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RESEARCH MEMORANDUM

A SURVEY OF THE CURRENT STATUS OF THE ELECTRONIC RELIABILITY PROBLEM (U)

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ABSTRACT

The problem of evaluating and improving the reliability of military electronic equipment is of great importance. The problem is made difficult by the increasing complexity of electronic gear, the stringent performance requirements, and the severity of operating environments, particularly in aircraft and missiles. Reliability is a systems problem and is discussed from this point of view in seven sections dealing with: general background of the problem, tube reliability, component reliability, system reliability, personnel and organizational factors, theory of reliability, and application of the theory to military electronics. The concept of critical complexity is introduced, and a new approach, reliability control, is suggested as an effective means of achieving and maintaining reliability in the development, production, and use of complex electronic systems.

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INTRODUCTION

The increasingly serious problem of reliability in military electronic equipment has received considerable emphasis during the past two years. There are several programs to obtain reliability data in the field and to improve tube and component reliability, and a study of the problem has been made by the Research and Development Board. To date, however, there has been no unified review of the technical and quantitative aspects of the reliability problem.

This paper is a status report whose purpose is to outline the general problem of reliability in military electronic equipment, to summarize the results of current reliability programs, and to develop a tentative theory of reliability for evaluation and prediction.

In a problem of such broad scope and complexity it is impossible to consider in detail the many new developments in tubes, components, materials, and techniques aimed at better performance capability. These advances in the rapidly expanding art of electronics will undoubtedly affect the reliability of future electronic systems, but whether they will improve or further degrade reliability can at present only be gauged from field experience. Attention has therefore been limited to those activities which are specifically aimed at reliability and which are based on field data.

It is hoped that this report will stimulate interest, first in reliability as a quantitative measure of quality in complex electronic systems, and second, in reliability control as an effective part of systems engineering, necessary to achieve and maintain reliability.

1. BACKGROUND OF THE PROBLEM

The scope and magnitude of the military electronic reliability problem will be outlined in this section. It will be shown that the problem is both important and costly. Some of the major reasons for unreliability will be considered and a method for dealing with the problem, reliability control, will be summarized. The stage will then be set for the discussion of current reliability efforts and results to date, in Sections 2 - 7.

1.1 Low Reliability of Military Electronic Equipment is a Serious Problem

Remarkable technological advances have been made in the field of electronics during the past decade. The impact of these developments on military activities has been dramatic and far-reaching. During World War II, radar, the proximity fuze, fire-control equipment, and sonar played crucial roles in winning the victory. Since V-Day the importance of electronics in warfare has greatly increased. It has brought about revolutionary changes in the rapidity and range of communication, in the speed and precision of controlling modern weapons, and in the detection and tracking of enemy weapons. To realize these potentialities it is imperative that electronic equipment operate reliably in the field. Yet it is generally agreed that present electronic equipment is unreliable to a serious degree. For example, a recent widely distributed report (Ref. 2) states that in 1950 only about one third of Navy electronic equipment was operating properly.

1.2 Unreliable Equipment is Costly in Operations, Materiel, and Personnel

Electronic failures have three serious effects. In the first place, failures in critical equipment jeopardize the success of vital military missions and may endanger the lives of military and civilian personnel. Excessive failures in airborne radar, for example, could degrade the effectiveness of an air defense system.

Secondly, electronic failures exact drastic economic penalties through heavy upkeep costs. It has been estimated that the cost of maintenance and replacements during the life of military electronic equipment is at least ten times the original cost of the gear (Ref. 41). Such an upkeep would be intolerable in television sets or home radios. With an expenditure of 4 billion dollars for military electronic equipment during fiscal year 1953, it is clearly important to cut down on this high support cost. Again, the strain imposed on production, supply, and storage facilities is indicated by the estimate that for every tube in the socket there is one on the shelf and eight in the pipeline. Thus only about 10 percent of the tubes purchased for the military are in use and 90 percent are moving in as replacements. Thus the excessive replacement of electronic parts diverts production, consumes shipping and storage space, and absorbs many manhours in paperwork.

Finally, unreliable electronic equipment imposes a heavy burden on the services by requiring many skilled electronics maintenance personnel. The shortage of such men, the long training period required, the rapid turnover and the lack of career incentives for such high caliber enlisted personnel, are all factors which make this a particularly acute problem. Some idea of the number of men needed is given by the rough statistic that one electronic technician is required for every 250 tubes. Thus an aircraft carrier with a total of 12,000 tubes must have about 50 electronics maintenance men. Indeed, so serious is the personnel problem that a post-war study (Ref. 3) by electronics experts reached the following conclusions:

''Military electronics would require several times as many men as would be available in the event of war. Electronic equipment is absolutely imperative for combat effectiveness, yet it will fail in a large proportion of cases through lack of maintenance personnel in time of war.'' The radical solution reached was that ''The design of all quantity production electronics equipment must be such that no maintenance whatever is required for the life of the equipment''.

It is clear that reliability is a serious problem. The next section will consider one of the underlying reasons - complexity.

1.3 One of the Causes for Electronic Unreliability is the Increasing Complexity of New Weapons

Electronic equipment is a major part of many of the new and improved weapons now being planned and developed. Their performance depends strongly on the increased speed, range and accuracy of communication, control, and detection offered by modern electronics. To achieve these performance goals, increasingly complex equipment has been developed and this complexity has in turn led to serious reliability problems which threaten the effectiveness, availability, and success of these vitally-needed new weapons.

For example, a recent report (Ref. 2) states that the number of vacuum tubes on destroyers rose from 60 in 1937 to 3200 in 1952, a growth of 50 in electronic complexity. The same report also cites examples of ground and airborne electronic systems with several hundred tubes, and it is well known that some military equipments have a thousand or more tubes.

In guided missiles the problem of electronic reliability is particularly acute and is probably the major factor in determining when missiles become operational (Ref. 5).

The effects of complexity on reliability lie in three areas: the parts (tubes, resistors, etc.), the system, and the operating and maintenance personnel. The primary reason why increased complexity has resulted in lower reliability is of course that with more parts there will be more failures. In fact, if the reliability of the parts is not changed but the number of parts in a system is increased, say, 5-fold, then the failure rate of the equipment will also be increased by a factor of five. Thus if the simple equipment had a 5 percent failure rate, the complex equipment has a failure rate of 25 percent, and the reliability has dropped from 95 to 75 percent.

In concept the solution to the complexity problem is simple: Decrease the part failure rates by the same factor that complexity is increased. This has not been done for most present complex equipments and the result is the current low reliability.

The secondary reasons why complexity lowers reliability involve system engineering and personnel. Complex systems tend to be more difficult to design, test, fabricate, maintain, and operate. More knowledge, experience, and skill are needed in each of these phases to offset the effects of complexity.

It is unrealistic to expect to achieve the high performance capabilities required of military electronics without complexity. Consequently the reliability problem can be solved only by drastic improvements in the areas mentioned above. This is not to say that simplification should not be pursued wherever possible - simplification to the essentials is urgently needed, but the essentials will still be complex.

1.4 Severe Environmental Conditions Cause Failures

Military electronic equipment must withstand a variety of severe environments. Mechanical stresses due to shock, vibration, and acceleration are high. These occur in shipping and handling for all types of equipment. For example, during the Pacific War up to 60 percent of airborne equipments shipped to the Far East theater were damaged on arrival and as much as 50 percent of the equipment and spares in storage became unservicable before use (Ref. 6). Gunfire in tanks, aircraft, and ships causes strong shocks, as does launching and booster separation in guided missiles. Weight and space requirements in aircraft and missile equipment favor fragile mechanical construction and make cooling difficult. Pressure, temperature, humidity, dust, and fungus are all sources of failure in equipment which may have to operate under arctic, desert, or tropical conditions and at extreme altitudes.

1.5 Improvement of Reliability is Slowed by the Shortage of Good Technical Data

There are five types of information which are necessary for the evaluation and improvement of reliability:

(1) Reliability Requirements: Without quantitative requirements for electronics systems and major components there is little incentive to design or test for reliability. The reliability of a radar is just as important a military characteristic as its range.

(2) Environmental Conditions: Data on the actual environments under which electronic parts and systems must operate are scattered, incomplete, and inconsistent. In many specifications the environmental requirements are unrealistic or tend to be based on existing environmental testing equipment rather than field conditions.

(3) Tube and Component Reliability Data: There are few good data on the reliability of standard electronic parts in military environments. Consequently the designer, even if he had complete environmental data,

would be unable to select the best tubes and components for his application. By ''good reliability data'' is meant statistical information on the time to failure of tubes and components in known equipments under realistic conditions. By the same token, lack of such primary data handicaps the general improvement program, since the most important trouble areas cannot be identified for priority and action.

(4) Cause-of-Failure Data: It is obviously impossible to improve unreliable parts and systems unless there is information as to why equipment is failing. To improve existing gear and to avoid the same mistakes in new equipment a feedback of cause-of-failure data from the field is needed. This information requires careful technical effort and cannot generally be obtained from routine maintenance personnel. Cause-of-failure data are separate from the survey type data on reliability mentioned in the preceding paragraph. Thus reliability data are of two types:

(a) Survey Data: What is failing and what is its failure rate?

(b) Cause Data: Why is it failing?

The survey data are needed to determine the reliability of equipment and to indicate the most important trouble spots. The cause-of-failure data are then needed to actually make the improvement.

(5) Reliability Design Data: Much reliability knowledge exists in the electronics industry in the form of design and operating experience. Unfortunately the lessons which have been learned in tube and component design and application, and in circuit and system design (e.g., Ref. 7) are often not available on projects, either because this knowledge has not been gathered and put into useful form or because it has not been properly distributed. Thus every new crop of designers tends to repeat the same unnecessary mistakes, with resultant low reliability. Defects which occurred and were eliminated in World War II equipment are again being found in present gear.

In addition to these hardware considerations, personnel and organization factors must be considered in reliability and a useful breakdown of the entire problem will now be discussed.

1.6 The Five Areas of Reliability

It is convenient to split the electronic reliability problem into five areas:

Tubes
Components
Systems
Personnel
Organization

In each area there may be defects which cause electronic failures in the field, and in each area there are problems of evaluating the reliability, determining cause of failure, and making improvements. Tubes include all types of electron tubes, most of which are receiving tubes. Components comprise all non-tube electronic and mechanical parts such as resistors, capacitors, transformers, switches, connectors, relays, meters, etc. A tube or component is defective if it fails under expected military usage, not because of improper application or abuse. Such inherent defects may usually be attributed to faulty design or manufacture. An electronic system, such as radar, is an assemblage of electro-mechanical parts functionally interrelated to perform a specified function; it includes test and auxiliary gear necessary for the functioning of the prime equipment. System defects are failures basically due to errors, omissions, ignorance or bad judgment in designing or manufacturing the system. Examples are faulty choice or application of tubes or components; failure to design for normal transportation or design shocks or for severe or unusual environments such as fungus, dust, humidity, or heat and cold; and failure to provide adequate test gear. Personnel includes everyone who comes into direct physical contact with the equipment in any phase from manufacture to end use, including fabrication, assembly, inspection, packing, shipping, storage, installation, testing, operation and maintenance. Personnel failures may occur in any of these phases. Organization is a loose term including other activities and personnel in both government and industry which affect reliability of military electronic equipment but which are not in direct contact with the system. Examples of organizational defects are faulty systems planning, insufficient field testing of equipment before production, failure to provide necessary spare parts and sufficient maintenance personnel, and inadequate feedback of field failure data to designers.

The five areas overlap and are interrelated. Nevertheless they provide a framework within which the various reliability programs can be discussed. Before doing this, however, the role of reliability in the development and use of a weapon system will be outlined to conclude this background section.

1.7 Electronic Reliability is a Womb-to-Tomb Problem in Complex Weapon Systems

Electronic reliability is only one important aspect of the general problem of weapon system reliability. Electronic equipment must be used in conjunction with other equipment and men as part of a weapon system. In a bomber aircraft, for example, the weapon system includes not only the communication-radio-radar gear, but fire-control equipment, engines, hydraulic and fuel systems, and crew, all of which contribute to the performance and reliability of the system. To effectively play its role, the electronic equipment must be integrated into the weapon by means of systems engineering. The systems approach in the development of air weapons has been discussed extensively by Major General D. L. Putt of the Air Force Research and Development Command (Refs. 8 and 9). In order to put reliability into perspective it will be useful to summarize the major characteristics which must be considered in planning, developing, procuring and using a weapon system.

System Criteria

There are seven factors which determine the overall military and economic worth of a weapon system. These are (1) Performance Capability, (2) Reliability, (3) Accuracy, (4) Vulnerability, (5) Operability (ease of operation by service personnel), (6) Maintainability (ease of maintenance), and (7) Procurability (including producibility, availability in time, and ease of logistics supply).

An optimum weapon system achieves the most effective balance of these factors for the least cost to the nation. While certain of these criteria may be in conflict (for example, extreme performance and reliability), it is important to note that engineering improvements for reliability (e.g., simplicity, interchangeability, and accessibility) will in many cases also improve operability, maintainability, and producibility, with a net gain in system worth.

The system approach also shows that reliability must be considered in all phases of the system from ''womb-to-tomb''. This consideration is particularly important in guided missiles. The life cycle for electronic equipment is shown in Figure 1 (Ref. 2)

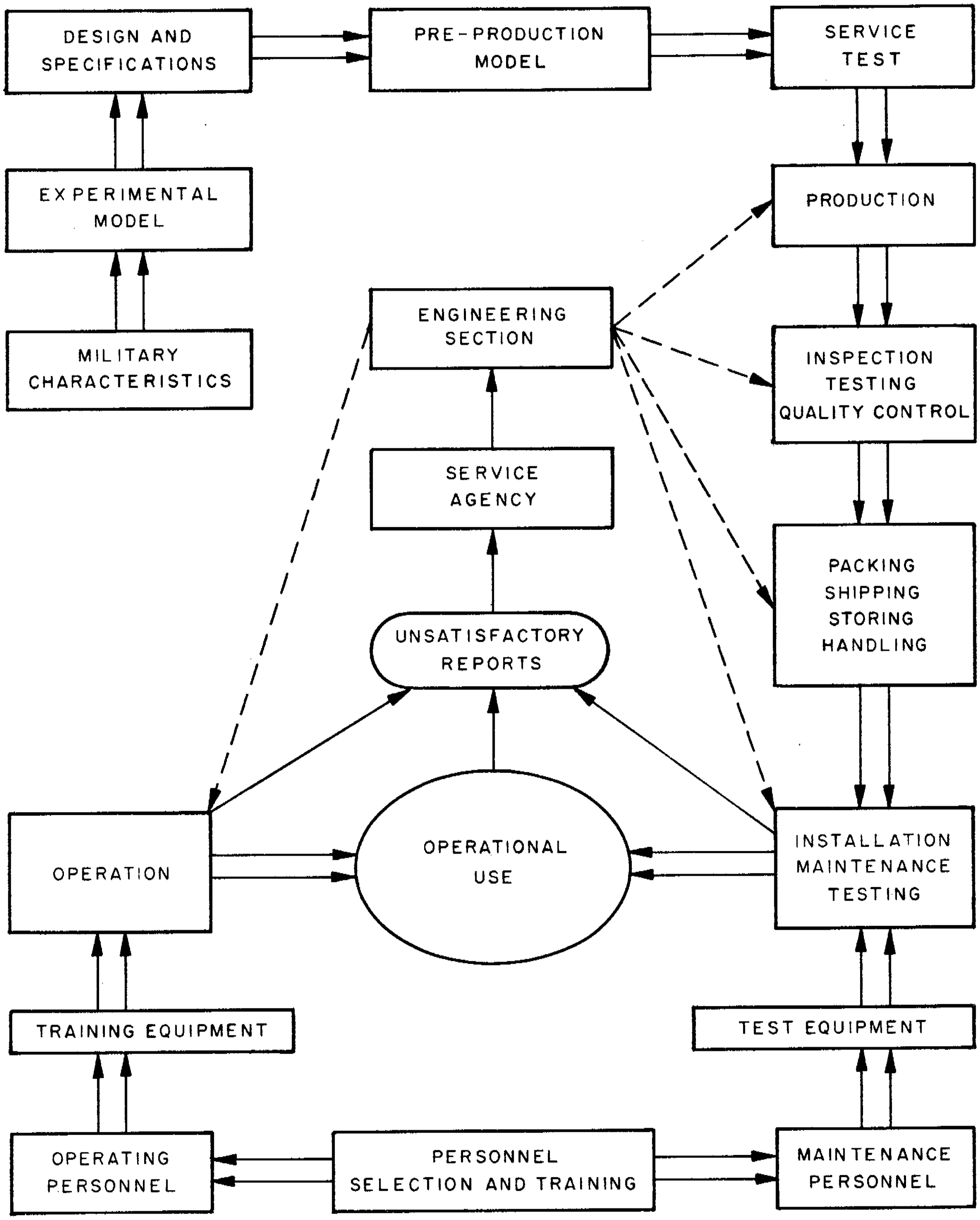

Fig. 1— Flow diagram of electronic equipment showing feedback of engineering information from unsatisfactory reports

and in more detail in Figure 1a. Reliability should be considered at each of these phases during development and early field tests. In the later period when the equipment has been put into operational use, a continuous monitoring of reliability is necessary, with feedback of reliability information as shown.

Reliability Control

In order to solve the difficult problem of reliability in a complex weapon system it is necessary to organize and direct the technical effort. This organized systems activity has been called reliability control (Ref. 5). It is the systems analog to component quality control used to maintain quality in manufactured components. Reliability control is the coordination and direction of technical reliability activities through scientific planning from a systems point of view.

There is no sharp distinction between reliability control and the usual engineering methods of improving reliability. Nevertheless, it is important to recognize that reliability control differs in degree from conventional engineering in three respects: first, overall system planning is emphasized; second, statistical analysis of failure data is used as a control; and third, constant surveillance of the system through feedback of failure data is required in all phases of development, production, and use.

Reliability control consists of the following cycle of five steps:

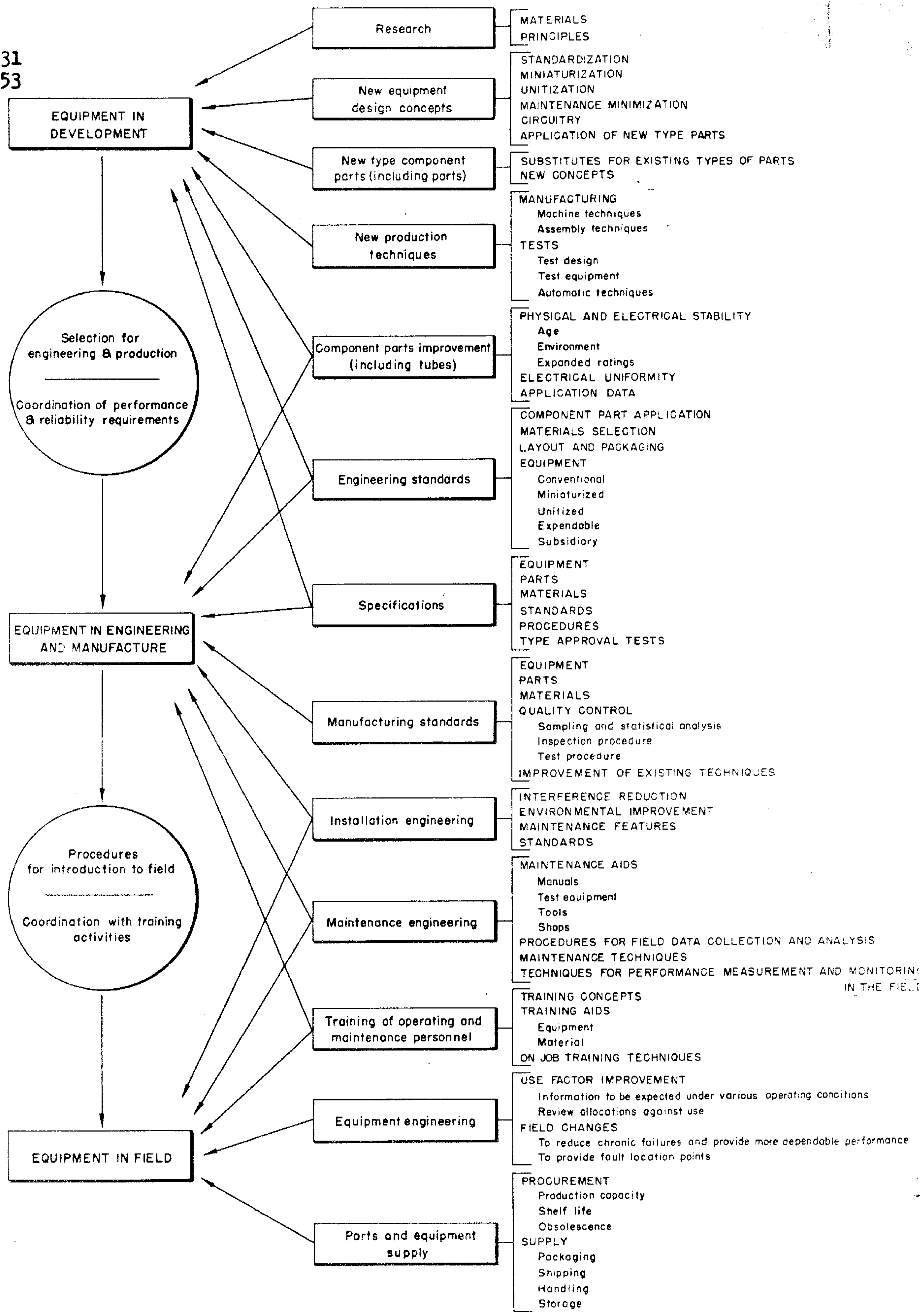

Fig. Ia — Electronic Equipment Reliability Program

Courtesy of
Vitro Corporation of America

(1) Determination of Requirements: Reliability requirements must be established for the system and its components. From the definition of reliability, this demands specification of the required performance limits, the operating time, and the environment, as well as the required reliability.

(2) Collection of Data: Reliability data on component and systems failures and their causes must be collected in statistically significant amounts.

(3) Analysis: The data must be analyzed to determine whether the requirements are met, to establish the most important areas and causes of failure, and to recommend methods of improvement.

(4) Improvement: Action must be taken to remove the most important defects and reduce the failure rate to the required level.

(5) Surveillance: A continuous and critical surveillance of the system must be carried out to ensure that the ''improvements'' actually reduce the failures, to anticipate and examine new and unsuspected sources of failures, and to review and modify requirements.

This concludes the background discussion of the problem, which may be summarized as follows.

1.8 Summary

The problem of achieving and maintaining an adequate reliability in military electronic equipment is important, complex and difficult. In the face of rapidly increasing complexity more reliable tubes and components are needed. In addition, better selection and application of parts are necessary in systems design. Simpler operation and maintenance must be achieved to ease the heavy requirements for skilled electronic personnel. Finally in both industry and the military more and better reliability information must be collected, analyzed, and made available if reliability efforts are to be properly directed toward effective improvements.

Reliability measures the overall effectiveness of present complex and costly weapon systems. Low reliability in electronic equipment is a challenge to the military services and the electronics industry. It can be met by bold and intensive engineering and administrative effort. The solution to the problem is inextricably bound up with the healthy development of future electronics.

During the past few years several programs have attacked the electronic reliability problem. These efforts and the results to date will be summarized in the next four sections.

2. TUBE RELIABILITY

It is well known that about half the failures in military electronic systems are caused by tubes. Tubes as a class have a failure rate which is 20 or 30 times that of resistors or capacitors, which are the next most frequently failing parts. This high failure rate, the complexity of tube structure and function, the numerous types and classes of tubes, and the vast quantities of tubes used in military equipment all combine to make tube reliability one of the most crucial technical areas of the electronic reliability problem.

The immediate problem in tube reliability, however, is organizational, educational and economic rather than technical. It is not so much a question of what can be done to tubes to improve their reliability, but what can be afforded in terms of man hours and production capacity. So far, what has been done is to look critically at existing radio tubes and make an assessment of all the weak points in their design. Steps have then been taken to correct all these points at once. Although there are indications that this has been done with some success it is estimated that for ''reliable tubes'' it has reduced the total production capacity by half and increased the cost of individual tubes up to 10 times. Obviously it is important to gain an accurate idea of what really are the weak points in tubes and concentrate on these alone. This requires a statistical evaluation of tube failures in the field under actual military operating conditions. Such a program is now being carried out by Aeronautical Radio, Inc., and Cornell University and will be discussed shortly.

It has also been found that many of the ''tube failures'' are caused by poor circuit design and misapplication of tubes. These are system defects, not tube defects, and will be treated under system reliability in Section 4.

Tube defects arising in design and manufacture are the subject of numerous research and development projects in progress in the United States and England. Most of these efforts are concentrated on receiving tubes which are the **preponderant** class of tubes in military usage. In order to speed the research and development work, the Panel on Electron Tubes of the Research and Development Board has been given the responsibility of coordinating these projects and formulating a program which should ultimately result in greatly increased tube reliability. To aid the panel in its work, the three services, industry, and the British Military Service representatives have informed the panel as to past activity and current and future programs on electron tube reliability. These may be summarized as follows.

2.1 The Work of Aeronautical Radio, Inc. (ARINC)

Among the first people to face up seriously to the problem of tube reliability were the commercial airlines. About 500 tubes are used in the communication and navigation equipment of a DC-6 airliner and although some of these are in duplicate standby units the repair and maintenance problem using normal broadcast tubes is very serious. Accordingly in 1946 the airlines set up an organization called Aeronautical Radio, Inc. (ARINC) to collect and analyze defective tubes and return them to the tube manufacturer. As a result of these analyses certain tube types were improved by exercising extreme care in assembly, giving maximum attention to details, and checking each part as well as the complete assembly. All tubes were tested for shorts, continuity, shock, and transconductance. Samples were subjected to vibration, filament cycling, and life test.

The specifications controlling the improved tubes lay down *what* end results are required, not how they should be achieved. Uniformity of performance is maintained by the distribution curve method rather than by a set of limits (Refs. 11, 12, 13). While JAN limits are used to determine the maximum spread of acceptable value variation, the median of the distribution curve is allowed to vary only a small percent from ''bogie'' value. This results in more uniform tube characteristics because the sample distribution is controlled rather than individual tubes, and it emphasizes *lot* acceptance or rejection, rather than selection or culling.

In its four years of operation with the airlines, ARINC achieved notable success in improving the reliability of some ten tube types. The work was discontinued at the beginning of the Korean hostilities.

The ARINC program since 1950 has been focussed on military tube problems. Under a joint service contract failed tubes are collected at various military installations, together with reliability data on the failure or cause of removal, hours of use, etc. At Norfolk the study includes 11 ships in the Atlantic Fleet and 23 carrier-based and 10 land-based aircraft. At Cabaniss Field the work involves 200 ARC-27 UHF communication equipments in as many aircraft. Similar studies are underway for the Army at Fort Bliss Texas, and for the Air Force at Carswell Air Force Base, Texas. By March 1953, some 42,000 tubes were under surveillance, about 85 percent being standard JAN types; the remainder are the new ''reliable tubes'', both military and ARINC types (Ref. 10). Analysis of the returned tubes and the data is carried out at ARINC headquarters in Washington, D. C. This pinpoints the troublesome types of equipments, particular units and tube types or sockets giving difficulty, and unusual environmental conditions which may be involved. After ARINC has tabulated the data the tubes are sent to Cornell University (see below) and to the tube manufacturers for detailed laboratory examination.

By the end of 1952 over 25,000 tubes had been received by ARINC. Of these about 5000 were controlled tubes (installed by ARINC, kept under surveillance in the controlled tests, and having known operating times to failure or removal), and 20,000 were semi-controlled tubes (other than those in the controlled tests, with failure data but not operating times). The work has progressed to the point where statistical data has identified specific misapplications and tube defects (Ref. 10).

For example, 6AR6 tubes suffered more electrical and fewer mechanical failures than other tube types; 832A tubes suffered four times as many failures due to broken glass as the average of all other tubes in the semi-controlled tests; type 1641 tubes suffered a high percentage of failures due to fragile anode seal structure; and 6AG7, 6SN7GT, 6C4, and 12AU7 tubes showed considerable susceptibility to the formation of cathode interface impedance (''sleeping sickness''). An example of misapplication concerns two different equipments, both using two 1Z2 rectifier tubes. One equipment suffered a total of 25 1Z2 failures, whereas the other had none. Investigation showed that the manufacturer of the first equipment had failed to use the prescribed series impedance in the plate circuit of the tubes.

More general statistical results include the following:

(1) An analysis of 14,110 removed tubes in the semi-controlled tests shows the following breakdown of causes:

37 percent - Mechanical Failures (such as envelope defects, loose supports, defective filament or heater, and shorts).

27 percent - Electrical Failures (such as low mutual conductance and plate current).

36 percent - No Apparent Failure (by ARINC tests).

(2) The analysis also indicates that tubes used in airborne equipments suffer about twice as many mechanical and only about half as many electrical failures as tubes used in fixed installations.

(3) Data from the controlled tests indicate that standard JAN tubes suffer a fairly constant failure rate of about 3 percent in the first five hundred hours, excluding the initial high failure rate. This applies to receiving tubes in shipboard and airborne equipment. Transmitting tubes have a higher failure rate.

(4) There is a high early failure rate ranging from 5 to 15 percent in the first 20 hours for airborne tubes. For fixed installations and shipboard equipment this ''infant mortality'' rate is considerably lower.

(5) Based on limited data, the failure rate of the new improved tube types appears to be only about half that of the JAN tubes.

To summarize, the ARINC work has two goals, evaluation and improvement. It is virtually the only program to obtain good data (including operating time before failure) on military electronic equipment in the field. Indeed, the evaluation of the actual reliability of the many current ''improved'' and ''reliable'' tube types is one of the most important aspects of the program, for in no other way can it be shown that these new tubes are significantly improving electronic reliability. While results to date are encouraging for certain tube types, more data are needed to assess the improved reliability which it is hoped that the new tubes will provide.

2.2 The Cornell Tube Program

The Armed Services have long realized that an accurate knowledge of the causes of the tube failures in their equipment is essential to the success of any effective reliability program. So far the modifications that have been made to standard receiving tubes in an attempt to make them more reliable have been based on the experience of the tube manufacturers, who have made a rather intuitive assessment of the weak points in a vacuum tube. This has probably led to more improvements being made than are strictly necessary so that the cost of the tubes is higher than it need be. The only way to correct this is to have accurate knowledge of the causes of failure in service.

Accordingly, a Signal Corps contract has been placed with the Engineering Faculty of Cornell University to make a detailed analysis of as many of the service failures as it proves practicable to collect. It has been realized that it is futile to rely on the services themselves returning failed tubes; consequently ARINC has been put under contract to collect failed tubes and forward them to Cornell. To aid in the failure analysis, the field data and test results are recorded on punch cards for automatic sorting.

The results of the analysis are presented to the tube manufacturers. Each company receives the full analysis of failures for all makes; to protect proprietary interests other manufacturers' tubes are not identified.

By the end of 1952 some 12,000 tubes had been received by Cornell. These tubes had been manufactured over a seven year period by nine tube companies. Despite this some definite results were reached for seven tube types (6AG7, 6AK5, 6AR6, 6C4, 6J6, 6SN7GT and 12AU7). In general it was found that miniature types are prone to glass troubles, that close-spaced tubes have excessive shorts, and that life-deterioration is serious on all seven types.

2.3 The Minnesota Tube Study

A survey of electron tube problems was made during 1951 by a group of engineers and physicists of the University of Minnesota. The work was done under the Navy for the purpose of formulating recommendations for research and development programs leading to greater tube reliability.* The final report issued 31 December 1951 recommended four broad programs for both immediate and long-range improvements in tube reliability:

(1) Improvement of reliability of present-day tubes as used in current military applications by obtaining realistic environmental data, by determining the

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*Contract N8onr-66211

limiting environmental conditions, particularly mechanical, in which current tubes can live, and by developing a procedure for pre-service testing of early mechanical failures.

(2) Improvement of selection and application of tubes by establishing a central agency to disseminate complete information on tube characteristics and environmental conditions to both the designers and the users of electron tubes and electronic systems; by establishing Reliability Boards in each of the military services with authority over the final development and manufacture of systems; and by requiring that acceptance of systems be based on approval trials under service conditions.

(3) Mechanical improvement of tubes by study and investigation of tube structures, by experimental use and study of new materials such as synthetic mica and ceramics, by modification of present designs, and by better processing through more control of production environment.

(4) Improvement in non-mechanical factors through basic research on oxide-coated cathodes and new thermionic emitters; coordination and guidance of applied research; and intensified work on such items as vacuum melted nickels, cathode poisoning, substitutes for coated cathodes and wire heaters, and saturation emission.

Throughout the report particular emphasis is laid on the need for better mechanical design of tubes, an improvement which must be based on a more coordinated and realistic knowledge of field conditions.

2.4 The Military Tube Program

The present Army-Navy-Air Force programs to improve tube reliability cover the following areas:

Procurement of Improved Tubes
Collection and Analysis of Field Data on Tubes
Tube Application Engineering
New Tube Design and Development
Tubes for Guided Missiles

These activities will now be discussed briefly.

Procurement of Improved Tubes

The severe shock and vibration accompanying gunfire caused many tube failures in naval fire control radars during World War II and in 1944 the Navy began a program to obtain more rugged tubes. Shock and vibration equipment was developed to aid in the testing, and structural modifications were made in standard tube types to increase their resistance to shock. As a result of this program, the Navy ''Ruggedized'' W-Series tubes were evolved, covering some 40 tube types.

A second line of improved ''ARINC Series Tubes'' has been developed as a result of the ARINC studies. These tubes embody minor structural modifications and are produced under more rigorous test and inspection procedures. The ARINC line includes some 16 tube types, which, in most cases, are plug-in replacements for existing types.

A third line of tubes, the Air Force ''A-Series'' includes some 12 tube types which are being modified along the same lines as the ARINC tubes but will not necessarily meet ARINC specifications.

Finally, there are a number of ''reliable'' subminature tube types which have been developed by the various tube manufacturers. These are modified or new designs following conventional lines and are produced under more controlled conditions and subjected to additional tests.

It is apparent that there is a need for a consolidation of service requirements and specifications for reliable tubes. Such a program has been initiated by the three services and the Panel on Electron Tubes, the new line of tubes to be known as ''Military Control'' tubes instead of ''reliable'' tubes. The new specifications will include additional tests and inspections to decrease early sudden failures, to define more clearly the life operating characteristics of the tubes, and to provide circuit designers with more data on performance capabilities and limitations of tubes as a step toward more reliable equipment.

Collection and Analysis of Field Data on Tubes

A tube surveillance program is being carried out by ARINC under a joint service contract, as has already been discussed above in the ARINC section.

Tube Application Engineering

Good tube application involves selecting the best tube for the purpose, designing the circuit so that the tube operating characteristics lie in the proper ranges and include a safety margin, and packaging and mounting the tube to protect it from severe external environments. To achieve these aims, tube application engineers from the tube industry are investigating service electronic equipments in production plants and in the field, including guided missiles, and consulting with designers on new equipment. This program is being carried out by the Coordinating Group on Tube Reliability under the Panel on Electron Tubes, in collaboration with tube manufacturers; by the end of 1952 it involved some 139 field engineers in 123 assignments. It is also planned to issue a series of tube usage bulletins, of which the first has already appeared (Ref. 14).

New Tube Design and Development

The development of new and perhaps radical tube designs is necessary to achieve a much higher order of reliability than can be obtained with conventional tube design. One part of the improvement program concerns the redesign of present tube structures to obtain much higher resistance to shock and vibration. In addition, the use of ceramic spacers is being explored as a replacement for the present mica spacers, which decompose and lose their structural strength when heated and have a tendency to flake and wear under vibration or uneven cathode heating. The glass used in tube envelopes is also unsatisfactory because of its fragility, susceptibility to electrolysis, lack of dimensional control in its manufacture, the limits it imposes on holding dimensions during sealing and on outgassing during tube processing. To improve these defects the use of ceramic envelopes is being investigated. Closely related to these design and material improvements is the use of better processing of tubes by controlling the temperature, humidity and lint conditions, and by better techniques of sealing and degassing.

Longer term work is centered on design of tubes for stacked assembly in highly automatic factories. The type of construction proposed is similar to that of the planar microwave triodes, i.e., various electrodes are mounted on disks separated by ceramic spacers. This development is aimed at speeding the production of high quality tubes and minimizing the variability introduced by human operators.

Tubes for Guided Missiles

The particularly stringent reliability requirements on tubes in guided missiles have been recognized for some time. To meet this problem the Navy has tightened specifications and included additional requirements for the improved tubes now being procured for missiles. In addition, the ARINC tube program has recently been extended to include tube surveillance projects for certain missiles. Finally, two symposia on tube applications in guided missiles were held in 1951 under the sponsorship of the Research and Development Board, and the papers, given by prominent applications engineers, were published and widely distributed by the Panel on Electron Tubes (Ref. 15).

2.5 The British Tube Program

The British program to obtain reliable electron tubes has been quite similar to the American program and differs mainly in emphasis. It is divided into four phases:

(1) Improvement of Current Production Type Tubes Without Affecting Socket Interchangeability

This phase essentially is completed insofar as development work is concerned. It consisted of a ruggedization effort to enable commercial prototype tubes to meet stringent vibration and shock requirements.
Both the government laboratories and the tube industry are agreed that vibration testing is the best yardstick to measure mechanical quality. They believe that the higher the frequency of vibration the less time it takes to determine the quality of a tube. This is to say that tube deterioration is a function of vibration frequency and time at any acceleration level. They vibrate

reliable tubes for a total of 90 hours at a frequency of 170 cps. A large amount of vibration equipment is being built in the tube industry to vibrate at this frequency and at variable frequencies up to 1000 cps. At present the government and the industry are attempting to write these mechanical tests into their procurement specifications.

(2) Development of New Tubes to be Manufactured with Present Production Machinery and Techniques

Probably the most significant feature of this phase of the reliability effort is the development of a series of miniature tubes with flying leads (small diameter wire). The advantages claimed for this construction are (1) the elimination of troublesome sockets and a significant drop in contact resistance, (2) the reduction of glass problems due to mechanical stress caused by pin loading, and (3) the use of new equipment packaging techniques that simplify heat transfer problems. They also expect an improvement in maintenance practices by making it more difficult to remove tubes.

(3) Improvement of Long Life Tube Characteristics and Emission Capabilities

This phase basically is a research effort involving the investigation of new cathode materials and work on oxide coatings.

(4) Development of Tubes that can be Manufactured with a Degree of Reliability Giving Assurance of no More than 1/4 or 1/2 Percent Failures in the First 1000 Hours

This phase of work may be the most important of the over-all British reliability effort. To meet its objectives obviously will require a major advance in the science of tube manufacture. The British believe this can be accomplished only by the use of mechanized assembly operations. To this end they have designed a new type of tube structure and developed a semi-automatic assembly and processing scheme.

2.6 Tube Failure Rates in the Field

The failure pattern and the failure rate of tubes in military electronic equipment in the field will now be considered. There is only a small amount of field data available on tube reliability; on the other hand a considerable amount of life-test information has been collected by the various tube manufacturers during laboratory tests. These laboratory test data on tube failure and lives are of great importance in controlling production quality, establishing specifications and directing improvement efforts (e.g., see Refs. 16 and 17). Can it be used to predict field failure rates in tubes?

The answer is no; for assessing field reliability of electronic equipment, laboratory data on tube failures and life tests is of no direct use at present. There are three reasons for this: (1) The test conditions are not in general representative of field operating conditions; (2) The effects of good or bad application, known to be important, cannot be assessed; and (3) The effects of good or bad maintenance, also very important, cannot be taken into account. It is therefore necessary to turn to studies of field failures in tubes.

Statistical studies on the pattern of failures have been carried out on current equipment by Aeronautical Radio, Inc., and on some World War II radars and radios by the RAND Corporation (Ref. 18). Both of these studies indicate two conclusions for radio-radar type equipment.

(1) About half the equipment failures are caused by tube failures and

(2) Tube failures tend to occur randomly with operating time, independently of the age of the tubes or their accumulated operating time.

If the tubes are replaced as soon as they fail, the tube failure rate is constant and is the reciprocal of the average time between failures. If tube replacements are not made during the mission or required operating period, the fraction of unfailed sets (the reliability) declines exponentially with the operating time.

In both cases the statistical pattern of failures is described by the Exponential Law for Reliability. This law is discussed in Section 6.6, where it is shown to depend on one constant, the failure rate per survivor (or hazard). Thus the observed random pattern of tube failures requires that the fraction of surviving sets failing per hour at any operating time be constant. It follows that τ , the mean time to failure per tube, is also constant (since τ is the reciprocal of the failure rate per survivor) and it will be convenient to use τ in discussing field data.

Values for the mean time to failure for tubes in military electronic equipment have been reported over a wide range (Refs. 1, 10, 19). Low values for τ (corresponding to high failure rates and low reliability) of the order of 500 or 1000 hours have been found; on the other hand values of the order of 50,000 or 100,000 hours have been achieved for equipment in which an extreme effort was made to achieve reliability. It is seen that the extreme values of τ differ by a factor of 100, implying a corresponding factor of 100 in the values of the failure rates! The values of τ for most military equipments are estimated to range from about 2000 hours to about 20,000 hours.

Some of this variability is undoubtedly due to the current role of the electron tube as a ''reliability villain'', which results in spurious reports of tube failures. Tubes are also easy to remove, replace and blame even when they are not at fault; the ARINC results indicate that a third of the removed tubes are not defective. In addition, when the first component or tube fails (primary failure), one or two other tubes may suffer abnormal circuit conditions and fail also (secondary failures). This ''clustering'' further inflates the reported tube failure rate. ARINC has found that the exponential law holds for the primary tube failures but is obscured if the secondary failures are not eliminated.

There is some evidence that the failure rate increases in going from fixed land-based systems to shipboard to airborne equipment, presumably because the environmental severity tends to increase in that order. For example, the ARINC results of Section 2.1 indicate values of about 6000 hours per tube failure for aircraft sets (including 5 percent early failures) and about 16,000 hours for shipboard and fixed ground systems. The RAND analysis indicated values of about 7000 hours for ground based equipment and 4000 hours for airborne gear. Environmental severity is undoubtedly a factor in electronic reliability and may be of decisive importance in certain weapons, such as missiles, which are subjected to unusually stringent environmental conditions. These results will be used in Section 7.1 to reach some estimates of equipment reliability.

Environmental conditions are only one factor, however, and two other factors, application and maintenance, are also important. For example, field data indicate that even under similar environments the tube mean time to failure may vary by as much as a factor of <u>ten</u> from one type of equipment to another!

2.7 Summary

Some of the important conclusions regarding tube reliability may be summarized as follows:

(1) Tubes appear to be responsible for about half the failures in electronic equipment in the field, although this fraction may be as low as one-third and as high as two thirds.

(2) Tube failures occur randomly with equipment operating time; the mean time between tube failures for most military equipment is estimated to range from 2000 hours to 20,000 hours.

(3) Airborne tubes appear to suffer a somewhat higher failure rate than tubes in fixed ground and shipboard equipment. Higher early failure rates and more mechanical failures in airborne tubes suggest that airborne environments are more severe.

(4) In addition to environment, however, proper tube application and good maintenance practice are also important, as indicated by wide variations in tube failure rates from one equipment type to another under similar environmental conditions.

(5) Tube failures may be broadly classed as mechanical failures or electrical failures; both are important, with

mechanical failures dominating in airborne equipment and electrical failures dominating in fixed ground and shipboard gear.

(6) Limited data indicate that the new ''reliable'' and ''ruggedized'' tube types have a failure rate only about half that of standard JAN types.

In the next section the status of component reliability will be reviewed.

3. COMPONENT RELIABILITY

The problem of reliability in electronic components is much more important than has generally been assumed. From the fact that about half of the failures in electronic equipment are attributed to tubes it has been widely concluded that the tube reliability is the major problem. This is a dangerous half-truth; it is true that tubes, when compared with resistors or capacitors, have a very high failure rate. On the other hand tubes are only about one-tenth of the total parts, and it is clear that even if tubes were completely reliable, the failure rate of electronic equipment would only be halved, a small improvement in the present intolerable situation. Components as well as tubes must be made more reliable if we are to have reliable electronic equipment. In view of the many classes of components and the long period required to evolve improvements, the component reliability problem is indeed serious.

While component failures are serious in all types of electronic gear, they are particularly crucial in continuously-operating equipment such as a search radar. This is because the down-time required to locate and replace a component is much longer than for a tube. In shipboard equipment, for example, several hours are required for components as against 20 or 30 minutes for tubes. This means that 80 or 90 percent of equipment down-time is due to component failures. Judged on this basis, component failures are far more important than tube failures in many military missions. In addition, more maintenance hours are obviously required for component repairs, and far more skill is required to trouble shoot and repair components than to test and replace tubes. It is estimated that mechanical failures in components are responsible for 65 percent of the down-time in shipboard equipment.

Much current effort is being spent on ''improved components''. Useful summaries are contained in Refs. 3, 23, 42, and 43. These projects are concerned with improved performance or capability, with more stable operation, with operation under more severe environmental conditions, and with new materials and methods. These are all important aspects of the rapidly developing field of electronics and will result in new components and new applications. Yet it does not follow that these efforts will significantly improve component reliability. Very few of the current component projects are based on field data, either as to cause of failure or environmental conditions, and without this information it is unlikely that any large improvements will be made in component reliability.

The programs which <u>are</u> specifically aimed at improving component reliability are briefly summarized in the following paragraphs.

3.1 The Vitro Program

Under a Navy contract the Vitro Corporation has studied component failure rates in ship and shore electronic equipments. Tubes are excluded from the study. The results were reported in 1952 in Ref. 20, from which the material in this section has been drawn.

Some 30,000 fleet failure reports on 160,000 equipments during 1950 were analyzed together with data on the number of spares issued for repair and replacement. Table I lists the seven most frequently failing components, accounting for over 60 percent of the component failures and over 80 percent of the parts population. The total number of failures experienced by the 50 classes of components surveyed was about one million, representing an annual failure rate of about 5 percent. Roughly 20 percent of the failures were caused by mechanical damage, the rest by part instability and deterioration.

Table I indicates that resistors and capacitors account for 40 percent of the failures. These two components are also the most numerous and their annual failure rates are only about 3 percent of their population. Nevertheless, this low rate is apparently too high for parts representing two thirds of the total parts population.

Table II shows that two types of resistors and two types of capacitors, together with connectors, account for 44 percent of all component failures. Further breakdown of each component class by stock number is revealing. Each stock number represents a particular component, different in its size, characteristics, etc., from any other component. For example, there are 1209 different mica condensers. The breakdown is shown in Table III, with the upper portion of the table separated on the basis of stock number population and the lower portion on the failure rate.

TABLE I - COMPONENT CLASSES HAVING MOST FAILURES

	Percent of Total Number of Components	Percent of Total Component Failures	Annual Failure Rate (Percent)
Resistors	38.5	26.6	3.3
Capacitors	26.9	13.7	3.2
Connectors	3.2	11.0	16.3
Switches	4.8	5.2	5.2
Transformers, Chokes and Coils	7.3	3.8	2.5
Relays	0.7	0.8	5.8
Meters	0.6	0.8	6.0
	82.0	61.9	3.6
42 Other Components	18.0	38.1	10.1
	100.0	100.0	5.0

TABLE II - COMPONENT TYPES HAVING MOST FAILURES

	Percent of Total Number of Components	Percent of Total Component Failures	Annual Failure Rate (Percent)
Fixed (GU) Composition Resistors	31.3	17.0	2.6
Connectors	3.2	11.0	16.3
Fixed Paper Capacitors	8.5	5.9	3.2
Fixed Mica Capacitors	13.6	5.5	2.0
Fixed (GU) Wire Wound Resistors	2.9	4.6	7.6
	59.5	44.0	

TABLE III - MICA CAPACITOR FAILURES

Basis of Selection	No. of Stock Nos.	Percent of Mica Capacitor Population	Percent of Mica Capacitor Failures	Annual Failure Rate (Percent)
Population more than 15,000	27	61.5	15.6	0.4
Population between 1500 and 15,000	167	28.9	35.7	1.1
Population less than 1500	1015	9.6	48.7	8.5
	1209	100.0	100.0	2.0
High Failure Rates	205	0.7	33.0	95.4
Remainder	1004	99.3	67.0	1.3
	1209	100.0	100.0	2.0

The analysis shows that 1015 of the 1209 stock numbers are low population items, comprising less than 10 percent of the total mica capacitors; yet these account for almost half the failures. On the basis of failure rates, stock numbers providing less than 1 percent of the population have one-third of the failures associated with them. The report goes on to state:

''This characteristic of the lower-population items accounting for the greatest number of failures is evident throughout the data. Switches providing 2-1/2 percent of the switch population account for 38 percent of the switch failures; less than 1 percent of the fixed-ceramic capacitor population contributes approximately 30 percent of the failures associated with this type of capacitor.

''The proportion of stock numbers with insignificant individual populations poses a serious problem. Annual issues of twenty-five or less of a stock-numbered item are by no means rare. A very large number of stock numbers show issues of five or less per year. These parts, in many cases, are not special-purpose parts or parts peculiar in the true sense. They are commonly used types of parts, but with less commonly used physical configurations or electrical characteristics.

''The problem presented by this situation is primarily one of logistics, but there are also important implications involving equipment reliability. The higher failure rates appear among the lower-population items. There are also the problems of non-uniformity in small production runs, the difficulties of procurement, the awkwardness of quality assurance among a large and diversified group of parts and the slow stock turnover with its increased shelf-life effects. From the standpoint of maintenance there are problems of increased storage, aging, more serious consequences from loss or damage, and the possibility that repair may be delayed by the unavailability of the parts. Each of these problems may be small in itself, but combined they can provide an important contribution to lowered part quality and lowered equipment reliability.

''In addition to selecting the most suitable and stable part, good application practice implies the avoidance of parts peculiar and of unusual values or configurations of parts common. That this has not been done in the past is evident in a recent survey by the Navy Electronic Supply Office which found that 52.1 percent of all stock-numbered items appear in no more than one equipment model and that 73.8 percent of all stock-numbered items appear in no more than two equipment models.''

3.2 The Western Electric Study

During the last year a component reliability program has been carried out by the Bell Telephone Laboratories under a Navy contract with Western Electric Company. The work is patterned after the early ARINC tube program; failed components are returned from the field for engineering diagnosis of defects. Since the age or operating time to failure is not included, the component reliability cannot be determined. Nevertheless about 1000 failed components (mostly from radio and radar sets) and their associated field reports have been studied (Ref. 21) and a number of improvements have been recommended.

Resistors show the greatest number of failures, with capacitors, transformers, inductors, switches, indicating instruments and relays following in the order listed. These results are in rough agreement with the Vitro conclusions. Table IV shows the breakdown into the major sources of trouble.

TABLE IV - MAJOR SOURCES OF TROUBLE INVOLVING COMPONENTS

- 43 % - Engineering
  - 33 % - Electrical
    - 11 % - Circuit (s)[*]
    - 10 % - Design (c)
    - 12 % - Misapplication (s)
  - 10 % - Mechanical
    - 0 % - Design (c)
    - 5 % - Material (c)
    - 5 % - Parts (c)
- 30 % - Operations
  - 12 % - Conditions (s)
  - 10 % - Manhandling (p)
  - 8 % - Maintenance (p)
- 20 % - Manufacturing
  - 18 % - Work, Inspection, Control (c)
  - 2 % - Defective Raw Material (c)
- 7 % - Other Causes

It is seen that component defects account for 40 percent of the failures, system defects for 35 percent, and personnel for 18 percent. Thus, of the failures attributed to components, about

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[*] Note: (c) = component defect, (s) = system defect, (p) = personnel defect (see Section 1.6).

half are caused by faulty components and half by improper application and use of the components.

The Vitro and Western Electric studies are the major American efforts to improve component reliability. Before reviewing the British component work, the status of transistors will be summarized briefly.

3.3 Transistors

Transistors may be expected to play an important role in the reliability of future complex equipments. The transistor, in addition to its widely publicized advantages over tubes in power and size, also promises improved reliability. Its inherently simple rugged construction, absence of a cathode, and light weight all make it particularly resistant to shock and vibration and mechanical failures. Typical units have withstood accelerations up to 20,000 g and vibrations up to 1000 g at frequencies up to 5 kc per second, and estimates of the life run to the order of 50,000 to 100,000 hours. To obtain this life it is probable that hermetic sealing will be necessary to protect the transistor from humidity effects which can cause deterioration. There are severe limitations in the use of transistors in certain applications, however. Tubes appear to be superior at frequencies above 30 megacycles and transistor performance appears to deteriorate seriously at temperatures above 175°C. It has been estimated that about 40 percent of the stages in airborne electronic equipment could be transistorized, with a corresponding reduction in the failure rate and a saving of about 25 percent in size and weight (Ref. 22).

To summarize, it appears first, that much critical equipment now in the field or in advanced stages of development will continue to require electron tubes; second, that transistors are limited to certain applications under certain conditions and can replace perhaps half or two-thirds but not all of the tube functions; third, that several years will be required to develop and field test new circuits for transistors; and finally, that tubes and transistors should both be developed for reliability, letting the natural process of selection determine the applications and the degree to which each device should be used.

3.4 The British Component Program

British experience in the European and Pacific theatres of the last war showed that the engineering design of radar systems was unsatisfactory under arduous service conditions and extremes of climate. After the war a comprehensive inter-service program to improve the engineering design of radar systems was instituted at the Telecommunications Research Establishment (TRE), one of the larger British research and development laboratories (Refs. 23, 24, 25). This program may be summarized as follows:

(1) Develop an equipment testing method which gives a correlation between test results and life of equipment under service conditions.

(2) By means of this test program, find the weak points in components and construction.

(3) Develop new components demanded by new constructional techniques and by weaknesses shown up in the test program.

(4) Develop new constructional techniques to take advantage of new components and to rectify difficulties brought to light by equipment tests and field performance.

The philosophy of this program is to use field data to set up simulated but realistic environmental and usage tests for electronic equipment, and to base reliability analysis and improvement on the results of these tests. One reason for this approach is the belief that information on equipment failures sent in by operational groups is not reliable, in agreement with experience in this country. The major parts of the British work are as follows:

The Inter-Service Pan-Climatic Test Schedule K-114

The heart of the British component improvement program is the extensive K-114 schedule of tests to which prototype and production models are subjected. This schedule was drawn up in 1946 and includes conditions of high and low temperature, pressure, humidity, shock and vibrations, fungus and, in some cases, salt spray, dust, etc. The conditions of test are equivalent to the worst climatic and usage conditions that can be found in any part of the world and are not exaggerated.

Accelerated tests covering most conditions can be made in two weeks; the complete schedule requires about five weeks. By testing prototype models to this schedule, design and component modifications can be incorporated before final tooling is started.

Engineering Design Requirements

From field and laboratory experience TRE has suggested that certain design criteria should be considered in the early design stage of military electronic equipment. These factors, which are believed essential for reliable world-wide operation, are listed in order of priority as follows:

1. Adequate performance
2. Reliability
3. Capability of operation under world-wide conditions
4. Ease of servicing and maintenance
5. Light weight
6. Simplicity of controls
7. Adequate packaging

As the result of the K-114 tests a number of conclusions regarding these factors have been reached. These are described in some detail in Ref. 25 and involve sealing of equipment, pressurizing of airborne equipments, heat dissipation in sealed containers, accessibility for servicing, prevention of corrosion, and packaging to minimize transport damage.

Component Reliability

Statistical analysis of equipment failures under the K-114 test indicates that (1) 60 percent of the component faults were due to poor manufacture or the use of unsuitable materials;

(2) 35 percent were defects due to bad design or faulty application, such as electrical or thermal overloading; and (3) About 5 percent of the faults were fundamental, requiring research to establish the cause. Of the total failures occurring in these tests about 80 percent were caused by humidity, heat, and fungi, and about 20 percent were due to mechanical failure caused by shock and vibration. This has led TRE to conclude that hermetic sealing offers significant improvement in component reliability, although the technique also raises problems of dissipating heat in such sealed containers. The importance of hermetic sealing is strongly suggested by the results of a series of K-114 tests on twelve sets of equipment of which four were sealed and eight were left unsealed. There were only 8 faults in the sealed equipment as compared with 146 faults in the unsealed units.

New Components and Construction Techniques

Guided by the analysis of component and system reliability data from the K-114 tests and field data, TRE has carried out a broad program aimed at developing improved components and establishing new techniques of fabrication. Work has been done on metal film resistors, printed and potted circuits, miniature and subminiature sealed units, methods of heat dissipation, and many other developments (Ref. 26) aimed at the eventual automatic production of reliable subminiature electronic equipments capable of withstanding world-wide climatic and service conditions.

3.5 Summary

The problem of electronic component reliability may be summarized as follows:

(1) Probably a third to a half the failures in electronic equipment are caused by component defects.

(2) Of the failures attributed to components, about half are due to faulty components and half to improper application and use.

(3) In comparison with tubes and other causes of equipment failures, component failures impose the most serious drain on available maintenance capacity.

(4) The major cause of component unreliability is instability and deterioration of performance; the secondary cause is mechanical damage.

(5) The electronic components causing the most equipment failures are resistors, capacitors and connectors. These components comprise two-thirds of the component population and account for more than half the component failures.

(6) There is a tendency for the more commonly used components to be more reliable. More specifically, a relatively small number of component types which are used in large numbers tend to have relatively low failure rates. On

the other hand a large number of component types are used quite infrequently and tend to have relatively high failure rates. Each group accounts for roughly half of the total component failures.

(7) In one service about 25 percent of the stock-numbered items (i.e., specific types of components) are used in three or more equipment models; in other words, 75 percent of the listed component types are used in only one or two equipment models. These components which are used only rarely and in small numbers give rise to serious problems in production, supply, and maintenance, and one area for reliability improvement concerns the elimination of such ''parts peculiar'' wherever possible, and the use of standard parts.

This concludes the discussion of component reliability and leads to the problem of system reliability.

4. ELECTRONIC SYSTEM RELIABILITY

The ultimate goal in the overall problem of electronic reliability is to improve system reliability. Tube and component improvements are only a part of this goal, however, since there are major defects on the system level. These system troubles must also be located and removed. As with tubes and components, this improvement must be based on good field data, including both survey data to establish failure rates and cause-of-failure data to remove the specific defects.

Yet despite the need for system reliability data, only a fraction of the reliability effort has gone into this problem. Some data on system failures have been obtained in the course of the tube and component reliability programs. In addition, various types of equipments have been the subject of special reliability studies from time to time and may provide some reliability data (e.g. the airborne intercept radar reliability study of Ref. 1.) Considerable study has been made of war-time data on equipment failures and some rough failure rates have been established. Before discussing failure rates, however, current efforts aimed at improving reliability on the system level will be reviewed.

4.1 Factors in System Design and Maintenance

During the past several years various programs and activities have been initiated to improve system reliability and maintenance. Some of these developments are summarized in the following paragraphs.

Shock and Vibration Data

An extensive collection of information on shock and vibration conditions in trucks, trains, ships, aircraft, and missiles is contained in the Shock and Vibration Bulletins issued by the Research and Development Board. For other types of environments there appear to be no such collections of data, although thought is now being given by the military services to the compilation of ''environmental catalogs'' of available data on service conditions.

Controlled Environments

While shock and vibration are probably the most serious environmental factors in causing equipment failure there is no question but that temperature extremes, together with high humidity and low pressure, are also important, particularly for airborne equipment. Various methods of heat dissipation are being studied at Cornell Aeronautical Laboratory and at Ohio State University. (See Ref. 23 for a bibliography on heat transfer in electronic equipment.) Consideration is also being given to the possibility of using a closely controlled atmosphere of reduced temperature and humidity for major electronic units. Laboratory and field tests indicate that this will materially increase equipment reliability.

Electronic Systems Design Criteria Handbook

It has been emphasized that certain critical data needed for the improvement of electronic reliability do not exist. However, it is also true that large amounts of useful design and application data do exist but are not available to the tube, component and system engineers. A multitude of government and industrial programs are yielding quantities of technical information on the electronic arts. This information, if made available in useful form and kept up-to-date, holds many of the keys to improvement of reliability in military electronic equipment.

A Handbook combining engineering data from these various sources offers an ideal means for accomplishing this. A Handbook would also serve as a means for bringing together much other information pertinent to good equipment design. Data from specifications, preferred lists, etc., could be presented together with technical data in a coordinated manner. System information and requirements as to environmental conditions, packaging, storage, quality control, etc., could be presented in a unified manner with data on circuits, tubes and components.

A preliminary study of such a Handbook has been carried out in some detail by the Vitro Corporation (Ref. 28) for the Navy and is now under consideration.

It is believed that such a Handbook would be a major step towards better electronic reliability, in view of the present rapid growth in electronics technology, the large number of electronic engineers spread over a wide area, and the rapid turnover of engineers which makes the accumulation of sound design practice so difficult.

System Specifications

During the last year the general specifications for ship and shore electronics equipment have been rewritten to emphasize reliability. The specification stresses greater use of preferred and standard parts, reliable tubes, and the use of high quality materials. It also stresses simplicity in design, ease of installation and maintenance, and the use of test points for fault location and performance checks. The approval of console layouts, arrangement of operating controls, and other human engineering aspects is required prior to release for production. Temperature limits and test requirements have been revised. Particular care has been taken to make the requirements of this specification realistic, easily administered, and practical to enforce.

Simplification

Many military electronic equipments, when critically examined, are found to be unnecessarily complex. By pruning such equipment, reliability, producibility, maintainability and operability can often be increased. Two approaches can be taken: The first approach is to simplify the equipment under fixed requirements of performance, flexibility, etc. The second method is to modify the requirements so that simpler equipment will be acceptable. The two approaches often go together and are employed to varying degrees in the services.

To emphasize the need for simplicity and reliability the Navy has solicited proposals from electronic equipment manufacturers as to methods for design simplification. In several specific equipments significant reductions in weight, size and complexity have been achieved. In one system, for example, the number of adjustments was reduced from 22 to 8 as a result of a design and requirements review.

Contractural incentives to the manufacturer offer another means of simplification. Many present contractural procedures tend to penalize the manufacturer who simplifies his equipment. A complex electronic answer to a set of specifications is usually easier to develop than a simple answer. Twenty tubes with associated circuitry can be made to satisfy a group of functions more quickly than a simple circuit with ten tubes. With competitive bids for developmental work under fixed-price contracts with price at a minimum, there may be insufficient funds to develop and deliver anything but a complex equipment. A low-priced development contract can be the most costly in terms of production costs, low reliability, critical performance, and high maintenance. The problem of providing engineering incentives for reliable, simplified, mature equipment through contractural guarantees is under consideration. If the difficult economic and military factors can be satisfactorily resolved, this change in contract philosophy promises to improve equipment by rewarding quality as well as quantity.

Maintainability

Closely related to the concept of simplification is that of maintainability. During the past three years there have been several programs to study the problem of maintenance in electrical equipment.

One outstanding project, Maintenance-Minimization in Large Electronic Systems, has been carried out by the Stanford Research Institute under the Office of Naval Research (Ref. 29). The problem is to design electronic systems so that faults can be located and repairs or replacements made in the shortest time and with the least possible effort. The problem is one of great complexity and includes both human engineering and electronic design. Some of the hardware factors involved are reliability, accessibility, the use of test points, monitoring equipment, and unitized and replaceable subassemblies. New components and new construction techniques have been reviewed (Ref. 23) and utilized in the study. A prototype radar system using these new methods has been constructed and preliminary tests indicate that performance can be monitored to within 3 db and that time off-the-air for fault location and maintenance is decreased tenfold. The work has far-reaching implications of great importance to future design, production and use of military electronic equipment and to its reliability and maintainability in the field.

Another project, at the Bureau of Standards (Ref. 30), is concerned with the prediction of incipient tube and component failures as a means of improving reliability and maintenance. Using performance tests ''sick'' parts can thus be replaced before they ''die'' and cause a system failure. An experimental electronic ''failure predictor'' has been developed and tested on six 18-stage radio receivers which were subjected to 1000-hour accelerated aging tests (extreme temperature and voltage cycling). At regular intervals the receivers were checked with the predictor. It was found that 75 percent of all tube failures could be detected many hours before they actually caused equipment failure. This represented 90 percent of the slow deterioration-type tube failures. Data on component failures were insufficient to justify any conclusions as to their predictability.

4.2 Partial and Total Failures in Systems

Having considered improvement efforts, it remains to discuss system reliability and failure rates. Both partial and total failures will be considered.

Partial failures in electronic equipment result in degraded performance, whereas total failures result in equipment breakdown or abort. Both types of failure occur in military operations and the degree of degradation which can be accepted depends on each particular equipment in its operational context. The influence of slight degradation in performance is to diminish the system accuracy (e.g., in a navigation system) or decrease the performance capability (e.g., radar range).

Partial failures may be very serious:

a. A survey (Ref. 31) of ground, ship, and airborne radar sets during World War II showed that the performance of the average set tested was 15 db below the rated value for the radar, thus cutting the maximum range on aircraft in half. Some of the sets were as much as 40 db down, with maximum ranges cut to only 10 percent. This degradation appeared to be caused by component deterioration and by the lack of test equipment for routine performance checks by maintenance personnel.

b. Surveys of shipboard electronic equipment indicate that partial failures may greatly exceed total failures and are very dependent on the quality of maintenance. In 1950, for example, 33 percent of the equipment was operating properly, 56 percent was operating poorly, and 11 percent was inoperative. The ratios of operational: partial failure: total failure were thus 3:5:1.

A more detailed understanding of the extent and causes of partial failures in military electronic equipment can only be reached on the basis of good field data on system performance and reliability. Nevertheless it seems clear that partial failures constitute an important aspect of the electronic reliability problem.

Turning now to the question of total failures, what can be said about the failure rate of military electronic equipment in the field?

From a limited amount of direct data on field failures in tubes and equipments it appears that the following major conclusions can be drawn:

The Exponential Law

> The reliability of ground based, shipboard, and airborne radio-radar type electronic systems in the field tends to follow the Exponential Law:
>
> $$R = e^{-rt}$$
>
> in which the reliability (R) depends on the required operating time (t) and not on the age of the equipment. The failure rate (r) is proportional to the complexity of the system, and is constant for a given type of system under fixed conditions of maintenance and operation.

The reliability of radio-radar type equipment thus declines exponentially with the operating time and the complexity. The theory will be discussed in Sec. 6 and its application to electronic equipment will be considered in more detail in Sec. 7. The Exponential Law should be regarded as a reasonable working hypothesis to estimate the order of magnitude of the reliability of complex electronic systems. Much further study, based on good system and part failure data, is required before it can be used precisely or extended to other equipments (see Sec. 7.3).

This concludes the section on systems and it remains to discuss briefly the personnel and organizational factors in reliability.

5. PERSONNEL AND ORGANIZATION

It will be recalled from Sec. 1.6 that the term ''personnel'' was defined to include people who come into direct contact with the hardware, from production to field use, i.e., people who assemble, inspect, pack, ship, handle, install, operate and maintain electronic equipment. In any of these phases personnel failures may result in unoperational gear. As with the hardware factors, there are almost no quantitative data concerning these software or human factors in reliability: How many faults are caused by personnel, why they occur, and what can be done to remove the errors. The need for a survey of personnel reliability, particularly in maintenance, is pointed up by the large number of civilian technicians currently employed to maintain electronic equipment in the field.

Present efforts to improve the personnel factors in reliability include the provision of better manuals, the use of human engineering to improve operability, and the ''maintenance-minimization'' work already discussed (Sec. 4.1).

The remaining area of reliability is ''organization''. Organizational factors include all personnel and activities which affect electronic reliability but which are not themselves in direct contact with the hardware. These include system performance and reliability requirements, systems planning, administration of hardware development and procurement, specifications and contracts, procurement and training of personnel, collection and distribution of reliability information, and reliability reports or surveys. Figure (1a) relates these and other factors in a detailed breakdown of an electronic reliability program.

Both personnel and organization factors have been considered by three high-level reliability committees which will now be briefly described.

5.1 The Ad Hoc Group

A useful survey of the general problem of electronic reliability was carried out in 1951 by the Ad Hoc Group on Reliability of Electronic Equipment in the Research and Development Board (Ref. 2) and a number of recommendations were made. Many of the findings and conclusions of this group have already been considered in this paper.

5.2 The AGREE Group

The recently formed Advisory Group on the Reliability of Electronic Equipment (AGREE) in the Research and Development Board will continue some of the functions of the old Ad Hoc Group. Its mission is to examine all phases of electronic reliability, stimulate interest in reliability programs, and make recommendations to civilian and government agencies concerning methods of improving reliability and education in reliability matters.

5.3 The CEAR Group

The third group is the ''Committee on Electronic Applications

(Reliability)'', or CEAR, under the Radio-Television Manufacturers Association (Ref. 32), with members representing the major electronic companies. CEAR has three objectives: (a) to collect and disseminate reliability information; (b) to plan a reliability education program for design engineers; and (c) to cooperate with other government and industrial programs for the improvement of electronic reliability.

This section concludes the review of reliability activities and programs. Some of the quantitative results obtained will be used in applying the theory to be described in the following sections.

6. THEORY OF RELIABILITY

The concepts and elementary theory of reliability will be developed in this section without reference to any particular equipment. Reliability will first be treated as a probability of success with no explicit dependence on operating time. The statistical theory of reliability as a function of operating time will then be considered for wear-out failures and sudden or chance failures.

6.1 The Concept of Reliability

Reliability is essentially the probability of success. A man or machine is reliable to the degree that the actual performance or behavior satisfies the required performance or behavior. The following basic definition of reliability will therefore be adopted:

> The reliability of a given component or system is the probability that it will perform its required function under given conditions for a specified operating time.

The reliability of an item of equipment may therefore be thought of as the fraction of a large number of such equipments which perform properly for the time and environment specified.

As an example consider a vacuum tube. One of its performance parameters is the transconductance. Suppose that for successful tube performance the transconductance must lie within certain limits for a specified time. These performance limits, together with the required operating time, define the task. A tube whose transconductance lies within the task limits for the required time is successful; one whose transconductance falls outside the limits during performance fails.

The distribution of performances can be established by measuring the transconductance of a number of tubes. Most of the tubes will lie inside the task limits, initially. During the operating time, however, some will drift outside and the performance distribution function broadens. At the end of the operating period a certain fraction of the tubes will have a transconductance inside the task limits. This fraction is the probability that a tube will perform within the task limits during the operating period, and is numerically equal to the reliability.

Similar remarks hold for the remaining performance parameters. In general the performance distribution will thus include all the operating characteristics necessary to determine the state of the system for the purpose at hand, and in the same way the task will include all the performance limits, so that each performance parameter in the performance distribution is matched by performance limits in the task. The reliability of the system is then the probability that all the performance parameters lie within their task limits for the duration of the operating period.

It is important to note that the reliability depends not only on the spread of the system performances (which is affected by the environment) but also on the task and the operating time. In general the reliability of a system is decreased if the task limits are narrowed or the operating time is increased. The reliability also tends to be lowered if the performance spread is broadened, either through less quality control or through increased environmental severity (e.g., by high temperatures in the above case of the tube transconductance).

Several remarks are in order concerning the above definition of reliability. In the first place it is clear that reliability is a quantitative engineering factor of merit which can be evaluated by straightforward technical means, similar, for example to radar range. To evaluate reliability it is thus necessary to state quantitatively what criteria of success are being used in terms of required performance limits and operating time.

In the second place, the definition emphasizes the environmental conditions under which the system is functioning, since these conditions may affect the performance and hence the reliability. This environment may be external to the system or internal, in the sense that the operating system generates its own environment. In a missile, for example, the guidance system may suffer external shocks in launching and internal heat from its own power supply.

In the third place, the definition is general in that it can be applied to any situation. For example, the reliability of a radar system can be evaluated (a) under laboratory conditions, (b) in field service tests, (c) in storage, (d) in combat. The storage reliability, for example, would refer to the fraction of systems which did not deteriorate under given conditions for a specified storage period. Unless otherwise qualified, however, ''reliability'' as used in this paper will mean ''combat reliability'', and the ''reliability'' from other than combat situations (e.g., laboratory testing) must be investigated to establish its relevance to the combat reliability.

Finally, several alternative definitions of reliability have been used:

(1) Time-on-the-Air: Reliability$_a$ is that fraction of the total required operating time during which the system is operating satisfactorily.

(2) Average Success Rate: Reliability$_b$ is that fraction of the systems in use which operates satisfactorily over a given period of time. If the failure rate of a radar is 20 percent per year, for example, the reliability$_b$ is 80 percent.

(3) Mean-Life: Reliability$_c$ is the mean life[*] of the system under the given operating conditions.

Time-on-the-Air is a useful measure for continuously operating equipment, such as a search radar. Average Success Rate for a year, for example, is useful for scheduling replacements. In general, it is not the same as the basic definition, since it includes failures during maintenance, storage, standby, etc., in addition to combat operating time. The Mean-Life definition is useful only if the

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[*] See Section 7.3

pattern of failures is known (Ref. 16). For example, if two tube types have the same mean life, but different early failure rates, their reliabilities for short missions will be different.

Various numerical measures are thus available for reliability, provided the meaning of such terms as ''perform properly'', ''failure'', and ''on-the-air'' is made definite. It is clear that many equipments have virtually a continuum of possible performances, and the two-valued classification of such a spectrum into success and failure is often unrealistic and may bypass the important problem of partial failures or performance degradation as discussed in Sec. 4.2. For simplicity, however, the treatment in this paper will be limited to total failures.

6.2 System Reliability and Part Reliability

The relation between system reliability and part reliability is greatly simplified if it is assumed that the part reliabilities are independent. This assumption may be questioned in particular cases, and should not be accepted uncritically as generally valid. Assuming for the present discussion, however, that the part reliabilities are independent, and assuming that failure of any part will fail the equipment, the over-all equipment reliability (R) may be written as the product of the reliabilities of its parts:

$$R = p_1 \cdot p_2 \cdots p_m \tag{1}$$

Here $p_1, p_2, \ldots, p_m$ are the reliabilities of the m individual parts. An interesting special case arises when all parts have the same reliability ($p_1 = p_2 = \cdots = p_m$); then

<u>Series:</u> $$R = p^m \qquad (2)$$

Table V shows how the equipment reliability depends on the part reliability and the complexity (number of parts).* It is clear that the system reliability decreases exponentially as the complexity increases. This is shown in Fig. 2 for simple systems having up to 20 parts.

For more complex systems the part reliability must be very high if a reasonable system reliability is expected. In this case Eq. (2) may be approximated by

$$R = (1 - q)^m \sim 1 - mq \qquad (mq \ll 1) \qquad (3)$$

where $q = 1 - p$ is the probability of part failure. The relation is valid provided the part unreliability q is small compared to the reciprocal of the number of parts $(1/m)$. For example, if $q = 1/10,000$ is the part unreliability, a system of 1000 parts will have a reliability of about 90 percent, which is close to the value of 0.905 from Table V for $p = 0.9999$. Fig. 3 shows R as a function of q for some large values of m.

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*Complexity can be compared on this basis of number of parts only between two equipments which utilize similar parts. Of two equipments using different types of parts or which differ in design (e.g. a hydraulic system and an amplifier) such a simple comparison of course cannot be made.

TABLE V - EQUIPMENT RELIABILITY(R) AS A FUNCTION OF COMPLEXITY(m) AND PART RELIABILITY(p)

Number of Parts (m) in Series

Part Reliability (p)

R ↘	1	3	10	30	100	300	1000	3000	10,000
0.1	0.1	0.001	10^{-10}	10^{-30}	10^{-100}	10^{-300}	10^{-1000}	10^{-3000}	$10^{-10,000}$
.5	.5	.125	.001	9×10^{-10}	8×10^{-31}	5×10^{-91}	9×10^{-302}	8×10^{-904}	5×10^{-3011}
.7	.7	.343	.028	2×10^{-5}	3×10^{-16}	3×10^{-47}	10^{-155}	2×10^{-465}	10^{-1549}
.8	.8	.512	.107	.001	2×10^{-10}	8×10^{-30}	10^{-97}	2×10^{-291}	8×10^{-970}
.9	.9	.729	.349	.042	3×10^{-5}	2×10^{-14}	2×10^{-46}	5×10^{-138}	3×10^{-458}
.99	.99	.970	.904	.740	.366	.049	4×10^{-5}	8×10^{-14}	2×10^{-44}
.999	.999	.997	.990	.970	.905	.741	.368	.050	4.5×10^{-5}
.9999	.9999	.9997	.999	.997	.990	.970	.905	.741	.368
.99999	.99999	.99997	.9999	.9997	.999	.997	.990	.970	.905

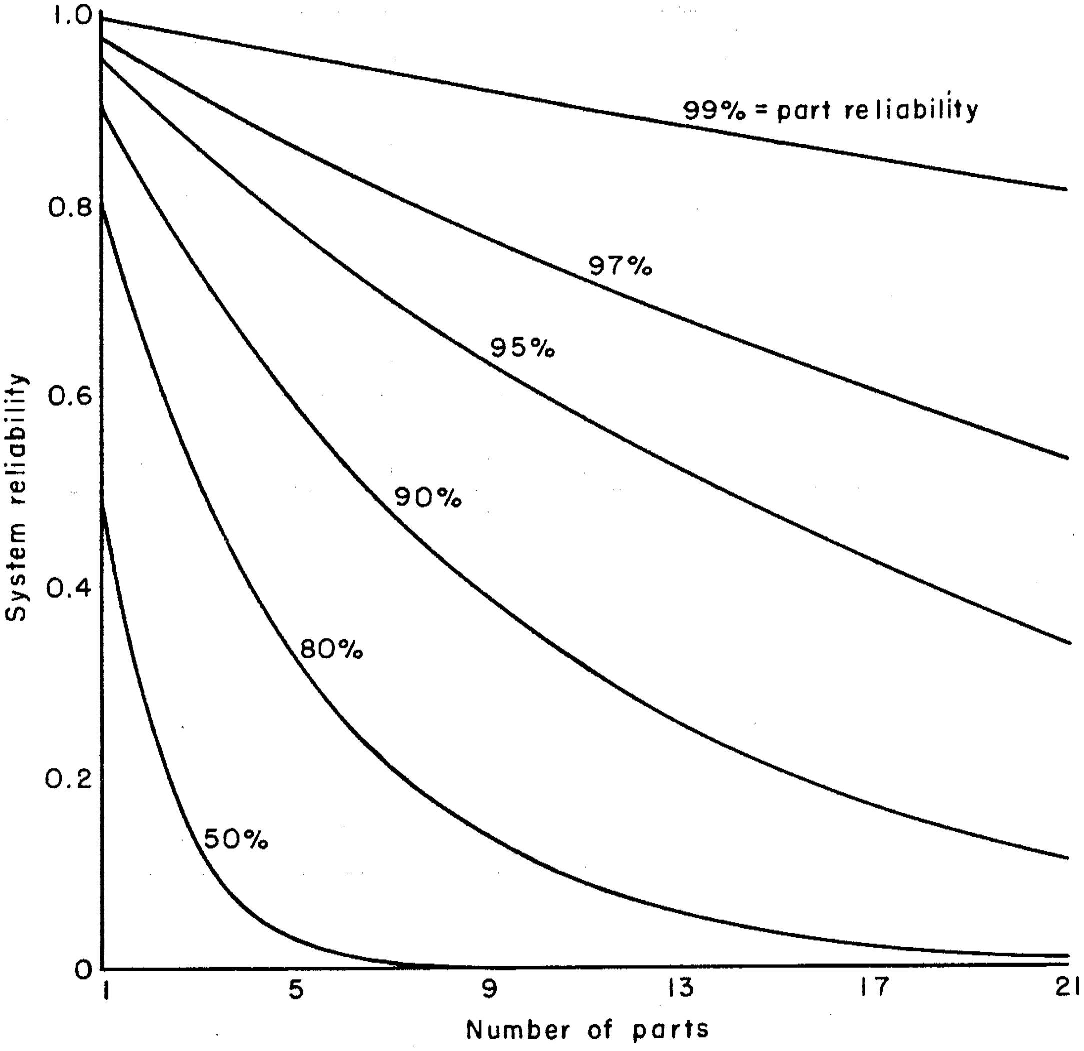

Fig. 2 — System reliability vs complexity

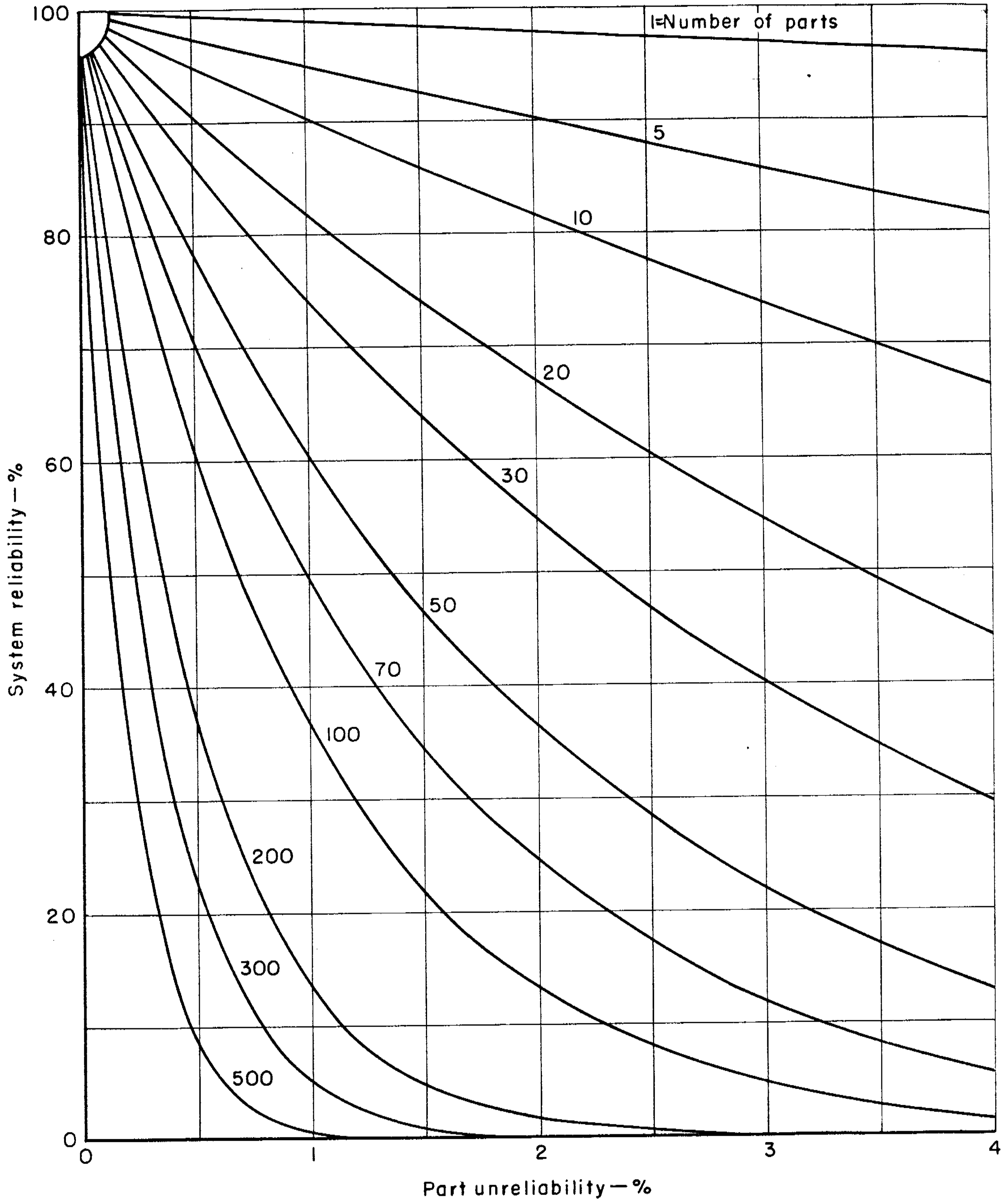

Fig. 3 — System reliability vs part unreliability

Both Eqs. (2) and (3) may also be used to discuss the dependence of the system reliability (R) on the mean part reliability p where $p = (p_1 \cdot p_2 \cdots p_m)^{1/m}$ is the geometric mean of the m different part reliabilities. Thus Eq. 3 indicates that for a system reliability of 90 percent the mean part unreliability $q = 1 - (p_1 \cdot p_2 \cdots p_m)^{1/m}$ must not exceed 1/10m.

Series and Parallel Systems

The above remarks were based on the supposition that the components are in series, in that failure of any part fails the equipment. If the parts are in series, then, the equipment reliability is the product of the part reliabilities, and the number of parts is a useful measure of complexity.

In analogy to an electrical network of resistors or capacitors, however, parts need not be functionally in series, but may be in parallel.

(a) Series (b) Parallel

FIGURE 4 - Series and Parallel Systems

For example (see Fig. 4), if current must be passed from A to B by means of relays, when the relays are in series both relays must close; but when they are in parallel only one of the relays must close. Letting p designate the reliability (probability of closing on command) of a single relay, the reliability of the series system is evidently $R = p^2$. For the parallel system, since both relays must fail to fail the system, the probability of failure of the system is $Q = 1 - R$ and is given by $Q = (1 - p)^2$, since the probability of failure of a single relay is $1 - p$. The reliability of the system is therefore $R = 1 - Q = 1 - (1 - p)^2$. In general, the reliability of a parallel system of m similar components is seen to be

<u>Parallel:</u> $$R = 1 - (1 - p)^m \tag{4}$$

To summarize: A series system is one in which failure of any part fails the system; it has a reliability

<u>Series:</u> $$R = p_1 \cdot p_2 \cdots p_m \tag{1}$$

which is the product of the part reliabilities. A parallel system is one in which all components must fail in order to fail the system. The unreliability of a parallel system,

<u>Parallel:</u> $$Q = q_1 \cdot q_2 \cdots q_m \tag{5}$$

is the product of the part unreliabilities, and its reliability is $R = 1 - Q$.

Equation (4) shows that the reliability of components in parallel increases markedly over that of a single component. (For a more detailed analysis see Ref. 33.) A few examples are given in Table VI and shown in the upper part of Fig. 5.

TABLE VI - RELIABILITY FOR A SYSTEM OF PARALLEL PARTS

Reliability of a Single Component	Reliability of Two Components in Parallel	Reliability of Three Components in Parallel
0.5	0.75	0.875
.7	.91	.973
.9	.99	.999

It is seen that with a part reliability of only 0.5, a redundancy of 6 results in a system reliability of about 0.98; similarly, Table VI shows that for three parts in parallel, each having a failure rate of 10 percent, the system fails only once in 1000 times, a remarkable increase in the reliability. Redundancy is thus a valuable design principle for obtaining high system reliability. Some remarks concerning its application to present and future electronics will be made in Section 7.4.

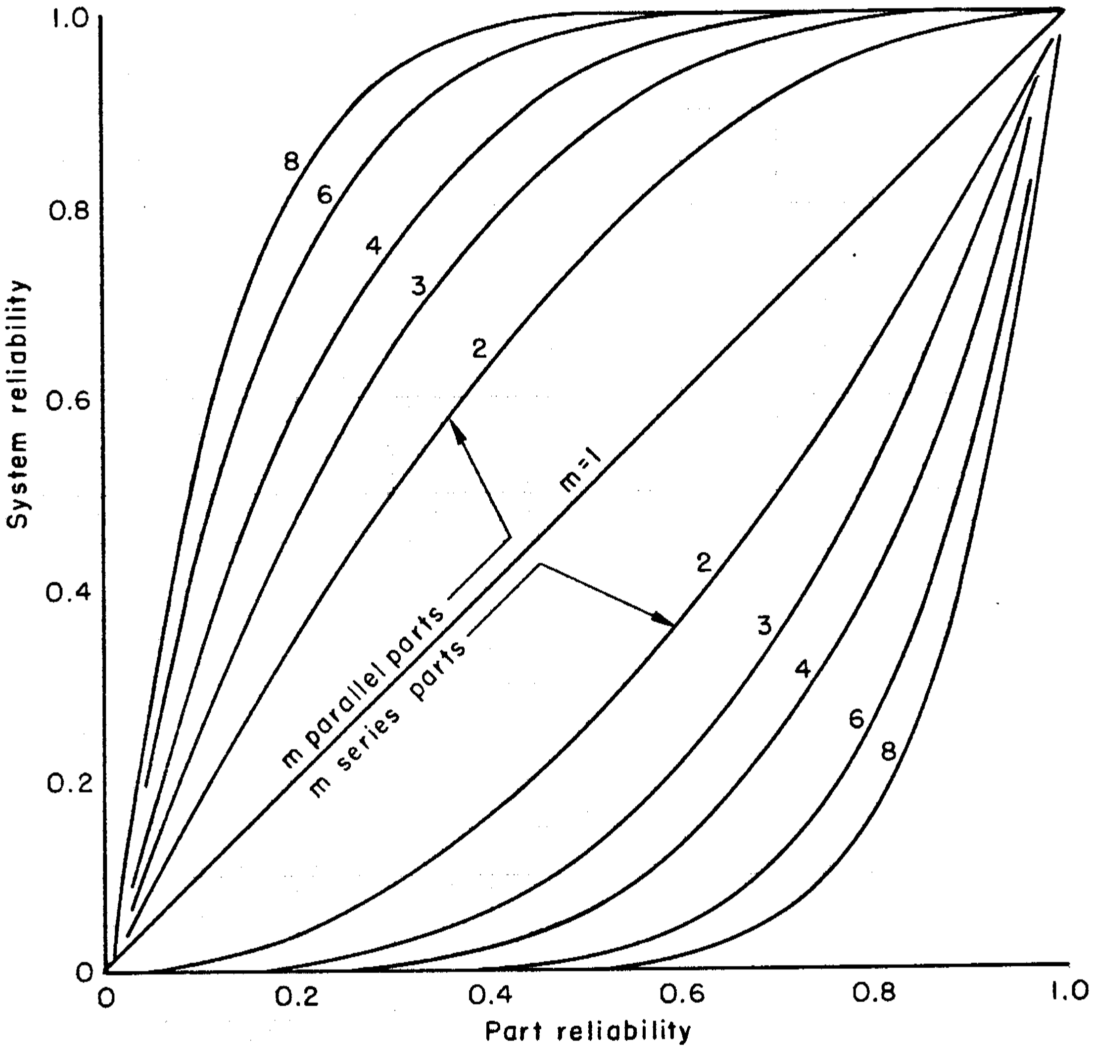

Fig. 5——Reliability of a system of m identical parts

6.3 Dependence of Reliability on Operating Time

It is a truism that the probability an equipment will fail in two hours of operation is greater than the probability it will fail in the first hour. Having thus established that reliability varies with operating time, we must consider how it varies. This question is of particular importance in evaluating or predicting the effectiveness of military electronic equipment.

Of a group of new radar sets put into continuous operation without replacement, it may be expected that some will be initially defective, due to manufacturing defects or damage in shipment or installation; an additional number will fail occasionally as time passes, from the normal rigors of the environment or from inherent weaknesses which were not apparent initially; and as operating time accumulates still further, the onset of old age will be accompanied by a more rapid rate of failure of the sets still remaining. This general description is useful for mechanisms as diverse as automobile tires and human beings.

Figure 6 shows such a failure pattern for some imaginary sets. The three curves show the reliability, failure rate, and hazard as functions of operating time. Each of these curves plays a role in understanding the failure pattern, as will now be explained.

Failure Rate

In Fig. 6 the failure rate curve shows the fraction of initial sets failing per hour as a function of the operating time. It

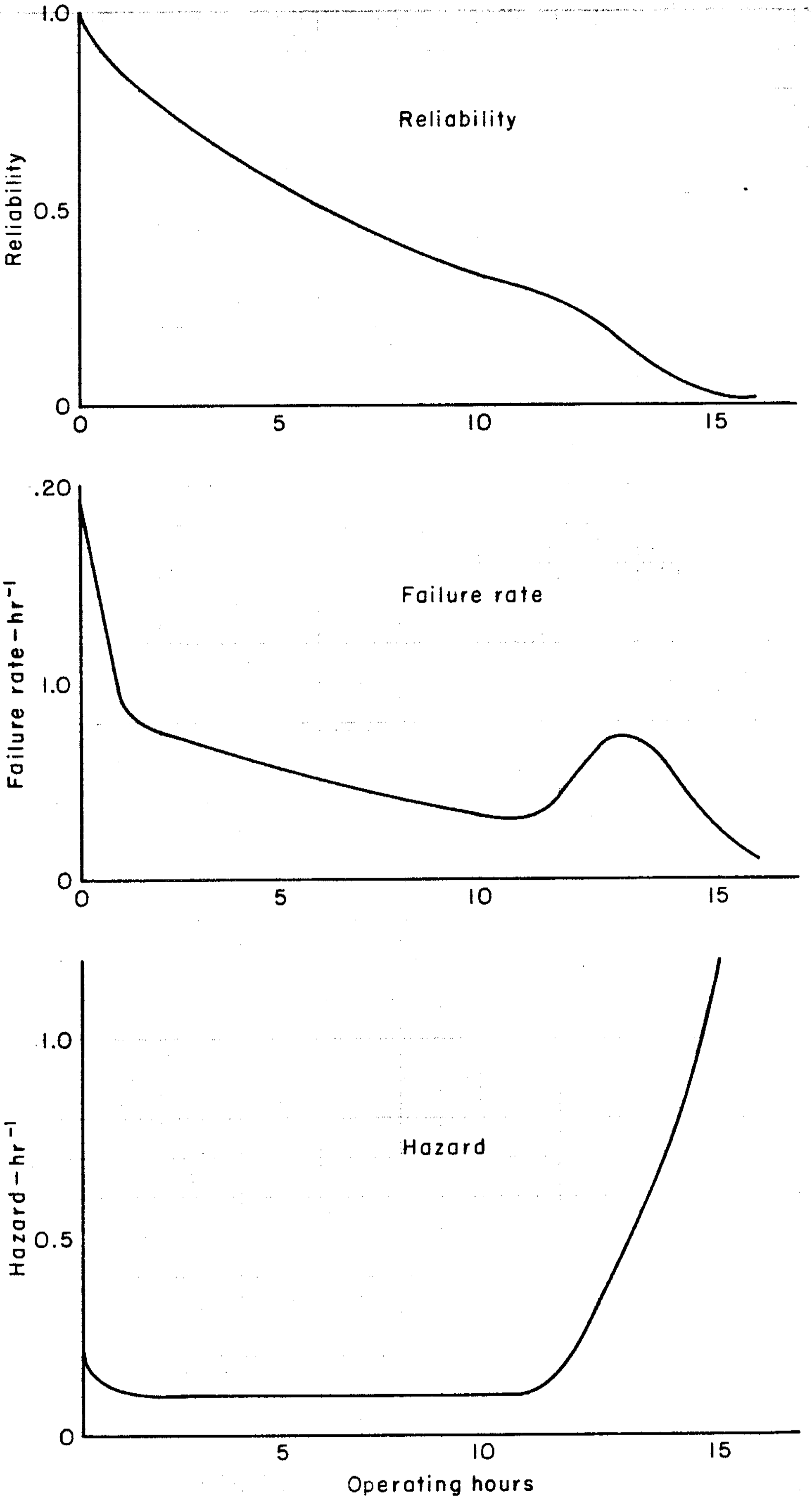

Fig. 6 — Theoretical failure curves

exhibits the typical high early failure rate (comparable to a high infant mortality), an intermediate region of low failure rate, and finally a hump in the failure rate (corresponding to the higher death rate in old age). The reliability curve for the sets is seen to drop rapidly during the first hour, then more gradually until 12 hours, when, with the onset of old age, it again declines more rapidly.

Hazard

The hazard curve shows the fraction of survivors failing per hour as a function of the operating time. It differs from the failure rate because it is based on the survivors and not on the starting population. Hazard is thus the probability of failure per hour for the survivors at a particular time, and is useful in answering such questions as ''What is the probability of breakdown in my 3-year old car?'' or ''What are the odds that a group of radar sets which have survived 6 hours of flight in an 8-hour mission will survive the next 2 hours?'' The hazard curve in Fig. 6 drops at first, corresponding to the rapid rate of initial failures; it then levels off at a constant value of 10 percent per hour, indicating that the probability of the survivors' failing in any one hour does not depend on how long they have operated; finally the hazard increases rapidly beyond 12 hours, as the effects of old age increase the probability of failure.

6.4 Statistical Theory of Reliability

A brief discussion of statistical reliability will be given in this section as a base for the quantitative results to be used later. A more detailed treatment is given in Ref. 18.

Table VII shows the failure data for Fig. 6, such as might be recorded from field observations. An initial group of $N = 1000$ sets is turned on at the beginning of the operation. The number of survivors $S(t)$ at operating time t hours starts at 1000 and drops to 855 at the end of the first hour, during which 145 sets failed. $F(t)$ is the total number of sets which have failed by time t; for example, it is seen that 995 sets have failed at 17 hours. Since the sum of the survivors and failures at any time is equal to the original number of sets,

$$S + F = N . \tag{6}$$

The reliability $R(t)$ is the fraction of survivors, and the unreliability $Q(t)$ or failure probability is the fraction of failures, so that

$$R(t) = S(t)/N, \qquad Q(t) = F(t)/N \tag{7}$$

and

$$R + Q = 1 . \tag{8}$$

The number of sets failing per hour is dF/dt (the absolute failure rate) and <u>the failure rate $Y(t)$ is the fraction of initial sets failing per hour</u>:

TABLE VII - FAILURE DATA FOR FIG. 6

t	S	F	R	Y	Z
0	1000	0	1.000	.200	.20
1	855	145	.855	.093	.11
2	769	231	.769	.077	.10
3	692	308	.692	.069	.10
4	623	377	.623	.062	.10
5	651	439	.561	.056	.10
6	505	495	.505	.051	.10
7	454	546	.454	.045	.10
8	409	591	.409	.041	.10
9	368	632	.368	.037	.10
10	331	669	.331	.033	.10
11	298	702	.298	.030	.10
12	263	737	.263	.042	.16
13	203	797	.203	.066	.33
14	128	872	.128	.073	.57
15	63	937	.063	.050	.80
16	21	979	.021	.026	1.23
17	5	995	.005	.010	

t = operating time in hours
S = number of survivors
F = cumulative number of failures
R = reliability
Y = failure rate
Z = hazard

$$Y = \frac{1}{N} \frac{dF}{dt} = \frac{dQ}{dt} = - \frac{dR}{dt} \qquad (9)$$

It is seen that the failure rate is the rate of increase in the probability of failure and the rate of decrease in the reliability.*

The hazard $Z(t)$ is the ratio of the number of failures per hour dF/dt to the number of survivors S at that time:

$$Z = \frac{1}{S} \frac{dF}{dt} \qquad (10)$$

and since $dF/dt = - dS/dt = - N\, dR/dt$ it follows that

$$Z = - \frac{1}{R} \frac{dR}{dt} . \qquad (11)$$

Integrating (11) gives an important general relation between the reliability and the hazard:

$$R = e^{-\int_0^t Z dt} \qquad (12)$$

Using (9) and (10) and $R = S/N$ a second important relation can be derived between the reliability, failure rate and hazard:

$$\boxed{Y = RZ} . \qquad (13)$$

6.5 Initial Failures

The example in Fig. 6 assumed that there were no failures when the sets were turned on, so that at the reliability was unity at time $t = 0$. In general, however, there will be failures at or near the

---

*The values of Y in Table VII were obtained from the slope of the reliability curve in Fig. 6; the values of Z were calculated from R and Y , using Eq. (13).

beginning of the operating period, and it is convenient to call these initial failures; more specifically,

> Initial failures are failures occurring at or near the beginning of the operating period, within a time interval small compared to the required operating time.

Thus, suppose that F_o initial failures occur in the initial population of N sets. Then the initial reliability can be written

$$R_o = 1 - F_o/N = 1 - Q_o \, , \tag{14}$$

Q_o being the initial unreliability, and the general expression (12) for the reliability becomes

$$\boxed{R = R_o \, e^{-\int_o^t Z \, dt}} \tag{15}$$

where R_o is the reliability at time $t = o$

6.6 Chance Failures and the Exponential Law

If the hazard is constant, say $Z = r$, and no replacements are made, then Eq. (15) gives the Exponential Law for Reliability:

$$\boxed{R = R_o \, e^{-rt} = R_o \, e^{-t/T}} \tag{16}$$

Thus the reliability declines exponentially with operating time. The quantity T is the mean time to failure and is the reciprocal of the hazard r . T has a double significance in reliability:

No Replacements: If no replacements are made Eq. (16) describes the reliability, and the mean time to failure is that operating time ($t = T$) at which the reliability has dropped to $1/e$ or 37 percent of its initial value.

Replacements: Consider a single set subject to constant hazard $Z = r = 1/T$. It has a constant probability of failure per hour of operating time and the probability that it will not fail in an operating time t (its reliability) is given by Eq. (16). If each failed part is replaced as soon as it fails, the failures will occur randomly in time at a constant rate; T, the mean time to set failure, is then the average time between these randomly occurring failures and r is the average failure rate per hour. (If a group of N such sets are considered instead of a single one, then the reliability for the group (probability of no failure in time t) is $R = R_o^N e^{-Nt/T}$, the average time between failures is T/N, and the rate of failure is N/T. Thus the failures in a group of N sets occur N times as frequently as those for a single set, as would be expected.)

Figure 7 shows the exponential law for sets having a constant hazard $z = r = 0.1 \text{ hr}^{-1}$, the same value as the flat portion of the hazard curve in Fig. 6. Thus 10 percent of the survivors fail

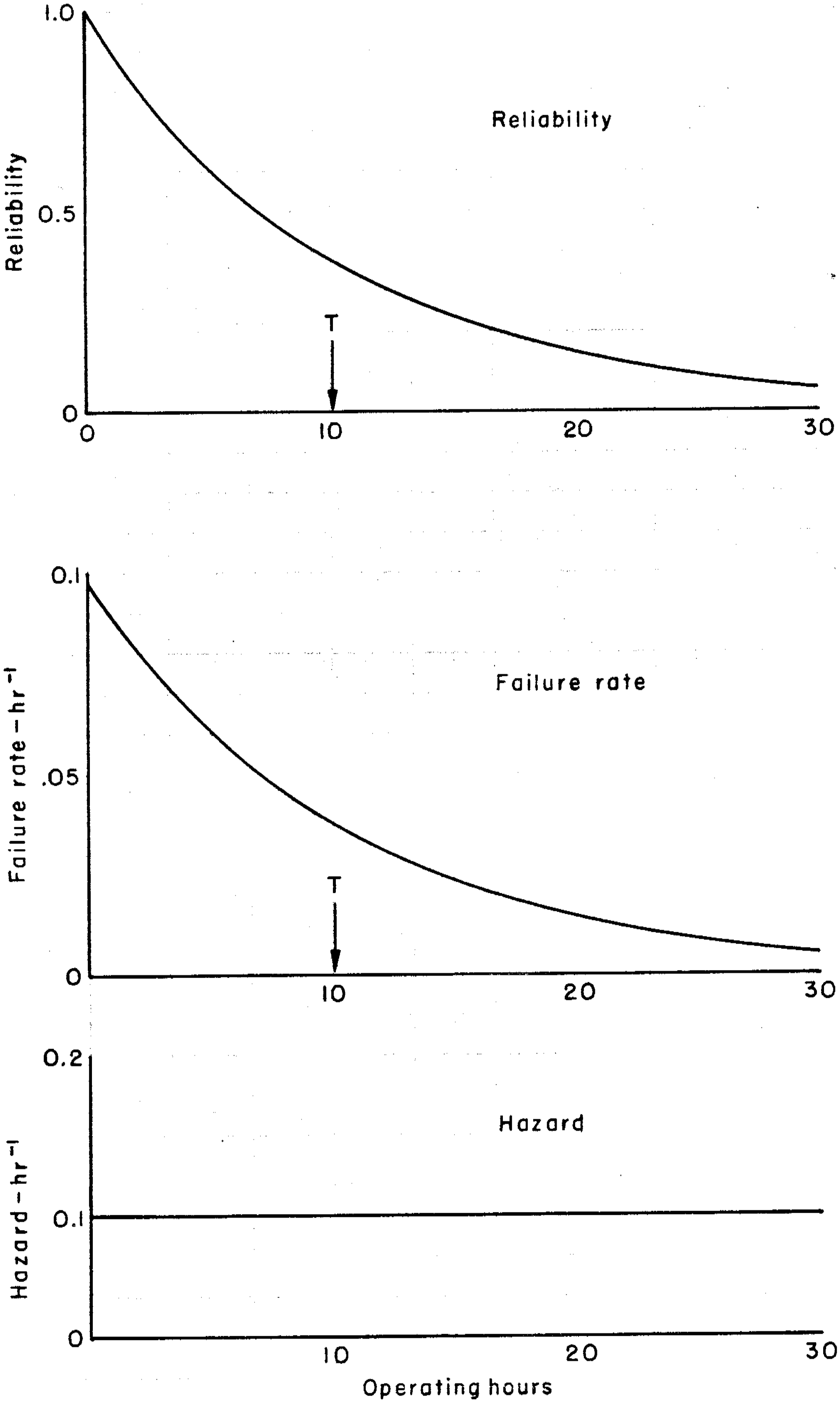

Fig. 7 — The Exponential law

in each hour, and the mean time to failure is $T = 10$ hours. For simplicity it is assumed that there are no initial failures ($R_o = 1$). The reliability

$$R = e^{-0.1t} = e^{-t/10} \tag{17}$$

and the failure rate

$$Y = 0.1e^{-0.1t} = 0.1e^{-t/10} \tag{18}$$

both decline exponentially and at $t = 10$ hours both have dropped to 37 percent of their initial values.

Chance Failures:

The exponential law describes the reliability of a population of elements in which the failures tend to occur randomly in time. The reliability of an exponentially-failing population depends only on the required operating time t and the constant hazard r and not on the ages of the elements. It is thus suited for describing failures which are ''accidental'' or ''random'' or ''chance'', such as punctures in tires, deaths from lighting, human errors in clerical work, and failures in tubes and other electronic components which may occur, for example, because of shocks in transport, handling or operation (Ref. 18). The term ''chance failure'' has therefore been used as a general term to describe such failures.

> Chance Failures: Those failures which are caused by random, accidental, unexpected, or unusually severe conditions arising during the operating period.

This definition thus concerns the physical causes of failure and the state of knowledge about these causes. It is admittedly vague but it is useful in describing certain failures qualitatively.

Now while it is clear that ''chance failures'' will follow the exponential law it is likewise true that *failures arising from any causes whatever will also follow the exponential law, provided only that the failures occur randomly during the operating time*. In particular, wear-out failures may follow the exponential law, as will be explained in Sec. 6.9 below. *The fact that the reliability of a group of mechanisims or humans follows the exponential law does not necessarily mean that the failures are unpredictable or unpreventable*; the random ''chance'' occurrence of traffic deaths certainly does not mean that accidents are inevitable!

Mathematical Basis for the Exponential Law

The exponential law is a special case of Poisson's Formula (Ref. 34). Let a set of events (failures) be distributed randomly in time, T being the mean time between failures. The average frequency of failures is thus $1/T$ failures per hour, and the expected number of failures (ϵ) in the time t is $\epsilon = t/T$. Poisson's Formula then states that the probability of m failures in the time t is

$$P_m = \frac{\epsilon^m}{m!} e^{-\epsilon} \tag{19}$$

From this it is seen that the probability of no failures $(m = 0)$ in the time t is given by the exponential law $R = e^{-\epsilon} = e^{-t/T}$.

6.7 Wear-Out Failures and the Gaussian Law

It is well known that many items such as shoes, tires, etc., wear out. In general,

> Wear-Out Failure refers to those cases in which no overt or abrupt failure has occurred but the item has more or less gradually reached the failed state through the deterioration or depletion of some quantity, structure, or function necessary for successful operation.

As in the case of chance failures, this is a qualitative definition; although it is vague it is useful for descriptive purposes.

Now it is a familiar fact that many wear-out failures can be described by the Gaussian Law of Reliability. If, for example, a group of new incandescent lamps are life-tested, it is found that their ages at death tend to cluster around a mean life time $\bar{t}$, half the failures occurring before and half afterward. There are few very early or very late failures, the failure rate being low initially and reaching a maximum at the mean lifetime. The hazard is very low initially, and rises rapidly after $\bar{t}$. This familiar pattern of failure can be described by the Gaussian Law or Normal Distribution in which the failure rate as a function of operating time t is given by

$$Y = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\bar{t}}{\sigma}\right)^2} . \qquad (20)$$

From Eq. (9) the unreliability $Q(t)$ is given by the time integral of the failure rate

$$Q(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^t e^{-\frac{1}{2}\left(\frac{x-\bar{t}}{\sigma}\right)^2} dx \, , \tag{21}$$

from the beginning $(t = 0)$ of the operation to its end at time t. $Q(t)$ can be evaluated from tables of the ''normal probability integral'' in many handbooks. The reliability as a function of operating time is then

$$R(t) = 1 - Q(t) \, . \tag{22}$$

In these expressions $\bar{t}$ is the mean lifetime and σ the standard deviation which determines the ''spread'' of the hump in the failure rate curve given by Eq. (20). The hazard curve $Z(t)$ can readily be computed from the general relation $Z = Y/R$.

An example of the Gaussian Law is shown in Fig. 8 for 100 imaginary short-lived flood lamps. The lamps show no failures during their early life, but as the average life $\bar{t} = 5$ hours is approached, the failure rate increases rapidly and reaches its maximum at $\bar{t}$. The failure rate then drops off again at longer operating times. The reliability is nearly unity for early times, drops to 50 percent at 5 hours, when half the lamps have failed, and then decreases very rapidly at later times. The hazard is zero initially and increases slowly to 0.8 failures per hour per survivor. Beyond $\bar{t}$ it increases almost linearly and reaches 5.2 hr^{-1} at 10 hours.

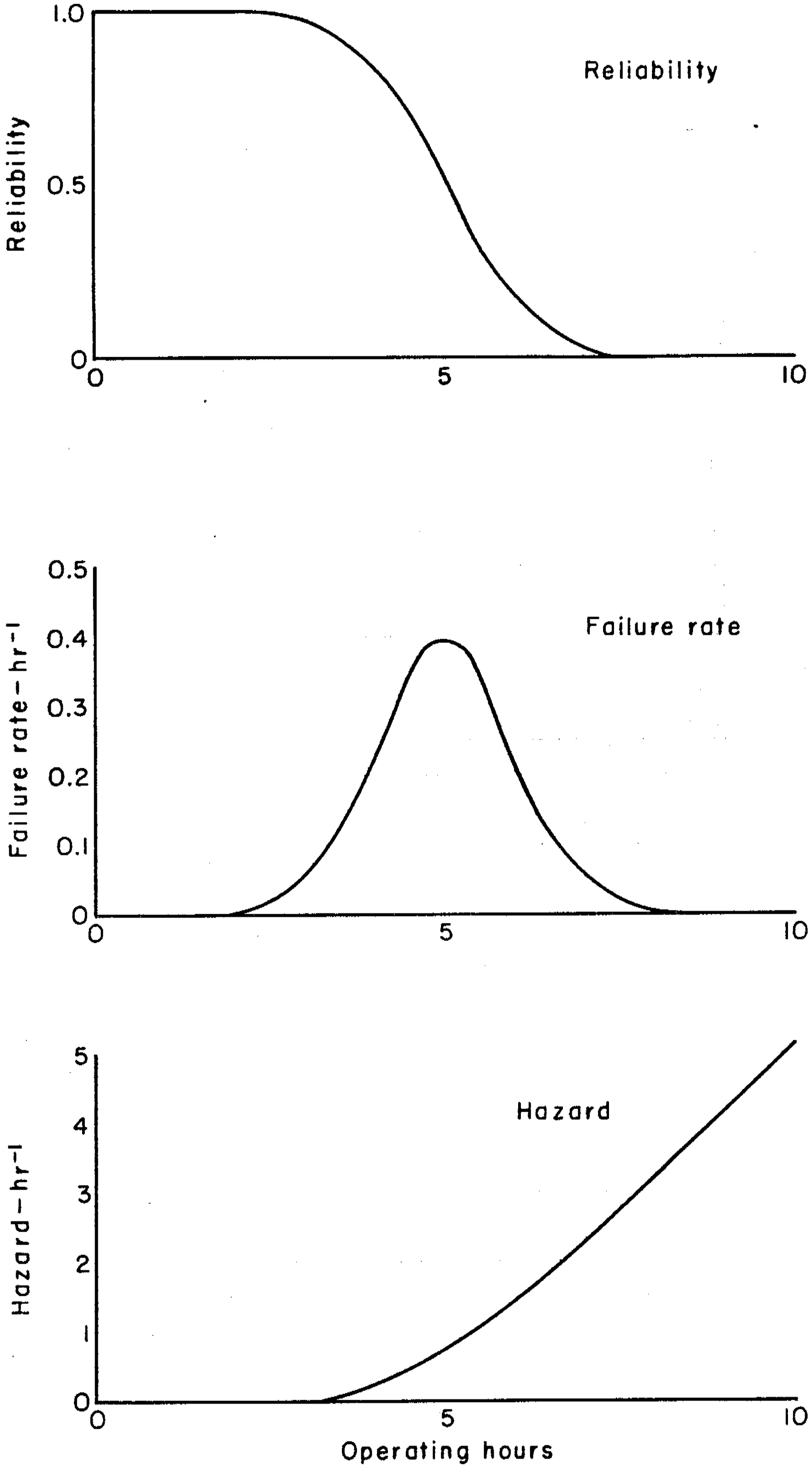

Fig. 8 — The Gaussian law

This increase in the hazard function with operating time emphasizes the fact that with wear-out failures the failure rate of the survivors depends strongly on how long they have operated, in sharp contrast to the exponential law.

6.8 Distinction Between Age and Operating Time

In the above discussions it was assumed, for simplicity, that the mechanisms were all new at the start of the operation (''mission'') for which their reliability was being assessed. This means that the age and the mission operating time were equal. For most actual military electronic equipment this is a grossly unrealistic assumption, since very few missions are made with new equipment. Even expendable missiles and torpedoes will usually have been tested or stored, often for considerable periods, and non-expendable equipment will have been used in previous missions as well.

Thus virtually all electronic equipment will have aged under various conditions of storage, testing, and previous use before it is employed in a given mission, and this past history may or may not influence the mission reliability.

To avoid confusion the following definitions will be adopted:

Age: A general term referring to accumulated time for a mechanism before it is used in a mission.

Calender Age: Calender time since a mechanism was new.

Operating Age: Accumulated or total operating time prior to the mission of interest.

Storage Age, Testing Age, etc., are similarly defined.

Corresponding to each age a mean life can be defined as the average at which pre-mission failure occurs. For example, certain tubes which die in storage may have a mean storage life of one year under certain storage conditions; or a hydraulic valve in a missile may have a mean testing life of eighteen hours. In electron tubes ''life'' usually refers to the mean testing age at which failure occurs under specified ''life-test'' conditions.

Turning now to the mission of interest, the time variable is the mission operating time for the mechanism (e.g., hours since take-off for an airborne search radar). The average operating time at which failures occur during the mission will be called the mean time to failure. For the exponential law characterizing random electronic failures, the mean time to failure is a significant measure of reliability as explained at the beginning of the previous section. Moreover, the fact that the mean time to failure for a given set is about the same, regardless of how often the set has been used in previous operations, means that the set mean time time to failure is independent of operating age. For certain equipments (e.g., missiles), however, the storage and testing age might affect the mean time to failure; this would occur if there were deterioration during storage so that the set were prone to fail soon after turning it on for the mission, or if the set were harmed by too severe testing before use.

To summarize: There are two times to be distinguished in discussing reliability in a population of electronic sets, the age of the sets before their use in a mission, and the operating time during the mission. Corresponding to the age there is a mean life or average age for failures occurring before the mission (in testing, storage, etc.), while during the mission the average operating time at which the sets fail is the mean time to failure. Having made these distinctions the way is now clear to discuss the reliability of a group of sets which have different histories and hence mixed ages.

6.9 Reliability for Populations Having Mixed Ages

In much military electronic equipment the population involved in a given mission of interest is composed of sets having mixed ages, the sets themselves having parts with mixed ages. Thus the usual statistical theories which describe the probability of failure as a function of age (e.g., tube failure vs tube age) are not directly applicable to the description or prediction of mission reliability, though such theories are important in understanding failure and improving reliability. For most military electronic equipment what is required is the reliability as a function of (mission) operating time for a population of sets having mixed ages.

In general, this problem leads to rather complex statistical theory. However, there are three simple results of particular importance to electronic reliability:

(1) A Population of Exponentially-Failing Sets:

If the sets are individually exponentially-failing, then, regardless of their ages, the population fails exponentially. The reason is simple: The probability of failure for the individual surviving sets (the hazard) is constant and independent of their ages; hence the mixing of ages has no effect on the probability of set failure at various operating times.

(2) Exponentially-Failing Parts in a Set:

If the set is composed of various parts, each failing exponentially, then the set also fails exponentially.

(3) Population of Arbitrary Elements with Constant Replacement Rate:

Consider a population in which the failed elements are replaced as soon as they fail. Eventually a steady-state situation will arise in which the failure rate and replacement rate are constant and equal to r . This means the probability of a failure in the population is a constant, independent of the age of the population as a whole. It follows that the occurrence of failure is described by the exponential law with the hazard r . This result holds regardless of whether the elements are the same or different or have wear-out or chance failures (see Ref. 40 for a rigorous proof).

This concludes the theoretical discussion of reliability which has been quite general. It remains to apply this theory specifically to electronic equipment.

7. APPLICATION OF RELIABILITY THEORY TO MILITARY ELECTRONIC EQUIPMENT

The theory of the preceding section will be applied to military electronic equipment in Sec. 7.1 and some examples given. In Sec. 7.2 the evaluation of reliability from field failure data will be treated briefly, and in Sec. 7.3 the validity and usefulness of the exponential law for reliability will be discussed critically.

7.1 The Exponential Law for Electronic Equipment

In order to apply the exponential law to electronic equipment a very simple model will be used in which all the parts individually fail exponentially. Thus suppose the set consists of m parts (tubes, resistors, capacitors, etc.) which have constant hazards (or survivor failure rates) $r_1, r_2, \ldots r_m$. The reliability of the m parts for an operating period t will then be

$$R_1 = e^{-r_1 t} , \quad R_2 = e^{-r_2 t} , \ldots R_m = e^{-r_m t} , \tag{23}$$

in which for simplicity there are assumed to be no initial failures. In addition it will be assumed that the reliabilities are independent and that the parts are in series so that failure of any one fails the set. Then the set reliability R will be the product of the part reliabilities:

$$R = R_1 \cdot R_2 \cdots R_m \tag{24}$$

or

$$R = e^{-rt} \tag{25}$$

where

$$r = r_1 + r_2 + \dots + r_m \tag{26}$$

is the set hazard. Thus the set hazard is the sum of the part hazards.

Since the part hazards are not usually known, it is convenient to simplify Eq. (26) by grouping the m parts into n tubes and c components:

$$m = n + c \; . \tag{27}$$

Now the <u>average tube hazard</u> r_n is given by

$$r_n = \frac{1}{n} \text{ (Sum of the } n \text{ tube-hazards)} \tag{28}$$

and similarly the <u>average component hazard r_c</u> is

$$r_c = \frac{1}{c} \text{ (Sum of the } c \text{ component hazards)} \tag{29}$$

so that the set hazard in Eq. (26) can be written

$$r = nr_n + cr_c \; . \tag{30}$$

and the set reliability is then

$$\boxed{R = e^{-(nr_n + cr_c)\,t}} \tag{31}$$

This is the general form of the exponential law for the reliability of electronic equipment for an operating time of t hours, in terms of the number of tubes (n) and components (c) and the average tube hazard (r_n) and component hazard (r_c) .

As an example, consider the field data on some airborne radar sets (Ref. 1), in which the average tube and component failure rates were

$$r_n = 0.0007 \text{ hr}^{-1}, \quad r_c = 0.0002 \text{ hr}^{-1} \tag{32}$$

corresponding to mean times to failure of about 1400 hours for tubes and 5000 hours for components. For the purposes of calculation let the number of tubes and components be

$$n = 100, \quad c = 1000$$

as in the example of Ref. 1. These numbers when substituted in Eq. (31), give

$$R = e^{-0.27t} \tag{33}$$

for the set reliability as a function of operating time, a plot of which is shown in Fig. 9. It is seen that the reliability is 76 percent at 1 hour and 58 percent at 2 hours. The second curve in Fig. 9 shows the reliability for a set with twice the complexity ($n = 200$, $c = 2000$):

$$R = e^{-0.54t} \tag{34}$$

For the more complex set the reliability is 58 percent for a one-hour mission and only 34 percent for a two-hour mission.

It is useful to simplify Eq. (31) still further by eliminating the component terms cr_c. Let α be the ratio of tubes to components,

$$\alpha = n/c \tag{35}$$

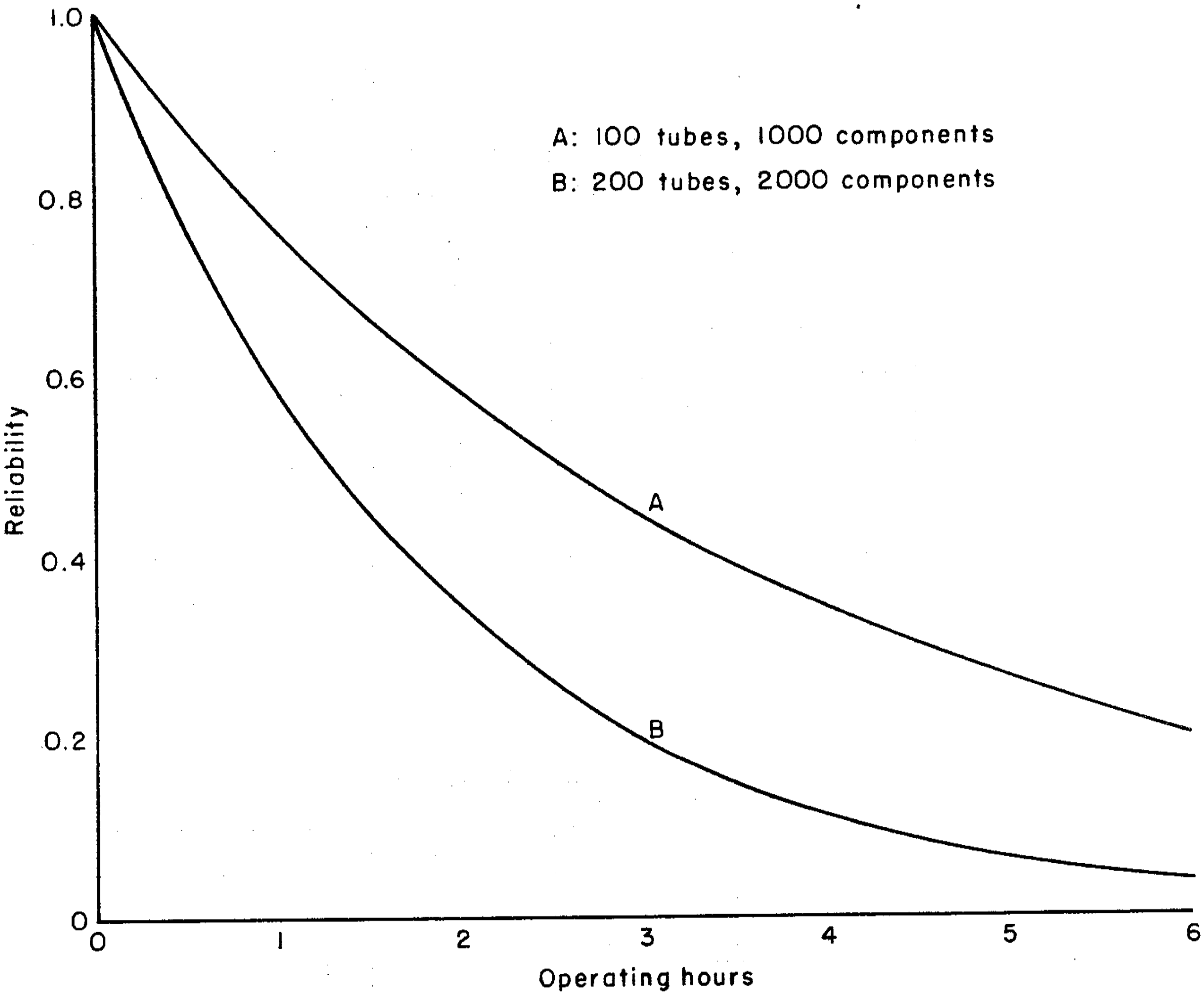

Fig. 9 — Reliability of airborne radar sets (Ref. 1)

and β be the ratio of the component hazard to tube hazard.

$$\beta = r_c/r_n \ . \tag{36}$$

Then Eq. (31) for the set reliability becomes

$$R = e^{-knr_n t} \tag{37}$$

where k is the ratio of the set hazard r to the total tube hazard nr_n :

$$k = r/nr_n = (\alpha + \beta)/\alpha \ . \tag{38}$$

To interpret k note that if replacements are made over a period of time so that the total populations remain constant (see Sec. 6.6) then

$$k = \frac{\text{Set failure rate}}{\text{Tube failure rate}} = \frac{\text{Set failures}}{\text{Tube failures}} \ . \tag{39}$$

Finally, recalling the definition of the mean time to failure (Sec. 6.6) it is seen that the set mean time to failure (T) and the tube mean to failure (τ) are given by

$$T = r^{-1} \ , \qquad \tau = r_n^{-1} \tag{40}$$

so that from Eq. (37) the set reliability is

$$R = e^{-knt/\tau} = e^{-t/T} \tag{41}$$

where

$$T = \tau/nk \ . \tag{42}$$

For military equipment it appears (Sec. 2.6) that roughly half the set failures are caused by tubes; hence $k = 2$, and Eq. (41) becomes

$$R = e^{-2nt/\tau} \tag{43}$$

with

$$T = \tau/2n \tag{44}$$

Equation (43) shows that electronic reliability declines exponentially with operating time and complexity, as measured by the number of tubes (n). This is shown in Fig. 10, where the reliability, Eq. (43), is plotted against operating time for various complexities. In these curves a value of $\tau = 16{,}666$ hours is used, corresponding to the 3 percent failure rate in 500 hours reported by ARINC for shipboard and fixed ground equipment.

Equation (43) also shows that the reliability increases as the tube mean time to failure (τ) increases; Fig. 11 shows the reliability R for a 1-hour mission plotted against τ for various complexities ranging from 50 to 10,000 tubes. As mentioned in Sec. 2.6 most military equipments appear to have a tube mean time to failure in the range of $\tau = 2000$ hours to 20,000 hours. For purposes of comparison, however, values of τ from 500 to 200,000 hours are shown. The drastic effect of complexity is clearly evident. At a value of $\tau = 2000$ hours, for example, a 50-tube set has a reliability of 95 percent for a one-hour mission; if the complexity is doubled to 100 tubes the reliability drops to 90 percent; and for 500 tubes it is only 61 percent.

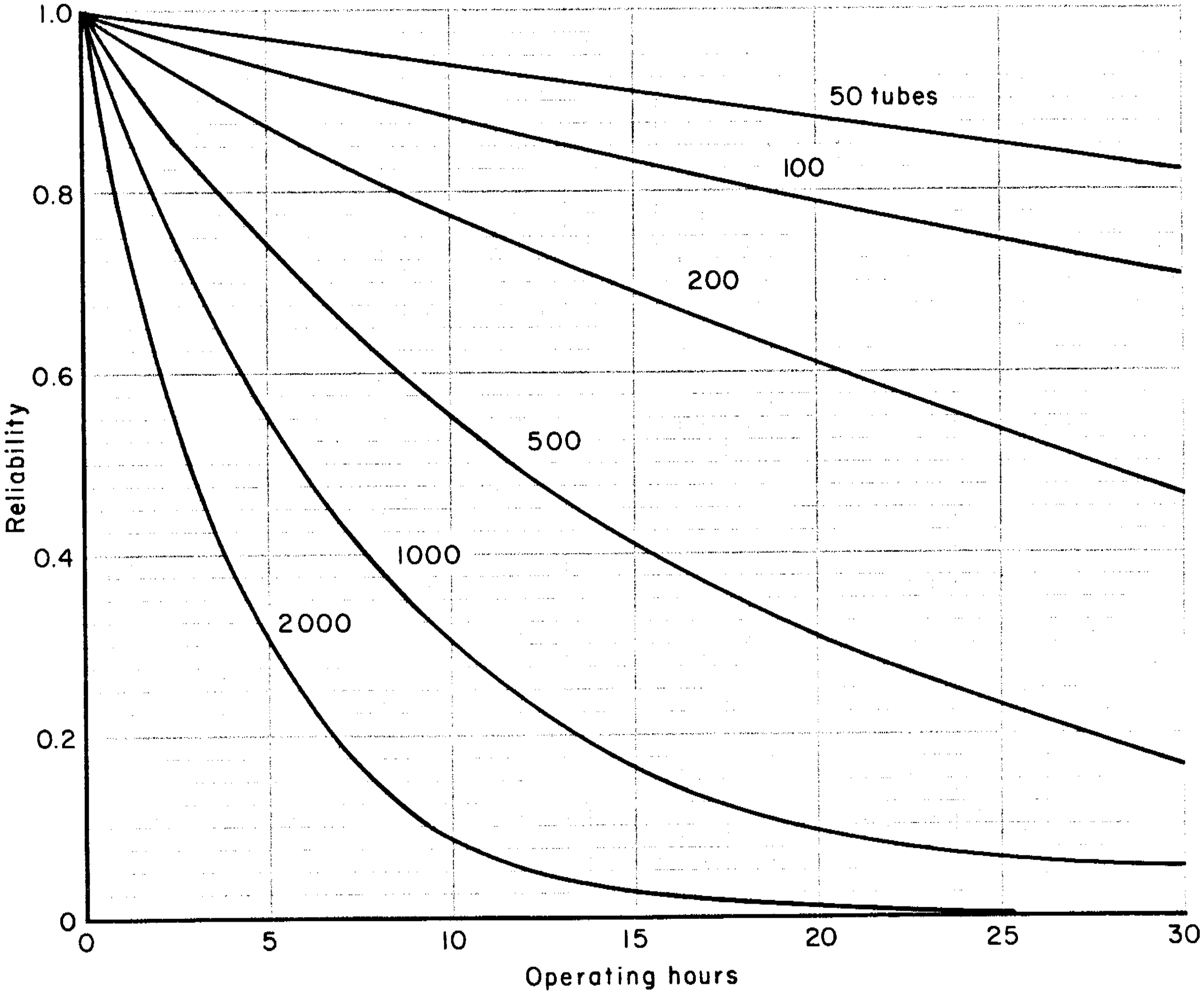

Fig. 10 — Reliability of shipboard and fixed ground equipment
(τ = 16,666 hours)

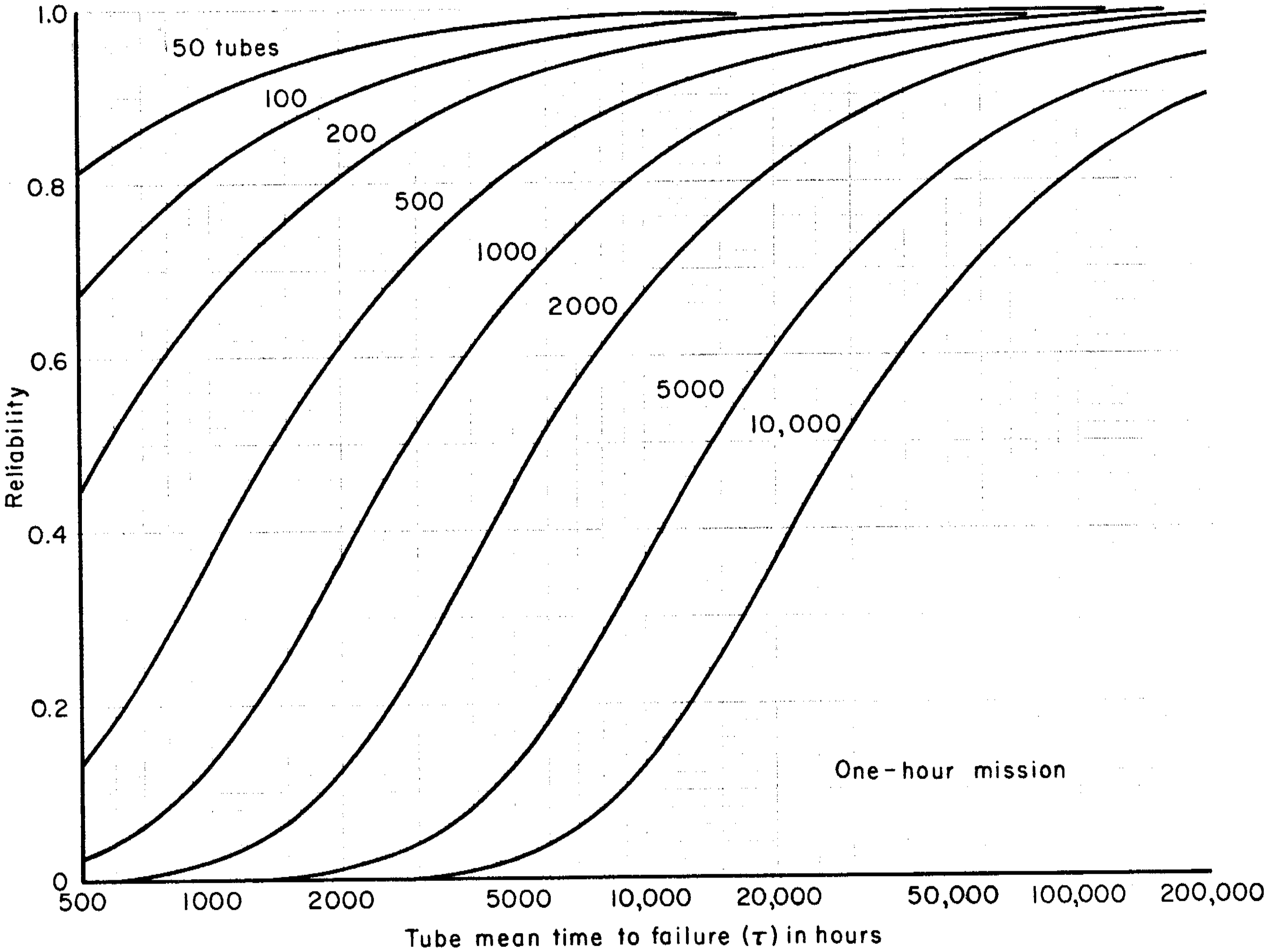

Fig. 11 —— Reliability for 1-hour mission vs tube mean time to failure

Figure 12 shows the same curves for a ten-hour mission. It is necessary to have quite reliable tubes and components for moderately complex systems with such a long operating time, if a reasonable reliability is to be achieved. For example, if τ is only 2000 hours as in previous examples, and $n = 100$ tubes, the reliability is only 37 percent. For a set with only 100 tubes a reliability of 90 percent requires a value of 20,000 hours for the tube mean time to failure, and for a 1000-tube set 90 percent reliability requires 200,000 hours per tube failure.

Set Mean Time to Failure

From the number of tubes and the tube mean life Eq. (44) can be used to calculate the set mean time to failure. For the set in the above example ($n = 100$ tubes, $\tau = 2000$ hours), the set mean time to failure is $T = \tau/2n = 10$ hours; thus the set may be expected to fail once every 10 hours on the average. For a set ten times as complex with 1000 such short-lived tubes, the time between set failures is only one hour. With medium-lived tubes ($\tau = 20{,}000$ hours) the set would fail once every ten hours, and with long-lived tubes and components ($\tau = 200{,}000$ hours), the set would fail only once every 100 hours and would have a reliability for a ten hour mission of 90 percent as noted at the end of the previous paragraph.

Component Mean Time to Failure

The preceding conclusions of course depend on the assumption that half the set failures are tube failure ($k = 2$), but the general

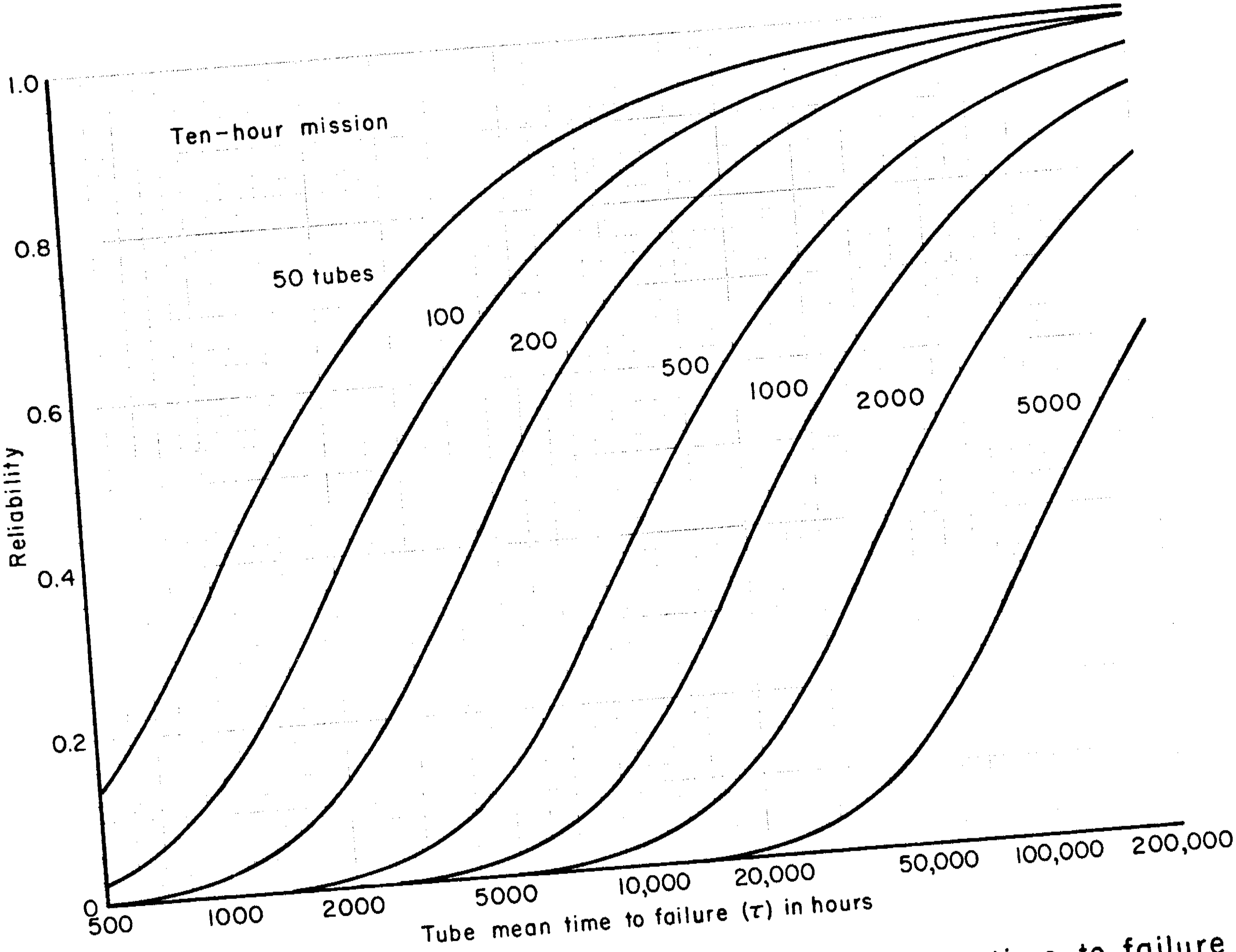

Fig. 12 — Reliability for 10-hour mission vs tube mean time to failure

magnitude of the results would not be changed if, for example, two-thirds of the set failures were caused by tubes ($k = 3/2$). This assumption that $k \sim 2$ means that the component reliability and the tube reliability are related, so that when various values of τ, the tube mean time to failure are used, it is implied that the component mean time to failure is correspondingly changed. More specifically, defining the component mean time to failure τ_c as the reciprocal of the mean component hazard r_c,

$$\tau_c = r_c^{-1} \qquad (45)$$

it is easy to show that τ_c is given by

$$\tau_c = \tau/\alpha(k - 1) \; . \qquad (46)$$

Thus τ_c is proportional to τ, and if the value $k = 2$ is used, $\tau_c = \tau/\alpha \approx 10\tau$, since α, the ratio of tubes to components, is of the order of 10 percent for most radio-radar sets.

The Exponential Law for High Reliabilities

If the reliability is high (above 70 percent) then the failure rate or unreliability Q is 30 percent or less. Eq. (41) can be written in the useful approximate form,

$$Q = knt/\tau = t/T \qquad (Q < 0.3) \qquad (47)$$

which has less than 4 percent error. From this expression it is clear that the probability of failure Q is the ratio of the operating time t to the set mean time to failure T. Using a value of

$k = 2$ for the set to tube failure ratio,

$$Q = 2nt/\tau \qquad (48)$$

and the reliability $R = 1 - Q$ can be calculated easily for quick estimates. Thus if the tube mean time to failure is $\tau = 2000$ hours and the set has $n = 100$ tubes, $T = 10$ hours; for a one hour mission, therefore, the unreliability is $Q = 1/10 = 10$ percent and the reliability is $R = 90$ percent. For a ten-hour mission $Q = 10/10 = 100$ percent and the calculation breaks down because Q is larger than 30 percent. Eq. (41) must then be used and the reliability is found to be $R = 37$ percent, $Q = 63$ percent.

7.2 Evaluation of Reliability from Field Data

The available evidence on military electronic equipment indicates that the pattern of failures is characterized by a constant probability of failure (constant hazard) which is independent of the age of the sets or the components. This gives rise to the exponential law for reliability:

$$R = R_o e^{-t/T} \qquad (49)$$

The equation can be used to predict the reliability for a given operating time t if the initial reliability R_o and the set mean time to failure T are known. There is at present no way to predict R_o, so that field data are required. For many equipments (radios, radar) it may be justified to assume that there are no initial failures so that $R_o = 1$. In other cases (e.g., missile guidance systems) some initial failures may be expected and R_o will have to be determined from field failure data.

Calculation of T from Field Data

Turning now to the quantity T, discussed in Sec. 6.6, how can T be determined from actual field data? In general, for any group of sets in which failures are observed to occur, the set mean time to failure or the set mean life, T, is defined by the equation:

$$T = \frac{\text{Total set operating time in set-hours}}{\text{Total number of set failures}} .$$

Two examples will illustrate the use of this equation. The sets are assumed to follow the exponential law, Eq. (49).

Ex. 1 - Multiple Sets with Replacements

Suppose N sets have a total of F failures during the observation period of t_o hours, all failures being replaced as they occur so that the dead time during which any set is off the air is small compared to t_o. Then the total set operating time is approximately Nt_o and the set mean time to failure for the sample* is

$$T' = Nt_o/F . \tag{50}$$

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*The values of T' obtained from a series of such experiments with a fixed F are distributed normally about the true T of Eq. (49) with a standard deviation of approximately $\sigma = T/\sqrt{F}$, so that $\sigma = 1/5\, T'$ if $F = 25$. Thus, two thirds of the time the estimated T' will lie within ± 20 percent of the true T if samples of 25 failures are considered. See Ref. 37 for further details.

Ex. 2 - Multiple Sets Partially Run to Failure

Let the N sets be turned on together and observed for a time t_o, during which F sets fail at time $t_1, t_2, \dots t_F$, no replacements being made. The total set operating time is then $t'_o = (t_1 + t_2 + \dots + t_F)$ for the F failed sets and $(N - F)\ t_o$ for the remaining unfailed sets, since these sets operated during the entire observation period t_o. The total set operating time is therefore $t'_o + (N - F)\ t_o$ and the estimated set mean time to failure is

$$T' = \frac{1}{F}\left[t'_o + (N - F)\ t_o\right] . \tag{51}$$

The sampling error is the same as in the first example (see footnote).

If all N sets are observed to fail at time $t_1, t_2, \dots t_F$, the expression for T' reduces to

$$T' = (t_1 + t_2 + \dots + t_F)/F \quad . \tag{52}$$

The values of T' calculated in the above examples can be used in Eq. (49) to estimate the reliability. If the set failures are classified into tube and component failures the data can also be used to compute k; knowing T', k, and n, Eq. (42) can then be employed to calculate τ', the corresponding estimated mean tube life.

Accelerated Evaluation of T, the Set Mean Life

Recent statistical studies (Refs. 37, 38) of the exponential law for reliability have established two conclusions of considerable practical importance in estimating the set mean life T for the test situation of Case 2. The first conclusion is that T' given by Eq. (51) is the best estimate of T, in a rigorous statistical sense. In the second place, it has been shown that for a given number of failures F, the goodness of this estimated value T' is independent of N, the total population tested, provided only that the estimate is based on the times to failure of the first F failures, as described above in Case 2. The importance of this result lies in the fact that if a large number of sets are tested the first F failures will occur in a much shorter time than if only F are tested until all fail. Thus the evaluation of T can be accelerated without losing accuracy. This result holds only to the degree that the set reliability follows the exponential law; it is not valid for the Gaussian Law, for example. Of course such an accelerated test requires more test items (sets, tubes, etc.) but the gain in time may justify this.

To illustrate the idea, suppose T = 50 hours is the true set mean life which it is desired to evaluate. (From Eq. (44) this could result from a set with 100 tubes having a mean tube life of 10,000 hours.) Further suppose F = 25 failures will give a satisfactory accuracy of estimate, as described in the footnote of Case 1. Now consider two tests. In the first (long test) a group of 25 sets is observed until all 25 fail. This will require an observation time of about 3.8 T (see Ref. 37) or 190 hours. From the 25 times to failure $t_1, t_2 \ldots t_{25}$ the estimated mean set life is $T'_1 = (t_1 + t_2 + \ldots t_{25})/25$. In the second (short) test $N = 100$ sets are observed only until the first 25 fail, at which time the test is stopped. This test will require only about .29T or 14.5 hours to run. Using Eq. (51) the estimate T'_2 is obtained from the 25 times to failure as explained in Case 2 above. Then the statistical theory assures that T'_1 and T'_2 are equally good estimates of T; further, the short test was run in only 14.5 hours as compared with 190 hours, a sizable saving in time. If this accelerated method is applied to tubes, for example, where large numbers are involved, very great time savings may be achievable.

This concludes the application of the exponential law to electronic equipment reliability. It remains to consider the justification of these results and the limits of their validity.

7.3 Validity of the Exponential Law

In this concluding section certain aspects of the exponential law will be discussed briefly, including the basis for the law and the conditions and equipment to which it should be applied.

To begin with, the general form of the exponential law for reliability is

$$R = R_o e^{-rt} = R_o e^{-t/T} \tag{53}$$

In this form the law gives the reliability as a function of operating time for any population of elements in which the hazard r

(fraction of survivors failing per hour) is constant. It has been found to characterize the reliability of many diverse components (Refs. 18 and 39) and it appears also to typify the reliability of certain complex systems composed of human and mechanical as well as electronic components.

As explained in Sec. 6.6, the exponential law holds for a population of systems (e.g., radar sets) if it can be established that any one (or all) of three conditions exist:

(A) Exponential System

An adequate sample of system failure data fits the exponential law reasonably well.

(B) Exponential Components

The system is composed of components which fail exponentially.

(C) Mixed Component Ages

The system consists of components having any failure patterns whatsoever but whose ages are mixed so that the component replacement rate is constant.

Condition A establishes the exponential law by statistical analysis of directly observed failure data. Condition B infers the exponential law for the system from the fact that the components fail exponentially, a more indirect argument than in A, and one which involves theoretical assumptions concerning the statistical and functional independence of the components in a complex system. Finally, Condition C is suggested by the fact that certain military electronic equipment (e.g., ground radars) suffer many failures and replacements early in life and then settle down to a more or less constant failure rate. C thus has the status of a plausibility argument for the exponential law unless actual replacement or failure data is available, in which case a direct statistical test can be made to establish or reject Condition A. It is apparent that A and B require failure data under actual or simulated field conditions; such data have been collected for military radios and radars.

The Exponential Law for Radio-Radar Reliability

Most of the field data which have been collected to date on military electronic reliability has come from complex radio-radar type equipment in aircraft and in fixed ground and shipboard installations. For such equipment it was shown in Sec. 7.1 that the exponential law could be written in the special form:

$$R = R_o \, e^{-knt/\tau} \qquad (54)$$

in which the dependence of the reliability on the number of tubes or complexity is made explicit. Radio-radar type equipment constitutes a large segment of all military electronics and performs vital military functions including communications, search and navigation, fire control, bombing, and countermeasures. It is therefore important to state the conditions under which the exponential law may be expected to be valid.

Most of the equipment from which the field data have been obtained are characterized by three features:

(1) Repeated Missions

The sets were used in many missions on a continuing basis. These missions varied from medium length (e.g., 1 - 20 hours in aircraft) to nearly continuous operation for periods of days or weeks (e.g., shipboard or ground radar).

(2) Continuous Replacements

Maintenance and replacement of both sets and failed parts were carried on more or less continuously for months or even years while the equipment was in operational use. In many cases, part replacements were even made during the mission or operating period of the gear.

(3) Relatively Constant Conditions During Missions

It is believed that the maintenance, operational, and environmental conditions did not change radically during the missions or operating periods. For fixed ground equipment this would be expected. It is less true for airborne equipments in which temperature and pressure changes may occur. For shipboard gear under non-combat operational conditions at sea the equipment environment should not vary greatly.

Both repeated missions and continuous replacements tend to mix the ages of the set and component populations, and this tends to justify the use of the exponential law. The relatively constant operational conditions during use favor a constant hazard and hence the exponential law. These vague arguments help to explain the observed exponential pattern of failure; they are not needed to justify the law for radio-radar equipments. The main point in listing the above conditions is to draw attention to the operational circumstances under which the exponential law has been observed. <u>There is little or no data to justify the use of the exponential law unless the above three conditions hold.</u>

For example, in one-shot devices such as torpedoes or guided missiles the guidance systems may all be new and may exhibit a different pattern of failure because of high early failures in the first few minutes of operation. Again, both of these devices are subjected to a changing environment ranging from high shocks during launching to mild conditions during the mid-phase, and ending in severe vibration or acceleration during the homing phase. To the extent that the components are vulnerable to these changing conditions, the hazard will certainly not be constant. Again, if missiles are suddenly used after a long storage, without maintenance or check out, the initial failure rate may be large and it would no longer be proper to assume $R_o = 1$ as in the radio-radar equipments where continuous maintenance helps to prevent initial failures.

Summary

The exponential law should be considered as a working hypothesis for complex electronic systems. It is supported by a limited amount of statistical data on failures of radios and radars in aircraft, ships, and fixed ground installations, obtained under noncombat military operational conditions. In the special form, Eq. (54), it shows the dependence of reliability on complexity, on mission operating time, and on tube and component reliability. It is useful for general order-of-magnitude estimates and planning factors, for which purposes it may usually be assumed that there are no initial failures ($R_o = 1$), that about half the equipment failures are caused by tubes ($k = 2$), and that the mean time to failure for tubes is of the order of $\tau = 10{,}000$ hours. For specific equipments where more accurate estimates are required for tactical or technical planning, field data must be obtained to evaluate the set mean time to failure T, as described in Sec. 7.2. The estimated value of T can then be used in the general form of the exponential law, Eq. (53). The law should not be applied to other types of equipment or to operational situations which differ greatly from the conditions (1) to (3) above unless justified by an adequate statistical study of the field reliability of the equipment in question.

7.4 The Future: Reliability, Complexity, and Redundancy

In this final section the conflict between reliability and complexity will be resolved by redundancy. This will require first a brief resume of the current trends in reliability and complexity in electronics, and second the formulation of criterion of critical complexity as a guide to the requirement of redundancy. Redundancy will then be discussed as a design principle necessary in any super-reliable or super-complex system.

Resume of Current Trends

The reliability problem is being attacked in three phases:

(1) The short-term quick fix programs, in which available techniques and knowledge are used to cure known defects in design and application of tubes and components, and in maintenance and use.

(2) The interim phase on a one or two year scale, comprising changes in maintenance practices and modifications in the design and use of present tubes and components to improve their reliability.

(3) The long-term phase (4 years or more) involving major and perhaps radical changes in the design of tubes and components, the introduction of new components and new

applications, and new principles of system design. This includes such work as that of the Stanford Research Institute (Ref. 23) and many other new developments in electronics not discussed in this report.

Current effort is concentrated on the first two phases. The short term work essentially removes obvious defects in order to realize the reliability inherent in present tubes and components if they are properly used. The modification efforts seek to improve the reliability of present parts within the limits set by the best present production techniques together with good system engineering, maintenance, and operation. As a rough estimate of this limit a value of $\tau = 200{,}000$ hours (23 years) for the tube mean time to failure will be used. This implies a large advance in reliability of tubes, components and systems. It represents a ten-fold decrease in failure rate compared with the better present equipment ($\tau = 20{,}000$ hours) and a factor of perhaps two or three over the best military gear yet built. It is comparable to the low failure rate which is expected in the best communications systems (e.g., submarine cable repeaters - see Ref. 35), and it may well be too optimistic for military equipment. Nevertheless this limit will be useful in obtaining an order-of-magnitude relation between reliability and complexity.

Critical Complexity

It is clear from Sec. 1.3 that the complexity of military electronic equipment is increasing rapidly from year to year - a tenfold increase in ten years is not unusual for radars. It is also clear from the exponential law that system reliability is declining exponentially with this increasing complexity and can be held to acceptable levels only by corresponding increases in the reliability of tubes and components. Even if present parts had the limiting reliability discussed above, it is clear that complexity will eventually outrun part reliability.

In short, *for parts having a given reliability, how complex can equipment become and still have an acceptable reliability?* The answer will, of course, depend on the required operating time t and on the values of τ and R. More precisely, *the complexity n^* for which the reliability has the minimum acceptable value R^*, will be called the critical complexity*. Assuming that R^* is at least 70 percent, Eq. (47) is applicable and gives n^* in terms of the *maximum acceptable unreliability Q^**:

$$n^* = Q^* \tau/kt \qquad (55)$$

Now using $k = 2$, as appears reasonable from previous discussions, and $\tau = 200{,}000$ hours to represent the limiting tube and component reliability, the equation gives the critical complexity as a function of the mission operating time t, and the maximum acceptable failure rate Q^*:

$$n^* = 100{,}000\, Q^*/t \quad . \qquad (56)$$

Table VIII shows n^* for various operating times for $Q^* = 1$ percent ($R^* = 99$ percent) and $Q^* = 10$ percent. ($R^* = 90$ percent).

TABLE VIII - CRITICAL COMPLEXITY VS OPERATING TIME

Operating Time	Minimum Acceptable Reliability 90 Percent	 99 Percent
1 hour	10,000 tubes	1000 tubes
2	5,000	500
5	2,000	200
10	1,000	100
20	500	50

It is seen that for 90 percent reliability the critical complexity is 10,000 tubes for a one-hour mission and 1000 tubes for a ten-hour mission. For 99 percent reliability the critical complexities are one-tenth as large. If the ultimate figure of $\tau = 200,000$ hours is not attained the critical complexities in the table must all be cut accordingly. Now it is well-known that some complex systems already have as many as 1000 tubes and must operate for as long as 10 or 20 hours. In view of the fact that most military systems probably have a value of τ in the neighborhood of 20,000 hours at most, it is clear that military equipment is fast approaching the critical complexity limits beyond which the reliability will rapidly drop below 90 percent.

Three conclusions regarding electronic equipment of complexity n can be drawn from Table VIII.

(1) For Subcritical Complexity ($n < n^*$) the equipment has not reached the critical complexity and tube and component improvements alone can ultimately yield satisfactory system reliabilities $R > R^*$.

(2) For Critical Complexity ($n \sim n^*$) the situation is marginal in the sense that the full ultimate reliability ($\tau = 200{,}000$) will have to be attained in the parts; to the degree that this goal is not reached, component improvement will not yield the required minimum reliability.

(3) For Super Complexity ($n > n^*$) the equipment complexity is greater than the critical complexity. Such a system will be called supercomplex. Supercomplex equipment imposes system reliability requirements which are beyond the present state of the art set by tube and component reliabilities.

Redundancy

What, then, can be done to provide high reliability in supercomplex systems? The answer, paradoxically, is to increase the complexity by adding redundancy. In the above argument and in the entire discussion of electronic reliability it has been assumed that complexity meant series complexity. Yet in Sec. 6.2 it was clearly shown that parallel complexity increased reliability.

In series systems the only way to improve reliability is by using more reliable components. For given component reliabilities, however, redundancy is the only way to improve reliability.

It is well known that redundancy is used in industrial applications where high complexity is involved and high reliability is required (e.g., telephone systems). Yet redundancy is employed only occasionally in the present design of military electronic equipment.

There are two types of redundancy commonly used in engineering, standby and continuous. Standby redundancy is typified by a copilot in an aircraft, who takes over the pilot's function in case of emergency, or by a parallel switch which can be closed to complete a circuit if the primary switch fails. Continuous redundancy is used when a bridge designer provides additional supports beyond the minimum number required, in order to share the load and prevent the failure of any one support from failing the bridge. Another example is the use of several push-pull tubes in a circuit in which the failure of one tube degrades performance but does not cause complete failure.

The distinction between standby and continuous redundancy is important because standby redundancy requires a ''decision device'' to detect failure and activate the standby component. This raises the whole problem of automatic failure detection in electronic circuits. Failure in the output of a component can be detected in many ways - by comparison with a standard if the output is constant or by comparison with an independent determination of the output (e.g., comparison of height from a radar height finder with the reading from a pressure altimeter). For any closed-loop feedback system, failures can be detected by modification and feedback of output to obtain a null-comparison with input (e.g., dividing amplifier output voltage by the gain factor so that it corresponds to input voltage, with which it can then be compared). For simple component functions, for discrete or digital functions, and for the detection of overt or complete failures, a decision device which is cheap and reliable can often be used. On the other hand, for complex component functions, for continuous or analog functions, and for detecting marginal failures or performance degradation, the decision device itself may become complex, expensive, and unreliable, and its use must be carefully considered in terms of the net gain to the system.

Redundancy has been suggested as a possible solution to the problem of reliability in guided missiles, and a mathematical analysis of the reliability of redundant circuits has been issued (Ref. 33). In computers various error-checking methods have been used both in the design and mode of operation (Ref. 36) and these may be useful in improving reliability in other electronic equipment.

Summary

It seems clear that present electronic system design principles must be modified and enlarged to include redundancy as a standard practice in applications where very high reliability is required or where the system is supercomplex. It is to be emphasized that redundancy offers the only method of improving reliability when components of a given reliability are used.

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