WADC TECHNICAL REPORT 59-240

AUTOMATION AND PERSONNEL REQUIREMENTS FOR GUIDED MISSILE GROUND SUPPORT FUNCTIONS

W. B. KNOWLES, Ph.D.
GENERAL ELECTRIC COMPANY

LIGHT MILITARY ELECTRONICS DEPARTMENT
ADVANCED ELECTRONICS CENTER AT CORNELL UNIVERSITY
ITHACA, NEW YORK

MAY 1959

CONTRACT NO. AF 41(675)-170
PROJECT NO. 7185-71584

AERO MEDICAL LABORATORY
WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

McGregor & Werner Midwest Corp., Dayton, O.
44-977 & 978-1000-7-24-59

FOREWORD

This report summarizes the work done by the Advanced Electronics Center, Light Military Electronics Department, General Electric Company, Ithaca, New York, under Contract No. AF 41(657)-170, Project No. 7709. The original Contract Monitor was Dr. W. P. Chase, formerly of the Maintenance Laboratory of the Air Force Personnel and Training Research Center. With the termination of that agency, Lt. A. W. Kibler and Mr. D. A. Topmiller of the Engineering Psychology Branch, Aero Medical Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, assumed contract monitorship.

Preparation of the report was done by Mr. A. M. Chammah, Dr. S. W. Davis, Mr. R. F. Hildreth, Mr. H. A. Lintner, Dr. W. B. Knowles, and Mr. C. G. Schnorr of the Advanced Electronics Center.

The authors wish to acknowledge the very important contributions of Dr. Chase (now with Rocketdyne Division, North American Aviation, Inc.) in setting out the original definition of the problem and in supplying access to the myriad sources of information needed in the course of the study. Furthermore, in an area where competing philosophies and arguments are often vigorously and vociferously propounded, his leadership created an atmosphere of objectivity and open-mindedness for which we are most grateful.

This study truly was made possible only by the cooperation of many people in discussing frankly with us their experiences in designing ground support equipment. We are particularly indebted to Mr. M. Nowak of Goodyear Aircraft Corporation, Mr. H. T. Richmond of Boeing Airplane Company, Mr. R. L. Holmes of Northrop Aircraft Incorporated, and Mr. R. W. Wilson of the Martin Company.

ABSTRACT

This report summarizes an investigation of the high skill level requirements found in missile systems employing automatic electronic test and checkout equipment. Automation has not resulted in lowering manpower demands because (1) testing and maintenance requirements and objectives have not been systematically defined and (2) manual operations have not been completely described or programmed. A "maintenance system" design approach is outlined as a method for overcoming these deficiencies. Further research is recommended in development of techniques for evaluating the design of test logic, maintenance operations, and manual tasks.

PUBLICATION REVIEW

This report is published for the exchange of information and stimulation of ideas.

FOR THE COMMANDER:

Walter F. Grether
WALTER F. GRETHER
Director of Operations
Aero Medical Laboratory

TABLE OF CONTENTS

I. INTRODUCTION

This study was undertaken to look into the relationships between automation and personnel requirements. The need for such a study arose when it became apparent that so-called automatic electronic ground support equipment was not leading to reduced personnel requirements as had often been claimed. Indeed, there was more than a suspicion that present day automatic equipment was creating greater and greater demands for more and better technicians and maintenance men than the Air Force can supply. Just what is the story? Does automation of necessity mean high personnel demands? Or is there something lacking in present automatic equipment that can be provided in future designs? If so, how can the use of automatic equipment be made to pay off in reduced demands for premium manpower?

As originally conceived, the plan for this study called for the analysis of the three Air Force missile systems closest to being operational at the time: Mace, Bomarc, and Snark. By considering only organizational-level testing and maintenance of the guidance and control subsystems, it was proposed to describe functions performed by automatic equipment and functions performed by men. A measure of degree of automation was to be derived from the division of labor found. Further detailed analyses of the manual tasks were to yield measures of skill and personnel requirements. It was then proposed to relate personnel requirements to degrees of automation. From observations of the efficacy of automatic and manual functions as they contributed to reliability, cost and economy, and weapon system operational goals,

---

Manuscript released by author 30 November 1958 for publication as a WADC Technical Report.

guidelines or suggested applications of automation were to be generated.

Very shortly after embarking on this plan it became apparent that it would have to be abandoned. For one thing, the range of automaticity represented in available support equipment is extremely narrow. For another, there are some exceedingly difficult problems in defining, much less measuring, automation and personnel requirements. Furthermore, even if it were possible to correlate measures of personnel requirements with a measure called degree of automation, these correlations would merely be somewhat superficial descriptions without a prior examination of the more basic interrelation. The really important consideration, at least at this point, lay in attempting to understand, rationally, what support systems attempt to do and how automatic equipment and men help them do it.

Furthermore, all things considered, the missiles now entering the Air Force weapon inventory are still largely experimental systems. The major emphasis has been on the design and development of the prime equipment. With few exceptions the importance of support functions in making a workable missile into an operational weapon was not realized until late in the development program. Everyone concerned with the design of missile systems has learned a great deal from the work that has gone on in the development of the Snark, Mace, and Bomarc. The important thing seemed not to be to simply compile data on what has been, but rather to profit from the experience gained on these programs and to attempt to gather together and interpret the significance of the new ideas, approaches, and developments that have come out of that experience. The same basic problem of how to capitalize on automatic techniques and keep manpower requirements low remained, but the answers were not sought in a detailed recording of what by now is ancient history. For the time being, the decision was made to develop a rational analysis of the factors influencing the design of missile support functions rather than to establish empirical relations between automation and personnel requirements.

The study consisted of interviewing design engineers, training people, government officials, officers, enlisted men, and students; of visiting factories, schools, government laboratories, and missile test centers; and of accumulating and studying numerous documents ranging from service records and class grades through production specifications and drawings to the latest versions of operational plans.

In addition, starts were made at developing some techniques that are needed in the future design of support facilities. The result is this report, which is a summary of the major ideas developed in the course of all this activity. The report is organized as follows. The first section presents some data showing the magnitude of the manpower problem posed by new weapon systems. This is followed by a section in which the concept of a maintenance system is developed as a way of handling automation and personnel requirements on a common basis. The remainder of the report outlines the factors to be considered in the design of a maintenance system and a discussion of some areas where additional research might be profitably undertaken.

II. PERSONNEL NEEDS AND SHORTAGES

Missile and manned aircraft systems are creating a demand for skilled technicians[1] that is far in excess of the number of available men who can be trained to satisfy that demand. The extent of the shortage is shown in a study (1) conducted by the Program Control Division, Directorate of Military Personnel, Headquarters USAF, and summarized here.

TABLE 1

ENLISTEES QUALIFIED FOR LEVEL-7 ELECTRONIC OR MECHANICAL TRAINING

Mental Category	Percent of Enlistees	Number of Enlistees	Number Qualified (Estimated)
I	9	7, 650	5, 500
II	28	23, 800	5, 200
III	45	38, 250	840
IV	18	15, 300	46
Total	100	85, 000	11, 586

Source: Ballard (1)

Table 1 is a breakdown of the personnel supply by mental categories, based on estimates for fiscal year 1958. The crucial facts here are that (a) only 15 percent of the 85, 000 men entering the Air Force each year are qualified by present aptitude

---

[1] In this report "technician" is used in the general sense of the term, i.e., a person skilled in the technical details of some area of endeavor, not in the restricted Air Force sense of an Air Force Classification System Skill Level 7 Specialty.

standards for training in advanced electronic and mechanical specialties, and (b) almost half of these are among the uppermost (brightest) 9 percent. In other words, to meet its requirements for such specialties as missile systems analyst or electronic maintenance technician the Air Force must draw upon a limited supply of highly intelligent people who are also in demand for other specialties.

TABLE 2

ESTIMATED SHORTAGE OF LEVEL-7 ELECTRONIC AND MECHANICAL PERSONNEL

Career Fields	Number of Men Required in Fiscal Year 1958 (Estimated)	Number of Men Required in Fiscal Year 1959 (Estimated)
251	68	76
30	11,388	13,906
31	385	1,754
32	4,142	5,735
33	242	596
34	408	239
Total Requirement	16,663	22,306
Available:		
For Retraining	1,031	784
Non-Prior Service*	11,586	11,586
	12,617	12,370
Total Shortage	4,046	9,936

*See Table 1

Source: Ballard (1)

Table 2 lists the estimates of 1958 and 1959 personnel needs in the six career fields with the highest electronic and mechanical aptitude requirements. When the number of qualified men is subtracted from the total requirement, the shortage is 25 percent for 1958 and 45 percent for 1959. Even this picture is too optimistic to be a true one, because it is based on the assumption that all qualified men will be assigned to these six specialties, a thing that in all probability will not happen. The shortages will therefore be much more severe than these figures indicate.

One often hears the claim that the replacement of manned aircraft with missile systems will reduce the need for skilled personnel; the information presented in Figure 1 does not substantiate this claim. It is estimated that in present-day missile systems 95 percent of the ground support personnel must be at the 5 and 7 skill levels; only 77 percent of the manned-aircraft ground support technicians are on these levels. The graph shows further that the percentage of personnel needing specialized technical training is also greater for missile systems than for manned aircraft. These figures clearly show that unless there is an over-all reduction in the absolute number of men required, which is extremely unlikely, the number of highly skilled technicians needed can only increase.

Further indications of the need for high-aptitude technicians and the role missile systems play in generating this need are obtained from a preliminary study (5) conducted by the AF Personnel and Training Research Center at Lackland AFB in July 1957. The study surveyed Qualitative Personnel Requirements Information reports and manning tables that detailed the manpower requirements by Air Force Specialty Code for various missile and manned systems. The study lists the systems making the greatest drain on high-aptitude manpower in the following sequences:

A. Ballistic Missile Systems

Two of the three systems analyzed require over 50 percent of the airmen to have Electronic AI's (Aptitude Indexes) of 80 or higher. (A score of 100 is maximum.) All require that 75 percent of the airmen have electronic or mechanical AI's above 60.

B. Non-Ballistic Missile Systems

C. Ground-to-Air Missile Systems

Three of these systems required 72 percent of the airmen to have electronic AI's above 80, and 92 percent to have electronic and mechanical AI's above 60.

D. Interceptors And Day Fighters

E. Fighter Bombers

F. KC-135 And C-132

For these systems less than 10 percent of the airmen require electronic AI's above 80.

The study also revealed that for calendar year 1956 only 7000 of the 101,000 entering airmen had electronic AI's of 80 or above. When this is matched against the fact

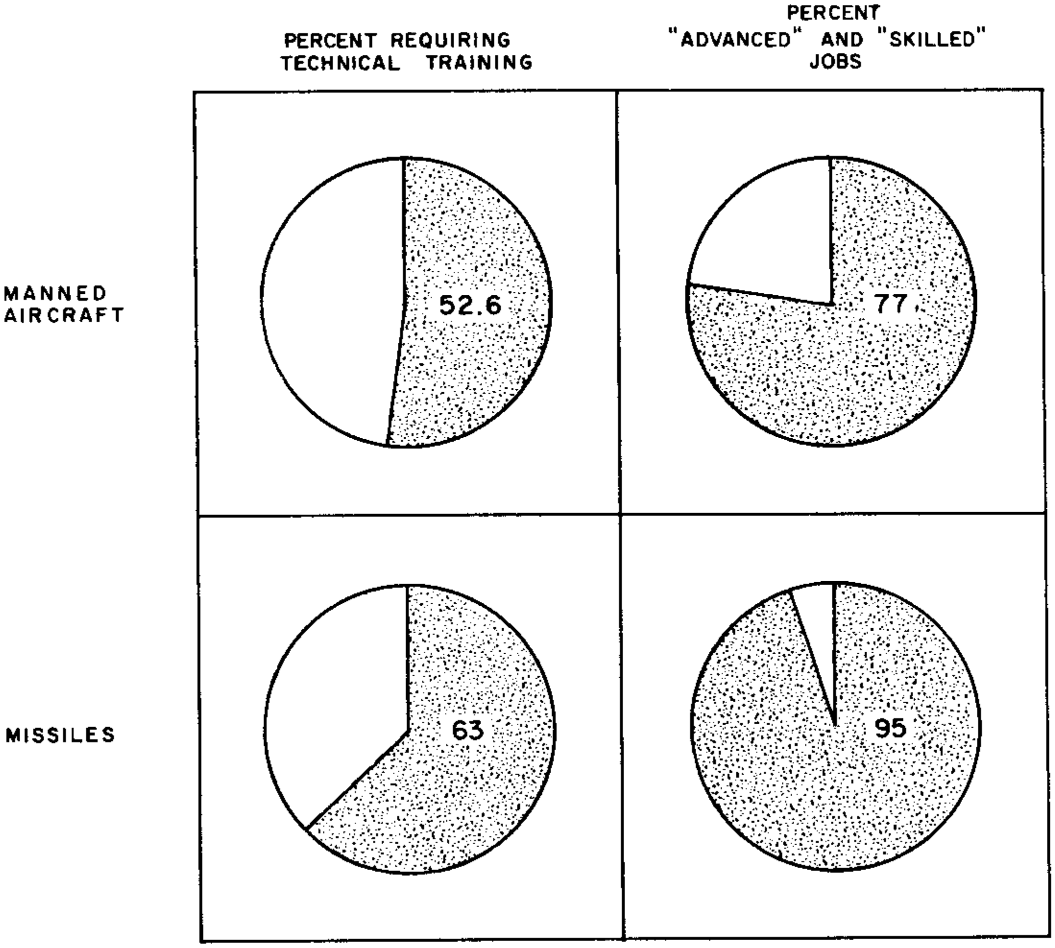

Figure 1. Skill and Technical Training Requirements for Missiles and Manned Aircraft. Source: Ballard (1)

that one squadron each for three ballistic missile systems (107A1, 107A2, and 315A) and one armament and electronic maintenance squadron serving three B-52 squadrons would require 350 such men or 5 percent of the total available this year, it can be seen that a very real shortage exists.

Even granting the possibility of errors in such manpower forecasts as these, the shortage of skilled technicians is not the figment of a statistician's estimation or something that is yet to occur; it exists today in actual operations. A base electronics officer at a Naval Air Station on the East Coast reports that only 60 percent of the available electronics technician positions are filled, and that only two well-trained electronics technicians are available for every five airplanes.

A visit to an Air Force base servicing AEW planes turned up reports that there were so few good technicians that radar observers were maintaining their equipment on their own time after regular patrol duty. Of the average four-year enlistment, less than one year was available for useful field duty. It was further revealed that very few (less than 10 percent) of the technicians were able to find jobs as electronics technicians in civilian life after their enlistment was over; the chief cause was lack of ability.

These few facts should be sufficient to indicate that there is a manpower problem and that current missile systems, even with their so-called automatic equipment, are going to aggravate it. Figure 2 shows some of the factors that can be manipulated to relieve the shortage. This is intended to show that the AF manpower structure at any-time is determined by the selection of people from the existing manpower supply, who are then trained to fill the needs of the various weapon systems in the Air Force inventory.

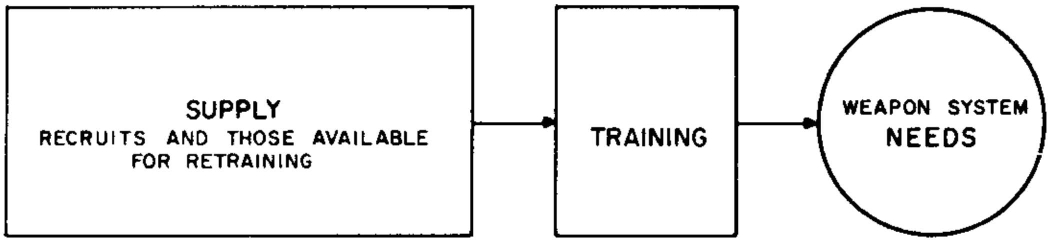

Figure 2. Block Diagram of Skill-Level Supply-and-Demand Situation.
Source: Ballard (2)

If the manpower shortage is to be relieved, work is needed in each of the three areas. Selective recruiting, improved aptitude testing, and creating of inducements to career enlistments are some of the efforts underway to improve the supply picture. Programs for improving the content, timing, and techniques of training are contributing to the efficiency of the training pipeline. But the most fundamental solution to manpower problems is to reduce the demand. It is largely through improved initial design of weapon systems that manpower demands can be lowered and pressure reduced on the training and supply links. Such improved design of the ground support for missile systems is the subject to which this study is addressed.

III. THE MAINTENANCE SYSTEM: A POINT OF VIEW

The manpower problems associated with current weapon systems have been described. Some of the more important factors involved in the creation of these difficulties, and possible ways of handling them, will be discussed subsequently. However, it is necessary first to define a few terms and develop some basic notions about ground support functions.

For missiles such as the Snark, Bomarc, Mace, and the even-larger ICBM's, nearly all of the site operations, except general housekeeping functions, are directed toward keeping a certain specified number of missiles in a state of operational readiness. (3, 9, 13)

With preselected targets, self-contained guidance, predetermined trajectories, remote command headquarters, etc., very few if any tactical or strategic decision functions are carried on at the site. In a sense the site, its equipment, personnel, and operation exist simply to service or maintain missiles. The missiles are employed by some other agency.

Furthermore, the present elaborate support or maintenance facilities are needed because things do go wrong with missiles; they must be continually checked, tested, disassembled, repaired. If, as engineering products, the airborne devices were completely reliable, or (more precisely) sufficiently dependable, there would be no need for the vast support complexes now seen. The Minuteman concept aims toward the ideal goal of eliminating the ground support functions. As one manufacturer put it, "We would really like to have a batch of sky rockets, capable of sitting out in the field for years just ready to go whenever anyone lit the fuze."

But electronics being what they are, this condition is not likely to be attained for a good many years. The problem is how to go about organizing the maintenance of missiles, so that the operational goals of the weapon system can be met without imposing undue costs — particularly within the context of this study — in highly skilled premium manpower.

It has been found convenient to think of the support of missiles in terms of a maintenance system designed, established, and run with the single goal of ensuring that the specified number of effective operational missiles are available when needed.

In the most general terms only four basic functions are performed within a maintenance system.(Cf.17) These four functions are

1. Sampling
2. Comparison
3. Interpretation
4. Action

Sampling includes all the procedures involved in extracting a piece of information or a measurement from equipment being maintained, transducing the information, and presenting it in a usable form. Take, for example, a technician manually checking the power supply voltage. The processes of hooking leads onto the appropriate test points, selecting the appropriate meter scale, and noting or recording the meter reading are all part of the sampling function. With an automatic checkout device the sampling function would include the initial cabling hookup and the programmed switching, voltage division, or analog-to-digital conversion built into the machine.

Comparison includes the processes by which the sampled data are checked against predetermined standards. The technician compares the meter reading against the nominal value and tolerances specified in his handbook. Automatic equipment can include a variety of comparator circuits and calibrated standards.

Interpretation includes the processes by which the result of the comparison is translated and given meaning in terms of what must be done next.

The technician may find the voltage within tolerance. He then interprets this to mean "proceed to the next test step." An out-of-tolerance value may send him to the handbook; he may find the meaning in his own memory by virtue of previous training or experience; or he may have to interpret the no-go as a hopeless condition for him, which necessitates calling on somebody else to find the trouble.

Automatic equipment varies in the amount of interpretation it does. Most testers interpret the result of a go comparison in terms of switching signals to proceed to the next step. Some of the simpler devices interpret no-go comparisons in terms of self-stop and self-check signals. A technician must then complete the interpretation by reference to a handbook or to his experience and training. At a somewhat higher level of sophistication automatic testers may turn on coded lights or dispense punched cards with printed diagnoses and repair instructions for the technician.

Action includes carrying out the procedures dictated by the interpreation of the test. When he gets an in-tolerance reading the technician proceeds to the next test. If the reading is out of tolerance he follows the handbook directions and makes an adjustment or replaces a module or proceeds through a number of other test steps. The actions built into automatic equipment are usually limited to switching to the next step after a go-comparison or stopping for and self-verifying a no-go. None of the equipment seen during this study was designed to go through auxilary troubleshooting sequences automatically or to make adjustments or to replace modules.

The examples given here are taken from the testing of electronic equipment but the same ideas can be extended to the maintenance of other classes of equipment. In inspecting a hydraulic line, for example, one looks at the line (Samples), looking to see how it differs from a normal line (Compares), decides what the appearance of this line means (Interprets), and leaves it alone or fixes it as needed (Acts).

If we lump together the data processing functions of sampling, comparing, and interpreting and call this combination a "test," we can consider the maintenance system as a sequence of tests and actions. When a missile is checked out and everything is in order so that no adjustments or repairs are necessary, the chain of events can be diagrammed as a straighnt-through sequence leading to the final action, "Ready-Hold" or "Fire." (See Figure 3.)

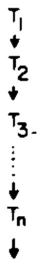

Figure 3. Confidence Tests

The purpose of this straight-through sequence is to ensure that everything is in order; these "confidence checks" form the trunk of what we have come to call a "testing tree."

When no-go's are encountered something must be done to the missile to restore it to a usable state; the trouble must be located and repaired before the confidence testing of the missile can proceed; thus, the testing branches out into a troubleshooting sequence. (See Figure 4.)

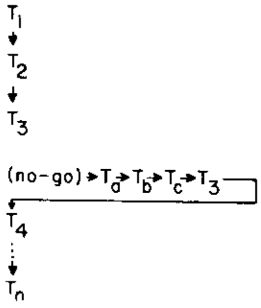

Figure 4. Confidence and Troubleshooting Tests

The side branch may be short, as when the remedy is the simple replacement of a designated easily accessible module, or it may be very long, as in the four-to-eight-hour complete system alignment required in one missile.

This method of looking at the organization of maintenance systems differentiates in its structure between confidence checking and troubleshooting tests.

The diagram also symbolizes the set of instructions, or program, for the maintenance of the missile. For most missiles the trunk or confidence checks are fairly well defined and the program carried out by automatic equipment. On the other hand, the branch or troubleshooting tests are usually left for the technicians to work through manually. The programming of these branches is usually not nearly as complete or as well-defined as the straight-through series of confidence checks.

The problem originally posed for this study was the relation between automation and personnel requirements. Automatic checkout and test equipment has been both touted as the means for reducing jobs to the point where almost anyone can run missile systems and condemned because just the opposite of this maintenance officer's dream has usually been the bitter reality. However, the praise or blame should not fall on automatic equipment or automation per se. Rather, one must look behind the equipment and ask (1) how well and how completely the program for the maintenance system has been worked out and (2) how judicious the division of effort between automatic equipment and men has been.

A completely automatic system would perform all functions (sampling, comparison, interpretation, and action) in both the confidence and the troubleshooting sequences. If the full program cannot be built into the maintenance equipment, parts of it must be built into the technicians. The way in which technicians are programmed is through training, experience, handbooks, and job aids. In the roughest sense the best and premium technicians are the ones who are capable of being programmed with minimum and often incomplete training, experience, and handbooks. Automatic equipment is essentially stupid; it knows no electronics and does only what it is programmed to do. Likewise, to avoid having to use only the brightest technicians, the manual parts of the maintenance system must be fully detailed and programmed. True, some functions should be relegated to machines if low-level people are to be used, but the biggest gains in lowering personnel requirements are bought when as much attention is paid to designing the technician's program as to programming the automatic equipment.

Complete programming and complete automation of the maintenance system are probably not possible. An appreciation of the reasons can be gained by examining the conditions that have made it possible to build fully automatic systems such as the missile itself and comparing these conditions with what would be required to design a fully automatic maintenance system. Missiles can be made to fly automatically because (1) they are asked to accomplish only a very specialized, sharply circumscribed mission; (2) the information transfers and mechanical processes required to perform these specialized missions are known and can be specified; (3) the means for implementing the information and power processing exist and can be built; and (4) it is economically feasible to do so. The building of a fully automatic maintenance system falters on one or all these points.

The missions the maintenance system must accomplish usually cover an extremely wide range, from simulation of portions of the flight conditions to isolation and replacement of an insignificant connector in the most inaccessible reaches of some piece of test equipment. Furthermore, it usually is not feasible to specify in advance all the things that a maintenance system will be asked to perform.

The amounts and types of information about the missile that the maintenance system must process in performing its support functions are enormous compared with the amounts and types the missile itself must process in actually performing its mission functions. Hence, any set of tests must of necessity constitute a sample of all the tests that could be made. Furthermore, the mechanical manipulations that are needed to perform repairs do not lend themselves to accomplishment by automatic machines.

Even if it were possible to state all the things a maintenance system might be expected to do and set out the information and power transfers needed to accomplish these things, the hardware is not developed to the point where it is possible to do it automatically. Evaluation of complex waveforms and replacement of modules are two examples of such tasks.

Lastly, the economic cost of building a fully automatic maintenance system would be staggering. As it is, the ground support equipment is responsible for between 50 and 90 percent of the cost of missile systems.

As long as highly complex, basically unreliable equipment is to be maintained at a high level of operational readiness, there will always be a problem of finding people to maintain that equipment, and no amount of practically attainable automation will dispense with the problem. This is not to say that automatic equipment cannot be used to advantage. It can, but the maximum advantage can best be achieved by recognizing and acting upon the fact that the support of missiles involves the design of an entire maintenance system in which the functions of automatic equipment and the functions of men complement one another. (Cf. 2)

IV. THE DESIGN OF A MAINTENANCE SYSTEM

The choice of the term "maintenance system" is a deliberate attempt to underscore the idea that the system design approach is as applicable to the development of support functions as it is to the prime equipment, perhaps more so. So long as missiles were largely experimental ventures this perhaps was not the case. With a purely experimental weapon there may be good reason to spend 10 years in prime equipment development, followed by 18 months on the test equipment, followed by less than a year on handbooks and training procedures.

Now that missiles, as well as other complex weapons, are here to stay, some more integrated and less compartmentalized design effort is needed. It is too costly, wasteful, and time-consuming to build an assemblage of apparatus that can be teased into working, only to have to go over the same ground again to make a truly operational system.

The hallmarks of a system design approach are (1) definition of operational objectives and limitations; (2) integrated design, in every area, aimed at maximum attainment of these objectives; (3) continuous evaluation, redesign, and re-evaluation in terms of criteria defined by the objectives; and (4) effective management of the phasing, timing, and communications among units of the design group.

Management problems themselves warrant a study several orders of magnitude larger than this program and will not be dealt with here. The following discussion will deal with (a) the factors that should be considered in setting the objectives and limitations for a maintenance system and then (b) test logic design as the most important and primary problem to be solved in achieving these system goals. Evaluation techniques, which are needed to give direction to the ongoing recycling of the design process, are discussed in Section V.

A. Objectives and Limitations

The framework within which a maintenance system is designed is structured by many factors in the over-all weapon system. In general, the characteristics of the prime equipment and the operational concept for the weapon system set the initial direction for the maintenance system development. Additional factors such as logistics concepts, manpower availability, and costs enter later in development to modify and constrain the maintenance system design.

1. Prime Equipment Characteristics.

Two missile systems with similar operational objectives may utilize different instrumentation techniques, which place different requirements on the maintenace systems. Matador C and Mace are both relatively short-range tactical surface-to-surface missiles. The primary difference between the two is in their guidance systems. The differences in the guidance system have, more than anything else, dictated the differences in the maintenance requirements for these two systems. The Mace was originally called the Matador B, but with the new guidance system and greatly modified support concept the whole assemblage emerged virtually as a new weapon system.

Reliability of the prime equipment and reliability of the support equipment also influence the design of the support system greatly. For example, the maintenance recycle period for the Bomarc is dictated by the anticipated time-to-failure of portions of the liquid fuel system. If solid fuels are used or changes in the liquid fuel packaging are made, the need for recycling will be changed and the nature and amount of maintenace activity will change.

The attention given to making replaceable modules independent and interchangeable will also affect the load placed on the maintenance system. Some equipment is so designed that replacement of a unit requires extensive adjustment and realignment of a number of units with which it is associated in the subsystem. Other equipment is designed so that a defective unit can be immediately replaced with a good spare without touching the rest of the subsystem. Obviously, the two conditions place different requirements on the maintenance system.

The packaging of the prime and support equipment establishes another set of limits on the testing and repair functions. Modular or unit packaging and throw-away maintenance tend to reduce the number and detail of confidence and troubleshooting tests. On-site maintenance to the component level, of course, dictates a larger amount of testing and maintenance activity.

The maintenance system itself also imposes weight, space, and structural penalties on the equipment being maintained, and there are limits to what can be tolerated. For example, built-in test cables add weight to the missile; and the test equipment designer will not be permitted unlimited access to information sources in the missile. A missile with modular components and uncrowded, highly accessible packaging may be highly desirable from the maintenance man's point of view, but this consideration will be overridden if the operation of the missile is impaired.

2. Operational Factors.

The response time demanded for operational effectiveness of the missile is an extremely important factor that has many ramifications in the maintenance system design. It is generally realized that in most cases the time of firing is not to be left to our discretion. So long as the national policy is one of retaliatory defense the use of missiles will be only in response to an immediate, almost instantaneous threat. In nearly every case the goal is zero response time. Many of the fundamental differences in the support structure for the Bomarc and the Snark stem from the consideration given to response time needs. From the beginning Bomarc design objectives and specifications carried the requirement for a very short response time for a flight of several missiles. This requirement dictated the extremely simplified support structure that was eventually developed. The Snark, on the other hand, was well into development before rigid response time requirements were established. Subsequently, these requirements were tightened several times; at one point it was felt that the existing support structure and equipment could not possibly be modified any further to meet the response time requirements but that a whole new concept was needed.

Other factors, such as area of tactical deployment, site layout, access to centralized depot maintenance, and climatic and environmental conditions also determine what is possible and what is mandatory in the design of the maintenance system. The roles that environmental factors play in limiting performance of machine and men can readily be appreciated, but unfortunately they are often overlooked. Heat, cold, rain, dryness, noise, vibration, and shock all take their toll on equipment and men and pose a whole set of specialized problems in packaging and human factors design.

Whether or not the system is to be mobile or is to operate from fixed sites affects decisions about the instrumentation of tests and the packaging of test and checkout equipment. There are on record several examples of "mobile" systems that grew and grew until they became, with a sufficient number of trucks and other vehicles, transportable. There have also been "mobile" testers that for one reason or another became fixed installations, but were still encased in ruggedized steel cabinets capable of withstanding a 50-ft drop.

3. Other Constraints.

There are a number of quite important determining factors for which there is little well-organized, hard, factual data and which have, therefore, become areas of contention between competing maintenance philosophies. Among these factors are supply and depot maintenance backup, manpower availability and ability, and, of course, costs.

Broadly speaking, there are two general philosophies concerning Maintenance and Logistics Concepts. One holds that detailed troubleshooting and repair at the organizational level is not possible because of the excessive amount of equipment, spares, stockpiles, and skilled manpower required. This might be called the fully automatic, black-box replacement and throw-away maintenance school. This concept is based on the premise that efficient transportation and supply will give access to a centralized depot where detailed troubleshooting and repair can be done better and more efficiently (e.g., 19, 22).

On the other hand, the bits-and-pieces or component-and-soldering-iron school holds that supply systems never have been and never will be efficient enough and that the line organization must be self-sufficient. The premise here is that with enough spares and enough people capable of component repair the line organization can operate for extended periods independently of depot backup (e.g., 4).

Those not committed to either school make the more rational suggestion that different weapon systems operating in different locations and under different conditions might require different Maintenance and Logistics Concepts.

The issue of manpower ability and availability is usually one of the subsidiary areas of debate. The fact that some people can and do learn to do phenomenally difficult jobs of troubleshooting and repair is taken by the bits-and-pieces school as indicating that all men should be able to achieve the same proficiency. The module replacers argue that experience just as surely shows that not all people do become expert technicians. The issues become even less clearcut when it is asked just what can be expected of a 5 or 7 skill-level man and what an Electronic Aptitude Index of 80 really means. (8)

As in every design field, the maintenance system designer operates with the cost specter as a not-so-silent partner. Will it cost more to automate certain functions or would they be less expensive as manual operations? Will the initial engineering and development costs be offset by savings in operating costs? Does the price of automatic equipment offset the costs in selection, training handbooks, and facilities? Are the costs of support in keeping with the defensive value of the prime weapon?

The fact that there are so many and such diverse factors operating to influence the design of a maintenance system makes it imperative that they be stated and defined very early in the design process. Many of the requirements should be given in the General Operational Requirements and called out in the Design Specifications. In particular, response time, modular design, supply and logistics objectives, and manpower goals should be developed as part of the initial specifications.

Detailed attention to the maintenance structure should become an increasingly important part of preliminary systems analysis work. This will help in determining the division of development labor, time, and money among the several design areas. Techniques are also needed whereby operational objectives can be translated into design criteria so that at various stages the design accomplishments can be evaluated against the weapon system objectives. Fortunately, the above needs are coming to be recognized in several places; cost studies (15), design approaches, and evaluation techniques (14) are beginning to emerge that may tend to make the definition of objectives and limitations less of an impossible task than it now is.

B. Test Logic Design

Detailing of the objectives and limitations is only a prelude to further design of the maintenance system and, as stated before, serves first to establish a frame of reference within which the system must be designed, and later to set criteria against which any design may be evaluated. After defining the objective and limitations the designer's next jobs are (1) to determine what must be done to test and maintain the missile, (2) to select and organize the tests that are to be incorporated into the testing tree, and then (3) to specify the hardware and personnel required to implement the system.

Logical organization of the tests is essential to the design of an adequate maintenance system. The design of the testing logic, in fact, largely predetermines (1) the dependability of the missile systems; (2) the amount of testing required; (3) the amount and type of equipment required; (4) the division of testing functions between operators and automatic equipment; and (5) the required operator skills. Subsequent design actions can fail to realize the potentialitiy of a maintenance system based on a well designed test logic, but no amount of additional design effort or operator training can entirely overcome deficiencies in the test logic design. The diagrams in Figure 5 show what is involved in designing a test logic. At the left side of the figure is a detailed analysis of the missile system, showing the interrelations between the functional parts at several levels of description. Associated with each part are the functional requirements placed on that part by the missile designer. At the top level the characteristics of the entire missile are shown. The next level is a breakdown of major subsystems. Each subsystem is then further subdivided into functional parts, and this division is continued until, at the lowest level, the individual components of the missile are detailed in circuit diagrams.

The functional requirements spelled out on the diagrams will serve as criteria for the tests. At the higher levels they are given in such terms as terminal accuracy, thrust, and radar range; at the lowest level in terms of resistance, waveforms, etc. It is important that they be as detailed as possible and that they be realistic. This means that there must be close coordination between the missile design and the maintenance design. The maintenance designer cannot expect simply to requisition such a set of diagrams and specifications. In many cases, he will have to pry them from the missile designers. The missile design itself is a fluid thing, subject to modification on the basis of the Research and Development (R&D) evaluation program. The maintenance system designer must be in a position where he is informed of these modifications as they occur. This can be facilitated by an organizational structure that requires day-to-day contact.

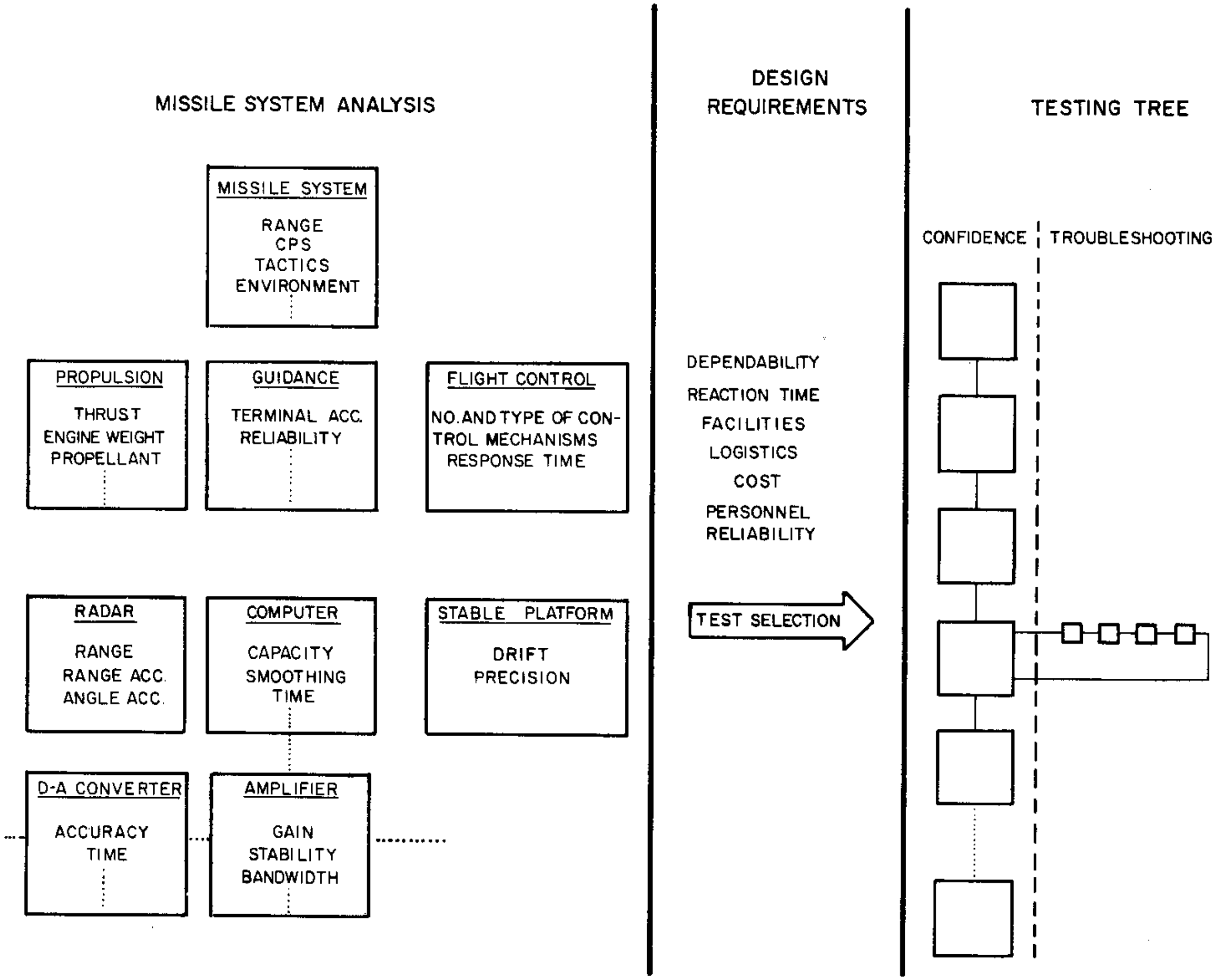

Figure 5. Test Logic Design

Unfortunately, the designer of the testing logic usually finds that ostensibly someone else has already done his job for him. A complete set of tests is generated in the process of the R&D evaluation program, and it is a great temptation to take these tests over directly and use them as a basis for design of the operational test equipment. However, R&D tests are meant for an entirely different purpose. The information obtained from them is used for experimental purposes and for missile design evaluation. For the purpose of trying to make decisions about the design of maintenance systems, the information is often redundant or even irrelevant. In other cases the description of the test program is incomplete, because R&D testing is done by trained engineers who depend on but often do not record fully their experience in analyzing the results. Attempts to mechanize or automate the R&D test program have in general been futile.

Before proceeding, it is necessary to return to the distinction between the two types of tests performed by the maintenance system. A confidence test is one intended to determine whether the missile flight will be a success or a failure. A troubleshooting test starts with the information that there is something wrong, and its purpose is to localize the malfunction to a part of the missile that can be repaired, adjusted, or replaced. The confidence tests are shown in Figure 4 as the straight-through sequence. The troubleshooting tests are shown as branches off the main sequence. The different purposes of the two types of tests require different approaches in the design of the logic.

1. Confidence Tests.

Ideally, the completion of a sequence of confidence tests would be the necessary and sufficient basis for drawing the conclusion that the missile will be successful when fired; i.e., the missile must pass the tests in order to be successful and passing these tests means it will be successful. Such a set of tests is the ultimate objective of the test designer. In practice, he will fall short of this ideal.

Any practical test sequence will lead to two types of errors: (1) accepting or passing some missiles that in fact are bad and (2) rejecting some missiles that are actually good. These errors arise from two sources: (1) errors in selecting tests and (2) the usual errors of measurement.

As pointed out above, tests are selected in the first instance on the basis of assumed or established relations between subsystem or component criteria and over-all missile performance criteria. If the postulated relationship between the subcriteria and over-all missile success are incomplete or invalid, inappropriate and faulty tests may be selected. This becomes a really serious problem when it is necessary to make tests at lower, detailed component levels, because of the length and tenuous nature of the logical chain relating the component criteria to the missile success criteria. The sheer number of parts at the lower levels and the complexity of their interactions often makes rigorous and complete analysis impossible or at least impractical. Only in some instances is it possible to describe the system dynamics mathematically in closed form. In others, at least partial solutions may be possible, and these solutions can be used as a starting point for an evaluation of the effect of some variables by means of simulation. In the majority of instances, however, the design engineer must rely on his experience to specify reasonable requirements.

Deficiencies in selecting tests also arise from the limitations imposed on the amount of testing that can be done (e.g., time, cost, access to information within the missile). Because of such limitations, a sampling of all possible tests must be selected, which means that there is always some risk at any given time of missing a critical fault.

Lack of perfect reliability was seen to be the basic reason for having a maintenance system, and the selection of tests may be based on known or assumed reliability characteristics. Some parts of the missile will have a low probability of malfunction. Eliminating these from a test sequence will thus contribute little to the error of accepting bad missiles, but ignoring a part with a high probability of malfunction will contribute significantly to this type of error. (The same consideration sometimes leads to the selection of tests of individual components as opposed to a functional test of a larger unit. In a complex module, for example, it may be more efficient to go directly to a highly unreliable tube rather than to attempt a dynamic over-all test of the module.)

Given a logically valid set of tests, some missiles may be erroneously accepted or rejected due to measurement errors. These errors are not simply mistakes that people and machines make in taking readings but are inherent, built into the test by the specifying of nominal values, tolerance limits, and the accuracy and precision of the measuring device. As such they are within the area of the maintenance system designer's cognizance. Although this is not the place to go into great detail on the theory of measurement errors, it may be pointed out that setting tolerances too close tends to produce a situation in which good missiles are rejected. Setting tolerances too wide tends to lead to the acceptance of some bad missiles. The problem is illustrated by an incident reported to have occurred in a Mace test firing. During several preliminary checkouts one particular test consistently turned up as no-go. Since previous experience had indicated that the specified tolerances for this test were too tight,the no-go's were overridden. The same thing happened at the firing. Later, the mission failure was traced back to the fact that the measurement was truly outside the acceptable operating range.

2. Trouble Shooting Tests.

One major difference between confidence tests and troubleshooting tests is that at the start of a sequence of troubleshooting tests it is assumed that a malfunction exists. The tests must either locate the malfunction or demonstrate that the confidence tests made the error of rejecting a good missile.

It is true though that some localization is done by confidence testing, even though this is not its prime objective. The amount of such localization depends on the structuring of the confidence tests; it might point to a subsystem, a module, or even a component, and efficient troubleshooting sequences should utilize the information already gathered. This might seem to be rather obvious counsel, but the fact remains that it is not unusual to find the confidence and troubleshooting sequences so completely divorced that identical tests are made in both areas. Some information was gained in order to know how to remove a module, but then the module is sent back to a unit tester or bench maintenance area labeled only "Rejected."

One might argue that the confidence test sequence is inefficient in terms of its basic purpose if it generates any information beyond what is required to determine whether or not the missile will be successful. However, it is impossible for the confidence test to arrive at the no-go decision without gathering some information that will be useful in localizing. The logic of the troubleshooting sequence should capitalize on the availability of this information and thus prevent further inefficiency by preventing redundant testing.

Several systematic approaches to the construction of troubleshooting sequences are now employed. One of these is commonly called data flow analysis, which amounts to tracing signals (or data) through a system until the malfunction is isolated. It is the kind of procedure that an experienced technician uses intuitively and when formalized has been found useful as a basis for training.

The half-split technique is an attempt to utilize what is known about the probability distribution of malfunctions within the equipment. The set of all possible malfunctions is partitioned into halves, each of which has an equal probability of containing the malfunction. A test is then performed to eliminate one of the halves. Each decision then makes maximum use of the information contained in each test.

At present, finding an efficient logic is largely a "cut-and-try" procedure. However, there are some methods available that show promise for converging systematically on a solution. The first method might well be the generation of such simplified descriptions as the Testing Tree. Redundancies, dead ends, and logically incomplete sequences can then be readily seen. More sophisticated approaches involving the application of symbolic logic and other mathematical techniques are also being explored.

3. Test Implementation.

Regardless of how it is done, systematic selection and detailed describing of tests will largely determine the amount of testing that can be done automatically. Automatic testers can only be built when the logical rules are completely detailed. Similarly, low-skill people can only be used in jobs that are completely spelled out and reduced to a procedure level. The alternative to detailing the tests beforehand, which is a designer's task, is to require a highly skilled man to work out the logic on the spot. Thus, operator skill is traded for design skill.

Once the test logic has been specified, the equipment and procedures needed to implement the tests are developed. The implementation of the tests is distinctly a matter of engineering and human factors ingenuity; the setting out of any list of formal rules that would apply to every specific design problem will not be attempted. There are, however, some general considerations that bear discussion.

If minimal personnel demands is accepted as one of the goals of the maintenance system design, the initial decisions on which tests are to be automated and which are to be manual carry through and prejudice all subsequent efforts to attain the goal. In the past it appears that tests have been automated where it was easy and well within the state of the hardware art to do so. When a readily available automatic design did not present itself, the operation remained among the manual procedures. The result is that automatic equipment has largely taken over simple switching and comparison operations rather than difficult interpretations and decision functions. It would seem that the need is not for bigger and better automatic switches but for machines that carry the designers skill and intelligence into organizational level operations.

Perhaps the point is best made by reference to a complaint one designer registered against some probing question about what he expected the operator of a system to do: "If I can figure out what he's supposed to do I'll make it automatic."

In recent years the "universal tester" has been advanced as a panacea for maintenance problems. Actually, none of the so-called universal testers really claims to be universal in the sense that it can be used to test everything in every system. (Cf. 12) At best, they claim to handle most tests commonly encountered in most systems. This means that either additional special-purpose testers or manual procedures will have to be designed to handle unique tests. It means further that the practice of making automatic that which is easy to make automatic is being followed, probably at the expense of technician time and talent for the difficult tests.

To repeat, a tester samples and transduces signals from the device. It performs comparisons and interpretations, and controls the timing and sequencing of operations.

The signals introduced into and taken from the device being tested are usually analog signals, and their handling usually involves specialized data conversion devices. The comparison, interpretation, and programming, on the other hand, are largely decision processes, which lend themselves to digital techniques. Testers designed with these distinctions in mind do offer promise of achieving some measure of uniformity and its consequent advantages. Such testers are essentially small-scale flexible-program digital computers for processing information once the analog-to-digital and digital-to-analog conversions have been provided for. Spares, supply, maintenance, handbook, and training problems are simplified because testers for different systems and devices can be put together from the same basic digital building blocks. With an appropriate number of card, magnetic tape, or punched-tape programs, the same tester can conceivably be used for complete system, module, and sub-unit checkout, as well as for any desired degree of troubleshooting.

The central digital data processing unit can well be termed universal, but it must be adapted to each individual case by specialized programs.

In opposition to the universal tester concept stands the more usual practice of designing a specialized unit tester for each major module or black box. Experience with unit testers has not been too satisfactory. The approach tends to produce an unwieldy array of equipment, in some cases 30 to 40 testers that have very low utilization rates but must be kept in adjustment and repair. Other disadvantages are that a testers-to-test-testers-to-test-testers kind of regression tends to develop so that the whole maintenance structure can only be kept working with a large population of highly skilled test equipment technicians. Furthermore, specialized unit testers are difficult to adapt to the endless changes in the prime equipment and tend to aggravate the obsolescence problem.

Unit testers are probably best reserved for production-line testing or centralized depot maintenance, where the volume of testing is large enough to make their use economical, where a few skilled technicians can be more efficiently used, and where the operation can be charged off against several organizational units.

The tape- or card-programmed testers offer advantages for organizational-level use in that they are readily adaptable to prime equipment changes and they tend to keep the amount of test equipment down. Instead of 30 to 40 unit testers there would be 30 to 40 unit programs and sets of input-output adapters. The utilization rate can be higher. Also, the corps of test equipment technicians can be smaller, since there would actually be less equipment and it would be made up of relatively few standardized building blocks.

It has been stated before that the programming of manual tests is implemented via handbooks and training. In this sense the design of handbooks and training programs is an integral part of the maintenance system design. It would be difficult to overemphasize the benefits in lowered personnel requirements to be gained through proper attention to these factors. Again, detailed logical analysis of the testing requirements and explicit descriptions of the manual operations are the basis for design of effective training and job aids.

Work done at the Army Human Resources Research Office (23) has shown that relatively unskilled personnel can be brought to a high degree of troubleshooting proficiency within a short time with special training methods. These methods are based on a detailed analysis of the device being maintained and the construction of a set of tests that logically reduces the number of possible alternative locations of faults, leading the technician directly to the malfunction. The technicians are given the "theory of operation" in terms of this fault isolation logic and then trained in the procedures for following the logic to isolate and repair faults.

Hoen and Wardel at the Maintenance Laboratory have developed a pocket-size troubleshooting guide (11) in which, by a system of index tabs and cross references, the technician is lead logically from symptoms and tests to malfuctions and directions for repair.

Within the past few years the Qualitative Personnel Requirements Information (QPRI) program has been instituted in an attempt to ferret out detailed descriptions of operator and maintenance tasks. The original objectives of this program were to provide inputs for manning and selection. However, design,training and handbook efforts have also attempted to utilize the kind of data generated by QPRI. By and large, the QPRI program has served a very important function in calling attention to the need for developing detailed information on manual tasks. In some respects it has been too successful, or at least too early, because the techniques presently used are not entirely adequate for the achievement of all these diverse purposes.

QPRI analyses are highly equipment-oriented. They tell, for example, which knobs must be turned, which switches thrown, what meter values read. These are useful data for writing handbooks and for gaining some informal insight into human engineering design problems, but they do not indicate the basic psychological makeup of tasks (7) and hence do not evaluate or measure the human performance requirements that have been designed into manual tasks, nor do they really provide anything like a rigorous basis for determining manpower needs.

V. EVALUATION: AN AREA FOR FURTHER RESEARCH

The development of evaluation techniques is one area in which further research is greatly needed, because without evaluation (and effective management) no system design effort is possible and any discussion of system design is academic.

Most people who have worked with the design of complex weapon systems recognize the iterative, cyclical, trial-and-error nature of the design process extending from the very first attempts to set out general ideas on through to the field use of the actual weapon. The translation of ideas into requirements and of requirements into designs is essentially an art rather than a science; we have no real understanding of what is involved in such processes. (Cf. 13) Nonetheless, weapon systems and devices are designed to perform certain specifiable functions, and ultimately it must be proved that the design leads to the accomplishment of these functions. A missile is required to be launchable within a given time, to travel a specified trajectory, and to hit a specified target with a specified accuracy. The performance of the missile can be, and is measured and evaluated against these criteria. At a lower level it may be specified that a power supply must operate at a given voltage and within a specified tolerance. Any power supply designed to meet these requirements can be evaluated against the criteria and redesigned if necessary.

The point of mentioning these examples is to show that in some areas of design, evaluation is done as a matter of course. There are, however, other areas of design in which evaluations are needed but are not done, and even worse, where evaluation techniques are almost completely lacking. Three important areas in maintenance system design where evaluation techniques need to be developed are

(1) Evaluation of test logic

(2) Evaluation of maintenance system operations

(3) Evaluation of personnel requirements.

Deciding what tests to include in confidence and troubleshooting sequences apparently has given ground support equipment designers no end of trouble. Examination of the tester programs for the systems studied in every case showed places where useless or redundant tests had been dropped, and places where additions had been made when it was found that some critical measurement had been overlooked. One group of designers described the "agonizing reappraisal" of their test logic that had followed a fruitless attempt to take over bodily and automate the R&D test schedule. It was almost impossible to get an answer from anyone to the question "How do you decide what tests to make?".

There are several mathematical and logical techniques that should be applicable to the problem of arriving at valid, efficient test programs. Among the techniques that could be investigated are symbolic logic, to check the validity and redundancy of test programs; information theory, to tie reliability data into the design of optimum troubleshooting sequences; and statistical decision theory, to assist in the rational determination of tolerance specifications. Since there was no opportunity in this study to explore the potentialities of any of these methods, they are mentioned here for whatever heuristic value this may have.

Organization and layout of the maintenance operations is also an area of difficult decisions. Anyone who has ever tried to find an up-to-date set of Operational or Maintenance Plans knows how great an understatement that is. Figure 6 shows in a highly simplified manner the work-a-day life of a typical idealized missile. Starting in standby, the missile is periodically checked. If it passes its confidence checks it is returned directly to standby. If faults are detected, repairs are made before the missile is returned to standby. On very rare occasions a missile may be taken from standby, put through a few additional checks, and launched. Some missiles fail to get launched. Figure 6 represents a very much oversimplified system. Figure 7 shows a generalized composite diagram of the functional states found in the three missiles studied.

The problem, of course, is to arrange mazes such as this (a) so that the required number of missiles is ready for effective launching when needed and (b) to build and operate the facility at reasonable cost. Industry is constantly faced with problems of a similar nature in tooling up for new product lines, in deciding to consolidate or decentralize operations, and in working out manufacturing-inventory-sales systems; application of operations research methods using cost-effectiveness models has proved helpful in solving them. (e.g., 6)

As part of this study a limited attempt was made to see how these kinds of models might be used in guiding maintenance system design decisions. Since the contract charter did not give access to cost data, it was possible to deal only with measures related to effectiveness. Figure 8 shows the results obtained with one model. Here the number of available missiles, N_G, is shown as a function of the reliability of the missile, p, and three measures of the support system quality: P_r, the probability of effecting a repair in a given time; α, the probability that upon test a truly good missile would check out as bad; and β, the probability that a truly bad missile would pass all tests and be called good. This analysis shows the limited advantages to be gained by straining to improve the support system, particularly in trying to keep marginally reliable prime equipment in repair. Obviously, the largest benefits are to be had by improving the prime equipment reliability. Other models work out such

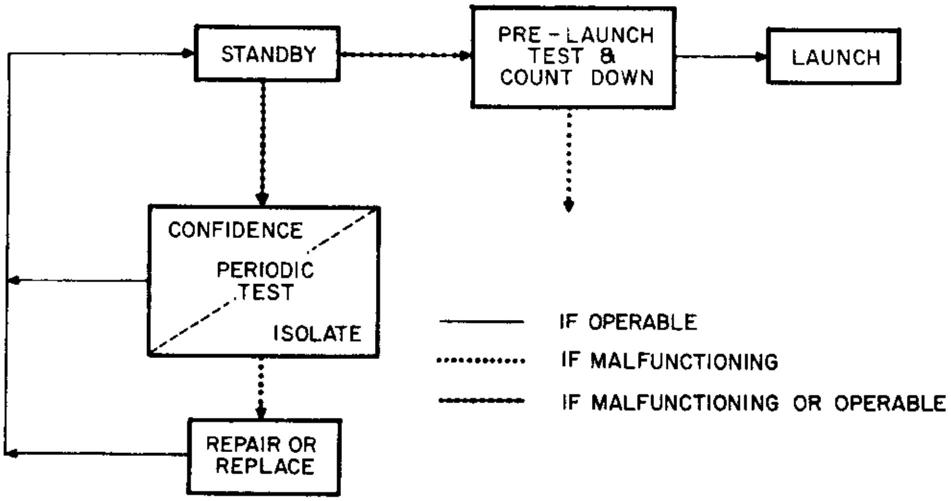

Figure 6. Simplified Functional Status Diagram

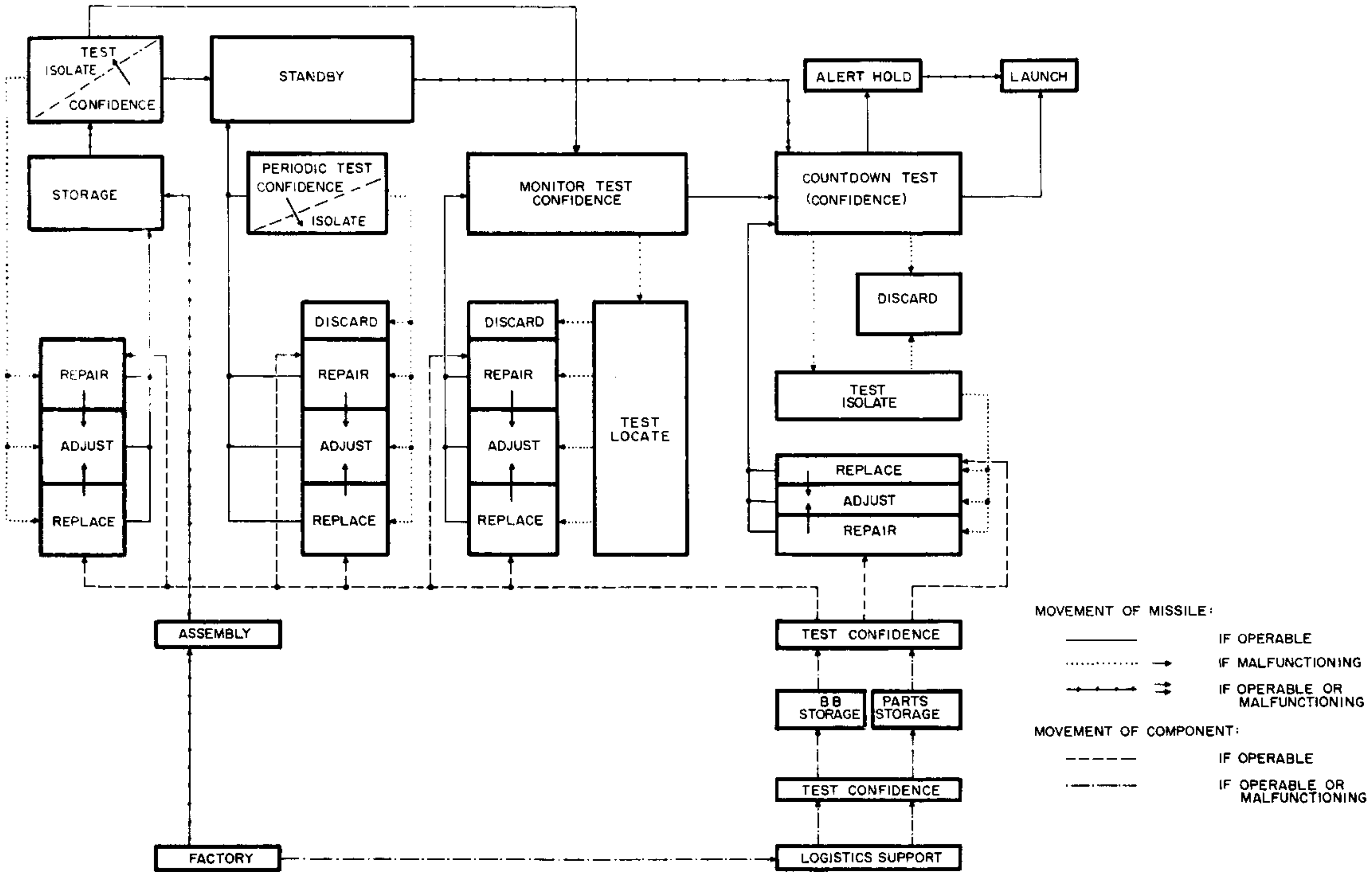

Figure 7. Composite Functional Maintenance Diagram

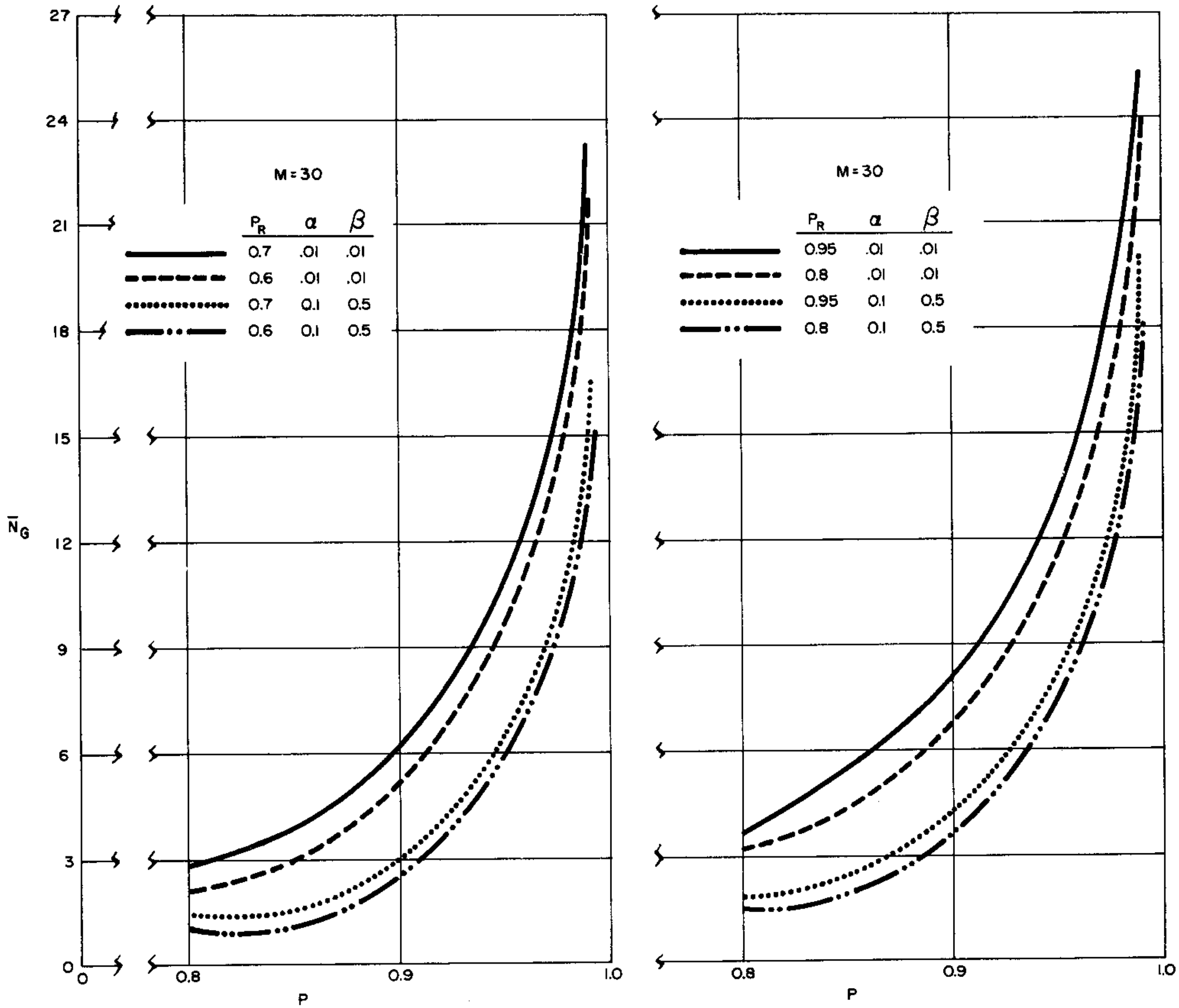

Figure 8. Mean Number of Available Missiles as a Function of Representative Missile and Ground Support System Qualities

relationships as those between the number of available missiles and the interval between testing, the failure-to-repair-rate ratio, and a number of others.

Fundamentally, operations analysis techniques are systematic methods of extrapolating from past experience to evaluations of proposed systems. A large amount of information on equipment, installation, development and personnel costs, typical times for testing and for repair, measures of maintenance performance, and many other variables would have to be gathered. It is a long jump from an abstract parameter such as α to such tangibles as real estate, men, and electronic hardware. But the same questions and decisions arise in every system design effort only to be handled by best guesses, experience, trial and error, and philosophic concepts. Better answers are obtained only with improved methodologies.

This report has already touched upon the matter of evaluating or measuring personnel requirements, and has indicated that existing approaches do not appear to offer a fundamental solution to the problem. The forecasting of the characteristics desired in men to fill newly created jobs, the like of which have never existed before, has put the field of personnel psychology to a real test. It has revealed how psychology is lacking in anything vaguely resembling a taxonomy of behavior. It has also shown how inadequate are the theory and practice of aptitude and proficiency testing.

The problem of specifying what talents, aptitudes, skills, interests, abilities, and so forth are needed to perform a job that exists only on paper is vastly different from setting up a selection procedure to screen candidates for well-established occupations. In selecting men for established positions, empirical correlation of the incumbents' performance with psychological tests or test batteries, and subsequent assessment of potential applicants with the same measures constitute the standard pragmatic procedure. But what to do when there are no incumbents to test? How does one go from task analysis set forth as "turn knob x, " "read waveform y," "observe light z" to a statement of the required Electronics Aptitude Index, education, and skill level ? Or, put the other way, if it is specified that a given job is to be designed for a level-3 semiskilled operator with less than a high-school eduction and an Electronic Aptitude

Index of 60, what does this tell a designer (or a psychologist) about what can be expected of such a man in the way of turning knobs, reading scopes, or comparing voltages?

A number of schemes have been proposed in attempts to reduce tasks to a few psychologically meaningful categories (e.g., 16). "Simple discrimination," "complex discrimination," "simple manual task," and "complex skill," are some of the categories suggested or used at one time or another. As part of this study an attempt was made at developing still another scheme. It is presented here not as a finished product, well validated and proved, but again because of the possibilities of developing such a tool for evaluating personnel requirements.

The point of departure was an attempt to put operator functions and automatic equipment functions within the same frame of reference. It is essentially an attempt to spell out the program of operator functions in much the same way that an abstract program can be written for automatic equipment. The handbook for the operation of the Mace guidance system checker (21) and the handbook describing the maintenance of this checker (20) were used to develop a shorthand for summarizing and describing the manual operations.

Very simple manual operations, such as connecting leads, throwing switches, and turning pots, were counted and numbers were used to designate these operations.

Manual operations that appeared to call for some degree of motor skill, such as nulling out sensitive servos, or dismounting heavy mechanical assemblages, were designated by the letter M.

Operations that called for predominantly sensory discrimination, such as meter readings, scope pattern interpretations, or visual inspections, were designated by the letter S.

In a number of operations the technician was required to make use of information read off earlier; these points were designated by R, for remember.

Quite frequently a point would be reached where what followed next was conditional upon obtaining one or another meter reading, on being able to accomplish a certain adjustment, or upon the combined results of several previous steps. These points were indicated by C for conditional, and the alternative courses of action were described.

Using these designations, a diagram of each part of the operating or maintenance procedure was built up. For example, the "crystal currents check" looks like this:

```
2-S-2-S
```

and the "antenna yaw gain adjust" looks like this:

```
       1
      /
3-M-M-C
      \
       1
```

but the "CRT sweep alignment" looks like this:

```
                1                              M
               /                              /
5-M-2-M-S-S-1-C-S* -1-1-S* -1-S* -1-M-C-1-2-1-S-1-2-S-1-S-1-S* -S-

     M
    /
C†-1-C-S*-1-C‡-2
```

*No instructions covering troubleshooting for this sequence.

†If the condition is not met, the operator goes back 6 steps and repeats.

‡If the condition is not met, the operator repeats the sweep alignment procedure up to this point. If it still is not met, he replaces one of three units and repeats the sweep alignment procedure, continuing this process until the condition is met.

The advantages seen for a descriptive scheme such as this are twofold. At one level it can be used as a rule-of-thumb procedure to demonstrate to a designer the structure of the tasks he has created for the technician. The task diagrams readily show such things as blind-alleys, closed-cycle loops, and other incompletely worked-out procedures. Suggestions for task simplifications and for additional automation can also be based on these diagrams. An a priori ranking of the functions from difficult to simple for the operator would seem to be C, R, S, M, 1. The rule of thumb would be to eliminate functions in this order.

Although no formal verification of the use of these diagrams has been made, informal discussions with design engineers as they were preparing maintenance handbook information indicated that the scheme was useful to them in determining what they wanted done. In several instances simpler procedures suggested themselves during the course of the analysis.

The second level at which this type of scheme may prove useful is in the prediction of aptitude requirements for personnel to accomplish the procedures finally worked out. Quite an extensive program of research would be needed before this would be possible.

The present categories are probably neither independent nor exhaustive. A way of summarizing such analyses in quantititative measures would also have to be worked out. What appears to be needed is a program of factor analytic and multivariate scaling studies to develop meaningful task descriptions, followed by a series of correlational studies to tie the measures describing various task structures with measures describing personnel abilities.

VI. SUMMARY

This study was initiated to look into the relations between automation and personnel requirements for guided missile ground support functions. The organizational level maintenance of electronic equipment for three representative and nearly operational systems (Snark, Bomarc, and Mace) was studied in detail. These investigations led to the conclusion that it is not automatic equipment itself nor simply the amount of automatic equipment that leads to excessive personnel requirements, but rather the use to which automation is put within the over-all support complex. In order to understand more fully the respective roles of automatic equipment and manual operations, a maintenance system concept was developed. It was argued that the design of the maintenance system centers in the detailed specification of the testing logic, rationale, or strategy; that this is the basis for efficient programming of automatic equipment and of manual tasks. It was further argued that the lack of attention to the programming of manual tasks is really the factor that has led to high skill-level requirements.

An attempt has been made, in this report, to develop in general outline the factors that must be considered in the design of a maintenance system. Four characteristics of a system design approach were given as (1) defining objectives and limitations; (2) integrated design in every area aimed at maximum attainment of these objectives; (3) continuous evaluation, redesign, and reevaluation in terms of criteria defined by the objective and the limitations; and (4) effective management, timing, and communications among units of the design group.

The kinds of constraints operating on a maintenance system were discussed, as were the factors involved in developing a test logic and translating it into equipment and manual tasks.

The development of techniques for evaluating (a) test logic, (b) maintenance system operations, and (c) personnel requirements demand further research. Some lines of approach to this research were suggested.

Effective management, the fourth characteristic of a system, although it is recognized as essential to the accomplishment of a maintenance system, was not discussed.

VII. REFERENCES

1. Ballard, N.L., Programs Control Division, Directorate of Military Personnel, Headquarters USAF, Washington 25, D.C., Personal Communication.
2. Bright, J.R., "Does Automation Raise Skill Requirements?" Harvard Business Review, XXXVI, 4 (July-August 1958), pp. 85-98.
3. Chase, W.P., et al., "Qualitative Personnel Requirements Information (QPRI) Change Report for Weapon System 309A (TM-76A Mace)," Air Force Personnel and Training Research Center, Advance copy, October 1957. Confidential.
4. Dostal, H.F., et al., "SM-62A Wing Maintenance Plan" (2 vols.), Northrop Aircraft Corp. Report No. NAI-56-279, 1 July 1956. Secret.
5. Ewart, E.S., "Rundown on Manpower Requirements of Weapon Systems," Disposition Form dated 15 July 1957, Air Force Personnel and Training Research Center.
6. Forrester, J.W., "Industrial Dynamics, a Major Breakthrough for Decision Makers," Harvard Business Review, XXXVI, 4 (July-August 1958), pp. 37-66.
7. Gagne, R.M., "Training Devices and Simulators: Some Research Issues," American Psychologist, IX (1954), pp. 95-107.
8. Harding, F.D., and L.D. Brokaw, "Implications of Air Force Personnel Information for Job Requirements," Personnel Laboratory, Wright Air Development Center, February 1958 (Technical Memorandum PL-TM-58-3).
9. Highland, R.W., "Initial Qualitative Personnel Requirements Information for Weapon System 200A (IM-99 Bomarc)," Air Force Personnel and Training Research Center, AFPTRC-TN-56-116, September 1956, AD-098-891. Confidential.

10. Hoehn, A.J., and A.A. Lumsdaine, "Design and Use of Job Aids for Communicating Technical Information," Air Force Personnel and Training Research Center, January 1958, Technical Report AFPTRC-TR-58-7, AD 152109.
11. Hoen, A.J., and W. Wardell, "Development of an Experimental Troubleshooting Guide for the F-86 D & L Electronic Fuel Control System," Maintenance Laboratory, Air Force Personnel and Training Research Center, December 1957, Technical Memorandum ML-TM-57-25.
12. Klivans, L.S., "Weapons Systems and Controls Require Automatic Checkout Equipment" (Part I), Electronic Industries, April 1958, pp. 70-76; (Part II), Electronic Industries, May 1958, pp. 80-86.
13. Larkins, J.T., "A Report of Qualitative Personnel Requirements Information for Weapon System Number 103A (SM-62 Snark)," Air Force Personnel and Training Research Center, AFPTRC-TN-57-38, March 1957. Confidential.
14. Malcolm, D.G., J.O.P. Hummel, et al., "A Method of Evaluating the Adequacy of Future Organizational Maintenance," The Johns Hopkins University Operations Research Office, Washington, D.C., Technical Memorandum ORD T 348, August, 1957, AD 141989.
15. Margoles, M.A., et al., "Costs of Alternative Methods of Operating the Intermediate Range Ballistic Missiles" (abridged edition), Rand Corp., R.M. 1850, 26 March 1956, AD 112408.
16. Ray, J.T., G.E. Passey, O.S. Adams, R.C. Smader, and`G.B. Simon, "A Technique of Job Activity Description for Weapon Systems: Task Equipment Analysis," Air Force Personnel and Training Research Center, Technical Report AFPTRC-TR-57-13, December 1957, AD 416419.
17. Spector, P., A.D. Swain, and D. Meister, "Human Factors in the Design of Electronics Test Equipment," American Institute for Research, Pittsburgh, Pa., April 1955, AD 81084.
18. Van Cott, H.P., and J.W. Altman, "Procedures for Including Human Engineering Factors in the Development of Weapon Systems," Aero Medical Laboratory, Wright Air Development Center, Technical Report 56-488, October 1956, AD 97305.

19. "IM-99 Weapon System Logistic Plan (Proposed)," 31 July 1957, H.Q. Ogden Air Material Area, Hill Air Force Base, Utah. Secret.

20. "Preliminary Handbook, Service Instruction, Automatic Atran Nose Checker," Customer Service Report No. 245, The Martin Company, Baltimore, Maryland, 15 September 1957, Revised 15 October 1957.

21. "Preliminary Handbook, Operating Instructions, USAF Series YTM-61B Missile, Missile Guidance Set AN/DPQ-4(XA-1)," Goodyear Engineering Report No. 8052, Goodyear Aircraft Corporation, 15 September 1957.

22. "TM 61-B Operational Requirements Study" (2 vols.), The Martin Company, Baltimore, Maryland, October 1956, Document No. ER 8285. Secret.

23. "Work Program for Fiscal Year 1959, Project Number 09550000 Personnel Management: Training Methods; Motivation, Morale, and Leadership," The George Washington University Human Resources Research Office, Washington, D.C., 30 June 1958.