NINTH EUROPEAN ROTORCRAFT AND POWERED LIFT AIRCRAFT FORUM

Paper No.79

DESIGN APPROACH TO OPERATIONAL RELIABILITY REQUIREMENTS

J.R. Lee

and

K.F. Lilford

Westland Helicopters Limited
Yeovil
England

September 13-15, 1983

STRESA, ITALY

Associazione Industrie Aerospaziali

Associazione Italiana di Aeronautica ed Astronautica

DESIGN APPROACH TO OPERATIONAL RELIABILITY REQUIREMENTS

J.R. Lee
and
K.F. Lilford
Westland Helicopters Limited
Yeovil, England

ABSTRACT

The paper presents the results of WHL studies of helicopter reliability and an approach to design of future aircraft for high reliability at acceptable cost, in terms of first cost, operating and support costs. The potential trade-off between reliability improvement measures and weight/performance parameters is explored with particular reference to the multi-market, multi-role basic vehicle design which are necessary for world helicopter markets.

Detailed results of a special Reliability and Maintainability research exercise are presented, identifying the major influences of design on reliability, and the potential areas of improvement. Specific emphasis is placed on reduction of main rotor inducted vibration. Results of a comparative field trial (in which the same subject aircraft were monitored both with and without a main rotor head vibration absorber fitted) are presented, together with the impact on reliability, direct engineering support cost and trade-off penalties. The subject of vibration reduction is then developed to show the potential effects of increasing the number of main rotor blades and the implications of more advanced vibration control features.

Other areas of reliability improvement are highlighted and major implications and trade-offs indicated.

1. INTRODUCTION

Operational reliability requirements are generally understood to be those numerical requirements specified in a Military Target or Requirement, and are defined in detail, with specific exclusions, in almost legalistic terminology. Certain systems or equipments may be excluded, such as Government Furnished Equipment, and external failure causes such as Foreign Object Damage and incorrect maintenance may also be excluded from the requirement. The intention of this paper is to take a much broader view of the design impact on reliability, recognising that detailed definitions relevant to specifications, guarantees or demonstrations are essential in their context, but the product reliability reputation (and that of the manufacturer) is subjectively assessed by the operator in terms of total effort, time lost and cost involved in corrective maintenance. For the purposes of this paper, 'operational reliability' is taken to be the operator's perception of reliability, including any condition which creates a need for corrective maintenance, whether this is a failure of equipment, environmental damage or deterioration, or damage during maintenance. All of these incur maintenance cost and all contain some element which is influenced by design.

A design approach to operaitonal reliability in this context must therefore be a broad based approach, acknowledging the influence of design on the whole spectrum of reliability. For the European rotorcraft designer this is especially complex because of the need to penetrate both military and civil markets in a wide variety of roles with variants of a single basic design.

2. DESIGN

Design features and trade-off for reliability in the basic vehicle must be carefully considered so that a benefit in one application does not become a burden in another. Figure 1 shows a comparison of various operational parameters for military and civil operations, all of which have an influence on reliability. In some cases the civil aircraft requirements will have the dominant influence, for example the high flying rates and airframe life, and in others the military requirement will dominate, for example mission success. Additionally the designer is faced with a very wide range of requirements and constraints within a single Target at the feasibility study stage. Each section of a Target is compiled with the assistance of operations and engineering specialists, each of whom requires a high level of performance in his particular field. It falls to the designer to integrate all the requirements and constraints into an acceptable production design, with the best balance of characteristics which the available design methods, analytical tools and engineering technology can produce. By definition this is a continual trade-off process in which there must be adjustment of one requirement in favour of another, where those requirements can be shown to be in conflict. In some cases the designer may consider, because of his knowledge of the performance of the next generation of equipment, or the need to compete in other markets, that a requirement is under specified, and will set a more stringent design aim than the Staff Target or Requirement demands.

The process of trade-off pre-supposes that one parameter can reasonably be related to another by some means. In some cases the trade-off is between very dissimilar requirements, for example in a recent conflict, battlefield support aircraft landing in soft ground suffered damage to communication aerials which, for maximum communication range, must be sited underneath the fuselage. Relaxation of the range requirement would permit resiting of aerials ina less vulnerable position or the use of less efficient flush aerials which are also less prone to accidental damage during maintenance and handling. There is an obvious trade-off between reliability (or robustness) and performance here which must be referred to the user for his judgement of the criticality of communication range. Close liaison between the designer, the procurement authority and the user is essential in trade-off studies.

3. ANALYTICAL TOOLS FOR TRADE-OFF

The majority of reliability trade-offs will be made against aircraft weight and first cost. The perameters of weight and cost are more tangible than reliability, and the estimating methods are better established and more widely understood than reliability parameters such as mission failure and defect rates. It is frequently necessary to explain the reliability parameters in terms which are more readily understood and can be directly compared with weight or cost. It is often beneficial to extend the study to include maintainability and support cost in order to give appropriate weighting to reliability.

It is important also to have a clear order of priorities within the reliability requirements. Military aircraft are principally designed around an aggressive scenario (with the possible exception of training and long range transport types) but the majority of their service life will be at peacetime flying rates, sortie patterns and maintenance practices, which are very different from the primary design parameters. Reliability parameters governing operational availability are mission failure rate and the requirement for a period of front line operation without corrective maintenance (sometimes known as sustainability). Defect rate will, however, govern peacetime spares supply and maintenance cost which is a very significant factor in military equipment procurement. There is an 'internal' reliability trade-off between the operational reliability parameters and the logistic parameter (defect rate) which must be addressed, particularly when considering redundancy to achieve the maintenance-free front line operating period.

The development of simple operational and logistic support models is an essential requirement for effective decision making in trade-off studies. Two basic models are needed :-

(a) Operational availability model, representing a datum scenario, including numbers of aircraft, their dispersal, sortie types and mix, environmental conditions, flying rates etc. This should be a global model, sufficiently representative of the envisaged operational scenario to be useful as a datum, without undue detail or complexity.

(b) Logistic Support model, representative of peacetime dispersion and support philosophy. This should also be a global model, sufficiently representative as a datum for comparison, but without undue complexity.

Use of these two models, progressively refining them during the early project phases, gives a rapid first estimate of the likely impact of reliability changes. Consistent use lends weight to reliability argument, and the outputs become familiar to contractor's and military staff other than the R&M specialists.

4. ENGINEERING TRADE-OFF FOR RELIABILITY

The effect of design decisions on reliability must always be considered but the major engineering trade-off is between reliability and weight. Additional redundancy, the addition of anti-vibration measures and cooling packs for avionics equipment all contribute significantly to reliability improvement, but incur weight penalty.

There are several ways in which a weight penalty can be reflected in operation, and positive decisions can be made on this in the early stages of design. At the earliest stages it may be possible to absorb a weight increase into a higher design All-up-Weight, restoring performance to maintain design criteria. This incurs additional weight penalty for increased power, fuel tankage and undercarriage strength and is seen in service as a fuel consumption penalty, and increased maximum AUW. The weight penalty may also appear as a reduction of disposable load, altering the payload/range characteristic. Where appropriate the provision of a main rotor head vibration absorber or refrigeration pack may be optional, reducing the overall penalty by allowing the operator to remove the equipment when operationally necessary. There is a different effective penalty in each of these approaches to weight trade-off against reliability and in some cases the requirements or stage of design will limit the available options.

Trade-off then is a complex activity which depends for success on clear definition and understanding of requirements, agreement of trade-off parameters and relative values, and acceptance of the negative elements of trade-off, reflecting these in later issues of Staff Requirements, Development Specifications and ultimately the Production Specification. Trade-offs for reliability are especially complex because of the difficulties of specifying, estimating and measuring reliability, and the wide ranging effect of unreliability on operations and support costs. Therefore the prime requirement in the design approach to reliability must be to identify those common factors which influence reliability in all applications and to ensure that the basic vehicle design approach maximises the benefits available through control of these common factors.

5. OPERATIONAL RESEARCH INTO HELICOPTER RELIABILITY

As part of the preparatory studies for what is now the EH101 project, an Operational Research Exercise was carried out jointly by Westland and the Royal Navy. The objective of the exercise was to establish in-service R&M achievement in comparison with the specification requirements, to identify causes of unreliability and high maintenance cost, and determine the measures which can be taken in design and development to reduce them. (See Fig.2).

The data requirement for this kind of analysis is more detailed and comprehensive than the normal services data systems can provide, and it was necessary to place a data retrieval team consisting of three WHL engineers and a Royal Navy senior rating on site at the operational base. Six aircraft were nominated for monitoring. Data concerning every maintenance action on the monitored aircraft (both planned and unplanned) was recorded by the team in fine detail. Each maintenance action was carefully assessed and categorised using specially devised categories and a computer data base system. The team were on site for 15 months and data from 1535 flying hours was collected and analysed. The data obtained has been extensively used in the early design phases of the EH101 project and has proved to be a very valuable aid to R&M design considerations.

The approach to identifying design influences was a broad-based analysis, covering all aspects of reliability and maintenance. Because the exercise was basic research and not any form of demonstration the team were able to assess their findings without constraint, the objective being to discover, not to prove, therefore providing the basis for the design approach presented in this paper.

6. ANALYSIS OF FAILURE CAUSES

Figure 3 shows a breakdown of the major primary causes of maintenance actions. The analysis is based on an engineering assessment of the mechanism by which each recorded fault was induced, and not the attribution, for example a fault which was assessed as being caused by human induced loads during maintenance may indicate an underlying design problem which could be resolved by improved robustness or better ergonomics.

Several significant aspects of design will contribute to reliability improvement in each of the major cause categories.

7. HUMAN INDUCED FAULTS

35% of recorded maintenance events fall into this category. This category of maintenance events includes all those where the causative influence is the human interface. Damage during maintenance dominates this category and was mainly concentrated around the engine and transmission area on the cabin roof and in access panels and working platforms. A large proportion of maintenance actions need access to the upper fuselage and cabin roof areas and the traffic of maintenance personnel on the aircraft is high. Lightweight fabricated structure typical of helicopter construction is prone to damage by maintenance induced loads which can produce significantly higher local stress than the aerodynamic stress. Three major design influences can reduce this contribution to maintenance cost:

(a) Improved maintenance ergonomics.
(b) Improved robustness of access provisions.
(c) Reduced maintenance requirements.

Maintenance ergonomics include such areas as the provision of remote fluid contents indication, ensuring that all ground power supply connectors are accessible from ground level, minising the need for maintenance personnel to climb on the aircraft for routine tasks, and the provision of adequate footsteps and handholds appropriately positioned for secure access. Robust provision must be made, ensuring that cabin doors do not foul footsteps when opened, and that parts which fall readily to hand as handholds or supports are suitable for use. 'No step' or 'No handhold' decals are not effective to protect fragile parts which are in natural positions for use by maintainers.

Reduced maintenance is a fundamental design consideration. Westland have adopted the CIVIL AIRLINE/MANUFACTURER MAINTENANCE PROGRAMME PLANNING guidelines of MSG 3 for all future projects. The Westland 30 Series 100 was the first helicopter to gain FAA certification on the basis of a formal Maintenance Review Board based on MSG 3. The procedure is designed so that only those tasks are selected which positively contribute to safety, reliability or economic benefit. Reducing the number of maintenance tasks and defining them as early as possible in the design process allows adequate provision for access and ergonomic considerations to be made. (See Fig.4).

8. OPERATING AND VIBRATIONAL INFLUENCES

26% of recorded maintenance events fall into this category. (The category 'cause not determined' would also contain faults which would be categorised here if the faulty equipment had been fully investigated and the primary influence identified. It was not possible to investigate all faults to this level particularly in avionic equipments where on-site repair investigation was to card level and therefore not deep enough for this type of categorisation). The vibrational influence was dominant in this category and was identified as the primary causitive influence in 20% of all recorded events and as a contributory factory in a further 10% of events. Assuming that vibration was at least contributory in half the 'cause not determined' category, it is possible that vibration was significant in 40% of the observed events.

Research into helicopter vibration control has been mainly focussed on the cabin and crew environment. The most significant vibrational influence in rotorcraft is the amplitude of vibration at main rotor blade passing frequency. Several design approaches to main rotor vibration control are available, ranging from anti-vibration mounts through resonant mass vibration absorbers, 5-bladed rotor head design to the latest research in Active Control Technology and Higher Harmonic Control. Following subjective trials of a main rotor head mounted vibration absorber on Royal Navy Lynx aircraft, a small scale trial was set up jointly by Westland and the Royal Navy to evaluate the effect of reduced vibration levels on aircraft reliability.

There is very little published data quantifying the relationship between helicopter vibration levels and reliability, although some trials were reported by the US Army in 1973 (see ref.1). To monitor groups of aircraft with and without a vibration absorber in order to generate enough statistically significant data at equipment level is prohibitive. However the small scale Westland/RN trial, involving three aircraft monitored with and without a vibration absorber fitted produced encouraging results as shown in figure 5. The best of the three aircraft showed a defect rate equivalent to 224 defects per 1000 flying hours over a monitored period of 400 flying hours with the vibration absorber fitted. This compares with a sample average defect rate of 453 defects per 1000 hours for the three aircraft when the absorber was not fitted. Not all the apparent improvement was due to reduced vibration, since the analysis showed a significant reduction in maintenance damage, primarily due to the high flying rate achieved, and the avoidance of unnecessary maintenance for training, robbery etc. The overall effect was an average reduction in defect rate of 85 defects per 1000 flying hours, (representing some 19% reduction) due to reduced vibration levels.

The benefits of vibration reduction are evident from this limited trial and it is estimated that the vibration absorber embodiment costs would be recovered within the first two years of operation through reduced maintenance and repair costs. The adverse trade-off is the weight penalty of some 50Kg which adversely affect payload/range performance and fuel consumption.

The Westland 30 civil helicopter has been developed from the Lynx military helicopter, and incorporates both a rotor head vibration absorber and an elastomerically attached raft for mounting the transmission. It is not realistic to compare total defect rates between the W30 and Lynx due to the differences between the aircraft, but the defect rates for systems with high commonality can be compared. It must however be emphasised that the Westland 30 data is limited to 1650 flying hours achieved in the first year of service (fig.6) whereas the Lynx is for a mature aircraft.

Studies show that greater reduction in main rotor vibration levels can be achieved at lower weight penalty by increasing the number of main rotor blades. This can only be economically achieved in the initial build of the aircraft and at this point the weight penalty can be accepted into the basic aircraft weight, maintaining performance to design requirements. Figure 7 shows a table of trade-off values for the vibration absorber approach to vibration reduction and estimated values for a five bladed main rotor head approach, for example as occurs in the development of the Westland 30 series 100/200 to series 300. The estimated reduction in defect rate for the five blade configuration is conservative, recognising diminishing returns as vibration is reduced and also the change in blade passing frequency.

For the future advanced concepts in rotor vibration control are being considered. Higher Harmonic control involves a significant increase in control system hardware, but offers very low levels of main rotor vibration. The direct reduction in maintenance cost versus vibration reduction must follow a trend of diminishing returns, but may result in an equipment vibrational environmental approaching that of fixed wing aircraft. This offers the prospect of better compatability of environment for role equipments common to rotorcraft and fixed wing, with a higher probability of achieving similar reliability in both applications. Whole Life Cycle Cost studies will be necessary to establish the trade-off here.

9. AVIONICS COOLING FOR IMPROVED RELIABILITY

One important aspect of reliability trade-off not studied in the Operational Research Exercise is the effects of operating temperature on avionic reliability. This was due to the fact that in a single trial in the benign UK environment there is not sufficient variation in outside air temperature to show any trends. Also it is not possible to relate defects directly to temperature as a primary cause since the failure mechanism stems from inherent component weaknesses which result in component failure at a high frequency due to higher temperature stresses. However the relationship between operating temperature and observed reliability of avionic equipment is well known and documented which enables designers to carry out trade-off studies on the effects of fitting environmental control systems.

Fig.8 shows a simplified relationship between ambient temperature and reliability of a typical avionics system, comparing the effect of forced fresh air cooling and three different levels of refrigerated air cooling 16, 32, 40 lb/min packs. Although equipment remains operable up to an OAT of +40° with fresh air cooling, a significant improvement in reliability is gained by providing refrigerated air cooling down to temperatures as low as +20°C.

The weight penalty associated with fitment of each size of refrigeration pack is also shown together with penalties in electrical power and fuel.

Life Support cost studies are in progress to further explore the potential benefits, including the effect of improved reliability on spare stock holdings, which may be a very significant saving. A possible recommendation from the study may be that the refrigeration pack should be an optional fit, embodied on all aircraft continually operating at sea level temperatures of +20°C and above.

10. POLICY AND PROGRAMME INFLUENCES IN RELIABILITY

A general discussion of trade-off for reliability would be incomplete without consideration of the effects of timescale and programme changes.

Time is a significant factor in measurement and proving of reliability. Relevant testing for reliability proving and improvement can only begin when equipment representative of the production standard becomes available. Between this point and the commencement of production deliveries, the most significant impact on reliability can be made through the Test, Analyse and Fix procedures of the reliability rig and flight testing phases (see fig.9). If this phase is cut short or allowed to overlap series production, then the opportunity for improvement diminishes and the cost of improvement rises. It is essential that relevant experience is gained very early in the development programme. Introduction of most new aircraft types in military service commences with intensive trials of some kind, using the first production aircraft. It is recommended that there is an earlier field evaluation, using the later development standard aircraft, to enable practical experience to be built into the earliest possible production aircraft. - i.e. put such an aircraft with an operational squadron for a few months.

Change of requirements or constraints late in the programme can have a very adverse effect on reliability. Cost or weight reduction exercises inevitably result in changes in the production version which have not been proven in development, and are not improvements as a result of development experience. Sound programme management and monitoring should ensure that late changes are minimised if the requirement and policy remain unchanged.

11. PROBLEMS TO OVERCOME

There are difficulties in obtaining acceptance of the results of trade-off studies and in achieving acceptance of the design requirements for high reliability.

During development much of the reliability data is based on prediction or limited test data that is not statistically significant whereas much of the performance, e.g. weight payload, speed can be assessed using known physical laws.

High levels of reliability or availability predominantly show financial benefits to the operator during operational use and especially as the aircraft becomes older, but they are achieved by spending front end money.

As reliability cannot be measured with accuracy during development, it cannot be specified in a development contract and there is inevitably a tendency for its achievement to take second place to those parameters which can be measured and are specified.

Even for a production contract, realistic reliability figures can only be obtained after three or more years into service which inhibits the specification of reliability requirements or incentives.

Vibration has a large impact on individual component reliability. In addition to overall design to low vibration levels, each individual component should be checked for the local vibration environment during development to ensure they are within acceptable limits for that particular piece of equipment.

Even if the policy described in this paper is followed some unanticipated unreliability will evolve during early production aircraft and it is necessary to have an adequate reliability improvement programme during the first few years of operation so that corrective action is taken before large numbers of unmodified parts are produced - that is some form of maturity programme.

All the problems listed can be overcome if both contractor and customer adopt a strong, and determined policy to achieve a highly reliable aircraft. The developing tools now becoming available to present realistic trade-off studies should contribute to this aim.

12. REFERENCES

(1) Vibration Effects on Helicopter Reliability and Maintainability (USAARMRDL Technical Report 73-11 April 1973).

	MILITARY	CIVIL
UTILISATION	200-400 HRS/YR	1000-2500 HRS/YR
AVERAGE SORTIE	1.5 — 4.5 HOURS	0.25 — 0.66 HRS
RELIABILITY PARAMETERS	AVAILABILITY BASED ON MISSION RELIABILITY IN INTENSIVE OPERATION 87%	DESPATCH RELIABILITY 98.5%
FATIGUE LIVES	7000 CONSIDERED "INFINITE"	50,000 CONSIDERED "INFINITE"
MAINTENANCE	NIL FOR 150 HRS OF INTENSIVE OPERATION	ELAPSED MAINTENANCE TIME CRITICAL TO ALLOW ALL MAINTENANCE OVERNIGHT

FIGURE 1

COMPARISON OF TYPICAL USAGE AND ENVIRONMENT FACTORS FOR MILITARY AND CIVIL AIRCRAFT

OBJECTIVES:-

TO ESTABLISH R & M ACHIEVEMENT OF RN LYNX IN SERVICE

TO IDENTIFY FAULT CAUSES AND IMPROVEMENT AREAS

TO PROVIDE A BASIS FOR R & M IMPROVEMENT THROUGH DESIGN & DEVELOPMENT

---

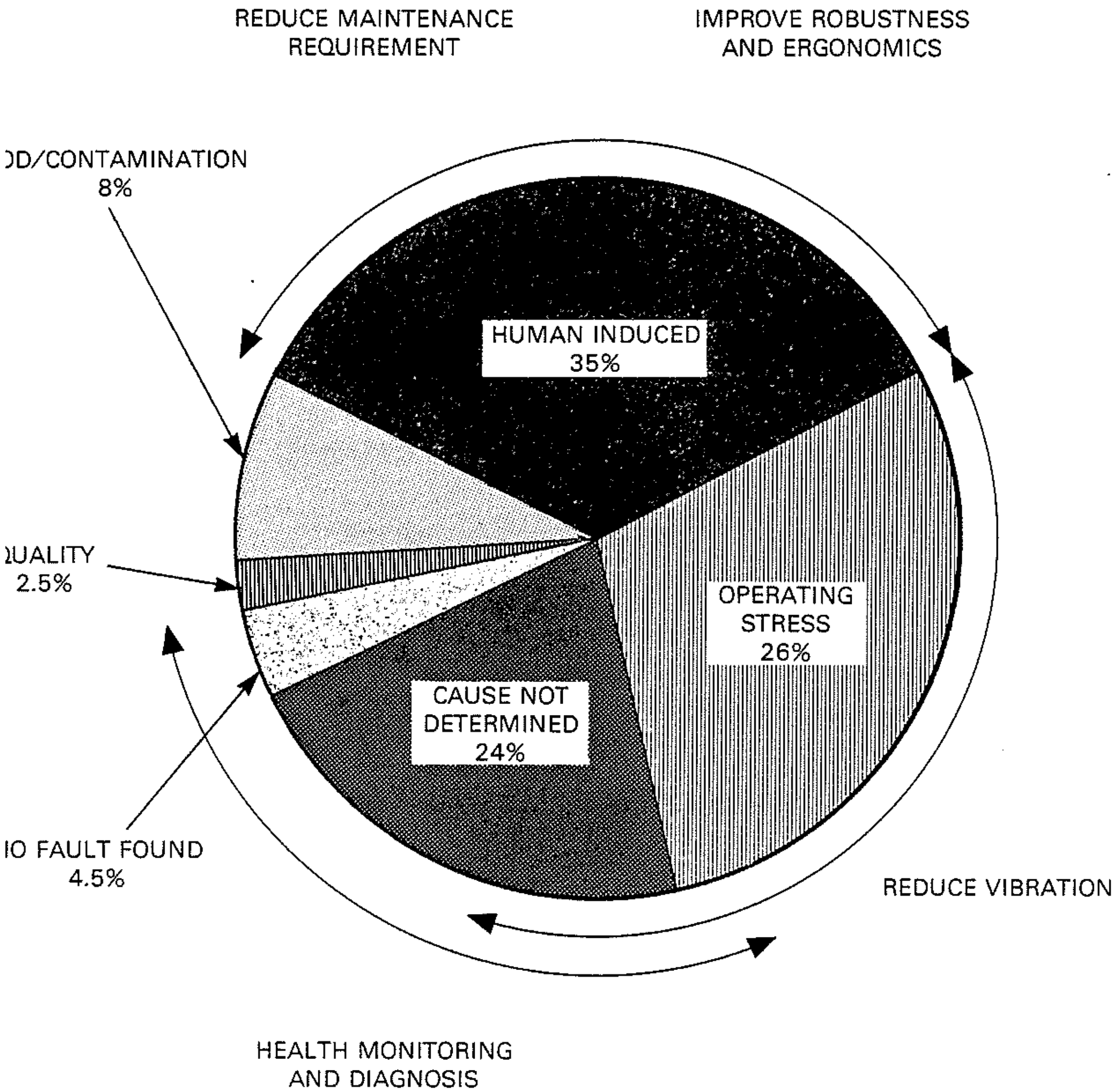
15 MONTHS MONITORING

6 LYNX AIRCRAFT

1536 FLYING HOURS

FIGURE 2

WHL/RN OPERATIONAL RESEARCH EXERCISE



MAINTENANCE EVENTS — **CAUSES AND DESIGN ACTIONS**

FIGURE 3

WHL / RN OPERATIONAL RESEARCH EXERCISE

- **AVOID UNNECESSARY MAINTENANCE** - M.S.G.3 LOGIC
- **MAINTENANCE ERGONOMICS** - IMPROVED ACCESSIBILITY
  - IMPROVED ROBUSTNESS
  - GROUND TEST CONNECTIONS
  - REMOTE LEVEL READINGS
- **HEALTH MONITORING DEVICES**
- **DIAGNOSTIC AIDS** - B.I.T.E./IN BUILT CHECK OUT SYSTEM (I.B.C.O.S.)

FIGURE 4

HUMAN INTERFACE - PREVENTATIVE MEASURES

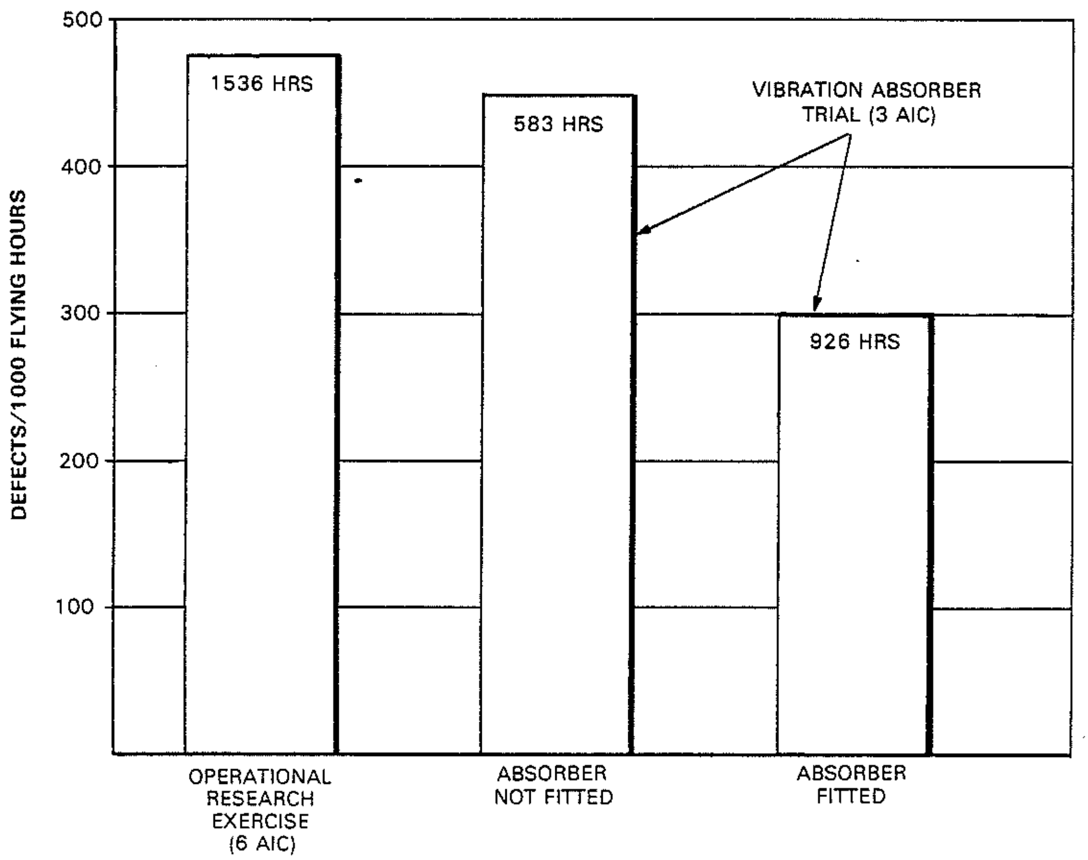


FIGURE 5

EFFECT OF VIBRATION REDUCTION ON DEFECT RATE

	LYNX MINUS ABSORBER	LYNX WITH ABSORBER	W30 WITH ABSORBER AND RAFT
TRANSMISSION (INCL:- HYDRAULICS, ELECTRICAL,FLYING CONTROLS, ETC.)	65*	37.5	22.8
AIRCRAFT SYSTEMS (INCL:- HEAD & BLADES, T.R. DRIVE, M.R. DRIVE)	105	60	61.5
PROPULSION	62.5	20.5	24

** All rates in defects/1000 flying hours*

WEIGHT PENALTIES

ABSORBER : 50 kg
RAFT : 112 kg

FIGURE 6

DEFECT RATE COMPARISONS

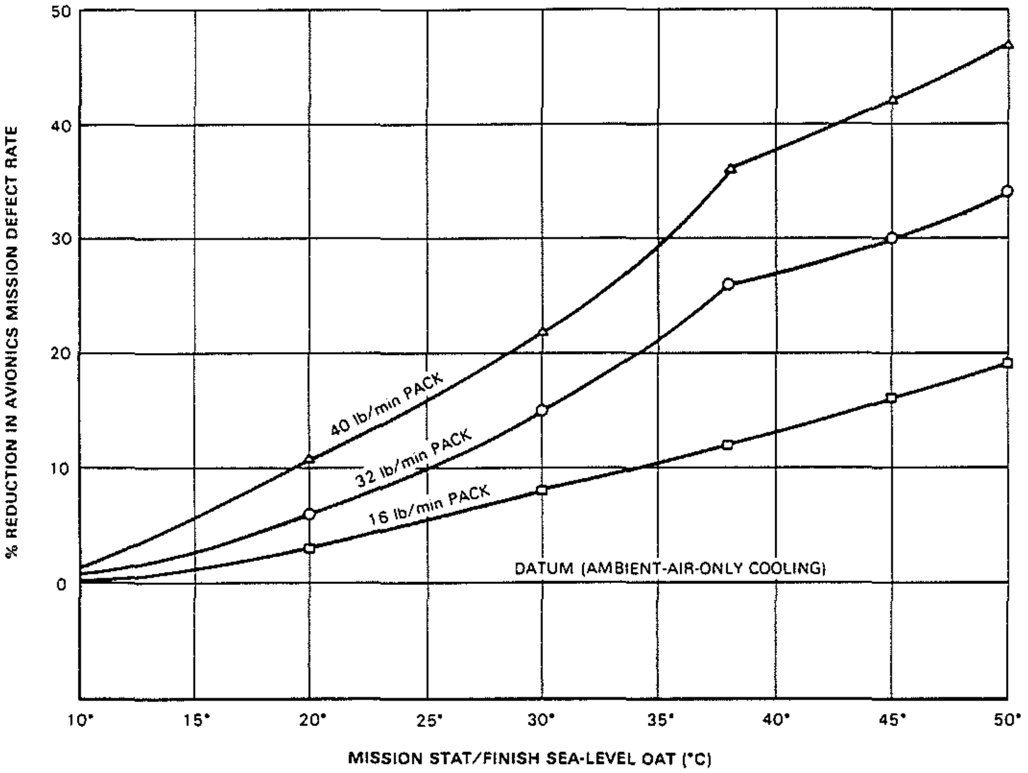
PARAMETER	4 BLADE HEAD WITH VIBRATION ABSORBER	5 BLADE HEAD NO ABSORBER
WEIGHT CHANGE	+ 110 lbf	+ 50 lbf*
VIBRATION REDUCTION (g)	- 35%	- 60%
DEFECT RATE CHANGE	- 85 DEFECTS PER 1000 HRS	- 100 TO 120 DEFECTS PER.1000 HRS

* NOTE

THIS IS THE PRIMARY WEIGHT CHANGE, THIS SHOULD BE DOUBLED TO TAKE ACCOUNT OF POWER INCREASE, FUEL CAPACITY AND STRUCTURAL STRENGTH.

FIGURE 7

VIBRATION REDUCTION TRADE OFF VALUES
FOR ROTOR SYSTEMS OF EQUAL BLADE AREA



COOLING PACK CAPACITY lbs/min	WEIGHT lbs	FUEL lb/hour	ELECTRICAL POWER
16	47	13	1.5
32	88	28	3.5
40	108	54	4.0

FIGURE 8

REDUCTION IN AVIONICS MISSION DEFECT RATE USING DIFFERENT COOLING PACKS TOGETHER WITH TRADE-OFF PENALTIES

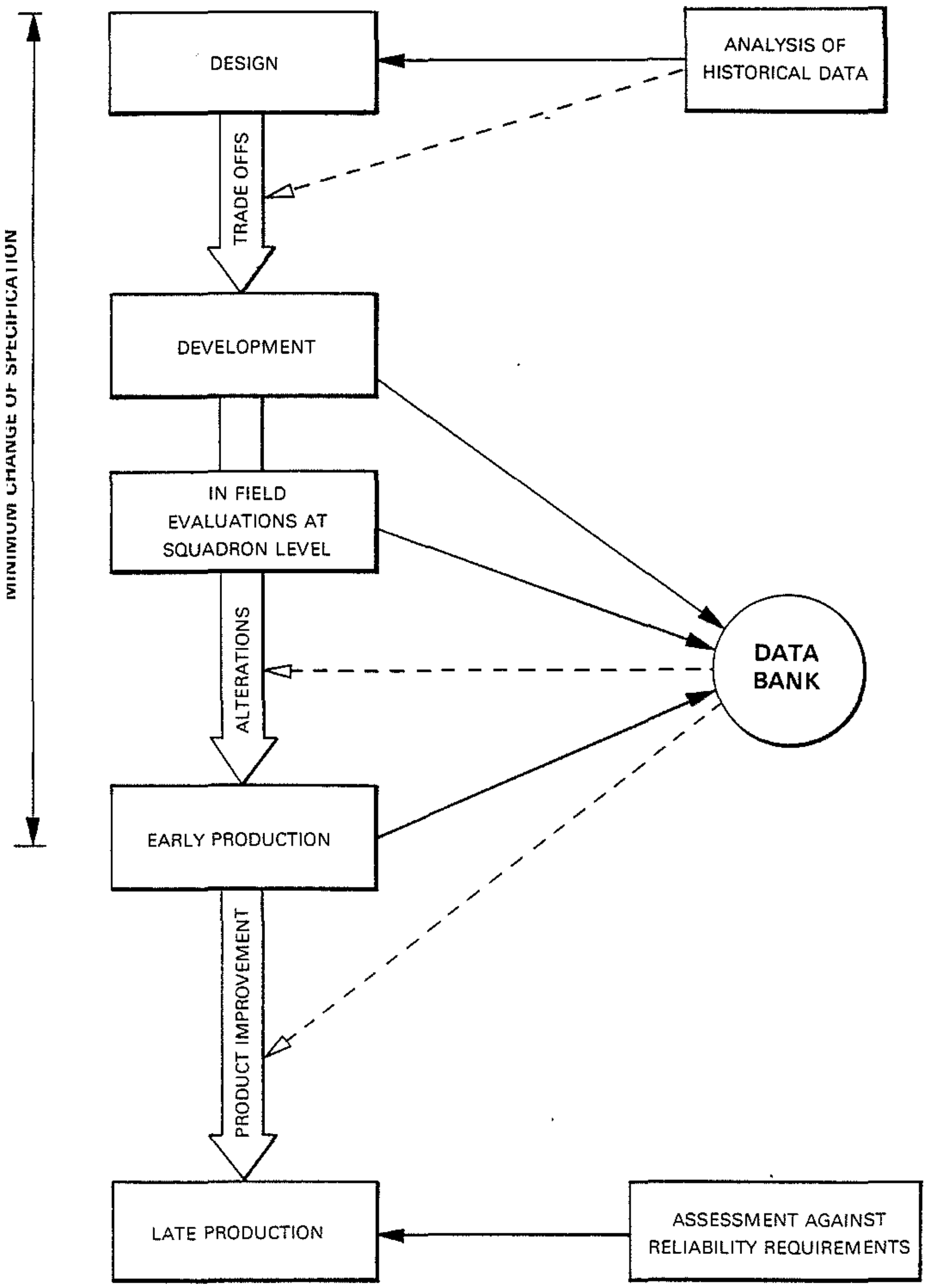


FIGURE 9

RELIABILITY SEQUENCE CHART