AEROSPACE-SYSTEM APPLICATIONS OF RELIABILITY TECHNOLOGY DERIVED FROM THE ELECTRONICS FIELD

CHESTER I. SOUCY
Head, Avionics Standards Branch
Air Materiel Command Headquarters
Royal Canadian Air Force
Ottawa, Canada

ABSTRACT

System effectiveness assurance techniques developed for electronics can be adapted to provide a guide for aerospace systems. Reliability alone is an inadequate goal requiring balance by maintainability. Graphs of reliability and maintainability show these have decreased between 1935 and 1955 due to increasing system complexity and stresses. Improvement goals up to 10,000:1 failure reductions for manned space vehicles will require other design changes besides system simplification and parts improvement. Extensions of mission times and communication-control distances will be astronomical in size. Rising acquisition costs for complex systems require reliability and maintainability improvements to decrease the budget portion consumed for maintenance. Aircraft accidents and failures are analysed, and human factors are examined in system design, and in misleading reporting and analysis of failures, including biased emphasis of failure rates in lieu of downtime. Reliability goals and achievements for aircraft, missiles, and satellites are represented graphically, and the 1,000:1 variation in failure rates in various vehicles and environments. Some current assumptions on failure distributions are queried, and the merits of the Weibull function are considered especially for mechanical devices. References are given for reliability and maintainability prediction and design techniques. Cooperation is recommended between military and industry organizations, and provision of adequate procurement policies and management support.

INTRODUCTION

In recent years the word "reliability" has acquired a narrower definition as depending only on the inverse of the failure rate. It no longer means dependability, since maintainability and other essential design parameters are not included. To ensure a proper perspective on related problems, I shall discuss the more comprehensive characteristic labelled "systems effectiveness." Such a broad treatment avoids the imposed separation of programs for reliability, maintainability, and other characteristics that has been common in the electronics industry. Thus, both the delays in progress and the confusion of competing and mutually exclusive engineering and assurance programs can be avoided [1]. Reliability is not a goal in itself, but only one important factor of several that are essential to systems effectiveness and aerospace mission success.

About twenty textbooks have been written from mathematical, quality control, and components' points of view; relatively little from the designer's point of view has appeared in the last few years. The one referenced [2] is the most consistent with the systems-effectiveness approach of this paper.

I realize that aeronautical engineers and others here concerned with aircraft design have always sought reliable designs to assure the safety of personnel and vehicles. You are accustomed to applying safety factors and anticipating effects of wearout and fatigue, whereas these concepts were lacking in most branches of the electronics industry until about fifteen years ago. The present paper discusses how the reliability technology developed for electronic and avionic equipment in commercial, and particularly in military use, can be extended—without its initial mistakes and misdirected efforts—and adapted to mechanical and overall aerospace-system requirements.

An accompanying challenge is presented: that you examine with scepticism, and purify with doubt and testing, the technology derived from the electronics field that, at present, may often be more assured than profound, and serve better as guidance than gospel.

INCREASING COMPLEXITY OF SYSTEMS

The rapid rise in complexity since the middle of World War II is one of the principal factors of the reliability and systems-effectiveness problem, not only for electronic equipment but for the entire aerospace system. Primarily, this is because the equipment failure rate increases in proportion, and the equipment reliability decreases exponentially, with the number of independent parts that can cause failure.

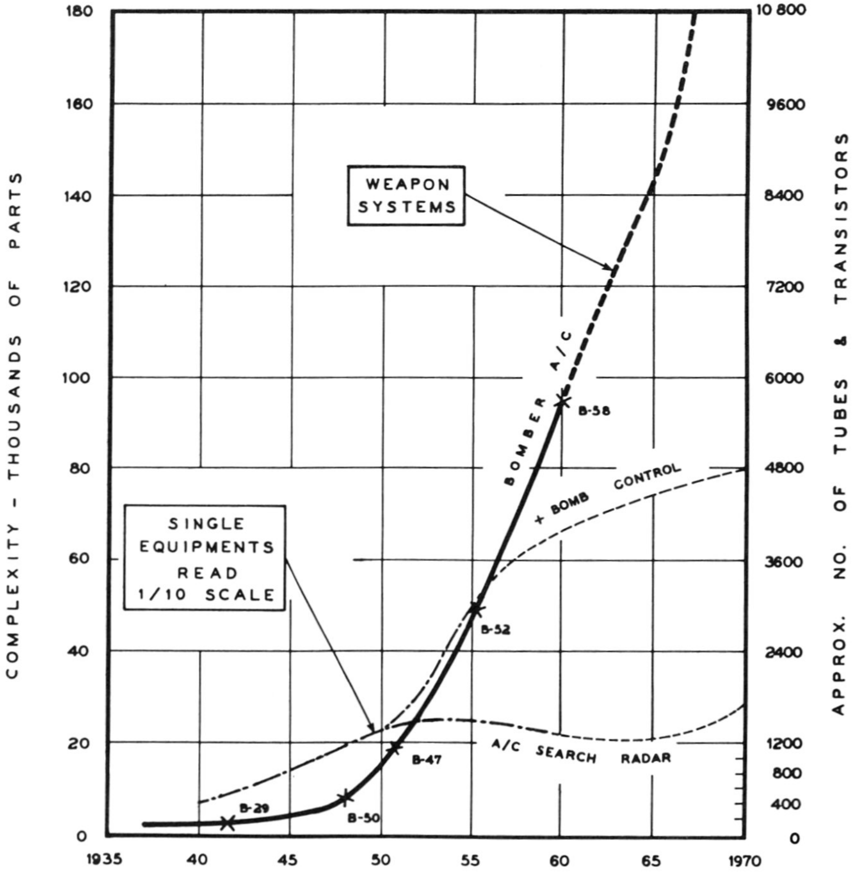

Figure 1. Increasing complexity of military electronics.

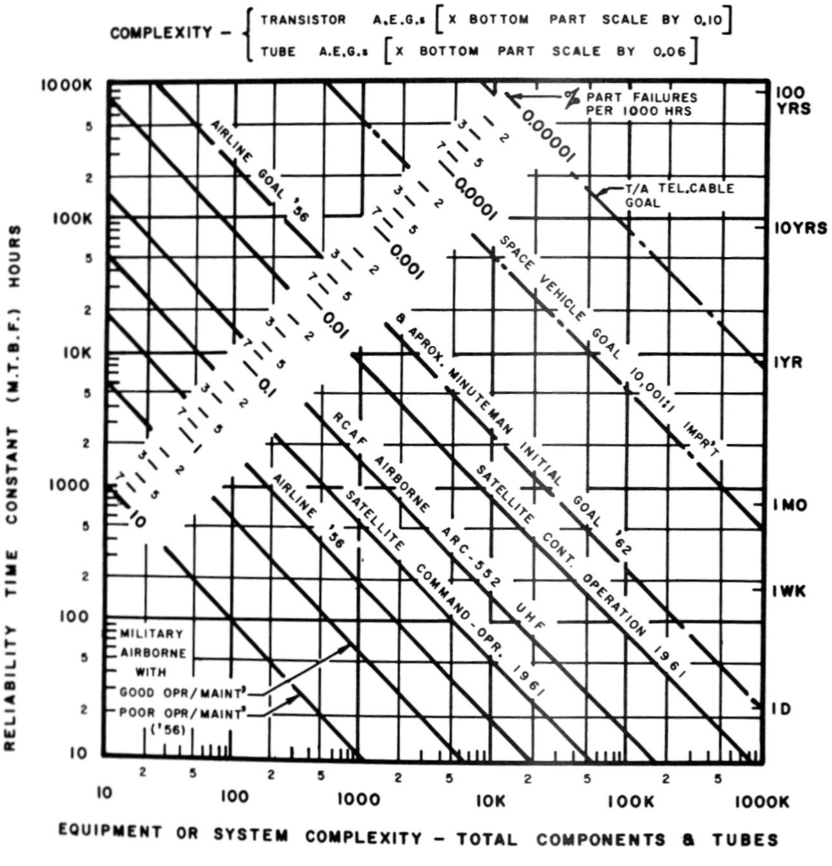

Figure 2. Reliability and failure rate dependent on complexity, design levels, and operating-maintenance environment.

The economic consequences of the need for greater maintenance support effort and skills in present-day systems, and—for military usage—the tactical consequences of increased failures, arise from the greatly increased complexity. Both demand equal attention. The electronic-system growth resulting from demands for more sophisticated performance is illustrated in Fig. 1, with data projected to 1970. This chart also shows, in an example of search-radar systems, a split in design tendencies since 1950, between simplification of design to improve reliability on the one hand and, on the other, an opposing accelerated increase in complexity due to adding new performance functions demanded by operational users. In Fig. 2, updated from my 1956 paper [3], the various curves are labelled according to the class of equipment, its usage environment, and the state of the art applicable to its performance or goal. The order of merit of the maturity achieved in the man-equipment-environment system is indicated on the diagonal scale of per cent (average) part failures per 1,000 hours. An inverse linear relation is shown between "complexity" and the "reliability time constant," which, unfortunately, is usually interpreted as the mean-time-between-failures (MTBF). The lower part-complexity scale is supplemented by equivalent upper AEG (Active Element Group) scales determined by the number of electron tubes or transistors and their relation to the total part population.

In 1956, my paper [3] and Robert Lusser's [4] warned of an increasing deficit between reliability improvements and the design demands of increasing complexity and severity of systems environments. In 1960, a provocative book, *The Crisis We Face* [5], challenged the adequacy of military weapons and aircraft. These dire prophecies by Steele and Kircher were too pessimistic, because they were based on outdated data and on ignorance of the unprecedented success in reaching the reliability goals of the Minuteman missile and of the then-unproven globe-girdling flights of pioneer American and Soviet astronauts.

Figure 3, which updates my 1960 estimate [1] of the increasing design load, optimistically predicts the closing of the gap between electronic system needs and the achieved improvement in parts, equipment, and circuit reliability. Figure 4 is based on Fig. 3 and on an RADC report re maintainability progress [6]. It shows how the deficit between needs and deeds widened up to 1955, due to the increasing complexity of systems and the then-current neglect of maintainability in design. The 1960 prediction that complex black boxes might be as dependable in 1966 as the simple 1935 models may appear optimistic even now, considering unstabilized current trends. The explosive growth of complexity between 1954 and 1964 of U. S. Navy fighter-bombers [7], shown in Fig. 5, exceeds the Fig. 1 rate and shows the ever-increasing dependence upon electronics.

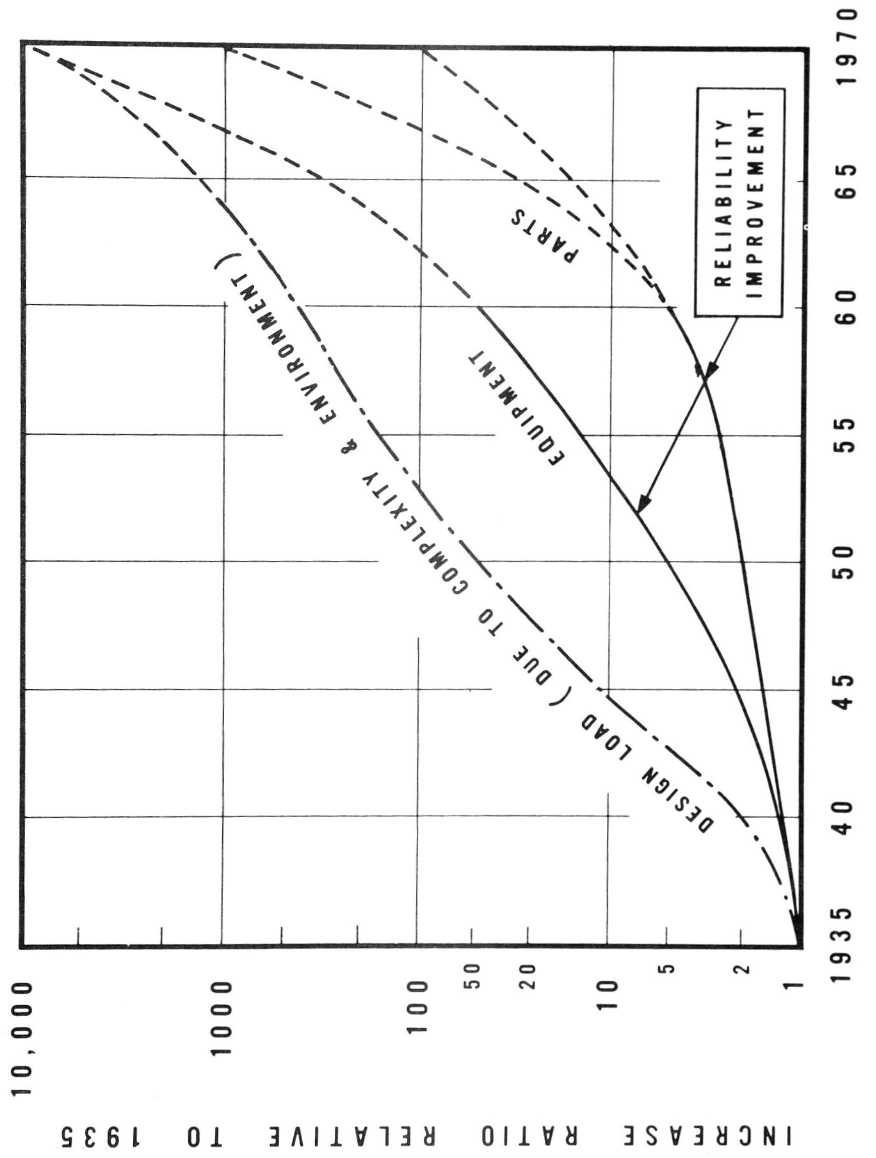

Figure 3. Increasing design load vs. reliability improvement.

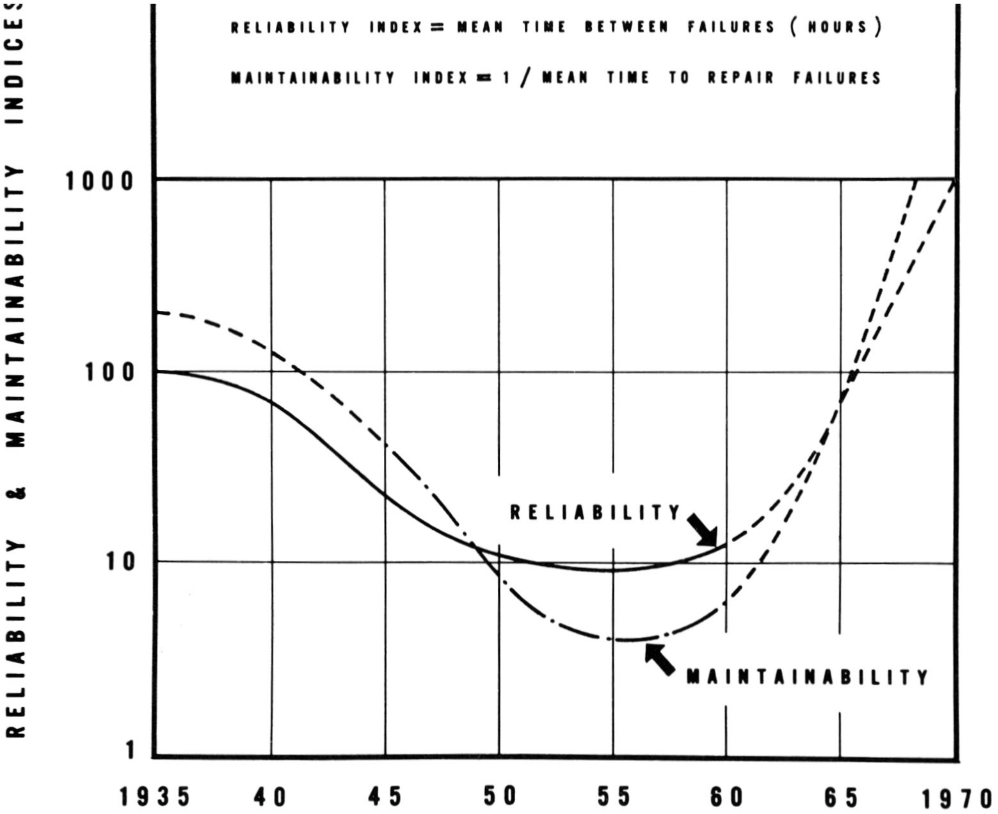

Figure 4. Decline and rise of military electronics dependability.

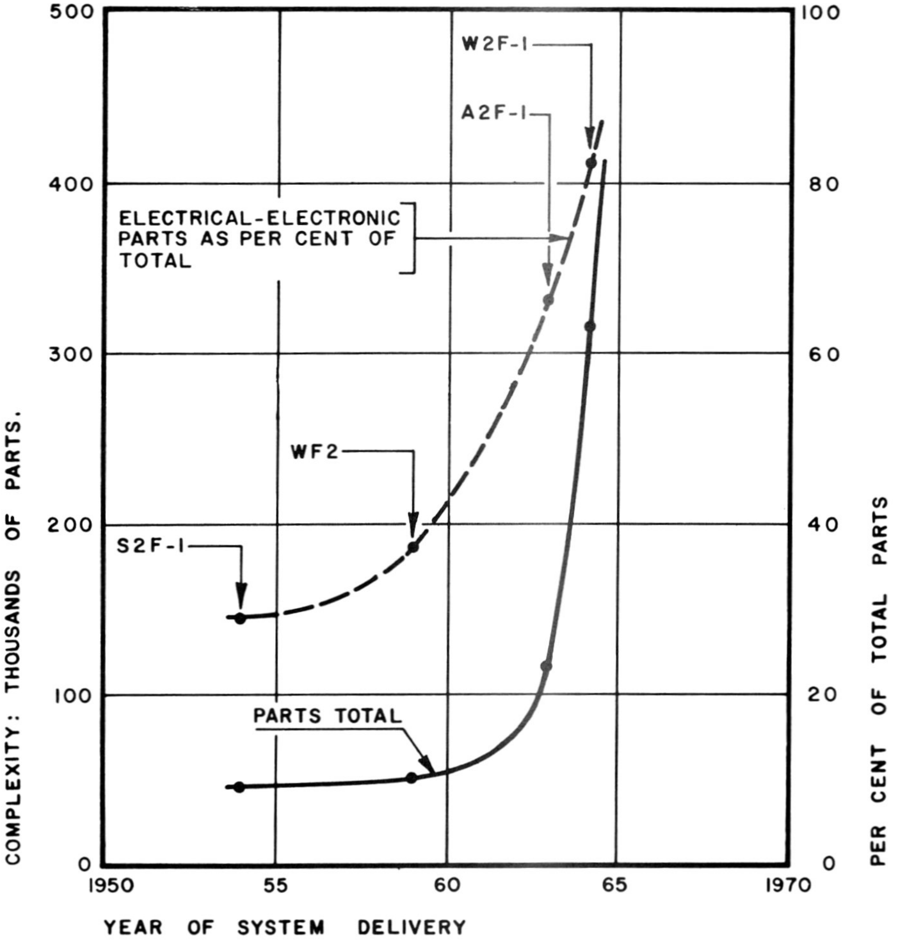

Figure 5. Accelerating complexity and electronics dependence in F/B aircraft series.

The improvements relative to 1935 in the state of the art required to reach the reliability goals of manned space vehicles having current complexity levels have been estimated as 10,000-to-1 [1,8,9]. However, Steele and Kircher are still supported by a 10, or perhaps, 100-to-1 uncertainty of reaching this goal, despite the reassuring reliability progress in the Polaris and Minuteman missile programs. The reliability improvement needed for earth satellites has been estimated as 200 times greater than that of current airborne communications equipment [10]. The superlative reliability goal of the transatlantic telephone cable, which assumes virtual elimination of the random failures characteristic of electronic equipment, is shown in the uppermost curve in Fig. 2. It attests to the feasibility of tremendous improvements with good component part and system design and quality control [11].

INCREASING ENVIRONMENTAL STRESS AND MISSION TIMES

The environmental stresses, increased up to seven orders of magnitude, to be faced by future aerospace systems are known and considered by designers. The mission time for military aircraft has been extended to 24 hours, and even longer with in-flight refueling. This is greatly exceeded in space travel, for example, 730 hours is predicted for a relatively short roundway moon trip. The much longer goal of 25,000–30,000 hours is proposed for economically feasible communications satellites, and the standby-readiness condition of missiles has been extended to three years. These represent an important new time-extension factor demanding from 30 up to 1,000 to 1 reliability improvements in a system of the complexity level of an aircraft-electronic-guidance system. High reliabilities are naturally demanded for reasons of economics and human safety in space travel. To evaluate the difficulties, it should be kept in mind that, for reliabilities of 99.9, 99, and 90 per cent, the associated mean times between failures must exceed the mission times by factors of approximately 1,000, 100, and 10. For a seven-month Mars return trip with a one-in-a-hundred chance of failure, the required MTBF would be 58 years (100 times greater).

Fortunately, there is, except for high radiation levels, an otherwise compensating uniform low-stress environment for satellites. This is even more favourable than that of laboratory computers in fixed ground environments in promoting long life, as shown in Fig. 6, which is based on several sources covering many usage environments [12–15]. This benefit is illustrated by the performance of satellites launched from the United States, including the command-operated ionosphere-sounding Alouette I. The latter, shown in Fig. 7, was designed by the Canadian Defence Research

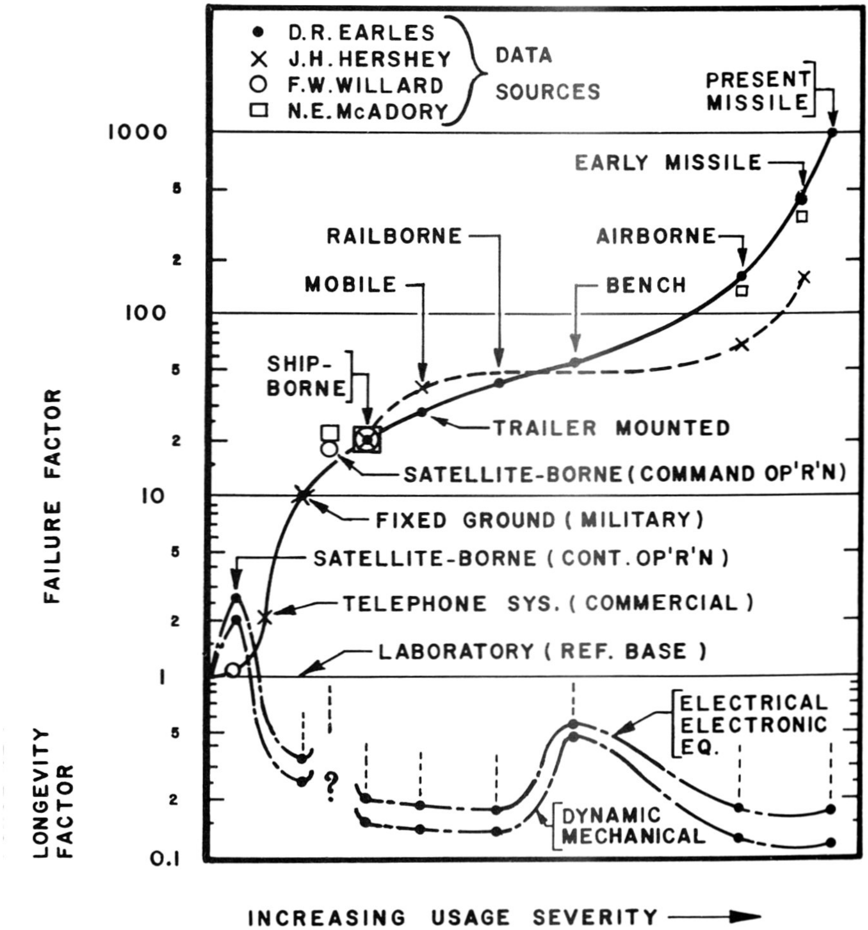

Figure 6. Failure rates and component longevity vs. usage environment.

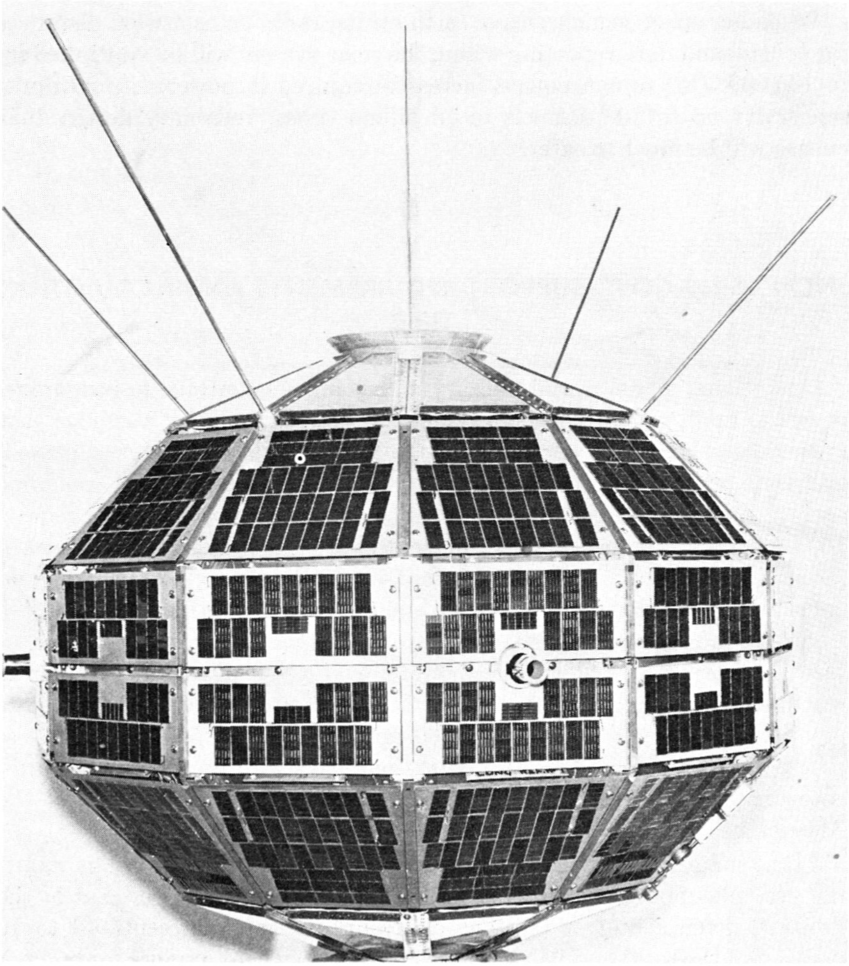

Figure 7. Alouette I ionosphere-sounding satellite, with 75- and 150-ft antennas retracted. (*Canadian Defence Research Board Photo.*)

Telecommunications Establishment, launched in September 1962, and was still operating a year and a half later.

In Fig. 6, the "longevity factor" provides a measure of the useful life period (wherein the "normal" failure rate is assumed to apply), which lies between the initially high "infant-mortality failure" period and final period with high "wearout failure" rates. While longevity tends to decrease with severity of usage, this decrease does not correspond directly with the increase in failure factor.

When our space vehicles leave earth orbits, radio transmission distances for control and data reporting within the solar system will be multiplied up to 100,000. Due to consequent increases required in power-output/input-sensitivity up to 100 decibels or 10 billion times, reliability design difficulties will be much greater.

INCREASING COST, SUPPORT REQUIREMENTS AND ACQUISITION TIME

Operational planners and military managements continue to encourage, or fail to limit, growth in system complexity, undeterred by warnings that critical complexity levels relative to the state of the art have been passed, and that maintenance costs and effort required will exceed our economic and personnel capabilities [1]. Since current weapon systems require 10,000 to 20,000 man-years development effort, the fantastic rise in cost of aircraft from about $2 per pound before World War II to $120 in 1962, and considerably higher for their weapon equipment fitted, is not surprising [9]. Figure 8 shows that aircraft costs are now accelerating at a still higher rate [7]. Former President Eisenhower's evaluation of a B-58 bomber as worth its weight in gold is no longer startling. For satellites, previous costs per pound of payload up to $15,000 may be reduced to $600 with less costly Saturn boosters (thus bringing them back into the "gold standard" category!), while $10/lb is optimistically predicted for future use of the Astroplane concept.

Many large aerospace systems cost from $1 to $35 million without counting ground support, which, for missiles, may amount to 85 per cent of the military defence budget [3]. The electronic portion represents 48 to 70 per cent of the total missile system cost, and 54 per cent or more for bomber and fighter aircraft [1]. For airlines, the percentage is much less.

For fighter aircraft, the maintenance effort per hour of flight exceeded a 50-to-1 ratio several years ago, and squadrons of missiles such as Thor, Atlas, and Titan—far from being pushbutton-operated as in the newspaper stories—require ten times more electronic technicians than jet fighter squadrons [1].

Yearly maintenance costs vary from about 25 per cent of initial capital costs quoted for airline electronic equipment to double for military avionics and up to twenty times for military ground electronics equipment [16]. While this data may not be directly applicable to aerospace systems, Messrs. Naresky and Klion [17] of RADC have provided a guide for re-

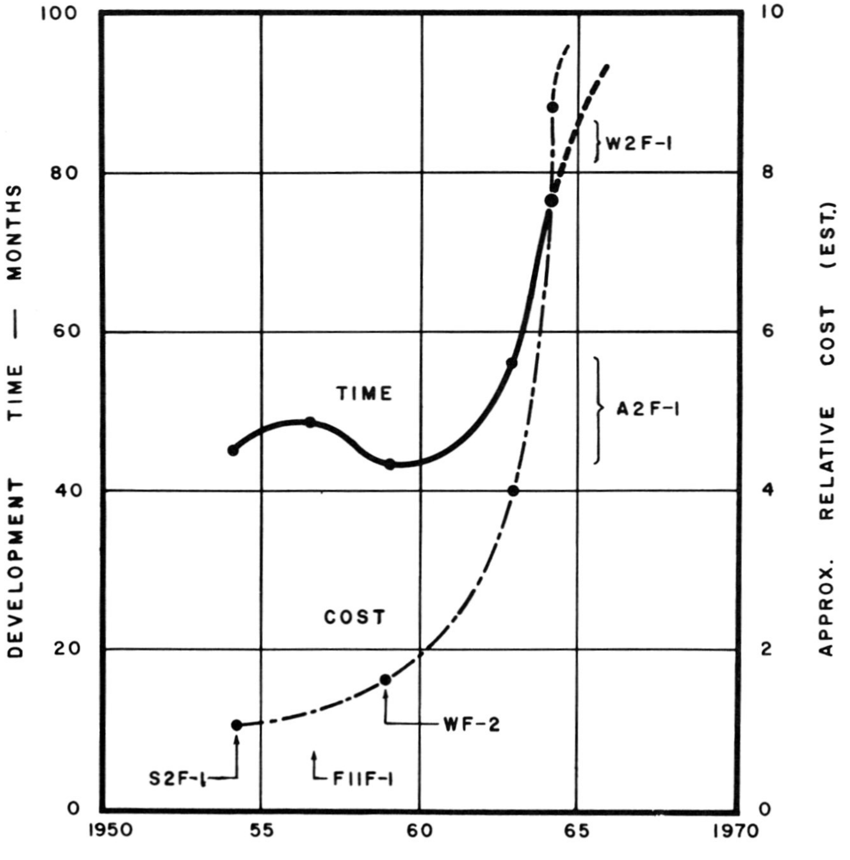

Figure 8. Rising development time and cost for aircraft series.

lating the cost of maintenance Cm (for a 5-year period), to the reliability achieved, thus:

$$Cm = \$2{,}700{,}000/[\text{Mean time between failures (hours)} + \$60 \times \text{number of tubes}]$$

Since the largest part of maintenance cost is for labour, varying from 19 to 45 times that for electronics material, the use of throwaway modules may be economically justified [1].

Figure 8 shows the increasing development time for the same series of U. S. Navy aircraft referred to in Fig. 5 [7]. Extra reliability-programme effort generally lengthens the development time. However, it expedites the final acquisition and satisfactory operational use through elimination of extensive delays for remedial fix-it programmes. Correction of unreliable designs during or after production costs about 10 to 1,000 times more than during initial design.

Excessive increases in capital costs for complex new systems, rather than the remonstrances of design engineers (who continue to attempt the currently "impossible" new tasks), will likely be the most effective deterrent in restraining future system complexity growth. Maintenance costs are rated at about 30 per cent of the defence budgets of many countries. Because maintenance and operating costs are rising to higher proportions, users find it harder to divert enough funds for more costly new capital equipment. Official public statements in Canada indicate that previous availability of 50 per cent of defence funds for equipment acquisition has declined to less than 20 per cent in 1963. The obvious economic conclusion is that we must reduce the proportional cost of maintenance support through improved reliability and maintainability.

SYSTEMS APPROACH TO DEPENDABILITY

To be dependable, a system or device, obviously, must not only be reliable in the sense of having a low rate of failure, but, to take care of the inevitable failures and their correction, it must be maintainable. *Maintainable* is herein defined as easy to repair, not requiring an unacceptable amount of preventive maintenance to anticipate and prevent failures in use. Due to an unbalanced perspective of the problem of dependability, we have permitted an arbitrary separation of the well-recognized "reliability" aspects from the neglected and poorly understood "maintainability" aspects. Thus, two inseparably related parts of systems effectiveness or dependability have unfortunately become the divided responsibilities of separate groups. As a result, progress both in design for maintainability and in developing quantitative specifications for its assurance has been retarded by several years compared to advancing reliability techniques. Although evaluation techniques for systems effectiveness have been developed [2,18], present military specifications [19,20] and evaluation and prediction techniques [21,22] still separate maintainability from reliability. The correlated specification of system reliability and maintainability requirements, and their allocation to subsystems in electronic, electrical, and mechanical categories, are lucidly covered in an official (restricted) British report [23] and in more extensive ARINC reports prepared for the U. S. Navy [18] and as a training text [2].

SIMPLIFICATION AND COMPONENT IMPROVEMENT ALONE ARE INADEQUATE

While simplification has actually halved the failure rates of some equipment on redesign, we have to face and to master the problem of providing reliability in complex systems. The largest known, the United States Air Force's 412L System, including radar, data processing, and communication facilities, has over 41 million electronic parts, and the Nike-Hercules missile has a total of 1.5 million parts. Reduction in the number of different *types* of parts is part of the desirable process of simplification. Designers of the U. S. F-111 TFX Fighter Aircraft have reduced the transistor types from 90 to 11, and this will help to meet a part-reliability goal of a stiffer level than for the Minuteman missile. The number of circuit elements and interconnections can be reduced in future electronic equipment by the use of solid-state and integrated microcircuits, and failure reductions thereby up to 10-to-1 are predicted [9].

Early reliability programs stressed what appeared to be the obvious and basic solution of improving component parts, together with some secondary consideration of eliminating misapplications that were based on both ignorance of electrical and physical stresses and strengths, and on carelessness in design. A better perspective and knowledge of controlling factors, as discussed later, led to an "equipment" approach and later to a system analysis and, finally, to the "man-equipment-environment-system" view essential for aerospace systems. The improvement of parts, besides being slow, will not produce the needed system improvements of up to 10,000:1. Improved system design, use of redundancy and of other methods such as electrical feedback for providing equipment tolerance of part deterioration and failure, and especially application of human engineering to the man-equipment system will be required. There is a danger of neglecting these other methods in concentrating on component-part research and improvement. Some doubt has even been expressed of the parts improvements claimed between the years of 1954–60 [24], although improvements of over 100-to-1 have been proven in the reliability program for the Minuteman missile.

By improved circuit design, application of parts, and improved manufacturing procedures, reliability improvements of 6-to-1 in a USAF airborne radar system, and of 5-to-1 in the Athena computer of the Titan missile, were achieved without replacing any parts.

CONTROL FACTORS

Designers and planners of future aerospace systems cannot afford to be misled by inadequate, misinterpreted, or poorly analysed failure data, or to be biased by unproven theories and preconceptions. Failures of electronic equipments as reported by users were initially blamed chiefly on the parts and particularly on tubes. Analysis and engineering investigation summarized in Fig. 9 have revealed the inadequacy of the reporting both as to the reality of the failures and their causes. Thus we see that human factors as well as equipment and system design, and also the quality of the parts, determine the dependability of the man-equipment-environment system [3].

Poorly reported and analysed failure data have misled designers. We have acquired a bias from early investigators who concentrated interest on the *rate* of failures, instead of what, in most cases, is more important operationally and economically, the amount of *downtime* or of impaired operation. "Availability," or the ratio of "uptime" to "uptime + downtime," is dependent upon maintainability as well as reliability factors, and is generally more significant than failure rate.

With rising complexity and decreasing maintainability and reliability, the downtime for military aircraft has risen from 50 per cent in 1956 to 75 per cent in 1962, according to U. S. Navy statistics [9]. The increased maintenance effort required for mechanical devices is particularly significant.

Analyses in previous papers [1,16] of the field-reported causes of failures in electronic equipment, and laboratory study of failed equipment, have revealed how misleading field reports can be. The faults can be summed up, in broad categories, as shown in Fig. 9, as ⅓ due to inadequate design and manufacture of component parts including tubes, ⅓ due to faulty operating and maintenance practices, and ⅓ due to inadequate system and equipment design including misapplication of parts. The corresponding data for mechanical systems are not known, but are likely to be somewhat similar.

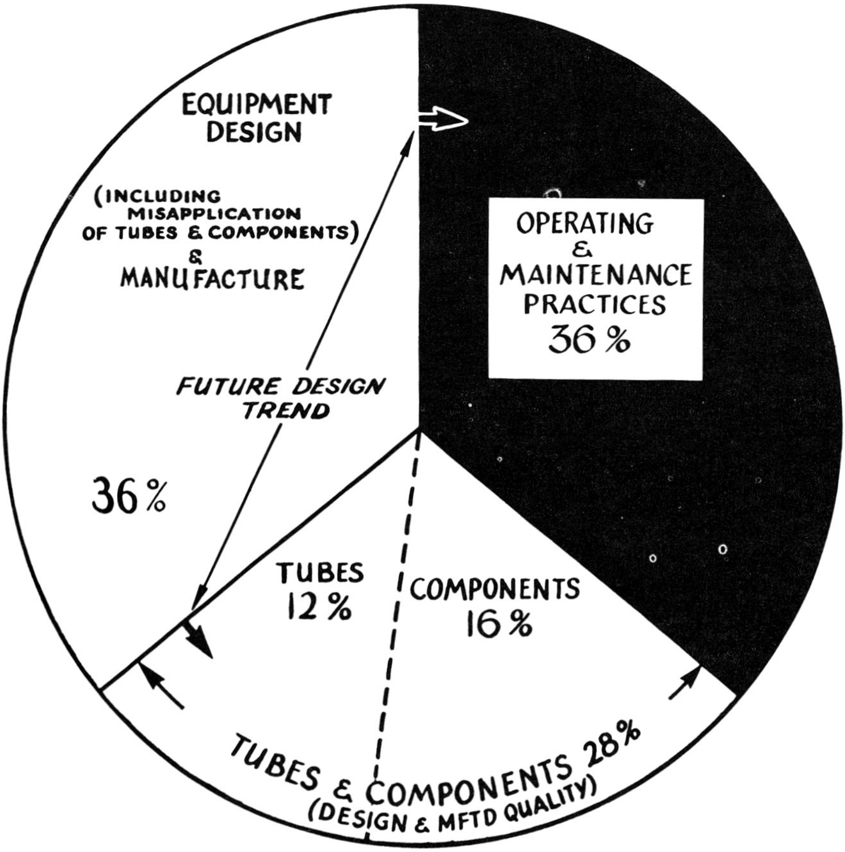

Figure 9. Rough analysis of control factors for failures generally in military electronic equipment.

Table 1 shows the wide range of U. S. Navy [25], RAF, and RCAF data on aircraft failures. The breakdown into various subsystem areas (excluding personnel causes) indicates wide variations including class differences between bomber, fighter, and transport aircraft. It is clear that mechanical troubles still predominate in aircraft despite the growing electronics complexity.

TABLE 1

SYSTEM BREAKDOWN OF AIRCRAFT FAILURES

Subsystem	*Per Cent of Total*	*Remarks*
Powerplant and engines	3–37.5	
Hydraulics and pneumatics	5–20	
Airframes	10–34	Highest in carrier landings
Instruments	12–34	
Radio communication	10–35	
Navigation, bombing, armament	2–60.5	Highest in B-58 Bomber initially
Unknown and miscellaneous	Up to 13	
Oxygen and fuel lines	Up to 18	

RCAF data do not differ greatly from RAF or United States Navy and Air Force data in showing that personnel factors account for about half of aircraft accidents, with materiel (which occurs at a lower proportion than for the RAF and USAF), and maintenance deficiencies, the other principal factors as shown in Table 2. Despite increasing complexity and speed of flight between 1955 and 1962, the ratio of aircraft destroyed per 1,000 flying hours has been reduced about 4 to 1, and the fatalities over 9 to 1. The average cost per aircraft accident has risen to $49,000 in 1962 according to U. S. Navy data, amounting to a yearly total of 283 million dollars, equivalent to the cost of a Forrestal-class aircraft carrier. The corresponding total personnel loss amounts to 9 per cent of the pilots trained per year [25].

TABLE 2

CAUSE FACTORS FOR RCAF AIRCRAFT ACCIDENTS & FAILURE INCIDENTS

	Percentage of Category Total			
Cause	*Accidents*		*Failure Incidents*	
	1961	*1962*	*1961*	*1962*
Aircrew	45.9	48.9	6.1	3.8
Materiel total	22.2	23.9	70.9	71.9
Maintenance	14.4	13.3	8.6	10.0
Obscure	9.3	6.4	8.4	10.0
Other	8.2	7.4	5.9	4.3

Failures in RCAF airborne systems (called "incidents" in Table 2) include materiel deficiencies as the principal cause. Based upon experience with electronics equipment failure data (See Fig. 9), I believe that engineering analysis would show that personnel and maintenance factors would share more responsibility in nonmechanical areas at least, and these data should be interpreted as "failures claimed."

THE PERSONNEL SUBSYSTEM

An important member of the reliability-maintainability engineering team is the human-factors specialist, a combination of an applied psychologist and systems engineer. Only by making the best of the human operators in the "personnel subsystem," as it is aptly called by the United States Air Force, can the most effective and reliable systems be achieved. This applies not only in the military field, but, even more critically, in the field of space travel.

Some designers have been distracted from taking a proper interest in the design of the personnel subsystem because of a trend, given considerable management support in the military sphere a few years ago, to supersede the man by an electronic computer or an automatic-control device [26]. We must recognize the fact that high-speed computers and electronically actuated automatic-control mechanisms in systems exceed in response speed and precision the unaided capabilities of human beings. However, instead of rejecting man in the system, the mechanism must be adapted to aid him. The high frequency of failures caused by human errors should persuade us to simplify the tasks of the operator and maintenance technician. Despite the limitations of humans, it is the opinion of several analysts that the addition of a human to a space vehicle may improve its reliability and economy of design by as much as 70 per cent, despite a weight penalty of 5 or 10 per cent [1,27]. However, one of the most serious deficiencies of man's reliability, particularly with respect to future space travel, is his inability to extend his period of vigilance and problem-solving proficiency much beyond twenty consecutive hours [1].

ROLE OF HUMANS IN SYSTEMS AND FAILURE REPORTING

In the experimental flights of USAF's X-15 aeroplane, 53 per cent would not have completed the specified missions, and 31 per cent would have resulted in complete destruction of the vehicle, without the decision-making ability and judgement of the pilot.

In an open 1963 briefing on the Mercury manned-space-flight program, the project staff frankly acknowledged that one flight was completed, and safe reentry and return were accomplished in another, only by allowing the human to replace faulty automatic control. As a result of this experience, the designers of the two-man Gemini spacecraft have announced that 50 per cent of the previously automated control functions will be transferred to the astronauts.

Data in my previous paper [3] and Fig. 6 confirm the rather startling fact that both the nature, and the quantity, of failures vary more widely with the operating-maintenance practices used at different bases than with the electronic equipment and the parts used. If, for various reasons, such as statistical convenience, unscientific procedures, ignorance or carelessness, we shut our eyes to the human factors in the man-equipment-environment system and recognize only the measurable physical environment, we can support the fiction that the failures are due only to parts. We must also then believe that these "scapegoat" parts have failure rates that vary over 1,000-to-1, as apparently indicated in Fig. 6, between laboratory and other various usage environments. Many currently used failure-prediction guides do not acknowledge these variations due to operating-maintenance-usage environments and questionably screen out unconfirmed and all types of failures other than these acknowledged as due to materiel deficiencies [28].

System designers cannot afford to ignore the fact that human errors are the common factor in part, equipment, and system unreliability in design, manufacturing (82 per cent responsibility according to a Sandia Corp. study [29]), and operating phases [9]. Human errors are not limited to the one-third control factor shown in Fig. 9 assigned to the operating-maintenance factor. In missile firings, failures starting as high as 60 per cent due to human errors may fall to reported values of 20 to 35 per cent with two years of experience, but, even then, are suspected of amounting to 50 per cent if reporting were more accurate [26,30,31]. Due to the common failing of field personnel in not reporting mission or operating failures caused by misadjustments but reporting only when parts are replaced, our available data on this failure category do not generally represent its true proportion, which has run as high as 50 per cent of total failures. Despite the high incidence of failures due to human factors, many missiles and aircraft manufacturers surveyed in 1960 had no human-factor studies organized [31].

To obtain valid failure reporting, we must understand the motivations of operators and maintenance technicians and their tendency to cover up for their own mistakes and those of their team-mates by failing to report failures, thereby avoiding guilt implications [30]. In investigations employing interview-in-depth techniques, those questioned are freed from fear of censure, and interviewing replaces the bad report-writing habits that are encouraged by the equipment-oriented design of the reports themselves. Such uninhibited interviews disclose that normal written reports concentrate on items of faulty construction and especially on faults in parts. They also reveal that faults in missiles due to mechanical design are eleven times higher in percentage of the total, and those due to faulty operation are nearly three times higher than those shown in written reports [30].

The statement of a very experienced organization in the field of failure investigation is concurred in, namely: "It is ARINC's opinion that any method of measuring which ignores unconfirmed failures is misleading" [32]. If instead of discounting unconfirmed failures these are given special attention by the maintenance and aircrew personnel, a drastic reduction can be achieved. In the case of the RCAF's Air Training Command stations, this cooperative effort resulted in a 50 per cent reduction within a year. For the RCAF generally, unconfirmed failures of airborne electronic equipment range from 15 to 43 per cent of the total. One Canadian airline reports a 25 per cent incidence in this category.

The removal of an UHF Radio Set from an aircraft, plus testing on the bench and reinstallation, consumes an average of three hours of maintenance labour, whether repair is required or it proves to be an "unconfirmed" failure. If such incidents are not evaluated as failures of the total man-equipment system, true reliability and maintainability data required for system effectiveness assurance will not be obtained.

BLACK-BOX DEFENSIVENESS

Errors in failure diagnosis and bias in reporting are not limited to technicians. There is another bias, which may be called "black-box defensiveness," which designers and logistics support staffs, and even specialists in reliability analysis and prediction, must guard against. While maintaining a sophisticated and critical attitude toward the technician's limitations, we can fall into equally serious error by screening out unconfirmed failures, writing these off as errors in technician diagnosis, or as errors in operating, if not confirmed by engineering tests. Also often disregarded in analysis, in the few cases where the technicians report them, are the failures due to maladjustments.

The vital point for both designer and maintenance specialist is that any loss of effective use of a system is equally serious in operation, whether due to imagined failures, or whether due to operator error or inadequate maintenance.

MATHEMATICAL MODELS AND PREDICTION TECHNIQUES

A number of mathematical models have been developed for reliability. Some have been tested in application to operating equipment [2,33,34]. Others cover maintainability [2,21,35,36] and systems effectiveness [2,18], and relate these to the controlling factors. These models cannot be discussed here in detail but may be consulted in the references given. Some studies have been conducted comparing various reliability prediction methods [2,28]. Prediction guides [22,37,38], which include some mechanical and electromechanical components, and military specifications on prediction [38,39] are available.

Some studies apply to the space system [40] and missile [41] fields; some take into account human error [33], and some embrace mechanical systems [42,43]. Related to these prediction methods for evaluating designs before the hardware stage are allocation techniques [2,44,45] for distributing overall system requirements between component subsystems.

Mathematical reliability models are based on assumptions about failure distributions. The so-called "bathtub" curve, with high initial "infant mortality" and final wearout portions similar to those for human mortality, is commonly assumed to apply to failure of electronic equipment and the component parts thereof, with the long middle part corresponding to a constant failure rate. Although many reported tests have confirmed this pattern, some recent Canadian test results on ceramic capacitors and fixed resistors show that the initial decreasing infant-mortality rate may change to a rising rate, indicative of wearout, without exhibiting any constant-failure-rate middle portion [46].

Recently, many analyses [2,34,47,48] of failure studies have advocated use of the Weibull function for relating failure data to time, where failure rates, such as in the case of mechanical parts, are not constant with time.

RELIABILITY TIME RELATIONSHIPS AND UNREALISTIC EXTRAPOLATIONS

The formulae for the intrinsic reliability of electronic systems in other than launch phases of one-shot missiles are:

$$R_t = e^{-nt/m_p} = e^{-\lambda t} \qquad \text{or, in per cent, } R_t = 100e^{-\lambda t} \tag{1}$$

Whence system MTBF $= m_s$

$$= \frac{m_p}{n} = \frac{-t}{\log_e R_t} \tag{2}$$

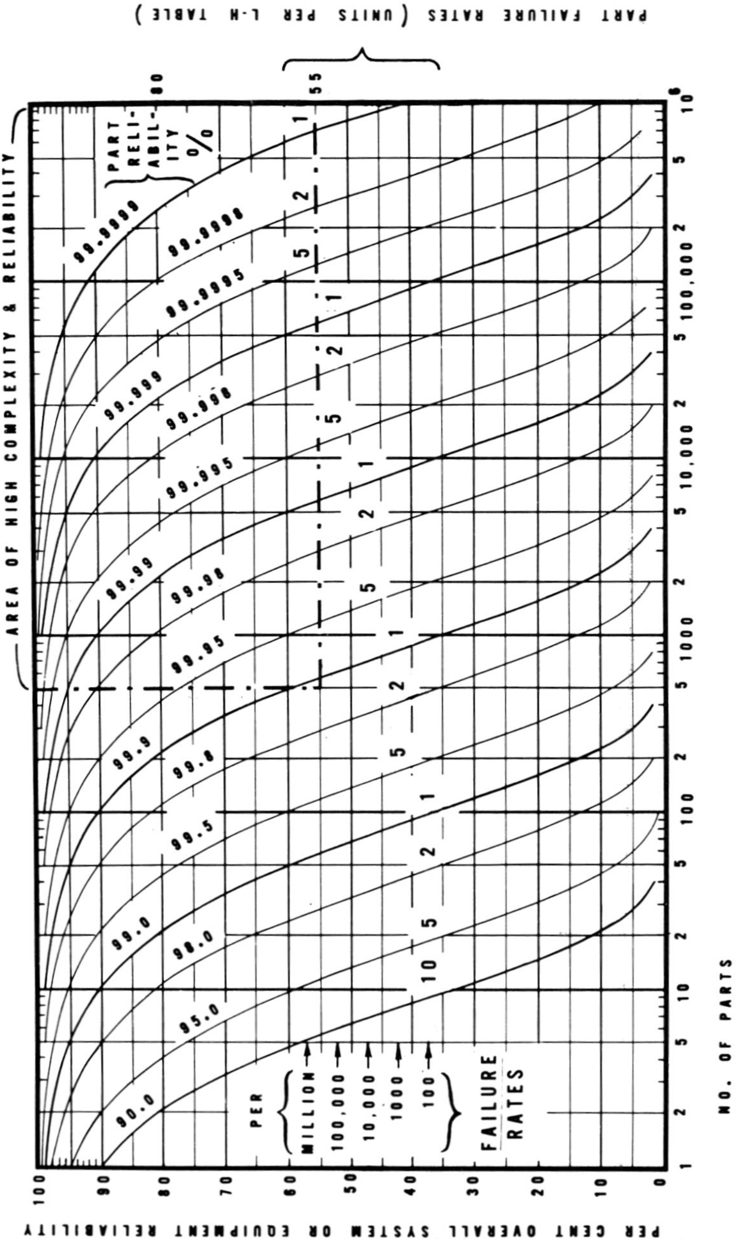

Figure 10. System reliability vs. parts and part reliability.

These disclose the facts that reliability (R_t) declines exponentially with time t, the number of independent parts n or complexity, and with the rate of part failure. System failure rate $1/m_s = n/m_p$ is usually designated λ; m_s and m_p are, respectively, the mean times between failures (more appropriately designated the "reliability time constants") of the system and average individual parts, and $e = 2.71828$ (base of the Naperian logarithms).

These convenient exponential formulas, which can be applied by nomograph or by a special reliability slide rule, are not applicable to most mechanical and electromechanical parts, such as gears, motors, and bearings, whose failure rates are not constant but tend to increase with time due to wearout, fatigue, and corrosion.

Instead of the common chart limited to impractically small systems, Fig. 10 based on the Eq. (1) relationship, relates the number of parts to part and system reliability, in the absence of redundancy, and where the system reliability is the product of the individual part reliabilities.

The exponential relation is usually considered to apply between failures and time in electronic equipment. On this basis it is common practice to invert failure rates, derived from tests performed over a relatively short time, into equivalent mean-time-to-failure values. As an example, it is stated that transistors having a failure rate of 0.0004 per cent/1,000 hours will have an MTBF of 28,500 years.

A chart of human mortality will show a low and nearly constant human failure rate between the ages 5 and 30. By employing the same inversion, an equivalent MTBF of 820 years can be estimated. No one would believe a statistician who seriously predicted this Methuselahn life figure, far exceeding the known 70-year expectancy. However, few question the validity of MTBF predictions of 28,500 years for Minuteman missile parts, based on tests carried out for only about 1/100,000 part of this time and assumed to remain valid when extrapolated from down-to-earth experience out to the "wild blue yonder" of space.

It would be easier to keep our feet on the ground, if the suggestion of Weaver and Smith [48] were adopted (as in Figs. 3, 7) to call the inverse constant derived from the failure rate the "Reliability Time Constant" instead of the "MTBF." In reality, it may exceed the true mean life figure by several orders of magnitude in the case of parts with very low failure rates tested only in their early life period.

VARIATION OF FAILURES DURING MISSION

Until recently, an important fact was obscured by the prevalent assumption of constant failure rates. Figure 11, taken from the paper of Horn and

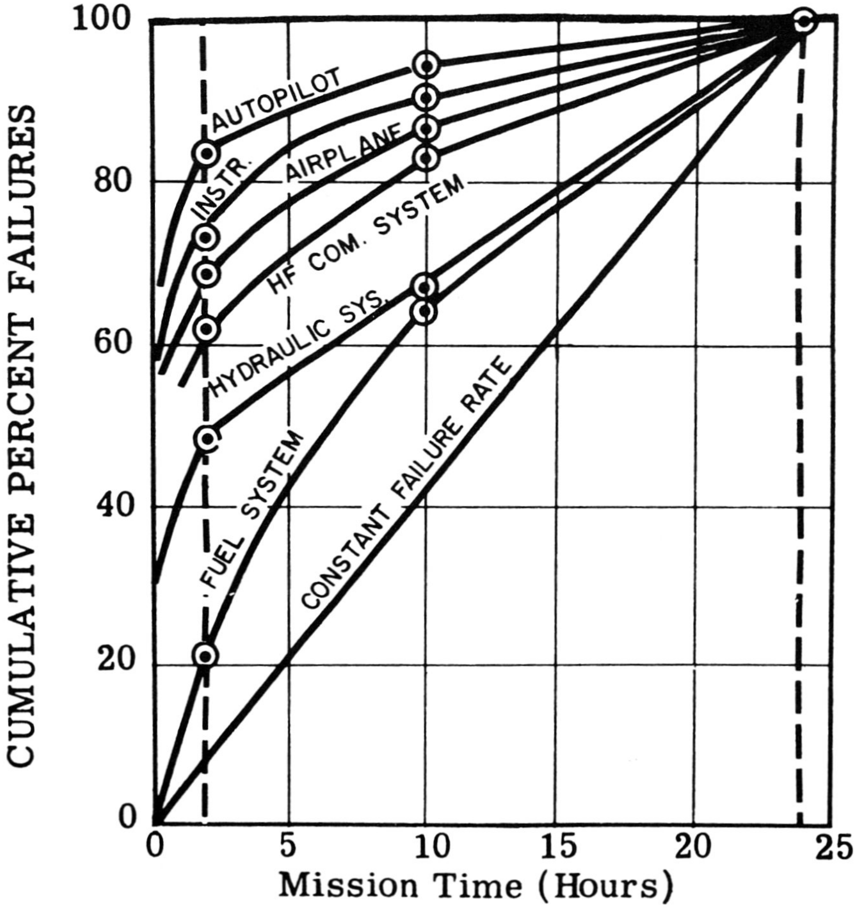

Figure 11. Cumulative per cent failures vs. mission time. (*Horn and Shoup.*)

Shoup of Boeing [47], shows how the percentages of the total failures in each separate equipment category of electronic, mechanical, and electromechanical systems vary over a 24-hour aircraft mission period. It is evident that these failures are not constant, i.e., haphazard, and do not follow the exponential law usually assumed.

On the basis of such evidence, we must reconsider present practices of treating failure rates as constant, and recognize the facts and reasons for high initial failures in aircraft missions. Horn and Shoup estimate that the transient stresses of take-off account for 15 to 20 per cent of the differences between early failure rates and those occurring later in the mission. Shocks of starting up equipment (more fully investigated in an ARINC study [49]), and those due to rapid environmental change, which produce increased electrical, mechanical, and thermal stresses, may cause 35 to 45 per cent of the difference. In addition, 25 to 35 per cent of the difference may be due to the belated effect of prior maintenance actions [47].

In the RCAF use of the reliable AN/ARC-552 Radio Set, shown in Fig. 12, failures in short-mission fighter aircraft are four to five times greater than in transports but are only 30 per cent more in maritime reconnaissance aircraft. Obviously, to obtain the facts and to control reliability performance, we must employ failure-reporting and analysis methods that break down failure data relative to time *during* the mission.

DESIGN FOR RELIABILITY AND MAINTAINABILITY

Good design concepts for effective systems of any type must be based on a proper foundation of operational research and formulation of minimized requirements [50]. To supplement production and design review procedures, there is a large body of reference and guide information available from the technology developed in the electronics, missile, and space fields, although little of this is to be found in current theoretical textbooks on reliability. Design techniques for protection from climatic, vibration and shock stresses have become generally known [51] even for space environments [2], but adequate knowledge of thermal engineering is not yet universal among electronics designers. References are given for treatments of design areas that cannot be covered here in detail, including connections, soldered [54], welded, and wrapped [55]; cooling [52], design review [2], human factors [29] and the philosophy of man in the system [53], maintainability [2,36,56], modularization [57,58], packaging [51], process and quality control [11], production operator training techniques [59], redundancy [2,60], testing to AGREE requirements [61], testing—automatic [62], testing to failure [63] and unattended operation [64].

Several military design guides are available [64–70].

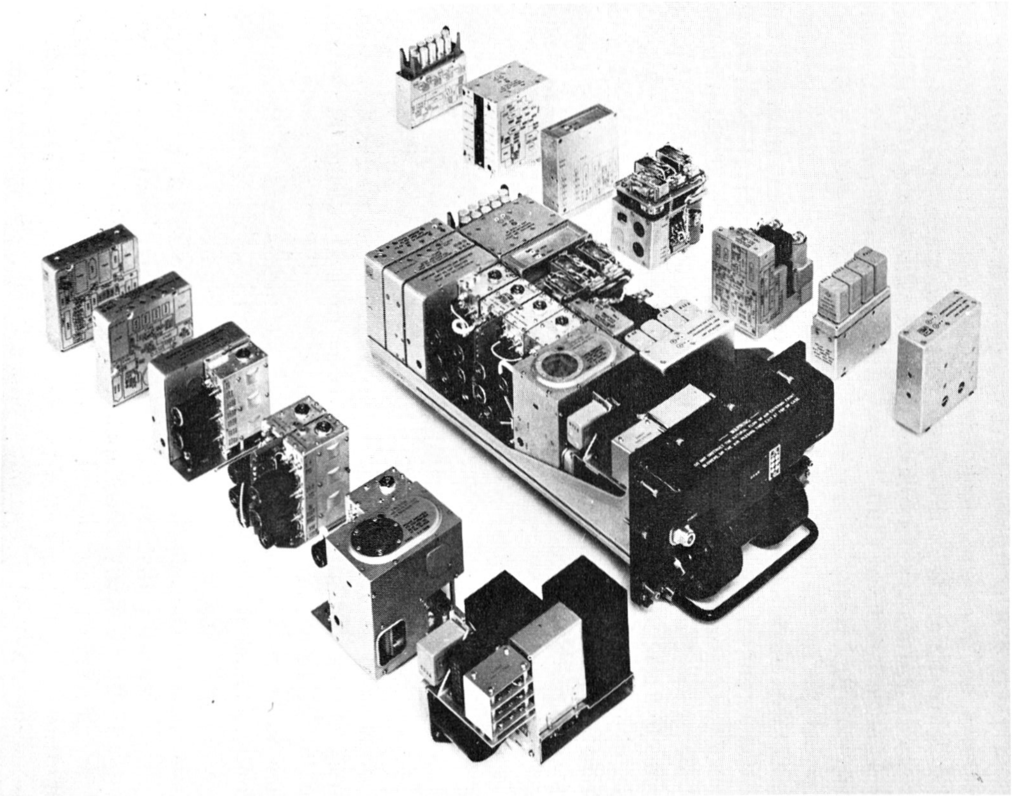

Figure 12. RCAF AN/ARC-552 UHF radio set and separated modules. (*Collins Radio Co. Photo.*)

TESTING LOW-FAILURE-RATE PARTS

It can be seen from Fig. 10 that large systems will require very low failures, or corresponding high reliabilities, in individual parts. Not only failure rates of 0.0001 per cent per 1,000 hours for the Minuteman missile electronic parts, and still lower rates of one-tenth of this ultimately for space travel, but even rates one hundred times greater, impose difficult-to-impossible testing problems in terms of cost, time and effort. In place of a more general mathematical appraisal of the problem, perhaps, the example of the Atlantic Telephone Cable System will illustrate the point. To assure a 90 per cent probability of no failure of the 6,000-part system over a 20-year period, the part failure rate must be less than 1 per million per year. Testing of this single system would require 400 years to establish this fact [71]. Much recent study has been applied to statistical testing procedures to minimize the testing effort; and early hopes of substantial shortening of test time by accelerating failures through high stresses have not produced very effective solutions. Use of tests to destruction to determine modes of failure, to increase strengths through redesign, and to reduce the variance in strengths, when combined with the application of engineering judgements appear to constitute the most promising approach to this fantastic design problem [63].

MECHANICAL SYSTEMS

In aircraft and vehicular design engineering practice, use has been made of safety factors and safety margins based on a knowledge of product variability in performance under stress.

Some investigators have applied the techniques and mathematical assumptions about failure distributions derived from the electronics field to systems involving mechanical, pneumatic, hydraulic, and structural components, and especially to missiles. Others have denied the validity of this [9], or generally distrust failure prediction and statistical analysis techniques [72]. Similarly, their applicability to chemical products as in solid rocket engines has been questioned [73]. Undoubtedly, suitable modifications in techniques must be made to recognize the greater effects in the mechanical field of wearout. These are radically different than for electronic parts, for which only 4 per cent of the total failures are attributed to wearout. For normal mechanical wearout, the mean life occurs where there is a 50 per cent survival, not 36.8 per cent assumed for electronic devices following an exponential distribution; also the variance of the failure distribution around the mean time must be known as well to evaluate the performance statistically for prediction use. A gaussian or normal distribution of mechanical failures has been generally assumed, but it is reported that a symmetrical normal distribution is rarely observed in field failures; and, where the data are obtained solely from reporting of removals, they are most closely approximated by the exponential relation [74]. Mechanical and electromechanical components in vast USAF communication systems have quite different failure responses than electronic parts, and are responsible for 89 per cent of the total operating failures [75]. Use of the exponential is justified for missile systems with short part-usage time [76], while several studies advocate for mechanical systems the use of Weibull functions [47,74–76] and of prediction techniques based on mechanisms of failure [63,76].

Figure 11 shows that it is mechanical systems, rather than electronic systems, that have nearly constant failure rates during an aircraft mission. Various studies indicate that dynamic mechanical parts have the shortest life expectancy; next are thermomechanical (such as engines), pneumatic/hydraulic, electromechanical, and then come electrical and electronic parts with the highest life expectancy [13,23,43].

We have been accustomed to treat as negligible those mechanical failures occurring within the initial time period, which is only a small fraction of the time to normal wearout. These may have rates which may be as small as 1/100, 1/1,000, or even 1/10,000 the rate at the peak failure period. In complex systems requiring very low part failure rates, this low-rate, haphazard or exponentially related failure component cannot be treated as insignificant.

Mechanical failures have been shown earlier to be a large factor in aircraft systems. In missiles, up to 60 or 80 per cent of all failures have been attributed to mechanical devices. I would stress that, if current rates of improvement in electronic systems continue as predicted, the chief stumbling blocks to mature designs may well become the mechanical portions of aircraft and missiles, unless there is a parallel concentration of attention on this field comparable to that in electronics.

Technical papers concerning the reliability of electromechanical and mechanical equipment have appeared occasionally since 1959 [76,77,78]. Attention to this field has increased considerably this year, extending the limited failure data accumulated in the avionics and electronics fields, and also considering the relationship of the factors of time, temperature, speed of rotation or translation, bearing load, etc. [77].

Estimates of the hourly failure rates of components of hydraulic flight-control systems vary from a few parts per million for lines and fittings to 360 for actuating cylinders [78], and corresponding mean times to failure vary from 200,000 to 1,200 hours in U. S. Navy fighter aircraft.

Since 1958, several flight-control-system reliability projects have been sponsored by the Wright Air Development Center of the USAF for which reports are available through official channels. A 97 per cent reliability requirement has been specified for the flight-control system of the B-58 aircraft, and mean-times-to-failure or other overall reliability requirements have been specified for the B-58, F-106, and F-108 aircraft flight-control systems and flight and engine instruments.

CONCLUSION

This presentation has not attempted to cover many management aspects of the subject. However, it seems fitting to remind you that, given adequate design capabilities, the final system effectiveness will depend upon procurement practices and policies. Systems effectiveness assurance should not be relegated as the sole responsibility of designers and quality control engineers, important though their parts are in the team effort. It is not technological problems but management difficulties that experience has proven are the chief deterrents in most programmes [79].

My final suggestion is to expedite aerospace system effectiveness programmes by military-industry cooperation in joint studies and committee discussions. The value of this has been proven in the electronics field, and the well-known "AGREE" Report on Reliability [80] is an example of such joint achievements.

Where not credited otherwise, the opinions expressed in this paper should be interpreted as the author's and not necessarily those of the Royal Canadian Air Force.

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