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DESIGN APPROACH TO OPERATIONAL SAFETY REQUIREMENTS

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ABSTRACT

The harnessing and control of energy for the purpose of flight constitutes a risk of some form of failure. The risk has to be reduced to an acceptable level, paying due regard to the consequences of the failure. The safety requirements which the helicopter designer must address are outlined and the safety record of helicopters is analysed to identify design solutions seeking further achievement of the safety of helicopter operations. Critical areas identified are rotor systems, transmission systems, engines and hydraulic systems for which future design possibilities are discussed in relation to safety improvement. The subject of crashworthiness is addressed and developments leading to crashworthy fuel systems and high performance undercarriages are described. The safety record of helicopters has progressively improved and further positive steps in improvement will only be achieved by the acceptance of weight and cost penalties.

1. INTRODUCTION

No accidents equates to no flying is a truism often quoted. The harnessing and control of energy for the purpose of flight constitutes a risk of come form of failure. The aim of the designer must be to reduce that risk to an acceptable level paying due regard to the consequneces of a failure. Failures may be considered either as defects affecting operational reliability or as hazards affecting operational safety though this distinction will be related to the circumstances at the time of the failure and not necessarily to the form of the failure. The subject of operational reliability is being covered at this Forum in Paper No.79 and it is clear that there is a relationship and common ground to be found between safety and reliability.

This paper outlines the safety requirements which the helicopter designer must address and will analyse the safety records of helicopters in order to identify design solutions in the context of seeking further assurance of the safety of helicopter operations.

2. HELICOPTER SAFETY REQUIREMENTS

Aviation of most, if not all forms, is now controlled by regulatory agencies whose purpose is to establish and enforce certain standards which are thought to contribute to aviation safety. Manufacturers are required to substantiate the airworthiness of their products against particular conditions of operation to the satisfaction of the appropriate agencies. Operators are required to abide by codes of practice laid down by the regulatory agencies.

The regulatory function is performed by national agencies but two agencies, the Civial Aviation Authority (CAA) in the United Kingdom and the Federal Aviation Authority (FAA) in the United States have produced regulatory codes for civil helicopters. Each Authority prescribes airworthiness requirements (BCAR's and FAR's respectively) applicable to specified categories of rotorcraft against which airworthiness certificates are issued enabling operation within their spheres of responsibility.

The particular airworthiness requirements issued by CAA and FAA covering civil helicopters are:-

Civil Aviation Authority:-

BCAR Section G covering all rotorcraft

Federal Aviation Authority:-

FAR Part 27 covering normal category rotorcraft up to 6000lbs maximum weight,

FAR Part 29 covering transport category rotorcraft.

In setting safety requirements the principle adopted, in particular by CAA, has been to maintain an inverse relationship between the probability of an occurrence and the degree of hazard inherent in its effect as illustrated in Figure 1 taken from BCAR's.

In recognition of the wide spectrum of helicopter capability each authority classifies its requirements against performance in the event of an engine failure during flight.

BCAR's distinguish between the following groups of rotorcraft:-

Group A	Rotorcraft with more than one Power-unit, with performance such that, in the event of the failure of one Power-unit, it is possible either to continue the flight or to land back on the take-off area.
Group A1	Group A rotorcraft, having engineering standards such that the probability of an Emergency Landing may be considered as Remote.
Group A2	Group A rotorcraft, having engineering standards such that the probability of an Emergency Landing may be considered as Reasonably Probable.
Group B	Rotorcraft with performance such that, in the event of the failure of one Power-unit at any point en-route, a landing has to be made.

It should be stated that CAA holds that no current helicopter is capable of meeting the requirements of Group A1 (Ref.2). A new classification is under consideration by CAA related to helicopter weight, number of passengers and single engine performance (Ref.2).

FAR Part 29 similarly distinguishes between the following categories from a performance viewpoint:-

Category A	Rotorcraft which in the event of a failure of one engine can achieve a specified rate of climb at a specified altitude above the take off altitude.
Category B	Other rotorcraft.

It would not be appropriate to consider in this paper the detail of these requirements. Particular features will be addressed following consideration of the safety record.

3. HELICOPTER ATTRIBUTES

The helicopter as a flying machine offers unique capabilities enabling it to be operated in flight regimes not available to other aircraft. The speed envelope typically offered by helicopters ranges from a zero speed, i.e. hover capability, to forward, backward, sideways and vertical flight, together with rotational ability. Its manoeuvre envelope is such that it is fully controllable in all these regimes of flight. Additionally, its design enables controlled power off descending flight (autorotation) which can be arrested at an appropriate height to achieve a safe touch down. These attributes confer significant advantages in safety of operation during the various phases of a flight as follows:-

Take off - A vertical take off can be offered allowing operation from restricted sites virtually irrespective of wind direction. Flight heading can be selected at an early opportunity. Controllability in all directions is immediately available at lift off.

Climb out - A vertical or steep climb out is available virtually irrespective of wind direction from restricted sites with reduced noise hazard.

Flight - Flight may be carried out at any speed from zero up to a maximum cruise speed with the option to operate at a loiter speed conducive with a minimised power requirement. Autorotative capability is available over a wide speed/altitude envelope.

Descent - The descent profile may range from the vertical or very steep to the very shallow and may be carried out at any forward speed from zero to maximum cruise. Emergency, power off, descent is available by autorotation.

Landing - Landing is conventionally carried out at zero forward speed, i.e. the helicopter stops and then lands unlike the fixed wing aircraft which lands and then has to stop.

Taxiing - Whilst conventional taxiing is available to wheeled helicopters there is the capability to air taxi at slow speed close to the ground enabling the helicopter to proceed directly to its intended parking position irrespective of ground features and conditions.

These attributes, whilst conferring a wide range of capability and providing inherent safety in operation, result in certain features which have to be allowed for in the design of the helicopter.

High Installed Power Requirement - Helicopters require a higher level of installed power in relation to their weight than required by fixed wing aircraft. This is not only to provide the hover capability but also to overcome the rotational drag of the rotors (profile power) whilst maintaining the rotor size and rotational speed within reasonable bounds.

High Utilisation of Rotatable Parts - The design of the helicopter is dominated by rotating machinery the dynamic system, i.e. engines, transmission and rotors, constituting some 25% of its AUW. This derives from a need to operate the rotor at a relatively low rotational speed which results in the generation of high torques within the system.

Vibration - The preponderance of rotating parts, alternating air forces acting on the rotor blade, due to the periodic variations of airflow encountered in forward flight, and periodic impulsive air forces produced as rotating blades pass near to the helicopter structure giving rise to a wide range of vibratory inputs. A multitude of exciting frequencies are produced which will be transmitted to the helicopter structure.

4. HELICOPTER SAFETY RECORD

Having accepted that the pursuit of flight constitutes some risk of failure which may lead to an accident that risk should be compared with other risks in every day life and for self imposed hazards which have been stated as (Reference 3):-

	Death risk per hour of exposure per million participants
Bus (UK)	0.03
Rail (UK)	0.05
Private Car (UK	0.6
Passenger Flying	1.0
Canoeing	10.0
Mountaineering	27.0
Motor cycle racing	35.0
Rock climbing	40.0

Thus, of the normal modes of transport, passenger flying carries the highest risk of fatal accident per participant but the risk is an order less than those activities which are generally considered to be of high risk.

Aviation accident statistics are however normally expressed as the number of accidents per 100,000 hours of flight time. Figures have been obtained for British registered aircraft from CAA statistics and these are shown below with comparable data for road and rail travel (Reference 4).

	Period	No. of Accidents		No. of Accidents per 10,000 hours		No. of Accidents per 10,000 flights	
		Total	Fatal	Total	Fatal	Total	Fatal
Public Transport Aircraft	1972-81						
Fixed Wing		90	9	0.96	0.1	1.72	0.17
Rotary Wing		17	3	2.89	0.51	1.68	0.3
Air Taxi Operations	1978-81						
Fixed Wing		8	1	2.45	0.3	2.63	0.33
Rotary Wing		1	0	2.56	-	1.73	-
Road Transport (1)	1971-81	1,543,470	-	4.7	-	-	-
Rail Transport (2)	1971-81	6,201	-	21	-	-	-

(1) The road transport accidents are those which resulted in personal injuries. The rate has been calculated from vehicle kilometres travelled assuming an average speed of 50 Km/hr.

(2) The rail transport accidents are those involving trains and include collisions, derailments, running into level crossings and other obstructions and fires. The rate has been calculated from total kilometres travelled assuming an average speed of 80 Km/hr.

Of immediate note is the reversing of the order of rail road and air transport compared with the previous table, which indicates the need to find a uniform method of expressing accident statistics.

Turning to the aviation accidents the method of expressing the rate affects the comparison between fixed wing aircraft and rotorcraft. Over the ten year period covered for the public transport category, helicopters show the higher rate per hour but the lower rate per flight departure. Over the period as a whole there has been a steady decline in the rates and helicopter rates are approaching those of fixed wing as shown in Figure 2 derived from United States General Aviation Accident Statistics.

It can be shown that this decline in the accident rates is related to improvement in design standards, the older types of helicopters exhibiting higher accident rates than more recent designs. Figure 3 shows the accident rates of helicopter types in USA over the period 1970-79 plotted against the date of the first flight of their prototype version. Whilst this data shows a wide variation between types a reducing trend can be seen, for which the advent of turbine in place of piston power must bear some credit.

5. CAUSES OF HELICOPTER ACCIDENTS

The causes of helicopter accidents may be classified as aircraft airworthiness failures or operational failures. CAA accident statistics for all British registered helicopters over 2300 Kg weight in the period 1968-81 show that of the 29 accidents, of which 4 were fatal, 15 (52%) contained an operational involvement and 14 (48%) an airworthiness aspect. The principal causes were as follows:-

Operational Aspects		Airworthiness Aspects	
Error of Judgement	5	Engine/Transmission	5
Weather	5	Rotors	5
Collision with Objects	3	Controls	2
Procedures	2	Electrics	2

The trend over the more recent years indicates that much of the decline in helicopter accident rates can be attributed to a reduction in airworthiness causes. Reference 5 shows that the proportions have changed over the last 5 years from 50/50 split indicated above to around an 80/20 split between operational and airworthiness aspects.

The helicopter designer must continue to strive to improve airworthiness but he may also be able to effect a reduction in the operational failures by addressing such features as crew workload, pilot aids, visibility, environmental control etc.

In order to identify the safety - critical systems and components of the helicopter - it is necessary to have a more detailed breakdown of airworthiness failures than the foregoing accident statistics can provide. An analysis of all reportable airworthiness failures whether or not they have resulted in accident helps in this respect. Figure 4 shows a breakdown of reported airworthiness incidents for British registered revenue earning aircraft during a recent 6 month period (Reference 6). Whilst the rates for helicopters and fixed wing aircraft are similar the breakdown is quite different, the helicopter being more prone to powerplant (rotors,transmission/engine) failures than fixed wing aircraft which suffer a much higher proportion of systems failures. The breakdown of helicopter airworthiness failures show the following areas to be the most prevalent:-

Rotors and Transmission
Engines
Hydraulic Systems
Oil Systems
Landing Gear

It should be noted that the source statistics (Reference 6) do not separate rotors and transmission.

6. SAFETY IMPROVEMENT

The improvement of helicopter safety must lie in addressing the critical areas identified from the accident and airworthiness statistics. Some of the possibilities for improvement in these areas will now be discussed.

6.1. Rotor Systems

The introduction of composite materials for rotor blades will provide damage tolerant, corrosion free, multi load path designs of practically unlimited life. The technology for the construction of blades of composite material is well established. Westland has introduced composite tail rotor blades for Sea King and for Westland 30 and retrofit composite main rotor blades for Sea King/S61 variants will be available from 1984. A composite main rotor blade of advanced aerodynamic design (Figure 5) is under development for future variants of Lynx and Westland 30.

Paper 79 to be presented at this Forum (Reference 1) will show how suppression of rotor induced vibration reduces defect incident rates by improvement of the environment in which helicopter components are required to operate. Research is being conducted at Westland into the use of Higher Harmonic Control of rotors which promises significant reduction of rotor vibration.

The Lynx/Westland 30 semi-rigid rotor (Figure 6) represented a step forward in simplicity, integrity and ruggedness whilst providing exceptional agility and control response. The EH101 rotor head is articulated but utilises elastomeric bearings in composite fixtures with dual load paths. The failure modes in the composite parts are "slow" and means of failure detection (including optical means) are being addressed. Bearingless rotor hubs (Figure 7) will offer further simplification and provide fail safe multiple load paths, damage tolerance and unlimited life.

6.2. Transmission Systems

Westland designed gearboxes (Figure 8) employ external gears minimising the possibility of jamming due to intermesh tooth fragments in the event of tooth failure. The handing of the helical gears results in the rotor shaft support bearings being relieved of most of the lift loads in power-on flight with consequent benefits in life and reliability. An extensive development programme is underway at Westland into higher ratio conformal gears and high speed bevel gears. Combining these with a multiple load path output stage and a semi-skeletal gearcase has led to the Advanced Engineering Gearbox (Figure 9). The AEG enables an overall ratio of 95/1 to be obtained in three stages against the four stages applicable to conventional designs, thereby increasing reliability whilst reducing size, weight and costs.

Significant progress has been made at Westland in developing on-line health monitoring systems described in Paper No.38 (Reference 7) being presented at this Forum. These cover vibration monitoring to detect the rare but potentially catastrophic fracture modes in gears, wear debris monitoring for all common wear modes in gears and bearings and monitoring of oil flows, pressures and temperatures to detect oil system problems.

6.3. Engines

the airworthiness requirements applicable to helicopters place emphasis on performance in the event of engine failure and catgegorisation is based on this feature. From a design viewpoint the principal consideration to be addressed is the provision and availability of installed power. For single engine helciopters the installed power requirement is determined by hover performance requirements or maximum cruise speed power requirements if higher. For twin engine helicopters consideration has to be given to single engine performance in the event of an engine failure.

The relatively high power requirement of the helicopter negates the simple solution of installing double the power requirement on twin engine helicopters. The rating structure of current helicopter turbine engines is such as to minimise the weight penalty. Single engine contingency ratings are specified for limited duration. Figure 10 illustrates the rating structures of the Rolls Royce Gem and the General Electric CT7 engines, by expressing their single engine contingency ratings as a percentage of the total maximum continuous rating available from twin engines. These are compared in Figure 10 with the variation of helicopter power requirement with forward speed expressed as a percentage of the hover power requirement for a range of aircraft weights. The comparison indicates the installed power margin that is necessary to be able to fly on one engine given the ability to hover with two. It should be noted that the percentage installed power margin required reduces with increase of all up weight due to the effect of the increase in disc loading. An improvement in single engine contingency ratings as a percentage of normal twin engine ratings would improve safety margins. This would require an engine technology improvement as contingency ratings are set by high temperature creep considerations.

The effect of increasing installed power to weight ratio on the single engine performance of Westland 30 is illustrated in Figure 11.

The improvement in FAA, WAT compliance of the Gem 60 powered Series 160 aircraft over the Gem 40 powered Series 100 is about 1,700lb at a given temperature or 15°C at a given weight. The single engine performance of the CT7 powered Series 200 variant is such that the maximum all up weight is completely unaffected by Sea Level WAT limitations up to ISA +35°C.

6.4. Hydraulic Systems

BCAR's and FAR's require duplicate hydraulics in order that one failure will not endanger the aircraft. A precautionary landing has to be made if one of the systems fail. The current Westland 30 has Duplex Main Flight Control Servos powered by two entirely independent hydraulic systems one of which additionally powers the Tail Rotor Servo which reverts to manual control in the event of a failure of that system. Considerable experience with Lynx indicates that failure is more probably in the Power General Section the integrity of the servos being substantially higher. The failure probability of one of the current power generation systems is 0.23×10^{-3} per hour whilst the probability of failure of one lane of the main servo system is 0.2×10^{-7} per hour. The introduction of an Auxiliary Power Generation System dedicated to providing power to either of the two Main Power Generation Systems in the event of a failure would decrease the probability of failure of Hydraulic Supply after failure of one primary system from 0.23×10^{-3} to 0.84×10^{-7} per hour. It would therefore be safe to continue a flight after a single Power Generation System failure.

This Triple Hydraulic System is shown in Figure 12 showing either gearbox or electrical driven options for the auxiliary systems. The former is the most appealing option in terms of weight, cost, reliability and power requirement. It will be able to be fitted with minor disturbance to existing systems and would constitute a weight penalty of some 15Kg.

6.5. Crashworthiness

Whilst the foregoing has described improvements in critical systems to increase safety margins it is also necessary to reduce the risk of injury in the event of an accident. The subject of crashworthiness has tended to be addressed in connection with military applications. Two developments are however relevant to civil applications, high performance undercarriages and crashworthy fuel systems.

A crashworthy undercarriage has been designed for future variants of Lynx and is under consideration for Westland 30 variants. This will be a wheeled undercarriage design for normal landing up to 12 ft/sec (Lynx is currently 7½ ft/sec). Frangible units utilising plastic extrusion would accept a 20 ft/sec rate of descent for the 80-85 percentile crash case. The main wheel unit design is shown in Figure 13, the frangible element being located at the top of the main oleo leg. The weight penalty associated with such a provision is around 25 Kg. Consideration is also being given to ensuring personnel survival for rates of descent up to 30 ft/sec.

The provision of elastomeric fuel tanks of greater material strength, self sealing couplings, flexible pipes etc. would provide protection against rupture and hence fire in the event of a crash. The inclusion of a full crashworthy fuel system would incur a weight penalty of some 20 Kg.

Whilst such features can be seen to reduce the risk of injury in the event of an accident it should be stated that there is a reluctance on the part of the operators to accept the associated weight penalty and hence payload reduction.

7. CONCLUSION

Safety or airworthiness requirements enforced or self imposed exist to reduce the risk of accidents. The designer must address these requirements whilst achieving balance between aeronautical and commercial factors. It is to our credit that the safety record of helicopters has been steadily improved in spite of the difficult nature of helicopter design features. This paper has described some possibilities for further improvement in those areas shown to be critical to airworthiness and hence to safety. It is recognised that additional weight and hence reduction in performance and increase in cost are likely consequences. We need to compare this with the price of human life and ask if we are prepared to pay these penalties.

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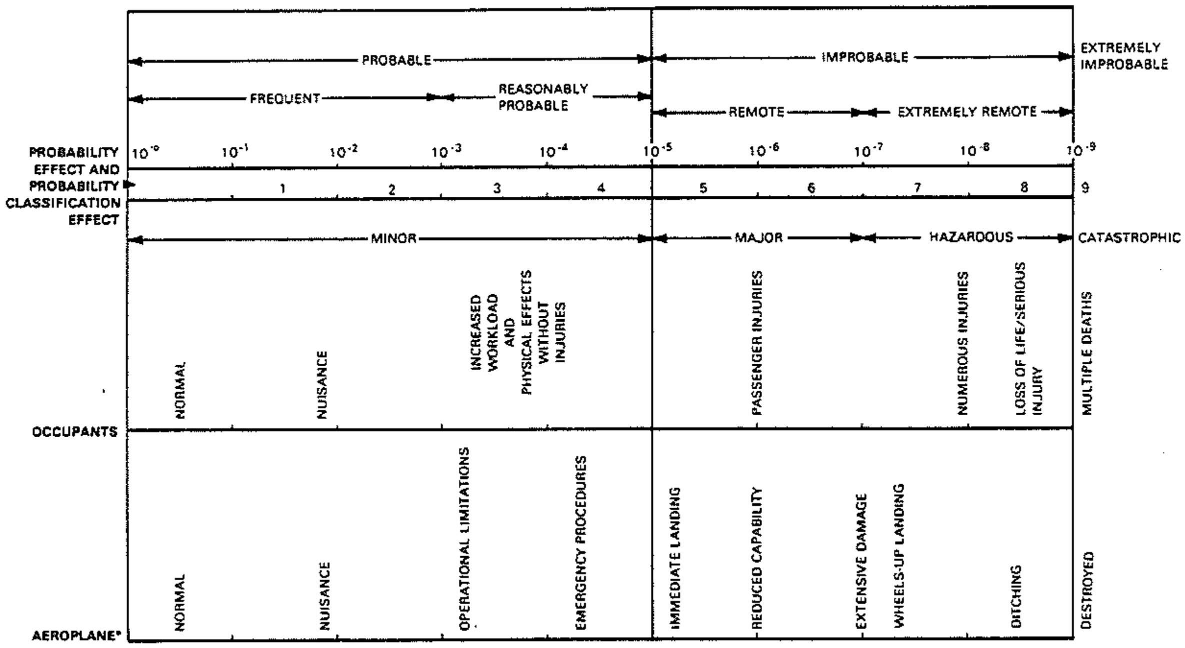
5.	D. Bender	BO105/BK117 Safety and Survivability Paper Presented at Flight Safety Inc. Offshore Helicopter Operating Safety Seminar, Brighton, England, October 1982.
6.		CAA Paper No.82022 Analysis of Occurrence Data from Aircraft over 5700 Kg, January - June 1981. Civil Aviation Authority, London, December 1982.
7.	D.G. Astridge, J.D. Roe	Health and Usage Monitoring in Helicopters. Paper No.38, 9th European Rotorcraft Forum, September 1983.



** THE POSITIONS OF SOME OF THE ITEMS ON THIS SCALE WILL VARY FOR DIFFERENT AEROPLANE DESIGNS*

FIGURE 1
RELATIONSHIP BETWEEN PROBABILITY AND SEVERITY OF EFFECTS

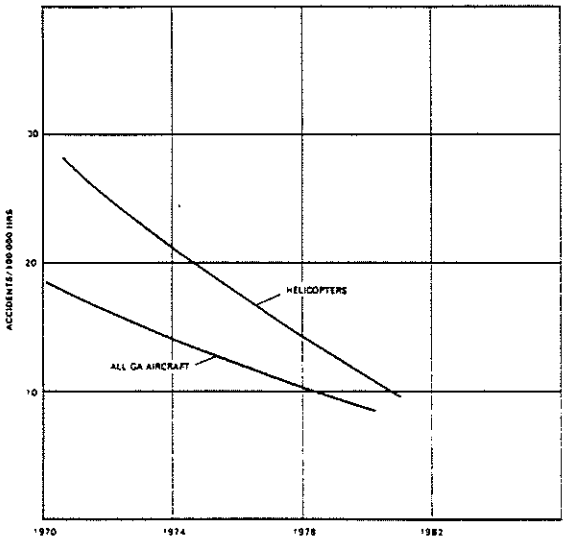


FIGURE 2
USA - GENERAL AVIATION ACCIDENT RECORDS

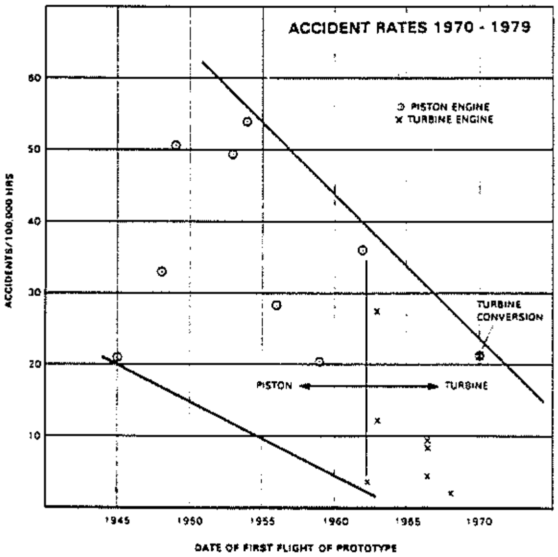
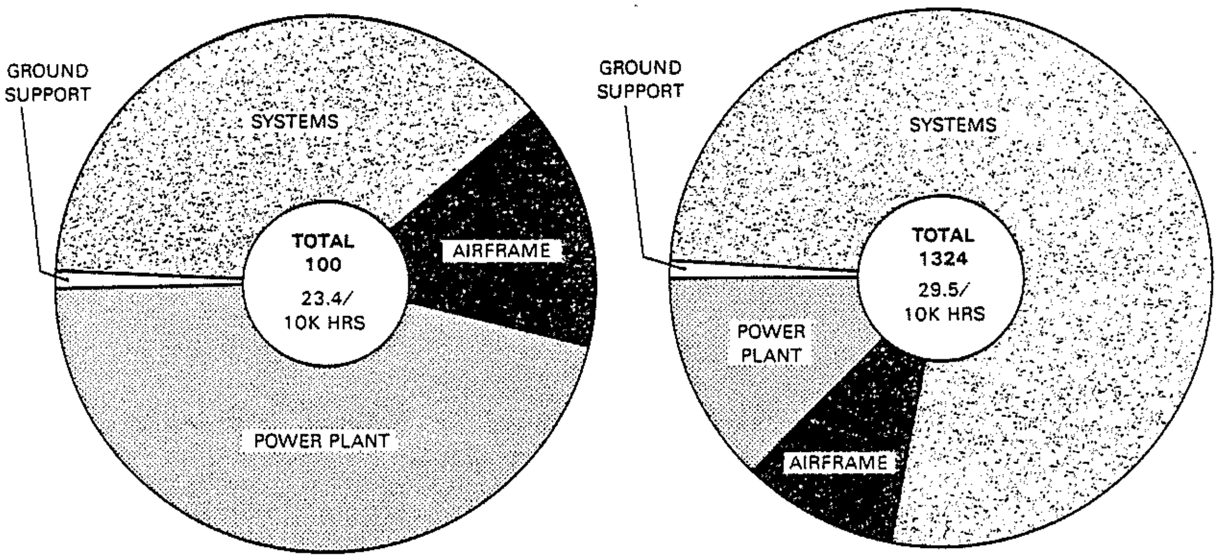


FIGURE 3
HELICOPTER ACCIDENTS VS AGE OF DESIGN

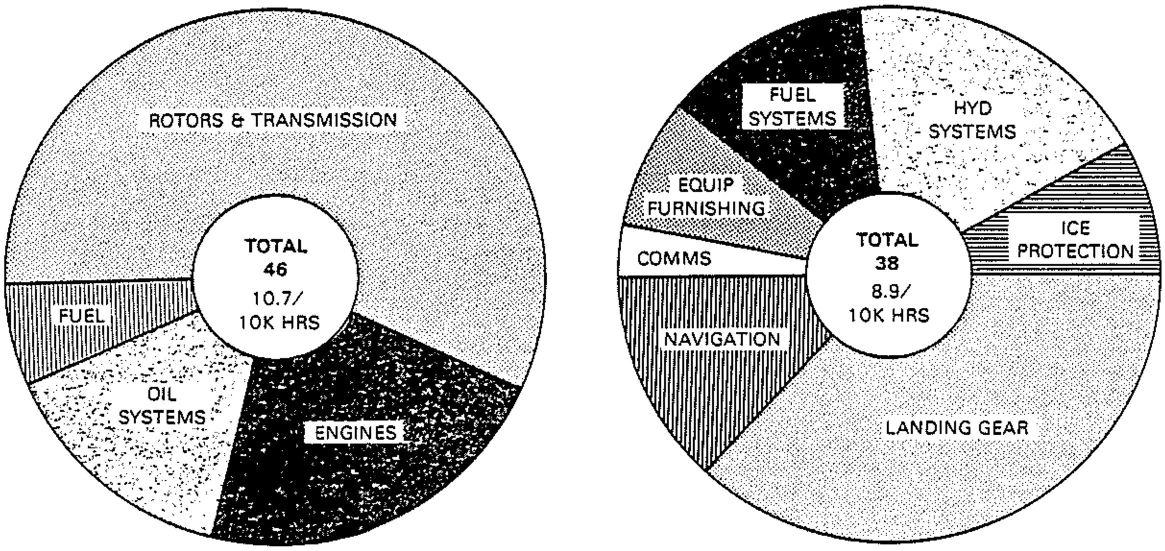
UK REVENUE EARNING AIRCRAFT JANUARY — JUNE 1981

CAA PAPER 82022



HELICOPTERS

FIXED WING



HELICOPTER POWER PLANT

HELICOPTER SYSTEMS

FIGURE 4
REPORTED AIRWORTHINESS FAILURES

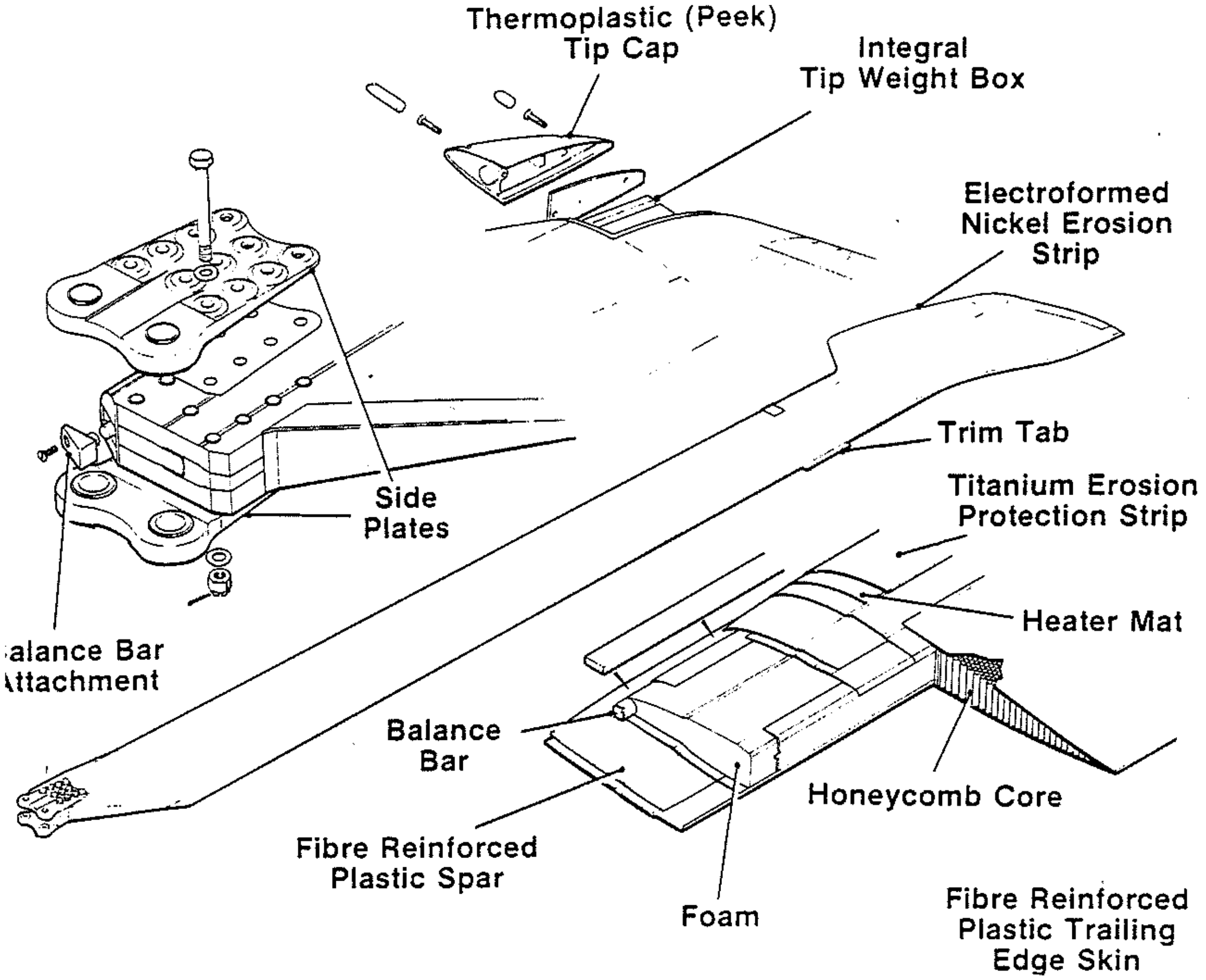


FIGURE 5
LYNX/W30 COMPOSITE BLADE

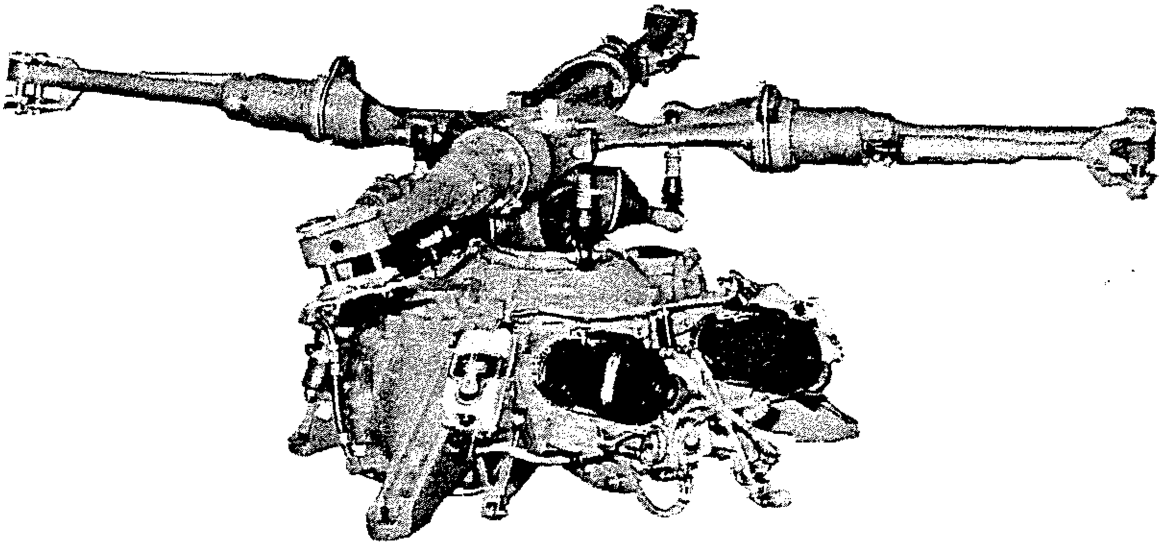


FIGURE 6
LYNX ROTOR HEAD & GEARBOX

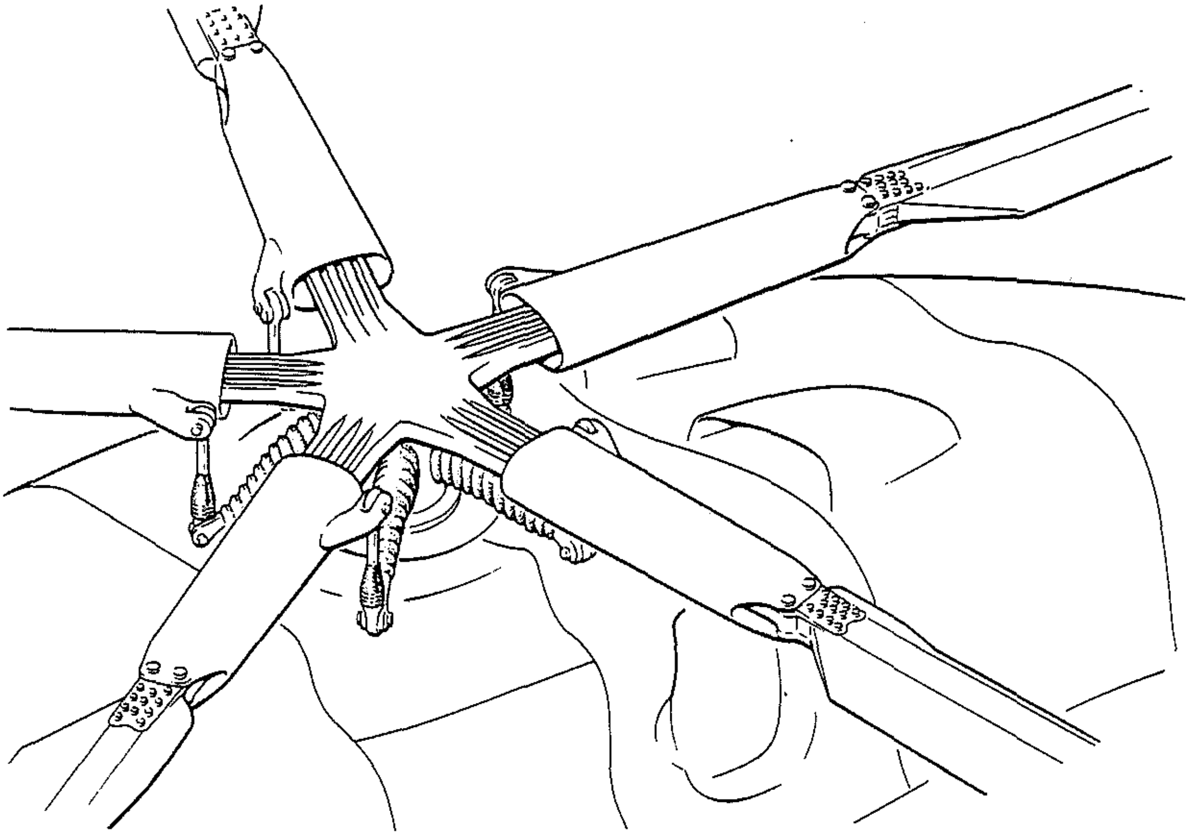
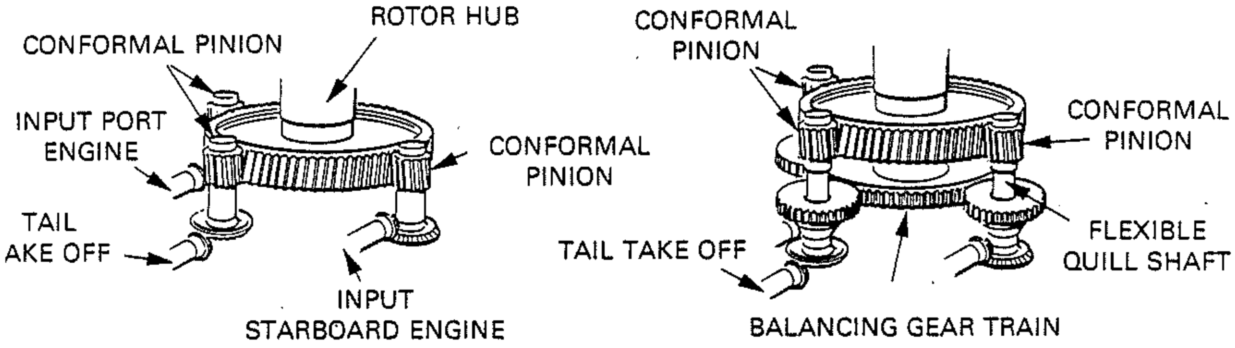


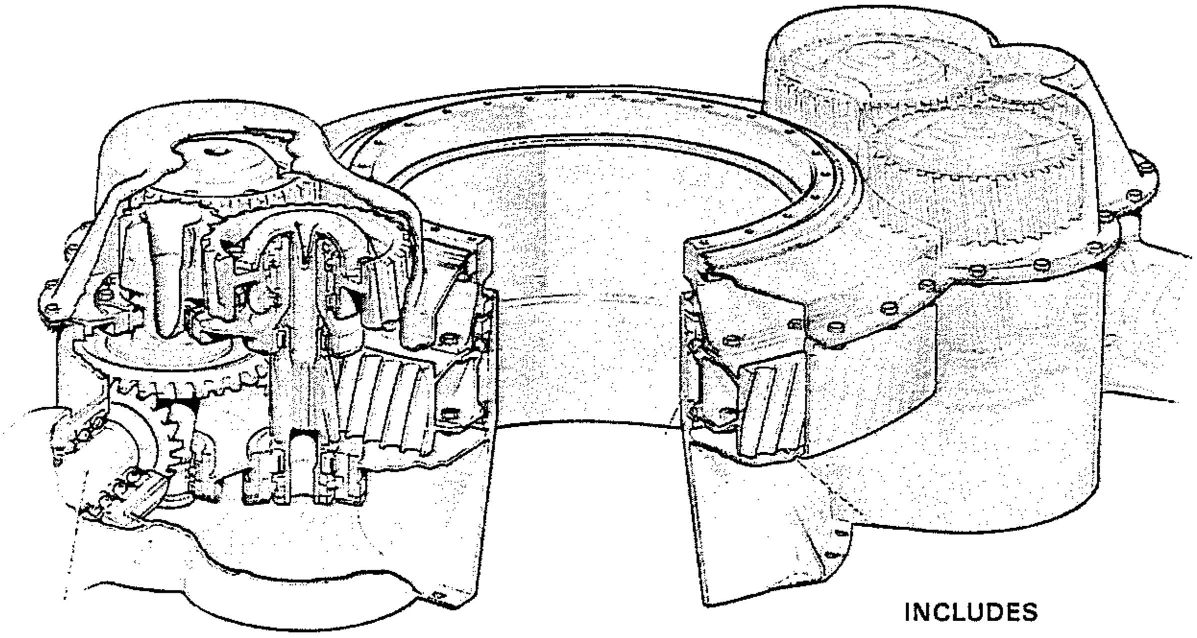
FIGURE 7
BEARINGLESS ROTOR



2-PINION

3-PINION

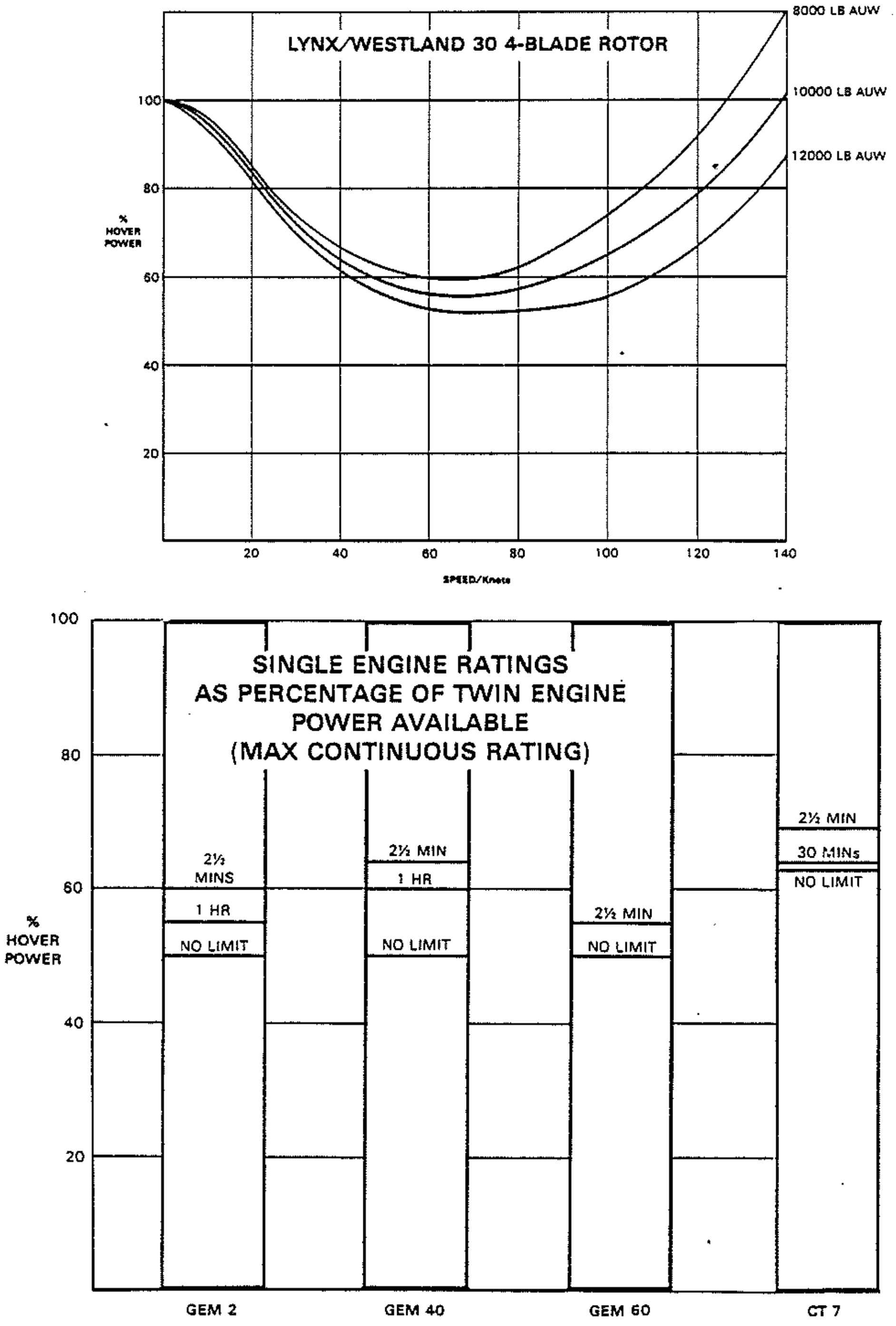
FIGURE 8
LYNX/WESTLAND 30 GEARBOX ARRANGEMENTS



INCLUDES

HIGH RATIO CONFORMALS
HIGH SPEED BEVELS
SEMI-SKELETAL GEARCASE
HIGH SPEED CLUTCH

FIGURE 9
ADVANCED ENGINEERING GEARBOX



POWER REQUIREMENT AS PERCENTAGE OF HOVER POWER

FIGURE 10

INSTALLED POWER CONSIDERATIONS

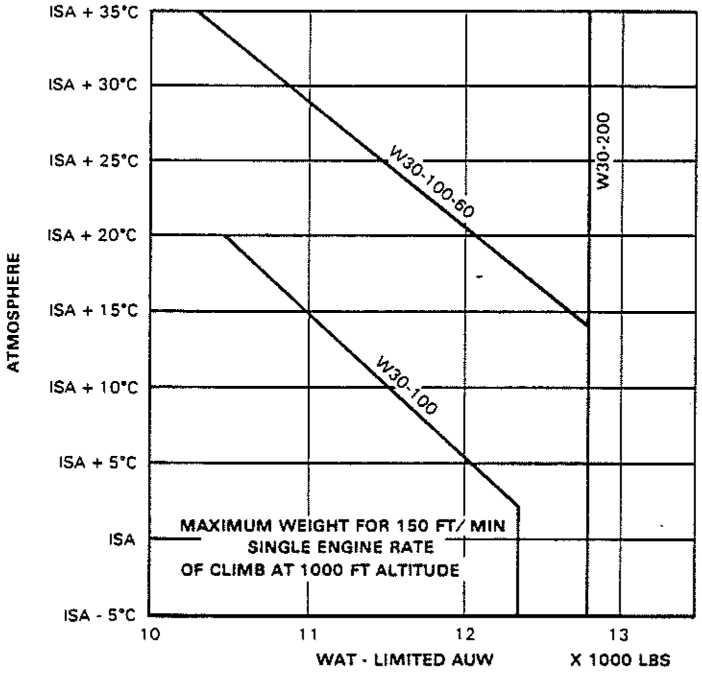


FIGURE 11
WAT LIMIT AT SEA LEVEL

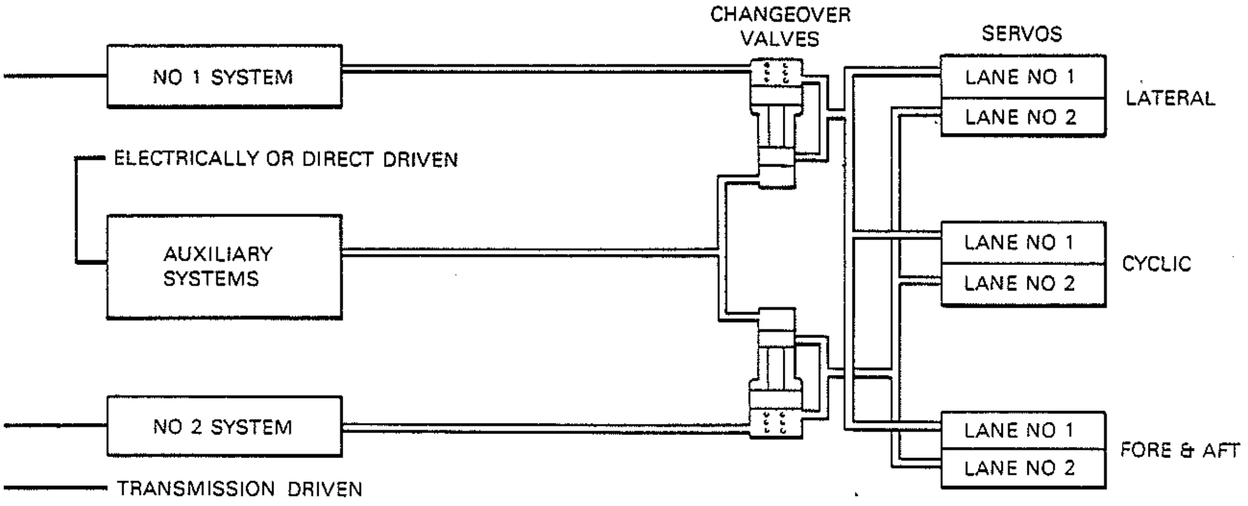


FIGURE 12
TRIPLE HYDRAULIC SYSTEM

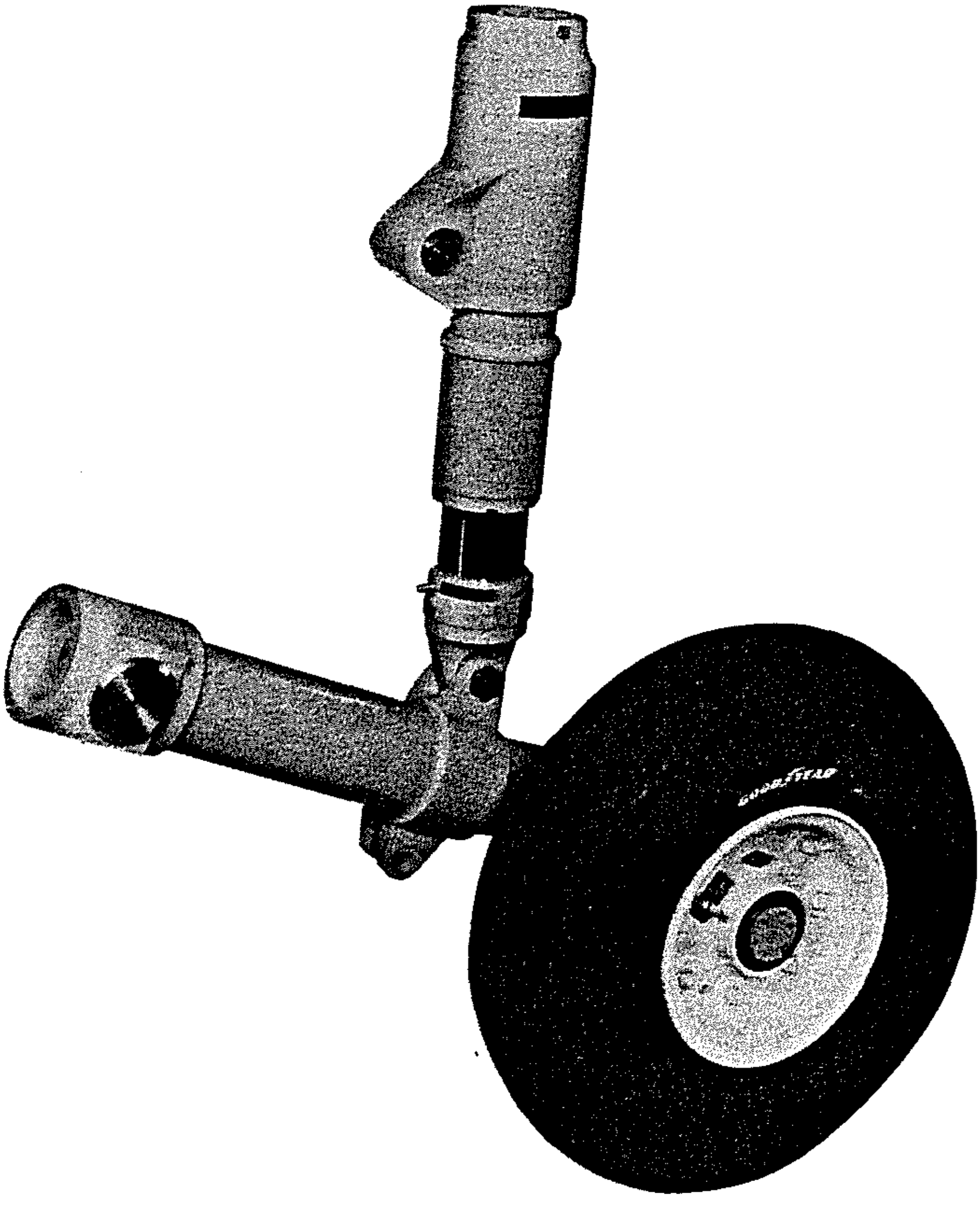


FIGURE 13
CRASHWORTHY UNDERCARRIAGE

Courtesy Fairey Hydraulics