THE QUEST FOR MECHANICAL RELIABILITY IN AIRCRAFT

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ABSTRACT

Unreliability of mechanical systems and equipment in aircraft sometimes causes accidents, sometimes prevents successful completion of missions, but mostly manifests itself in minor defects.

Mechanical failures and defects usually result from unforeseen events which may be of three kinds: those amenable to quantitative analysis, those assessable qualitatively on the basis of design experience, and those revealed by testing. Variability is an important factor in defect patterns and the probability of achieving expected life.

Aspects of design, development, and testing that are important for achieving high reliability, long life, and minimum maintenance effort are discussed.

INTRODUCTION

The title of this paper could well embrace all activities contributing to mechanical reliability: drawing up specifications, design, development and testing, manufacturing, inspection, and use. It concentrates on those aspects with which the aircraft designer is most closely concerned, namely design and development of mechanical systems.

The extent of mechanical unreliability is described and the nature of mechanical failure, failure mechanisms, and variability are discussed. Engineering design is considered as a creative art and the importance of design teaching is emphasised. It is pointed out how knowledge gained from experience of failures, and ground and flight testing are contributing to improvement of reliability. Achievements in attaining very high reliability in powered systems essential to safety are reviewed.

THE EXTENT OF MECHANICAL UNRELIABILITY

Figure 1 shows the contribution of airframe mechanical defects in a number of different types of military jet aircraft. Mechanical defects are taken as those arising in the mechanical parts of the systems such as flying controls, air conditioning, hydraulic systems, and in mechanisms such as locks and releases, which form part of the airframe as distinct from engines and operational equipment.

Unreliability influences maintenance effort, mission success, and safety. Figure 2 shows the contribution of mechanical unreliability from these aspects, and represents average values for a number of types of military aircraft. One-quarter to one-third of defects are mechanical. They absorb maintenance effort in squadrons, and cause accidents, and sorties to be abandoned in about the same proportion. Abandoned sorties, however, do not give the whole picture of the effect of defects on the mission success. Sorties are sometimes abandoned because of minor mechanical defects found just before take-off that might impair safety but would not necessarily cause the aircraft to return to base if they occurred in flight. Typical instances are signs of leakage of hydraulic fluid and incorrect extension of undercarriage shock absorbers. Furthermore, sorties are continued after the occurrence of defects in operational equipment that would render the

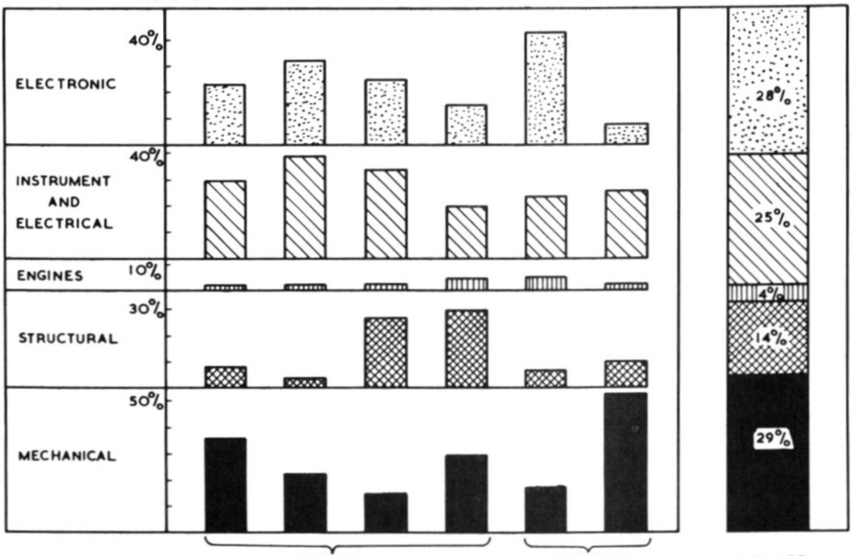


Figure 1. Distribution of defects by system.

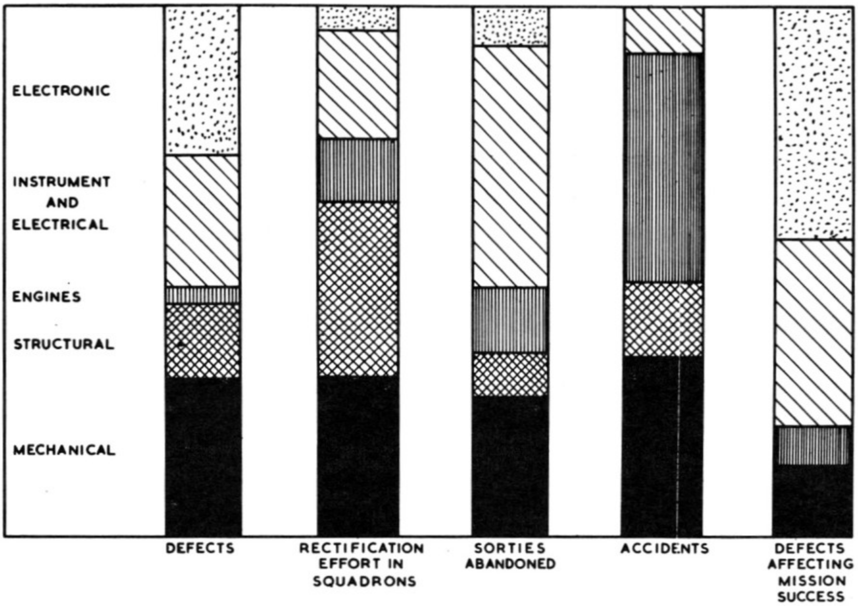


Figure 2. Distribution of unreliability by system—different aspects of reliability.

mission ineffective if the equipment was needed. A different view is obtained if the proportion of defects likely to impair the success of the mission is estimated for each category—i.e., mechanical, structural, electronic. This has been done to obtain the bar in Fig. 2 showing defects affecting missions. It is based on an estimate that 70 per cent of defects in electronic equipment and engines, 50 per cent in electrical equipment and instruments, and 20 per cent of airframe mechanical defects would probably impair mission success. Here it can be seen that defects in the mechanical systems of the aircraft are overshadowed by those in operational equipment.

Mechanical unreliability defined in a broader sense is more extensive than is indicated in these diagrams since much of the unreliability of instruments and the mechanical parts of electrical components, as well as nearly all engine defects, is mechanical in nature.

THE NATURE OF MECHANICAL UNRELIABILITY

Mechanical unreliability consists of unexpected failure or malfunction of a mechanical system when a potentially destructive force acts against the resistance of the mechanism. Destructive force may be environmental, externally applied or generated internally by the mechanism itself. In its widest sense destructive force includes not only mechanical force such as acceleration, vibration or pressure, but all forces contributing to mechanical breakdown such as the presence of a chemically reactive fluid or a foreign body. Weaknesses include deficiencies in mechanical properties such as strength and wear resistance, and in measures such as protection, drainage and positioning that may be needed to counter destructive forces.

Figure 3 shows the forces and weaknesses involved in mechanical failure. The relationship between them may be the simple one illustrated, for example, the seizure of a piston in a cylinder under excessive side load. Or it may consist of a complex chain of events involving feedback through one failure mechanism which then produces the final destructive force, for example, the contamination of oil by wear debris causing wear of gears, thereby generating dynamic loads that cause fatigue. Innumerable examples could be quoted from experience to illustrate the effects listed. Here are just a few:

1. Leakage of air from the relief valve of a pneumatic system caused by lifting of the valve from its seat in response to vibration.
2. Breakup of sintered bronze filter elements subjected to vibration. These are examples of the same destructive force, environmental vibration, acting against two different forms of mechanical weakness, unwanted dynamic response in the first case and insufficient fatigue strength in the second.
3. End-float in a spindle in a flying control mechanism allowed part of the mechanism to foul adjacent structure.
4. Control stops out of line with a lever allowed the stops to be overridden.

Here the weakness consisted of excessive dimensional tolerances, the forces being self-generated.

5. Hydraulic selector valve leaking due to a damaged seating.
6. Hydraulic jack cylinder and piston scored.

These are both examples of inadequate protection against fluid contamination.

Some of these examples seem trivial and obvious mistakes, but are typical of much of mechanical unreliability, which consists of an aggregate of such occurrences, individually infrequent and seldom repeated in quite the same way.

Some failure mechanisms consist of well-defined processes that have been the subject of general study so that they can be analysed quantitatively if the working conditions in the mechanism can be sufficiently defined.

Fatigue in rolling contact and scuffing of gear teeth are examples of this category.

Another category of failure mechanisms can be understood only qualitatively. Examples are the proneness to jamming by a foreign object, the possibility of malfunction due to incorrect assembly, or corrosion where drainage is inadequate. Insight, judgement, and experience in foreseeing the possibilities and designing to prevent them replace quantitative analysis in dealing with these.

A third category is where several processes are involved in a failure, each of which could be conceived in quantitative terms but where the interactions between them are complex. Failure of rubber seals of hydraulic jack rods is an example of this category. Distinct types of seal failure are recognisable; wear, extrusion, compression set, and break-up of material.

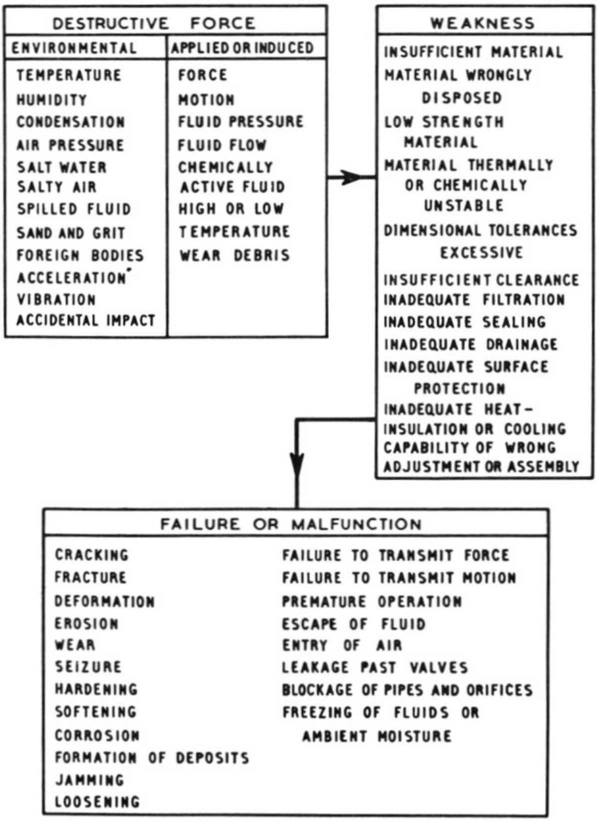


Figure 3. Forces and weaknesses in mechanical failure.

Fluid temperature and pressure, rate and length of stroke, clearances, surface finish, chemical effects, and contamination play interacting parts in these processes. Development testing is the designer's best tool for revealing failures in this category.

VARIABILITY OF FAILURE PROCESSES

Reliability engineering demands a judicious blending of the qualities of the engineer and statistician. The engineer thinks of failure as a determinate process. He looks at causes and effects. For him there is no random failure. The statistician on the other hand views failure as a process of chance. If a random time-distribution of failures fits observed events closely enough he is ready to accept it. The meeting point between these views comes in considering variability in failure processes and the ways this can arise; but first it is worth looking at some examples of failure distributions.

Figure 4 shows the hazard rate (constant in a truly random process) during the life between overhauls of two types of electromechanical components in use in service aircraft, electrically driven actuators and fuel pumps. Many of the failures were mechanical rather than electrical. As can be seen from the percentages surviving to the end of their scheduled lives, these are examples of unreliable equipment. Points to note are the high initial failure rate and the absence of any indication of wearout. The failures

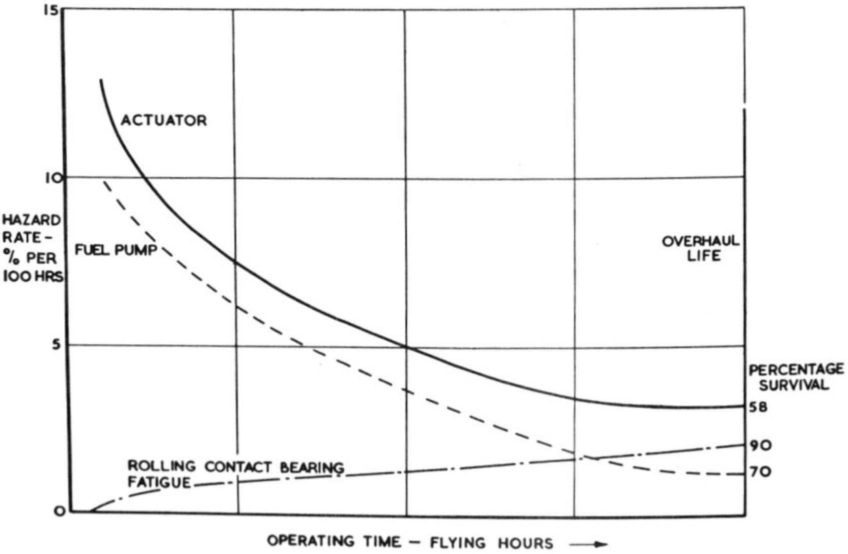


Figure 4. Hazard rate of components during operating life.

included ball-bearing fatigue failures, bearing seizures, stripped gears, oil leakage due to shrunken joints and flexing of cover plates, entry of oil into friction brakes, broken springs, excessive wear and corrosion. These assemblies exhibit numerous modes of failure each contributing its share of variability to the whole. Ball-bearing fatigue is only one failure mode present whose variability can result in failures at almost any time during the operating life. It is common practice to rate bearings for a life which 90 per cent can be expected to exceed. Tallian [1] has shown that of the 10 per cent expected to tail, the earliest failures could occur after as little as 4 per cent of the required life. The lower curve in Fig. 4, based on his paper, shows the failure distribution that could be expected of a bearing selected for the required overhaul life on this basis.

Variability in a mechanism arises from variations in material properties, dimensions, surface finish, processing of materials; in maintenance procedures and adjustments permitted by specifications, drawings, or instructions for use; and by departures from these limits due to inadequate inspection. The manufacturing and inspection methods that are available ultimately limit what the designer can do to control variability in dimensions and surface finish, but in practice economic factors such as the cost of improving tooling, more elaborate inspection equipment, more extensive inspection and increased rejection rates, influence him to permit the widest tolerances he considers acceptable. The same is true of material properties, though to a lesser extent, since a 100 per cent inspection of material properties throughout the whole batch of material is impracticable. It cannot therefore be established with certainty that no piece of material has less than the minimum required strength. Some fabrication processes, such as welding and tightening of joints, are not amenable to precise control or inspection for consistency. The provision of adjustments is a source of variability since it allows maladjustment in service.

The importance of variability of load and strength has long been recognized in the aircraft structural field. Pugsley [2] first showed how loading and strength statistics could be brought together to determine safety factors related to structural accident rates for aircraft, and he emphasised the fundamental importance of collecting load and strength statistics. These have since formed an important part of aircraft structural research, first in the realm of static strength, and subsequently in fatigue. These ideas have already found their way from the structural to the mechanical field in their application to fatigue strength of helicopter transmissions and gears [3,4]. Data on the variation in fatigue strength of gears are at present few, but this subject is now receiving more attention. Other failure mechanisms where more study of variability would be useful, are rate of wear, and breakdown load of lubricant films between sliding surfaces.

Figure 5 shows the variation in life to failure of some dry film lubricated bearings used in flying control surfaces. Figure 6 shows the variation in failing load of mineral oil in a lubricant gear test machine [5]. The effect of surface finish of the test gears can be seen.

Unreliability can be caused by the variation in performance of a mechanism, for example, the blow-off pressure of a relief valve, or the release load of an automatic release. Factors such as the condition of the lubricant, and dimensional variations can cause erratic behaviour, particularly where friction forces affect dynamic behaviour. In tests to determine the variation in performance of nominally identical undercarriage shock absorbers [6] it was found that design features and operating attitudes conducive to high bearing friction increased the variability in shock absorber closure nearly fivefold.

DESIGN

It is indisputable that good design thinking is the very root of reliability. Without it all subsequent efforts can be of but limited avail. Extra time spent refining a design on the drawing board will repay itself many fold in obviating costly and time-consuming remedial measures later.

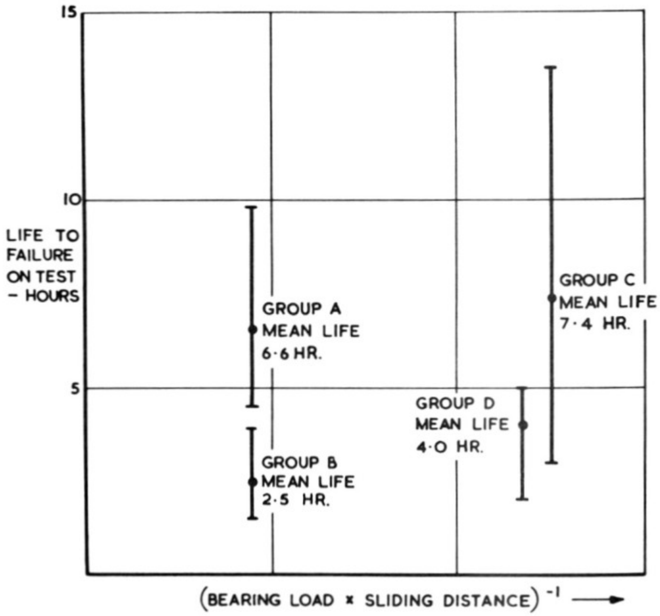


Figure 5. Variation in life of dry-film lubricated bearings.

Design is a creative art; it is not a science—as Clausen [7] in recent years has reminded us. There may be many possible designs that would meet the intentions of the specification but almost certainly not one of them would fulfil completely every requirement, restraint, and recommendation. It is found that demands clash, and, after careful appraisal of all practicable designs, the one that is chosen to go ahead is inevitably a compromise in some respects. A satisfactory design must take account of a large number of factors—characteristics of materials, performance, efficiency, weight, bulk, safety, life, cost, and many others—which all influence it in different ways. A critical analysis of the design may be made to see how it stands in relation to each factor. But success is unlikely to attend attempts to arrive at a design solely by synthesis. Conceiving possible schemes that should

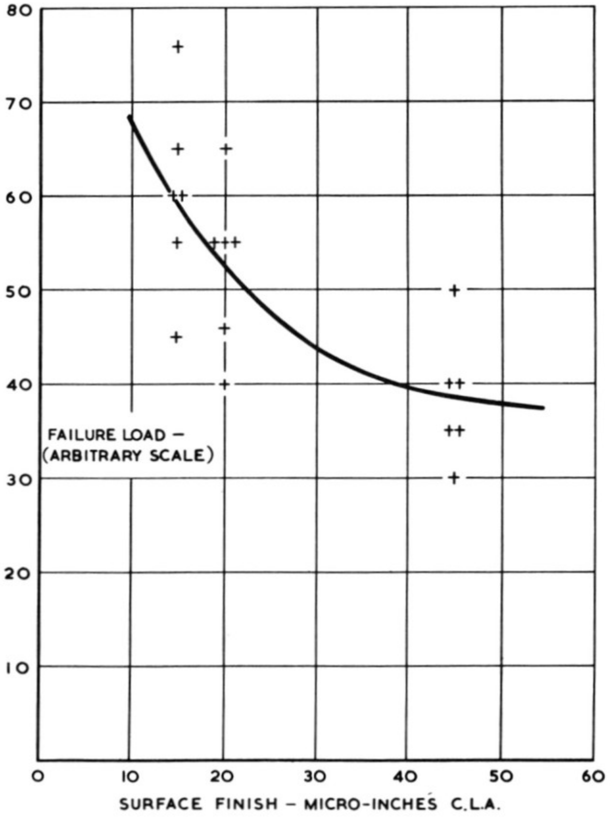


Figure 6. Variation in failing load of mineral oil in a lubricant gear test machine.

meet the major requirements is the essential creative work of the designer: he and his team then examine each to see how it stands up to the total requirements of the specification. By a series of evolutionary steps he gradually selects and refines the design until he has achieved an elegant creation. In science too, though it is largely analytical, there is also a parallel creative element in conceiving a hypothesis to explain observed phenomena. The hypothesis is then tested against the observations; if it fits it may stand for some time—until its imperfections are discovered by later more searching observations. Some hypotheses turn out to be most unreliable; others, conceived in the light of wider knowledge, remain unassailable.

The processes of decision making in design have been analysed in a most revealing and helpful way by Marples [8] who has described the progressive series of decisions from the large to the small and the detailed, each aimed at accepting what is good and rejecting what is bad. He discusses the organizational levels of responsibility for taking these decisions within a large design office staff.

Some people have inherent ability, sometimes genius, for creative design. It is not entirely a thing that can be taught, though experience and familiarity with mechanical science and technology is a necessary prerequisite including up-to-date knowledge of materials and manufacturing workshop processes.

Chaddock [9] has expressed the interesting view that engineering design should be taught in a manner akin to that in other creative arts such as music, painting and literature. He points out that education in these arts is not confined to learning the techniques of composition or the chemistry of paints and the care of brushes; but includes a large measure of individual creation and of critical appreciation of the work of others and of past and present masters. He advocates giving more opportunities to students of mechanical engineering to indulge in critical and constructive appreciation of actual designs of a wide variety of mechanical engineering creations. The Fielden Report [10] also encourages the setting up of special centres in areas of particular industries where close contact can be made with relevant industrial organizations for training students in design.

Reliability is of course only one factor in design. Performance, weight, airworthiness and cost are others. The early designers could take all these factors into account themselves, but with the growth in complexity and in numbers of people in design offices today, each of these factors may now be handled separately by different groups of people. So we have the weights engineers, the reliability engineers, and more recently the value engineers—all of whom are associated with the design team and play their parts by providing information, analysis, and constructive criticism.

KNOWLEDGE GAINED FROM EXPERIENCE OF FAILURES

The study of past mistakes is one of the most fruitful ways of increasing knowledge. Nowhere has this been better demonstrated than in accident prevention. Likewise where unreliability affects maintenance costs and mission success, finding out the physical causes of past failures can make a major contribution to design knowledge.

The foundation for failure investigation is a good reporting system. It must provide statistical information in order to indicate what is causing the most trouble, and information about the nature of the trouble to help the manufacturer, who needs to know the operating conditions of the equipment and its history in service. The sheer volume of defects, coupled with the number of different people who have to contribute to providing the information and the channels of communication between those who find defects and those who investigate them, makes adequate reporting a difficult administrative task. The airlines and the armed services have done much to bring home to manufacturers the information about defects in their equipment. But one still hears complaints among manufacturers that they do not get enough information. To overcome this problem manufacturers provide their own channels of information through service representatives stationed with the users.

Investigation of defects is usually done by the manufacturers. Often it is clear from inspection of the failed part that a fairly simple remedy such as strengthening the part or changing the material will avoid further trouble, but when this is done the fundamental nature of the failure mechanism may not be gone into. Sometimes it is unnecessary to do more than look into the detailed design assumptions to discover that the limitations of the mechanism have not been appreciated. A typical example was the failure of a grease-lubricated bearing, which examination of the design showed to be running on the limit of speed, under unfavourable installational and environmental conditions. To attempt to discover the fundamental cause and understand fully the failure mechanism can sometimes require a lengthy investigation, which does not always provide conclusive answers. In an investigation of stripped gears in a fuel pump (Fig. 7) the failures could not be reproduced in ground rigs, although evidence was found to suggest that dynamic loading of the gear teeth due to self-induced vibration was involved.

Obtaining defective parts for investigation with a full and accurate history and understanding of their behaviour in service is easier for the user than for the manufacturer. However, because the user needs to repair the components quickly to use them in service again they are stripped down on an overhaul line without time for a thorough investigation. In this way much useful information can be lost. Plans are now being made with a British airline to acquire this information by investigation of selected parts on the spot to see what general lessons can be learned about the causes of failure.

Another way in which failure experience can be used is by critical review of a design by people with plenty of experience of troubles in service. The Services and airlines help in this by making experienced servicing personnel available for consultation by designers from the earliest stages, sometimes by locating them at the manufacturers' works. Critical review of all the different designs of mechanisms fulfilling the same function, by someone with knowledge of failures in service in that type of mechanism, has often led to new or improved design and test requirements in official specifications.

The lessons learned from defect investigations need to be brought right to the drawing board to be effective. Design check lists, or reliability quizzes [11] are a means of reminding the designer of points that have been overlooked in the past. The Society of British Aerospace Companies, with the help of the Defect Investigation Section of the Ministry of Aviation,

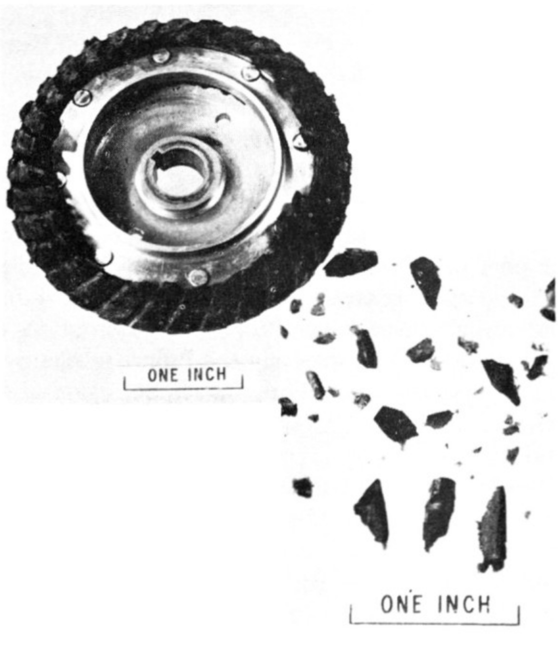


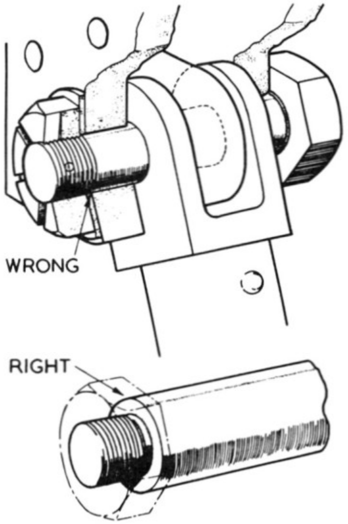
Figure 7. Failed gear wheel in a fuel pump.

have issued a detail design information handbook [12], which draws attention to design errors that have caused trouble, and shows by means of simple and clear illustrations the wrong and the right way (Fig. 8).

TESTING

THE PROBLEM OF ESTABLISHING FAILURE RATES

Testing to establish statistically that the failure rates of systems under their expected operating conditions are below a target value has gained acceptance in the electronics field where it originated [13]. The assurance that this can give in advance of using the equipment raises the demand for similar forms of testing to be applied in the mechanical field. There are fundamental differences between mechanical and electronic systems which create difficulties in proving failure rates in ground tests. In mechanical systems, the assemblies such as pumps, filters, and valves, which make them up and which can be considered as the physical counterparts of the electronic units, are individually of low complexity compared with the system as a whole. Their failure rates are low compared with electronic units and would require aggregate testing times running into hundreds of thousands of hours to demonstrate them individually to a worthwhile level



HINGE ASSEMBLY BOLTS.

IT HAS BEEN REPORTED THAT A WING FOLDING MECHANISM FAILED DUE TO THE HINGE ASSEMBLY BEING EXCESSIVELY TIGHTENED.

IT IS IMPORTANT TO ENSURE THAT BOLTS USED IN THE ASSEMBLY OF SUCH FITTINGS ARE DESIGNED TO PREVENT OVERTIGHTENING OF THE NUT. A SHOULDER BOLT WITH A SPECIFIC TOLERANCE ON THE SHANK DIMENSION IS A SATISFACTORY METHOD.

Figure 8. Information sheet S.B.A.C. detail design information handbook.

TABLE 1

Assembly	Target MTBD (hours)	MTBD of similar equipment in service	Number needed for a 5,000-hr test
Hydraulic pump	3,300	1,000– 3,000	13
Accumulator	6,250	220–16,000	25
Undercarriage jack	11,000	8,000–50,000	43
Shuttle valve	21,000	32,000	83

of confidence. The first column of Table 1 shows some targets of mean time between defects (MTBD) required to meet a reliability requirement for a hydraulic system. The second column shows the range of MTBD experienced with similar types of equipment now in service. The third column shows how many specimens would each have to be tested for 5,000 hours in a sequential test in order to demonstrate, with consumers' and producers' risk of 10 per cent, that their MTBD's did not fall below the required level, or exceed it by a factor of 2. The underlying assumption of random failures, which in practice represents failures in electronic systems well enough, is doubtful for mechanical assemblies. Nevertheless, the figures quoted do give a rough idea of the testing effort that would be required. These relate to defects affecting mission success. For reasons of safety of the aircraft in flight, the MTBD's of hydraulic assemblies such as those in a duplicated flying-control system would need to be 2 orders higher.

The testing time could be reduced if the system were tested as a whole. However, by the time system testing takes place the reliability of the constituent assemblies should have already been established in order to ensure timely development. Furthermore, if the MTBD of the system is found to be below the target as a result of failures in a few assemblies, these will not necessarily be the only ones contributing to its total unreliability.

A fundamental difference arises from the relatively high contribution of failures in the interconnections such as pipes and linkages between assemblies in mechanical systems, compared with those in electrical cables interconnecting electronic units. In hydraulic systems, failures in tubing and couplings are the greatest single cause of system failure. Failures in interconnections are critically dependent on how well the whole installation is done in the aircraft, and vibration is an important factor. It is generally impracticable to excite vibration of the whole system with its interconnections correctly, and obtain the correct response throughout. Without this the failure rates experienced in a ground test rig cannot be expected to correspond to those of the system installed in the aircraft.

Attempting to establish failure rates with statistical confidence by ground-rig testing in the development stage is thus seen to be an expensive and uncertain process. Moreover, it does not in itself improve reliability. A more practicable and worthwhile approach towards improving reliability is through thorough development testing that is aimed directly at bringing weaknesses to light at the earliest possible stage, beginning with the assemblies, since it is here that reliability is first built into the system. Testing a group of assemblies to failure at increasing load levels is a way of determining variability, and helping to establish a safe margin above working conditions. Nixon [14] has provided some striking examples (Figs. 9 and 10) of the improvement in reliability obtained, often cheaply and simply, through tests to destruction on only quite a small number of units, and has pointed to the moral: more thorough development testing in the first place to "press where it hurts."

DEVELOPMENT AND PROVING TESTS OF SYSTEMS

In recent years tremendous strides have been made in ground-rig testing of mechanical systems of aircraft, predominantly as a consequence of the

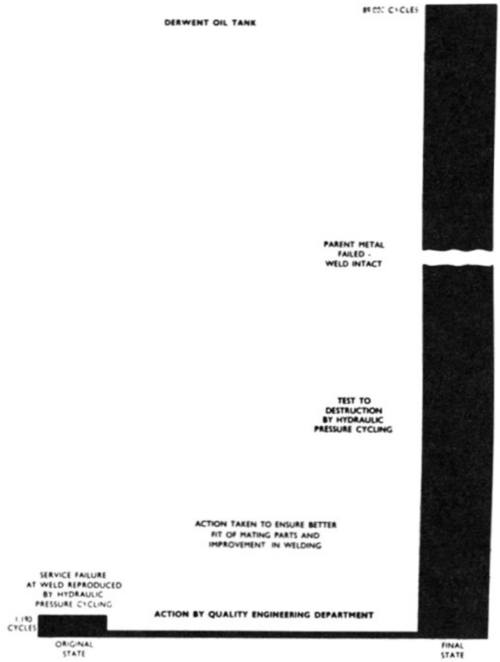


Figure 9. Improved reliability resulting from investigation by quality engineering department.

greater dependence on these systems for safety in flight, but also because it is more economical to discover faults in ground rigs than to suffer interruptions in flight tests. Ground rigs have become elaborate and reproduce as far as practicable all the important flight characteristics and environments. Excellent examples of complete systems ground rigs are those for the B.A.C. One-Eleven (Fig. 11) and the VC 10 (Fig. 12) civil transport aircraft, which have been described and illustrated in recent publications [15,16]. For example, for the B.A.C. One-Eleven an integrated systems rig for the hydraulics and the flying controls was built full-size with all components laid out in their correct relative positions connected by the right lengths of pipe or wire. Prior to inclusion in the system, rig components underwent individual development tests. In the rig the whole system is repeatedly operated to reproduce all modes of usage. Development work is first undertaken to ensure compatibility of components and proper system functioning. Then a thorough test is made of all fault conditions that could be expected to arise to ensure that the redundancy is adequate and sufficiently independent to enable the flying controls and essential services to operate to stringent flight-safety standards. Rig running can be

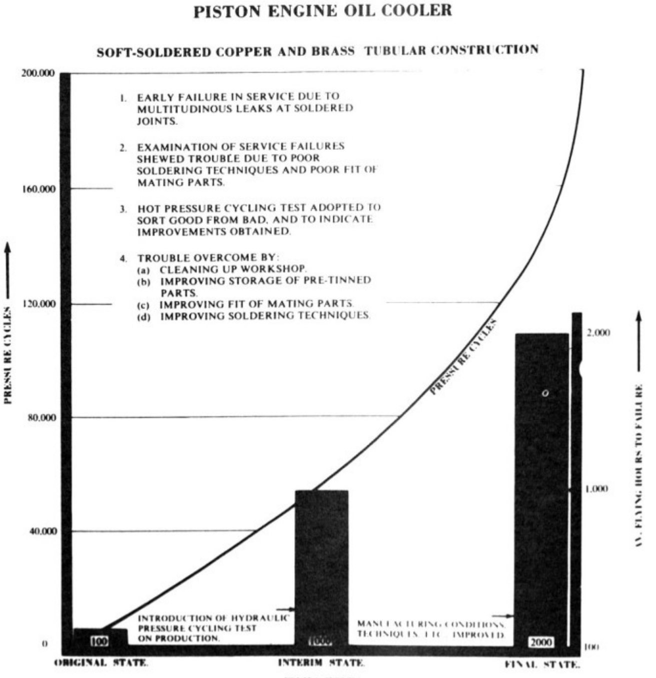


Figure 10. Improved reliability consequent upon quality engineering.

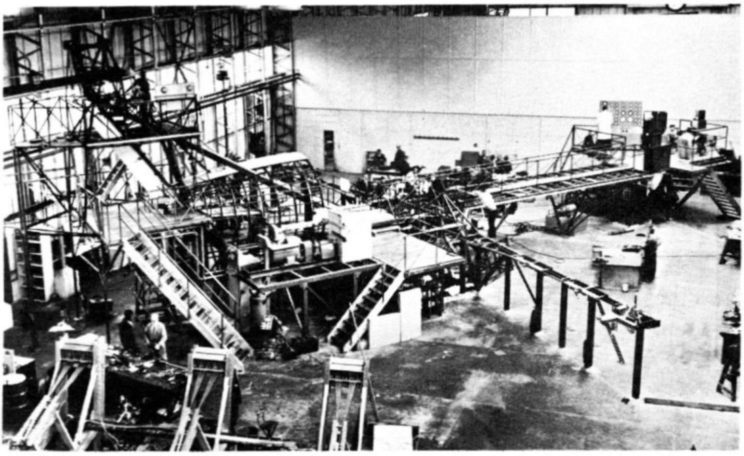


Figure 11. Flying controls and hydraulic system test rig—B.A.C. one-eleven.

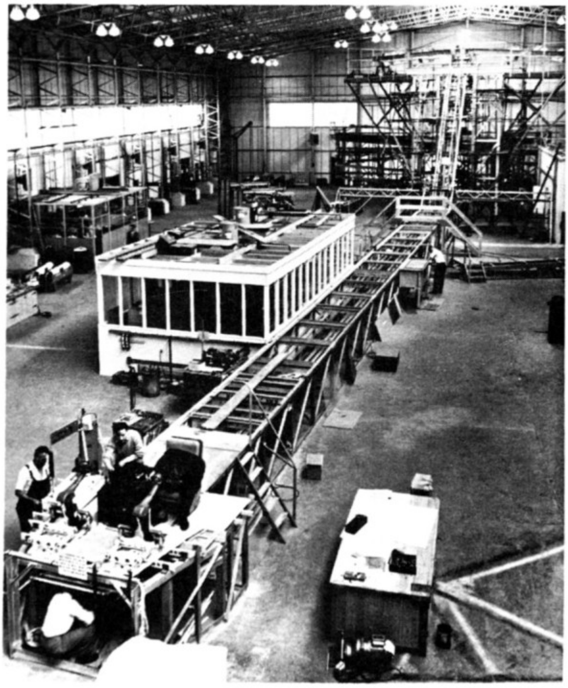


Figure 12. Flying controls and hydraulic system test rig—V.C. 10.

used also to determine the endurance of components operated for long periods under typical duty cycles. In this way the rig work can give information on which decisions can be made on suitable overhaul lives of components for initial use in service. Servicing and rigging procedures for the controls can also be worked out on the rig.

Thorough rig testing of this kind makes for sound development of systems to the high level of reliability required to provide safety in flight.

Whereas it would be uneconomic and in some respects impracticable to reproduce the full conditions of flight, almost all of those having an important bearing on system behaviour can be reproduced. Temperatures both high and low are readily achievable by external heating or by refrigeration. Low pressure can be provided in altitude chambers and in local boxes surrounding particular components only—for example, electric generators and motors. For cabin air conditioning and pressurisation systems with their associated temperature and pressure-control systems, complete cabins or representative sections of them can be tested in altitude chambers embodying external heating of the cabins by radiant heaters to represent aerodynamic heating, and at the same time the air supply and cooling systems can also be included so that the whole system can be operated under closely representative conditions. A facility for this at the Royal Aircraft Establishment, Farnborough, is illustrated in Fig. 13.

The susceptibility of components to vibration is normally checked by individual component vibration tests, but, if necessary, vibration can be included in subsystems forming part of the integrated systems rigs. For flying-control systems it is desirable to introduce good representation of the structural elasticity of mountings of control runs and actuator mountings to establish proper testing of servo stability and impedance.

FLIGHT TESTING

When all has been done to discover and rectify weaknesses in design by ground testing, there are some that inevitably remain undetected until flying begins, since it is only then that the equipment operates in the full environment for the first time. In the fairly short time available for flight testing, attention tends to be concentrated on the more serious shortcomings affecting safety or operational effectiveness. However, many apparently minor defects also crop up which in this short time appear as isolated cases. If there are no clear signs of bad design or manufacture they tend to be disregarded, and eventually contribute to the low rate, seemingly random occurrences that make up the bulk of unreliability. There is, however, a wide variation in these low defect rates of individual assemblies; those with the higher rates account for most of the defects that occur. In a

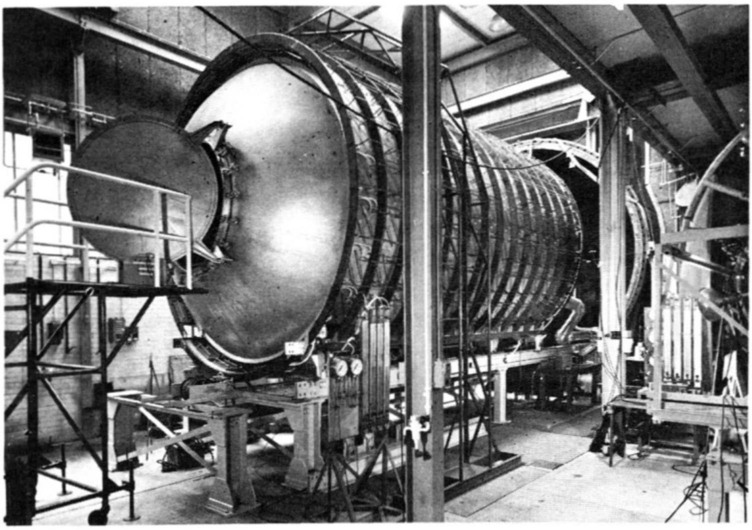


Figure 13. Cooling and pressurization systems test facility at the R.A.E.

number of widely different aircraft types about 30 per cent of all defects arose in only 2½ per cent of assemblies and about 70 per cent arose in only 20 per cent of assemblies. There is thus a good chance of the worst offenders soon coming to light.

Operational reliability flight trials of British military aircraft are conducted by the Ministry of Aviation's Aeroplane and Armament Experimental Establishment at Boscombe Downs. They consist of several hundred hours of flying under conditions representing intensive use. Arctic and tropical conditions are obtained in flights from overseas bases. All defects are recorded and investigated by experienced engineers and great emphasis is placed on determining the underlying causes of failure. Poole [17] has described how in the reliability trials of the Whirlwind 7 Helicopter, 240 hours were flown in 70 days, which led to improvements in the clutch, fuel filter, and rotor blades, among other things. Figure 14 shows a hose in the hot-air duct of a cabin air-conditioning system which burst during operational reliability trials. Hot air escaped onto a nearby transistorized speed sensing unit in the a-c generating system, causing an electrical power failure. The cause of the burst was diagnosed as poor alignment of the two pipes, aggravated by poor pipe support downstream of the joint and poor jigging upstream at the engine connection. Recommendations concerning the cause and cure were at first not accepted and the defect was treated as an isolated case. The same failures recurred during early service, until

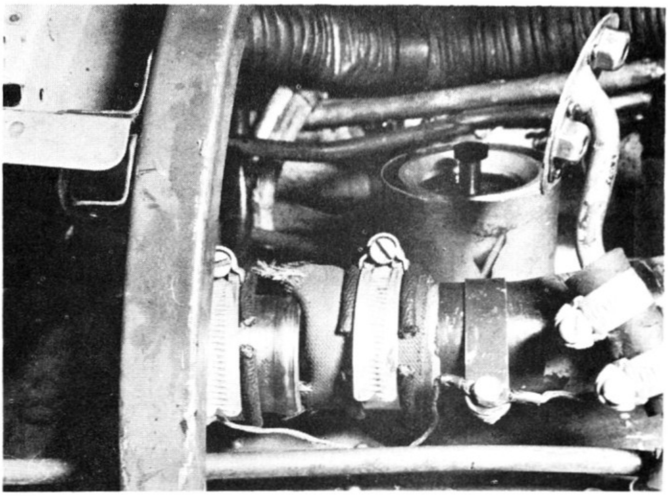


Figure 14. Burst hose in hot air duct.

cured by a modification to re-route the pipe, and provide means for alignment, and an external strap around the joint. This is a good example of the need to pay attention to the seemingly isolated case.

ACHIEVEMENTS TO DATE

From the very beginning of aviation the quest for reliability has been in the forefront. Although we are not dealing with engine reliability it is important to recognize the tremendous efforts made in achieving it, because of what can be learned from them. The main approaches are undoubtedly high quality of design and very extensive and thorough development testing. The importance of keeping stresses to reasonable levels has been fully appreciated. To quote but one example, the life of turbine blades can be increased 44 times by a reduction in operating temperature of 100°F and in engine speed of about 4 per cent at a cost of 6 per cent loss in thrust and a gain of 4 per cent reduction in specific fuel consumption [18]. Defect rates have been reduced to a low level and overhaul periods increased as service experience is built up. For example, 4,500 hours is now achieved by Rolls Royce Dart engines operated by British European Airways.

In the past two decades the importance of mechanical systems in aircraft has greatly increased. Many are essential to safety and operational effectiveness instead of being useful accessories. Flying controls depend on power actuation, human survival on cooling and pressurization, and automatic navigational and attack systems control the aircraft to fulfil military roles. For these reasons reliability as high as that of the airframe structure is demanded, especially of hydraulic and electrical systems, which provide power for these services. At the same time these systems have become more complex and have increased tremendously in power because of the additional duties they have to perform. A satisfactorily high level of reliability against failure has been achieved by high quality of design and manufacture, extensive development testing, and in essential services by redundancy, usually in the form of two completely independent systems. Automatic landing systems now coming, with their complicated electronic and electro-mechanical control systems, need triplicated channels to achieve high enough reliability to satisfy stringent air transport airworthiness regulations. However, with the large number of parts at risk in systems, due to their increased complexity and redundancy, defects, while not affecting safety, occur at a rate calling for a lot of maintenance effort in rectification and replacement of parts, checking system behaviour, making adjustments, and in periodic overhauls. Strenuous efforts are needed to keep them down to a tolerable level.

The foregoing review has been included to show that mechanical reliability is now of equal importance to structural reliability from the point of view of airworthiness and discharge of operational duty. Furthermore, it should be appreciated that mechanical reliability of the required order has been successfully achieved, albeit by use of redundancy. Redundancy has, however, also come to be used in the airframe structure, usually referred to as fail-safe design. Despite everything possible being done to improve the reliability of individual components and systems it would be unwise to expect that redundancy could be dispensed with in favour of single high-reliability channels. There are still too many uncertainties to make this a sensible course—human errors, material flaws, manufacturing variations. The extremely high level of reliability of individual channels would be virtually impossible to demonstrate within the time scale available. Redundancy has been accepted as the best practicable course in the field of propulsion by having at least more than one engine to transport aircraft.

CONCLUDING REMARKS

We conclude by reiterating the points we have intended to emphasize:

1. Reliability is founded, as it always has been, upon good design and thorough development.

2. Learning from past mistakes contributes to increased design knowledge.
3. The existence of variability must be recognized and allowed for in design and testing.

Trite though these may sound, they are nevertheless fundamental to achieving reliability.

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