Whither Reliability?

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Introduction

RELIABILITY assurance is a new engineering discipline. Many engineering managers are wondering what place it has in their organizations and whether or not it is here to stay.

Achievement of operational integrity in modern complex aerospace systems requires, to a degree never accomplished before, the integration of various engineering and management disciplines. The consequences of failure of modern aerospace systems, and the unreasonable maintenance and support resources now required to keep a system operating over its lifetime, indicate that reliability and maintainability are among the most serious problems facing us today. Engineering work has been done on the methods of measurement of reliability of system designs and hardware and on quality procedures. A start has been made on procedures to assist the designer in developing a design which meets, on paper, specified reliability requirements. However, practically no systematic work has been done on designing and organizing manufacturing methods, processes, and facilities to assure reproduction of a product of specified minimum reliability.

The next world war, or future contained local wars, will be fought and decided with the weapons and skilled manpower that are available on the day that fighting breaks out.[1] The great economic potential of our nation is no longer decisive; what counts is how much of our economic resources we are willing to divert to our defense in advance of the outbreak of the conflict, and how clever we are with this investment. There is no longer any room for waste. We must develop methods that enable us to design the final aerospace configuration on paper, to do so with hundreds of associated specialized design teams geographically dispersed all over the country, and to have the system work right the first time.

The associated concept of maintainability is also of fundamental significance. The cost of maintaining a complex aerospace system over its lifetime may exceed ten to one hundred times the initial cost of the equipment.[2,3] The decreasing availability of first-line weapons,[4,5] and the increases in skilled manpower required to keep them in combat-ready condition,[6] constitute serious problems for the military. This is depicted in Fig. 1,[7] which shows how the mission capability of advanced Naval weapon systems is degraded due to increasing down time on deck. There are two major reasons for this: manpower requirements and avionics. The lower curve shows how the Navy's experienced maintenance capability is dropping sharply because of the retirement of experienced technicians who were recruited during World War II. Although this problem has been foreseen for some years, it has not been possible for the Navy to provide for orderly replacement of these skilled men.

Figure 2[7] lists the causes of nonreadiness of Naval aircraft for the period 1959–1961 and points out the increasing influence of avionic equipment as a factor. These numbers identify airborne electronic subsystems as the prime contributors to aerospace system operational unreliability and as the prime targets for reliability improvements.

Figure 3 shows the relationship between total operating cost and reliability for the proposed Missileer aircraft.[8] Although this contract was later canceled, the conditions indicated by this graph are considered correct. It is obvious that within this range any significant increase in weapon system reliability will pay off in tens of millions of dollars (see also Refs. 9–12).

In commercial and private flying, the first obligation is air safety. During the period January 1, 1958 to January 1, 1963, aircraft mechanical malfunctions contributed to or were the cause of 160 air carrier accidents (31% of the total), resulting in 544 fatalities, 61 serious injuries, destruction of 28 aircraft, and substantial damage of 129 others. If airline traffic expands as predicted, and all predictions to date have underestimated actual growth, at present accident rates there will be 10,000 fatalities annually by the year 2000, only 36 years hence.[10]

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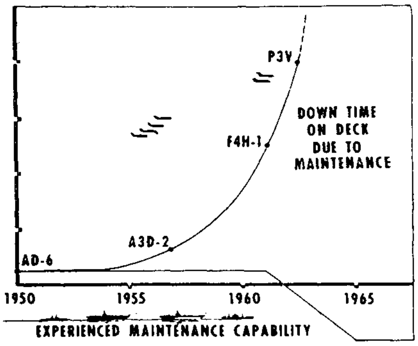

Fig. 1 Mission capability degradation of Naval aircraft.

The advent of manned space flight has added a new dimension to the reliability problem. A new spacecraft on its first flight must exhibit the same level of reliability which an aircraft achieves after a long ground test and flight test development period. In manned spacecraft, the emphasis on design and manufacturing assurance, and on ground testing, must be a different order of magnitude than for earthbound aircraft.

Development of Statistical Reliability Concepts

Product Rule

The first application of modern reliability engineering was undertaken in Germany during World War II by Lusser on the V-1 program.[13] Lusser showed that the product rule applied to the reliability of a system consisting of a series of components; that is, when the simultaneous successful operation of a number of components is required for system success:

$$R_s = R_1 \times R_2 \times R_3 \times \ldots$$

The effect of this rule is shown in Fig. 4. The decrease in reliability is spectacular as the number of operating units increases. However, the rule must be applied with expert understanding, since it only applies to components with a reliability less than 1.0. In any complex machine, many components are expertly designed in accordance with known laws of nature, and their reliability is equal to 1.0,[14] that is, they never fail under normal operating conditions. However, all advanced systems contain components that have been at least partially designed by trial and error, and unexpected operating environments may occur. These two factors establish a reliability of less than 1.0 for many components; such components must be identified, and to them the product rule applies.

Lusser developed a comprehensive statistical-designed component test-to-failure program and established statistical standards for the evaluation of the test results. These procedures were patterned after those used for materials strength testing and for structural element testing in airframe design. These concepts were refined on the V-2 and Wasserfall programs and then brought to the United States after World War II by Lusser and his associates. Lusser's use of the product rule has been generally accepted in this country, but his margin-of-safety and test-to-failure concepts have not enjoyed any extensive popularity. These latter concepts were partially adopted by Redstone Arsenal on its successful missile programs, and they still appear in Command Regulation 705-1,[15] but Redstone has been the only procuring agency to adopt this approach.

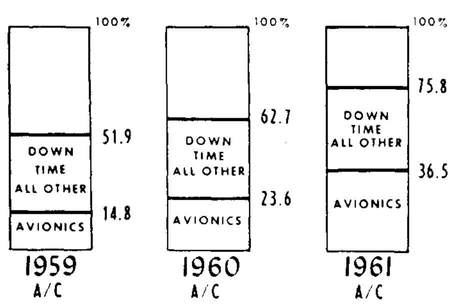

Fig. 2 Causes of nonreadiness in Naval aircraft.

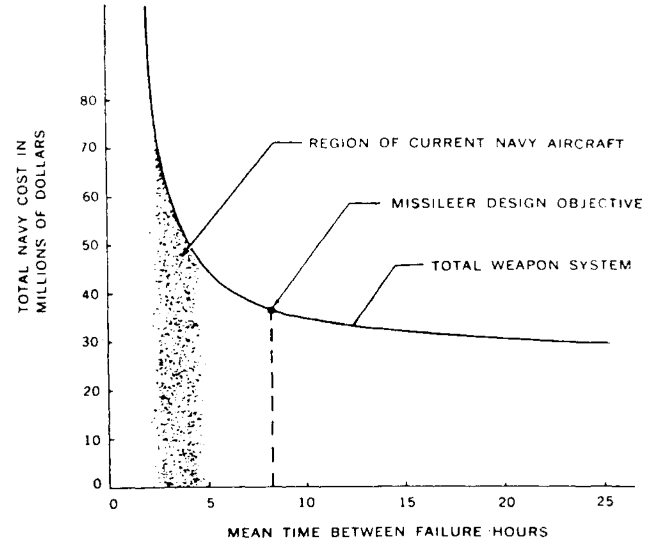

Fig. 3 Five-year cost of maintaining capability to hold one combat-ready Missileer on station.

Redundancy

The effects of limited component reliability to some extent can be overcome by redundancy. In a two-component parallel system, success is assured if either component operates. The product rule in this case is applied to system failure, since simultaneous failure of both components is required for system failure:

$$Q_s = Q_1 \times Q_2$$

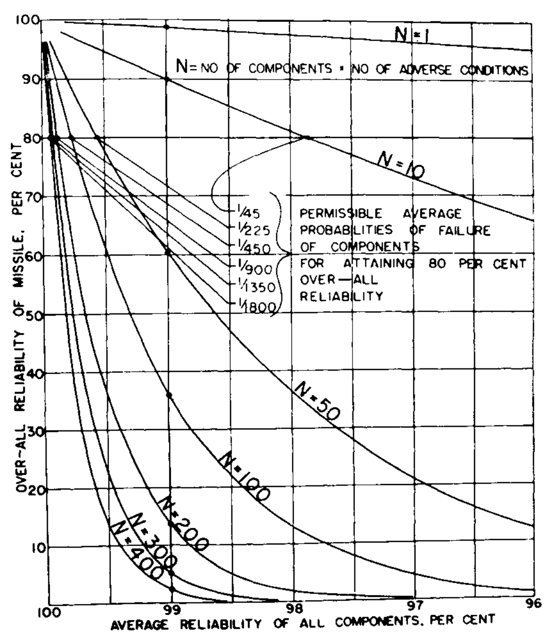

Fig. 4 Over-all reliability as a function of complexity and component reliability.

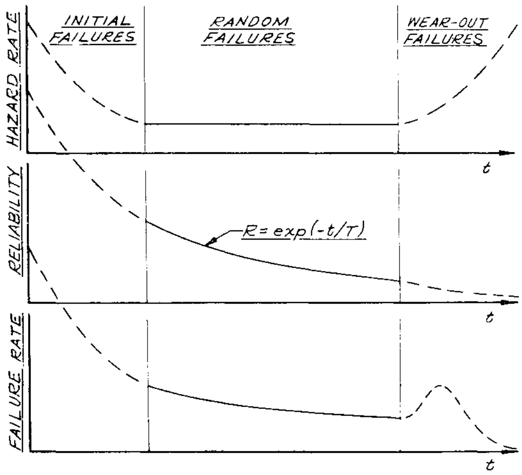

Fig. 5 Statistical reliability theory.

Since an attempt to operate the system (trial) will result in either success or failure,

$$R_s = (1 - Q_s) = 1 - (1 - R_1)(1 - R_2)$$

$$R_s = R_1 + R_2 - R_1 R_2$$

Redundancy is classified as active or standby. In active redundancy, both components are operating continuously, and either component can assume the entire operating load in event of failure of one unit. In standby redundancy, a sensing and switching unit detects failure of the operating unit and switches the standby unit into the circuit. In many standby systems, the sensing-switching device is the least reliable part of the system.[16] In some cases, the sensing-switching function is performed by the pilot; when this can be done, it is normally the most reliable way of performing the function.

Redundancy is a costly method of attaining higher reliability, since it increases cost, weight, space, and maintenance requirements. Furthermore, it should be possible to check functionally all redundant elements to assure that they are operating properly before the start of each flight or launch. A standby element that is defective, and whose failure remains undetected, can be more dangerous than no standby at all, because the operator may rely on its being available in an emergency that he might have avoided, had he known that the standby was not operative.

In some cases the reliability of a smaller unit in an actively redundant application is higher than that of a single larger unit carrying the entire load. This occurs with hydraulic pumps in flight control systems where the redundant pumps can be smaller than a single pump. Redundant pumps do not have to be designed to take the full load for prolonged periods, and they are more reliable than larger pumps in similar airborne applications.

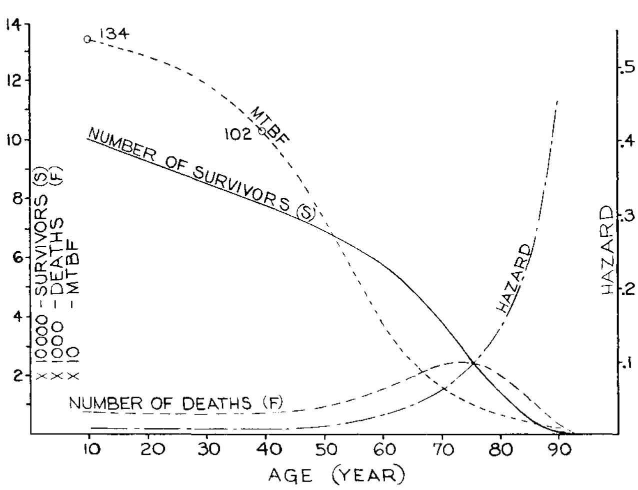

Fig. 6 American mortality.

Statistical Reliability Theory

The next major contribution to the art, in the early 1950's, was a method of classification and statistical analysis of initial, random, and wear-out failures.[17] Initial failures were recognized as a manufacturing and quality control problem; wear-out failures, as a maintenance problem; and random failures, as a design problem. The following definitions were established.

A test will result in either success S or failure F as a function of time t. For N tests or trials:

$$N = S(t) + F(t)$$

Reliability

$$R(t) = S(t)/N$$

Failure Rate

$$Y = (1/N)\, dF/dt$$

Hazard Rate

$$Z = (1/S)\, dF/dt$$

For constant hazard ($Z = 1/m =$ const, that is, failures occur randomly),

$$R = \exp(-Zt) = \exp(-t/m) \qquad (1)$$

where $m = MTBF$ (mean time between failures) is a measurable component characteristic. These equations are plotted in Fig. 5. The hazard rate curve is commonly known as the "bathtub" curve. There is considerable confusion in the literature; the term "failure rate" is often substituted for "hazard rate." However, if failed units are replaced by good ones, that is $N, = S =$ const, the failure rate and the hazard rate are identical.

For those without a statistical background, the concept of $MTBF$ is difficult to understand. It should not be confused with average life, or with life expectancy. The concept can be clarified by reference to the American Mortality Experience Table.[18] This table is based on 100,000 males at age 10, and indicates the number of deaths and survivors for each succeeding year. The values for ages 10 and 40 are indicated in Table 1. If (dF/dt) is defined as the number of deaths per year, then the "hazard rate" and "$MTBF$" can be computed as shown. Note that the $MTBF$ of males age 10 is 134 yr, and for males age 40 it is 102 yr. These data are plotted for the entire age range in Fig. 6; note the almost constant hazard between ages 10 and 40.

This theory is applicable to any system that consists of many parts subject to random failures, but it has enjoyed particular popularity in the electronic industry. It allegedly provides the framework for methods of "measurement" of electronic equipment reliability, the accumulation of empirical data, and subsequently for the "prediction" of reliability. A great deal of effort has been spent on measuring the reliability of systems and components. Handbooks of failure rates of electronic components have become available.[19] Techniques have been developed for establishing numerical system requirements, for apportioning the requirements to lower level subsystems and components, for predicting the reliability of systems while the design is still on paper,[20] and for the laboratory reliability measurement of electronic equipment.[21] A more complete summary of the early history of the development of electronic reliability technology, and especially of the role of Government in this development, appears in Ref. 22.

Application

These statistical reliability concepts provide the framework for numerous government reliability specifications and handbooks. Probably the two best known documents in this class are MIL-R-27542A[23] and the AGREE Report.[21] (A representative list of reliability specs appears in Ref. 24; Ref. 25 also includes many reliability titles.) Among the requirements of MIL-R-27542, three items are directly related to statistical reliability concepts: 1) numerical specification of reliability requirements, 2) mathematical models for apportioning system requirements to lower levels and for predicting system reliability based on component data, and 3) a plan for demonstrating achieved reliability at a specified point in time.

The AGREE Report establishes in some detail the procedures for the specification and measurement of the reliability of pilot production and production models of electronic equipment; reliability is defined by Eq. (1). Reliability is measured in a truncated sequential life test, which is designed such that there is a 10% risk that acceptable equipment with $m = m_0$ will be rejected, and a 10% risk of accepting equipment with $m = 0.67\ m_0$ (lower limit), where m_0 is the *MTBF* specified in the contract. On "pilot-production" equipment, at least two units must be tested, and the accumulated test time on both units must be at least 3 m_0. On production units, a sufficient number of units should be tested simultaneously to assure that the test will be completed in 500 hr of elapsed time, but at least 4 units must be tested. The environmental test conditions are standardized to four levels of stress severity, namely, light, medium, high, and extreme. Environments are limited to vibration, temperature, on-off cycling, and input voltage. Depending on the intended application, the procuring agency selects one of these four standard stress levels, and reliability is measured as a function of time only, under the selected standard environment. This test procedure establishes with 90% confidence that the tested units equal or exceed the minimum specified numerical *MTBF*. By secondary calculation, the data available from the tests may be used to yield a reasonable estimate of the actual *MTBF*.

There exists a great deal of misunderstanding regarding the validity of the statistical reliability theory. Despite proven value, statistical methods cannot be introduced by fiat across the board as a new procedure applicable to all development areas.[26] Statistical methods should augment proven practices, not replace them. The most significant value of statistics comes from the applications of statistical engineering methods as a development tool, not as an indicator of achievement. The statistician must assume the role of teacher to the designer; it is still the designer who conceives the hardware. The establishment of a fruitful relationship between statistician and designer is not easy to achieve.

Consideration of Prior Experience

Some of the difficulties arise out of the classical clash between the statistical mathematician as a philosopher and the engineer who must accomplish his task by skillful approximation without adequate tools. The statistician takes measurements and establishes inferences only on the basis of his numbers; he frowns on the consideration of prior experience, upon which the engineer must rely to design his hardware. The classical statistician sincerely feels that there is something immoral about this use of prior experience; he refers to it as "pseudo science" based on "hunches and feelings."[27] Although there is another school associated with Bayes' theorem, which attempts to include the consideration of prior experience, this group has not as yet exerted any significant influence in reliability technology. References 28 and 29 represent one of the few serious attempts to do so.

The sentiments of the classical statistician have had a negative influence on introducing statistical concepts into the design process where it is most needed, and they have been partially responsible for the overemphasis on AGREE-type reliability measurement. Present statistical concepts have been developed to satisfy past needs associated with tax revenues, gambling odds, biological research, life insurance premiums, and the like. The problems associated with reliability assurance in modern aerospace system design are different from those considered by statisticians in the past. Although available statistical techniques are not yet being exploited to the fullest extent, there exists the necessity to develop new expanded statistical theories that include proper consideration of prior experience and which are more adaptable to the problems associated with reliability assurance in aerospace system design.

AGREE-Type Testing of Development Equipment

The AGREE Report[21] limits its proposed testing method to pilot production and production models of electronic equipment. In spite of their stated limited validity, the use of AGREE procedures or related concepts are often directly or indirectly specified for development programs of both electronic subsystems and complete aerospace systems. The AGREE approach is suited for *comparing* the reliability of two competing existing devices under the *standard* environment, but the ratio of the measured reliabilities may not remain the same under actual operating conditions, which are usually more severe than the standard laboratory test environments. Testing to confirm compliance with requirements, exclusive of an evaluation of design data, is a short-cut method, valid only on a fully developed article for a specific known application for which valid requirements can be written and where the validity of the acceptance test has been demonstrated.

For example, a weight control program is normally required during aerospace systems development. Weight estimates are prepared before design, and maximum weight requirements appear in the contract. A running weight estimate is conducted during design and development to assure at all times compliance with the requirements. The completed article is weighed to confirm the validity of the analytical techniques, not to assure compliance with requirements, as this has already been done by the analysis. At this point compliance with requirements can no longer be enforced; it is too late to do anything about noncompliance when compressed rigid schedules are involved.

The AGREE approach imposes severe constraints on aerospace system design. An aerospace system may include a number of electronic subsystems whose reliability has been determined by the AGREE method. The over-all weapon system requirement is usually established under assumption that the reliability of the electronics in the system will be the same as under AGREE test conditions. This imposes on the system contractor the obligation not to exceed the AGREE test environment in his weapon system. Although he may well be unaware of this hidden requirement, because of physical constraints he probably could not meet the requirement anyway, no matter how hard he might try. When the actual operating requirements become known, the AGREE Report provides no way of reinterpreting the test results in terms of the new environments.

An optimum design is achieved when the effort required to control the operating environment is balanced against the effort required to design a reliable device to operate in that

Table 1 American experience mortality

Age, yrs	10	40
Survivors, S	100000	78106
Deaths/yr, dF/dt	749	765
Hazard, $(1/S)(dF/dt)$	0.00749	0.00979
$MTBF\ (m) = 1/Z$, yr	134	102

environment. By standardizing on the test environment in advance, the system designer is deprived of an important variable that he could otherwise manipulate to optimize his design.

AGREE-type tests are customarily run after qualification testing is completed. This is much too late in a development program to demonstrate reliability. Should the specimens fail to pass the reliability test, effective corrective design action would probably require requalification. This process is so costly and time consuming that significant design changes are almost impossible to make at this time.

The use of the equation $R = \exp(-t/m)$ with m as the variable, results in a test where the greater the reliability R, the longer the test duration, and the more costly the test. The lead time for good items in a development program becomes excessive.[30] The funds spent in this manner to demonstrate the reliability of the more reliable electronic devices in a system could be spent better on improving those items whose reliability already is known to be inadequate.

The AGREE method assumes that all specimens are of equal strength. This assumption is unacceptable, since the unit-to-unit variation in "strength" (that is, resistance to failure) of airborne electronic equipment is one of the major causes of unreliability. Thus, AGREE and similar test methods, when applied to development testing, emphasize the wrong variables and do not get to the root of the problem of identifying the causes of unreliability.

Reliability in Terms of Measured *MTBF*

In MIL-R-27542A, "reliability" is defined as "the probability that a system, subsystem, or device will perform its required functions under specified conditions for a specified period of time." Most other government specifications and textbooks support this concept. The definition is a paraphrasing of AGREE-type testing when conducted in support of an equation such as $R = \exp(-t/m)$.

The term reliability means many things to many people, and a great deal of confusion results when the word unwittingly is used in different connotations. For a very large number of reliability engineers, the term has a very narrow meaning; it applies only to electronic equipment and it is a number (*MTBF*) measured in a laboratory test conducted under one of the four environmental levels defined in the AGREE Report. This concept is expanded in a number of government specifications which modify the AGREE test environments to better conform with a particular application. The engineers working under such specifications naturally define reliability as the values which they measure in their laboratories. A stated *MTBF* number is meaningless unless it is positively associated with the environments under which it was measured. This latter information is usually difficult to obtain. Sometimes it is classified. Occasionally contracts are changed or contain waivers modifying the test conditions outlined in the specification and this information is withheld when the *MTBF* number is stated.

Some prime contractors regard *MTBF* as one of several numbers, all of which are required to measure system reliability. They consider reliability as a characteristic of all types of equipment, not just electronics. In prime-contractor monitoring systems, the number of failures often is measured under actual field operation conditions, either through a service-wide trouble reporting system such as the BuWeps Malfunction Reporting Program (MRP)[31, 32]; through use of the contractor's field service representatives; through intensive observation of a limited field sample for a limited period of time; or through a combination of all these and other available methods. Methods of defining and classifying failures leave a great deal to be desired, but this deficiency applies to laboratory tests as well. However, laboratory reports are normally easier to analyze than are field reports.

Table 2 Predicted vs measured *MTBF* (MIL-STD-756)

Equipment	Prediction	Observation
High freq. communications	35.4	62.1
UHF communications	24.3	20.1
Radar	8.4	8.3

The preferred reference base is either airplane flight time or number of landings. These data are readily available on all aircraft in service and can serve as the reference for reliability measurement of all types of equipment, not only electronic devices. Aircraft flight time is only a fraction of the operating time for airborne electronic equipment. The ratios of total operating time to flight time for a number of A3J electronic subsystems vary from 5.9:1 to 9.9:1.[33] These ratios are normally measured by installing elapsed-time meters on the equipment. Complex electronic subsystems have many modes of operation; the elapsed-time meter normally indicates only a "power-on" condition. It is no measure of the degree of equipment utilization. It is also necessary to remember that there are significant differences between the military and the commercial operating environment.[34]

Reliability in Terms of Predicted *MTBF*

In MIL-STD-756[20] the term reliability is applied to a number computed on the basis of a mathematical model of the system, and on failure rates taken from MIL-HANDBOOK 217.[19] This "raw" number is multiplied by an empirical "use environmental factor" to correct it for the effects of the actual operating environment. The correlation obtained by this method is acceptable, as shown in Table 2. Prime contractors have access to extensive trouble reporting systems through which they can monitor their equipment throughout its service life.[32] The predictions based on these contractor-generated failure rates can be quite realistic.[35]

Development of System Effectiveness Concept

In 1957 McLaughlin[36] associated reliability with the weapon systems concept. Achievement of reliability was presented essentially as a design problem, along with performance, accuracy, maintainability, operability, vulnerability, and procurability. At that time, reliability was generally associated with quality control, safety engineering, or with maintenance and support. The major conceptual breakthrough in favor of reliability as a design function came as a result of a presentation in 1958 by Coates[37] and the supporting activities of his BuWeps-Industry Material Reliability Advisory Board (BIMRAB). The standing committees of this board are concerned with the review and preparation of new reliability specification requirements and reliability control practices.[38, 39] An annual conference provides an opportunity to discuss concepts with a wide industry representation.

The most remarkable reliability conference was the Sixth Navy-Industry Conference in 1962. Under the theme "Industry Advises the Chief," presidents of major Navy suppliers were invited to critically examine BuWeps procedures and to advise the Chief on what he should do to improve the operational integrity of Naval Weapons. One of the unique features of this particular conference never became apparent to an outside observer: an intensive exchange of information went on for some 18 months prior to the Conference between all levels of personnel in the Navy and in the speakers' organizations. The rank of the speakers and audience assured that this effort was approached in a serious manner.

Achievements of BIMRAB

The operations of BIMRAB and its annual conferences have provided an extraordinary forum for honest, open,

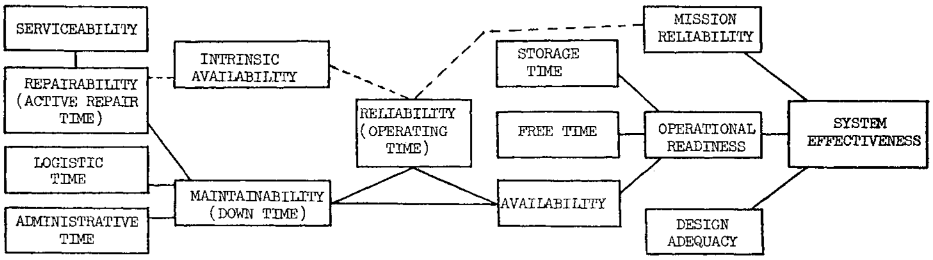

Fig. 7 System effectiveness.

frank, and straightforward talk on reliability issues between BuWeps and its suppliers. This relationship is unique; nothing approaching it exists in any other government procuring agency. This enlightened understanding between BuWeps and its suppliers is doing much to eliminate the public relations aspects normally associated with reliability technology, in particular, useless mathematical exercises, statistical mysticism, and other forms of professional charlatanism, which are so rampant in the field. BuWeps, in close cooperation with its industrial sup·liers, has taken a broad view of its service troubles and is progressing from a limited "reliability" viewpoint to an integrated concept of "systems effectiveness" (Fig. 7), which includes a strong design assurance program in connection with the development of all types of subsystems.[40] In Ref. 3 the interservice F-111 and F-4 series aircraft are cited as examples in which the best attributes of both WR-30[41] and MIL-M-26512[42] are skillfully combined. The system effectiveness concept is no longer restricted to BuWeps. Rector[43] of NASA calls for a new and different reliability approach on Apollo.

Implementing the System Effectiveness Concept

In nonelectronic areas, terms such as airworthiness, flight-safety, and safety factors have been used for over 25 years. These reliability assurance procedures associated with safety-of-life devices and services have been much more effective than those used in electronics. In order to apply the system effectiveness concept to the development of aerospace systems, one must define the functions to be performed. In this paper, the term reliability assurance engineering will be used to encompass maintainability, safety, and all other associated assurance concepts. The functions included in reliability assurance engineering will be derived systematically from an analysis of the ideal product development cycle, Fig. 8.[44]

Reliability Assurance Engineering

Ideal Product Development Cycle

The cycle begins with some practical, operational problem for which a solution is needed in the form of a physical device. Analysis of the problem eventually will lead to requirements for a device that may solve the operational problem. The design function transforms these requirements into detailed drawings and specifications, and the manufacturing function transforms the drawings and specifications into a physical product. The utilization of the product may terminate the cycle, but usually new aspects of the problem will become apparent, necessitating another round. Generally the cycle never terminates, and subsequent cycles may be slower and quite different from earlier cycles.

Quality Control and Reliability Assurance

The traditional role of quality control is to act as a feedback control function with respect to the manufacturing function. The product, in various stages of its fabrication, is compared to the detailed drawings and specifications. Deviations are noted and corrective action taken to eliminate them or reduce them to a tolerable level. Quality *assurance* assumes a wider role; for example, it may assume the responsibility for monitoring the design to assure that it is inspectable. However, such assurance activities are all directed toward reducing or eliminating future difficulties in the traditional quality control area.

Quality control engineers must be given almost exclusive credit for introducing statistical techniques into American industrial processes. Other contributions concern improved methods of specifying, classifying, and measuring product characteristics and defects; of incoming, in-process, and final inspection procedures; and of process control. Much work has been done on sampling techniques[45] and metrology, including instrumentation. MIL-STD-105D[46] has now been recognized as an international standard effective in the United States, United Kingdom, and Canada.

The role of reliability assurance throughout this product cycle bears a similar relationship to each basic function, as does quality control to the manufacturing function. In each case, the reliability assurance activity acts as a feedback control, comparing the function output to the input requirements, initiating and following through on corrective action, as necessary, to insure that the output will satisfy the requirements and that the final product will meet the anticipated need.

System Analysis

System analysis provides assurance that all aspects of the operational need are properly recognized and translated into meaningful and feasible hardware design requirements. The study of the operational need should result in the definition of an envelope of mission profiles. The analysis should be based on the largest significant system into which the product is to be integrated, and should consider the effects of probable changes in that system with time.

A special effort must be made to review and coordinate *all* environmental requirements and *all* pertinent factors, such as anticipated operating modes; required equipment life, availability, and utilization; availability and skill levels of operating and maintenance personnel; availability of existing or planned maintenance and support facilities; and provisioning schemes.

Design requirements should be expressed in suitable design parameters, both for the entire product as well as for the major subsystems. All essential variables that will affect

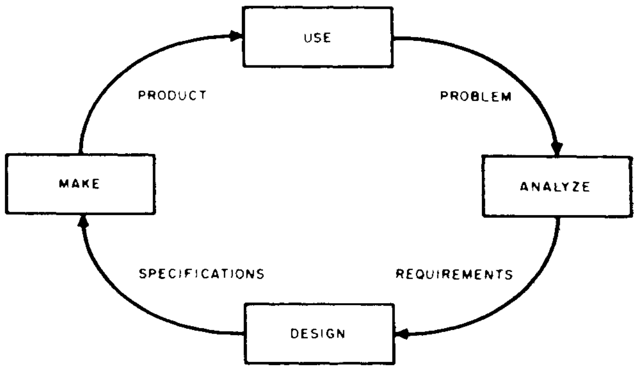

Fig. 8 Ideal product development cycle.

final product reliability must be included. Suitable design parameters are those that refer to valid theories and associated design control techniques and that can be verified by test. Unless achievement of a requirement can be verified by test, there is little purpose in including it in the specification. Unfortunately, few such suitable parameters have been developed in reliability technology; those in current use include: safety margins, mean-time-between-aborts, mean-time-between failures, mean-time-between removals, mean-time-between-maintenance, mean-repair-time, mean-time-between-overhaul, turn-around-time, launch rate, equipment availability, down time, ready time, administrative time, manhours of maintenance per hour of flight, etc. Except for structural safety margins, hardly any of these parameters are associated with effective design control techniques based on sound theory.

Established subsystem specification requirements should always retain a reserve for future growth or other contingencies, of which there will be many. For example, all complex systems tend to grow during the design and development phase, and there should be available a reserve of acceptable unreliability that can then be apportioned to the new items without decreasing system reliability below the contractual target.

Idealization

All phases of the system analysis should be considered from two basic viewpoints: 1) the ideal system, which represents the ultimate in functional desirability and is associated with no implications as to physical realization, development time, or cost; and 2) the optimum system, which is one of many which could be developed within the same set of physical, schedule, and economic constraints, but which, subject to the given constraints, is the one which most nearly approaches the ideal from a functional standpoint.

The system analyst must visualize the system requirements abstractly; that is, in a block diagram showing not hardware, but the essential functional nature of the devices or of quantities that could enter into the system requirements. All interfaces between all subsystems of the product must be clearly defined, as well as those between the product and the larger system of which it is a part. The feasibility of attaining all requirements should be investigated, and all design problems that require extensions of the state of the art should be identified.

A test plan should also be developed indicating what tests should be run, what functional units will be essential in running these tests, what data will be obtained, and why. The quantities to be measured for system evaluation should be indicated, as well as what data can be used to check other data and what precision is required for meaningful results. The plan should discuss how the test results can be checked and how they can be used to improve the design. Procedures should be established for the evaluation of partial test results that become available before the entire test program is completed.

It is necessary to know at this time what the test data will reveal about the system; otherwise it is easy to end up with a product that cannot be tested, or that if tested, yields meaningless data.

Optimization

The system analysis should encompass three basic considerations: 1) the optimum functional scheme, which should identify the relationship of all functions that will affect the product and influence future design decision; 2) the optimum plan of procedures, which pertain to carrying out the project; and 3) the optimum physical realization of the devices necessary to complete the product.

Although it is not possible at this stage to plan every detail of the project, it is important to have an explicit plan in as much detail as possible, and to keep this plan up-to-date throughout the many modifications and augmentations that will follow. A properly conducted system analysis is a key factor in determining whether a complex system will ever be completed or not.[47] Occasionally the system analyst will discover that the system cannot be designed logically on the basis of available information. Unrealistic reliability requirements also appear in many contracts that are not based on a system analysis, but are determined arbitrarily and included in the contract in order to comply with instructions of a higher procuring agency.

Design Assurance

If the basic design concept is sound, but subsequent execution of it is faulty, faults can usually be corrected after they are identified. But if the basic design itself is faulty, all may be lost. Design assurance is a dynamic, multistage process with evaluation and corrective action at many points throughout the design period. During a particular design, the state-of-the-art will change, and additional experience will become available from the manufacture or operation of similar products. All aspects of the design should be reviewed, including at least the following: performance characteristics (equipment, human operator); reliability; maintainability (human factors, logistics); producibility; value; and other factors.[40] The traditional techniques of design assurance are analysis and test; testing should be used to confirm analysis and to substitute where analysis is impractical; but it is expensive, it usually occurs late in the program, and at best it produces only partial answers.

Some current analytical techniques include establishment of requirements, reliability apportionment to lower levels, reliability estimates, determination of the reliability boundary and the environmental effects on reliability, configuration analyses and circuit analyses, applied mechanical loads and stress analyses, failure mode and effect analyses, electronic parts control, maintainability analyses (maintenance diagrams, accessibility, trouble and isolation analysis, limited life items, human factors), and safety analyses.[48]

The new requirements of WR-30 in effect call for designers to establish the trouble-shooting procedure (trouble detection, isolation, and repair or adjustment) as they design the product. In preparing this analysis, designers must visualize the system as it appears to the repair man in the field after failure occurs.

Reliability assurance testing

The testing program should be keyed to the analysis and the problems associated with the particular type of equipment. Generally, there are three levels of assembly about which some direction can be given, namely, components, subsystems, and aerospace systems. The definitions of these terms will overlap, depending on one's viewpoint. Transistor designers have sound reasons to consider a transistor a system, but the computer designer will consider the transistor a part, and the computer a system. In this paper, a subsystem is a major assembly of components, such as a propulsion unit, wing or fuselage, communications or navigation subsystems. A computer is usually considered a component, but depending on the functions it performs, it may become a subsystem. A subsystem need not be an integrated unit, but may consist of a number of units dispersed throughout the vehicle, such as a flight control subsystem. The term aerospace system refers to the assembly of subsystems required to perform an operational mission.

The reliability assurance testing program should be developed on the following basis.

1) Components: Reliability, maintainability, and safety should be determined analytically whenever possible, and always confirmed or demonstrated by test, as early as possible in the system development program.

2) Subsystems: Reliability assurance should be provided by analytical methods, supported in critical areas by whatever tests are feasible. Subsystem tests should verify that the predicted environmental conditions on each component are not exceeded, and that there is a margin of safety on every component of the subsystem. Subsystem tests should be run on the highest practicable level of assembly, and care should be taken to measure all interactions with the subsystem operating in a system simulator. Maintainability, integration, and safety tests assume greater significance on the subsystem level than they had on the component level.

3) Aerospace Systems: Maintainability and safety tests are a must on the system level, but reliability should be established analytically, based on component and subsystem tests. System reliability tests conducted after system assembly come too late in the development program; effective corrective action is costly and difficult and often impossible. The analytical predictions should be confirmed by actual operational data starting as soon as the system is introduced into service.

This approach cannot be applied rigidly in all cases, but it represents the normal procedures followed in the development of much equipment involving safety of life.

Tests-to-failure

In equipment involving safety of life, most reliability assurance testing consists of tests-to-failure and life tests. These tests are primarily screening tests designed to eliminate unsatisfactory designs. If a device is highly reliable, there is little point in measuring its reliability with any degree of accuracy when the available funds can be spent to greater advantage to improve the less reliable items in the system. Whatever tests are scheduled should be run as early as possible in the development program in order to supply information to the designer.

Tests-to-failure require careful specification of environmental conditions. No test should be scheduled until all applicable analyses have been completed and the weaknesses in the component have been identified. Tests should be run on the lowest level of assembly of functionally integrated interchangeable units. The terms "strength" and "stress" should be interpreted in their broadest senses to include, respectively, all factors either resisting or tending to produce failures. The number of tests that must be run to provide design assurance depends on the fraction of a design established by analysis, as opposed to trial and error. Any device designed in accordance with basic laws of nature requires one test to confirm the analysis[14]; thus, part of the problem is to identify those components that must be evaluated statistically. The basic cause of unreliability should be identified, and the test program designed to probe in the direction of these causes. The combined dynamic test environments should be judiciously selected to establish the weak points in the specimen. Tests do not necessarily have to duplicate operational environments, but the failures occurring in the laboratory should be exactly the same as those occurring in service at the same percent overload. In order to demonstrate the manufacturer's capability to reproduce a product of consistent and uniform strength, component tests to failure should be performed on several units, and the various specimens must all fail in the same mode when subjected to the same failing environments.

Tests-to-failure yield information of a type most useful to the designer, since achievement of reliability in the design stage depends to a great extent on the designer having a thorough knowledge of the strength of his components. The design engineer becomes personally involved if he is required to make a prediction (before the test) of the failure mode and to provide an explanation if the actual failures do not confirm the prediction.

Testing program requirements include schedules: classification of tests (development, maintainability assurance, reliability assurance, qualification, acceptance). Maintainability tests should be conducted before reliability assurance tests early in the development program on suitable mock-ups, if the actual equipment is not available. Reliability assurance tests should be completed before the approval of the qualification test plan.

Design reviews

Another technique that appears as a requirement is the formal design review.[49] The review must be chaired by a high-level individual, and all reviewers must be engineers with high technical qualifications. All interrelated disciplines should be represented, and all data pertinent to the review should be in the hands of the reviewers a reasonable time before the meeting to give all concerned a chance to study the data. The review team should critically examine the design from all possible viewpoints, using specialized checklists, which should be kept up to date.[48] The design review should not try to solve problems but to uncover them and recommend possible courses of action which might lead to a solution. Formal design reviews should be scheduled at key milestones throughout design and development.

Design approach

An organization's approach to design tradeoffs and to specifications is a significant factor in attaining reliability. The conservative approach is to make all design decisions in favor of reliability. This will result in a product that may have high reliability, but may not quite meet the performance and weight requirements. As soon as the item is operational, a weight-reduction-performance-improvement program will be instituted. The opposite approach is to design for maximum performance and minimum weight and to pray that the reliability will be adequate. When failures occur, the weak items are redesigned until adequate reliability is attained. Theoretically, both approaches should arrive at the same result. However, the conservative approach may never yield a product of the maximum performance and minimum weight, and the second approach may never result in a product with acceptable reliability.

Another aspect is the organization's approach to fulfilling specification requirements. One viewpoint is based on the *mistaken* assumption that the specification is a true and complete description of the customer's requirements for a new product; on new items, this is never the case. Nevertheless, the resulting approach is to examine each clause of the contract and then lay out the work such that every requirement of the contract or specification is satisfied with a minimum of work. The opposite viewpoint acknowledges the fact that a new system or product cannot be fully described before it is developed, and a contract is largely a gentlemen's agreement to work with the procuring agency on the development of the new system or product. A continuing analysis is made throughout the development of what needs to be done in order to accomplish the desired (probably changing) end objective. If the funding is inadequate, the deficiency is pointed out to the customer as soon as it is discovered. It is assumed that the procuring agency wants a good job and does not want something for nothing, but is obligated to maintain effective controls to assure that it gets its money's worth. Many will agree that flexibility in contractual matters is a necessity, but no one knows quite how to achieve it in the most responsible and economical manner.

Documentation

The *minimum* of documentation is still extensive and costly.[14] Those responsible for the generation of documentation should *understand* the requirements and continuously attempt to keep the paperwork to a minimum. Design assurance documentation serves two purposes: program control and design justification. For program control, analyses reports should be submitted and reviewed before design freezes and test plans, and test plans should be approved before start of test. For design justification, documentation should record the considerations that entered into a design decision, and the risks involved, for all items that might later fail in service. Should a failure actually occur later, the documentation should include sufficient detail so that, possibly years later, when no one associated with the initial design is available, a review can determine what design error was made, if any, and provide information so that better decisions can be made in implementing corrective action and in future designs.

Manufacturing Assurance

Manufacturing assurance applies a similar approach to the design and organization of the manufacturing facilities, tooling, and processes, and to personnel capabilities. This activity differs from quality control in that it is concerned with the before-the-fact design assurance of the manufacturing capability. Much work must be done before we learn how to identify the level of manufacturing and process control necessary to maintain required reliability for high-value, low-production aerospace equipment. The current approach is to do the best that can be done and assume that the resulting reliability is the best that can be achieved. Most normal manufacturing problems become magnified on space vehicles, especially manned vehicles. The required number of these vehicles is small, each is different, and each has to accomplish its mission on the first attempt.

Organization and motivation

The organization of a manufacturing facility, the methods of staffing and of providing incentives, should be determined by the type of product and the reliability that must be achieved. The transfer of manufacturing from a project-oriented experimental shop to a production organization is often accompanied by a serious degradation of reliability, although the production facilities may possess better designed and specialized tooling. Production personnel are motivated by factors such as pounds of production per man hour, which in turn establish a minimum acceptable level of quality in the facility, which becomes difficult to exceed. Such workers are not adjusted to giving special consideration to individual jobs as may be required for reliability purposes.

There is no such thing as an initially perfect set of drawings and specifications. Regular daily personal contact between the design engineer and all manufacturing, assembly, and testing personnel significantly involved in the initial construction and testing is essential to provide the shops with the correct interpretation of the designer's intent, and to provide the designer with the necessary information to correct his drawings and specifications. The greater the physical distance between the design office and the manufacturing, assembly, and test facilities, the more difficult it will be to provide effective communications. The smaller the number of units to be built, the more essential it is that this channel of communications be effective. In complex aerospace systems, which are designed and built by a large team of associated subcontractors located all over the country, it is becoming more and more difficult to establish and maintain this effective personal contact.

Eliminating human error

It is not uncommon for large, complex machined parts to have from 100 to 200 discrepancies when compared to the drawing, and each unit will have a different set of discrepancies. Many such parts are now being produced on tape-controlled machines to insure a minimum of unit-to-unit variation, even though the production of a few units may be spread out over considerable calendar time. In some cases it has proven effective to provide the assembly worker with components packaged so that they are available to him only in proper order for installation. He cannot install a component in the wrong way or in the wrong place or sequence. Much thought is being given to packaging to avoid damage in transportation and storage, both within a plant and between facilities, and to facilitate traceability and identification. Some electronic parts and equipment are stored under low-level power-on conditions. The use of clean rooms has become standard practice for certain type equipment.

Motivation and training of manufacturing personnel is an important factor in achieving reliability. On Project Mercury, NASA arranged visits of the astronauts to many critical manufacturing facilities for the purpose of encouraging production workers to associate their output with the man who was scheduled to fly the vehicle carrying the part they were making.

Formal procedures

Quality records are being used more and more intensively for systematically attaining improvement of manufacturing procedures. In one case quality records are continuously monitored for rejection rate by lot size, then by department, and then by operation. By identifying those operations responsible for the highest rejection rate, the manufacturing engineers can direct their efforts to improving those operations where the greatest gain can be achieved.[50]

In space work, it is becoming standard practice to require that all activities and procedures take place in accordance with written instructions. However, compliance must also be strictly enforced. Regular periodic critical examinations should be conducted to determine that the written documents are adequate for the intended purpose and that they are being complied with in all significant respects.

There are a great number of factors that determine whether or not a facility and its associated processes are capable of maintaining the inherent reliability during the product fabrication phase. Many of the factors involved have not been recognized as yet. There are few quantitative procedures to control to the extent required those factors that are recognized to have an influence on the suitability of the manufacturing process. Under these circumstances, it should be just as important to "qualify" the facility and the manufacturing process before release for fabrication as it is to qualify the product itself before release to production.

The contract should contain provisions for the immediate initiation of the formulation and implementation of corrective action, both with respect to design as well as to manufacturing defects. The speed with which corrective action is implemented, particularly with respect to those improvements that increase the overhaul period, is a basic factor in attaining reliability, especially when a small number of systems is involved.[51]

Raw materials

The manufacturing of raw materials also has a pronounced effect on the reliability of aerospace systems. At least two major problems exist in this field: obtaining precise knowledge of material properties under all pertinent environments and producing materials of uniform properties. Commercial consumers normally do not need to know material properties with the same precision as do aerospace manufacturers; there is little incentive for volume producers to do research and testing in order to obtain precise information on material properties for the small aerospace portion of their business. It is also often impossible for an aerospace manufacturer to obtain small runs of material with slightly different special properties, although there may be no technical reason why such material could not be manufactured. The astronauts' space suits for the lunar landing can be cited as one example of a new requirement for a small run of sophisticated materials whose properties must be known with precision and very carefully controlled.

Product Support

Among the responsibilities of the product support function is the evaluation of the extent to which the product satisfies customer needs. The group may also include trouble-shooting field engineers. Product support involves both contractor activity and operator activity, and in no other area do they so interlock and depend on one another. Normal buyer-seller relationships provide little motivation in this field. No product support group is worth its keep which is not completely motivated by a strong desire to "keep 'em flying" and which does not stand ready at all times, day and night, to exert superhuman efforts to live by this creed.

Product support planning

Product support planning must begin almost with the initial detail design of an aerospace vehicle. It involves analysis of mission requirements, strategic and tactical plans, manpower, training, and support equipment and facilities. It may require four years or more for the operator to develop the capability to support and operate a new aerospace vehicle. WR-30 is at present the best available document listing the information to be generated by the contractor and which the operator needs to develop his operational capability for a given aerospace system.

As an example of the planning required, it is estimated that the support manpower requirement for some modern high-performance military aircraft may run to over 70 man-hr of maintenance per hour of flight. To have such quantities of skilled manpower available at the right time and place is a major project. The product support plan must define the sources of this manpower, that is, reassignment of existing personnel or new recruitment. Training programs must be established, requirements for training panels and special devices must be developed, and instructors must be recruited and trained to man the training facilities.

Predicting maintenance requirements

Maintenance operations normally fall into two major categories: scheduled and unscheduled. Except for exceptional cases, scheduled maintenance can be established by the product support group based on past experience. Prediction of unscheduled maintenance requirements for new aerospace systems cannot be based solely on a general analysis of past experience. WR-30 requires a contractor to prepare a breakdown identifying within each subsystem those items subject to random failure or malfunction; estimating the failure rates and associated man-hour requirements for trouble detection, isolation, repair or replacement; and establishing the skill levels required for each defined job. This breakdown must be summarized in a meaningful manner to give over-all values for each subsystem as well as for the total system. Initial submittal of these data are required early in the design stage, with periodic revisions as the design and development progress.

One of the uses of these data is to develop a set of maintenance cards. Each card applies to a specific maintenance task and outlines the trouble-shooting, repair, and check-out procedure; the required tools, parts, special equipment, and skill levels; and (sometimes) the required number of manhours for each skill level. All of this information supplies the basis for the establishment of initial logistics and support activities.

The failure mode and effect analysis prepared during the design stage also serves as a useful document in establishing trouble shooting procedures, in establishing the contents of training programs, and in designing training devices which simulate actual failures. A new technique for detecting incipient failures is called *trend analysis*.[52, 53] Certain parameters are measured periodically and plotted for an individual machine. Surveillance is maintained over the trends exhibited by the plots; if there is a sudden change in the plotted values and they start to exceed certain limits, this trend is taken as an indication that a specific failure is about to occur. Application of the method at present is limited because of the lack of suitable instrumentation. Available instrumentation is designed for flight operations. Measurements for effective trend analysis purposes often must be more accurate. Expanded application of the method, therefore, depends on the development of specialized instrumentation.

Operational data reporting and processing

The empirical data for reliability studies are gathered by extensive operational and trouble data processing systems. Such data systems usually make extensive use of electronic data processing machines. The characteristics of such a data processing system is its ability to file large quantities of different types of information, to sort, collate, and combine all the various bits of information and perform accounting type of arithmetic with the data and then on demand to yield all of the information contained in the system bearing on a particular question in the format required.

There are also a number of unresolved legal difficulties associated with data systems which record deficiencies, particularly those information systems that present an easy exchange of information between contractors or between procuring agencies.[54] Component and subsystem manufacturers usually claim that information concerning deficiencies of their products is "proprietary." Technical personnel in government procuring agencies are primarily interested in obtaining hardware deliveries on schedule, and usually will go along with this claim and will not press the point.

Where Do We Stand Today?

The development of weapons systems in the past decade has been characterized by a growth in system performance capability by orders of magnitude, primarily due to two developments: the availability of more powerful propulsion units and the incorporation in the weapon system of many highly complex electronic subsystems. The rapid-growth of the electronic industry, and the necessity for the integration of this new equipment into the system, has created a multitude of new reliability problems. On the other hand, the development of the more powerful propulsion units has not produced reliability problems of anywhere near the same magnitude; in fact the achievement of gas turbine reliability has been noteworthy. In late 1959, unscheduled maintenance was seriously depressing airline profits.[55] The airlines instituted an intensive reliability improvement effort, which, together with other actions, has resulted in a spectacular improvement in the profit situation. Although engine reliability improvement is the most dramatic item (in terms of increased time between overhauls), the reliability improvement encompassed all mechanical subsystems. The total impact of these improvement programs is currently becoming apparent.[56]

An Analysis by Subsystem

A bar chart indicating the author's estimate of the comparative reliability attained by various types of aerospace flight hardware is given in Fig. 9. Two types of bars are shown. The cross-hatched bars are used to denote the reliability status of equipment whose acquisition procedures are molded by safety of life considerations, whereas the solid bars represent the reliability of hardware procured under competitive commercial practices. Safety of life depends on the continuous

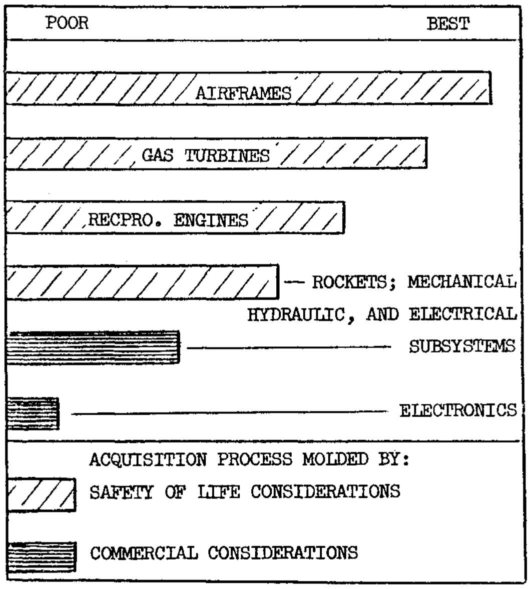

Fig. 9 Comparative reliability of aerospace flight hardware.

safe functioning of the airframe, powerplant, and flight control and environmental control subsystems; it is the primary consideration in all factors associated with these subsystems, and no solid bars are shown.

Each type of equipment seems to attain in major steps a characteristic level of reliability, which depends on the degree of innovation and sophistication associated with that type of equipment. Once a given inherent level of reliability is reached, further improvement can only be attained gradually and with great effort.

Airframes

Figure 9 indicates that airframes have attained the highest relative level of reliability. Structural failures are rare; when they do occur, the cause of failure is determined and the deficiency is corrected so that the same failure will not reoccur. However, there are still many unknown factors associated with the precise determination and control of the strength of materials under conditions of repeated and/or dynamic loads, high temperatures, and thermal shock, as well as with the transmission of dynamic mechanical and thermal energy through the airframe.[57, 58] Analysis techniques include the careful determination of operating environments; the control of the strength of materials; the design of mathematical models to represent the proposed structure; the design of the structure based on the foregoing such that adequate margins of safety prevail; verification of analytical predictions in laboratory tests; and flight verification of the specified applied environments. Flight tests also serve as the basis for the extrapolation of operational environments for the next aerospace system. The procedures are constantly being improved, particularly with respect to fatigue and life characteristics. Statistical techniques are being used more and more in designing flight tests and determining operational environments.[59–61]

Aircraft Gas Turbines

The reliability of jet engines in Fig. 9 is also rated as excellent, although not quite as good as airframes. The in-flight shut down failure rates for the engines in the Boeing 707 and 720 and the Douglas DC8 are shown in Fig. 10. The scheduled time between overhauls on these engines is now between 4000 and 5000 flight hours. In evaluating these achievements it should be noted that these engines are complicated machines, which consist of some 24,000 parts, making up 300 different assemblies, with an almost infinite number of possible modes of failure.[62]

Rockets; Mechanical and Electrical Subsystems

Depending on application, rocket engines, mechanical, hydraulic/pneumatic, and electrical subsystems may or may not affect safety of life, and two bars are shown for this group in Fig. 9. As a general rule, whenever safety of life is involved, special care is taken and the reliability achieved is on a higher level.

Rockets

The procedures followed during the development of the RL 10 rocket engine to assure reliability in the final product deserve serious study, especially in view of the fact that the production rates are low compared to those of jet powerplants. In general, the development of the RL 10 followed the same practices as those used in developing a new jet engine.[26] The RL 10 is a liquid-hydrogen, liquid-oxygen engine and represents a major advance in rocket propulsion. As of January 30, 1964, the RL 10 was credited with eight successful space firings out of eight attempts.[63] The conclusion to this analysis is that the pressure to safeguard human life provides an effective incentive to develop methods to assure high systems reliability.

Mechanical and electrical subsystems

Power-operated flight-control subsystems are highly complex mechanisms that must be integrated into the airframe. They include many types of mechanical, hydraulic, and electrical elements. The design of such subsystems requires consideration of a wide scope of factors, many of which elude analytical treatment.[11]

The advent of powered flight-control systems in the early 1950's posed a formidable problem affecting safety of life. In the face of this challenge, BuAer developed a new and different qualitative analytical approach, which has since been developed into an effective design assurance technique known generally as failure mode and effect analysis.[64–66] Such an analysis should be performed by an expert other than the designer in order to introduce an independent viewpoint. The analysis consists of a critical review of the system and identification of all critical components or functions, preferably in a functional block diagram and a sequence of operations chart. Each critical item is in its turn assumed to fail in its various possible failure modes and in critical combinations with other system failures. An estimate is made of the environmental levels at which each failure mode will occur. For each assumed failure mode, the consequences of the failure are determined, the compensating provisions are investigated, and the probability of occurrence and the criticality of the failure are computed. The analysis becomes really significant when it is verified by a test-to-failure program, which demonstrates that the system will fail in the modes and under the environments as predicted in the analysis. Unless a designer has a good feel for the circumstances under which his design will fail, he is not in a position to design a reliable aerospace product. These verifying tests-to-failure must be run as early as possible in the development program, so that effective corrective action can be taken when deficiencies are uncovered. When the failure effect analysis approach is intelligently combined with systematic tradeoff studies, it appears to constitute one of the most powerful available techniques for the reliability control of the design phase.

Among the major technical problems affecting the reliability of mechanical systems are those associated with heat transfer, fatigue, friction (including wear), and control of leakage. We still do not have completely satisfactory solutions to many "simple" design problems that have been with us for many years, such as reliable hydraulic and electrical quick disconnects.

Electronic Equipment

In commercial operations, failed avionic equipment is quickly and easily replaced and is seldom responsible for schedule delays. There is, therefore, little commercial pressure to provide greater incentives for improving reliability. Procedures protecting safety of life are expensive and can only be justified when the need has been demonstrated. Such procedures are therefore normally adopted, by regulation, only as a reaction to fatal and well-publicized accidents. Since relatively few accidents have been definitely ascribed to airborne electronic equipment in scheduled airline operation, consideration for safety of life exerts little or no influence on the procurement for electronic equipment; hence only a solid bar is shown in Fig. 9. Military procurement practices for advanced airborne electronic systems emphasize performance and the maintenance of competition between suppliers. There has been little or no effective emphasis on design control procedures; in particular, no effort has been made by procuring agencies to adapt to electronic design the effective design control techniques that have been successful in the other areas discussed previously.

Design assurance

Methods for predicting reliability during the design stage have been developed, and within limits these methods will give reasonable answers. Table 2 gives predicted and observed values for three complex contemporary items of electronic airborne equipment.[35] The observed values were measured under actual operating conditions over a considerable period of calendar time and operating hours.

The current reliability of electronic airborne subsystems compares unfavorably with that of equipment involving safety of life. Both jet and rocket engines are new major items that are developed on compressed schedules concurrent with airframes. They have attained a much higher level of inherent reliability than have electronic subsystems and approximately within the same time interval since World War II. It has been shown that spectacular improvements in the reliability of airborne electronic equipment can be achieved by applying the same design controls that are currently used to assure the reliability of nonelectronic equipment involving safety of life.[67] In particular, the Army Ordnance Missile Command has followed this approach with success. Its Shillelagh missile is alleged to be one of the most reliable pieces of hardware ever developed. The Shillelagh reliability program is similar to the one described in Ref. 68. In my mind, there is no technical reason why electronic equipment cannot be as reliable as a jet engine.

Integrated circuits

At present, application of microminiaturization is limited to low-frequency, low-power, digital circuits. Nevertheless, intensive work is being done to expand this scope, particularly to find ways to perform tasks formerly requiring analog circuitry. The IMP Spacecraft[69] makes extensive use of integrated circuits and at this writing has been successfully operating in orbit for over three months. The major gain obtained from the use of integrated circuits on this spacecraft was the increase in reliability. Current test data are inadequate to determine component reliability properties with any degree of confidence, but there is some expert opinion that planar construction is more reliable than discrete elements under all maximum environments presently anticipated in aircraft and space vehicles.

Systems Approach

Although system effectiveness is becoming a popular concept, there are few examples of complete programs where this type of effort has been applied. Possibly the most publicized effort to date has been Minuteman. The contractor realized early in development that achievement of Minuteman reliability objectives would require a hundredfold increase in the state of the art and that, given the electronic components available at the time, this increase in reliability could not be achieved solely by superior system design. Hence it was recognized that part of the reliability program would have to be directed toward the improvement of the inherent reliability of available electronic components.

In addition to the parts improvement program, a vigorous program of reliability assurance in design and manufacturing was established. As in any pioneer effort, the Minuteman program included many new procedures that proved to be worthwhile, whereas others turned out to be less effective. It would therefore seem beneficial to conduct a comprehensive objective review of the Minuteman reliability effort to determine those features that proved to be significant.

Technical Causes of Unreliability

The four major causes of unreliability[11] are listed in order of importance as follows: lack of reliable methods for predicting operating environments; unit-to-unit variation in ability to resist failure of components that are within specification limits; design errors; and manufacturing errors (out of specification limits). Items 3 and 4 can be controlled by good inhouse reliability and quality control procedures. Solution to items 1 and 2 requires extension of present technology. These items constitute unresolved reliability problems of the first magnitude. Reference 11 suggests much that can be done to cope with these two serious items. Reference 44 quotes an Air Force management survey[70] of the practices of two dozen major contractors and lists the following deficiencies: 1) many design changes needed to correct earlier design oversights; 2) generation of system and interface specifications late in the program; 3) many design incompatibilities revealed in system test; 4) many reliability considerations made on an after-the-fact basis rather than in initial design; 5) unilateral design releases without design review; 6) engineering decisions not supported by analysis, tradeoffs not identified; 7) management is prone to correct only the visible problems rather than the basic cause; and 8) tendency toward excessive "management by exception" without adequate procedural control.

All of the items on this Air Force list are to a great extent correctable or controllable items, as are items 3 and 4 mentioned previously. It should be a requirement that all new reliability program plans include specific procedures to prevent recurrence of these listed deficiencies. Then we could turn our attention to the major problems associated with foremen-tioned items 1 and 2.

Administration of Reliability Programs

Reliability Incentives

Specification requirements alone can no more produce reliability than police power alone can create morality. There must exist positive incentives that reward the manufacturer when he produces a reliable product.

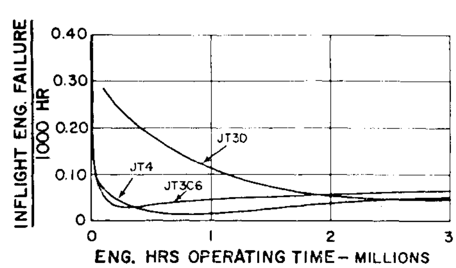

Fig. 10 In-flight engine failures in commercial operation.

Free market competition

In ordinary commercial life, competition among equipment manufacturers normally provides the incentive to establish and maintain a given level of reliability. If the product were never to fail or to wear out, the ideal market would eventually become saturated; there would be no replacement sales, and the manufacturer and his distributors would go out of business. The system must permit its successful practitioners to survive and make a profit. For the manufacturer and distributor to survive, there must exist some level of maintenance and replacement, that is, unreliability and wearout. There is a need for a steady or increasing demand on production facilities. Sales of spare parts and associated repair services are an important part of the commercial equipment business. When equipment breakdowns occur, prompt and friendly service provides continued personal contact with the customer and helps to assure future replacement sales. Over-all costs should consider, for equal technical performance, at least initial costs, useful life, maintenance and support costs, and probability of obsolescence. Competition tends to minimize the over-all cost to the customer at a level that permits the manufacturer and distributor to survive and make a profit.

Single source-rigid schedule procurement

The force of competition does not exist to the same extent in the development of new weapons and space systems as it does in commercial life. Product demand and market growth do not follow the laws of the free commercial market. New weapon and space systems are produced in small predetermined quantities on a rigid development schedule based on estimates of future requirements resulting from strategic or hostile developments. This new equipment usually involves advances in the state of the art, is very costly, and competitive parallel development is generally out of the question. The development risks are great due to the advanced technological character of the systems and the vast size and extended duration of the programs. Except in unusual circumstances, competition exists only in the proposal stage. Once a supplier has been awarded a contract, for all practical purposes he becomes the sole source for the item. There arises the serious problem of how to motivate a single source component or subsystem supplier to produce a reliable product in a situation where the more reliable is his product, the fewer units he will sell, and where the savings attained by the customer may be used to strengthen a competitor.

The need for positive motivation is magnified by the necessity for maintaining a fixed delivery schedule, particularly when long development periods are involved. If on the scheduled delivery date a single source item not involving safety of life does not meet the required reliability, there is very little the customer can do about it. It is too late for the customer to use his only effective club: to proceed with the transfer of all or part of the contract to another supplier. Within certain segments of the aerospace industry, concern for safety of life provides the strongest, and at times the only, motivation for achieving reliability.

Struggle for survival

A comprehensive study of the weapons acquisition process by Harvard[71] points out that defense contractors are subjected to considerable business insecurity. They must shift their product lines rapidly as technological advances are made, and they must compete with new firms entering their field with the help of government subsidies. This uncertainty with respect to future business results in a tendency to emphasize development of current weapons so as to enhance capability for future projects at the expense of good performance on current projects. The actual profit level on current contracts is secondary to long-term survival considerations. Of particular interest is the conclusion in the Harvard study that good past performance is not a reliable indication of good future performance in the development of advanced weapons. The effectiveness of so-called financial reliability penalty clauses is therefore open to serious question, when lack of profit, as long as it does not endanger company survival, is not necessarily a penalty, and when even actual money losses may be balanced by eventual gains in experience and facilities that may improve long-range survival potential.

The desire to maintain good relations with the customer with a view to future business, and concepts such as company image, reputation, and professional pride, all must be given consideration. Certainly these factors carry weight in companies that are completely dependent on the aerospace business. There are, however, a number of companies supplying major aerospace subsystems that also have sizeable commercial operations. Some of these firms are multidivisional giant corporations that make a large percentage of their profit on the commercial market. A few of them have been fighting hard over the past decade to attain status as prime system contractors. They do not relish the thought of accepting future subcontracts from the present primes; they intend to be prime on the next project. They may have little interest in helping the present prime to "look good."

Under these complex circumstances, and considering the extended time period between contract award and delivery, it seems to me that in some cases current contracts would be primarily valued for their potential in serving as stepping stones to future contracts. In five to ten years, when deliveries on current contracts are due, the organization will have in-house a sufficient number of subsequently acquired contracts to insure its survival. The current contract at that time will have made its contribution to the survival of the organization years ago, and customer complaints concerning lack of reliability will no longer carry any real weight. Hence it is important, at the time of original contract award, to keep in mind that reliability program proposals consist of both technical and public relations aspects.

Self-interest vs project interest

In my opinion, under present procurement practices, it is not in the self-interest of the supplier to make the all-out effort required to produce reliable equipment, when the procurement is for single-source, rigid-schedule complex items not involving safety of life and requiring extended development time. We lack the means for providing the incentive to make the manufacturer think of his product as a functioning part of the system. Until we learn how to achieve this realignment of interests, it seems to me that the customer must rely on his policing power to monitor all of the suppliers's key operations to assure that the work being done is in line with the customer's interests.

On recent contracts, the Department of Defense has been placing new emphasis on cost effectiveness. To meet this challenge, the defense industry must improve its operating methods. To do this requires an understanding of the aerospace system acquisition process. Within this framework, one of the jobs to be done is the development of a sound application philosophy for reliability and maintainability techniques.

It seems to me that under these circumstances an effective system of financial incentives could be developed which would provide for additional fee whenever an acceptable test plan is submitted on schedule and the test is completed on first trial as planned. This should be particularly effective with tests-to-failure, conducted during the early stages of design and demonstrating that specified minimum margins exist, and with qualification tests, when run by the customer or by an unbiased outside laboratory.

Subcontractor Control

A characteristic of modern aerospace systems is the large number of major subcontractors involved. Not too many years ago, a prime contractor manufactured a high percentage of what he sold. Today, a significant portion of the much higher cost of an aerospace system represents equipment designed and manufactured by subcontractors and suppliers.

Design is a dynamic process, and during the detail design and hardware development phase, every system and subsystem tends to grow as additional technical information becomes available, as interferences and interactions are discovered, as tests demonstrate that performance estimates are deficient, and as items and considerations that were overlooked are uncovered. In order to design a workable aerospace system in an efficient manner, the prime contractor should have complete control at all times over all design, including all supplier equipment, so that he can make the best tradeoffs and take advantage of the latest analytical and test information as it becomes available. Design is a cooperative effort, and there should be a free flow of information between the contractor's and supplier's designers, just as if the supplier's designers worked in the prime's design office. When a part fails in service, it makes little difference to the customer in whose shop the part was manufactured; the aerospace system carries the trademark of the prime.

In actual practice, the prime has limited effective control over the supplier's design and development activity. Suppliers consider a prime's monitoring activities at best as distracting, keeping them from progressing with the job of implementing the original specification. Many suppliers regard their design and manufacturing activities as proprietary, and they resent any intrusion by the prime. Whereas the prime feels a responsibility for picking the supplier's specialized brains in order to get the best possible equipment, the supplier only recognizes an obligation to deliver a piece of hardware in accordance with established contractual agreements.

Present traditional systems of supplier-control paperwork are designed, to an extent, so that they can be administered from a legal viewpoint; they are not always compatible with the engineering job to be done. For example, much reliability work is done merely because it is a contract requirement. In this situation, it is most important that the program plan be in writing and that the supplier understand what is required, and why, before the contract is signed. Otherwise, funds allocated for the reliability control program will be spent for other purposes.

There has been little open and honest discussion of these relationships between prime contractor and suppliers and their effect on reliability. There are many thousands of vendors, but only a handful of highly competitive primes. At reliability conferences and symposia, the vast majority of speakers and audiences consist of vendor representatives; they establish the atmosphere, and discussion tends to be one-sided and revolve around their problems.

Regardless of these conflicts of interest between the prime contractor and his vendors, there are areas where excellent relations exist. The outstanding example is between airframe and engine manufacturers. All of the physical and technical problems are there: concurrent development, extending over periods of years, of complex major equipment; coordination of extensive interfaces; and coordination of delivery schedules. The major reason for this good relationship is that safety of life is involved, and neither airframe nor engine manufacturer can afford to take any unnecessary risk in this respect.

Reliability Program Plans

Most reliability specifications require the submittal of a reliability program plan that becomes a contractual document. The plan spells out in detail what the supplier will do during design and development to assure that the product will achieve the desired reliability when it is delivered. A program plan should include a detailed listing of the specific proposed tasks, man-loading per task, and procedures to implement and control these tasks; it should identify the organizational unit with the authority and responsibility for executing each task, the method of control to insure execution of each task as planned, and the scheduled start and completion dates of each task. These data must be in a form that permits technical auditing by the procuring activity. The information provided should include the method of analysis to be used as a basis for achieving the proper balance of effort and resources from a reliability standpoint. Records should be maintained on the status of actions to resolve problems. The proposed manner of demonstration of reliability at stated confidence levels is required in some specifications.

Each program must be designed to cope with the specific problems associated with the hardware being procured. A weapon system plan should include provisions for reliability objectives or requirements; feasibility studies; reliability apportionment and assessment; formal design reviews; analytical techniques such as configuration analyses (tradeoff studies), failure mode and effect analyses, circuit analyses, mechanical and electrical stress analyses, maintainability analyses including trouble and isolation analyses and human factors considerations; materials and electronic parts control; test plans; configuration control and parts traceability; and design check lists. The plan should describe the reports to be submitted and indicate the submittal schedule.

The Task Ahead

Today almost all engineers and managers in the aerospace field have at least heard about reliability/maintainability; almost all new aerospace equipment contracts contain some reliability/maintainability requirements, and all large aerospace companies have responded by establishing special engineering groups.

Our commercial economy was built on the competitive system, but we are now organizing vast transient, geographically dispersed design teams consisting of former and future competitors, and we are requiring that isolated designers work intimately together as if they were sitting at adjacent desks, that they share their knowledge and their trade secrets, and that their companies put project interest ahead of self-interest.

Congressmen and senators are accustomed to purchasing consumer goods that are fully developed over a long period of time before they are put on the market. We are now asking these men to appreciate the risks and technical difficulties involved in a new and unique situation, one of developing over periods of years vast systems that are beyond the state of the art. We ask them for understanding when six successive Ranger shots fail, at tens of millions of dollars per shot.[72] The reliability problem is therefore not only a technical one; to achieve maximum reliability in aerospace systems, particularly in our space exploration program, will require modifications in our ways of doing business, and will require changes in basic attitudes on the part of everyone in any way associated with the program, from mechanic to top government official. This calls for responsible statesmanship in combining cost effectiveness and system effectiveness, giving due consideration to total cost of ownership over the equipment lifetime.

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