational readiness consists of and how it affects the manning problem.

3.6.1 Definition of Operational Readiness

The operational readiness of a weapon system which comprises a number of operational units; e.g., 18 aircraft per squadron, is defined as the number of on-line (ready) operational units divided by the total number of operational units in the system.

$$R = \frac{N_o}{N} = \frac{N - N_d}{N} \tag{2}$$

where

N_o designates operational units ready

N designates operational units assigned to the system

N_d designates operational units down for service.

This relationship may also be expressed in terms of time:

$$R = \frac{T - T_d}{T}$$

where T designates the sum of the average uptime and downtime of an operational unit and T_d designates the average downtime of an operational unit.

Generally, an operational unit will exist in one of three states:

a. in operation (t_o)

b. ready for operation (T_R)

c. down due to corrective or preventive maintenance (T_d)

Through this report, states a and b have been combined and are generally referred to as operational readiness.

If it is desirable to differentiate between states a, b, and c this may be done as follows:

From $R = \frac{T - T_d}{T}$, recognize that T is composed of

$$T = T_d + t_o + T_R$$

R represents the fraction of time the operational unit is in states a and b.

The fraction of the time in state a is given by

$$R_1 = \frac{t_o}{T}$$

where t_o is the time the unit is operating and, in state b

$$R_2 = \frac{T - t_o - T_d}{T} .$$

3.6.2 Unreadiness of Operational Unit

The contributions to unreadiness of an operational unit may be classified as follows:

a. Downtime due to scheduled maintenance

    (1) Scheduled Calendar Maintenance
    (2) Scheduled Usage Duration Maintenance

b. Downtime due to unscheduled maintenance

    (1) Scheduled Usage Occurrence Maintenance
    (2) Random Usage Maintenance

There are certain characteristics of scheduled tasks which make them relatively easy to assess.

a. The ability for accurate prediction is implicit in the word scheduled; viz., we always know in advance (with one exception, illustrated in Appendix IV) how much work has to be done and approximately when it will be done.

b. It is possible to schedule tasks for simultaneous performance of more than one task. For example, checks on the hydraulic system can generally be performed simultaneously with checks on electronic equipment. Obviously one task or package of tasks will require more time for performance than will any other. The downtime for this task or package represents the downtime contribution of that scheduled period.

c. Where maintenance is scheduled, the task or sequence of tasks which requires the most time to perform provides the limit to reduction in downtime, when the sequence is made up of tasks which cannot be performed simultaneously. Beyond this point, additional manning cannot significantly reduce downtime due to scheduled maintenance.

3.6.3 Formulation of Downtime Contributions

3.6.3.1 Calendar Maintenance

This consists of tasks which must be performed regularly, being scheduled on a calendar basis alone; i.e., daily, weekly, monthly, etc. It is assumed that all tasks having the same period are performed simultaneously or that they are grouped in packages which are compatible with available skills. The tasks within a package would be performed sequentially (see Appendices III and V):

Φ = length of time between performances of a scheduled task

T = given calendar time period (any convenient base such as month of year)

$t_{\Phi j}$ = time required to perform the jth specified maintenance task or package which is performed at intervals of Φ.

As discussed in remarks (of 3.6.2 above) there will be a task (or package of tasks) associated with one of the functions which will require more time to perform than any of the others performed at the same interval, Φ.

Call this time $\underset{j}{\text{Max}}\ t_{\Phi j}$

This means that, during a particular period, total downtime due to calendar demand type (T_c) is the weighted sum of the maxima for each different Φ. The weights are the number of occurrences during T, namely T/Φ.

$$T_c = \sum_{\Phi} \frac{T}{\Phi} \text{Max}\ t_{\Phi j}$$

Where all tasks cannot be performed simultaneously, the sequence of non-simultaneous tasks and/or packages of tasks which requires the most time to perform, determines T_c.

3.6.3.2 Scheduled Usage Duration Maintenance

This consists of tasks which must be performed after specific amounts of operating time; e.g., every 100 hours of operation. It is assumed that all tasks having the same period are performed simultaneously or that they are grouped in packages which are compatible with available skills. The tasks within a package would be performed sequentially, packages would be performed simultaneously.

Let

f = required number of operations which takes place per time period T

d = required duration of each operation

s = operating time between task performances

t_{sj} = total time required to perform the jth specified maintenance task or package which is performed at operating interval s.

Again, considering maximum task duration for each operating interval, the downtime due to usage duration demand types (T_{UDD}) is

$$T_{UDD} = \sum_{s} \frac{fd}{s} \max_{j} t_{sj} \qquad s = 8 \text{ hrs., } 25 \text{ hrs., } 1000 \text{ hrs., etc.}$$

Where not all tasks can be performed simultaneously, the sequence of non-simultaneous tasks and/or packages of tasks which requires the most time to perform determines T_{UDD}.

3.6.3.3 Scheduled Usage Occurrence Maintenance

This consists of tasks which must be performed after a specific number of occurrences (usually 1) of some mission or action by an equipment or operational unit. Except where the requirement is for performance after each occurrence, it may be treated the same as 3.6.3.2 above except that d equals the number of occurrences per operation. Where the task must be performed after each occurrence, it must be treated in conjunction with random usage maintenance in 3.6.3.4 below.

3.6.3.4 Random Usage Maintenance

This consists of tasks which must be performed as the need arises; for example, because of a failure of some element of the equipment or operational unit.

3.7 Calculation of Downtime for Random Usage Demands

The queuing tables are based on the utilization factor which relates failure rate of the item and the repair rate of a single repair channel; however, the logic of the mathematical model developed for this program presumes continuous time, both of operation and servicing of equipment (see Appendix I). Consequently, appropriate adjustments must be made for the non-continuous nature of the process and, also, for different time bases for operation and repair of equipment. The rationale for adjustment of the utilization factor is as follows:

Let

λ = demand rate of an equipment per operational hour

t = mean time to perform the task

t_o = time the equipment will be required to be capable of operating during a calendar period T

$\leq T - t_{se}$

t_{se} = time single equipment is down for preventive or scheduled maintenance

t_{sc} = time the channel is down for preventive maintenance.

The amount of work created for a single repair channel by a single equipment is given by

$$W_r = \lambda t \, t_o = \rho \, t_o$$

The time available for this work to be done is

$$W_a = T - t_{sc} = t_r \, .$$

The adjusted utilization factor is given by

$$\rho_A = \frac{W_r}{W_a} = \rho \, \frac{t_o}{t_r} \tag{3}$$

The adjusted utilization factor is used to enter the queuing table. See Section 3.11, Tables 7 and 8.

3.7.1 Determination of Units Down in Excess of Spares

From the appropriate entry in the queuing table, the mean number of units down in excess of spares is found. This number represents the number of operational units that will be down due to unavailability of operational equipments, after appropriate adjustments.

$T\text{-}t_{sc}$ is the time available for working on random type maintenance demands and the number of equipments down N_r is based on this period. During the time t_{sc} there are no equipments down due to random maintenance demands. Therefore, $\bar{N}_r$, the adjusted average number of equipments down for random maintenance over the entire period T, must be

$$\bar{N}_r = N_r \frac{T-t_{sc}}{T}$$

When computing the total downtime contributions of all units, each downtime (or number down) must be expressed on the same time base.

For channels which handle predominantly random usage maintenance, an adequate approximation to total downtime may be obtained by adding the amount estimated for queuing and maintenance associated with random usage, to the amount estimated for scheduled maintenance (see the procedure of Appendix III).

3.7.2 General Case

In general, there will be three conditions to consider in making a conversion of the utilization factor and for computing downtime.

a. The repair channel is down for maintenance. Equipment used in support of the operational unit will experience maintenance requirements. This equipment must undergo the maintenance requirements analysis to establish workload requirements.

b. The operational unit is down for scheduled inspection not chargeable to downtime.

c. The operational unit is down for scheduled maintenance chargeable to downtime.

Designate these times respectively as t_{sc}, t_{es1} and t_{es2}.

The adjusted utilization factor becomes

$$\rho_A = \frac{\rho\ t_o}{T - t_{sc} - t_{es1} - t_{es2}} = \frac{\rho\ t_o}{t_r} \qquad (4)$$

The number of operational units down becomes

$$\bar{N}_r = N_r \frac{(T - t_{es2})}{T} \qquad \text{for random usage maintenance}$$

and

$$\bar{N}_s = \frac{t_{es2}}{T} \qquad \text{for scheduled maintenance}$$

The time elements t_{es1} and t_{es2} are established as follows:

Let N be the number of operational units. If each unit requires a time t'_{es1} and t'_{es2} for non-chargeable and chargeable downtime, the total time required will be

$$N(t'_{es1} + t'_{es2}).$$

If the work shop consists of r repair channels, it is assumed each will equally share in these maintenance time requirements. Consequently, for each repair channel t_{es1} and t_{es2} become

$$t_{es1} = \frac{N}{r}\,(t'_{es1})$$

and

$$t_{es2} = \frac{N}{r}\,(t'_{es2})$$

The total potential downtime due to random usage maintenance generally is approximately the sum of the contributions of each work shop or independent location, since equipment generally has only one failure at a time.

However, the estimation of total downtime due to maintenance requires a more complex analysis. Within a particular channel, the maintenance times from various types of maintenance are additive in determining the potential contribution of the channel toward total equipment downtime. However, this additivity does not necessarily apply.

The total downtime on an equipment due to maintenance may be less than the sum of the maintenance times required of various shops. Often scheduled maintenance tasks can be performed simultaneously in different shops or even in different channels of the same shop. Sometimes equipment downtime can be further reduced by expedient scheduling of scheduled maintenance when corrective (random usage) maintenance is required. In Appendix II, a procedure is given for estimating the net downtime where channels can work in parallel.

For maintenance demands involving numerous parallel and serial tasks, PERT[1] (Program Evaluation and Review Technique) techniques may be useful in estimating total downtime. The critical path may point to situations in which total downtime

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[1] An approach of this type may be found in A U. S. Army Signal Corps Concept for Multi-Project Management, Project Comet, U.S. Army, Signal Corps Logistics Evaluation Committee, May 1962.

may be significantly reduced by provision of additional maintenance capacity, special maintenance equipment and/or additional spares. Many maintenance situations have a common structure so that a few standardized PERT networks may be developed to meet most of these requirements.

3.7.3 Minimum Number of Repair Channels and Spares

For a specified location or work area, the minimum number of repair channels and spares required are given by

$$r_{Min} = N \rho_A$$

$$L_{Min} = N(\rho_A - R)$$

where

R = Operational readiness requirements

r = number of channels

L = number of spare units

N = number of operational units

ρ_A = adjusted utilization factor

The minimum number of repair channels must be consistent with skill and workload requirements:

Let

P designate the maximum number of personnel required simultaneously for any given task assigned to a work shop

D designate the total man-hours required for all scheduled tasks assigned to that work shop

$\bar{P}$ designate the mean number of personnel required per task.

If the product of P and shift duration T is greater than D, the personnel are not being over utilized.

If the product of P and shift duration T is greater than or equal to D, the personnel are not being over utilized.

$$(P + k\bar{P})T \geq D \quad \text{where } k\bar{P} \text{ is an integer.}$$

The total number of repair channels is

$$k + P/\bar{P} = r.$$

The number of personnel obtained above must be consistent with the total work in terms of skill required. Thus, in adding repair channels, the required skills must be added. The total number of personnel of a specific skill is obtained by computing the total skill workload W_j and dividing by shift duration T. That number of personnel of skill j is given by

$S_j = W_j/T \geq 1$ and/or rounded to the next larger integer.

Thus,

$$r \bar{P} > \Sigma S_j.$$

If this condition does not hold, personnel of the required skill type must be added until satisfied.

3.8 Manning Adjustments to Compensate for Waiting Lines

In order to convey clearly the trade-off relationships, four graphs have been prepared. These graphs show representative trends and are not based on actual calculations. These graphs are shown in Figures 1, 2, 3, and 4. A brief explanation follows each figure.

3.8.1 Trade-off of Personnel and Downtime

The reduction of waiting time in task performance results in increased operational readiness of the operational units.

Each work area will contribute to unreadiness of the operational units. The effect of adding personnel (or repair channels) to a work area will depend upon the number of personnel assigned and their utilization. Hence, in achieving a given level of operational readiness for the system, the total number of personnel required will depend on how the operational readiness is achieved. The technique that will yield minimum personnel requirements follows:

a. Determine the change in operational readiness resulting from addition of a repair channel to each work area.

    (1) From the method for estimating operational readiness and downtime, Sections 3.6 and 3.7, respectively, determine the contribution from each work area to downtime of the operational unit. See, also, Appendices II (Procedures for Calculating Downtime), and III (Downtime Estimation of Simultaneous and Sequential Performance of Tasks).

    (2) Determine the reduction in downtime due to the addition of a repair channel at each work area. This

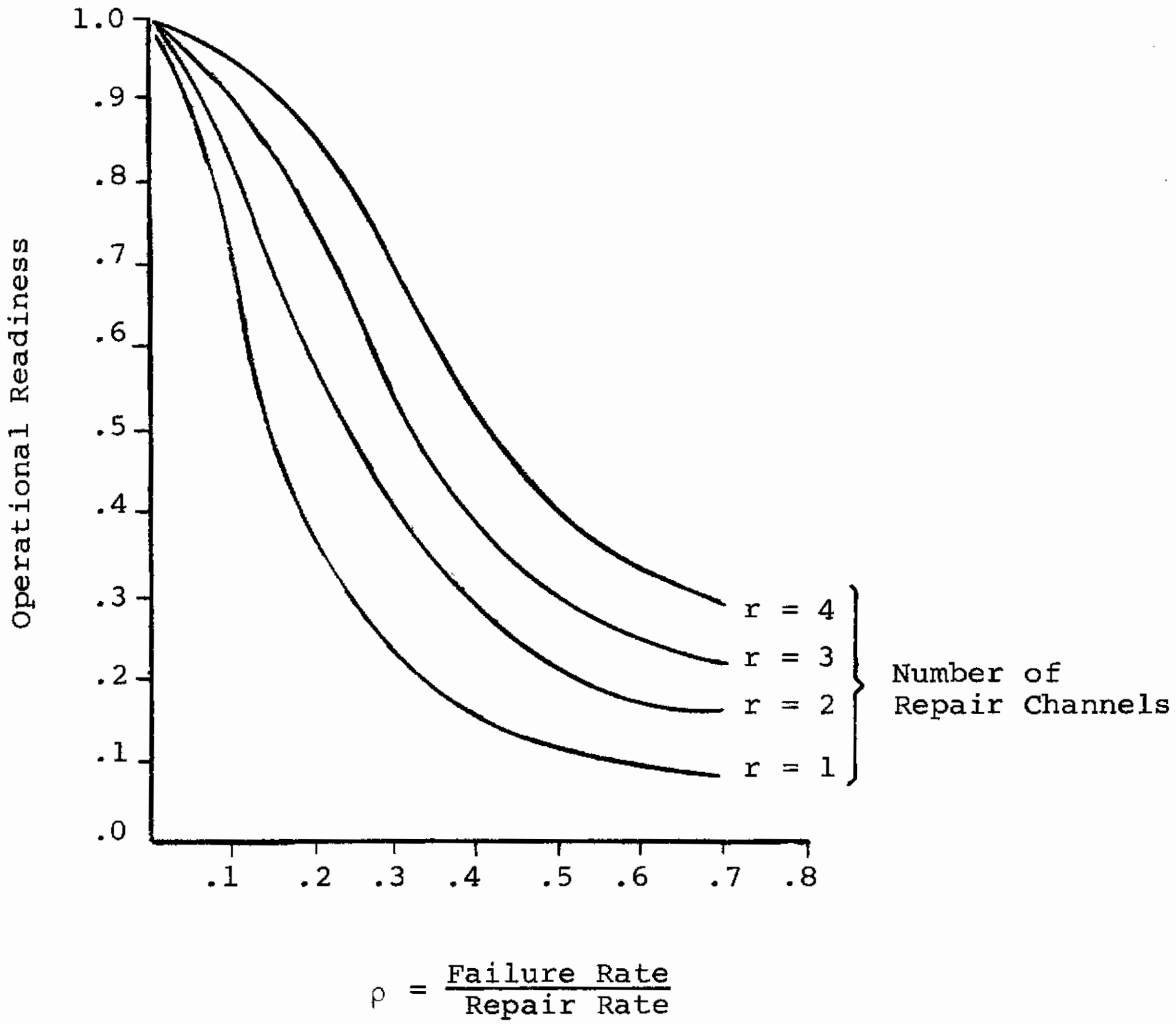

Figure 1. Operational Readiness Related to Utilization Factor and Repair Channels

The figure is based on a fixed number of spare black boxes and operational units. For a specified value of the utilization factor, operational readiness may be increased by addition of repair channels. For a fixed operational readiness level, observe that additional repair channels are required as the utilization factor is increased.

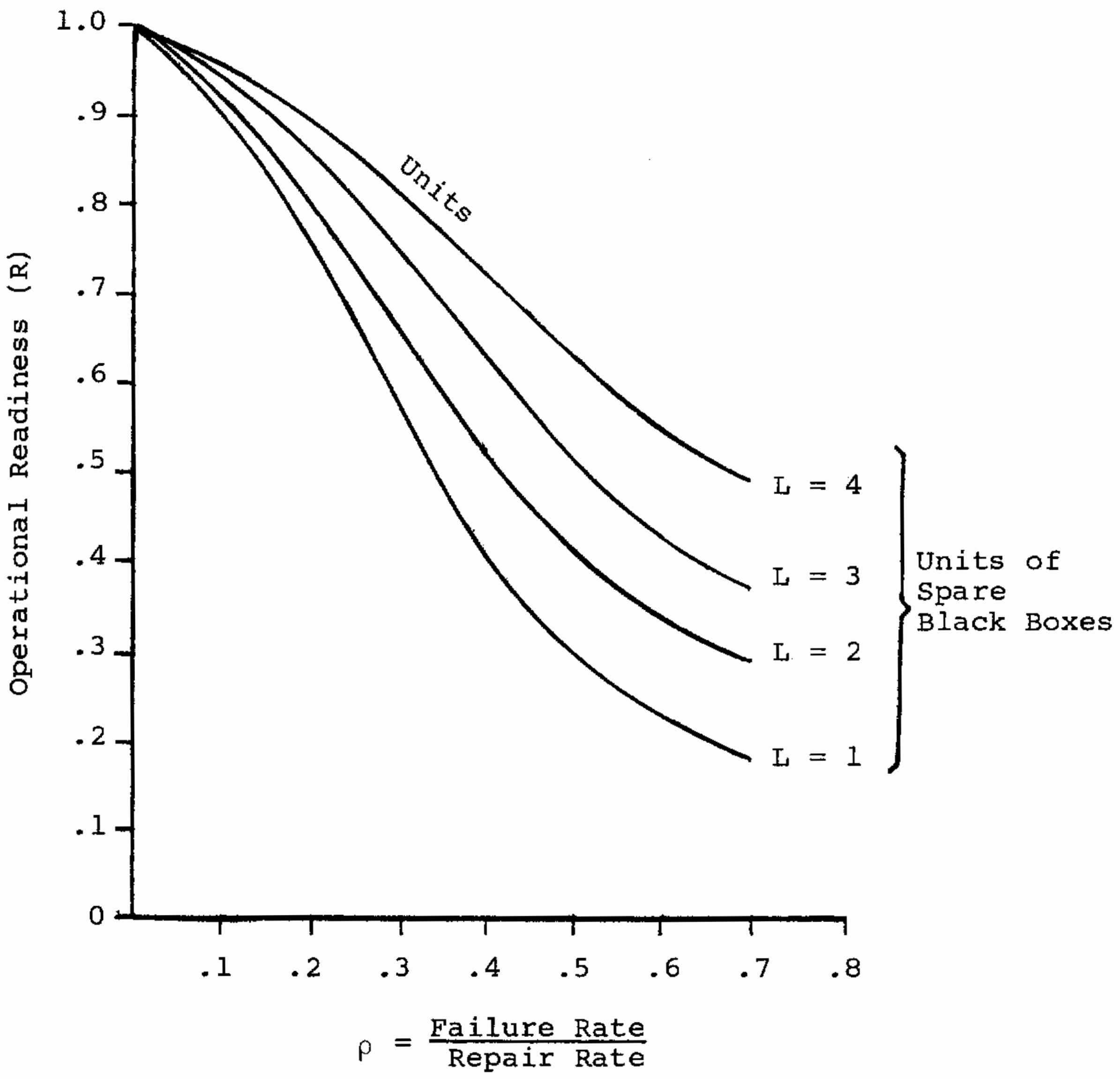

Figure 2. Operational Readiness Related to Utilization Factor and Spare Black Boxes.

The figure is based on a fixed number of repair channels and operational units.

For a specified value of the utilization factor, operational readiness may be increased by addition of spare black boxes. For a fixed operational readiness level, observe that additional spare black boxes are required as the utilization factor is increased.

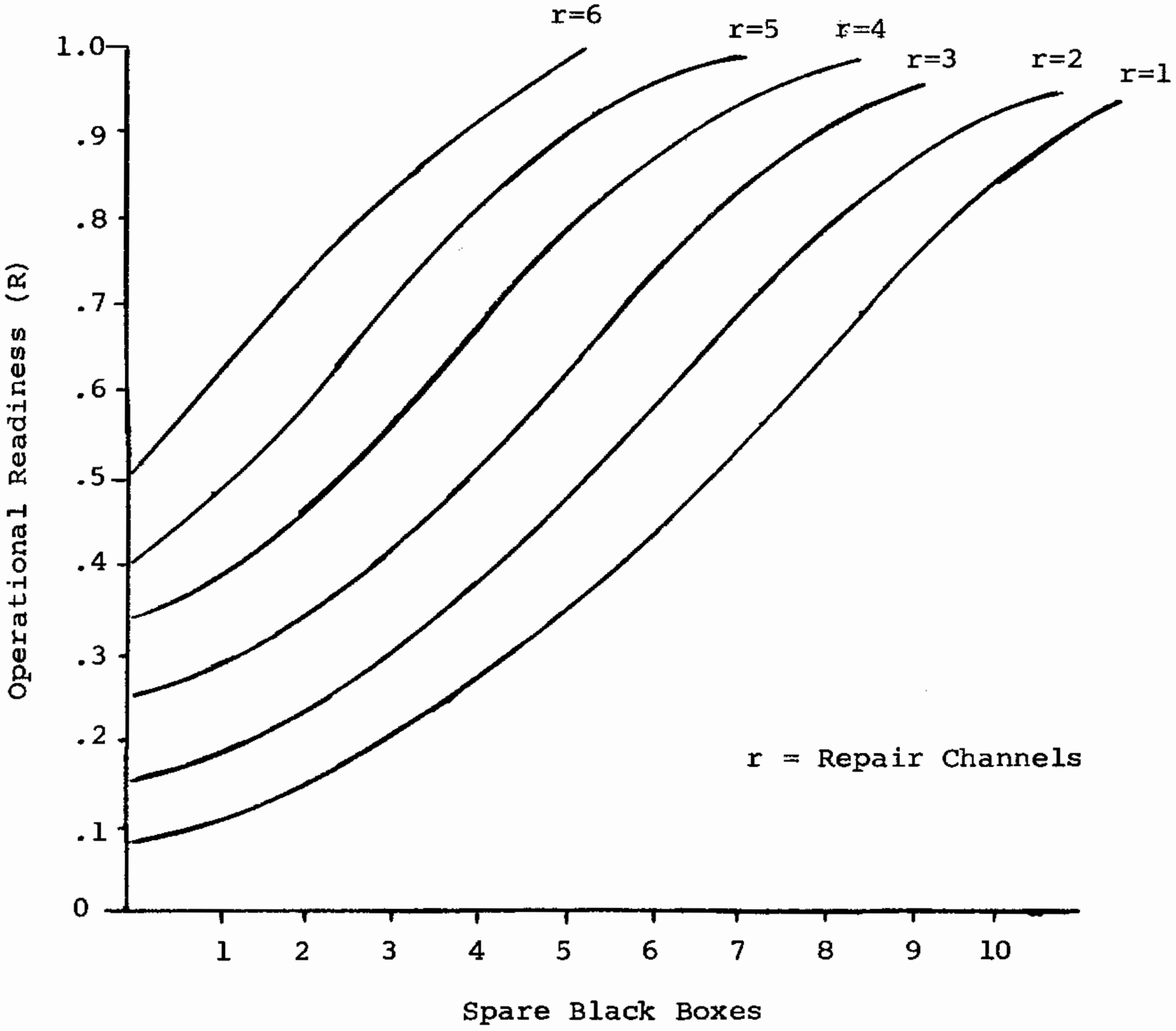

Figure 3. Operational Readiness Related to Feasible Combinations of Repair Channels and Spare Black Boxes.

The figure is based on a fixed number of operational units and a fixed value of the utilization factor. For a specified operational readiness level, several combinations of spare black boxes and repair channels are generally feasible for achievement. Observe that, as spare black boxes are increased, the required number of repair channels is decreased.

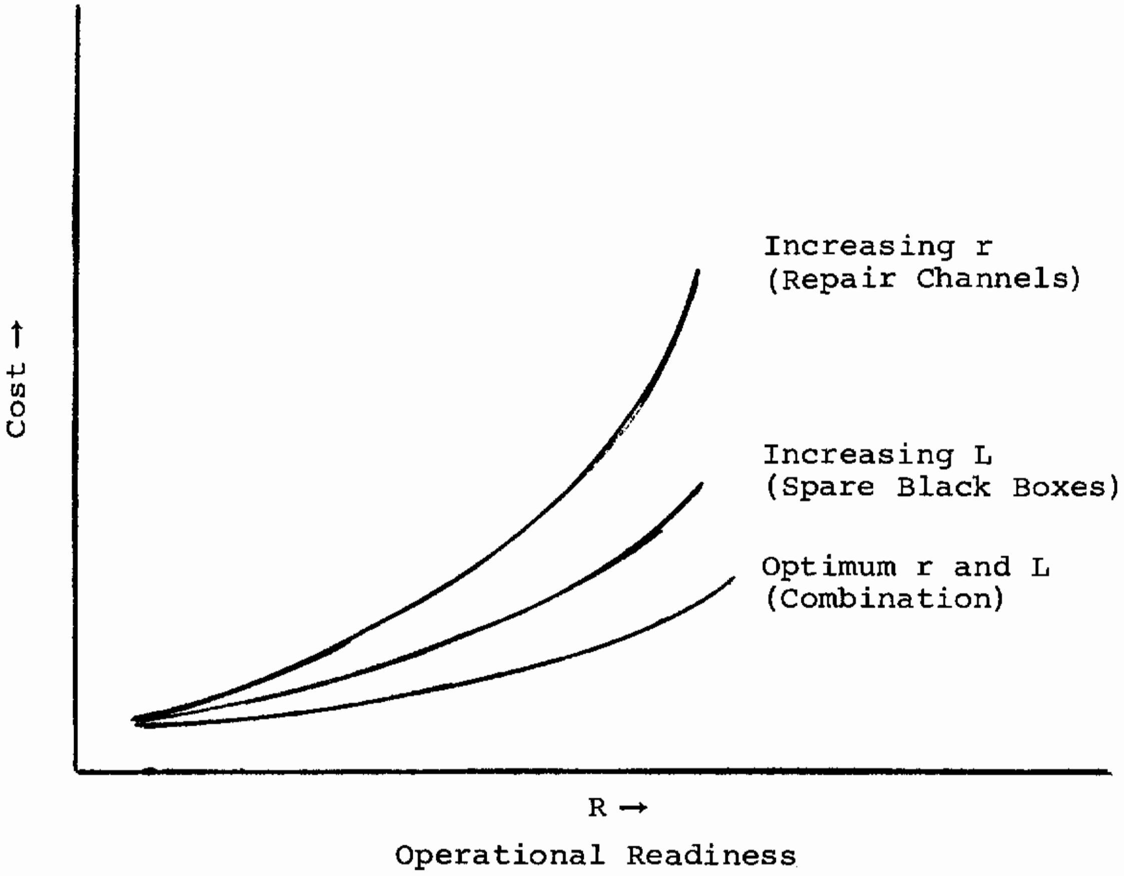

Figure 4. Least Cost Method of Improving Operational Readiness.

The figure is based on a fixed number of operational units and cost ratio between spare black boxes and repair channels. These curves reflect several ways of achieving a specified level of operational readiness. In general a combination of spare black boxes and repair channels gives a least cost method of achieving an operational readiness goal.

reduction in downtime may be achieved through reduction in scheduled and/or non-scheduled demands.

(3) In considering reduction in downtime due to scheduled demands, the following factors are considered:

(a) Tasks are grouped for simultaneous performance of the tasks in a group.

(b) The number of repair channels involved in each group of tasks is equal to the number of tasks in the group.

(c) The task groups are incapable of simultaneous performance.

(d) The duration of each task group is determined by the duration of the longest task in the group.

(4) Select Max d_i, where d_i is the difference in time between the maximum duration task and the next most time consuming task in the ith group of tasks. The downtime reduction due to the addition of one repair channel will be estimated by Max d_i for performance of the maximum duration task.

b. Determine maximum increase in operational readiness per additional person from the preceding step. This increase in operational readiness per additional person is determined by dividing the total increase in operational readiness by the repair channel size, since some repair channels will consist of more than one man.

c. Select that work area possessing the largest increase in operational readiness per additional man for the first additional repair channel.

d. Recalculate achieved operational readiness. If operational readiness goal is achieved, proceed to Trade-off of Personnel and Spares, below. If operational readiness is not achieved, repeat step b through d until achieved.

A simplified illustration of this procedure is given in Section 3.11.

3.8.2 Trade-off of Personnel and Spares

The minimum manning achieved above does not take advantage of spares. Queuing tables are prepared which provide trade-off between personnel and spares. To further reduce personnel by capitalizing on spares, the following procedure may be used:

a. The operational readiness change from the substitution of a spare unit for a repair channel is determined from the queuing table. This is done for all work areas (this is applicable only to those areas possessing more than one repair channel).

b. Select that repair channel that yields maximum return in operational readiness when a spare unit is added.

c. Recalculate operational readiness of the system. If operational readiness is less than required, proceed to step e.

d. Continue steps b and c until an additional spare unit will reduce operational readiness beyond permissible level. Proceed to step f.

e. Repeat step b using (first) two spare units. These two units represent the largest increase in operational readiness from all possible substitutions. Remove only one repair channel. Repeat using three spares, four spares, etc., until the specified level of operational readiness is achieved.

f. The number of personnel in the system now constitutes minimum manning utilizing spares.

This procedure may be extended to incorporate achievement of operational readiness at minimum cost provided cost estimates of personnel (by skill) and spare units are available.

The procedure for minimizing cost in achieving a specified level of operational readiness would be based on (see Section 3.11.4):

a. cost of a repair channel[1] (i.e., men and prorated cost of equipment)

b. cost of spare unit.

The preceding procedure would be repeated, except the selection of which repair channel to add or remove from the system would be based on operational readiness change per unit cost. In the manning trade-off routine above, the relative cost of personnel of different skill is obviated by the assumption that the task requires at least a lower limit specified skill level for performance. A higher skill level than required, would perform the task at the same rate. In all such cases, the lower skill alternative would be taken.

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[1] A repair channel is a maintenance man or maintenance team which follows a specified sequence of actions in repairing a black box. For a more detailed definition of repair channel, see the Glossary.

3.8.3 Determination of Personnel for All Shifts

There may be several shifts during a working day. These shifts may or may not be of equal duration and the workload per shift may vary with the shift.

For any combination of shift durations, the procedure described in the steps contained in Section 3.1 through 3.8 is applicable. The basic process is repeated for each shift. This yields the total manning required to support the several shift operations.

There will be, in general, different numbers of personnel and spares required (as calculated above) at each work area for different shifts, if the shift duration or operational performance requirements vary with shifts. The number of spares required will be the maximum required for any shift at each work area.

Due to excess spares introduced by considering all shifts (more than required to meet operational requirements) the operational readiness should be recalculated.

Sum the total manning requirements for all shifts in each specialty field and skill level.

3.8.4 Determination of Back-up Personnel

Up to this point in the manning procedure, it has been assumed that the personnel are 100% available, which is not the case. Back-up[1] personnel are required to compensate for this (AFM-26-1). The number of back-up personnel are based on specialty field and skill level, using experience factors.

Appendix VI developed a general expression for estimating the Personnel Effectiveness Factor. This factor is used as a multiplier of the manning requirements computed in Section 3.9.

In cases where a specific skill workload requires less than one man, judgment may be used to establish either 1 or 2 men.

3.9 <u>Non-Organizational Support</u>

Not all workload generated by the operational unit will necessarily be handled at the organizational level. The effect of a transfer of workload to a higher level must be explicitly accounted for in total manning calculations.

a. Utilization of Existing Facilities (Case I)

Tasks are broken out and allocated to various echelons consistent with existing facilities for task performance. The procedure given in Section 3.8 is applied at each echelon involved.

---

[1] Back-up personnel are those assigned to the organization, but not engaged in primary work.

b. Isolated Locales (Case II)

When sharing of existing facilities is not practical, tasks which require low demand skills either must be performed by a higher echelon at another location or must be performed locally by men whose skill fields will have low utilization. In special situations where both alternatives are very costly, men having skills not requiring high utilization may be trained to perform tasks in other fields as well. Choice between these alternatives lies primarily in trade-offs between having skills and facilities at low echelons or extensive inventories there and in the pipeline.

In either case above, a mathematical model has been developed which describes the relation between the using organization and the support organization. The model is sufficiently general to describe the effect of more than one using organization on the support structure; e.g., ten squadrons of fighter planes.

3.9.1 Multi-Level Support System

This section presents a discussion and development of the physical configuration associated with the support network, to include the associated parameters related to manning requirements. It represents a generalization of the single-level model developed in Appendix I.

3.9.1.1 Description of Support System Model

Multi-echelon maintenance takes two general forms, one dealing with the operational unit as a whole, the other dealing with subdivisions of the operational unit at various levels of assembly. More expensive and specialized facilities, more special skill fields and/or higher skill levels are found at successively higher echelons. In the first form, the entire operational unit is maintained at all echelons. For example, maintenance of the airframe generally follows this pattern - washing and simple visual external checks at the first echelon; at the next echelon, replacement of normally replaceable sections, simple skin work, etc.; and at the highest echelon, work on main structural members, checks for overstress, etc. In the second form, each echelon maintains lower levels of assembly of the end item than the next lower echelon. For example, in Minuteman, operating ground electronic equipment is repaired by replacing defective drawers in the racks of equipment. At the next echelon, the drawer is repaired by replacing the defective printed wiring board assembly. This, in turn, may be repaired at a higher echelon by replacement of defective parts.

3.9.1.2 Model Logic and Configuration

The model describes the transfer and processing of operable and/or inoperable pieces of equipment among the elements of the weapon support system. This support system is made up of maintenance shops established and deployed on the basis of level of maintenance capability.

3.9.1.2.1 Model Logic Discussion

Spares may be considered to be maintained at the stations at each maintenance level. Upon an arrival of a failed unit at the ith level from the jth level, a spare unit, if available, is immediately sent to the jth level from the ith level, leaving the ith level with one less available spare unit, and one more unit in for repair. When it enters a service channel, the failed unit is repaired and returned to spare status.

In some instances, various tasks should be performed at different levels, requiring that units be sent from first one then another and still another level for total repairs; i.e., a scheduling or sequencing of tasks might be necessary.

The spares provide replacement for units in transit between echelons as well as those being repaired or in line awaiting repairs. A procedure for making trade-offs among spares, personnel and other costs may be found in Reference 8.

3.9.1.2.2 System Configuration Arrival Rates.

Statements about the model can be made as follows:

a. All field failures[1] will not necessarily be sent to the first maintenance level. Some percentage of them θ_1 will go to the first level.

b. The remaining $1 - \theta_1$ field failures will be sent to some higher level.

c. Some percentage θ_2^1 of the failures at the first level will be sent on to level two. Some field failures (θ_2) will also arrive at the second level. (The superscript designates sender and the subscript designates the receiver.)

d. Similar statements can be made concerning arrivals at higher levels.

A logic diagram of the flow of failure and/or tasks generated by the operational units follows on the next page. In the logic diagram, only arrival rate from the (i-1) to the ith maintenance level is shown.

Let

$\lambda^* = \lambda N$ - total field failure

---

[1] This is applicable to scheduled maintenance tasks also.

θ_i^k - the fraction of failures arriving at the ith level from the kth level

θ_i - fraction of the field failures going directly to the ith level

Then, the arrival rate, Γ_1, at the first level is $\Gamma_1 = \theta_1\lambda^*$. The arrival rate at each successive levels will be

$$\begin{array}{ll} \text{Second} & \Gamma_2 = \theta_2\lambda^* + \theta_2^1\Gamma_1 \\ \text{Third} & \Gamma_3 = \theta_3\lambda^* + \theta_3^1\Gamma_1 + \theta_3^2\Gamma_2 \\ \text{Fourth} & \Gamma_4 = \theta_4\lambda^* + \theta_4^1\Gamma_1 + \theta_4^2\Gamma_2 + \theta_4^3\Gamma_3 \\ \vdots & \\ \text{Mth} & \Gamma_M = \theta_M\lambda^* + \theta_M^1\Gamma_1 + \theta_M^2\Gamma_2 + \ldots + \theta_M^{M-1}\Gamma_{M-1} \end{array} \qquad (5)$$

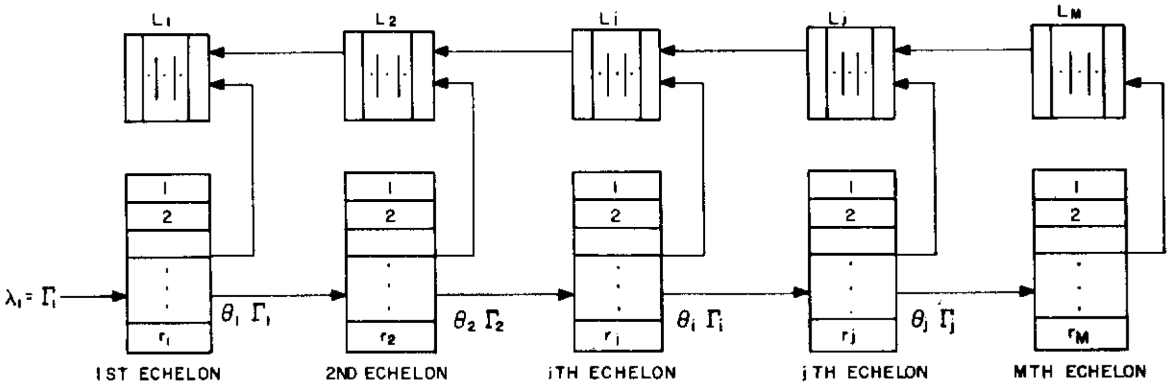

Figure 5. Logic Diagram of Task Flow in the Maintenance System

In the diagram, λ_i and Γ_i are defined above. θ_i is the portion of task arrivals at the (L-1) level that are sent to the ith level maintenance shop; r_i and L_i represent the repair channels and spares maintained at the ith level maintenance shop.

The final determination of arrival rate depends upon the assignment of values to the θ_i^k. This is achieved through an analysis of task occurrence rates, and the subsequent allocation of maintenance tasks to the maintenance levels.

The values assigned the repair and arrival (failure) rate would be obtained in using the prediction techniques discussed in Section 2.3. The allocation of maintenance may take one of two general forms:

(1) tasks would be assigned based on the capability of the nearest existing support facilities,

(2) tasks and facilities would be jointly optimized; i.e., facilities would be constructed to process certain tasks in addition to using existing facilities.

3.9.2 Manning Requirements of the Support Network

Basically, non-organization personnel become a significant factor of logistics and maintenance support through the concept of a repair channel. By definition, a repair channel is a maintenance man or maintenance team which follows a specified sequence of actions in repairing a black box.

In any particular maintenance location, echelon and shop, it is possible to estimate the maintenance tasks that will be performed there, including the skill requirements for that performance. This is true of all of the necessary scheduled maintenance, which by its very definition has a specified frequency of occurrence.

3.9.2.1 Maintenance Demand By Skill

The following procedural analysis will consider non-organizational (i.e., field and depot) maintenance demand by skill.

a. The total amount of labor made available for the performance of tasks must be as large as the total task workload when expressed in equivalent units. The amount of available labor may be expressed as the number of men, possessing a certain skill, multiplied by the amount of time each of these men will actually be available to utilize this skill.

The concept of skill has meaning in that maintenance demand requires the performance of maintenance tasks, and associated with each of these tasks is a certain skill. Therefore, our discussion will revolve around the task concept.

b. The workload for a particular skill depends upon the frequency of occurrence of those tasks that require that skill. A knowledge of these frequencies, together with the time it would take one man to perform the tasks will permit calculation of the men needed for total task completion.

Let λ_i be the total (allowing for duplication of assemblies) frequency per unit operational time of task [i], at a given location, and t_{si}, the required time requiring skill [s].

Then, if the system in question is operating continuously (24 hrs./day), the minimum number of men with skill [s] would be

$$\text{Men (min)} = \lambda_i t_{si}$$

for each task [t]. Considering all the tasks requiring this skill then would mean

$$\text{Men (skill s)} = M_s = \sum_i \lambda_i t_{si}$$

c. The very fact that we are considering system failures, implies that the system may not always be available; i.e., there will be times when the entire system is down[1]. During this time, there can be no new demands for maintenance. Therefore, we want to introduce an operational readiness factor (R) which will only consider the time the system is in an operational state.

d. In very much the same way, during the time that the system is in an operational state, a task can only manifest itself if the system (more specifically the unit generating the task) is actually operating.

Hence, define b_i as the portion of the time the unit generating task [i] is scheduled for operation.

This modification changes our previous result to

$$M_s = \sum_i \lambda_i t_{si} b_i R \qquad (6)$$

Equation (6) would be the minimum number of men with skill [s] provided these men worked around the clock. It is necessary to extend this result to practical circumstances by considering personnel skill availability. This availability (a_s) would be defined as the portion of the time that skill [s] will be made available for task performance.

e. Since each man is only working (a_s) of the time, total manning for skill [s] is

$$M_s = a_s^{-1} \sum_i \lambda_i t_{si} b_i R \text{ for fixed [s].}$$

---

[1] It is possible to make an adjustment in cases where the end item is not completely inoperative.

For all skills at a location, the total manning (M) is

$$M = \sum_s M_s = R \sum_s \sum_i a_s^{-1} \lambda_i t_{si} b_i$$

where subscript i is summed over only those tasks allocated to the location.

f. Two more points are to be made:

(1) It can be seen from the previous equation that M_s may not be integral. If not, then consider the next larger integral value (call it m_s), and assume that this would be the number of men of skill [s] that would be assigned. The average efficiency of skill [s] would then be M_s/m_s.

(2) As developed here, this calculation of M_s has not considered random effects. The manning may be adjusted to include random effects using the single echelon shop model and adjustment procedure described in paragraphs 3.5 through 3.8.

3.10 Errors

In general, sources of error are independent of each other and thus will tend to compensate for each other. Since they involve biases in both directions, there is further compensation. Collectively, they are generally overshadowed by the errors due to uncertainty about the characteristics of the hardware that make up the system.

Potential Sources of Error

The following are potential sources of error:

a. Operational performance requirements generally exceed actual demand. This will tend to overman for actual operation of the operational units (this is not really a source of error, but a safety factor).

b. Personnel utilization schedule does not account for full emergency capabilities; however, it does provide for consideration of emergency schedules. Again, this is not a source of error but a built in safety factor.

c. Cannibalization will provide uncounted spare black boxes in rare instances, where different necessary replacement items for two equipments or systems of the same type are not available in a "reasonable" time. Sparing policy should be such that this expedient is rarely used and quickly remedied by repair of the cannibalized item.

d. Failure and repair rate estimates. Where there are many separate tasks which enter the estimation of λ and μ, relatively large errors in estimates for individual tasks are ameliorated by compensating errors for other tasks so that over-all errors are relatively small. Variance of the average of a sample of N errors is $\frac{1}{N}$ times the variance of the individual values.

In work shops having a small number of repair channels and a low utilization of repair channels, error will be primarily reflected in

(a) decreased operational readiness if the error tends to underestimate work and probably require adjustment of one repair channel,

(b) insignificant effect on manning and operational readiness if workload is overestimated.

In work shops having low workload, errors are more likely to occur. These errors would probably involve one or two repair channels.

In work shops having high utilization (50% or above) with a large number of repair channels, error will primarily be reflected in

(a) decrease in operational readiness if error tends to underestimate work,

(b) an increase in operational readiness if error tends to overestimate work.

Errors in work shops having heavy workload are not likely to be significant due to the greater awareness of work requirements.

In summary, errors in manning will be reflected in changes in operational readiness. The net effect, if shops are over- or undermanned due to errors in failure and/or repair estimates, will be a decrease in operational readiness. The magnitude of this decrease will depend on the operational readiness goal established. For a high level of operational readiness (.95) this may be in the order of 20 percent, whereas for a moderate level of operational readiness (.70) this error may be in the order of 10 percent. Note, it is not anticipated that the total number of men would change significantly. What would be required is the reallocation of personnel to shops.

e. Local command tends to use self-adaptive control in assignment of personnel which yields performance of personnel which is better than average performance capability. This error is not readily measured, but with time it may be assumed to even out; i.e., training increases skill of slow learners, while the fast workers will adjust to adequate performance rates. (There will still be exceptions.)

This error tends to result in overmanning, the extent being inversely related to the error in the basic manning plan (i.e., an "optimum" manning schedule offers little room for improvement, whereas a bad one offers a great deal). This source of error, large or small, tends to compensate for other errors whatever the source. This error should be a small one in the direction of overmanning.

f. Incomplete task recognition; not all tasks are recognized. This creates demands for personnel not expected. The magnitude of errors from this source diminishes as the hardware of a system becomes more detailed and "firmer." Experience in predicting will provide a guide to the quantitative adjustment required to minimize this error.

This error, along with estimating errors of reliability and maintainability, is closely tied to knowledge of the hardware, and these errors are, by far, the most significant errors introduced into the manning prediction.

It is anticipated that all personnel skill types will be identified through identification of the equipment functions. For low demand skills, relatively large estimation errors are permissible without causing errors in manning and nonrecognized tasks will predominantly fall into this category. For skills having high work demands, there is generally greater awareness of the tasks required with resultant better estimation accuracy. In fact, it may be that the accuracy of workload prediction is proportional to the workload magnitude.

Significant errors in task recognition could be precluded by employment of a task checklist, which would cite standard tasks associated with known equipment and/or functions of operational units. Further, standard tasks relatively independent of the equipment would be incorporated into the checklist. The number of tasks that would not be recognized using the checklist procedure, would be controlled through the degree of detail required. In consequence of this, it seems reasonable to expect 90% of the significant tasks encompassing 95% of the total work to be obtainable from equipment and function definitions.

g. The use schedule of operational units may be such that all or some portion of the total number of operational units assigned will perform simultaneously; e.g., a flight of seven aircraft. This type of operational schedule has not been analytically explored in detail (Appendix VIII offers a technique that compensates for this flight pattern); however, the following observations may be made about the adequacy of the mathematical model used in this program to describe that type of schedule.

(1) If this type of flight described above is infrequent, the estimations obtained through the technique described in this report will provide a good approximation.

(2) If this type of flight schedule is common, the effect will be decreases in operational readiness and/or decrease in personnel utilization.

In the mathematical model developed in Appendix I, random arrival of demand and an exponential distribution of repair times are assumed. These exact conditions are seldom found in reality, however, they often represent a good approximation to reality. Typically, marked deviations from these conditions result in only small errors in queuing estimates.

Generally, repair times are closer to being constant than is indicated by the exponential distribution; i.e., the mean is greater than the variance. An item will be scrapped rather than repaired if the time (and, thus, cost) to repair is very large. Thus, the long duration "tail" of the exponential distribution is chopped off. Fixed times required for getting tools, making measurements, etc., in unscheduled maintenance tend to shift the mode of the distribution from 0 in the exponential distribution to some significant value. These factors both tend to make the mean larger than the variance since the former reduces the variance and the latter increases the mean. The effect of the approximation in such situations is to overestimate queues very slightly. The difference is less than 5% between delays when service is constant as compared to exponentially distributed (see Reference 12). Thus, for a wide range of conditions the approximation is more than adequate for prediction in the conceptual phase when arrivals are approximately random.

When arrivals are more evenly spaced than with the exponential distribution (i.e., probability of an arrival increases, the greater the time since the last arrival, and diminishes sharply on occurrence of an arrival), estimates of queuing are likely to be high. When they are bunched (i.e., probability of an arrival decreases, the greater the time since the last arrival, and increases sharply when an arrival occurs), queuing will be underestimated where the exponential distribution is assumed. However, note that special procedures are provided for dealing with bunching (Appendix VIII), thus significant errors from this source are also precluded.

3.11 Examples of Manning Prediction

3.11.1 Manning to Achieve a Given Operational Readiness

The basic objective is the determination of the manning requirements that will achieve a given operational readiness. This must be possible when given a system of N operational units with an estimated frequency of usage (f), and each occurrence of mean duration (d) per operational unit, per calendar time period.

a. System Description

For our hypothetical example, let the system consist of four aircraft.

b. Operational Requirements[1]

Each aircraft must be capable of operation for six (6) hours per day in an eight-hour operational shift, based on an expected three flights per day of two (2) hours duration each and with additional characteristics as follows:

(1) An operational readiness of .75 is specified. Based on any operational readiness that is achieved, the probability of having at least two (2) units being operationally ready at a randomly selected time can be determined.

(2) Probability of two (2) or more operational units being ready at a randomly selected time must be at least 0.95.

c. Shift Schedules

All maintenance is performed during a single eight (8) hour shift each day. All operational time on the aircraft will be accumulated during the same eight hour shift.

d. Determination of Workload

Failures in the aircraft require two types of maintenance:

(1) Scheduled Maintenance (for the present purpose, this may be either Calendar or Usage Duration Maintenance)

(2) Random Usage Maintenance

---

[1] See note at end of this section.

3.11.1.1 Scheduled Maintenance

Assume the following information to be known. Each aircraft is down an average of 0.5 hours each day for scheduled maintenance, or a total workload of 2 hours per day of scheduled tasks.

3.11.1.2 Random Usage Maintenance

Reliability analyses indicate that these random tasks will occur at a mean rate of 0.5 per operational hour per aircraft. From the given information,

f = 3 (frequency of operation per shift)

d = 2 hrs. (duration of each operation)

λ = 0.5 (failure rate per operational hour)

If the mean rate to repair (associated with each repairman) for each random task (t) is $\frac{1}{2}$ hr., then the work generated each day W is

$$W = (fd)\lambda t$$

$$= (3)(2)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right) = 1.5 \text{ Task Hours/day}$$

3.11.1.3 Determination of the Utilization Factor

$$\rho = \frac{\text{workload generated per operational unit, per unit time}}{\text{workload capability per channel, per unit time}}$$

Since some time will be spent in scheduled maintenance, the utilization factor must be adjusted by t_r.

Allowing time for scheduled maintenance, there are six (6) hours remaining per day for handling of those random tasks that occur.

t_r = 6 hrs. (time available for random usage task)

Therefore, the adjusted utilization factor ρ_A is

$$\rho_A = \frac{W}{t_r} = \frac{1.5}{6} \frac{\text{Task Hours/day}}{\text{Hours/day}}$$

$$= 0.25$$

From the value of ρ_A it is possible to make an initial estimate of the minimum channels needed. This ρ_A above is based on a single operational unit. If all four units are considered, four times as much work will be generated. The utilization factor must be restricted to values less than 1. Let r be the lower bound on the number of channels; this requires that

$$\frac{N\rho}{r} \leq 1 \text{ or } r \geq N\rho = (4)(0.25) = 1$$

This establishes a minimum of one channel for the system.

3.11.1.4 Operational Readiness

The operational readiness (R) of a system of N units has been defined as the number of ready operational units (N_o), divided by the total (N) in the system. This may be written:

$$R = \frac{N_o}{N} = \frac{N-N_d}{N} = 1 - \frac{N_d}{N}$$

Calculation of R means a calculation of N_d. To calculate N_d it is noted that the total number of units down are down either for scheduled tasks (N_s), or random tasks (N_r). Therefore,

$$N_d = N_s + N_r$$

For the average number of units down, the average number of units down for each maintenance demand type is needed.

3.11.2 Downtime Contribution From Scheduled Maintenance

If the given information is taken as the equivalent of 4 scheduled tasks per day, requiring 0.5 hour of maintenance time each, the contribution to $\bar{N}_d$ by scheduled tasks will be as follows:

$$\bar{N}_s = \frac{N_s t_s}{T}$$, where T is the shift duration.

Let $N_s = 1$ and t_s[1] $= 2$. A working day has been fixed at eight hours ($T = 8$). Thus, on the average, there will be

$$\bar{N}_s = \frac{(1)(2)}{8} = \frac{2}{8} = 0.25$$ units down per day for scheduled maintenance.

3.11.3 Random Usage Maintenance

For the random case, the number of units down is tabulated in queuing tables (Tables 7 and 8). These tables express the number of units down (average) as a function of (1) the number of units in the system, (2) the rate at which these units are failing, (3) the rate at which they are repaired, and (4) the number of channels performing the maintenance. Use of the tables will be made clear as the example progresses.

---

[1] Only one repair channel is assumed, hence the total time in scheduled maintenance must be performed by this one channel.

TABLE 7

OPERATIONAL READINESS MEASURES [N=4, r=1, ρ=0.25]

Measure	L = 0	L = 1	L = 2	L = 3	L = 4	L = 6
E(q+s)	1.241	1.711	2.191	2.678	3.169	4.156
N_r	1.241	0.938	0.767	0.643	0.554	0.437
N_o	2.759	3.062	3.233	3.357	3.446	3.563

TABLE 8

OPERATIONAL READINESS MEASURES [N=4, r=2, ρ=0.25]

Measure	L = 0	L = 1	L = 2	L = 3	L = 4	L = 6
E(q+s)	0.838	1.013	1.136	1.251	1.264	1.310
N_r	0.838	0.379	0.181	0.089	.043	0.011
N_o	3,162	3.621	3.819	3.911	3.957	3.989

Legend of System Readiness Measure:

E(q+s) = expected number of units in queue or service

N_r = mean number of units down

N_o = mean units operational

r = number of repair channels

N = number of operational units (aircraft)

L = spares

ρ = utilization factor

To determine N_r, the number of units down for random tasks, look to Table 7 for N = 4, r = 1, and $\rho = 0.25$. Directly from the table, under N = 4, $N_r = 1.241$. This N_r represents the mean number of units down during only that portion of the day that random tasks are being performed. N_r is adjusted as follows:

$$\bar{N}_r = \frac{N_r t_r}{T}$$

$$= \frac{(1.241)(6)}{8} = \frac{7.446}{8}$$

$$\bar{N}_r = .931$$

The mean number of units down ($\bar{N}_d$) is

$$\bar{N}_d = \bar{N}_s + \bar{N}_r = 0.25 + 0.931$$

$$\bar{N}_d = 1.181$$

Thus, R for the system with a single channel is

$$R = 1 - \frac{\bar{N}_d}{N} = 1 - \frac{1.181}{4} = 1 - 0.295$$

$$R = 0.70$$

Adjustment of Manning

Since this level of operational readiness does not meet requirements, add one channel to the system and recalculate $\bar{N}_d$. Go now to Table 8 with r = 2 and all other parameters unchanged; viz., N = 4 , $\rho_A = .25$. For this case

$$\bar{N}_d = \frac{N_s t_s + N_r t_r}{T} = \frac{(1)(2) + (0.838)(6)}{8}$$

Hence

$$R = 1 - \frac{\bar{N}_d}{N} = 1 - \frac{0.878}{4} = 1 - 0.220$$

$$R = 0.78$$

Since this value for R exceeds the required 0.75, the procedure for manning the system to meet a specified level of operational readiness can stop.

The equivalent form for expressing operational readiness (R) in terms of downtime and uptime is as follows:

$$R = \frac{T - T_d}{T} = 1 - \frac{T_d}{T} ,$$

where

T = total amount of uptime and downtime for the system (4 aircraft)

T_d = amount of downtime contributed by all maintenance

Total time T would be evaluated for 4 units; therefore,

$$T = 4 \times 8 = 32 \text{ hrs.}$$

$$T_d = T_{ds} + T_{dr},$$

where

$T_{ds} = t_s N_s$ (time down for scheduled tasks)

$T_{dr} = t_r N_r$ (time down for random tasks)

$$T_d = t_s N_s + t_r N_r = (2)(1) + (6)(.838) = 2 + 5.028$$

$$T_d = 7.028$$

$$R = 1 - \frac{T_d}{T} = 1 - \frac{7.028}{32} = 1 - 0.22$$

$$R = 0.78$$

This agrees with the result obtained previously.

3.11.4 Trade-off of Personnel and Spares

The effect of adding spare units to the system will now be considered. In the tables, 7 and 8, the L values represent additional spares (black boxes) to the system. From Table 8, note that adding one spare reduces N_r from 0.838 to 0.379, which corresponds to an R of .87, calculated as before. To see if this addition of spares will permit any reduction in channels, go to Table 7 for one channel, with L = 1. N_r in this case is 0.938, which yields an R of 0.76. Thus, a reduction of one channel is possible when one spare is provided. No further reduction of channel is possible.

The table below shows that an addition of one spare unit to the system with two channels permits a reduction to one channel. Therefore, minimum manning with spare is a single channel, while without float it is two channels.

Only one repair person is required for this eight-hour shift, excluding back-up.

L	r	R
0	1	0.70
1	1	0.76
0	2	0.78
1	2	0.87

Manning a System Possessing More Than One Skill

The first example will now be altered slightly by considering a system composed of two distinct black boxes, each black box requiring a different skill. The system structure will be essentially the same as before. However, the total system workload will be distributed between both boxes and, hence, work areas. In addition, the operational readiness requirement is 0.55, meaning at least 0.75 probability of having two or more aircraft ready at a randomly selected time.[1]

Designate the boxes and responsible work areas A and B. The total system demand, as before, is $(fd)\lambda = 3$ tasks/day, but distributed among the two black boxes as

$(fd)\lambda_A = 2$ tasks/day

$(fd)\lambda_B = 1$ task/day

Let the mean repair time of the channels at A be .875 hr./repair, and at B be 1.75 hr./repair.

Scheduled maintenance workload will be assumed evenly distributed between shops, so that, effectively, each shop may devote 7 hours per day for random tasks, and the total contribution of scheduled tasks to downtime is still $\bar{N}_s = .25$.

The scheduling of the maintenance tasks may be viewed in two ways:

a. The tasks may be scheduled for simultaneous performance, in which case the downtime contribution is the task duration of the longest of all such tasks.

b. Tasks can be performed sequentially, within each black box as well as between boxes. The downtime is then equal to the sum of the task times for all tasks at both locations.

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[1] See note at end of section.

The latter is assumed in this example. This also applies for the performance of random tasks by the two work areas, in that it is assumed that no two random tasks are performed at the same time on any one aircraft.

Calculate the channel adjusted utilization factor for each skill:

$$\rho_A = \frac{(fd)\lambda_A t_A}{t_r} = \frac{(2)(.875)}{7} = 0.25$$

$$\rho_B = \frac{(fd)\lambda_B t_B}{t_r} = \frac{(1)(1.75)}{7} = 0.25$$

where t_A and t_B are mean repair times of channels at A and B, and t_r is the time available for random tasks.

Since $\rho_A = \rho_B$, the same set of tables may be used for making calculations.

As before, the minimum number of channels at each work area is one, for a ρ of 0.25 and an N of 4. Calculate R for one channel at each area just as before; this time the queuing tables must be gone into separately for each shop. R will be equal to 0.40 for one channel in each shop (see Table 9). Thus, begin adding channels one at a time until the required goal is reached. Adding one channel to either shop, say Shop A, raises R to 0.48. which is still short of requirements.

Calculations below show the result of adding a channel to Shop B (Table 8, r = 2, L = 0).

$$\bar{N}_d = \frac{N_s t_s}{8} + \frac{N_{rA} t_{rA}}{8} + \frac{N_{rB} t_{rB}}{8}$$

$$= \frac{(1)(2)}{8} + \frac{(0.838)(7)}{8} + \frac{(0.838)(7)}{8}$$

$$= 0.25 + 0.733 + 0.733$$

$$\bar{N}_d = 1.716$$

$$R = 1 - \frac{\bar{N}_d}{4} = 1 - \frac{1.716}{4} = 1 - 0.429$$

$$R = 0.57$$

Thus, a minimum of four channels -- two for each skill -- is needed to meet requirements, if there are no spares.

TABLE 9

CONFIGURATIONS OF CHANNELS AND SPARES FOR TWO MAINTENANCE SHOPS

Number of Channels Per Work Area		Spares Per Work Area		System Operational Readiness
A	B	A	B	R
1	1	0	0	.40
		1	0	.46
		1	1	.53
		2	0	.50
		2	1	.56
		3	0	.53
		4	0	.54
2	1	0	0	.48
		0	1	.55
		1	0	.58
2	2	0	0	.57

This table is symmetrical. Therefore, if A and B are interchanged, the same operational readiness is obtained.

Requirements for channels can be reduced by additions of spares. As before, one, two, etc., spares are added successively to each work location, recalculating R each time. Table 9 lists the results of these additions. It can be seen that adding one spare to either Shop A, or B, will permit a reduction of one channel.

A further reduction, to one channel at each location, is possible by having two spares at one shop and one at the other, with a readiness of .56. Note that even with more total spares in the system -- for example, four at one shop and none at the other -- will not give as much operational readiness as with a configuration of two and one. This simple example above shows a reduction of two personnel utilizing spares for a one-shift operation. If a three-shift operation were required, other things equal, and a personnel back-up factor (number of men required per position in order to allow for furloughs, sickness, training, etc.) of (2) applied, this would mean 24 men for the three-shift operation. Whereas, using spares expeditiously, operational requirements may be achieved with only 12 men.

This could be accomplished (manually using tables) in approximately one man week. This anticipated effort is of small consequence when compared to a probable mistake of twenty excess personnel not contributing significantly to operational readiness, since this may represent 100 man-years of time wasted when projected over system lifetime at only one organization.

Alternatively, undermanning a system carries with it the consequence of having multimillion dollars of operational units down for want of a small number of additional personnel.

It may seem at first glance that this procedure would entail considerable effort. This is not anticipated to be the case. The organizational structure is such that there are a relatively small number of (almost) independent work shops. For each incremental improvement, it is required to make one calculation for each work shop; viz., trading off operational readiness with personnel (repair channel) and trading off spare black boxes with personnel.

Manning for Cost Minimization

Cost may be used to determine the optimum choice among the several alternatives. Adding more equipment units implies added capital investment. Adding repair channels implies added labor costs, and perhaps some capital investment in repair facilities. Since each change carries some cost, these added costs can be weighed against the possible improvements.

For example, if it were wanted to carry out cost minimization of the various trade-off alternatives, only needed would be to have a knowledge of (a) the cost of each type of spare, and (b) the cost of a repair channel. For purposes of illustration, assume the following costs:

a. Each spare costs X dollars.

b. Each repair channel costs 10X dollars.

From Table 9 note that with two channels in the system, and no spares, a readiness level of 0.40 can be achieved. Now, suppose that tactical requirements dictate that operational readiness be increased for this system from 0.40 to at least 0.55, with the same number of units; i.e., four.

There is a different cost associated with each of the ways of accomplishing this increase. The courses of action available are as follows:

a. Increase the quantities of spares.

b. Increase the number of repair channels.

c. Some combination of the above.[1]

The problem now is achieving the desired level of operational readiness at least cost. Below in Table 10 are the results of calculations to solve this problem.

<u>Note: Binomial Probability Distribution</u>

Part of the performance requirements for the system is that at least two aircraft must be ready at any randomly selected time, 95% of the time. The system has been manned, in example 1, to achieve an operational readiness of .76. The requirement may be approximated with the Binomial Distribution. The probability of at least n units being operational, given a total of N and an operational readiness of (R), is

$$P(N_o \geq n) = \sum_{N_o=n}^{N} \frac{N!}{N_o!(N-N_o)!} [R^{N_o}(1-R)^{N-N_o}] ,$$

where N_o is the number operational.

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[1] In considering alternate ways of achieving a specific number of operationally ready units, one fairly obvious way that should be considered is the addition of an operational unit.

TABLE 10

COST MINIMIZATION

Cost of Repair Channel = 10X Cost of Spare = X

Case	Specified Operational Readiness	N	L	r	ρ	Calculated Operational Readiness	Support Cost
1	.40	4	0	2	.25	.40	20X
2	≥ .55	4	3	2	.25	.56	23X
3	≥ .55	4	1	3	.25	.58	31X
4	≥ .55	4	0	4	.25	.57	40X

Reference to this shows that the choice of case 2 provides the most benefit in a least cost sense.

In the system, $N = 4$, $R = .76$

$$P(N_o \geq 2) = \sum_{N_o=2}^{4} \frac{4!}{N_o!(4-N_o)!} (.76)^{N_o}(.24)^{4-N_o}$$

$$= (6)(.76)^2(.24)^2 + (4)(.76)^3(.24) + (.76)^4$$

$$= .1996 + .4214 + .3336$$

$$P(N_o \geq 2) = .955$$

Alternatively, $P(N_o > n)$, N may be given, with the requirement to determine R for each operational unit. Standard tables exist for determination of the values required.

For the second case above, where the system was expanded to two work areas, the above $P(N_o \geq 2)$ drops to .76, corresponding to an R of .55.

3.12 Summary

3.12.1 Manning Prediction

It is anticipated that the manning prediction technique proffered in this report does not differ radically from intuitive procedures presently used by management personnel in the Air Force. The recognized differences lie in the formal structure of the manning problem. These differences are:

a. Mathematical statement of the manning goal.

b. The causal relationship between this goal and manning through the following:

    (1) Spares
    (2) Waiting time

The manning objective chosen in this report is mathematically equivalent to maximizing the total operational hours of the operational units, given a fixed distribution of skill hours.

Sometimes, it seems desirable to differentiate between peacetime and wartime manning. The objectives above are mathematically equivalent to maximizing total training time (of operational units) for a given investment in skill hours. As a manning objective in peacetime, maximizing total training time for a given skill hour investment has an intuitive appeal.

An important observation to be made is, if required, a parametric analysis may be performed on the operational requirements;

i.e., precise knowledge of operational requirements may not be known and it is desired to know how the manning varies as the operational requirements change. This ability to perform parametric analysis may be important in comparison of alternative systems or in jointly allocating fixed manning resources to two or more systems.

The technique will allow evaluation of error in input information through cause and effect relationships developed.

Having established causal relationships, required refinement of specific prediction techniques may be directed.

3.12.2 Recommendations

3.12.2.1 Operating procedures must undergo testing and modification to achieve a good usable end product. For a prediction procedure such as the one presented in the report, such testing should examine various key characteristics such as reliability and validity. A reliable procedure should permit different people to achieve about the same results given the same inputs. A valid procedure would have as its product, predicted manning close to that which actually is required to do the job. Potential error sources discussed in Section 3.10 should be subjected to evaluation via a test program for the manning technique. Analysis of causes of errors in predictions could lead to modification of procedures to remedy problem areas.

Test application of the procedure would also provide a check on the clarity and comprehensiveness of the procedures and would point out areas where rewriting or revision is required for ease of application.

3.12.2.2 The tables presented in Section 3.11, although adequate for the simple example given, are not suited for the broad spectrum of parameter values that will generally be encountered in practice. Furthermore, the form of the queuing tables as presented are not conducive to computational facility. Therefore, it is recommended that a set of queuing tables be developed. A general set of tables can be developed similar to those of Peck and Hazelwood (Reference 5), except that provision will be made for spares. These tables would be generally applicable and would meet most requirements in about 300 pages. The tabular format which could be more expediously employed is shown below. Ranges of parameter values could be established using typical organizational structures as guides. The uses of such a set of tables would be manifold; e.g., personnel trade-offs, inventory buffer levels, trade-offs between reliability and maintainability in the design of equipment.

Proposed Format of Queuing Tables

TABLE 11

N = Specific Number, r = 1

Utilization Factor ρ	Number of Repairable Spares			
	0	2	. . . .	L
.1	e			
.2				
.				
.				
.				
.9				

TABLE 12

N = Specific Number, r = 2

Utilization Factor ρ	Number of Repairable Spares			
	0	2	. . . .	L
.1	e			
.2				
.				
.				
.				
.9				

where N = number of operational units

r = number of service channels

L = spare black boxes (repairable)

e = number of units in excess of spares in or awaiting service

4. PERSONNEL TRAINING REQUIREMENTS AND SYSTEM PHASEOVERS

4.1 Introduction

The purpose of this section is to present a technique which will allow for scheduling of training-manpower resources in the Air Force. Specifically, a method is developed in which consideration is taken of

a. the training requirements in terms of time necessary to achieve a specified skill;

b. the phasing-in of new systems and the concomitant demands on available skills;

c. the phasing-out of old systems and the concomitant availability of skills; and

d. the manpower phasing into and out of personnel inventory because of enlistment and discharge.

4.2 Background

The manning of any system can be thought of in terms of a three-step program: (1) personnel selection, (2) personnel training, and (3) personnel deployment. However, planning and scheduling of phase-in and phase-over must take place prior to selecting the specific personnel to be involved. The factors of each of these steps will be discussed in turn.

a. Factors in personnel selection.

    (1) System requirements (those aspects of the system that establish qualitative and quantitative personnel requirements).

        (a) Nature of system requiring support; e.g., airborne radar or ground checkout equipment.

        (b) Mission profiles (data relating to mission goals and their accomplishment).

        (c) Reliability and maintainability requirements (probability of success goals and their effects on maintenance tasks).

        (d) Man-machine allocations (effects of possible man-machine trade-offs on manning requirements).

        (e) Results of task analysis (application of task-analysis data to qualitative manning estimates, limited to enumerations of required job specialty).

(f) Prediction of necessary skill levels (the final stage of preliminary manning assessment, involving quantitative estimates of the number of personnel required at each skill level within a job specialty).

(2) Personnel availability (considerations of current manning conditions and their implications for manning a proposed system).

(a) Use of available skill resources.

(b) Effectiveness of experience transfer (savings to be realized by employing personnel having prior training and related experience). This can be estimated from results of previous retraining programs where they have occurred. The measure lies in subsequent performance of trainees. Where there is not adequate history, treatment as recruits should provide a conservative estimate of success.

(3) Selection criteria.

(a) Previous training and experience

(b) Rating of past performance

(c) Test-battery scores

(d) Personality characteristics

(e) Likelihood of continued military service.

b. Factors in personnel training (variables involved in training selected personnel and the effects of those variables on system design).

(1) Training programs (factors pertaining to the development of an effective training program).

(a) Knowledge of results

(b) Avoidance of habit interference

(c) Variety of practice materials

(d) Methods used in training

(e) Knowledge of principles involved

(f) Effectiveness of guidance

(g) Duration of training program

(h) Motivation of trainees

(2) Training instructors (significant variables pertaining to instructor selection and performance, emphasizing their relationships to system-manning requirements).

(3) Training equipment (aspects of trainers and job aids that affect training-program effectiveness and, thereby, influence system-manning requirements).

c. Deployment of trained personnel (those factors arising from the assignment and deployment of trained personnel to specific tasks required by the proposed system).

(1) Constraints imposed by system (manning requirements arising from system configuration and deployment).

(a) Environmental conditions (effects of hostile environments on performance of personnel assigned to these locations).

Working environment - snow, wind, humidity, darkness (blackout), etc., as they directly impinge on the personnel while they perform their tasks. Here, the sources of estimates are experience and application of time and motion studies made in similar environments.

Some tasks must be performed on site on unsheltered equipment. If this is likely to occur during cold weather where protection of the hands is required, studies of the effects of gloves, heavy clothing, etc., on performance of the task must be drawn upon to provide adjustments to manning requirements to meet special local conditions.

Equipment design and support planning should include in their objectives, limiting requirements for work under adverse conditions. Effective design for maintainability will keep adverse climatic conditions from acting as a major problem in manning.

Location - potential sites as related to potential sharing of facilities, expected tour of duty and re-enlistments anticipated. Here again experience must provide a basis for adjusting requirements established for "normal" CONUS installations.

(b) Operational requirements (constraints imposed on system manning by operational readiness requirements and tactical deployment of the system). This is discussed more fully in Sections 1.1 and 3.4.

(2) Performance factors (the dependence of task performance upon workloads, work/rest cycles, vigilance requirements, etc.).

Information requirements for personnel selection are satisfied by (1) the system manning-skill analysis, (2) personnel records, (3) personnel systems records, and (4) training requirements to achieve satisfactory performance in a specified skill.

Overestimation of a man's capabilities to perform particular tasks is equivalent to underestimating the amount of work to be done and estimating his capabilities correctly. In general, these human capabilities are better determined than estimates of the amount of work to be done. The consequence of errors in estimates, thus, is appropriately discussed in Section 3.10 although, there, the focus is on errors in estimating demand.

4.3 Training Requirements

4.3.1 General

In most technical fields, there is a series of skill levels (3, 5, 7, 9) representing increasing amounts of skill, knowledge, and responsibility. Typically, the technician advances a level at a time to the highest level, with training and the passage of time being prerequisites for each step. Consequently, in order to have men continuously in the highest level, there must be a steady upward flow from the lower skill levels to replace those discharged or transferred, as well as to meet new requirements. Primarily because of low re-enlistment rates, only a small portion of the qualified men starting out in a field reach its high skill levels. Thus, there usually are several men at the lowest level for each one at the highest. Concomitant with this progression is a progression in grade (rank) and associated pay and privileges.

Manning requirements for a system should, in general, be designed into the system to provide ratios between numbers of men at the different skill levels and grades which are compatible with those practically attainable, considering re-enlistment and other problems.

Routines can be developed for comparing two policies, but it is not always practical to develop functional relationships among relevant variables that permit explicit optimization other than by exhausting all possibilities. In some instances, the number of alternatives is sufficiently small to permit examination of all of them.

4.3.2 Model Development

Assume that the average time in a skill level and the probability of promotion have the same average value for all situations involving the same promotion policy.

Let:

E_1 = entries per year into the lowest skill level

t_i = average time in skill level i in years

P_i = probability per year of advancement to skill level i from level (i-1), rather than receiving transfer or discharge, regardless of length of stay in level (i-1).

Then

$N_1 = E_1t_1$ = average number of men at level 1

$N_2 = E_1t_1P_2t_2$ = average number of men at level 2

$N_3 = E_1t_1P_2t_2P_3t_3$ = average number of men at level 3

or, generally

$N_i = E_1t_1 \prod_{j=2}^{i} P_jt_j$ = average number of men at level i, $i \geq 2$

The total number of maintenance men in a system having three levels, then, is

$$N_1t_1[1 + P_2t_2(1 + P_3t_3)]$$

Policy changes will affect these values: a high rate of advancement tends to reduce t_1 and t_2 and increase t_3. Re-enlistment rates may increase all of these values if the early attainment of high level of skill and concomitant grade tends to make a military career more attractive. Policy may lower them, if civilian offers to skilled men are more appealing because they attain the high level of skill before the investment in service toward pension becomes a strong incentive to re-enlistment.

Retraining of men with unneeded skills can distort the normal picture because, typically, these men enter skill levels with more time in service than men who enter the field initially; however, if a clear differentiation is made between skill level and grade, the problem can be avoided.

4.4 System Phaseovers

4.4.1 Training Schedules

Phasing-in new systems and phasing-out old ones is an almost continuous process for the Air Force. Obsolete equipment can be sold, scrapped, or used for training. Men with obsolete skills must be retrained or retired. In some instances, a man can remain in his field, requiring only familiarization with the new equipments. In others, however, changes of field are required. Selection of the best combination of changes to be made can be facilitated by use of linear programming as an optimizing technique.

Planning can be performed in several degrees of detail.

a. Assignment for transfer, especially where change of field is required. A typical objective might be to minimize total training required in terms of cost, measured in time or money.

b. Scheduling training and transfers during a protracted phaseover with objectives as in a above.

c. Scheduling training and transfers subject to limitations on training capacity during any particular period.

Planning can be revised as often as needed to meet changing requirements or to adjust to errors in estimates and predictions.

The first step is to determine which men will be available and what skills will be needed. Demand quantities must be adjusted as noted below to account for failures, etc.

The second step is to determine for each feasible combination of availability and requirements:

a. training time required for retraining from the initial to the final skill (or whatever is the cost attributed to the retraining), or

b. that the retraining in this line is not permissible because of the following:

    (1) required training time exceeds available time,

    (2) consequent promotion or demotion required to match skill level with grade, is contrary to policy,

    (3) aptitude requirements for the two jobs are sufficiently different to make successful conversion unlikely.

As appropriate, the following should also be determined:

a. The probability of successful conversion from each initial skill and level to each final skill and level to which conversion is feasible. Where available, previous experience on similar conversions may be used as a guide; otherwise, estimates of success can be based on that of recruits entering the same field.

b. Limits on training capacity and courses affected by each limit. This requires determining types and durations of courses required for each conversion, as well as any limitations on the order in which they can be taken.

4.4.2 Model Development

The parameters of the simplest model are as follows:

S_h = supply of skill h (career field and skill level)

D_j = demand for skill j (including adjustment to allow for uncertainty; i.e., exact time of phase-in of new system)

N_{hj} = number scheduled for training to convert from skill h to skill j

T_{hj} = training required to convert from skill h to skill j

P_{hj} = probability of successful conversion from skill h to skill j

T_{max} = maximum time available for training.

These are related in the objective function and the constraints which describe the linear programming problem. It is possible to minimize total training time subject to the constraints of available men and ultimate requirements.

Minimize

$$\sum_h \sum_j T_{hj} N_{hj},$$

subject to

$$\sum_j N_{hj} \leq S_h ,$$

$$\sum_h P_{hj} N_{hj} \geq D_j ,$$

and if a maximum training time is set,

$$T_{hj} \leq T_{max}$$

The objective function and the first two constraints determine the structure of the linear programming problem; the last constraint, along with other restrictions on permissible conversions determine the possibilities to be considered.

Extending the model to deal with gradual phase-in of a new system, the phase-in must be divided into time periods and skill supply and demand determined for each period. All possibilities must be considered subject to imposed constraints. The parameters are conveniently described as:

S_{hi} = supply of skill h available in period i

D_{jk} = demand for skill j to be ready in period k

N_{hijk} = number of h available in i to be trained for j to be ready by k

Other parameters remain the same. The objective function and constraints are now as follows.

In some instances, there can be varying degrees of success in conversion. For example, the degree of success may determine the level attained in the new field. In such instances, P's may be associated with more than one D.

Minimize

$$\sum_h \sum_j T_{hj} \left(\sum_i \sum_k N_{hijk} \right) ,$$

subject to

$$\sum_j \sum_k N_{hijk} \leq S_{hi}$$

$$\sum_h P_{hj} \sum_i N_{hijk} \geq D_{jk}$$

The linear programming problem can be solved by the Simplex Method or other methods which might take advantage of the peculiarities of the problem. See example on page 92.

4.4.2.1 Discussion of Model Information Requirements

The major problem is to achieve maximum benefit from personnel in related skill areas. Effectiveness is determined in part by the criteria employed to select personnel from related skill areas.

Determination of the training required can be made as it has been in past retraining programs. Where men remain within their fields, acquaintance with the new equipment may be all that is required.

Where there are revolutionary differences between old and new equipments, training in principles may be required as well. For changes of field, training required in the two fields must be compared, and common elements eliminated from the conversion course. Frequently, it will be possible to accelerate courses because students will have greater familiarity with Air Force terminology, practices, and procedures, and will have demonstrated motivation to learn in attaining previous Air Force Specialty Code (AFSC).

The probability of successful retraining can be estimated on the basis of results of earlier retraining programs wherefrom analogous conversions have been made. Where such data is not available, the estimates based on experience in initial training may be substituted. Estimates should generally be on the pessimistic side, since the cost of having a surplus is much less than the cost associated with a shortage of a particular skill.

The probability of successful retraining and conversion of the individual to meet the requirements of a new system will generally depend on both his initial skill and his intended new one. The success of such a program can be measured in terms of probability that a trainee will pass requisite tests, and that he will serve at least y additional years, including re-enlistments. At least one additional year would appear to be a minimum value for y if there is appreciable training involved. Specific requirements for trainees may vary (DOD or Air Force policy, state of National emergency), but the methodology will remain unchanged.

Additional conditions may be imposed on the desired personnel training allocation solution as follows:

a. Class capacity for a particular course of group of courses. There would be a constraint for each course wherein the limitations were significant.

b. Policy in terms of consequent promotion or demotion required to match skill level with grade.

c. Aptitude requirements for the two jobs are sufficiently different to make successful conversion unlikely. This may be estimated on past experience.

4.4.2.2 Implementation of Technique

The technique developed in the foregoing section for achievement of personnel-skill distribution is intended to be employed in one of two ways:

a. Case 1 - Application to a specific system under development (in conceptual phase), utilizing as skill resources specific inputs in terms of personnel availability.

b. Case 2 - Application to entire Air Force personnel-skill inventory, utilizing existing personnel skill systems and those anticipated.

For Case 1, the technique could be employed manually, contingent upon an upper limit in skill types required in the new system.

For Case 2, computer information-processing would be required. Fortunately, a computer program of the type necessary is available for a number of different computers. Hence, for implementation, only an information and data reduction system would be required.

4.4.2.3 Sources of Information

Required information relevant to the availability of skills is obtained from the following:

a. anticipated phaseout of existing systems in the Air Force inventory,

b. enlistees anticipated,

c. discharges, and

d. promotions.

Required information relevant to the demand for specific skills is obtained from Manning Prediction (covered in Section 3), and applies to each anticipated system entering Air Force inventory and the time-phasing of the entry of the system.

Required information relevant to the time required to train a person from skill level i to skill level j $(i < j)$ is obtained through standard procedures employed by the Air Force in the past.

4.5 Example

Consider a situation in which men with three skills, A, B and C will become available at the beginning of time periods 1 and 2. At the beginning of periods 2, 3 and 4, men with skills a and b are required. For each possible retraining alternative, training time and probability of success is determined. These data are presented in Tables 13, 14, 15 and 16.

Practically, this problem may be solved almost by observation; however, for illustrative purposes, the linear programming matrix for Simplex solution is presented in Figure 6. Note that there is a separate entry for each possible retraining alternative. Impossibility of scheduling eliminates some combinations such as A1 into b2.

Input Data for Example of Phaseover Training Scheduling

TABLE 13

Availability
(in Number of Men)

Skill Time Period	A	B	C
1	30	14	10
2	20	12	

TABLE 14

Demand
(in Number of Men)

Skill Time Period	a	b
2	16	9
3	17	
4		16

TABLE 15

Training Time
(in Number of Periods)

Avail. Demand	A	B	C
a	1	1	2
b	2	1	1.5

TABLE 16

Probability of Success
(in Fraction of Men Successful)

Avail. Demand	A	B	C
a	.8	.9	.7
b	.6	.9	.8

Z	1	1	2	1	1	1	1	2	1.5	1	2	1	1	0	0	0	0	0	M	M	M	M	
	A1 a2	A1 a3	A1 b4	B1 a2	B1 b2	B1 a3	B1 b4	C1 a3	C1 b4	A2 a3	A2 b4	B2 a3	B2 b4	A_1	B_1	C_1	A_2	B_2	a_2	b_2	a_3	b_4	
A_1	1	1	1											1									30
B_1				1	1	1	1								1								14
C_1								1	1							1							10
A_2										1	1						1						20
B_2												1	1					1					12
a_2	.8			.9															1				16
b_2					.9															1			9
a_3		.8				.9		.7		.8		.9									1		17
b_4			.6				.9		.8		.6		.9									1	16

Z Training Time

Figure 6. Linear Programming Matrix for Simplex Solution of Training Phaseover Problem

Objective is to minimize training time.

M is an arbitrarily high training time used to assure that the solution will meet all requirements

A1 represents those in skill A available at the start of period 1

a2 represents those in skill a required at the start of period 2

A1 a2 represents those A1 who are retrained to meet demand a2

Analogous definitions apply to other terms.

Because the values selected are simple, in this case, there are several equivalent solutions involving meeting a3 with various combinations of A1 and A2. One solution of these is given in Table 17.

TABLE 17

Optimum Schedule
(in Number of Men Scheduled)

From To	A1	B1	C1	A2	B2	Average Numbers Obtained
a2	20 (16)					16
b2		10 (9)				9
a3	2* (1.6)			20 (16)		17.6
a4		4 (3.6)	2 (1.6)		12 (10.8)	16
Not used	8		8			
Total Available	30	14	10	20	12	

The upper number of pairs (e.g., 20) represents the number of men assigned from the source represented by the column heading (e.g., A1) to fulfill the demand represented by the row identification (e.g., a2). Entries in parentheses (e.g., 16) represent average number successfully retrained out of the number above it.

*Actually 1.125 before rounding upward because an integral number is required.

5. SKILL-DESIGN TRADEOFFS

5.1 Introduction

The black box of the conceptual phase is manifested physically in subsequent phases as all or part of one or more assemblies which is independently removable from the system or equipment of which it is a part. How this transformation is made from concept to reality -- from black box to removable assembly -- has a significant effect on the manning requirements as well as on other system support factors.

5.2 Skill vs. Packaging

The standard guides for design for maintainability (see Reference 10) are valuable in designing for economical manning. Some of the most important of these rules are concerned with packaging. For example a few of them are:

a. Make removable packages in easily handled sizes.

b. Package so that a fault in the equipment can be isolated to the package by means of quick, simple tests.

c. Standardize packages.

There are other rules which are also of importance which are rarely found in guides for maintainability:

a. Equipments, assemblies, subassemblies should be packaged so that fault isolation to the next lower level of assembly can be performed by an individual with skill in only a single field.

b. Package, at each level of assembly, such that there is required a minimum of skill diversification for removal, replacement and checkout, at that level of assembly.

c. Items requiring special test equipments, rare fields or high skill levels should be packaged so that they can be readily and economically sent to depots of manufacturers for repair. (This implies the package should not include expensive hardware whose maintenance does not require the special treatment.)

d. Locate items such that the relative ease of access is correlated with frequency that access is needed.

e. Minimize access and other interference problems on items requiring scheduled maintenance at the same general time.

5.3 Manning Considerations

The interactions among support philosophy, packaging, and manning trade-offs should be analyzed. Potential trade-offs that can affect the system design include:

a. Manning can be reduced by building fault isolation features into the equipment itself or by designing the equipment for use with special test equipment.

b. By packaging equipment appropriately and planning to do maintenance on packages at high echelons, only low skills (perhaps those of the operators) are required for first echelon maintenance. The price will be an increased inventory investment.

c. Design for discard-at-failure maintenance reduces manning requirements. Trade-off relationships are complex. (Refer to IBM report for a simplified examination of some of the aspects of the problem. See Reference 11.)

5.4 Subsystem Design Considerations

Subsystem design engineering may be directed to estimate manning requirements using the manning prediction technique proposed in this report. Criteria to be invoked would be either cost or manning minimization using as parameters reliability, maintainability, spare black boxes, and personnel skill as related to the operational readiness trade-off technique.

In implementing this procedure specific ground rules would be established by the Air Force. These rules would include statements of

1. Skill availability for operation and/or maintenance of the subsystem.

2. Maximum number spare black boxes to be considered (This could be established through cos of repair channels and subsystem packaging.)

3. Time elements to be considered (exclusive, since contractors will not in general be able to project their equipment into the operational environment).

4. Minimum levels or goals for reliability and maintainability for each level or assembly.

Air Force would have responsibility for adjustment of complete manning and operational readiness to operational environments.

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APPENDIX I

SINGLE-SHOP QUEUING MODEL

In a maintenance shop, at a particular time, there will be a certain number of units undergoing repair and others awaiting repair. The number of units undergoing and/or awaiting repair constitutes a unique state for the shop.

Consider the maintenance shop cycle as consisting of two stages: Stage 1, the repair channels and spare boxes; and Stage 2, the operating black boxes (Figure 7). We can think of this as a model of a single workshop-type activity such as a radar maintenance shop. Failed and repaired black boxes move through the cycle according to certain probabilistic rules. To keep the desired number of black boxes operating, maintenance personnel and spare units are kept at Stage 1 and N operation positions at Stage 2.

Units in Stage 2 are in an operating state. As units fail, they move into maintenance shop for repair. Either repair is immediately begun in one of the repair channels by one (or more) of repairmen (or crews), or a repair waiting line forms. Once units are repaired they move into the spare waiting line and then into operation when any one of the N operating positions is empty.

Cycle Characteristics

Consider the characteristics of the cycle:

1. The time required by the repairmen to perform maintenance, the tasks required to correct failures, is assumed to be having an exponential distribution. The average repair time is symbolized by μ^{-1}, the reciprocal of the average repair rate, μ.

2. The arrival rate at Stage 1 is also a random variable which has an average value of $n\lambda$. This is derived from the average failure rate, λ, of the individual operating units, and the number of units, i, operating at a particular time.

3. Service is considered to be on a first-come-first-served or on a random basis (the average downtime and average number down is the same for both rules).

4. Stage 1 maintains r repair crews, each with a repair rate μ.

5. At no time are there more than N units operating.

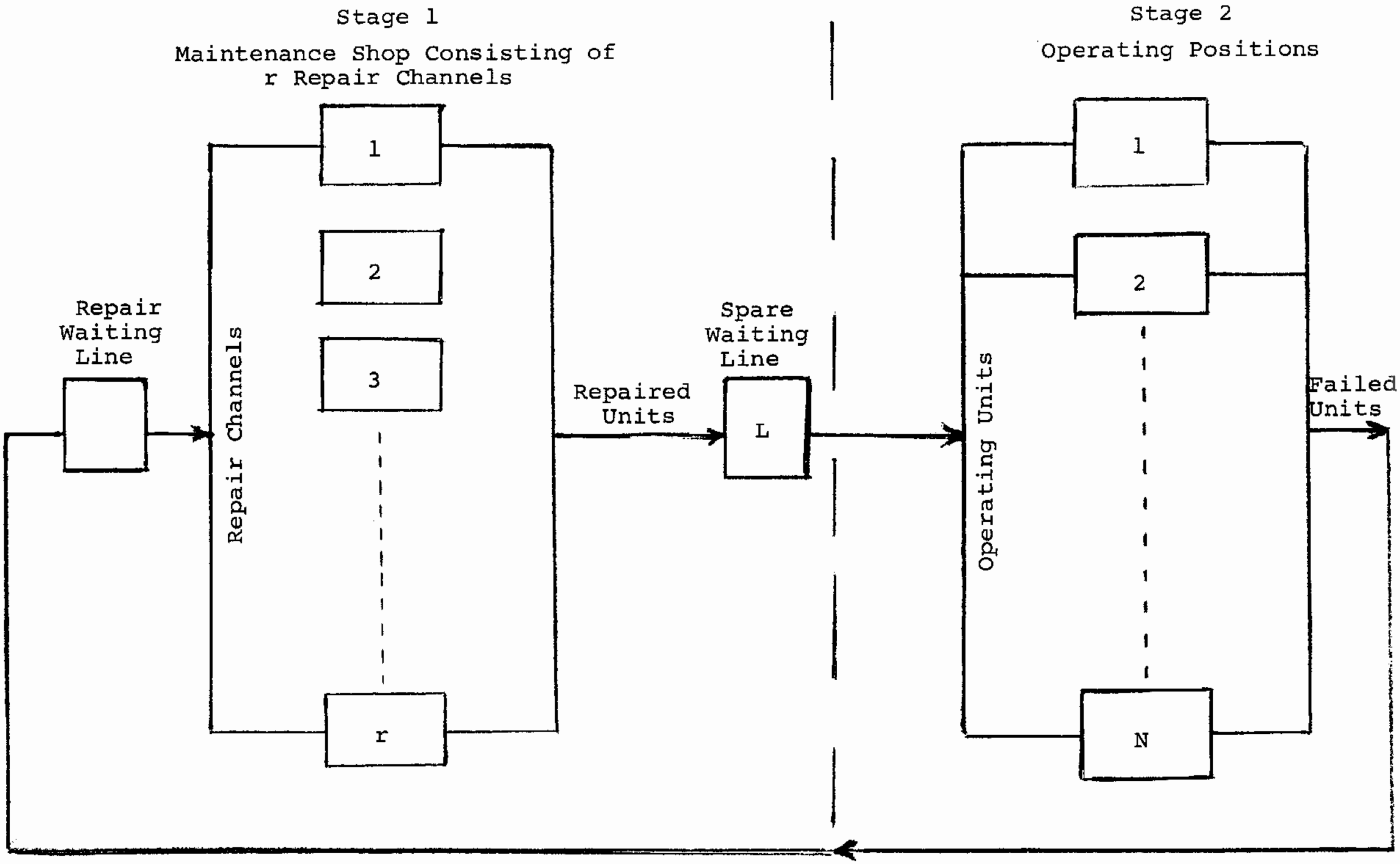

Figure 7. Flow of Repaired and Failed Units

6. There are (N + L) units in the cycle. N_o is the desired number of units operating.

These characteristics represent measurable parameters which permit a mathematical description of the maintenance shop.

Maintenance Shop Mathematical Model

Suppose that the system consists of equipment comprising (N + L) units, identical, and that, at most, N of the (N + L) units must be operational. The problem is to determine the expected (average) number of units operational, and/or the probability that at least n units are operational where $n \leq N$.

The state probability equations P_n given below provide the general solution to this problem.

Two cases must be considered:

Case I Number of channels exceeds the amount of spares; i.e., $r > L$

Case II Number of channels is less than or equal to the amount of spares; i.e., $r \leq L$

Since at any time one and only one state may exist, the sum of their probabilities must be one. Thus, noting that P_o is an explicit factor of each P_n we can let

$$k_n = \frac{P_n}{P_o}$$

and then note that

$$\sum_{n=0}^{N+L} P_n = \sum_{n=0}^{N+L} k_n P_o = P_o \sum_{n=0}^{N+L} k_n = 1$$

From this P_o can be determined

$$P_o = [\sum_{n=0}^{N+L} k_n]^{-1}$$

The average number of units in queue or service [E(q+s)] is

$$E(q+s) = \sum_{n=1}^{N+L} n\, P_n$$

The average number of units in queue is

$$E(q) = \sum_{n=r+1}^{N+L} (n-r) P_n$$

$E(d)$ = average number of failed units for which no replacements are available

$$= \sum_{n=L+1}^{N+L} (n-L) P_n$$

The average waiting time for units in excess of spares is

$$E(t_w) = \frac{1}{\mu} \sum_{n=L+1}^{N+L} (n-L) P_n$$

The average number of units operational is

$$E(n) = N - E(d)$$

Derivation of these state equations can be found in Reference 2, Saaty, Elements of Queuing Theory, Chapter 4.

For Case I, the following steady state probabilities apply:

$$P_n = \frac{(N\rho)^n}{n!} P_o \qquad n \leq (L+1) \qquad n \leq r$$

$$= \frac{N!}{(N+L-n)!} \frac{N^L \rho^n}{n!} P_o \qquad n \geq (L+1) \qquad n \leq r$$

$$= \frac{N!}{(N+L-n)!} \frac{N^L r^r \rho^n}{r! r^n} P_o \qquad n \geq (L+1) \qquad n \geq r$$

For Case II they are:

$$P_n = \frac{(N\rho)^n}{n!} P_o \qquad n \leq (L+1) \qquad n < r$$

$$= \frac{r^r (N\rho)^n}{r! r^n} P_o \qquad n \leq (L+1) \qquad n \geq r$$

$$= \frac{N!}{(N+L-n)!} \frac{N^L r^r \rho^n}{r! r^n} P_o \qquad n \geq (L+1) \qquad n \geq r$$

To recapitulate the definitions of symbols used

N = desired number of units operating

L = spares, units in excess of N

λ = failure rate of a single operating unit

μ = repair rate of a single channel

r = number of repair channels

n = number of units actually operating

P_i = probability that exactly i units are operating

$\rho = \frac{\lambda}{\mu}$

Derivation

Since the number of units which are not operational can range from zero through $N + L$, the number of possible states assumed by queue and service is $N+L+1$. The system is performing satisfactorily if N_o operational units are available; therefore, it is convenient to distinguish two cases:

The system is in state $E_i, (0 \leq i \leq L)$, with probability P_i.

The system is in state $E_i, (L + 1) \leq i \leq (L + N)$, with probability P_i.

The index i designates the number of units which have failed. Observe that case (1) implies that there are $L - i$ available spare units, and exactly N units operating, while case (2) implies that there are no available spares, and exactly $N - (i - L) = N + L - i$ units are operating.

The assumption of exponential breakdown characteristics depends upon empirical studies of the time incidence of random component failures in complex machines, all other contributory causes of failure having been eliminated by "debugging." This relationship is of the form:

$$P_o = e^{-\lambda h} ,$$

wherein P_o is the probability of failure-free operation, h is the time increment during which a failure may be expected to occur, and λ is the mean failure rate.

Since the probability of failure-free operation, P_o, is $e^{-\lambda h}$, the probability of one or more failures, is $1 - e^{-\lambda h}$.

By Taylor's theorem,

$$e^{-\lambda h} = 1 - \lambda h + o\ (h^2),$$

wherein the notation $o\ (h^2)$ indicates terms which are negligible when h is very small. The probability of one or more failures is

$$1 - e^{-\lambda h} \approx 1 - (1-\lambda h) = \lambda h$$

Observe that if $0 \leq i \leq L$, the probability density of the failure distribution in the interval $(t, t + h)$ is $N\lambda h$, while if $i > L$, the probability of a failure in the interval $(t, t + h)$ is $(N + L - i)\lambda h$. Similarly, the probability density of the repair distribution in $(t, t + h)$ is $r\mu h$, if $i \geq r$, and $i\mu h$, if $i < r$.

The steady-state relations are developed as follows: Equations are wanted for the probabilities $P_i(t)$ for finding the system in state E_i at time t. Suppose the number of failed units is less than the number of repair channels, and less than the number of spare units available. To calculate $P_i(t+h)$, note that at time t+h, the system can be in state E_i only if one of the following conditions is satisfied:

1. At time t the system is in state E_i, and during the interval $(t, t + h)$, no change occurs; the corresponding probability is $P_i(t)[1-N\lambda h - i\mu h]$.
2. At time t the system is in state E_{i-1}, and a transition to E_i occurs (i.e., one unit fails). The corresponding probability is $P_{i-1}(t)[N\lambda h]$.
3. At time t the system is in state E_{i+1}, and a transition to E_i occurs (i.e., a unit is repaired). The corresponding probability is $P_{i+1}(t)[(i+1)\mu h]$.
4. During the interval $(t, t + h)$ two or more transitions take place. This condition can generally be neglected, since the order of magnitude of the probability of simultaneous failures is quite small.

Since the first three alternatives are mutually exclusive, their probabilities can be added. Therefore,

$$P_i(t+h) = [1-N\lambda h-i\mu h]P_i(t) + N\lambda hP_{i-1}(t) + (i+1)\mu hP_{i+1}$$

Transposing the term $P_i(t)$ and dividing by h yields:

$$\frac{P_i(t+h) - P_i(t)}{h} = -(N\lambda+i\mu)P_i(t) + N\lambda P_{i-1}(t) + (i+1)\mu P_{i+1}(t)$$

Taking the limit as h → 0, and setting the result equal to zero gives an equation for the steady-state condition:

$$P_i'(t) = -(N\lambda+i\mu)P_i(t) + N\lambda P_{i-1}(t) + (i+1)\mu P_{i+1}(t)$$

$$= 0, \quad (i \leq L; i<r)$$

By similar reasoning, all the other steady-state equations may be calculated:

$$P_o'(t) = -N\lambda P_o(t) + \mu P_1(t) = 0$$

$$P_i'(t) = -(N\lambda+i\mu)P_i(t) + N\lambda P_{i-1}(t) + (i+1)\mu P_{i+1}(t)$$

$$= 0, \quad (i \leq L \text{ and } i<r)$$

$$P_i'(t) = -(N\lambda+r\mu)P_i(t) + N\lambda P_{i-1}(t) + r\mu P_{i+1}(t)$$

$$= 0, \quad (i \leq L \text{ and } i \geq r)$$

$$P_i'(t) = -[(N+L-i)\lambda+i\mu]P_i(t) + (N+L-i+1)\lambda P_{i-1}(t)$$

$$+ (i+1)\mu P_{i+1}(t) = 0, \quad (i>L \text{ and } i<r)$$

$$P_i'(t) = -[(N+L-i)\lambda+r\mu]P_i(t) + (N+L-i+1)\lambda P_{i-1}(t)$$

$$+ r\mu P_{i+1}(t) = 0, \quad (i>L \text{ and } i \geq r)$$

$$P_{N+L(t)}' = -r\mu P_{N+L}(t) + \lambda P_{N+L-1}(t) = 0.$$

Setting the above equations equal to zero is equivalent to taking (See Feller, Reference 7, Page 409):

$$\lim_{t\to\infty} P_i(t) = p_i, \quad i = 0, \ldots, N + L.$$

These limits must satisfy the relations:

$$\mu p_1 = N\lambda p_o,$$

$$(N\lambda+i\mu)p_i = N\lambda p_{i-1} + (i+1)\mu p_{i+1}, \quad (i \leq L \text{ and } i<r),$$

$$(N\lambda+r\mu)p_i = N\lambda p_{i-1} + r\mu p_{i+1}, \quad (i \leq L \text{ and } i \geq r),$$

$$[(N-i+L)\lambda + i\mu]p_i = (N-i+L+1)\lambda p_{i-1} + (i+1)\mu p_{i+1},$$

$$(i>L \text{ and } i<r),$$

$$[(N-i+L)\lambda + r\mu]p_i = (N-i+L+1)\lambda p_{i-1} + r\mu p_{i+1},$$

$$(i>L \text{ and } i\geq r),$$

$$\lambda p_{N+L-1} = r\mu p_{N+L}$$

Suppose p_2 is calculated for $i\leq L$ and $i<r$. One may write:

$$(N\lambda+\mu)p_1 = N\lambda p_o+2\mu p_2$$

Recalling that $\mu p_1 = N\lambda p_o$, and subtracting from either side gives:

$$N\lambda p_1 = 2\mu p_2$$

Such an expression, which enables calculation of p_{i+1} when p_i is known, is called a recurrence formula. When recurrence formulas are calculated for p_i for all relations between i, L and r, the following formulas result:

$$i\mu p_i = N\lambda p_{i-1} \quad (i\leq L,\ i<r) \tag{7}$$

$$r\mu p_{r+s} = N\lambda p_{r+s-1} \quad (s = i-r,\ i\leq L,\ i>r)\ . \tag{8}$$

$$(L+t)\mu p_{L+t} = (N-t+1)\lambda p_{L+t-1},\ (t = i-L,\ i>L,\ i<r). \tag{9}$$

$$r\mu p_{r+t} = (N-r+L-t+1)\lambda p_{r+t-1},\ (t = i-r,\ i>L,\ i\geq r). \tag{10}$$

$$r\mu p_{N+L} = \lambda p_{N+L-1} \tag{11}$$

Finally, expressions for p_i are calculated in terms of p_o, using equations (7) through (11).

Two cases are considered: (1) Where $L<r$ and (2) $L\geq r$. If we let = $N\lambda/\mu$, and p_i be the probability that i units are not operating, then the following steady-state probabilities apply:

Case I $L<r$ (The number of channels exceed the quantity of spares.)

$$p_i = \begin{cases} (\rho^i/i!)p_o & i\leq L+1 \\ & i\leq r \\ p_{L+s} = \dfrac{(N-1)!}{(N-s)!}\,\dfrac{\rho^{L+s}}{N^{s-1}(L+s)!}\,p_o & i>L+1, s=i-L \\ & i\leq r \\ p_{r+t} = \dfrac{(N-1)!}{[N-(r-L+t)]!}\,\dfrac{\rho^{r+t}}{(N^{r-L+t-1})r^t r!}\,p_o & i\geq L+1, t=i-r \\ & i\geq r \end{cases} \tag{12}$$

Case 2 $L \geq r$ (The number of spares is equal to or exceeds the number of repair channels.)

$$p_i = \begin{cases} (\rho^i/i!)p_o & i \leq L+1 \\ & i < r \\ p_{r+s} = \dfrac{\rho^{r+s}}{r^s r!} p_o & i \leq L+1 \\ & i \geq r \quad s=i-r \\ p_{L+t} = \dfrac{(N-1)!}{(N-t)!} \dfrac{\rho^{L+t}}{(N^{t-1})(r^{L+t-r})(r!)} p_o & i > L+1 \\ & i \geq r \quad t=i-L \end{cases} \qquad (13)$$

Now

$$\sum_{i=0}^{N+L} p_i = \sum_{i=0}^{N+L} p_o k_i = p_o \sum_{i=0}^{N+L} k_i = 1 \qquad (14)$$

if we define k_i as the ratios p_i/p_o which can be determined from the steady-state expressions (12) and (13).

From (14)

$$p_o = \left[\sum_{i=0}^{N+L} k_i \right]^{-1}$$

where $k_o = p_o/p_o = 1$

The expected number of units in queue or service $[E(q+s)]$ is

$$E(q+s) = \sum_{k=1}^{N+L} kp_k$$

The expected number of units in queue is

$$E(q) = \sum_{k=r+1}^{N+L} (k-r)p_k$$

APPENDIX II

PROCEDURES FOR CALCULATING DOWNTIME

Procedures for estimating downtime resulting from scheduled calendar maintenance, usage duration maintenance, and occurrence per usage maintenance are developed in this appendix. The procedures do not include consideration of simultaneous performance of overlapping tasks. Where overlapping tasks are present, the technique developed in Appendix III would be employed.

Determination of downtime due to random usage maintenance requires employment of the queuing model developed in Appendix I and illustrated in Section 3 of the report.

A. Procedure for Calculating Downtime Due to Scheduled Calendar Maintenance

1. The time period T is determined by the least frequent fixed calendar task; e.g., 6 months, 1 year, etc. Then the frequency of all other calendar tasks can be expressed in terms of T.

2. On the basis of a work analysis, each identified task is assigned an estimated performance time.

3. List all tasks that will be scheduled during time period T. These are ordered with respect to their time periods. Identify with each task:

    a. its associated function and black boxes,

    b. its time to perform (t_j) obtained in 2 above.

4. Order tasks having a common frequency into groups which can be performed simultaneously. Tasks possessing common frequency are ordered by repair time t_j.

5. Select the largest t_j from the ordering of each group at each period. This is Max W_{pj}, ranging over all j's in any particular period (p).

6. Sum of Max W_{pj} over all p establishes the downtime contribution for calendar demands.

B. Procedure for Calculating Downtime Due to Usage Duration Maintenance

The inputs required for determination of usage duration demands are (a) frequency of operation, and (b) expected duration of each operation. This information is provided as part of the operational performance requirements.

1. The cumulative total operational time, s, must be determined for each task. This (s) is a time period analogous to (p) for the calendar maintenance case.

2. List all tasks that are scheduled based on usage duration. These are ordered with respect to cumulative operational time (s).

3. On the basis of a work analysis, each identified task in (2) has an estimated time to perform.

4. Identify with each task:

   a. its associated function and black boxes,

   b. its time to perform (t_j) obtained in (3).

5. Order tasks having a common frequency into groups which can be performed simultaneously.

6. Tasks possessing common cumulative operational time are ordered by repair time (t_j).

7. Select the largest t_j from the ordering of each group of each time period. This is Max W_{sj}, ranging over all j's in any particular period (s).

8. Sum of Max W_{sj} over all (s) establishes the downtime contribution for usage duration demands.

C. Procedure for Calculating Downtime Due to Occurrence Per Usage Maintenance

1. Identify those tasks which have as their basis occurrence per usage of the operational unit.

2. Required frequency (f) of operation per time period is available from the operational performance requirements.

3. Determine the demand frequency for each task. This demand, λ'_{ej}, is identical to the operational unit operating frequency, implying performance of the task immediately before or after operation.

4. To each task is assigned an estimated time to perform.

5. Order tasks having a common frequency into groups which can be performed simultaneously. Tasks common to a group are ordered by repair time t_j.

6. Select the largest t_j from the ordering of each group at each period. This is Max W_{pj}, ranging over all j's in any particular period (p).

Multiplying by f yields total downtime during a period T for this task-type.

APPENDIX III

DOWNTIME ESTIMATION OF SIMULTANEOUS AND SEQUENTIAL PERFORMANCE OF TASKS

Maintenance on an aircraft which has just landed will follow the pattern described below:

1. Simultaneously, various checks and other routine maintenance tasks are performed. These checks and other tasks are well defined, and each, for most purposes, can be considered to require a fixed time to perform (T_i).
2. During the performance of these tasks, defects may be discovered with probabilities of p_i. Time to repair these defects often may be assumed to be distributed exponentially with a mean of ($1/\mu_i$).

It is desired to know the average time that the aircraft will be down and, perhaps, to have some notion of the distribution of downtimes. These can be obtained by using the general mathematical model below.

Given:

N	independent tasks
T_i	duration of fixed time component of total time required for task i. (Time for check or routine maintenance.)
p_i	probability that there will be a variable time component of total time for task i. (Probability of detecting a defect.)
$1/\mu_i$	average duration of variable time segment of task i (mean-time-to-repair defect).
μ_i	repair rate for task i.

then

$$
\begin{aligned}
f_i(t) &= 0 \,, && t < T_i \\
&= \infty \,, && t = T_i \text{ (point value of } 1-p_i, \\
& && \quad \text{see } F_i(T_i)) \\
&= \mu_i p_i \exp[-(t-T_i)\mu_i] && t > T_i
\end{aligned}
$$

$$F_i(t) = \int_0^t f_i(t)\,dt$$

$$\begin{aligned} &= 0\ , && t < T_i \\ &= 1-p_i\ , && t = T_i \\ &= 1-p_i \exp[-(t-T_i)\mu_i] && t > T_i \end{aligned}$$

where

$f_i\ (t)$ = frequency distribution time to completion of task i

$F_i(t)$ = cumulative distribution of time to completion of task i: probability of completion by time t.

Generally, there will exist a fixed task having maximum duration (T_m). The downtime expected for the operational unit will be that associated with this T_m plus any overlapping work required because of unaccomplished random portions of other tasks.

The cumulative distribution for the time to completion of all tasks must be the product of those for individual tasks.

Thus

$$F(t) = \prod_{i=1}^{N} F_i(t) \qquad t > T_m\ ,$$

and consequently,

$$f(t) = F'(t) = \sum_{i=1}^{N} (f_i(t) \prod_{j\neq i} F_j(t)), \qquad t > T_m\ ,$$

where

T_m = maximum fixed duration.

Let

T_D = downtime

$$= T_m + \int_{T_m}^{\infty} (1-F(t)\,dt)$$

p_i is estimated on the basis of the frequency of a task occurrence.

If the system is considered to consist of black boxes, each having associated a failure rate λ_i, and an operating duration t_i (during which if a failure occurred, it would not be detected or detected, but not repaired, until after complete duration t_i had passed; this is equivalent to periodic status evaluation), then p_i is given by $\lambda_i t_i = p_i$.

APPENDIX IV

DETERMINATION OF SCHEDULES INVOLVING MANDATORY REPLACEMENTS AND ("WHICHEVER COMES FIRST") MAINTENANCE

Case I - Mandatory Replacements at Specified Time Intervals

Let

t = time to actual replacement in hours

B = usage rate, the average fraction of total time the equipment operates

$f(Bt)$ = failure probability density function

t_o = mandatory period for replacement in hours

λ = unit failure rate per operating hour

Assuming fairly uniform usage, the contribution to average time of operation by units which fail during the period 0 to t_o, is given by

$\int_o^{t_o} t\, f(Bt)dt$, and the

contribution by units which last until t_o, is

$t_o \int_{t_o}^{\infty} f(Bt)dt.$

The addition of these times constitutes the average time to replacement.

For the exponential failure distribution, this becomes

$$\bar{t} = E\{t\} = \int_o^{t_o} t\, B\lambda\, \exp[-B\lambda t]dt + t_o \int_{t_o}^{\infty} B\lambda\, \exp[-B\lambda t]dt$$

$$= \frac{1 - \exp[-B\lambda t_o]}{B\lambda}$$

When $B\lambda t_o$ is small, this expression may be approximated by

$\bar{t} = t_o - \frac{B\lambda t_o^2}{2}$ = effective time between replacement

(for $B\lambda t_o < .23$, the error is less than 1%).

Case II - "Whichever Comes First"

In addition to symbols defined for Case I, let

τ_o = number of operating hours requiring mandatory replacement

$g(\tau)$ = frequency distribution of operating hours for periods of t_o.

We must examine two situations - the first, when the number of operating hours during calendar time t_o is less than τ_o $(\tau < \tau_o)$; the second, when it is greater.

In the first situation, to approximate the average time between maintenance actions, first determine the average operating time (τ_1) during t_o, when it is less than τ_o, and the fraction of time this occurs (P_1).

$$\tau_1 = \frac{\int_0^{\tau_o} \tau g(\tau)\,d\tau}{\int_0^{\tau_o} g(\tau)\,d\tau}$$

$$P_1 = \int_0^{\tau_o} g(\tau)\,d\tau$$

Note, in some instances the replacement will be brought about by failure prior to t_o.

Then, for the second situation, find the average time (t_2) which it takes to accrue τ_o operating hours when this occurs before t_o calendar time has passed.

First we determine the average operating time τ_2 in t_o when it is greater than τ_o

$$\tau_2 = \frac{\int_{\tau_o}^{\infty} \tau g(\tau)\,d\tau}{\int_{\tau_o}^{\infty} g(\tau)\,d\tau}$$

Divide by τ_o to determine the number of changes per t_o if there are failures

$$\frac{\tau_2}{\tau_o} = \frac{\int_{\tau_o}^{\infty} \tau g(\tau)\, d\tau}{\tau_o(1-P_1)} \quad .$$

Divide into t_o to determine average time (t_2) per τ_o operating when τ_o occurs in less than t_o

$$t_2 = \frac{\tau_o t_o}{\tau_2} = \frac{t_o \tau_o (1-P_1)}{\int_{\tau_o}^{\infty} \tau g(\tau)\, d\tau}$$

but, the operating rate, B, is just

$$\frac{\underline{\text{Operating time}}}{\text{Calendar time}} = \frac{\tau_1}{t_o}$$

for the first situation, and

$$\frac{\tau_o}{t_2}$$

for the second.

Then, substituting these in the equations for Case I and weighting according to probabilities of occurrence, we obtain:

$$\bar{t} = \frac{P_1 t_o}{\tau_1 \lambda} \left[1 - \exp(-\lambda \tau_1)\right] + \frac{(1-P_1) t_2}{\tau_o \lambda} \left[1 - \exp(-\lambda \tau_o)\right]$$

where t_2 is substituted for t_o as appropriate calendar time in the second situation.

APPENDIX V

ESTIMATION OF EXPECTED REPAIR TIME FOR PERIODIC CHECKS INVOLVING A SEQUENCE OF FIXED- AND RANDOM-DURATION TASKS

Suppose a unit is scheduled to operate in some arbitrary profile, but knowledge of its operability is gained periodically.

Let the period between checks be t_o.

Let s(t) be the probability density function of failure during time t_o.

The probability that a failure will exist at the period check becomes

$$\int_o^{t_o} s(t)dt = P,$$

and the probability that a failure has not occurred is (1-P). If the time for task performance is, respectively, for failure and not failure, T_1 and T_2, the mean time performing the task becomes

$$\bar{T} = PT_1 + (1-P)T_2$$

If

$$s(t) = \lambda e^{-\lambda t} \quad \text{(exponential failure distribution)}$$

then

$$P = (1-e^{-\lambda t_o})$$

$$\approx \lambda t_o - \frac{\lambda^2 t_o^2}{2} \quad ,$$

where λt_o is small (error less than 1% where $\lambda t_o < .12$).

APPENDIX VI

FACTORS AFFECTING BACK-UP PERSONNEL AND ESTABLISHMENT OF EFFECTIVE WORKING RATE OF PERSONNEL

When calculating personnel requirements in terms of the amounts (and kinds) of work, consideration must be given to how effectively the available time can be used in job performance. That is, how many effective work hours, per man, per year (or per unit time) can be expected for the performance of required tasks?

It is recognized that operational commanders have prerogatives and policies in establishing how personnel time shall be allocated. However, for computational purposes, it is convenient to assume the following six categories as comprising a man's normal duty hours:

Category I. Effective Task Performance

This includes the time assigned work is actually being performed, plus any situation where the man is not working, but is physically available for work.

Category II. Authorized Absences, such as

a. Furlough
b. Illness
c. Three-day passes
d. Emergency Leave
e. Days off (e.g., Sunday, holidays, etc.)

Category III. Training Requirements, such as

a. Training Films
b. Lectures
c. Hand arms Qualification
d. Physical Fitness Program

Category IV. Rest Periods, including Coffee and Smoke Breaks

a. Scheduled
b. Unscheduled

Category V. Administrative Activities, such as

a. Pay call
b. Paper work not directly required for performance of primary responsibilities

Category VI.[1] Miscellaneous

a. AWOL
b. Stockade (Awaiting Court Martial)

A routine for considering the factors in estimating manning can be developed as follows:

Let

T = Number of days per unit of time (year, month) used as a basis for calculation[2]

F = Amount of furlough (in days) allotted per T

P = Average amount of other leave (in days) allotted per T

S = Average sick time (in days) required per man per T

For each of the six categories listed, there will be variation about the estimated mean time spent in each category. The important feature to be considered is that this variation is controllable.

Then, the number of days during the time period (T) that a man will be physically available for work, on the average, is

(1) $T - (F+P+S)$

This value assumes that every day is a work day. Normally, policy provides for days off duty in addition to furloughs and special leaves. Thus, if the policy is to be off $(1-\theta)$ of the days, then the duty days per T would be

(2) $\theta[T-(F+P+S)]$ from (1)

If we define K as the number of hours of duty per day, then the number of duty hours (h) per t is

(3) $h = K\theta[T-(F+P+S)]$ from (2)

---

[1] This category is not considered to be significant with respect to its contribution in terms of average time-consumption; it is only included here so as to make the list more nearly complete.

[2] Symbols used in this appendix are defined in it. Definitions other than those given here do not necessarily apply here. Definitions given here do not necessarily apply elsewhere.

Now, for effective work, define the following:

t = fraction of time spent in Category III - Training

f = fraction of time spent in Category IV - Rest

The fraction of available time spent at effective work would be

$$(4) \quad E = h[1-(t+f)]$$

If this result is expressed as an effectiveness ratio (r):

$$(5) \quad r = \frac{E}{24T} = \frac{h[1-(t+f)]}{24T} = \frac{\text{effective work time (hours)}}{\text{unit time (hours)}} .$$

Since r is smaller than one (1), it is necessary to compensate for the periods of non-effectiveness described above. This is done by multiplying "raw" requirements by an effectiveness conversion factor:

$$(6) \quad R = 1/r ,$$

which allows us to adjust or convert the manpower estimate based on perfect effectiveness ($r=1$).[1]

The following example will serve to clarify the analysis. The estimates used in this example are not based on documentation experience; the numbers chosen are for illustrative purposes only. AFM-26-1 gives a breakdown of time spent in the various categories based on experience.

$T = 365$ days (1 year)
$F = 30$ days
$P = 10$ days
$S = 10$ days

$\theta = 6/7$
$K = 8$ hours
$t = .25$
$f = .10$

From equation (3), $t_h = K\theta[T-(F+P+S)]$, and substituting

$$h = 8 \cdot \frac{6}{7}\,[(365) - 30 - 10 - 10]$$

$$= \frac{48}{7}\,(315) = 2160 \text{ hours}$$

---

[1] R is necessarily an average value because many key inputs to its calculation are averages. When large numbers of men are involved, the actual situation at any given time is likely to be near average (except when deliberate action is taken to the contrary, such as granting holiday leaves). When small numbers of men are involved, provision must be made for meeting situations in which significantly fewer than the average number of men are available for periods of several days.

From equation (4), $E = h[1-(t+f)]$, and substituting

$$E = 2160\ (1-0.25-0.10)$$

$$E = 1404 \text{ hours}$$

Referring to equation (5):

$$r = \frac{E}{24T} = \frac{1404}{(24)(365)} = \frac{1404}{8760} = .16$$

Referring to equation (6):

$$R = \frac{1}{r} = \frac{1}{.16} = 6.25$$

The results of this example can be interpreted to mean that on the average, only about one-sixth of a man's available time can actually be utilized for reducing the workload.

The number of personnel (M) required to accomplish the workload requirement can be determined from:

$$(7) \quad M = R \cdot \frac{W}{24T}$$

Suppose that during a certain six-month period (T = 182 days). The workload requirement (W) is estimated to be 87,360 man-hours including appropriate allowance for imperfect utilization of maintenance personnel.

Using the values mentioned above, and 6.25 determined for R in the previous example, M can be calculated as follows:

$$M = 6.25 \cdot \frac{87,360}{(24)(182)} = 125 \text{ men.}$$

In time of emergency, it is expected that average available man-hours per man, per day can be increased by changes in routine and policies. Particularly:

1. F and P can be reduced (shorten or cancel furloughs and leaves).
2. θ can be increased (lengthen work-week, say, from six to seven days).
3. K can be increased (lengthen work-day, say, from eight to ten hours).
4. t can be reduced (reduce training not directly related to job skill and shift from classroom to OJT).

The gains made in this manner may permit a much larger workload to be handled by the same personnel.

For illustration, compare the R previously calculated with that based on emergency policies.

Factor	Normal	Emergency
T	365	365
F	30	5
P	10	5
S	10	10
θ	6/7	1
K	8	10
t	.25	.15
f	.10	.10
r	.16	.29
R	6.25	3.39

Note that here the gain is almost by a factor of two.

APPENDIX VII

CHARACTERISTICS OF TASK PACKAGES

The manning prediction technique developed in this report is not based on precise information. The concept of "task" and "black box" is intentionally defined as "reasonable work unit," since it is presupposed that detailed information is not available. This section has been prepared to indicate the information requirements for complete scheduling and, hence, more precise 'task' definition. It is not suggested that all the information specified below is required for manning prediction.

In general, one tests all the tasks to be performed at a site. Certain descriptive characteristics of the tasks are then determined. The information then is processed to form a task package. The task package represents the workload for an individual to perform. This is defined as an assigned task package in the system.

The procedure can be used for both operator and maintenance personnel. It is anticipated that this procedure can be used during all phases in system definitions; however, at any specific time all the information required may not be available and, therefore, the combining of tasks will be accomplished without data necessary for precise prediction. As system definition progresses, the manning estimates will be more accurate.

The information requirements developed below can be used to define all tasks in the system. Briefly, the information requirements are:

1 - The tasks that are to be performed

2 - Maintenance or operator task

3 - Number of occurrences

4 - The portion of the mission that the task occurs in

5 - Status of equipment at task requirement

6,7,8 - Describes the skill necessary for task performance

9-22 - Gives the pertinent information which describes the task.

TASK CHARACTERISTICS

1. Task - This describes actions necessary. In order to obtain the tasks, an analysis of the functions that are to be performed in the system must be made.

2. Type of Task - Designates that the task is a maintenance (M) or operation (O).

3. Number of Occurrences - Designates the number of times this task is duplicated in system.

4. Mission - If the task occurs during a specific portion of the mission, reference periods of occurrence in mission profile; e.g., (Take-off, countdown, missile guidance, etc.)

5. Status - Designates the status of the equipment at the time the task is being performed. It can be operative (O), inoperative (I), stand-by (S).

6. Career Field - Designates career field of the person to perform task. An example could be radio operator, programmer, communication specialist, etc.

7. Special Requirements - Designates special requirements needed to perform the tasks not shown in specialty field. For instance, if a specific task is to receive radio communications, the special requirement of the operator might be that he must be able to copy code at a certain minimum rate.

8. Level - Designates minimum skill level necessary to perform task.

9. Permissible Time Delay - Designates allowable delay between occurrence of a stimulus (receipt of information) and starting the appropriate response. If a response is required immediately to a stimulus, the time delay of the task is zero. If there is an allowable time delay in which a response can be made, then the time is stated. If delay depends on systems status this dependency is indicated; e.g., available inventory status.

10. Duration - Designates time taken to respond to the stimulus after the time delay to the completion of the task.

11. Storability - Designates the ability to reproduce information when appropriate subsequent to its receipt. Storability measured by the probability that the stimulus will be accurately recalled when appropriate.

12. Demand Type Schedule - Designates the type of scheduling being used for this task.

    a. Random (R) - This task can occur at any time.

    b. Continuous (C) - This task is continually being performed.

c. Specific Schedule (S) - Occurrence planned or accurately predicted in terms of time of occurrence (e.g., scheduled maintenance).

d. Dependent (D) - Task is keyed and occurs only after the start of some other task(s).

13. Frequency - Designates frequency with which the task occurs. This information is dependent on the information in 12.

a. If 12 is random (R), give the average number of times this task can occur in a 24-hour period.

b. If 12 is specific schedule (S), give the schedules time and point of reference start time.

c. If 12 is continuous (C), then (13) is not applicable (NA).

d. If 12 is dependent (D), list the frequency of the dependent task per keying task and multiply by an incident factor frequency of keying tasks.

14. Priority - The priority of a task depends on the state of the system. Priority indicates an order of preference for performance of tasks.

a. For an essential task the probability of successful performance of the mission will be decreased if the task is not performed.

b. Non-essential tasks are those tasks which will not effect the success of the mission. These tasks fall into two categories:

(1) Non-essential I - tasks for the purpose of safety (such as checking out instruments, checking out the indicator lamp).

(2) Non-essential II - tasks used in recording information which will not be used in subsequent tactical action.

The following code might be used to indicate priority:

Priority 1 Priority 2 Priority 3	All essential tasks fall into these priorities
Priority 4	Non-essential I tasks fall in this priority
Priority 5	Non-essential II tasks fall in this priority

15. Type of Maintenance - For maintenance tasks. The code to use is as follows:

Code	Type of Maintenance
1	Calendar
2	Usage Duration
3	Occurrence Per Usage
4	Random Usage

16. Maintenance Priority - This will be entered if the task is in the maintenance category. The coding of maintenance priority is as follows:

    a. Critical - The system performance depends upon the completion of this task as soon as possible.

    b. Major - The performance of the device depends upon the completion of this task as soon as possible.

    c. Minor - The system and/or device performance can be affected if this task is not performed within a reasonable amount of time.

    d. Shop - This task involves repair of assemblies which are spared and may be performed at other locations.

17. Senses - Designates senses required of the personnel to perform the task; e.g., visual, aural, etc., or a combination of senses. (Numerous quantitative measures are available.)

18. Operator Response - Designates actions the personnel must perform to the stimulus. Some examples of response are: manual-one hand, manual-two hands, feet, oral.

19. Permissible Mobility - Designates distance the personnel can be from the stimulus (or response point) and respond.

20. Area of Location - Designates the code area in which the task is to be performed.

21. Dependency on Other Tasks - Designates the preceding task(s) that set this task in motion. The purpose of this is to give a time relationship of tasks. This will allow task scheduling.

22. Task Proximity - Designates tasks which are combinable time-wise. For instance, if two tasks are combinable, but are not in compatible proximity, then combination is not allowable.

APPENDIX VIII

METHOD FOR ESTIMATION OF ERROR IN OPERATIONAL READINESS DUE TO MULTIPLE AIRCRAFT FLIGHTS

In some operational environments, multiple aircraft flights will predominate. For random usage maintenance this may create bulk queues; however, the mathematical model of Appendix I will provide a good result for the arrival rates anticipated. For scheduled-per-usage-occurrence-maintenance in conjunction with random usage maintenance, it may be necessary to consider a downtime correction factor. This correction factor may be developed as follows:

Let

n = number of operational units in a flight

r = number of repair channels assigned

t = time duration for performance of tasks after flight for each aircraft

$\bar{t}_w$ = mean waiting time per aircraft not accounted in the mathematical model

The total aircraft time spent awaiting maintenance is given by

$$[T = (n-r)t + (n-2r)t + \ldots + (n-(k-1)r)t + Rt]$$

where $0 \leq R \leq r, \quad R = n - kr, \quad r \geq 1.$

$$= n(k-1)t - t\,r \sum_{i=1}^{k-1} i + Rt$$

$$= \left[\frac{(k-1)\,r}{2} + R\right] kt$$

The mean time spent waiting for maintenance per aircraft is

$$\bar{t}_w = \frac{T}{n} = \frac{kt}{n}\left[\frac{(k-1)\,r}{2} + R\right]$$

when

$R = 0$

$$\bar{t}_w = \frac{1}{2}\,(k-1)\,t = \frac{1}{2}\,\frac{(n-r)}{r}\,t$$

This downtime would be included in the calculation for operational readiness. The routine for adjusting personnel to achieve the required level of operational readiness would remain the same. See Section 3.

APPENDIX IX

METHODS OF PREDICTING RANDOM TASK TIME

In the text, two methods for predicting random task performance time for repair of electronic systems were mentioned. These methods will be described in greater detail in this appendix. The first method, "RADC Maintainability Prediction Technique," described in Appendix IX-A, is intended to be applied principally to equipments proposed in the conceptual phase of system development that are similar to existing equipment, or equipments incorporating slight modification.

The second method which is a revision of "Maintainability Prediction Procedure for Designers of Shipboard Electronic Equipment and Systems," is described in Appendix I of Astia Report AD-405779 (Reference 12).

This method is intended to be applied to equipment lacking detail design information, requiring only knowledge of (1) configuration of the system in terms of levels of assembly, (2) test features; i.e., built-in or external test equipment, (3) replacement level of assembly, and (4) requirements for checkout or alignment.

APPENDIX IX-A

The use of this prediction technique to evaluate the maintainability of an equipment is approached from a sampling basis. A sample of representative tasks, for an equipment, is selected from the total tasks available. Scoring each of these tasks through the use of the design checklists is then accomplished. The repair time is determined from the relationship:

$$\log_{10}(\text{repair Time}) = 3.54651 - (0.0251A + 0.03055B + 0.01093C)$$

The steps for prediction are:

a. Selection of sample size
b. Determination of task sample
c. Task prediction
d. Calculation of maintenance indices

<u>Selection of Sample Size</u> - The sample size to be used in the prediction is dependent upon the statistical accuracy desired. With stated accuracy requirements (k) and desired confidence level, the sample size (N) which satisfies these requirements is computed as follows:

$$N = \left[\frac{\phi\sigma}{k\bar{X}}\right]^2$$

where:

ϕ = Confidence level

σ = Population variance

$\bar{X}$ = Population mean

k = Accuracy

The observed field data provides a basis for determining the sample size needed for a typical prediction problem. The ratio of $\sigma/\bar{X}$ for the field data was found to be 1.07. For example, a sample size of 50 will permit stating the mean with an accuracy of ± 25%, with a confidence of 90%.

Determination of Task Sample - The application of the prediction technique during the various phases of equipment development basically involves the evaluation of hypothetical part failures as maintenance tasks.

The process of task selection will be illustrated by means of an example. Essentially, two basic ingredients are required to determine the parts to be used for tasks: (1) number of parts by class in the equipment (part complexity), and (2) the predicted average failure rate of each part class. A typical equipment will be used to illustrate the steps involved. The equipment has two identical channels; therefore, evaluation of one channel will be sufficient because maintenance actions due to a particular part failure will be identical in either channel. Part reliability data for this illustration were obtained from previous field evaluations. In actual practice, reliability data may be obtained from a prediction performed for the equipment being analyzed, from published average failure rates for part types, or from field data on similar type equipments.

Table 18, "Part and Failure Distribution," summarizes the data. Here are listed the number of parts, average failure rates, and the expected number of failures for one thousand hours of equipment operation. From the expected number of failures (Table 18), the percent contribution of each part class to the total expected failures was computed. The actual number of parts for each class was then determined for a sample size of 50. Table 19, "Part Class Sample Size," shows the tabulated data. Note that tubes contribute approximately 82% of the expected number of failures. Tubes, therefore, accounted for 41 of the maintenance tasks (82% of 50). The number of remaining tasks were determined in a similar manner.

After determining the distribution of the desired sample, it is necessary to select actual parts from the equipment to use as simulated maintenance tasks. This can be accomplished by

TABLE 18

PART AND FAILURE DISTRIBUTION

Part Class	Quantity (Single Channel)	Average Part Failure Rate 1000 Hours	Number of Expected Failures Per 1000 Hrs
Motor	25	.00189	.04725
Capacitor	1280	.00010	.12800
Diode	4	.02983	.11932
Connector	335	.00032	.10720
Relay	43	.00359	.15437
Coil	349	.00033	.11517
Resistor	2459	.00015	.36885
Switch	162	.00045	.07290
Transformer	160	.00133	.21280
Tube	380	.01567	5.95460
Total	5197		7.28046

TABLE 19

PART CLASS SAMPLE SIZE

Part	Contribution to Total Expected Failures (%)	No. of Failures for Sample Size of 50	Actual Sample Used
Motor	.65	.3	0
Capacitor	1.76	.9	1
Diode	1.64	.8	1
Connector	1.47	.9	1
Relay	2.12	1.1	1
Coil	1.58	.8	1
Resistor	5.07	2.5	2
Switch	1.00	.5	1
Transformer	2.95	1.3	1
Tube	81.79	40.9	41
Total	100%		50

coding the parts and using a random selection technique such as a table of random numbers to select the desired number of parts in each class.

Task Prediction - The design prediction is accomplished by completing the three design related checklists for sample tasks. Specifically, these checklists are: A, Scoring Physical Design Factors; B, Scoring Design Dictates-Facilities; and C, Scoring Design Dictates-Maintenance Skills. These checklists are presented at the end of this appendix, together with all instructions necessary for scoring each item.

The scoring for each item ranges from 0 to 4. Intermediate values of 1, 2, and 3 are provided for some questions where the nature of the characteristic being assessed may take on varying magnitudes. This is contrasted to the yes-no situation. The questions have been framed in a manner that permits general application across equipment lines.

To illustrate the scoring process, the scores obtained for the sample maintenance analysis task are shown in Table 20. The task was reviewed for items that pertain to each question and the questions were then scored in accordance with established criteria.

TABLE 20

Checklist Scores

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
A	4	2	4	2	0	2	2	2	3	2	4	4	4	2	4	41
B	1	4	4	4	4	2	4	▨	▨	▨	▨	▨	▨	▨	▨	23
C	1	3	3	2	1	2	2	2	2	2	▨	▨	▨	▨	▨	20

Predicted repair time . . . . 40 Min.

To illustrate further how checklist scores are obtained some of the specific scores in Table 20 will be examined. In checklist A, question two received a score of two (external latches and fasteners meet two of the criteria that they are captive, need no special tools, and require only a fraction of a turn for release.) Examination of the equipment drawings reveals that the drawers are fastened by four multiturn screws, and the equipment T.O. indicates that these screws are captive. Since these screws can be removed using a common screw driver, the only criteria for question A not met is that they require more than a fraction of a turn to release. In checklist B, question one received a score of one (2 or 3 pieces of test equipment are needed). An oscilloscope, multimeter, and tube checker were used to accomplish this task. For checklist C, question five received a score of one (above average requirement for logical analysis). This score was assigned because the initial symptoms gave very little indication as to the cause of malfunction and because a number of the major units had to be checked to isolate the trouble to a functional area.

SCORING CHECKLISTS

CHECKLIST A - SCORING PHYSICAL DESIGN FACTORS

The intent of this checklist is to determine the impact of equipment packaging, physical layout, etc., upon maintenance time. Data analysis reveals that the aspects considered by this checklist exhibit the greatest influence upon maintenance time. Consequently, particular attention must be exercised during the completion of this checklist.

Discussion - Questions 1 through 4 consider access, both internal and external, in association with facility with which it can be gained. The external aspect relates to covers, panels, drawers, etc., which appear on the periphery of the equipment. Shields, safety enclosures, etc., would come under evaluation when considering the internal portion.

Methods of securing modules, components, and parts are of concern in questions 5 and 6. These questions would be rated with respect to the part assumed failed in association with other units which may come under surveillance in the course of the troubleshooting action. Since testing of some part types requires removal from the circuit, the facility with which this may be accomplished is important. Also, the time required to replace the defective unit is of concern.

Questions 7 through 11 relate to securing maintenance information required to diagnose logically the defective part. Examination of maintenance data has provided that this element of time contributes more than 50 percent to total maintenance requirements. The intent of this series of questions is to determine the relative ease with which the needed data may be secured. Further, it is to be determined if this data is supplied directly by the equipment through built-in indicators or test equipment, or if external test devices are required. Additionally, identification and labelling of test points and parts are assessed because of their contribution to the diagnostic process.

Question 12 determines the need for circuit adjustments. Such adjustments can be time consuming, hence this area is of vital importance. The ability to test the defective part without removal from the circuit is determined by question 13. The facility to accomplish in-circuit testing will further aid the maintenance process.

Questions 14 and 15 consider protective devices and safety precautions which must be exercised by maintenance personnel. Safety shields, interlocks, etc., are necessary precautionary devices which must be provided in equipment possessing hazards such as high voltages, x-rays, etc. Although they are necessary, their presence will slow the maintenance task accomplishment. Consequently, such situations must be appraised.

Checklist A, Scoring Physical Design Factors

1. Access (External)
    - a. Access adequate both for visual and manipulative tasks (electrical and mechanical) 4
    - b. Access adequate for visual, but not manipulative, tasks 2
    - c. Access adequate for manipulative, but not visual, tasks 2
    - d. Access not adequate for visual or manipulative tasks 0
2. Latches and Fasteners (External)
    - a. External latches and/or fasteners are captive, need no special tools, and require only a fraction of a turn for release 4
    - b. External latches and/or fasteners meet two of the above three criteria 2
    - c. External latches and/or fasteners meet one or none of the above three criteria 0
3. Latches and Fasteners (Internal)
    - a. Internal latches and/or fasteners are captive, need no special tools, and require only a fraction of a turn for release 4
    - b. Internal latches and/or fasteners meet two of the above three criteria 2
    - c. Internal latches and/or fasteners meet one or none of the above three criteria 0

4. Access (Internal)

   a. Access adequate both for visual and manipulative tasks (electrical and mechanical) 4

   b. Access adequate for visual, but not manipulative, tasks 2

   c. Access adequate for manipulative, but not visual, tasks 2

   d. Access not adequate for visual or manipulative tasks 0

____

5. Packaging

   a. Internal access to components and parts can be made with no mechanical disassembly 4

   b. Little disassembly required (less than 3 min.). . . . 2

   c. Considerable disassembly is required (more than 3 min.) 0

____

6. Units - Parts (Failed)

   a. Units or parts of plug-in nature 4

   b. Units or parts of plug-in nature and mechanically held 2

   c. Units of solder-in nature 2

   d. Units of solder-in nature and mechanically held . . . 0

____

7. Visual Displays

   a. Sufficient visual information on the equipment is given within one diaplay area 4

   b. Two display areas must be consulted to obtain sufficient visual information 2

   c. More than two areas must be consulted to obtain sufficient visual information 0

____

8. Fault and Operation Indicators (Built-In Test Equipment)

   a. Fault or malfunction information is provided clearly and for rapid action 4

   b. Fault or malfunction information clearly presented, but requires operator interpretation 2

   c. Fault or malfunction information requires no operator interpretation, but is not clearly presented 2

   d. Fault or malfunction information not clearly presented and requires operator interpretation 0

9. Test Points (Availability)

   a. Task did not require use of test points 4

   b. Test points available for all needed tests 3

   c. Test points available for most needed tests 2

   d. Test points not available for most needed tests . . 0

10. Test Points (Identification)

   a. All test points are identified with required readings given 4

   b. Some are suitably marked 2

   c. Points are not marked and test data is not given . . 0

11. Labelling

   a. All parts labelled with full identifying information and all identifying information clearly visible. 4

   b. All parts labelled with full identifying information, but some information hidden 2

   c. All information visible, but some parts not fully identified 2

   d. Some information hidden and some parts not fully identified 0

12. Adjustments

a. No adjustments or realignment are necessary to place equipment back in operation 4

b. A few adjustments, but no major realignments are required 2

c. Many adjustments or major realignments must be made 0

13. Testing (In Circuit)

a. Defective part or component can be determined without removal from the circuit 4

b. Testing requires removal 0

14. Protective Devices

a. Equipment was automatically kept from operating after malfunction occurred to prevent further damage. (This refers to malfunction of such areas as bias supplies, keep-alive voltages, etc.) 4

b. Indicators warned that malfunction has occurred . . . 2

c. No provision has been made. 0

15. Safety (Personnel)

a. Task did not require work to be performed in close proximity to hazardous conditions (high voltage, radiation, moving parts and/or high temperature parts) 4

b. Some delay encountered because of precautions taken 2

c. Considerable time consumed because of hazardous conditions 0

CHECKLIST B - SCORING DESIGN DICTATES-FACILITIES

The intent of this questionnaire is to determine the need for external facilities. Facilities, as used here, include material such as test equipment, connectors, etc., and technical assistance from other maintenance personnel, supervisor, etc.

Discussion - Questions 1 through 3 evaluate the material requirement. Such requirements can best be determined from a maintenance analysis of the assumed tasks. This analysis will establish the need for test equipment and other materials.

Technical assistance requirements are evaluated by questions 4 through 7. Evaluation of these questions can best be accomplished by viewing task requirements as imposed by the equipment with respect to the typical technician's capabilities. It has been found that the average Air Force technician is a high school graduate who has had 20 to 36 weeks of training in electronic fundamentals and specialized equipment. He receives additional on-the-job training after being assigned to a field maintenance activity. On the average, he is 24 years old and has been in the service 4.6 years. His attitude and motivation toward his job have been found to be satisfactory. Specific experience on the assigned equipment was noted to be 1.3 years. Reviewing detailed analysis of maintenance tasks performed by Air Force technicians has provided that a logical or systematic approach to the defective part normally is not used. The equipment task requirements for personnel viewed within this framework should permit effective scoring of this checklist.

<u>Checklist B, Scoring Design Dictates-Facilities</u>

1. External Test Equipment

    a. Task accomplishment does not require the use of external test equipment 4

    b. One piece of test equipment is needed 2

    c. Several pieces (2 or 3) of test equipment are needed 1

    d. Four or more items are required 0

    ____

2. Connectors

    a. Connectors to test equipment require no special tools, fittings, or adapters 4

    b. Connectors to test equipment require some special tools, fittings, or adapters (less than two) 2

    c. Connectors to test equipment require special tools, fittings, and adapters (more than two) 0

    ____

3. Jigs or Fixtures

   a. No supplementary materials are needed to perform task 4

   b. No more than one piece of supplementary material is needed to perform task 2

   c. Two or more pieces of supplementary material are needed 0

____

4. Visual Contact

   a. The activities of each member are always visible to the other member 4

   b. On at least one occasion, one member can see the second, but the reverse is not the case 2

   c. The activities of one member are hidden from the view of the other on more than one occasion 0

____

5. Assistance (Operations Personnel)

   a. Task did not require consultation with operations personnel 4

   b. Some contact was required 2

   c. Considerable coordination required 0

____

6. Assistance (Technical Personnel)

   a. Task required only one technician for completion . . 4

   b. Two technicians were required 2

   c. Over two were used 0

____

7. Assistance (Supervisors or Contract Personnel)

   a. Task completion did not require consultation with supervisor or contract personnel 4

   b. Some help needed 2

   c. Considerable assistance needed 0

____

CHECKLIST C - SCORING DESIGN DICTATES-MAINTENANCE SKILLS

This checklist evaluates the personnel requirements relating to physical, mental, and attitude characteristics, as imposed by the maintenance task.

Discussion - Evaluation procedure for this checklist can best be explained by way of several examples. Consider first question 1, which deals with arm, leg, and back strength. Should a particular task require the removal of an equipment drawer weighing 100 pounds, this would impose a severe requirement on this characteristic. Hence, in this case the question would be given a low score (0 to 1). Assume another task which, due to small size and delicate construction, required extremely careful handling. Here question 1 would be given a high score (4), but question dealing with eye-hand coordination and dexterity would be given a low score. Other questions in the checklist relate to various personnel characteristics important to maintenance task accomplishment. In completing the checklist, the task requirements for each of these characteristics should be viewed with respect to average technician capabilities.

Checklist C, Scoring Design Dictates-Maintenance Skills

		Score
1.	Arm, leg, and Back Strength	
2.	Endurance and Energy	
3.	Eye-Hand Coordination, Manual Dexterity, and Neatness	
4.	Visual Acuity	
5.	Logical Analysis	
6.	Memory - Things and Ideas	
7.	Planfulness and Resourcefulness	
8.	Alertness, Cautiousness, and Accuracy	
9.	Concentration, Persistence, and Patience	
10.	Initiative and Incisiveness	

APPENDIX IX-B

The tabular breakout of this technique obtaining task time requirements is especially suitable for manning purposes. This is due to embodiment of the black box concept implicit in the tabular breakout and ease of separation between time spent on the operational unit and/or the time spent at a remotely located work shop.

The repair time at a location is obtained by summing the time required to perform the following operations:

1. Determination of location of failure (i.e., to the black box) between referenced levels of assembly
   - (a) utilizing organic test equipment,
   - (b) utilizing accessory test equipment and built-in test points.
2. Removal and replacement of failed black box, between referenced levels of assembly.
3. Alignment and/or checkout of failed black box between referenced levels of assembly.

Tables 21, 22, 23 and 24 contain time estimates corresponding to operation 1(a), 1(b), 2, and 3 above, between the referenced levels of assembly.

For Tables 21 and 22, the desired isolation time is obtained from the intersection of the row representing the functional level at which the isolation feature is effective, and the column representing the level at which replacement will be made. For example, if a system has an isolation feature with built-in test equipment which is effective at the group level, and if the system is to be supported through replacement of a particular assembly whenever a failure occurs within that assembly, the isolation time will be 0.056 hour. This time is obtained from the intersection of the "GROUP" row and "ASSEMBLY" column.

Table 23 provides immediate access to replacement time, which includes disassembly, interchange, and reassembly times. The times are differentiated according to whether the item replaced is a pluggable or soldered-in type. For example, if the replacement of an assembly, which is pluggable, must be made at the unit level, the replacement time is 0.243 hour. This time is obtained from the "UNIT-PLUGGABLE" location.

Table 24 provides the alignment and checkout times, as applicable, at the level at which the alignment or checkout is performed. For example, suppose that the final steps in a repair action involving the replacement of a failed assembly in a unit, are alignment of the assembly and checkout of the unit. The alignment time is 0.030 hour, obtained from the "ASSEMBLY-ALIGNMENT" location, and the checkout time is 0.138 hour, obtained from the "UNIT-CHECKOUT" location.

TABLE 21

ISOLATION WITH SELF-TEST FEATURES

Level at Which Test Feature is Effective	Level at Which Replacement is Made							
	Subsystem	Equipment	Group	Unit	Ass'y	Subass'y	Stage or Circuit	Part
System	0.039	0.056	0.073	0.089	0.106	0.121	0.136	0.150
Subsystem	-	0.039	0.056	0.073	0.089	0.106	0.121	0.136
Equipment	-	-	0.039	0.056	0.073	0.089	0.106	0.121
Group	-	-	-	0.039	0.056	0.073	0.089	0.106
Unit	-	-	-	-	0.039	0.056	0.073	0.089
Assembly	-	-	-	-	-	0.039	0.056	0.073
Subassy.	-	-	-	-	-	-	0.039	0.056
Stage	-	-	-	-	-	-	-	0.039

TABLE 22

ISOLATION WITH EXTERNAL TEST EQUIPMENT

Level at Which Test Feature is Effective	Level at Which Replacement is Made							
	Subsystem	Equipment	Group	Unit	Ass'y	Subass'y	Stage or Circuit	Part
System	1.179	1.417	1.569	1.700	1.821	1.924	2.022	2.100
Subsystem	-	1.179	1.417	1.569	1.700	1.821	1.924	2.022
Equipment	-	-	1.179	1.417	1.569	1.700	1.821	1.924
Group	-	-	-	1.179	1.417	1.569	1.700	1.821
Unit	-	-	-	-	1.179	1.417	1.569	1.700
Assembly	-	-	-	-	-	1.179	1.417	1.569
Subassy.	-	-	-	-	-	-	1.179	1.417
Stage	-	-	-	-	-	-	-	1.179