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HELMGOP- Helicopter main gearbox loss of oil performance optimisation

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Helicopter Main Gearbox Loss of Oil Performance Optimization - HELMGOP

Final Report

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Abstract

Helicopters provide a versatile means of transporting people, material and equipment in a varied range of environments. They are totally dependent on their rotor transmission (RT) systems, which provide the critical links from the engines to the main rotor, tail rotor and ancillary systems. These RT systems are in turn totally dependent on a functioning lubrication system, and a number of significant helicopter accidents have been caused due to loss of this lubrication.

Current certification requirements for Category A helicopters require that gearboxes which use pressurized lubrication systems must show a capability to continue operation for a period of 30 minutes after suffering a loss of oil. However, this has not always been met in service with current designs.

This report has been commissioned by EASA in order to assess the key factors that affect the lubrication system and its run-dry capability. It forms the output for EASA contract EASA.2011.C23 HELMGOP - HELicopter Main Gearbox loss of Oil Performance optimisation.

The report presents methods for assessing the reliability of pressurized lubrication systems and the ability to continue powered operation for an extended period having suffered loss of oil. The research includes an assessment of MGB design and architecture, lubrication systems and reliability techniques. Safety risk modelling was conducted which included fault tree analysis of MGB oil system related accidents and incidents.

Work has been carried out to assess alternative lubrication methods/techniques that may allow gearboxes to operate for longer than 30 minutes in the event of a lubrication system failure. It is therefore recommended that the requirement for run-dry capability to be increased. This reflects not only the increasing range that off-shore helicopters must travel, but also the advances in lubrication technology that have been achieved.

The certification standards for civil helicopters are less prescriptive than those for military types, and it is suggested that more detail be added to advisory material with regard to running lubrication tests.

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Abbreviations

AC : Advisory Circular
ART : Advanced Rotorcraft Transmission
ASRM : Aviation Safety Risk Model
BBN : Bayesian Belief Network
BCAR : British Civil Airworthiness Requirements
CATS : Causal model for Air Transport Safety
CHTGM : Committee on Helicopter Transmission Gear Materials
CM : Certification Memorandum
CS : Certification Specification
DSA : Design Safety Analysis
EASA : European Aviation Safety Agency
FAA/R : Federal Aviation Administration / Requirement
HELMGOP : HELicopter Main Gearbox loss of Oil Performance optimisation
HFACS : Human Factors Analysis and Classification System
HSS : Helicopter Safety Study
ID : Influence Diagram
MACHINE : Model of Accident Causation using Hierarchical Influence Network Elicitation
MCS : Monte Carlo Simulation
MGB : Main Gear Box
MTBF/R : Mean time between failure / removal
RIF : Risk Influencing Factor
SSI : Structural Significant Item
TCCA : Transport Canada Civil Aviation
TSB : Transportation Safety Board
VIM-VAR : Vacuum Induction Melt – Vacuum Arc Remelt
VMPL : Vapour/Mist Phase Lubrication
XPS : X-ray Photoelectron

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1 INTRODUCTION

1.1 Background

Helicopters provide a versatile means of transporting people, material and equipment in a varied range of environments. They are totally dependent on their rotor transmission (RT) systems, which provide the critical links from the engines to the main rotor, tail rotor and ancillary systems.

There have been a number of significant accidents involving the loss of helicopters due to a failure of the Main gearbox lubrication system. A particular case in point was the crash of a Sikorsky S-92 C-GZCH off the coast of Newfoundland in 2009, described in **TSB Report A09A0016**. Recommendation **A11-01** of this report stated:

> *The Federal Aviation Administration, Transport Canada and the European Aviation Safety Agency remove the "extremely remote" provision from the rule requiring 30 minutes of safe operation following the loss of main gearbox lubricant for all newly constructed Category A transport helicopters and, after a phase-in period, for all existing ones.*

Current EASA CS-29.927 certification requirements for Category A helicopters require that gearboxes which use pressurized lubrication systems must show a capability to continue operation for a period of 30 minutes after suffering a loss of oil. Many Category A helicopters fly sectors which are over one hour and in the event of a main gearbox loss of oil could require a forced landing over hostile terrain.

This report has been commissioned by EASA on the basis of the above recommendation. It forms the output for EASA contract EASA.2011.C23 HELMGOP - HELicopter Main Gearbox loss of Oil Performance optimisation. The purpose of this research is to evaluate methods of improving both the reliability of pressurized lubrication systems and the ability to continue powered operation for an extended period having suffered loss of oil. The outputs of the study work include recommendations to amend certification standards and acceptable means of compliance where appropriate. Recommendations will also be made to support the design of gearbox lubrication systems.

1.2 Project Objectives

The HELMGOP project has been carried out as a collaborative project between two departments at Cranfield University within the School of Engineering. These are the Department of Air Transport and the Turbo-machinery Group. The former has focused on the literature review of helicopter safety and reliability techniques, while the latter has concentrated on the research and testing of the gear and lubrication system components.

The project has been carried in the phases as specified in the tender document, and are summarised as follows.

Literature Survey (Task 1)

Review of key information to address the objectives of this project, namely reliability analysis of lubrication system, and run-dry capability, based on the following components:

i. Historical analysis of rotor-transmission failures, drawn from both accident and incident reports.
ii. Study of the principle types of design of helicopter main gearboxes, focusing on the lubrication systems. This will also include a review of the airworthiness requirements that relate specifically to demonstrate the 30 min continued operation after loss of oil.
iii. Review of techniques for safety and reliability analysis of helicopter gearboxes.

Review of lubrication system reliability (Task 2)

Task 2a is based on the literature review of accidents and incidents, and analyses the causal and contributory factors that may have led to loss of oil. Task 2b will be primarily concerned with the creation of a representative computer model to simulate the operation of the Main gearbox. In order to facilitate a free comparison of different types, the helicopters studied will be referred to as Type A, Type B and Type C. These are all large twin turbine engine Category A helicopters. Types A and B have civil and military applications, while Type C is purely military.

Review of gearbox capability to continue functioning after loss of oil (Task 3)

Helicopters are highly dependent on their transmission systems, which provide the vital links from the engines to the rotor and ancillary systems. Components are highly loaded and must be manufactured to a high degree of accuracy; the lack of redundancy implies that this is a ‘series-chain’ system.

Limitations of this study include the fact that it is difficult to adequately represent the hardware from a complete MGB without being able to build one. In this case, the intent of Task 3b has been met by testing of a representative gearbox where the materials and operating conditions are comparable to a helicopter main gearbox.

1.3 Report Format

The report aims to describe the activities that have been carried out to fulfil the requirements for the project.

Chapter 2 is aligned with Task 1 of the project, and contains a review of literature for the design and architecture of MGB lubrication systems, plus failure Diagnostics / prognostics and reliability. There is also a section on MGB Testing techniques.

Chapters 3 and 4 are aligned with Tasks 2a and 2b. Chapter 3 reviews the system reliability of MGB Lubrication, and Chapter 4 is the reliability analysis that has been carried out as part of this project.

The final phase of the project, Task 3 is reported in Chapters 5 and 6 – these contain the experimental set-up followed by the results and analysis of the experimental testing.

The report concludes with discussion and conclusions in Chapter 7 onwards, which draw together the findings of the research and summarise the key findings. Recommendations for the potential changes to the certification standards have been made, together with promising new techniques for analysis and testing.

The overall activities of HELMGOP can then be summarized as per Figure 1.

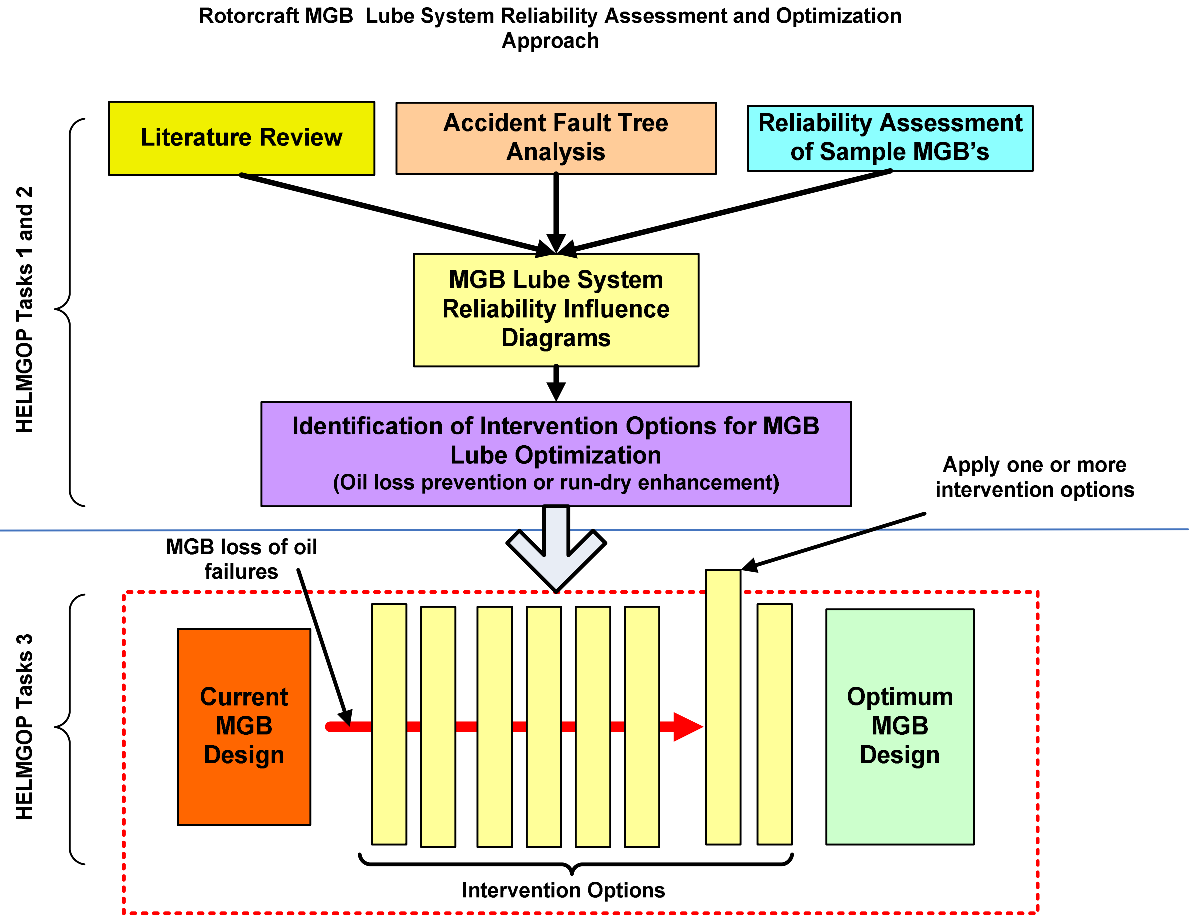


Figure 1-The overall activities of HELMGOP

PART ONE

Deliverables of HELMGOP TASK 1

2 LITERATURE REVIEW

2.1 Design and Architecture of Helicopter MGB

Papers and reports discussing concepts of helicopter MGB in regard to design configurations, technical features, materials, manufacturing, and operation; are presented in this section.

2.1.1 Design configurations and thermal behaviour

The search for alloys with better material properties for use in helicopter gearboxes has been a research topic for decades. For instance, the Committee on Helicopter Transmission Gear Materials (CHTGM) in 1979 called for new alloys that can withstand the increase in demand for high performance, reliability, and survivability. *The major limitation of alloys previously used for MGB's is its tendency to score and scuff under high temperature conditions. However, advanced alloys with improved high temperature properties, while increasing the resistance to scoring and scuffing, tend to have lower ductility and fracture toughness*. Thus the call was launched for new high temperature alloys that may also provide improved capability against surface distress.

Through the previous decades, the USA National Aeronautics and Space Administration (NASA) laid definite basis for progression in the overall transmission design concepts, mainly as per the rolling-element bearings, traction drives, spiral bevel gears, and spur gears (Fischer G. K (editor).1981). Chaiko L I. (1990) reviewed transmission systems of Soviet helicopters transmissions in terms of transmitted power, weight, reduction ratio, RPM, design configuration, comparison of different type of manufacturing methods, and a description of the materials and technologies applied to critical transmission components. The report included mechanical diagrams of the gearboxes and their test stands. Chaiko concluded that current transmissions of the Soviet helicopters have good reliability during their service life and have good weight to torque ratio when compared to western-made helicopters. Similar comparison with Soviet helicopters was previously conducted by Stepniewski & Shinn (1983)

The 1990's also witnessed the launch of several detailed studies on advanced designs and technologies for helicopter transmission under the title of "Advanced Rotorcraft Transmission (ART) program" (Kish J G. 1993, Henry Z S.1995, Lenski J W. 1995). The objectives of the Advanced Rotorcraft Transmission program were to develop the technology necessary to advance the state-of-the-art in helicopter transmission design and achieve a 25% reduction in weight, a I0 dB cabin noise reduction, and a 5,000 hour mean time between removals (MTBR), representing approximately a two to one improvement in reliability. As example of the program achievements, Sikorsky conducted a series of preliminary designs of split path and split torque transmissions to evaluate the weight, reliability, and noise improvements. A split torque gearbox with a high reduction ratio was determined to be 23% lighter, greater than 10 dB quieter, and almost four times more reliable than the baseline two stage planetary design. The improvements were attributed to extensive use of composites, spring clutches located at the transmission input, advanced high hot hardness gear steels, the split path configuration itself, high reduction ratio, double helical gearing on the output stage, elastomeric load sharing devices, and elimination of accessory drives.

Testing on a half scale gearbox proved that the concept of the split path gearbox with high reduction ratio. Topological tooth modifications permitted the high face width to diameter ratio double helical pinions to operate with good load distribution. Parallel research to the ART program also indicated achievements in oil-off survivability of tapered roller bearings, design and evaluation of high contact ratio gearing, finite element analysis of spiral bevel gears, computer numerical control grinding of spiral bevel gears, gear dynamics code validation, and others (Krantz T. L. 1992,1994).

Lewicki and his teams (Lewicki and Townsend.1989, Lewicki et al. 1993, 1994) performed a series of extended experiments on Advanced Transmission Technologies (ATT) such as the advanced-design spiral-bevel gears, the high contact ratio gears, and the cantilever-mounted flexible gears. New designs with a full fillet radius to reduce gear tooth bending stress (and thus, weight), and other lower-noise design (through modified tooth geometries) were introduced. Vibrations were reduced through these designs as well.

Rao et al. (2005) presented a new chemical technology to repair and enhance properties of transmission gears (sun and input pinions). This process, known as REM chemical superfinishing treatment was found to remove minor foreign object damage (FOD) by uniformly removing a minimal amount of material on the gear teeth (less than 0.0001 inch deep), while meeting original manufacturing specifications for geometry. The process also resulted in enhanced surface quality and did not exhibit detrimental metallurgical effects on the surface or sub-- surface of the teeth. It was also found to eliminate grey staining, an early precursor to pitting. The characterizations performed in this effort show that this process does not degrade gear dimensional or metallurgical properties below OEM specifications for new gears, provided the used gears meet these specifications, and the tooth thickness is on the order of 0.0003 inch above the low specified limit. Three of the mass finishing processes that are commercially available were evaluated: Mass Finishing Inc (MFI.), Extrude Hone, and REM Chemicals Inc.

Hansen et al (2006) applied the isotropic superfinishing technique to the Sikorsky S-76 transmission, namely to the third stage spur bull gear and mating pinions along with the second stage bevel gears of MGB. Isotropic superfinishing is a chemically accelerated vibratory finishing process that is capable of generating surface finishes with an Arithmetic Mean Roughness (Ra) < 3 micro inches. Tests results showed that noise, vibration, and operating temperatures were shown to be significantly reduced due to the lower friction between the meshing gears. This is a result of lowering the surface roughness through a controlled process that removes the surface irregularities (asperities) caused by machining, grinding and/or shot peening. This produces a very unique surface texture that is described as isotropic (non-- directional) and is characterized by an Ra < 4 min. (0.1 mm).

This technology has since been flight certified and integrated into the S-76C+ with several aircraft in commercial service. Detailed findings indicate that Superfinished S-76C+ main transmission gears have the following qualities:

i. Lower friction.
ii. Lower vibro--acoustic noise.
    a. Third stage bull gear 1x mesh reduced by 7 decibels.
    b. Second stage bevel pinion and gear 1xmesh reduced by 3.7 decibels.
iii. Lower operating temperatures.
    a. 5° C temperature reduction when compared to baseline main transmissions during the standard Acceptance Test Procedure (ATP).

A series of experimental studies on thermal behaviour of various configurations of gears and their lubrication was carried out by Handschuh et al. (Handschuh R F. (1995), Handschuh R, Kilmain C. (2005), Handschuh R F, Zakrajsek J J.(2006)). Looking at different gears configurations, many operational parameters were varied to investigate their effects on the various gear trains thermal behaviour. The data taken was also used to validate the boundary conditions applied to the analytical models.

Inputs were varied in terms of gear configuration (helical, spiral bevel) time, position, speed, and applied loads. It is concluded that speed and load affected lubricant fling off temperatures measured across the gear mesh face width and at the axial location. Changing the speed from 12500 to 15000 rpm had a more dramatic effect than increasing load from 30% to 100%, while reducing the lubricant jet pressure from 80 to 60 psi reduced the power necessary to drive the facility, but the effect was rather small (approximately 5 HP) and caused the lubricant temperature difference between inlet and exit to increase up to 10 °F. Full shrouding reduced power loss while increasing the temperature difference between lubricant input and output as well.

Handschuh et. al. (2007) also investigated the thermal behaviour of gear systems in relation to gear finishing. The oil inlet temperature was varied from 160 to 250 °F. Also, the test gears were run as-ground and after isotropic superfinishing (ISF). In-depth temperature measurements were made across the face width and at the axial end of the gear mesh. Supply power measurements were made at varying speeds and loads up to 5000 HP and 15000 rpm (pitch line velocity to 24000 feet per minute). The tests indicated that:

Superfinishing provided no measurable performance benefit to the high speed gearing system. The film thickness to composite surface roughness was 2 or greater for most of the tests conducted. Increasing lubricant inlet temperature provided the most beneficial effect to the performance of the drive system.
Thermocouple rakes and arrays installed in the test gearbox provided data that the fling-off temperatures vary with location across the face width of the gears as well as the location

within the gearbox where the temperatures were measured. The idler–idler gear meshes typically produced the highest rake and array temperatures measured in all tests.
The change in flow rate (due to lowering the lubricating jet pressure from 80 to 60 psig) had only a very minor effect on power loss.

There are many techniques for applying superfinishing to MGB gears. Some of these techniques are already in place and flight-certified. However, the overall temperature reduction is not greatly significant (5° C temperature reduction when compared to baseline main transmissions during the standard Acceptance Test Procedure (ATP)). Superfinishing, in general, offered improvements for noise and vibrations reduction rather than remarkably influencing the thermal behaviour of the MGB components.

More importantly, there is no data indicating superfinishing offers an improvement under MGB run-dry conditions. Reduction in temperature offered by superfinishing has no effect when oil temperature passes 90° C onwards (Chen et. al. 2011).

Handschuh et. al. (2010) indicated that the operation of high speed gearing systems in the transmissions of tiltrotor aircraft has an effect on overall propulsion system efficiency. Recent work has focused on many aspects of high-speed helical gear trains as would be used in tiltrotor aircraft such as operational characteristics, comparison of analytical predictions to experimental data and the effect of superfinishing on transmission performance. Instead of the single helical gear configuration that was previously used, Handschuh et al. utilized double helical gears that can be configured to either pump the air-oil environment from the centre gap between the meshing gears to the outside of tooth ends or in the reverse direction. Tests were conducted with both inward and outward air-oil pumping directions. Results are compared to the earlier baseline results of single helical gears. Having assessed the design impact on the oil temperature, and thus the gear train performance, the writers concluded:

> Double helical gear trains that outwardly pump the air— lubricant mixture axially produced the highest performance when compared to other tested conditions that included inward pumping double helical gears and single helical gear trains (ground and superfinished).
> Double helical gear trains that have an inward pumping arrangement produced similar performance results with or without shrouds. The results from these tests were in between the outward pumping arrangement being better than outward pumping without shrouds and not as good as outward pumping with shrouds.
>
> The double helical, outward pumping shrouded arrangement was also the best when lubricant pressure was reduced, providing the lowest temperature increase at nearly all conditions. The data from the rake probes showed that the most significant difference was at the 15000 rpm condition with the double helical gear, outward pumping arrangement being the one with the lowest temperature increase between the oil inlet temperature and the maximum rake probe temperature.

Chen et. al. (2011) indicated the difficulty of thermal energy dissipation from planetary gear trains due to their high-power-density design combined with their limited space. They thus introduced a thermal network model for temperature prediction in planetary gear trains based on the principle of the conservation of energy. The model was applied to analyse the transient temperature of the three stage 2K-H planetary gear trains used in Φ6.3m earth pressure balance (EPB) shield machine in series. Results showed that the temperature rise of the sun gears is quicker than the other parts, and the *planetary gear train doesn't reach thermal balance after the oil temperature reached 90 degrees*, so an efficient cooling system should be compelled.

Yin et al. (2011) surveyed the various developmental stages of helicopter power transmission system technologies since the 1950's up to date. They thus characterized the main advancements achieved on the transmission into four MGB design generations within the areas of: Input rotational speeds, power density, reliability and mean time between removals (MTBR) (also indicated as Time Between Overhaul (TBO)), efficiency, and survivability. Details are provided as per Table 1.

Table 1 - Main technical parameters of helicopter transmission developments (Yin et al 2011)

	Generations				
	1st	2nd	3rd		4th (Prototype)
Into service	1950's	1960's	1970's-1980's	1990's-2000's	21 century
Models (Samples)	Mi-4 Bell 47 S-51 Ka-18	Mi-6, Mi-8 UH-1C Bell 209 SA 321	A129 UH-60A AH-64A CH53	Mi-28, K-50 UH-60L AH-64D Tiger, NH-90	Comanche UH-60M AH-64M
MGB input speed (rpm)	<3000	<7000	<20000	>20000 (Tiger=6000)	>20000
MGB total speed ratio	13: 47 (Mi-4)	28:57 (Super Frelon)	81 (UH-60A)	81 (UH-60L)	81 (UH-60M) 64:79 (Comanche)
MGB TBO (h)	<600	<1200	1500-3000	3000-4000	4000-5000
MGB ratio of weight to output torque (Kg'(Kgf.m))	~ 0.075	~ 0.070	~ 0.067	0.060~ 0.063	0.056~ 0.058
MGB loss of lubrication operation capability	No requirement	No requirement	30 min	45 min	> 45 min (Comanche reached 60 min)
HUMS	None	None	Partially	Partially	Full

Yin and team also gave detailed presentation of various MGB design configurations, structural analysis techniques, as well as the application of new materials and related process technologies. They listed the main transmission configurations in Table 2.

Table 2 - Various MGB configurations typically used to join input from two engines (Yin et al 2011)

Configuration	Power train stages setting	Characteristics
First type	Cylindrical gear combining stage → Bevel gear angle turn stage → planetary gear stage	Most conventional design. Loads on bevel gears are large, thus overall MGB weight may be increased.
Second type	Bevel gear angle turn stage → cylindrical gear combining stage → planetary gear stage	Used for wide combining distance between two inputs (through two bevel stages), but not suitable if this distance is small.
Third type	Bevel gear angle turn stage → bevel gear angle turn and combining stage → planetary gear stage	Also used for wide combining distance between two inputs (through two bevel stages). The structure is compact with smaller diameter and height. Limited number of components leading to improved reliability.
Fourth type	Gear train of fixed axis (simple fixed-axis gear train and split torque gear train). (A planetary gear stage can be added at the last stage for higher speed ratios)	Simple design with fewer gears and bearings. Small height. Can transmit larger power using the split-torque arrangement. Improved strength and fatigue life, thus more often used for modern aircrafts.

Liao et. al. (2011) researched aspects of oil loss capability of helicopter MGB. They defined seven factors that can influence such capability:

i. Temperature distribution of different MGB parts when temperature rises.
ii. Gears backlash and bearings clearances.
iii. MGB structure (geometry)
iv. Structures for deposited oil.
v. Strength and stiffness of structure.
vi. Materials and heat treatment of parts.
vii. Characteristics of lubricants.

They defined the weakness of the MGB to be the sliding friction shim between the first stage of the sun gear and the first stage of the planet carrier. This shim, which is designed to isolate parts of different materials and to provide for sliding and supporting of the rotating parts, is identified here as a major weakening point to the MGB run dry capability. In case of oil starvation, this shim will glue and cause high friction-induced heat rise. The writers replaced the old tin bronze shim with an improved one which is a composite of three layers: Two self-lubricating materials were used at the outer sides of the shim, and a steel material is used for the inner section. The improved MGB was subjected to a run dry test that continued for 34 minutes after the “low oil pressure” indication of oil loss. They thus concluded that a self-lubricating material can highly improve the MGB run dry characteristics.

2.1.2 Design reliability

Astridge (1989) considered the transmission system to be a major helicopter airworthiness-related source of accidents and unreliability. Gears, lubricating system components, bearings, and freewheels are respectively the major risk-associated internal parts of the transmission. Reflecting on previous accidents, Astridge listed lessons learnt regarding MGB and its lubrication system design features to be:

i. Provide oil recirculation with redundancy / emergency features.
ii. Minimize pipework external to the MGB, or ensure some component dipping at all times.
iii. Ensure effective oil content measurement.
iv. Ensure adequate oil filtration and wear debris capture provisions.
v. Tooth design for spiral bevel gears should ensure gear separation tendency rather than pulling into mesh.
vi. Solid ground spacers or shims are preferred to soft aluminium laminated shims.
vii. Effective means for detecting bearing roller contact fatigue is essential for planetary gears running directly on rolling elements.

Similarly, referring to the overhaul data of a sample of MGB's, the author listed the following possible risk initiators in regard to safe operations of MGB's:

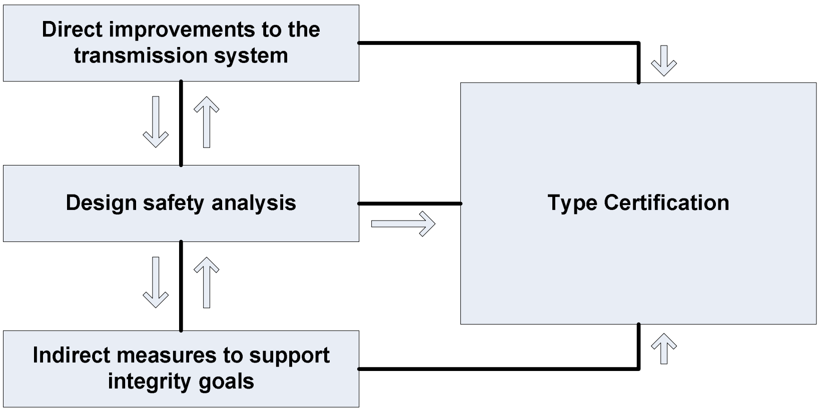
i. The practice of adequate condition monitoring of MGB parts during overhauls.
ii. Corrosion of gears, bearings and shafts.
iii. Micropitting of gears teeth
iv. Debris damage (crater in raceways) caused by rolled-in debris.
v. Sight glass staining.
vi. Human error.

In related work, Astridge (1996a) discussed the Design Safety Analysis (DSA) concept as a major element of the MGB certification process. Details are given by Figure 2. Observing accidents and incident data currently available don't allow for numerical manipulation to analyse catastrophic MGB failures, he thus proposed DSA as a practical solution to fill the gap. DSA is to be conducted through a two phased procedure:

i. Hazard analysis of the design configuration that defines functions of all components, and the associated consequences if these functions are lost.
ii. Detailed analysis to determine probabilities of occurrence for any of the failures listed by the hazard analysis.

Rotorcraft, by nature of design, are more vulnerable to airworthiness defects, this clearly obvious in terms of reliability rates assigned to helicopters when compared to fixed wing. For instance, the required reliability for the control system of an aeroplane is set to be 'Extremely

Improbable', given numerically to be less than 10-9 per flying hours, while the historic rate of failure within helicopter fleets led to the new term in probability of 'Very Remote' quantified to be less than 10-6 per flying hours especially introduced to rate the rotor transmission system performance.



Direct Improvements	Indirect measures	Design safety analysis (DSA)
Design: Shaft/ gear layout Shaft/ gear details Bearing details Freewheel details Seal details Casing layout and details Lube system Materials specification Analysis of loads Analysis of strength **Manufacture & assembly:** Critical parts process Materials / QA Production methods Inspection / QA Loads test/ flow test **Certification tests:** Materials Components/ Lub. system Static and fatigue Environmental Oil loss tolerance Endurance, Type, Flight **Maintenance:** Maintenance manual MRB procedures Maintenance QA **Operation** Flight manual Emergency processes	**Cockpit displays:** Torque indications/ limits Rotor speed indications/ limits Oil system warnings & cautions Oil system advisories Oil system parameters displays Freewheel actuator status HUM system caution/ displays Subjective noise/ vib./ smoke/ etc. **Maintenance indications:** HUM (interrogation /transfer) Ground inspections/ aids Oil sample inspection Magnetic debris inspection Visual inspections / borescopes	**Hazard analysis:** System interface definitions System functions definitions Operating conditions definitions Classification of function failures **Detailed analysis:** Design details/ parts numbers Analysis structure: function basis Postulate: Component contribution to function Component/ system failure modes Components failure causes Risk reduction features in design: Direct measures Indirect measures including HUM Generate failure database Determine datum failure rates Quantify risk reduction measures Quantify adverse factors in design Determine failure rates predictions: Single critical failures Common cause failures Cascade failures Dormant failures Combinations of independent failures Basis for system failure rate determination Determine catastrophic failure rate for the transmission system

Figure 2 - Transmission system integrity - The principal contributory elements with examples (Astridge 1996b)

For Category A helicopters, the UK certification programme (BCAR G778) published by the British Civil Airworthiness Requirements (1985) for instance, indicates that "*the probability of failure of rotor and transmission system, from all causes, that would prevent the flight to the intended destination, (or for a declared time interval) and a controlled power-on landing shall be Very Remote*". In later work, Astridge (1996b) showed helicopter type transmission certification process to be the collective output of direct design improvements, design safety analysis, and a list of indirect measures that work to support integrity of the system. This can be showed as per Figure 2. It is seen that DSA provides a means for auditing both direct and indirect design measures incorporated for their contribution to failure risk reduction.

Table 3 - Historic failure modes relating to direct design / improvements of the transmission and their associated primary risk reduction measures (Astridge 1996b)

Component/ failure mode/ cause	Primary risk reduction measures
Gear bolted flange failure due to fretting/ corrosion	One- piece gear/ shaft structure
Gear failure due to inadequate mesh patterns	Load test after assembly + recorded mesh patterns
Planet gear failure due to sharp roller edge radius	Spherical or super blended cylindrical rollers
Gear failure due to 'into mesh' design + soft shims	Avoid 'into mesh' gear design
Gear failure –factors: surface treatment + bore finish	Avoid black oxide and phosphate treatments
Gear failure due to oxide inclusions in the steel	Modern 'clean' steel production+ material testing
Gear fatigue failure, including weak design	As above
Accessory drive gear failure – weak design	As above
Roller bearing failure – weak design	As above
Shaft failure – weak design	As above
Main rotor drive failure (hydrogen embrittlement)	As above
Main rotor drive fatigue failure	As above+ modern analysis and fatigue testing
Shaft failure due to inadequate quality control	Modern production methods and quality control
Plain journal bearings supporting critical gear-failure	Use rolling elements bearings
Roller bearings failure- incorrect installation/ assembly	QA load test with vibration/ wear debris analysis
Reversed assembly of non-symmetrical thrust bearings	Symmetrical design or baulking features; or as above
MGB oil loss- oil pipes- failure (maintenance errors)	Avoid external oil pipes
MGB fire-chafing electrical cables clipped to oil pipes	As above
MGB oil loss- distortion of filter bowl (maintenance)	Distortion-free filter bowl design
MGB oil loss from causes other than above	Incorporate an emergency oil system
Critical thrust bearings- blocking of oil jets at overhaul	Fully duplicated oil supplies + oil flow QA inspect.
Quill coupling failure due to lack of lubrication	As above
Bearing failure due to casing oilway not drilled	As above + modern quality control procedures
Quill shaft failure due to oil contamination	Fine filtration with non-sourcing bypass design
MGB failure due to failure of oil cooler fan belts	Shaft driven oil coolers
Gearbox failure- no internal inspection for 16 years	MRB procedures
Freewheel failure (sprang type) - misassembled	Load test after assembly
Freewheel failure (cam &roller type)- roller spit out	As above + high capacity design
T. r. drive disconnect coupling –slippage/ disconnection	Improved design / lubricant/ maintenance procedures
T. blade pitch rod bearing failure- marginal lubrication	Locate control rod bearing outside T R drive gear

Astridge identified three categories of failure modes of the transmission referring to actual historical data. These failures and their suggested remedies are presented in Tables 3, 4 and 5 respectively:

1. Historic failure modes relating to direct design / improvements of the transmission.
2. Historic failure modes relating to transmission performance monitoring provisions.
3. Failure modes not experienced in current or past transport helicopters.

Table 4 - Historic failure modes relating to transmission performance monitoring provisions and their associated primary risk reduction measures (Astridge 1996b)

Component/ failure mode/ cause	Primary risk reduction measures
MGB mounting failure- underestimated load cycles	Torque usage monitoring- GAG* and MRF** torque bands
MGB failure due to excessive external load	External load indicating and monitoring
MGB oil loss due to departure of chip detector	Improved integrity sensor mounting arrangement
MGB oil loss due to omission of magnetic plug seals	Remote indicating system avoids frequent plug removal
MGB failure due to wear debris ignored	Quantitative wear debris monitoring + auto logging
MGB failure due to oil pressure warnings ignored	High reliability sensors + unambiguous warning Systm.
MGB failure due to chip detector indications ignored	High reliability wear debris monitoring system
MGB failure due to oil analysis trends misunderstood	Promulgation of historic health monitoring trends
MGB bearing failure – thermal breakdown of the oil	Oil temperature- time exposure monitoring
TGB failure due to oil level indication misread	Remote indicating level sensor + cleanable sight glass
TGB failure due to incorrect part fitted	Vibration & wear debris monitoring (gears/ bearings)
TGB departure due to vibration induced by coupling wear	Vibration monitoring of couplings shafts
TR drive hanger bearing seizure – contamination in manufacture	Temperature or vibration monitoring of hanger bearings
TR drive failure- misaligned support bearing	Tail rotor drive vibration monitoring

* GAG: Ground-air-ground induced load cycles

** MRF: Main rotor shaft and blade-pass frequencies

Table 5 - Postulated failure modes, not found in the catastrophic data, and their associated primary risk reduction measures (Astridge 1996b)

Component/ failure mode/ cause	Primary risk reduction measures
Seal failure due to manufacturing/ assembly errors	Oil level monitoring (rotors stationary)
Casing fracture (affecting oil supply)	Slow leak: as above; fast leak: oil system indications
Casing fracture (not affecting oil supply)	Vibration/ shock monitoring of casing / shafts
Pinion/ Shaft failure due to salt water corrosion	Vibration monitoring of gears + oil analysis
Bearing failure due to salt water corrosion	As above + wear debris monitoring
Overheat failure of critical bearing	Temperature monitoring of bearing outer race
Failure of low resistance lightning conduction path	Conductivity measurement (at intervals)

It is worth noticing that the previously postulated failure mode of MGB casing fracture in the 1990's as per Table 5 is understood to refer to casing fractures that may initiate from the case structure itself (e.g. as a result of vibration) without the influence of 'external' inputs.

It is worth highlighting that in some cases (G-ASNL -1983, G-REDL -2009) the MGB casings were ruptured due to failures of internal rotating components (external inputs to the casing structure) though from inside the MGB. As seen, Tables 3, 4, and 5 show that the MGB failures (indicated in dark background) represent an important share of the overall failure distribution. Furthermore, it can be seen that the MGB oil system is, more specifically, vulnerable to large number of failure scenarios.

Roberts et al. (2010) indicated that eliminating or reducing performance and safety problems can be achieved with a thorough understanding of potential failure modes in the designs that lead to these problems. The majority of techniques use prior knowledge and experience as well as Failure Modes and Effects as methods to determine potential failure modes of aircraft. During the design of aircraft, a general technique is needed to ensure that every potential failure mode is considered, while avoiding spending time on improbable failure modes. In this work, this is accomplished by mapping failure modes to specific components, which are described by their functionality. The failure modes are then linked to the basic functions that are carried within the components of the aircraft. Using this technique, designers can examine the basic functions, and select appropriate analyses to eliminate or design out the potential failure modes.

The above described method was previously applied to a simple rotating machine test rig with basic functions that are common to a rotorcraft (Tumer et al (n.a)). The authors used information derived from engineering drawings and specifications, accident reports, and functional bases to establish a link between functionality of components and the potential failure modes of helicopter systems.

Table 6 - The C matrix of helicopter engines

Element	Description	Element	Description
C1	air discharge tubes	C16	impeller
C2	bearing	C17	mount
C3	bleed valve	C18	nozzle
C4	bolt	C19	nozzle shield
C5	compressor case	C20	O ring
C6	compressor mount	C21	P3 line
C7	compressor wheel	C22	plasting lining
C8	coupling	C23	pressure control line
C9	diffuser scroll	C24	pylon isolator mount
C10	exhaust collector	C25	rear diffuser
C11	fire wall	C26	rotor
C12	front diffuser	C27	shaft
C13	front support	C28	spur adapter gear-shaft
C14	governor	C29	turbine wheel
C15	housing		

Table 7 - The F matrix of helicopter engines

Element	Description
F1	bond failure
F2	corrosion
F3	fatigue
F4	fracture
F5	fretting
F6	galling and seizure
F7	human
F8	stress rupture
F9	thermal shock
F10	wear

The information has been used to draw similarities between different designs using matrix manipulations of the component, failure, and functionality data. The overall goal is to address the failure modes early in conceptual design. To achieve this goal, functions are mapped to failure modes that are experienced by a component that performs the particular functions. The concept implied mathematical manipulations of two initial matrices representing all the components of a given helicopter system (here taking engines as a case study) that suffered from historic failures (C- matrix) and the modes of those failures (F- matrix). Tables 6 and 7 list these components and their collective known failure modes:

An initial input matrix (CF) is then formed referring to historic data of the number of component failure events for each single failure mode. For instance if component C4 (bolt) had failed in 3 different occasions through mode F6 (Galling), then the entry in CF will be:

$$CF_{4\text{-}6} = 3$$

If there are no historic records of C4 that previously failed through mode F6, then the entry will be: $CF_{4\text{-}6} = 0$

The initial CF matrix for helicopter engine case is given as:

$$CF = \begin{bmatrix} CF_{11} & CF_{12} & CF_{13} & \dots & CF_{1\,10} \\ CF_{21} & CF_{22} & CF_{23} & \dots & CF_{2\,10} \\ CF_{31} & CF_{32} & CF_{33} & \dots & CF_{3\,10} \\ \dots & \dots & \dots & \dots & \dots \\ CF_{29\,1} & CF_{29\,2} & CF_{29\,3} & \dots & CF_{29\,10} \end{bmatrix}$$

By carrying out multiple transformations of this matrix, as detailed in the publication, it would be possible to analyse and predict the effect of potential failure modes on the various components of helicopter engines. The theory is applicable to other systems including MGB's.

Further, Yin et al (2011) showed the development of the MGB strength and life analysis through the decades as per Table 8. They concluded that new characteristics regarding materials used for MGB included higher degrees of purity, ultra-high case hardness, high core toughness, and high application temperature. Three generations of steel alloys were basically used for MGB internal components such as AISI 9310, M50Nil, and CSS-42L, with varying working temperature range of 150C° to 535C°. Aluminium alloys such as A375.0, 7075, and magnesium alloys such as ZE41A, WE43 are well applied for MGB casing.

Table 8 - Strength Analysis method and its required typical material properties (Yin et al 2011)

Time	Method of strength analysis	Typical material property data
Before 1960's	Static strength evaluation	$E,\ \mu,\ \rho\ ,\ \delta,\ \varphi,\ \sigma_b,\ \sigma_\Upsilon$
1960's	Safe life and vibration analysis	S-N Curve
1970's	Strain fatigue theory, limited life design	ε- N Curve
1980's	Fracture mechanics theory, damage tolerance design	Fracture property K_{lc} , $d\alpha/dN$, ΔK_{th}
1990's	Reliability design, probability life design	$-3\ \sigma$ data, flow feature and distribution

Bhaumik et al. (2007) studied the failure of an intermediate gearbox of a helicopter that resulted in an accident. A systematic failure analysis was conducted to find out the cause of failure. Examination revealed that fatigue fracturing of the driving gear was responsible for the gearbox failure. The teeth of the gear were severely damaged by spalling. Fractographic study revealed multiple fatigue crack initiation at the tooth root regions. It was established that the failure was caused due to improper assembly of the gear. A detailed analysis of the failure and its sequence account is presented. It is established that one of the roller bearings was not assembled properly on the driving shaft. There was relative movement between the shaft and bore of the bearing resulting in fretting damage.

Once sufficient clearance was established due to fretting, the driving gear probably began pounding (low amplitude) on the driven gear causing excessive load on the teeth. This in turn would have resulted in excessive wear on the loading flank as well as fatigue crack initiation in the gear. The polishing wear seen on a localized region of the non-loading flank confirms the improper meshing and/or misalignment of the gears resulting from improper assembly. Another similar study by Bhaumik et al. (2008) indicated that statistics show that majority of service failures in aircraft components occur by fatigue and it amounts to about 60% of the total failures. A number of factors influence the fatigue life of a component in service:

i. Complex stress cycles,
ii. Engineering design
iii. Manufacturing and inspection
iv. Service conditions and environment
v. Material of construction.

Tongbo and Gaiqi (2011) discussed failures that may occur in the development and service of the helicopter transmission system. The mode, characteristics, cause, and corrective actions provided were summarized as per Table 9.

Table 9 - Failure modes, effects, and causes of the transmission parts (Tongbo and Gaiqi. 2011)

Parts	Failure modes	Failure effects and hazards	Main causes of the failure	Failure classification
Gear	Tooth surface pitting	It may lead to spalling and other severe defects, It could be detected by chip detector	Excessive surface stress and/or insufficient tooth surface durability	Minor
	Tooth surface spalling	Affecting gear meshing , enlarging vibration and may lead to tooth breakage		Major
	Tooth surface scratch / scoring	Scratches further deterioration may lead to scoring and other severe defects affecting gear meshing, enlarging vibration and leading to tooth breakage	Load concentration or insufficient lubrication	Major
	Tooth breakage	Loss of transmission function	Excessive loading, insufficient tooth load capacity or excessive vibration	Catastrophic
	Gear rim and web breakage	Loss of transmission function	Excessive vibration	Catastrophic
Bearing	Spalling	Affecting or total loss of supporting / centring functions	Excessive surface contact stress and/ or insufficient load capacity	Major
	Overheating and deformation	Failing to provide normally supporting / centring functions	Incorrect lubrication, design, or manufacture	Minor or major
	Wear	Affecting supporting / centring functions	Unsuitable bearing surface and lubrication condition	Minor
Shaft	Breakage	Loss of transmission function	Excessive loading and / or insufficient load capacity or excessive vibration	Catastrophic
	Excessive vibration	Leading to breakage resulting in loss of transmission function	Unsuitable design, manufacture, assembly, dynamic balancing and operation conditions	Major or catastrophic
	Spline excessive wear, spalling, and breakage	Affecting or total loss of transmission function	Unsuitable design, manufacture, assembly, and operation conditions	Minor, major or catastrophic

Coupling	Breakage	Affecting or total loss of transmission function	Unsuitable design and manufacture	Major or catastrophic
	Delamination or bolt looseness for flexible film coupling	Affecting transmission function and may lead to severe damage	Unsuitable design, manufacture, assembly, and operation conditions	Major
Clutch	Breakage	Loss of transmission function	Incorrect assembling operation, end load concentration, excessive loading and / or vibration	Major or catastrophic
	Spalling	Enlarging vibration, leading to breakage that can result in loss of transmission function	Excessive loading and /or vibration	Minor or major
Casing	Breakage	Loss of supporting and reacting loads functions	Excessive loading, insufficient static or fatigue strength , uneven distribution of the strength	Catastrophic
	Excessive deformation	Affecting the supporting and reacting loads functions of the casing	Excessive loading, insufficient stiffness, uneven stiffness distribution	Major
Lubrication system and components	Failing to accomplish the expected performance	Affecting or total loss of lubrication and cooling functions	Unsuitable design and/ or manufacture of the lubrication system	Major
	Element physical crack	Affecting or total loss of lubrication and cooling functions	Unsuitable design and/ or manufacture of the lubrication components, operation conditions	Major
	Oil leakage	Affecting the normal operation of the gearbox		Major
	False warning			Minor or major

Finally, Zamponi et al. (2011) used Finite Element Method (FEM) to analyse main gearboxes behaviour under various loads resulting from overall weight reduction requirements. For lighter weights, modern MGB designs use materials such as aluminium and magnesium alloys, and include the integration of several functions within the same part (like shafts which gather one or more gears, splines and integrated bearings raceways). These particularities in the design require some specific methodologies for power transmission modelling, especially for highly loaded bearings. FEM is a key method in this orientation that helped analysing MGB design aspects in regards to expected loads and required material suitability.

2.2 MGB Lubrication

A review was carried out of following papers and reports which discuss the overall concepts of helicopter MGB lubrication systems.

2.2.1 Analysis of lubrication system oil starvation

Rosenlieb J W (1978) performed an analysis and system study to provide design information regarding lubricant and coolant flow rates and flow paths for effective utilization of the lubricant and coolant in a once- through oil -mist (micro fog) and coolant air system. A system was designed, manufactured, coupled with an existing rig and evaluation tests were performed using 46mm bore split-inner ring angular-contact ball bearings under 1779N (400 lb.) thrust load. An emergency lubrication aspirator system was also manufactured and tested under lost lubricant conditions. A total of fourteen step-speed tests and two extended period tests were performed with the mist and cooling air system. Bearing speeds as high as 3 x 10 DN were obtained in the step-speed tests. No problems were encountered except at speeds above 2.5 x 10 DN where cage instability and excessive cage to land wear were encountered in several tests. Successful operation was obtained with an oil flow rate as low as 51 cc/hr. in another test a total air flow of only 0.283 scm (10 scfm) supplied at a temperature of 359O~ (185 ^{o}F) was found adequate to maintain the bearing temperature below 505 K (450^{o}F).The testing also demonstrated the feasibility of using an emergency aspirator lubrication system as a viable survivability concept for helicopter main shaft engine bearing for periods as long as 30 minutes.

Coe (1984) used two computer programs (Planetsys and Spherbean) to analyse the thermal behaviour of a planetary power transmission after oil has been drained from it. ‘Planetsys’ could simulate the thermomechanical performance of a multistage planetary power transmission, including the operation of a spherical roller bearing. ‘Spherbean’ could predict the performance values for a spherical roller bearing in a planetary application, including the effects of misalignment with outer-ring rotation. Using the two programs simultaneously, and after a steady-state analysis was obtained, the transmission temperatures were calculated as a function of time, *assuming dry friction*. A transient thermal analysis was obtained for a transmission system operating after the lubricating oil had been drained from it. These calculated thermal analysis values were then compared to actual experimental data of THE OH-58 helicopter main rotor transmission gearbox that was left operating till *complete failure after oil drainage*. *Complete failure of the gearbox occurred after about 30 minutes*. During the experiment, the transmission was operating at a 75-percent power rating of 150 kW (202 hp) and contained three planets mounted on double-row spherical roller bearings. Both computer programs produced reasonable results. Steady-state results obtained from the two programmes agreed with experimental test values. See Table 10.

Table 10 - Steady-State MGB run dry experimental and calculated temperatures (Coe. 1984)

Description	Temperature (K)		
	Experimental data	Calculated data	
		Planetsys	Spherbean
Mast Shaft:			
Lower	364	366	365
At carrier	364	366	365
At mast bearing	364	365	365
Planet bearing:		366	365
Outer ring	Not collected		
Spherical rollers	Not collected	366	364
Inner ring	Not collected	366	364
Cage	Not collected	364	363
Carrier arm		365	364
Lower case-outer wall	364	362	361
Upper case:			
At joint	Not collected	366	366
At ring gear	364	366	366
At mast bearing	361	363	364
Ring gear		367	367

For the steady- state analysis, the predicted temperatures of the mast shaft and the upper and lower cases were within 3 K (5° F) or 1% of the corresponding measured values. For the transient analysis the temperatures predicted by 'Spherbean' were within 3% at an elapsed time of 15 minutes and within 9% at 25 minutes. 'Planetsys' predicted temperatures slightly higher than 'Spherbean' using the same coefficient of friction (0.075). With zero misalignment, 'Spherbean' predicted that the *sun gear* would be the hottest component at an elapsed time of 20 minutes. 'Spherbean' also predicted that the bearing cage would experience a large rapid increase in temperature if the bearing became misaligned by 1° misalignment.

Gethin and Medwell (1985, 1987) presented an analysis employing the finite element method to assess the performance of high speed journal bearings operating with incomplete films. The method examines the effect of including the contribution of the ruptured film zone to the power consumption of a bearing having two diametrically opposed axial grooves at 90 ° to the load line. One of the consequences for a bearing operating in a starved condition is that the reduction in mass flow of the lubricant in the bearing will produce less power loss. However, the energy generated in the form of heat must now be removed through convection by less side leakage, and this could be accompanied by higher temperatures.

Results showed that due to lubricant starvation, all bearing design parameters were affected significantly. The lubricant side leakage was greatly reduced such that when 25% of the bearing inlet width is filled, there was no side leakage until the bearing operated at very high eccentricity ratios. The presence of the squeeze film effect explained the rapid rise in load carrying capacity for such a high degree of starvation.

As already pointed out, the reduction of lubricant flow can lead to excessive temperatures being generated in the bearing. However, in most practical applications the analysis of lubricant flow will probably be complicated by carry-over effects (eg from the ruptured film or, more usually, from a second oil inlet port) which must be taken into account with any inadequacy of lubricant supply. Considerations must also be taken to the use of proper lubricants that can provide for higher component film thickness, increased load carrying capacity and improved corrosion resistance which will provide increased life for drive system gears and bearings (Henry and Stapper. 1998).

Olaru and Gafitanu (1993) developed a complex analytical model for the starvation mechanism in ball-race contacts, in correlation with thermal effects. From the theoretical results it was found that in high speed, mist-lubricated ball bearings, the reduction factor of the film thickness by starvation and thermal effects can be computed in correlation with the ball-race lateral oil meniscus thicknesses. Experimental investigations of 7206 C angular contact ball bearings, operating between 5000 and 35 000 min^{-1}, are in good correlation with the theoretical results when only starvation and inlet shear heating have been included. When the ball bearing temperature increases, both the theoretical and experimental results show that starvation occurs at smaller ball-race lateral oil meniscus thicknesses, by decreasing the oil viscosity.

2.2.2 Possible intervention concepts to oil starvation

Kreider and Lee (1987) suggested two main approaches to operating MGB under oil starvation conditions: To design into the system an auxiliary source that would provide minimal lubrication following oil supply interruption. This lubricant could either be supplied continuously or activated by changes in various performance parameters. The other approach has been to design into the components (bearings) a greater tolerance to operate under extreme lubrication starvation conditions.

Kreider and Lee undertook oil-off experiments which could be considered a successful part at extending the oil-off survivable capability of a tapered bearing. The thirty minute oil-off goal was achieved in this program (roller bearings) for speeds up through 11,000 rpm (0.72 million DN) for the ribbed cup design; however, to operate up through 37,000 rpm (2.4 million DN), an auxiliary oil supply was necessary. The ribbed cup- style bearing achieved a longer survivable time than the ribbed cone style.

McGrogan (1976) demonstrated the feasibility of utilizing an air-oil mist combination to lubricate high loaded gearboxes after the main lubrication system shut down. Preliminary step-speed and endurance tests on a regenerative - closed loop test rig were conducted. Figure 3 illustrates this concept. For the preliminary testing at 10 krpm, the mist nozzle position, the oil/air flow ratio and tooth contact pressures (690, 1034 and 1380 Megapasca1s) were varied using two lubricants (a MIL-L-23699, type II ester and a formulated synthetic hydrocarbon) in order to optimize the nozzle position and oil/ air flow ratio. Then in the step-speed tests, the speed was varied between 10 krpm and 20 krpm, with a radial nozzle placement (based on visual results of the preliminary test) and a tooth contact pressure of 1034 MPa. Using the same two lubricants, the heat balance data indicated a 15 to 20% increase in heat generation, but a superior tooth surface with the conventional jet spray system.

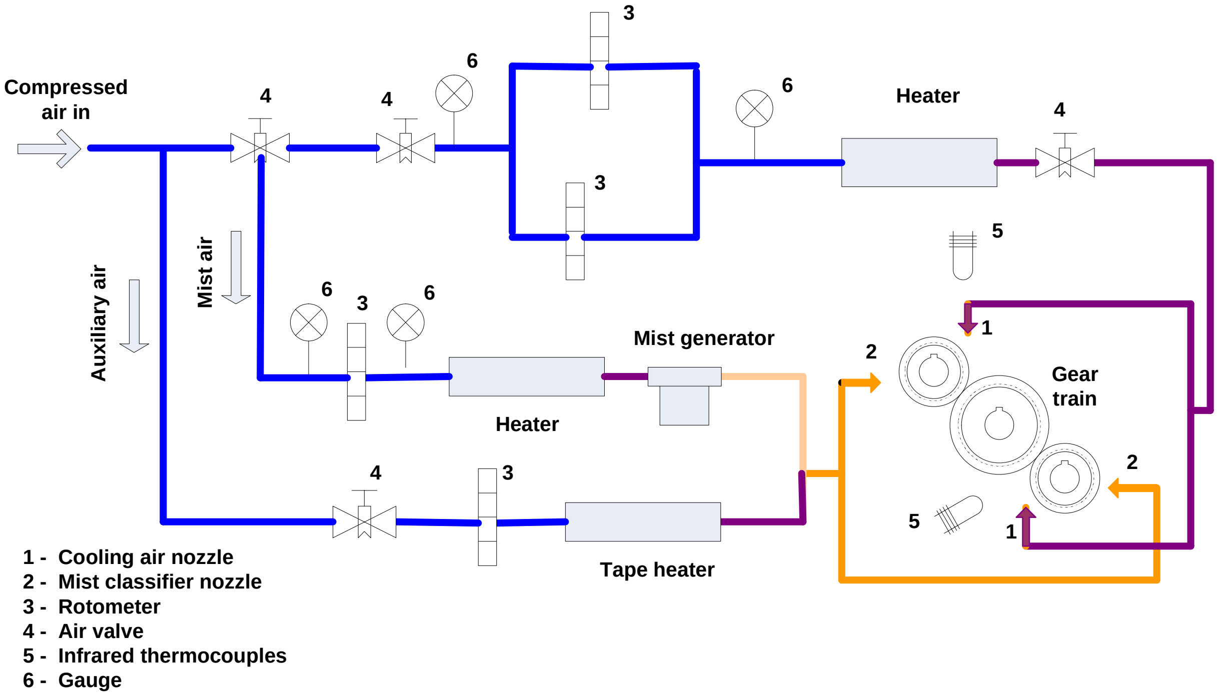


Figure 3 - Mist lubrication air delivery system – schematic (Reproduced from McGrogan 1976)

This test demonstrated the feasibility of using a once-through oil-air mist lubrication system in a two mesh gearbox. A step-speed study, run at 10 krpm to 18 krpm and at tooth pressures of 590 and 1034 MPa with the two lubricants, and an endurance test run at 14 k rpm and 1034 MPa of the emergency aspirator mist system resulted in a successful completion of a 5 hours endurance test with the MiL-L-23699 lubricant. The success of this rather severe test demonstrated that an aspirator mist system is a good candidate for an emergency lubrication system in a helicopter transmission.

Mitchell and Coy (n.a) tested the efficiency of 11 different lubricants. It is found that for a given lubricant, the efficiency increased as temperature increased and thus as viscosity decreased. Between lubricants, efficiency was not correlated with viscosity. There were relatively large variations in efficiency with the different lubricants whose viscosity generally fell in the 5 to 7 centistoke range. The lubricants had no significant effect on the vibration signature of the transmission. In another orientation Miyoshi (1998) studied the fundamentals of solid lubrication applications. In particular, he studied the solids properties of clean surfaces, namely: adhesion, friction, and wear. He presented details on various properties usually required to produce self-lubrication effects under severe loads and high temperatures.

One of the initial works that investigated the use of oil mist lubrication for high load high temperature applications was conducted by Pytko and Bednarek (1975) who gave guidelines for determining pressure gradients in feed nozzles; for selecting oil mist generators in terms of output, oil and air preheating, and oil refill intervals; for selecting the type and viscosity of oils; for determining the dimensions of compressed-air and oil-mist lines; and for laying out systems without pockets that accumulate condensed oil. A sample system design was presented.

Itoigawa et al. (1998) introduced an oil and air lubrication system for ball bearings supporting a high speed spindle. The authors concluded that such oil/ air lubrication arrangement maintains friction losses and temperature rises in low levels comparing with other lubrication systems, e.g., oil jet or oil mist lubrication. In this study, rotating speeds of the ball in an angular contact ball bearing lubricated by the oil and air lubrication system are observed in various oil supply rates. In addition, quasi-static model analysis of the ball motion is carried out. A schematic diagram of oil and air lubrication principle is given as per Figure 4. The oil and air lubrication system consists of a distributor and oil pressure equipment. The distributor discharges a very small amount of oil measured by reciprocating motion of a constant-quantity piston into pressurized air. The reciprocating motion of the constant quantity piston is given by hydraulic pressure which is intermittently introduced into the piston by a solenoid valve. So, the oil supply rate is adjusted by changing an oil discharge interval. As a tube in which the oil and air flow is made of material which possesses low wettability against the oil such as PTFE, many small oil drops are formed in the tube.

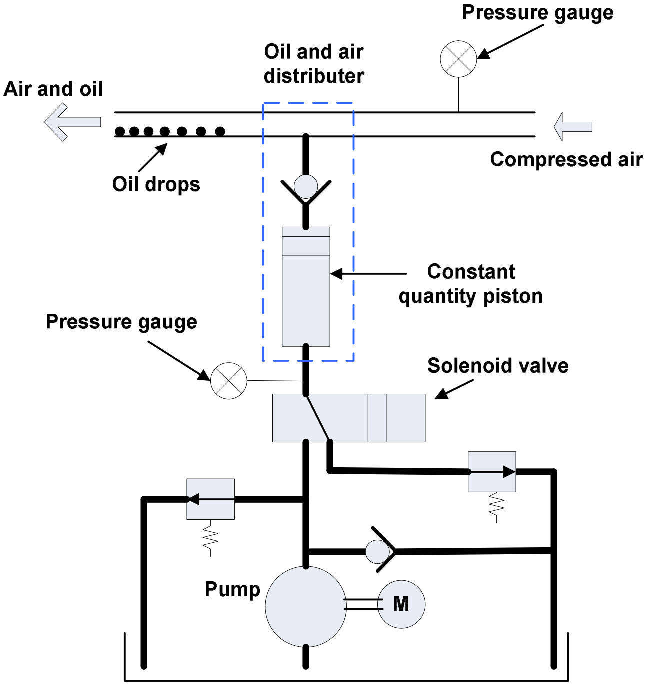


Figure 4 - A schematic diagram of oil and air lubrication principle (Reproduced from Itoigawa et al. 1998)

Experiments indicate that the angular velocity of the ball varies with the oil supply rate even at the constant spindle speed. Furthermore, the model analysis suggests that the ball angular velocity is considerably concerned with an inlet film thickness. From the both results, a relationship between a starvation factor in the ball-race contacts and the oil supply rate is derived for the ball bearing under the oil and air lubrication. When the bearing is running in the starved condition at low oil supply rate, a reduction of oil film thickness brings very low temperature rise. However, severe starvation induces metallic contacts or, in the worst case, bearing seizure. Therefore, an adequate oil supply rate must be selected in practical spindle bearings.

Itoigawa et al. (1998) thus concluded that for the machine tools, the oil and air lubrication system has two advantages over other lubrication systems; First, this lubrication system is superior to the other lubrication systems in size and cost because an oil cooler, oil recirculating devices and complicated piping are not necessary. Second, temperature rise caused by drag loss and churning loss is suppressed at relatively low level because of a small supplied oil amount. This is so valuable from a viewpoint of precision preservation that many high speed and high precision machine tools have come to be equipped with the oil and air lubrication system. In addition, the oil and air lubrication is superior to grease lubrication with regard to maintainability, since new oil without deterioration by oxidizing is supplied continuously and stably.

Oil properties have their direct influence on the performance and wear rates of the transmission components. For instance, Krantz and Kahraman (2005) investigated the influence of lubricant viscosity and additives on the average wear rate of spur gear pairs. In general, the wear rate was found to be inversely proportional to the viscosity of the lubricant and to the specific film thickness. The measured wear was related to the as-manufactured surface roughness, the elastohydrodynamic film thickness, and the experimentally determined contact fatigue lives of the same specimens. Lubricants with similar viscosities but differing additives and compositions had somewhat differing gear surface fatigue lives and wear rates.

A few researchers have explored the possibility of employing alternative lubrication methods/techniques in order to allow gearboxes to operate for over 30-minutes in the event of a catastrophic lubrication system failure (Handschuh and Morales (n.a.)). With higher speed engines being introduced, the requirements for the drive system become increasingly more difficult. The drive system must be lightweight, which minimizes the opportunity to use the gear bodies to absorb the tremendous amount of heating that takes place. In many cases, the amount of heat generated because of the high speed and load requires an emergency lubrication system that negatively impacts the aircraft's weight, complexity, and cost.

One such lubrication method is vapour and/or mist lubrication. Another reason for exploring mist and vapour lubrication is due to potential weight savings. A liquid lubrication system is approximately 15% of the total gas turbine engine weight and as such vapour/mist lubrication systems offer considerable advantages (Van Treuren et al 1998).

Traditionally there are three types of lubrication schemes under the theme of vapor/mist systems. In a regular oil-mist lubrication system, mineral or synthetic hydrocarbon oil is delivered, in an air stream, as a fine oil mist to mechanical components where the oil-mist coagulates on the wearing surfaces providing lubrication. No intended reaction between the oil and the metal surfaces occurs and the oil functions as a normal liquid lubricant within its operating temperature range. In gaseous lubrication a light hydrocarbon gas, such as acetylene, is delivered to mechanical components operating at sufficiently high temperatures that the gas decomposes on the wearing surfaces generating a lubricious graphitic material which provides lubrication. For the vapour/mist phase lubrication (VMPL) method, an organic liquid is either vaporized or misted and delivered in an air stream to mechanical components operating at high enough temperatures that the organic molecules react in the wearing surfaces generating a lubricious deposit which provides effective lubrication (Handschuh and Morales 1999 and 2000, Handschuh et al. 2007b).

The lubricant formed by the chemical reaction has been shown to offer lubrication up to 300^{o}C, however, continuous operation eventually leads to serve wear (discussed later in this section). An advantage of the mist delivery over vapour is that the increased momentum of an oil mist droplet allows better penetration across the pressure differential created by windage in high-speed bearings or gears. Upon reaching the bearing or gear, the surface temperature provides heat input required to complete vaporization and to initiate the chemical reactions (Van Treuren et al 1998). It has also been stated that the oil mist delivery approach offers additional cooling to the bearing (Van Treuren et al 1998). Interestingly, Handschuh and Morales (1999) reported that lubricant delivery as a mist to rubbing surfaces worked as well as vapour delivery prompting the phrase ‘vapour/mist phase lubrication’(VMPL).

2.2.3 Concept of vapour/mist phase lubrication (VMPL)

The concept for VMPL involves the delivery of organic molecules, via a carrier gas such as air, to rubbing components such as ball bearings or gear teeth. See Figure 5. At the rubbing surfaces several things may occur dependent on the nature of the organic molecules. For example, (Lauer et al.1990) reported lubricious graphite deposit can be generated at the rubbing surfaces if a hydrocarbon gas such as ethane is delivered via a nitrogen gas carrier (Wedeven. 1996). Another example involves the reactive vapour/mist phase method in which organophosphates molecules are delivered, either as a fine mist or vapour in an air carrier to the rubbing surface where they react with the metal surface to generate a metal phosphate/pyrophosphate lubricating deposit (Graham and Klaus 1985, Morales et al (2005). Other lubrication arrangements are shown in the schematic in Figure 5.

In application of these lubrication schemes a disadvantage of the hydrocarbon option is that aircraft must carry cylinders of compressed hydrocarbons and nitrogen. The nitrogen is needed to avoid combustion of the hydrocarbon. VMPL only requires compressed air and a small misting unit containing an organophosphate. The organosphosphate reacts with the gear surfaces to form a lubricious deposit that possesses excellent load carrying capacity however continued reaction will eventually lead to gear surface wear. The unanswered question is how long such a lubricating system will last before severe wear develops on the gear faces.

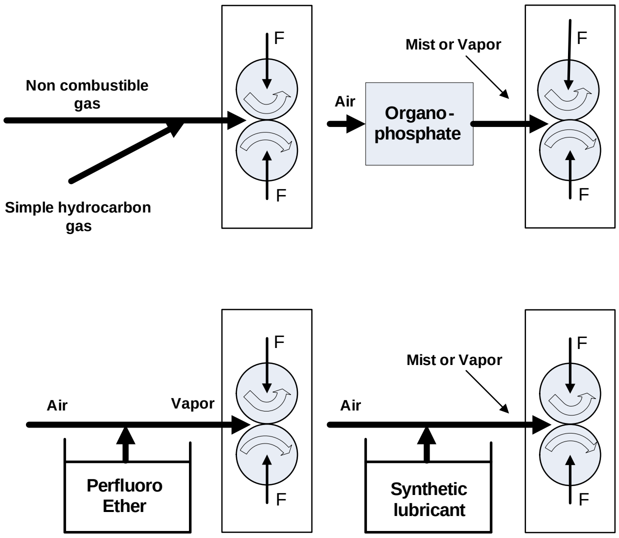


Figure 5 - Comparison of possible emergency lubrication systems (Handschuh & Morales 2000)

2.2.4 Experiments on VMPL

Handschuh and Morales (2000) investigated the use of VMPL by undertaking comparisons of baseline tests, using a synthetic lubricant that would be typically employed in operation, with an organophosphate mist lubrication system. Temperatures were measured for both test cases and the gear teeth inspected using an X-ray photoelectron spectroscopy (XPS). A schematic of the experimental test is detailed in Figure 6.

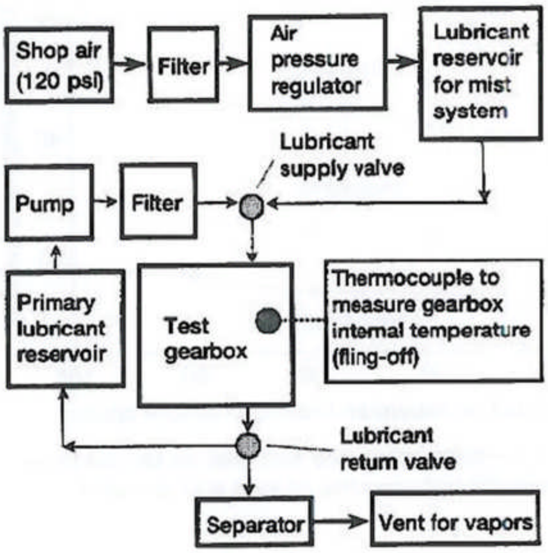


Figure 6 - Lubrication test with liquid and VMPL systems (Handschuh and Morales 2000)

Key results from these tests (Handschuh and Morales 2000) are presented in Figures 7 and 8. Figure 7 shows that mist lubrication caused a reduction in gear temperature from 28 minutes of operation whilst no-mist lubrication caused the gear temperature to continually increase. The decrease in temperature from the mist is attributed to a reduction in coefficient of friction since the relative sliding speeds remain unaltered. It must be stated that temperature measurements were taken with a thermocouple at the out of mesh position, referred to as the fling-off temperature. There was some evidence that the surface geometry was altered though it was stated (Handschuh and Morales (2000) this effect on the magnitude of heat generation should be minimal. It was noted that the rate of mist flow was stated as low – what is low and what effect of mist rates have on the on durability of gears is unknown at this stage. Observations of the dry test run (Figure 7) showed a large rise in temperature over a relatively short duration – as would be expected.

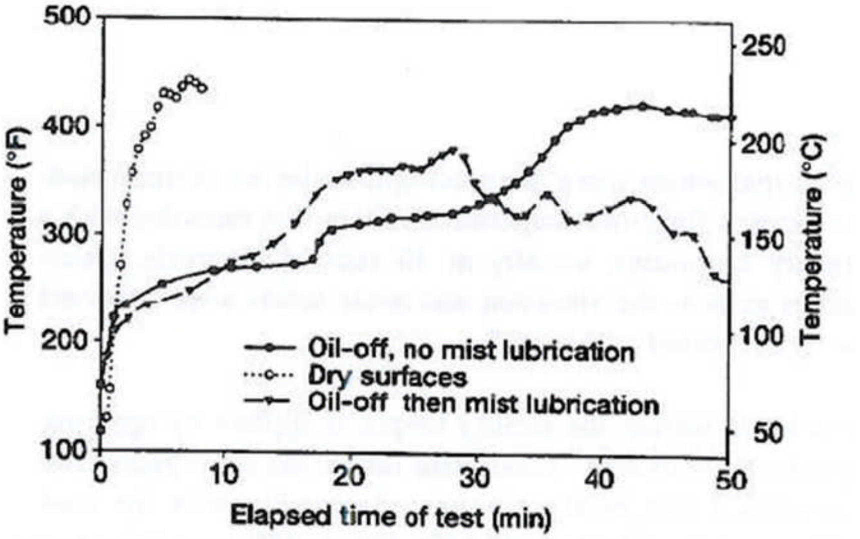


Figure 7 - Effect of lubrication conditions at 1.32GPa Hertizian contact stress (Handschuh and Morales 2000)

Figure 8 showed some interesting features with the no mist condition offering the best operating condition. For the no-mist test the rig was operated without the aid of the mister though it relied on the gear oil that remained in the gearbox case after the principal lubrication system was shut off. The authors noted that had the gears operated longer until depletion of the residual oil had occurred, severe wear would have been experienced. For the mist condition, the temp of the gears increased initially and then reduced to levels seen with the no-mist condition, this lasted for a period after which the temperature levels increased. The total test duration was 80 minutes.

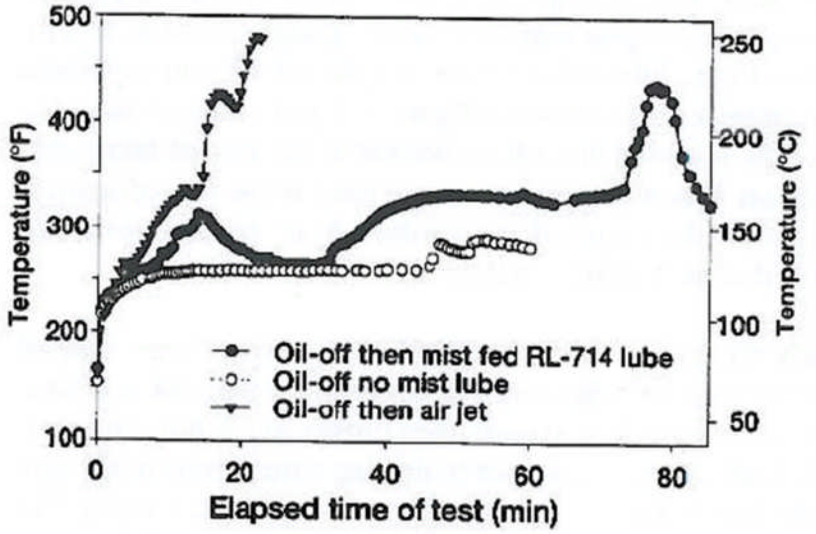


Figure 8 - Effect of lubrication condition on temperature at 1.71GPa Hertizian contact stress (Handschuh and Morales 2000)

Another study by Handschuh and Morales (1999) stated that the initial formation of an iron phosphate film on the rubbing ferrous surface, followed by growth (by cationic diffusion) of a lubricious pyrophosphate-type coating over the iron phosphate was the reason organophosphates work well as a vapour/mist phase lubricant. The iron phosphate film serves as an antioxidant and binder for the lubricating film (Van Treuren et al1998). It was also noted (Handschuh and Morales 1999) that this mechanism leads to depletion of surface iron atoms and to eventual lubrication failure. Essentially as long as iron is present at a wearing surface the vapour lubricant will offer lubrication. In this particular investigation the mister was filled with aryl phosphate ester.

The majority of studies in mist/vapour phase lubrication have employed liquid phosphate ester. Whilst this lubrication method works well, as stated its continuous use can lead to unacceptable wear rates. An alternative to this ester was proposed by Handschuh and Morales (1999) and Handschuh et al. (2007b). The lubricant proposed involved the addition of some amount of 'ferric acetylacetonate' (1%) in the organophosphate.

Gears tested by Handschuh and Morales (1999) were of spur type and manufactured from AISI 9310 gear steel. The test rig was of back-to-back configuration operated at up to 10,000rpm with a maximum contact stress on the gears of 1.7GPa. The lubricating mist system employed 0.41MPa (60psig) shop air and the mist flow rate was 2.0 x 10^{-4} cm^3/sec (3 x 10^{-6} gpm). Temperature measurements were taken with a thermocouple at the out of mesh position, again referred to as the fling-off temperature; taken every 30 seconds. The mist jet was positioned to lubricate the gear teeth just before they entered the contact zone. The authors reported that this lubricant led to the formation of an iron phosphate film and it was suggested this could circumvent iron depletion on ferrous surfaces vapour/mist lubricated with organophosphates. The inspection of the gears revealed some wear on the gears but with very little surface metal removal and no discoloration.

For successful VMPL the excessive wear problem must be solved/ addressed. Handschuh et al. (2007b) also investigated some of the properties of a polyphenyl thioether liquid. Polyphenyl thioethers are derivatives of polyphenyl ethers where one or more of the oxygen atoms in the polyphenyl ethers are replaced by sulphur atoms. An initial investigation into the use of a thioether as a VMPL lubricant was conducted using a high temperature reciprocating pin-on-plate tribometer (Handschuh et al. (2007b). The tests revealed that the thioether was able to lubricate a ceramic pin and plate pair, at temperatures greater than 450 °C, with a coefficient of friction less than 0.05 with minimal wear of the substrates.

The lubricant was then tested on case-carburized and ground AISI 9310 spur gears. The specified surface hardness of the test gears, as commercially supplied, was Rockwell C 58–62. For these tests the mister was filled with thioether and delivered at 15ml/hr in a flowing air stream of 400l/hr. A thermocouple was installed inside the gearbox to record the temperature of the turbulent air near the rotating gears (10,000 rpm), see Figure 9.

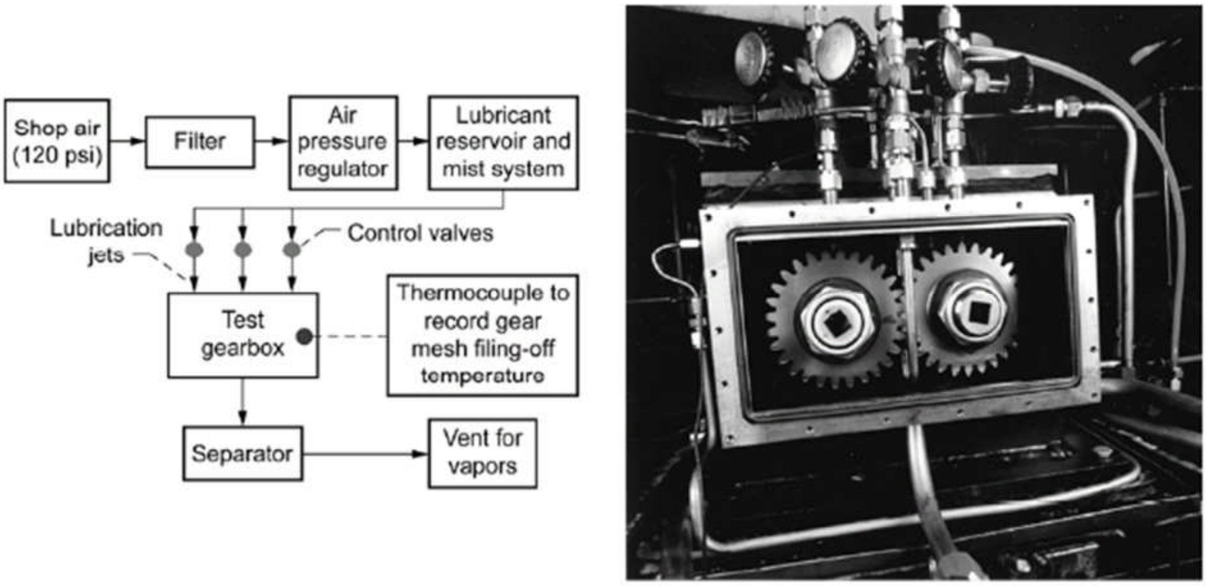


Figure 9 - Test rig and configuration employed for thioether liquid test (Handschuh et al. 2007b)

The results from this study clearly showed a dramatic improvement over the results from investigations that employed synthetic paraffinic oil and a phosphate ester oil (Handschuh and Morales 1999, 2000, 2005). For instance, the primary evidence that good lubrication was provided, using the thioether, was the observed minimal gross wear on the gear teeth even after 35 hours of operation. Gear tooth wear, however, was observed using the paraffinic oil and phosphate ester after only 10 min of operation in other investigations. The fling-off thermocouple temperature readings for the thioether test was constant at 107 °C with no fluctuation, whereas for the previous tests the temperatures were much higher, in some cases approaching 205 °C, and the temperatures fluctuated up and down Handschuh et al. (2007b). Figure 10 shows a test condition over 320 minutes of operation noting the gear temperature and corresponding vibration levels remained constant.

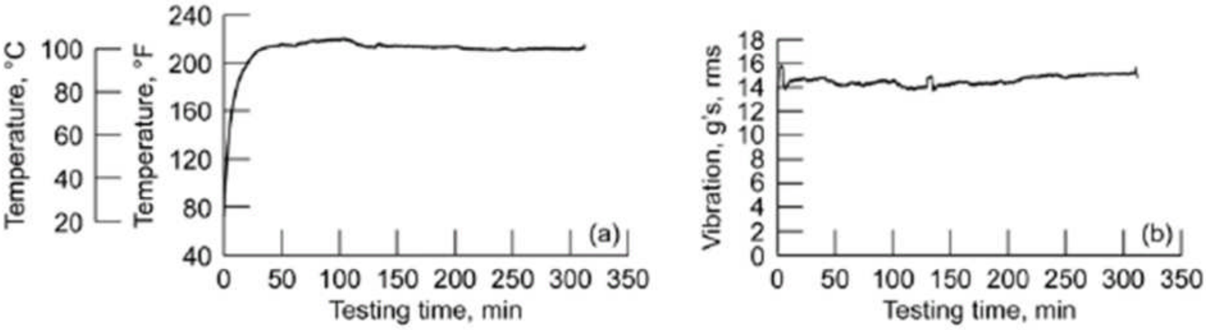


Figure 10 - Temperature (a) and vibration (b) measurements for the gearbox test under mist lubrication (Handschuh et al. 2007b)

Observations of the gear set at were undertaken at defined intervals. Figure 11 shows wear patterns observed after 7 million cycles (12hrs) of operation. Similar wear patterns were observed after 35hrs of operation. The results of this test are a significant advance in the use of VMPL.

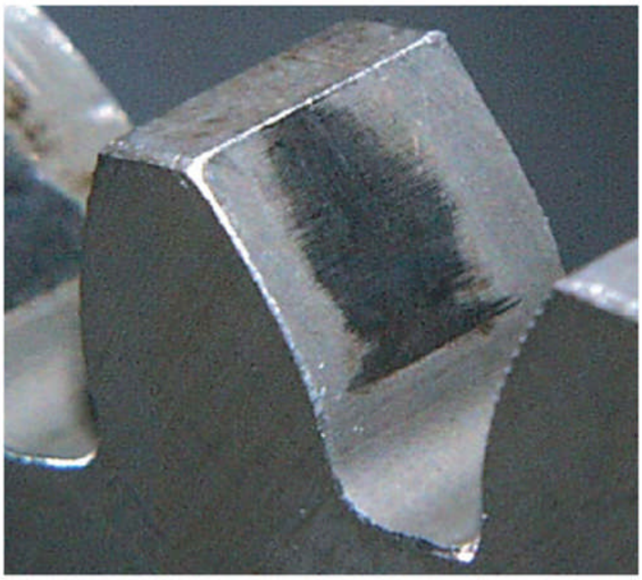


Figure 11 - Gear wear after 12 hours of operation under mist lubrication (Handschuh et al. 2007b)

Lastly, in the mid 1990's the vapour-phase lubrication was tested on a bearing in an Allison T63 gas turbine. Van Treuren et al (1998) noted the technology had developed sufficiently by this point such that gas turbine engine bearings could be lubricated for several hours by vapour/mist lubrication. The authors conducted test which were run at 35,000rpm with a modification of the lubrication system to bearing no. 8 employed to ensure a mist form lubrication. The mister was an Alemite Model 4955 with a tertiary-butylphenyl phosphate lubricant, DURAD 620B. The mister used air at 0.00066m^3/s at 1.72 bar and was set to supply 13ml of lubricant per hr. The test was conducted for a total duration of 60minutes. Results showed for the initial 13minutes the bearing temperature rose steadily to equilibrium at 283^{o}C and remained at this temperature for the duration of the test. A comparison of the operating parameters of the gas turbine showed minimal difference between the vapour and liquid lubrication systems. There was some evidence of wear on the bearing at the end of the test programme in the form of a light scratch on the inner race which ran for a third of the circumference.

2.3 MGB Reliability and Risk Assessment

The following papers and reports discuss MGB operation reliability and risk assessment, both during normal operational settings, and in the case of oil loss.

Dougherty and Barrett (1978) approached the problem of civil helicopter reliability. Their study showed that 78 % of the reliability problems of civil helicopters can be categorized into 30 problems. These problems were analysed to determine causal factors and to recommend corrective actions. Of the 30 problems that were analysed, Table 11 lists their relative impact on some of the helicopter systems.

Table 11 - Relative impact of some of the reliability problems of the civil helicopter (Dougherty and Barrett. 1978)

System	Relative failure rate within the 30 categorized problems (%)	Unscheduled maintenance man-hours needed to solve these problems (%)	Repair parts cost to solve these problems (%)
Propulsion (Turbine power)	35.3	25.1	66
Drive (transmission)	13.9	35	21.3
Rotor	12.2	19.7	11.4
Airframe	19.9	10.1	1.2
Landing gear (including floats)	9.4	5.6	
Fuel	5	1.1	
Hydraulics	4.1	2.8	

Dougherty and Barrett (1978) then listed many requirements that they set as reliability targets for civil helicopters. Among those targets:

i. Redesign and testing to reduce spalling of transmission bearings
ii. Redesign to improve lubrication of drive shaft hanger bearings
iii. Redesign main transmission housings on one model helicopter to reduce mounting lug cracking
iv. Use. the latest gear materials and improved process and quality controls to reduce

Fraser (1983) developed necessary instrumentation to provide inflight computation and indication of the current values of fatigue life expended for critical gears in single- or twin-engine helicopter transmission systems. The basic transmission load data in the form of total time spent in a number of contiguous torque bands are continually updated and stored during flight. The basic load data together with values of life expenditure for critical gears for the current flight can be automatically printed out after flight. This development opens the way towards fatigue life monitoring of individual transmissions. Fraser and King (1986, 1988) also conducted a series of experiments and tests to establish an estimate for the fatigue life usage of critical gears in the main rotor gearboxes of Sea King helicopters. The test equipment is capable of monitoring actual life usage of individual gear boxes in "damage" or "life fraction" terms. Some 479 hours of in-flight load data covering 227 flights and 8 main sortie types have been accumulated. These data have been analysed and it has been concluded that for practical purposes, the lives of the gears in the main rotor gear box are not limited by fatigue. It is thus approved that estimates of the safe fatigue life of critical helicopter transmission components may be made if in-service load data together with component fatigue data are available.

Warburton et al. (1998) reported progress towards the development of procedures and techniques for assessing the reliability of components at the design stage. From a fundamental understanding of the degradation and failure processes and their relation to the underlying operational, environmental, materials and design variables, the paper develops procedures to support reliability prediction of mechanical devices using an electromechanical actuator as a case study. The methodology is illustrated by particular reference to the process of sliding wear leading to jamming of the actuator.

Embrey (1992) discussed the Influence Diagrams (ID) approach to system reliability assessment. The ID techniques, a detailed probabilistic safety assessment tools, work to graphically and numerically illustrate the various factors influencing the reliability of the system under study, and the multiple influence impacts of each of these factors on the others. Embrey used the ID technique to investigate the influence of management and organizational inputs on the overall technical system reliability. An overall representation of a generic accident ID is given as per Figure 12.

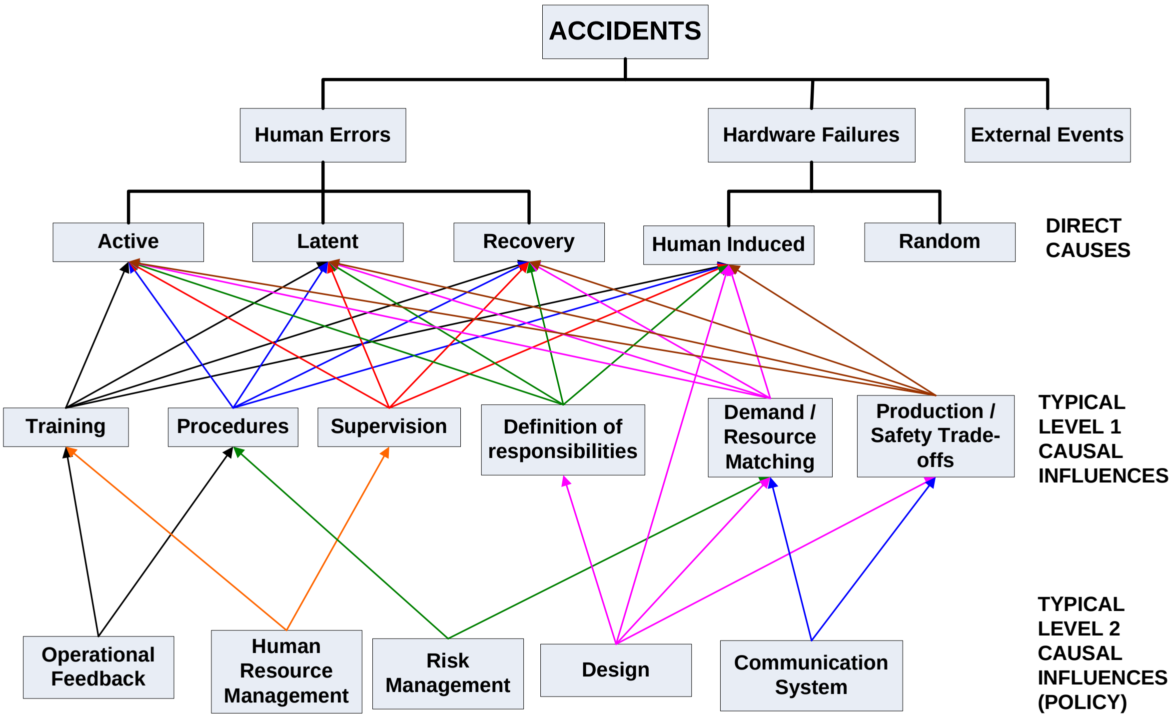


Figure 12 - Generic Influence Diagram model for accident causation (Embrey 1992)

Similar work was also performed later by Hokstad et al. (2001) who used the ID approach to assess risks associated with operating helicopters over the North Sea. The approach, being so detailed and fact-representing, can be used for assessing reliabilities of pure technical systems, the MGB being a key example as will be shown later within part two of this current report.

Holmberg K (2001) highlighted the use of tribology concepts in the complex scope of reliability, in particular for the high load applications. Some of the tribology related methods to improve reliability are the reliability design, component lifetime, condition monitoring and diagnosis. To be of value for reliability uses, the tribology data are set in terms of endurance life and probability of failure. It is concluded that the tribological understanding of friction and wear mechanisms and the generation of reliable friction and wear data for different material combinations and operational conditions is of great importance for the determination of the reliability and availability of machines and production systems.

Nickol (2008) described detailed risk assessment procedure that was applied on a given silent aircraft project. A combined team of subject-matter experts and systems analysts developed a list of 27 risk items, and evaluated the level of risk for each item in terms of the likelihood that the risk would occur and the consequences of the occurrence. A typical risk matrix is given by Figure 13.

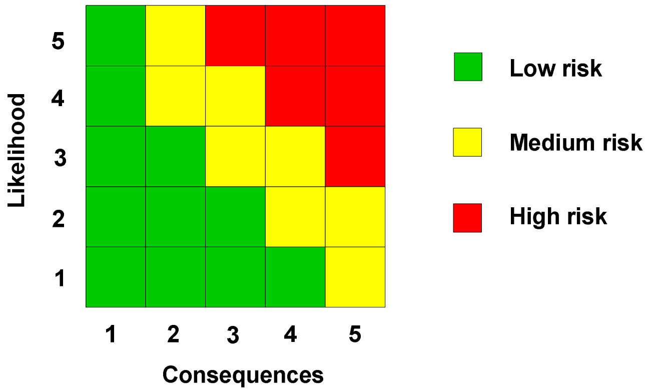


Figure 13 - Risk matrix (Nickol 2008)

The likelihood definitions ranged from not likely (rating = 1) to near certainty (rating = 5); the incremental steps between were low likelihood (rating = 2), likely (rating = 3), and highly likely (rating = 4). See Table 12.

Table 12 - Definitions of Consequence Metrics

code	Consequences envelope
1	Minimal or no impact in meeting requirement(s)
2	Minor shortfall, ~90 - 95% of requirement(s) can be met
3	Moderate shortfall, ~75 - 90% of requirement(s) can be met
4	Significant shortfall, ~ 60 - 75% of requirement(s) can be met
5	Unacceptable shortfall, < 60% of requirement(s) can be met

Using the risk matrix, 7 of the 27 items are identified as “high risks” meaning that the combination of likelihood and consequence put them into the top one-fourth of the risk matrix. Items in “medium risks” region of the matrix are also to be considered during the overall risk management strategies of either mitigation, avoidance, assumption, or transfer were recommended for each risk. The approach is applicable to virtually all high risks technologies including helicopter transmissions.

Liu et al. (2011) stated evaluative methods of technology readiness which are used in the national background projects development. The methods conduct helicopter transmission system technology maturity research and assessment of native significant project according to methods of technology readiness assessment. The conclusions indicate that methods of technology readiness assessment have very important promoting action to native project development and scientific decision-making. The project which adopts mature critical technology implies processes that guarantee the schedule of project development and reduce risk of project development. Actualizing assess methods of technology readiness can be an important part of project development risk management.

2.4 MGB Testing and Certification

The following papers and reports discuss MGB testing, both during normal operational settings and in the case of oil loss.

2.4.1 Testing helicopter MGB oil system performance

Townsend et al. (1976) ran the OH-58 main transmission gearbox at varying output torques, speeds, and oil cooling rates. The gearbox was subsequently run to destruction by draining the oil from the gearbox while operating at a speed of 6200 rpm and 36 000 inch-pounds output torque. Primary cause of gearbox failure was overheating and melting of the planet bearing aluminium cages. Complete failure of the gearbox occurred in 28.5 minutes after the oil pressure dropped to zero. The gearbox air/oil cooler has sufficient cooling capacity margin for hot day take-off conditions at a 117 % power rating. The alternating and maximum stresses in the gearbox were approximately 10 % of the endurance limit of the material. An interesting relation could be obtained between the applied torque, oil cooler inlet area available (oil inlet area blockage percentage), and the oil temperature as per Table 13.

Table 13 - MGB oil outlet temperature as a function of oil cooler blockage with varying speed and output torque (Townsend et al. 1976)

Speed (rpm)	Output torque (in-lb)	Oil cooler blockage area (%)	Oil out temperature (^{o} F)
5580	48 000	10	204
	56 000	55	204
6200	2 500	100	173
	12 500	100	200
		80	174
	24 000	100	225
		90	200
		70	179
		50	173
		0	167
	36 000	100	244
		75	200
		50	186
		45	183
	48 000	100	244
		87	230
		50	199
		0	191
	56 000	90	246
		80	230
		40	210
		0	197
5820	24 000	75	199
	36 000	60	200
	48 000	50	200
	56 000	50	200

Rosenlieb J W.(1989) designed a test rig to evaluate the performance of a spherical roller bearing with a geared outer ring operating under conditions similar to those of a planet bearing in a helicopter transmission. The configuration is an extension of the widely accepted four - square gearbox arrangement. It provides for testing of two bearings simultaneously with outer ring rotation, misalignment, diametrically opposed loading through the gear teeth, and under race lubrication. Instrumentation permits the measurement of: inner and outer ring temperature, bearing drag torque, degree of misalignment, outer ring speed, cage speed, and applied load. Full details on the test equipment, parameters, and procedures were provided.

Lewicki et al. (1992) performed a full-scale transmission testing to evaluate a group of advanced lubricants. Experimental tests were performed on the OH- 58A helicopter main-rotor transmission of NASA transmission test stand. The objectives of the program were to develop and demonstrate a separate lubricant for gearboxes with improved performance in life and load-carrying capacity. The goal of these experiments was to develop a testing procedure to fail certain transmission components using a MIL-L- 23699 based reference oil and then to run identical tests with improved lubricants and demonstrate improved performance. The tests were directed at components that failed due to marginal lubrication from Navy field experience. These failures included mast shaft bearing micropitting, sun gear and planet bearing fatigue, and spiral bevel gear scoring.

A variety of tests were performed and over 900 hours of total run time accumulated for these tests. Some success was achieved in developing a testing procedure to produce sun gear and planet bearing fatigue failures. Only marginal success was achieved in producing mast shaft bearing micropitting and spiral bevel gear scoring. Again, the paper details equipment, conditions, and procedures of the tests. Many tests procedures and facilities were also discussed through a number of the various publications which were already discussed in the previous sections of this literature review. Some of these are the works by Chaiko (1990) and Krantz (1992).

Handschuh (2001) tested spiral bevel gears, being important drive system components of rotorcraft currently in use. Spiral bevel gears are required to transmit very high torque at high rotational speed. Operational characteristics for thermal and structural behaviour for bevel gears are relatively small in comparison to that found for parallel ones. Handschuh summarized the results of the fully detailed tests to have shown that operating temperature is affected by the location of the lubricating jet with respect to the point it is injected and the operating conditions that are imposed. Also the stress measured from slow-roll to very high rotational speed, at various torque levels, indicated little dynamic affect over the rotational speeds tested. Details of the test rig and test parameters were fully described. Handschuh and Kilmain (2005) again provided detailed description of a series of practical tests that investigated the influence of speed and load on thermal behaviour of high-speed helical gear trains.

2.4.2 Comparison of airworthiness requirements for gearbox run dry testing

A review was carried out on the airworthiness requirements for gearbox run dry between civil and military aircraft. The documents reviewed include the specification standards EASA CS/FAR 29 and MIL-HDBK-516B (DoD 2005) and their accompanying guidance materials, AC 29 (FAA 2003) and the Joint Services Specification Guide (JSSG 2009). Further details are discussed in **Appendix C**.

2.4.2.1 Gearbox Run Dry Test Duration

For civil helicopters, it is stated that the transmission has to be tested for continued safe operation for 30 minutes after the crew is aware of a failure in the lubrication system (DoD 2005, CS 29.927(c). Although a 30 minutes requirement is stated, the recommended test procedures for this was to cause an oil leak and test the gearbox for 15 minutes after illumination of low oil pressure warning, FAR29.927(c). It is not clear if the 30 minutes includes duration of at least 15 minutes for the oil to drain prior to low oil pressure warning. In addition, the amount of oil remaining in the gearbox upon low pressure warning is not stated. As such, the actual run-dry time of the gearbox within the 30 minutes tests is ambiguous. For military helicopters, it is stated that *"the gearboxes shall function for at least 30 minutes after complete loss of the lubricant from the primary lubrication system."* (JSSG 2009, Appendix K, para.3.4.11.8) As such, the military requirement is more specific in defining the dry-run time of 30minutes for gearbox testing.

2.4.2.2 Run Dry Test Load Spectrum

The load spectrum for the dry run test also differs between the civil and military requirements. The civil load spectrum is to simulate autorotation and continue rotation for 15 minutes before simulating a minimum power landing (FAA 2003,29.927, para.c). The military load spectrum requires 2 minutes at hover, 26 minutes at cruise and 2 minutes for vertical landing. The military load spectrum is much more stringent, this is to provide escape landing on hostile territory during emergencies (JSSG 2009, Appendix K, para.3.4.11.8) which would not apply in civil requirements.

PART TWO

Deliverables of HELMGOP TASK 2

3 REVIEW OF MGB LUBRICATION SYSTEM RELIABILITY (Task 2A)

3.1 Applying Fault Trees for MGB Oil System Accidents and Incidents

3.1.1 Formal helicopter accidents reports pool

A thorough research was conducted via various available databases and other data sources to form a comprehensive population of relevant helicopter accidents and incidents formal reports to serve the HELMGOP project requirements. Candidate accidents reports were selected in accordance to specified strict criteria.

3.1.1.1 Reports Selection Criteria:

i. Final official formal reports.
ii. Of sufficient technical details so as to establish adequate sequence of events.
iii. Either of events within the lubrication system, or of external (1) events that influence the lubrication system (including human input).
iv. Written in English (there is no access to the whole group of Eastern helicopters for instance, or to Western reports written in other languages due to time limitations).

Applying the above criteria, a total of 12 reports were selected out of initial screening input of 1232 reports as detailed in Table 14. The selected reports which were directly related to MGB lubrication system failures are given as per Table 15.

Table 14 - Data mining of helicopter accidents formal reports screening and selection process

Country	Authority	Reports found from initial screening search	Reviewed reports	Reports selected for further analysis
UK	AAIB	206	55	4
Canada	TSB-Canada	115	15	4
Australia	ATSB	179	23	1
USA	NTSB	713	78	1
France	BEA	16	16	
Other		3	3	2
Total		1232	190	12

3.1.1.2 Detailed accidents analysis using Fault Trees:

Detailed fault tree analysis to identify various primary and secondary failures of the MGB lubrication system for each of the selected cases was performed. Findings are listed as per Table 16 of next Section 3.2. Samples of the Fault Tree diagrams are given as per **Appendix A** of this report.

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(1) External: The accident may include events not involving the lubrication system components in particular, but involve other parts of the MGB (e.g. Gear fracture due to manufacturing error)

Table 15 - Accidents and incidents involving helicopters MGB lubrication systems (All categories)

S	Date	A/c	Register code	Country	Reference/ Report	Description
1	12 Mar 09	Sikorsky S-92A	C-GZCH	Canada	TSB – Canada A09A0016	Total loss of MGB oil due to fracture of oil filter bowl fixing titanium studs
2	28 Nov 01	Aerospatiale AS-335-F2	N355DU	USA	NTSB – USA MIA 01FA006	Failed MGB oil pump
3	08 Mar 04	Schweizer 269C-1	C-FZQF	Canada	TSB – Canada A04Q0026	Normal flow of MGB oil obstructed due to incorrect positioning of input quill bearing housing
4	04 Feb 08	Schweizer 269D-1	G-TAMA	UK	AAIB – UK EW/C2008/02/04	Seizure of MGB pinion outer bearing due to oil starvation
5	06 Aug 03	Enstrom F-28F	G-BXXW	UK	AAIB – UK EW/C2003/08/03	Failure of MGB rear bearing due to inadequate lubrication
6	01 Apr 09	Aerospatiale AS332 L2	G-REDL	UK	AAIB – UK Report 2/2011	Loss of MGB oil due to MGB case rupture (failed 2nd stage epicyclic planet gear- Non oil system failure)
7	11 Mar 83	Sikorsky S-61N	G-ASNL	UK	AAIB – UK EW/C815	Loss of MGB oil due to MGB case rupture (failed a spur gear - Non oil system failure)
8	Jan 2008	Sikorsky S-92A		Sarawak-Malaysia	TSB – Canada A09A0016 . P70	MGB input module overheating that led to slow oil leak (1)
9	Apr 2005	Sikorsky S-92A		Norway	TSB – Canada A09A0016. P70	Failure of drive of MGB oil pump (2)
10	02 Jul 08	Sikorsky S-92A	VH-LOH	Australia	TSB – Canada A09A0016. P70	Total loss of MGB oil due to fracture of oil filter bowl fixing titanium studs
11	16 Dec 02	Sikorsky S-61N	C-FHHD	Canada	TSB – Canada A02P0320	The plain bearing in the main gearbox cover for the number 1 input pinion failed, lost lubrication, and disintegrated
12	08 Nov 01	EUROCOPTER SA315B	C-GXYM	Canada	TSB – Canada A01P0282	The input freewheel unit (IFWU) and drive shaft assembly failed because of the wear on the internal parts caused by the repeated heavy lift operations and because of the contamination suspended and trapped in the lubricating oil between the unit's rotating parts

(1), (2) These two accidents were not further analysed in details using Fault Trees due to insufficient data available on them.

3.2 Primary & Secondary MGB Failure Modes Due to Loss of Oil

3.2.1 Definitions

Failure:
The occurrence of a basic component failure as a result of inherent internal failure mechanism therefore requires no further breakdown. Example: failure of a resistor in open circuit mode.

Fault:
The occurrence or existence of an undesired state for a component, subsystem or a system as a result of a chain of failures or faults, therefore it can be further broken down. The component operates correctly except at the wrong time because it was commanded to do so.
Example: The light is failed off because the switch is failed open, thereby removing power.

Primary failure/ fault:
A component failure that cannot be defined further at a lower level - Example: diode inside a computer fails.

Secondary failure/ fault:
A component failure that can be defined further at a lower level, but is not defined in detail.
Example: A computer fails.

3.2.2 Fault tree analysis findings

The basic aim of performing this fault tree analysis was to get detailed understanding of triggers, causes, and event sequences for these MGB oil system related accidents and incidents. This can be achieved through detailed identification of all primary and secondary failures and faults. The analysis showed that there is no general pattern or sequences that these events usually follow. It is rather evident that there are no two similar accidents or incidents of them that are of exact nature. There may be some similarities in some events, but the overall sequence, nature, depth, or importance of each event found to be different either up or down stream of the accident.

In the analysis sequence, the events were traced in detail from their origins (triggers) until the point at which the MGB lubrication system lost its functionality as per the designed parameters. However, further destructive consequences on the aircraft are listed in generic informative format. The output of this analysis helped lay a deep understanding on the various failure scenarios and mechanisms that the MGB lubrication system can suffer as a result of different inputs (e.g. design errors, mechanical failures, oil quality, human input, etc.). This gained understanding will directly feed into the next stages of this project, namely, the brainstorming process that will lead to the formation of various influence diagrams that represent the problem under focus. Detailed listing of the primary and secondary failures and faults found through this analysis is given as per Table 16.

Table 16 - Primary and secondary failures and faults found using Fault Tree analysis of the selected helicopter MGB oil system related accidents and incidents

S No.	Case	Description	Primary failures / faults	Secondary failures / faults	External qualifiers
1	C-GZCH	Total loss of MGB oil due to fracture of titanium studs securing the MBG oil filter bowl.	Galling of the titanium studs	Fracture of first stud.	Increased removal / installation cycles of studs. Improper pre-load installation of studs during maintenance. Increased cyclic loads on studs during flight.
				Fracture of second stud.	Increased load on the 2nd stud after failure of 1st one. Increased removal / installation cycles of studs. Improper pre-load installation of studs. Increased cyclic loads on studs during flight.
				Loss of MGB oil from oil filter bowl.	None
				Plastic collapse of teeth of the tail take-off pinion (to tail rotor shaft).	Continued MGB operation after loss of oil.
				Damage to two tapered roller bearings of the tail take-off pinion shaft.	Continued MGB operation after loss of oil.
				Loss of axial and radial constraints of the main rotor brake disk.	Continued MGB operation after loss of oil.
2	N355DU	Failed MGB oil pump	Oil pump idler gear seized.	Oil pump drive shaft separated (Overstressed in torsion) at mid span (Power to oil pump lost).	None
				Total loss of MGB oil pressure.	None
				High temperature overstress damage of teeth of the combining gearbox input gears (from engines).	• Continued MGB operation after loss of oil pressure.
				High temperature overstress damage of teeth of the combining gearbox intermediate gears.	• Continued MGB operation after loss of oil pressure.
				High temperature overstress damage of teeth of main drive gear (from the combining gearbox).	• Continued MGB operation after loss of oil pressure.
				MGB - Engine combining gearbox failed	• Continued MGB operation after loss of oil

				(Torque drive to MGB bevel gear driving main rotor head is significantly reduced)	pressure.
			Incorrect human input	MGB low oil pressure indicator bulb was removed before flight	Human individual error
				No oil pressure readings were provided to pilot (Manufacturer’s service bulletin to install a MGB oil pressure gauge was not implemented)	Human organizational error
3	C-FZQF	Normal flow of MGB oil obstructed due to incorrect positioning of input quill bearing housing	Incorrectly installed MGB input quill bearing	bearing housing rotated 90 degrees clockwise in relation to MGB oil input and output ports)	Multiple Human individual errors (maintainer + inspector)
				No oil flow to MGB input quill bearing (oil starvation).	None
				High temperature skewing failure of input quill bearings (bearing parts jam together when its cage fails).	Continued MGB operation with no oil flow to bearing.
				Sudden stoppage of main gearbox.	None
4	G-TAMA	Seizure of MGB pinion outer bearing due to oil starvation	Debris dropped into the MGB oil gallery	Oil gallery feeding the outer bearing of MGB input pinion was blocked	Multiple Human individual errors.
				No oil flow to MGB input pinion bearing (oil starvation)	None
				High temperature skewing failure of input pinion outer bearing (bearing parts jam together when its cage fails).	Continued MGB operation with no oil flow to bearing.
				Intermittent binding (Seizure) of the MGB input pinion outer bearing	None
				Intermittent stoppage of the MGB.	None
5	G-BXXW	Failure of MGB rear bearing due to	Low Quantity of MGB oil was	Poor lubrication of the rear MGB bearing	• Human individual error

		inadequate lubrication	available before flight start. Poor quality of MGB oil (heavy sludgy contaminated oil was available within system).	High temperature skewing failure of rear MGB bearing (bearing case broken)	Continued MGB operation with no oil flow to bearing.
				Rear MGB bearing seized (rollers jammed sideways)	None
				Output pinion shaft (from MGB) turning in the inner race of the seized rear bearing produced high temperature (650º C)	None
				Hardened skin of the pinion shaft was softened	None
				Slackness of shaft produced multiple fatigue cracks	None
				Fracture in torsion of the MGB pinion shaft (carrying power from MGB to tail drive shaft) at the rear end of the MGB	None
				Damage to the flexible coupling at the forward part of the tail drive shaft	None
6	G-REDL	Loss of MGB oil due to MGB case rupture	MGB outer case fracture	Loss of MGB oil pressure	Failed 2nd stage epicyclic planet gear- Non oil system failure Many external technical and human inputs
				Extensive leak (loss) of MGB oil	None
7	G-ASNL	Loss of MGB oil due to MGB case rupture	MGB input casing fracture	Loss of MGB oil pressure	Failed 1st stage of No. 1 spur gear - Non oil system failure Many external technical and human inputs
				Extensive leak (loss) of MGB oil	None
8	VH-LOH	Total loss of MGB oil due to fracture of titanium studs securing the MBG oil filter bowl.	Galling of the titanium studs	Fracture of first stud.	Stud was repaired just before the flight Increased removal / installation cycles of studs. Increased cyclic loads on studs during flight.
				Fracture of second stud.	Increased load on the 2nd stud after failure of 1st one.

					Increased removal / installation cycles of studs. Increased cyclic loads on studs during flight.
				Loss of MGB oil from oil filter bowl.	None
9	C-FHHD	Failure of the plain bearing in the main gearbox cover for the number 1 input pinion.	The plain bearing in the main gearbox cover for the number 1 input pinion failed	The bearing adjacent carbon seal broke down.	None
				Bearing lost lubrication (grease) , and disintegrated.	None
				Oil spray out from the MGB on to the pinion shaft	None
				The number 1 pinion rapidly overheated and weakened.	Continued MGB operation after loss of oil. Rotational imbalance due to bearing fracture.
				Local fire started within the area (base of transmission)	None
				Fracture of the No 1 pinion.	None
				Malfunction of the No. 1 free wheel unit,	None
10	C-GXYM	The input freewheel unit (IFWU) and drive shaft assembly failed.	Contamination suspended and trapped in the lubricating oil of the MGB input free wheel unit (IFWU)	Wear of internal parts of IFWU	Repeated heavy lift operations. Inadequate human input (maintenance)
				MGB IFWU failed.	None
				Failure of drive to MGB	None

3.3 Review of Various Approaches to MGB Reliability Assessment

A survey of literature has been carried out in the area of risk and reliability as applied to HELMGOP. Many significant accidents and incidents can be modelled by some form of graphical representation e.g. Fault tree analysis (FTA), Markov analysis. However, one of the challenges for MGB lubrication systems is that the event rates (frequencies) of the causal factors for failure are not easily quantified.

There follows a review of modelling techniques that hold promise for the task at hand. It must be stated that these are aimed at all sources of aviation risk, including operations, human factors, and ATC as well as technical failures. However, the techniques used can be employed for HELMGOP when it comes to representing the reliability of a MGB lubrication system, and the factors that influence the run-dry time. This will be discussed later.

3.3.1 Aviation Safety Risk model

One very useful approach has been proposed by **(Luxhøj 2003)** who has developed the Aviation Safety Risk Model (ASRM). This makes use of the Human Factors Analysis & Classification System (HFACS) proposed by **(Wiegmann and Shappell 2003)**. HFACS is a classification scheme which has been developed to capture and analyse the different types of human error that occur. The framework draws on the work of Reason**,** who developed the so-called "Swiss-cheese" model of accident causation **(Reason 1990)**. ASRM was originally developed for use by US Naval Aviation, but has since been used more widely within the aviation industry.

The ASRM uses Bayesian Belief Networks to model the uncertainty within the model, using either data or the opinion of "experts". The network is created to represent the dependencies between the different factors identified by applying HFACS. Data has been obtained by examining case studies of accidents, e.g. Air Ontario Flight 1363 **(Luxhøj 2003).** The steps followed are given below, and as listed the technique is aimed at assessing the impact of technology "insertions":

i. Select and analyse a real accident case
ii. Identify the case-based causal factors
iii. Construct an influence diagram depicting causal factor interactions
iv. Build a Bayesian Belief Network (BBN)
v. Insert technologies/interventions
vi. Evaluate the relative risk associated with the insertions.

This technique has only been applied to limited accident scenarios. However, models are being created using the extensive HFACS database.

3.3.2 Eurocontrol Integrated Risk Picture

The Integrated Risk Picture is a major work by Eurocontrol which has been used in the development of the Single European Sky (SES). As the aim of the latter is to enable a greater number of aircraft to fly in Europe, a number of new technologies may be adopted – the role of the IRP is to assess any change to overall risk from these developments.

The two major steps taken in the IRP were to first define the system / operation, and then carry out the risk assessment. This used a Top-down approach which was calibrated against accident and incidents experience, and based on five main ATM-influenced accident categories. The Fault tree approach was used as it was decided that this was widely understood and allowed for a combination of multiple causes to be represented.

The concept behind the IRP process to make a 'Top-down assessment' based on analysis of historical accident sequences and analysis of causal factors. In this way it was possible to estimate base event probabilities from actual frequencies. This gave a so-called baseline to represent the safety state in 2005. The second stage was then to carry out a Predictive (bottom-up) analysis to try to predict the future state, based on forthcoming changes to the ATM framework.

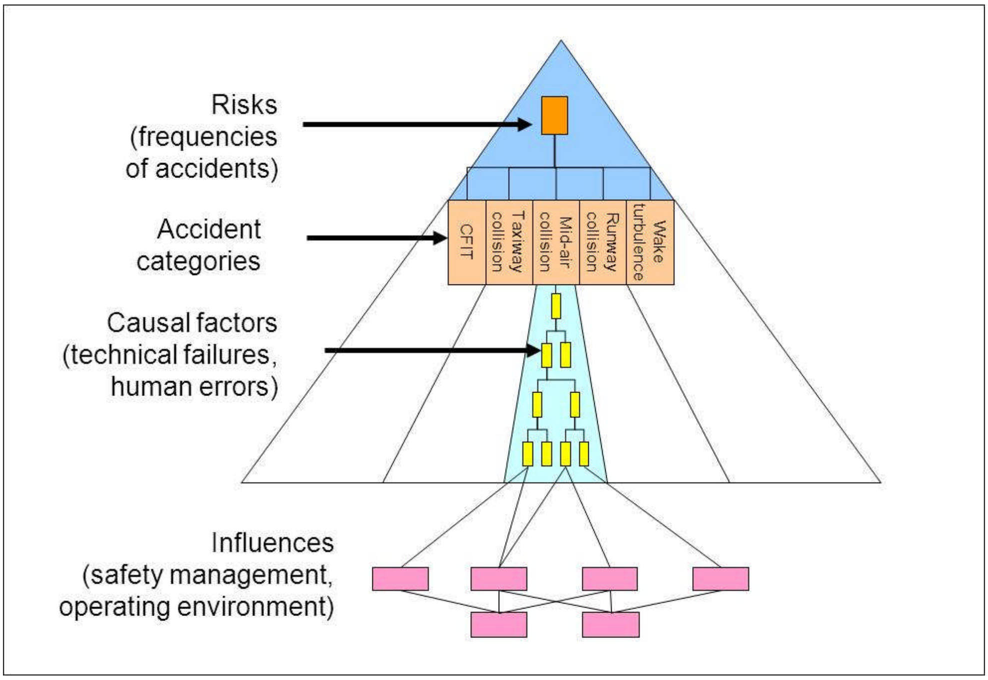

Figure 14 - Overall ATM Risk Model Structure (Eurocontrol, 2005)

An Influence model is then used to make modifications to the base events. The hierarchy of influences can then be adapted to represent common-causes which can affect more than one base event. Compared with the SINTEF approach, the IRP model has four Influence levels rather than three **(Herrera et al. 2010).** These are operational, technical, managerial, and regulatory (Eurocontrol. 2005). Figure 15 gives a view of how different influences may affect the value in the base event of a fault tree.

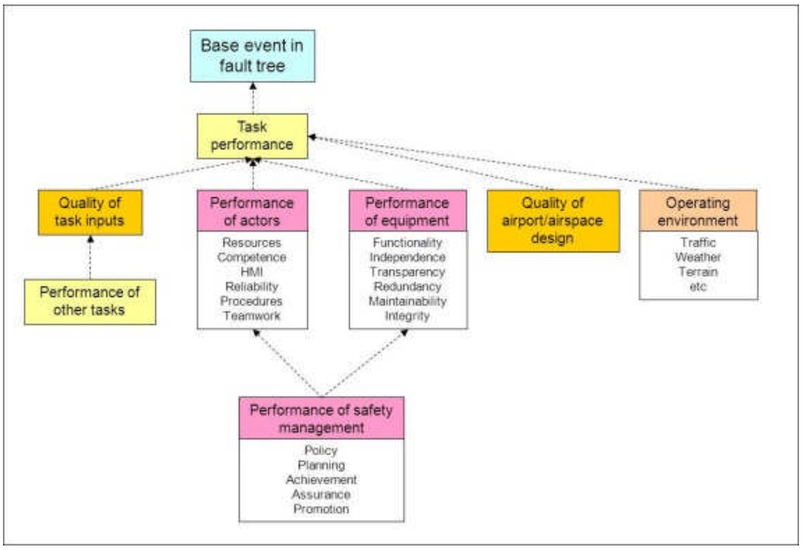

Figure 15 - Generic influence model (Eurocontrol, 2006)

3.3.3 Causal Model for Air Transport Safety

Of significant interest is also the Causal Model for Air Transport Safety (CATS) developed at TU Delft (**Ale et al, 2008)**. This appears to feature many aspects that are similar to those described above. The basic parts of the CATS model are shown in Figure 16, where it can be seen that three elements are used. A Bayesian Belief Network is used to as an Influence diagram, which affects the events used in the Fault Tree above. The FT then feeds in to an Event sequence Diagram (ESD), which is similar in concept to an Event Tree Analysis (ETA).

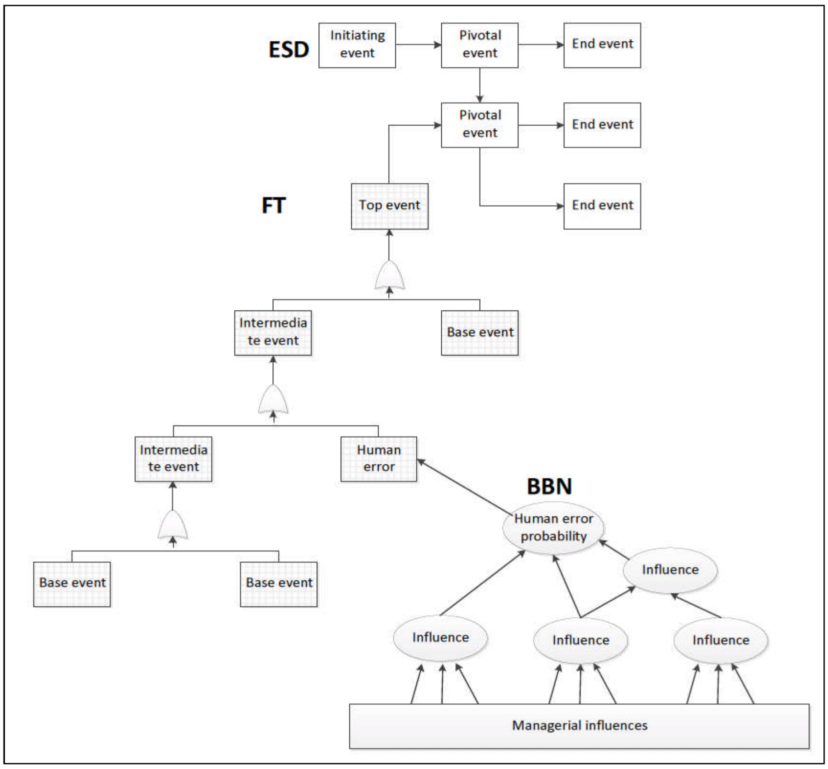

Figure 16 - Basic constituents of the Causal Model for Air Transport Safety (CATS) (Ale et al 2008, Lin 2011)

3.3.4 Generic MGB Oil System reliability assessment using Influence Diagrams

As discussed before, the Influence diagram concept can be used to supplement the traditional Fault or Event Tree. Analysis of causal factors will often allow a Fault tree model to be produced in so far as the data exist to allow this to done. However, many management, organisation and cultural factors cannot be clearly included as "events". The same can also be said for many physical degradation processes which affect systems (including gearboxes) e.g. wear, corrosion and fatigue. The actual failure itself may be an "event", but there is a whole process that leads up to it, with many different influences.

Similarly as reported before, a generic model of accident causation was proposed by (Embrey 1992) which showed a combination of Event and Likelihood/Influences layers. This was entitled a Model of Accident Causation using Hierarchical Influence Network Elicitation (MACHINE), and features two distinct layers, namely Event layer and Likelihood (Influence) layer, hence the term *Event-likelihood model* (Kumamoto and Henley 1996).

This technique was refined and adopted in the Helicopter Safety Studies performed by the Norwegian Industrial management organisation, SINTEF. The work was originally published in two reports entitled "Helicopter Safety Study"; HSS-1 was based on work carried out in 1989/1990, followed by HSS-2 (Hokstad et al, 1999). A further update is also available in HSS-3 (Herrera et al. 2010) which studied the effect of adopting measures recommended by HSS-2 plus new initiatives such as Safety Management Systems (SMS).

The work focused on North Sea helicopter accidents and incidents over a given time period in order to calculate the risk in terms of fatalities per million person flight hours. This was achievable due to the recording of flight hours and personnel carried by the North Sea operators. The work studied the factors that influence risk in terms of Frequency (e.g. Operations Procedures, Air Traffic & Navigational services) and Consequence (e.g. Impact absorption upon hard landings, Stability on sea).

These factors are termed Risk Influencing Factors (RIFs), defined as a group or set of factors/ conditions that influence the risk. Note that a RIF is NOT an event. These were used at 3 levels within the influence network, namely, operational, organisational, and regulatory and customer related. See Figure 17. Estimated values for the respective importance of each RIF were elicited by means of a series of expert panels, which then allowed the RIFs with the largest impact on overall risk to be identified. Data for the models is also obtained from:

i. Accident and incident reports / Deviation reports
ii. Expert judgements and workshops (SME)
iii. Questionnaires / Management interviews
iv. Inquiries/reviews

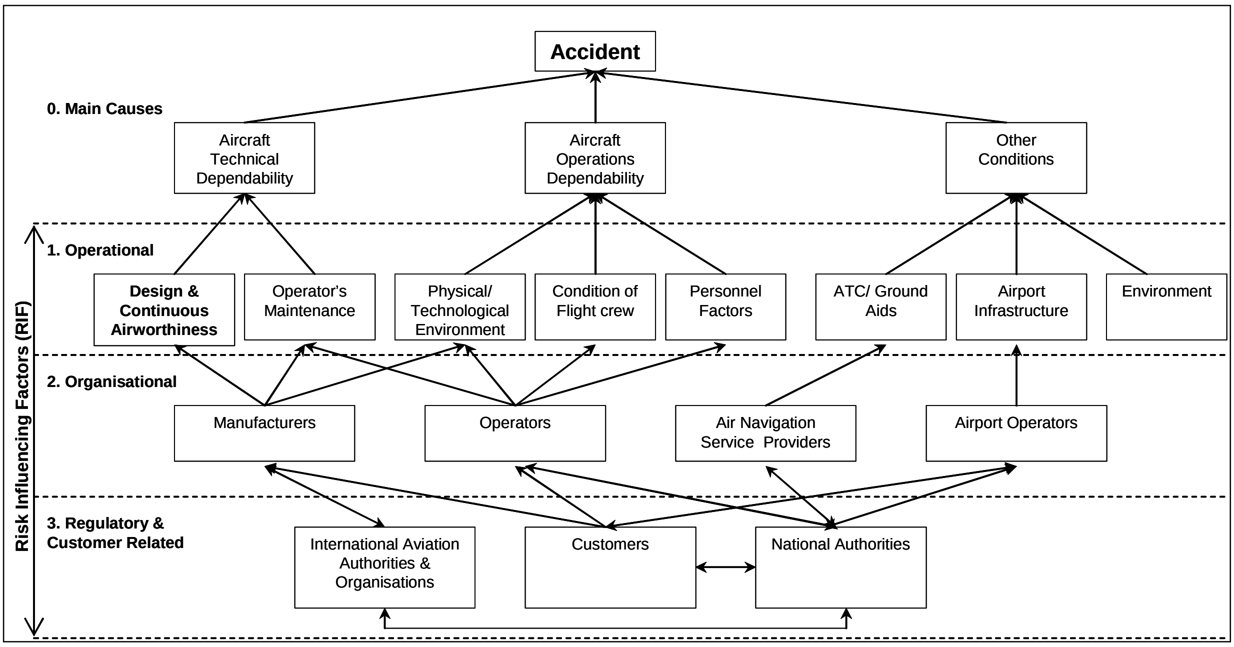

Figure 17 - Influence Diagram for frequency (Hokstad et al. 1999)

Work to formulate a similar influence diagram for the HELMGOP project has been carried out as a key task. This model is described in detail in Section 4.2 and has been used to evaluate the effect of different design and maintenance factors on the overall performance of the MGB. The notation adopted for HSS is as follows, where Risk Influencing Factor "RIF **x.y"** means RIF number y at level x, where the value of x is 1 for Operational RIFs, 2 for Organisational RIFs and 3 for Regulatory & customer related RIFs. The other terms used are:

- Status of RIF **x.y** = Status (**x.y)**
  = Probability that a deviation caused by RIF **x.y** has occurred during 1 flight hour i.e. probability that the RIF has bad state.
- Weight (strength) of RIF **x.y** = W_j **(x.y)**
  = Probability that an accident j occurs, given that RIF **x.y** has caused a deviation (i.e. RIF has a bad state).
- Contribution of RIF **x.y** to accident type (j), Contrib_j **(x.y)** = W_j (**x.y) x** Status (**x.y)**
  = Probability that accident type (j) caused by RIF **x.y** occurs during 1 flight hour.

The HSS project used a total of eight Incident/Accident (I/A) categories, listed for j = 1 to 8 with examples being incidents/accidents on landing or take-off, critical system failure, mid-air collision, collision with terrain. Hence the risk is comprised of two parts:

f_j = f(I/A j) = Frequency for Incident / Accident category j, for j = 1 to 8

$\mathbf{C}_j$ = C(I/A j) = Consequence for Incident / Accident category j, for j = 1 to 8

The overall risk is quantified as R = f x C, where f is the accident frequency and C is the consequence. Therefore the total risk is calculated as: $R = \sum_{j=1}^{8} f_j . C_j$

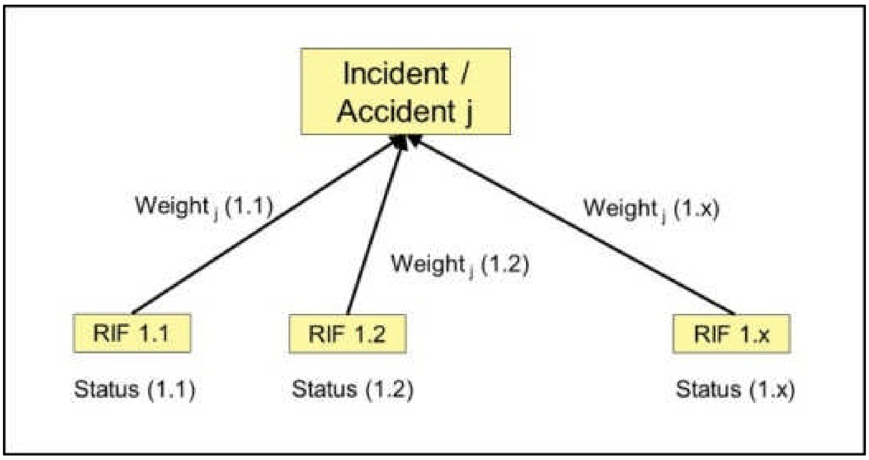

Figure 18 - Weights and status of RIFs (Hokstad et al. 1999)

3.4 Applying the Influence Diagram Approach to HELMGOP

Work to formulate similar influence diagrams for the HELMGOP project has been carried out and is reported in Section 4.2. Using accumulated data, and fault/ failure information regarding the MGB oil system malfunction (as per output from all previous activities already accomplished in HELMGOP project), an overall influence diagram approach is adopted to resemble the two possible remedies for the HELMGOP optimization problem, namely, the loss of oil prevention enhancement *(prevention)* and the MGB run dry capability enhancement *(mitigation)*. This is generically illustrated as per Figure 19.

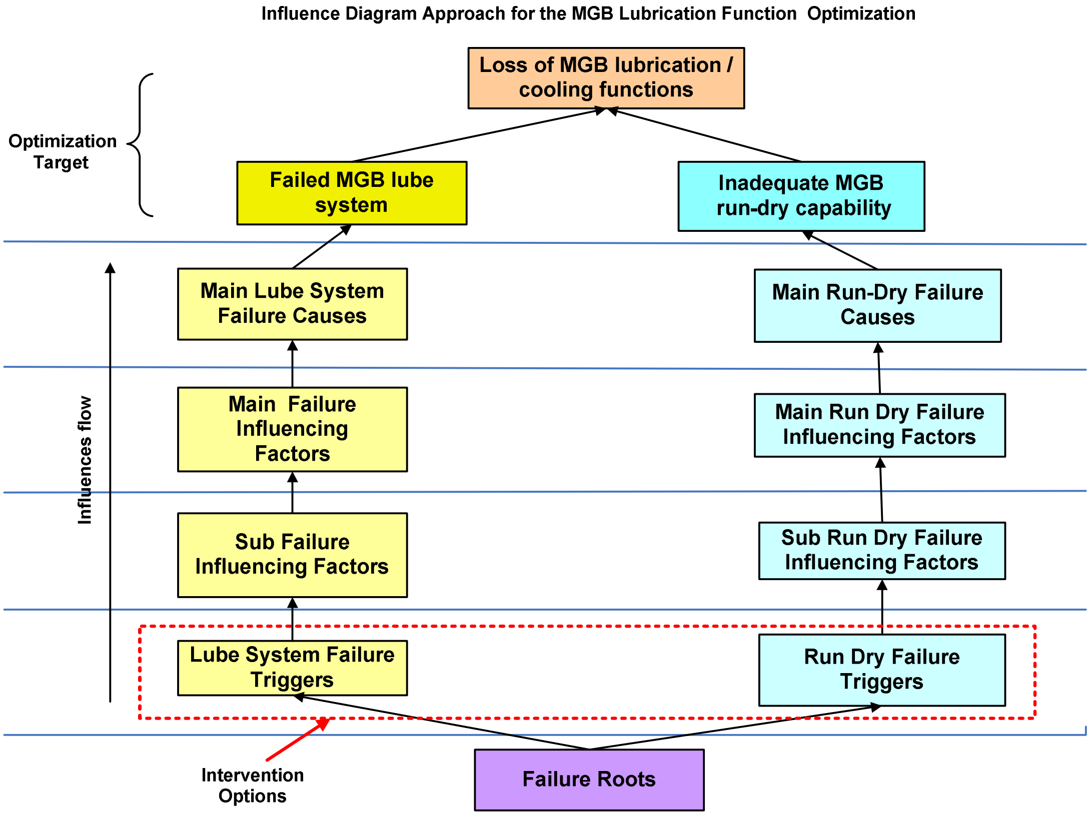

Figure 19 - Generic influence diagram approach for HELMGOP optimization problem

Table 17 lists all possible intervention techniques that can be considered for MGB oil loss optimization target. The listed intervention options are in fact direct manifestation of the "triggers influences" or risk influencing sub-factors as will be discussed later in Section 4.2. Influence diagram approach is utilized along activities of first tasks of this research to help focus the orientation of later tasks.

Table 17 - The overall possible intervention options of HELMGOP

Optimization Area	Main Failures Areas	Intervention Options
Lubrication System Reliability Enhancement	Oil Quality Oil Quantity Oil Flow Pressure	SRK errors / Memory errors (Human) Design for maintenance Internal oil pockets / Pools Oil absorbent materials Auxiliary non pressurized oil dropping source Auxiliary oil-air mist Auxiliary pressurized oil system Oil system re-configuration Material modification Prevention of Internal parts failures. External input prevention
MGB Run-Dry Capability Enhancement	MGB Components MGB Manufacturing	Parts heat expansion clearance enhancement MGB heat dissipation capacity enhancement Parts mechanical strength enhancement Material heat resistance enhancement Material wear resistance enhancement Material self-lubrication property enhancement Advanced parts machining Parts coating Parts super-finishing Parts chemical treatments Manufacturing procedures enhancement (including human input)

3.5 Reliability Review of Sample MGB Designs

This section presents the review carried out on oil-based lubrication systems in helicopters and it is carried as part of the HELMGOP project to improve helicopter gearbox run-dry situations. This has significant impact on safety as lubrication and cooling contributions up to 31% of transmission related accidents (Astridge D G 1992). In this report, a review is carried out on the designs from the Type A, Type B and Type C helicopters. The objective is to identify commonality and strength in designs between different helicopters and to understand how these designs affects the reliability of gearboxes for safe operation. In addition, a comparison of airworthiness requirements between civil and military helicopters is carried out.

The scope of the review is outlined as follows:

v. Basic lubrication system description and design
vi. Key lubrication system failure modes
vii. Reliability Assessment for Type A, Type B and Type C lubrication system
viii. Comparison of airworthiness requirements for helicopter lubrication systems

3.5.1 Basic helicopter lubrication system description and design

The function of a lubrication system is to lubricate and cool the transmission bearings and gears. However, the design of a lubrication system can vary widely across different applications and industries. For helicopter lubrication systems, schematic diagrams in the maintenance manuals for the Type A, Type B and Type C helicopters have been reviewed. The common lubrication system components and their functions are shown in **Appendix B**. In all of the designs, a pump driven by the helicopter's accessory gearbox provides the pressure head to distribute the oil from the sump to the oil gallery. Common safety measures include oil filters, metallic chip detection, oil temperature and pressure sensors. The layout of a basic lubrication system without redundancies is shown in **Appendix B**. The difference in design between helicopters depends largely on the layout and redundancies of these common components.

3.5.2 Key lubrication system failure modes

From the basic lubrication design, a Failure Mode & Effect Analysis (FMEA) is carried out to identify the key failure modes. The FMEA worksheet is shown in **Appendix B** and the key failure modes that contribute to run dry situations are the complete loss of oil and complete loss of oil pressure. The key components that can contribute to these failures are the oil sump, oil passageway, oil pumps, oil filters and the oil filter bypass. In addition to the FMEA, a literature review of lubrication system related accidents was carried out and summarized in Table 16 of Section 3.2 of this report. From the 10 incidents reviewed, the most frequent failure mode of lubrication system was loss of oil pressure due to contaminants/debris in the lubricant (3 cases) and pump failure (2 cases). This is followed by loss of lubrication oil caused by fracture of the oil sump (2 cases) or fracture of related structure (2 cases). These findings are consistent with the results from the FMEA.

3.5.3 Type A, Type B and Type C lubrication system reliability

With the functional description of a lubrication system and its key failure modes, a reliability assessment is carried out for the 3 helicopter types. This assessment considers (1) complete loss of oil and (2) complete loss of oil pressure as these are the only failure modes that contribute to run-dry situations. The Reliability Block Diagram (RBD) method is employed in the assessment and is guided by (BS EN 61078). Due to limited data, a set of MTBF for the components are assumed across the helicopters for comparative purpose.

The assumed MTBF are broadly estimated from the Type A maintenance data as shown in Table 18. For structural significant items (SSI) such as oil sump and oil passageway, a MTBF of 10,000FH is assumed. For system components such as oil pump and oil filters, a MTBF of 2,000FH is assumed. A lower MTBF is assumed for the latter as they are typically replaceable if defective compared to the SSI which typically has to be discarded.

Table 18 - Type A oil system fault Data

System faults	Type A MTBF[1]
Loss of oil (including leakages)	9600FH
Lubrication component fault	1300FH
Oil system cooling fault	13200FH
Emergency Lubrication System fault	47800FH

3.5.3.1 Type A Lubrication System

From the Maintenance Manual, the lubrication system consists of a single oil sump, two oil pumps and a single oil cooler. It also features an emergency lubrication system consisting of an independent oil sump and emergency pump and this system bypasses the oil cooler. The system layout is shown in Figures D1 and D2 in **Appendix D**. The RBD for loss of oil and loss of oil pressure are shown in Figures D3 and D4 respectively.

3.5.3.2 Type B Lubrication System

From the Maintenance Manual, the lubrication system consists of a single oil sump, an oil pump and a single oil cooler. It features a single emergency pump that activates upon low oil pressure in the main oil pump. The system layout is shown in Figures D5 and D6 in **Appendix D**. The RBD for loss of oil and loss of oil pressure are shown in Figures D7 and D8 respectively.

3.5.3.3 Type C Lubrication System

From the Maintenance Manual, the Type C lubrication system consists of a dual redundancy system with each system consisting of an oil sump, an oil pump and oil cooler. The system layout is shown in Figures D9 and D10 in **Appendix D**. The RBD for loss of oil and loss of oil pressure are shown in Figures D11 and D12 respectively. Notably, the Type C features a unique safety measure where 'wicks' are located at key gears and bearing locations. These wicks retain oil during a run-dry situation and continue to lubricate components through capillary action. Although this does not improve the reliability of oil and oil pressure loss, it does improve the run-dry capability of the transmission significantly.

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[1] Courtesy of Royal Air Force

3.5.4 Design Comparison

A summary of the probability of failure for both failure modes for the 3 helicopters types is shown in Table 20. From the review of the 3 helicopter lubrication systems, it can be observed that the design can vary widely although the key components are similar. The Type A, with dual redundancies in oil sump and triple redundancies in oil pumps performed only marginally better than the Type C with dual redundancies. For the Type B, the risk of oil pressure loss is marginally lower than both the Type A and Type C. This suggests that a redundancy at the component level is comparably more effective to building redundancy for the entire oil system.

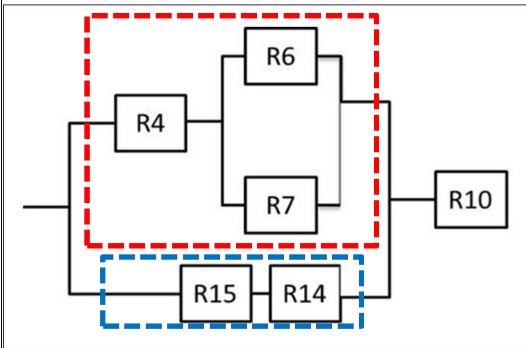
Table 19 - Summary of the probability of failure for both failure modes for the 3 helicopters types

Prob. of occurrence at time of 5 hours	Basic	Type A	Type B	Type C
Loss of Oil	9.995E-04	5.001E-04	9.995E-04	5.001E-04
Loss of Oil Pressure	3.005E-03	5E-04	5.124E-04	5.061E-04

4 GENERIC APPROACHES TO MGB LUBRICATION SYSTEM RELIABILITY ANALYSIS (Task 2B)

4.1 MGB Lubrication System Reliability Assessment Using Monte Carlo Techniques

The Monte Carlo Simulation technique (MCS) is used, within the second task of HELMGOP, to study the overall reliability of the MGB lubrication system. The technique can be applied where there is uncertainty in the failure rates for the components of a given multi-component system. Detailed description of the technique concept and mathematics is given in **Appendix E**. The reliability block diagram for the Type B helicopter (see Figure D.8 in **Appendix D**) was used as an example for this MCS process. The reliability block diagram for "Loss of oil pressure" in the system is represented in Figure 20. The usual way to assess reliability would be to apply Boolean logic, which would end with an equation below for the system reliability R_{sys}.



	Components	MTBF (hrs)
R4	Oil Pump	2000
R6	Oil Filter	2000
R7	Oil Filter Bypass	2000
R10	Oil Passageway	10000
R14	Emergency Pump	2000
R15	Low Oil Pressure Switch	2000

$$R_{sys} = R10 \text{ x } \left[1-\{[1-R4(1-(1-R6)(1-R7))].[1-R14.R15]\}\right]$$

Figure 20 - Type B RBD and test values for Loss of Oil Pressure

Using the above values of MTBF, the probability of oil pressure loss could be plotted as in Figure 21. This is helpful in showing how failure probability varies with time, and such charts are often used when setting a maintenance or inspection interval for example. However, as part of the HELMGOP study, it was decided that it would be useful to study alternative ways to account for the variability in the failure rates of components. It would also be possible to represent human factors errors in maintenance as well in the future. The MCS technique applied here is to calculate a Time to failure (TTF) for each component individually and then (based on the RBD logic) derive the time to failure of the system as a whole. The TTF is based on a failure rate that assumes an exponential distribution of times to failure. In summary, the steps are applied in the following manner:

i. Generate random numbers
ii. Calculate time to failure for each component
iii. From this, determine time for *system* to fail
iv. Repeat steps 1 to 3 for 'n' simulations

v. Plot the results as a histogram to show reliability

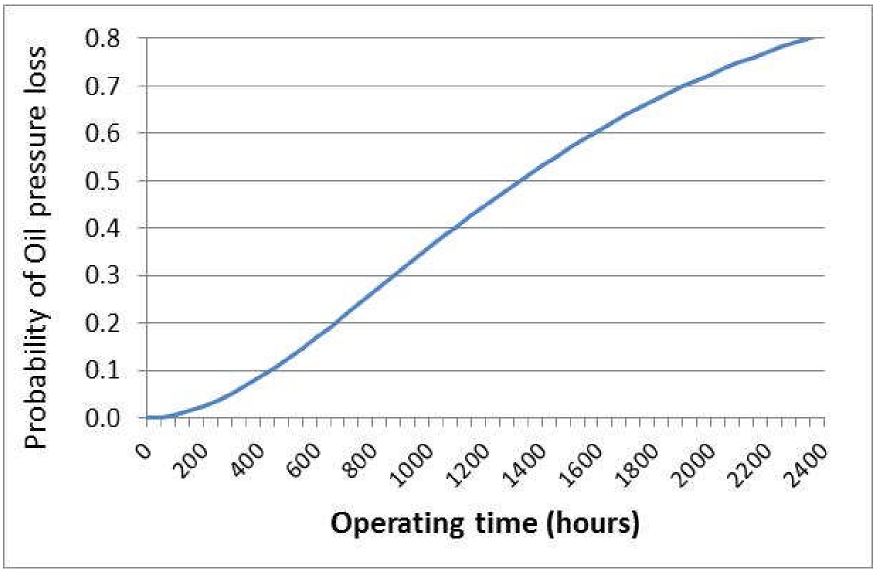


Figure 21 - Probability of oil pressure loss vs. operating time

Step 3 is based on the system logic, as shown in Figure 25. Due to redundancy between R6 and R7, the parallel network will fail at the *greater* of the two TTF values R6, R7 (T_{67}). This value is then compared with the TTF of the oil pump. If T_4 is less than T_{67}, then the TTF of the upper branch is T_4, otherwise T_{67} is used. The TTF for the Emergency pump (R14) and the Low oil pressure switch (R15) are then compared. As they are in series, the lower of the TTF values will determine which has failed first.

The next step is to compare the lower of [T_{14}, T_{15}] with the lower of [T_4, T_{67}]. This will then determine **T'**, the TTF for the parallel network in Figure 25. Finally the predicted TTF for the Oil passageway R10 should be compared. This is in effect a "single point failure", so if T10 is lower than **T',** then T_{10} is the system failure time. If **T'** is lower than T_{10}, then the former is the system failure time. It is the system failure time that is recorded in Step 3 above, and the experiemnt repeated in order to obtain a probability distribution of results. The values for MTBF are varied during the test in a limited manner, as in Figures 22 to 24. Greater use of the technique would involve using probability distribution rather than discrete values for each test.

Figure 22 shows the results from the first series of MCS tests. This uses fixed values of R10, R14 and R15 (as per Figure 20), with the values of R4, R6 and R7 varied from MTBF values 1400 hrs to 2400 hrs. As expected the left hand curve represents the most "unreliable" case for the system, where the Oil pump, filter and filter bypass all have MTBF of 1400 hrs. In this case, the probability of oil pressure loss is 26% at the 800 hour point, and the probability reaches 50% at approximately 1350 hours. If the MTBF figure increases to 2400 hours, the corresponding results are:

i. Probability of oil pressure loss 20% at 800 hour point
ii. Probability of oil pressure loss 50% at 1750 hour point

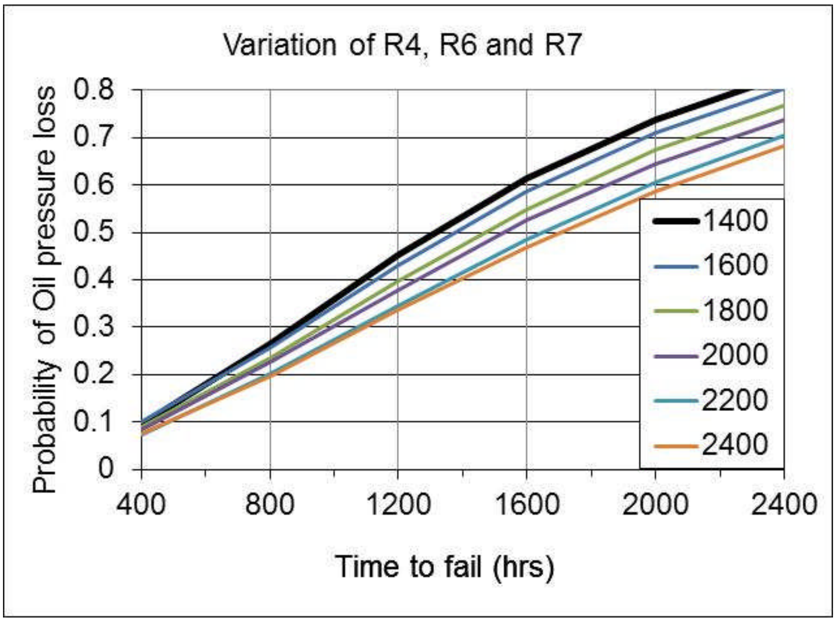


Figure 22 - Results from MCS; R10, R14, R15 fixed; R4, R6, R7 variable

The next series of tests (Figure 23) was to vary the MTBF for the Oil passageway between values of 8000 and 12000 hours. The probability of oil pressure loss is 23% at the 800 hour point (MTBF of R10 = 8000 hrs), and reaches 50% at approximately 1500 hours. If the Oil passageway MTBF increases to 12000 hours, the corresponding results are:

i. Probability of oil pressure loss 22% at 800 hour point
ii. Probability of oil pressure loss 50% at 1550 hour point

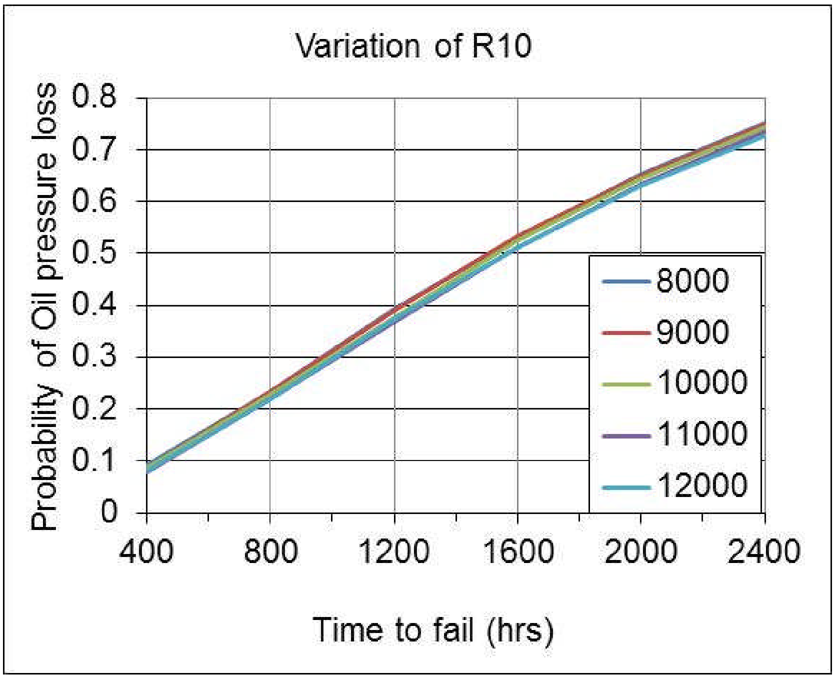


Figure 23 – Results from MCS; R4, R6, R7, R14, R15 fixed; R10 variable

As can be seen there is far less variability in the results. This is due to the high MTBF value used for this component. The way the logic diagram is shown in Figure 20, and the values used for the other components, mean that the system rarely fails due to R10. Therefore changing the MTBF value does not have a significant effect on the overall results.

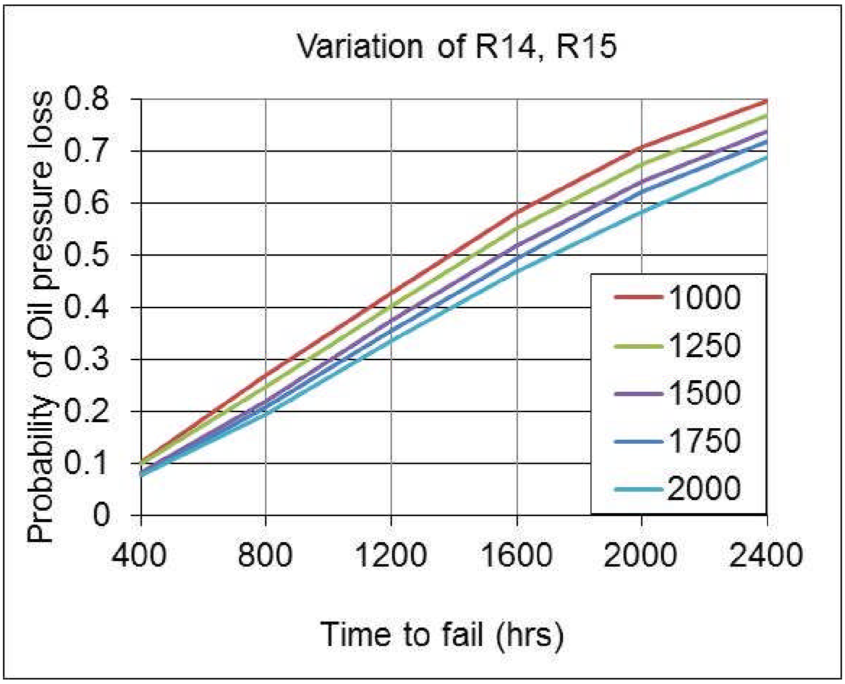


Figure 24 – Results from MCS; R4, R6, R7, R10 fixed; R14, R15 variable

The final set of results is based on variation in the MTBF values for R14 and R15, the Emergency pump (R14) and the Low oil pressure switch. These are varied between 1000 and 2000 hours, as shown in Figure 24. The probability of oil pressure loss is 27% at the 800 hour point (MTBF of R14 and R15 = 1000 hrs), and reaches 50% at approximately 1400 hours. If the MTBF values are increased to 2000 hours, the corresponding results are:

i. Probability of oil pressure loss 19% at 800 hour point
ii. Probability of oil pressure loss 50% at 1700 hour point

The variability in the results is similar to that seen in Figure 22, and show how the overall system reliability varies with time, according to the input parameters. Such a method is as part of a sensitivity analysis of the lubrication system, to determine key vulnerabilities and inter-dependencies. Instead of just one curve to represent the probability of failure (Figure 21), a whole family of curves can be used.

4.2 Component-Based Functional Analysis of MGB Lubrication System Reliability

4.2.1 Failure types of Helicopter MGB lubrication system

The pressurised lubrication system of helicopter MGB is crucial multi-component structure that provide for the good health and adequate operation of the MGB. This is generally secured through three interlinked functions:

a. Lubrication of moving components of the MGB.
b. Dissipation of heat produced due to friction between moving parts.
c. Provision of adequate lubrication system operation monitoring.

Accordingly, for the purposes of this study, a failure of the MGB lubrication system is considered to have occurred if at least one of these three functions failed, at any interval of time during the MGB operation, to be adequately provided by the lubrication system.

These three functions, individually or collectively, can fail to be adequately provided by the MGB lubrication system if one or more of four different types of failures occurred. These are the four main failure types of the MGB lubrication system that can be listed as:

i. Inadequate quality of the MGB lubrication system oil.
ii. Inadequate quantity of the MGB lubrication system oil.
iii. Inadequate pressure value of the MGB lubrication system oil flow.
iv. Failure of the facility for providing monitoring, caution, or warning information regarding the MGB lubrication system operation.

The functionality of the MGB lubrication system is influenced by these failures as listed by the following Table 20:

Table 20 - MGB Lubrication system main failure and corresponding functions

Main Failure Type	Threatened MGB Oil System Functions
Inadequate oil quality	Functions (a) and (b)
Inadequate oil quantity	Functions (a), (b), and (c)
Inadequate oil pressure	Functions (a) and (b)
Failed monitoring / alarm provision	Function (c)

It is difficult most of the time to set definite exact weights of the impacts induced by each type of failure on each of the MGB functions. This is due to the complex nature of the mechanisms through which there failure type initiate and propagate. For instance a single event of oil loss from the lubrication system can trigger almost all of the four types of failure to various extends, consequently it is unfeasible to exactly indicate the failure that is separately responsible for the failure of any of the three main MGB functions.

4.2.2 The need to analyse at the level of individual components of MGB lubrication system

Continuing with the single oil leak event highlighted above, such leak can occur due to failures of oil lines, fittings, seal plugs, gaskets, valves, external pumps, oil filters, oil coolers, accessory pads, the MGB case, and others parts of lubrication system. Oil leaks out of the system will thus depend, in their quantity and speed, on the position, structure, and functional characteristics of each one of these parts. It thus again unfeasible to exactly tell what lubrication system function will, or will not, be influenced by each type of leak from any of these parts. Other events than the oil leak can also take place such as pump failure, filter clogging, sensor / transmitter fault, or indicator bulb failure. It can thus be concluded that determining an exact reliability feature/ number of the helicopter MGB lubrication system when taken as a whole is unfeasible if not impossible. An alternate approach will be the one that assesses the reliability of the whole system by firstly analysing the reliability-related behaviour of each component individually to determine its influence on the whole system when all other parts' influences are isolated.

Two other vital inputs to the reliability of the MGB lubrication system are the influences of the human maintainers/ operators, and the role of the surrounding maintenance procedures involved. Consequently, the MGB lubrication system adequate operation is a product of complex interrelated influences of technical, human, and organizational inputs. These inputs are all considered as influencing factors on the reliability of the MGB lubrication system.

4.2.3 The Influence Diagram approach: Suitability for the current problem

As indicated before, the influence diagram (ID) approach is a new technique that is recently introduced to tackle multi-dimensional complex problems which involve internal mutual interference of multi factors that collectively produce a single overall event. The ID technique works to bridge between qualitative description of complex technical problems, and their quantitative specifications. This approach is powerful since it "can serve the three levels of specification of relation, function, and number" (Embrey 1992) of involved factors, and it works in both deterministic and probabilistic cases.

Because of its generality, the ID is an important tool for decision analysis and for formal description of relationships between factors jointly forming the problem at hand. More details on ID models are available in recent literature (Embrey 1992, Krakenes et al. 2009, Howard and Matheson 2005, Hokstad et al. 1999, 2001, Herrera et al 2010). For the purposes of this study, an ID model is introduced that describes the interrelationships between the four MGB lubrication system failure types and list their detailed main and sub-influencing factors. The model targets the assessment of the overall reliability of the MGB lubrication system, and the influence of each of these factors on that overall reliability.

4.2.4 The need of a generic model of analysis

The MGB lubrication system designs of various helicopter types are different in components layouts, structures, redundancies, and detailed performance specifications, although they all work to ensure adequate fulfilment of the main three functions of a lubrication system. This variation in designs dictates that a generic model is to be built that can accommodate all the differences between designs, and yet provides for specific focussed analysis for each component , or group of components, in terms of reliability and risk initiation probabilities. This study introduces such a generic ID component-based model.

4.2.5 Aim of applying the ID approach within HELMGOP

The aim of this part of the HELMGOP study is to introduce a generic model, based on authenticated evidence that can be used to evaluate unconditional probabilities of success and failure of the helicopter MGB lubrication system at a given set of inputs. A failure is considered to have occurred if any of the sub factors (as will be explained later) failed, at any given time during the MGB lubrication system operation, to exist (or not exist) or function (or not function) in accordance with design specification

4.2.6 Data sources for ID analysis model

The MGB lubrication system ID model is constructed referring to data and case studies from various resources, these included:

i. Relevant helicopter MGB's design specifications and architecture, with emphasize on lubrication system components.
ii. MGB lubrication system related formal accident reports.
iii. Findings of relevant accidents analyses using fault tree technique.
iv. Published literature on MGB lubrication system designs, structures, and failure modes.
v. Published literature on gearbox lubrication and gear failure diagnostics and prognostics.
vi. Industry consultation and experts opinions.
vii. Other sources.

4.2.7 Description of the ID model for helicopter MGB lubrication system reliability analysis

The ID model for helicopter MGB lubrication system function failure analysis is given in Figure 25. The figure consists of the 'MGB lubrication system functions failure' as the main event that is triggered by the occurrence of any, or all, of the 4 main failure types of the lubrication system. Going deeper in analysis, a total of 10 main influencing factors (main causes of risk to the adequate functioning of lubrication system) directly impact (collectively, in groups, or individually) on the occurrence (or non-occurrence) of any, or all, of the 4 main failure types above. Further down, a total of 15 sub-influencing factors are given. These are the utmost direct triggers of failures. This level generally lists the overall components of the MGB lubrication system, in addition to the influences of human individual and organizational behaviour. A failure of each, or any, of these sub-factors will definitely represent a cause of risk to the MGB lubrication system adequate functioning.

It can be noted that not all of the 15 sub-influential factors are of pure technical nature as parts of the lubrication system physical structure. In fact the first one of these is the influence of the organizational input to the system, namely the maintenance procedures adopted for a given MGB lubrication system. This is a critical input to the integrity of the system and to its adequate operation through both scheduled and reactive maintenance activities. Another external input to the MGB lubrication system reliability is the human activities carried on the system during maintenance or operation (e.g. walk-around checks errors). The evidence collected shows that both of these sub-influential inputs play a significant role in securing the required MGB lubrication system reliability. It should be considered here that the notion of 'sub-factor' does not imply that their influence is limited, or is of lesser importance to the overall reliability question. In the contrary, these 15 sub-factors are the actual events that can go wrong (by occurring or not occurring) thus triggering risks to the system. The ideal case of 100% MGB lubrication system reliability rating can be achieved *ONLY* if *ALL* of these 15 sub factors are 100% non-existent as causes of risk to the system (again by occurring or not occurring as events).

4.2.8 Model Justification

The ID model is composed of two constituents as described below:

1. Events

   These are the events represented collectively by the main reliability problem of the model (lubrication system failure), main failures, and main and sub influential factors. Each of these events is weighted for existence / occurrence with a given probabilistic value.
2. Influences

   These are connecters expressing the influential relations in which sub-factors influence main factors, main factors influence main failures, and those influence the overall system failure probability. Occurrence of any sub-factor will automatically trigger occurrence of, at least, one related main factor, and this will directly influence the upper levels of the model.

Referring to Figure 25, the construction of events and the presentation of their interlinking influences can be justified as follows:

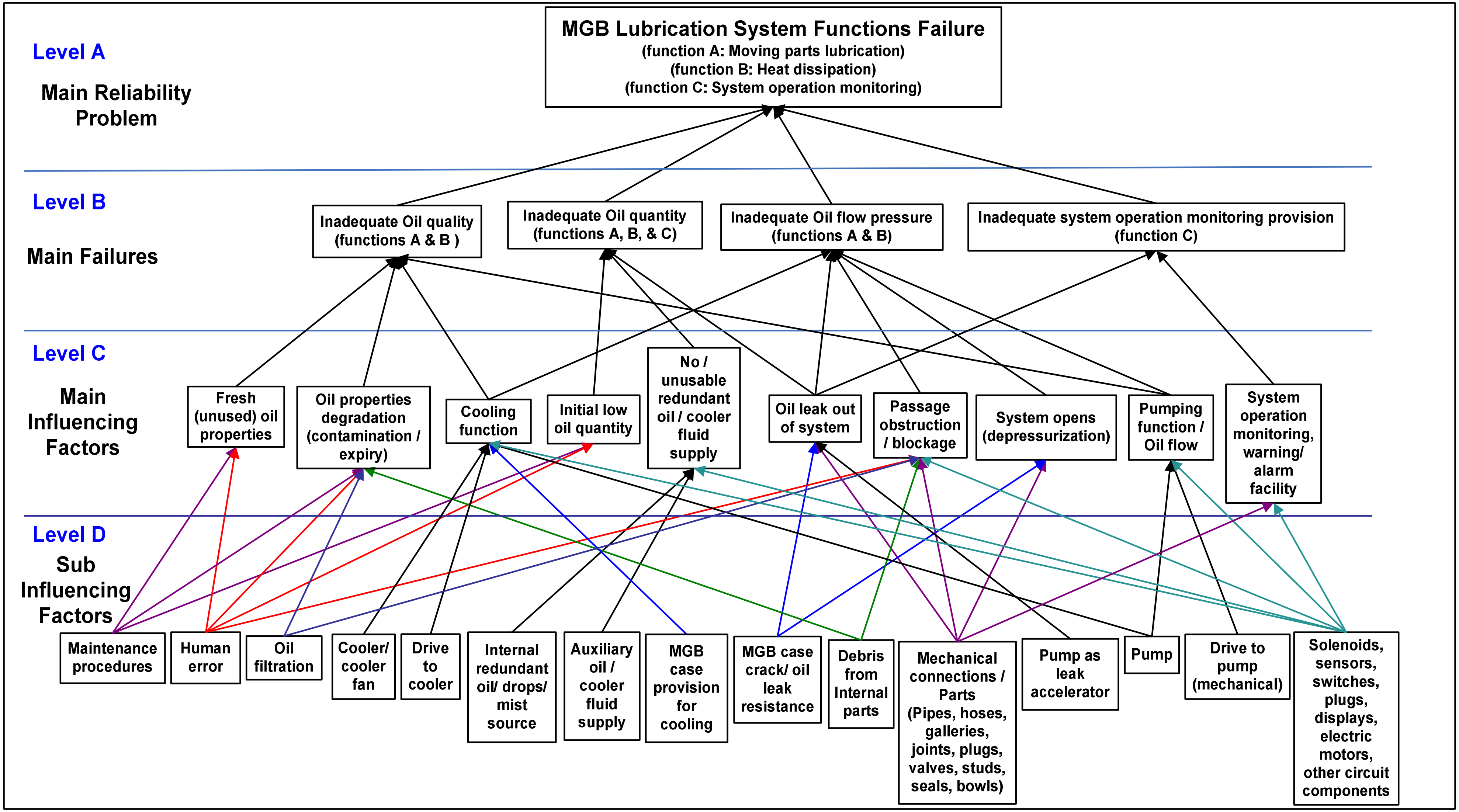


Figure 25 - Influence Diagram for helicopter MGB lubrication system function failure analysis

4.2.8.1 Justification of Level A:

A.1 MGB lubrication system functions failure (Level A):

As indicated in Section 1 above, evidence showed that the MGB lubrication system functions failure, which is the main reliability problem (event) of the model (Level A), is a direct result of the occurrence of any, some, or all of the 4 main failures below:

Inadequate oil quality (Level B)

The two functions of moving parts lubrication and heat dissipation are influenced by the quality of the oil working within the system. Properties like viscosity, purity, temperature, mineral content, multi-phase flow, and others play vital roles in providing for these two functions.

Inadequate oil quantity (Level B)

Oil quantity influences the provision of both lubrication and heat dissipation functions as well. Lesser amounts of oil will lead to the development of oil starvation symptoms and defects of the MGB moving parts, and will reduce the efficiency of heat dissipated. In fact, oil starvation further increases heat generation within the system. Another major effect of the event of inadequate oil quantity is the malfunction of the monitoring provision. For instance, loss of oil from the MGB can lead to only ambient temperatures within MGB cavity being read, not the actual oil temperature. Accordingly, the monitoring function will be influenced regardless of whether the physical structure of the monitoring facilities is still in adequate working order. In another orientation, evidence showed that larger oil quantity than the design requirements (over-filling) also has an adverse effect (influence) on the heat dissipation function (additional heat generation).

Inadequate oil pressure (Level B)

Evidence showed that a drop in oil pressure value will directly deviate the oil flow rate from its designed range, thus directly adversely influencing the provision of both the lubrication and heat dissipation functions.

Inadequate provision of oil system operation monitoring (Level B)

Evidence showed that failure of the monitoring, caution, or warning facilities can adversely influence the monitoring function within the lubrication system, and this will impact the overall system reliability. A simple example is the case when the oil level glass indicator is contaminated or covered such that no accurate oil level reading could be made. This can also occur if the oil level reading glass is located such that human factor issues may rise during the reading process. A more complicated case would be if no adequate prompt information / warning are provided (to the crew) to indicate that an auxiliary cooling system is activated as a result of major oil pressure drop in the main lubrication system. See the ‘G-REDW’ accident report (AAIB 2012).

4.2.8.2 Justification of Level B

In a similar manner, evidence showed that these 4 main failure types (in Level B) are in turn generated / influenced by sets of main influential factors (from Level C below it). This can be detailed as follows:

B.1 Inadequate oil quality (Level B):

This main failure is influenced by the following main influential factors:

Properties of fresh oil (Level C)

It is evident that the initial properties of fresh unused oil greatly influence the overall oil quality. For instance, if oil with specifications other than those required by the MGB design is used, then the quality of oil performance will deviate from the designed ranges of adequate operation, this usually includes variation in viscosity, specific heats, chemical behaviour, etc. Also, evidence from industry showed that some newly introduced oils with lesser viscosities performed well as cooling and lubricating agents, but adversely influenced the leak resistance capabilities of some critical seals. Higher rates of leaks are thus reported. Other example is if the oil chemical or physical properties are changed due to inadequate storing conditions (water or other vapours contamination). This will again influence the overall quality of the oil during MGB operation.

Oil properties degradation (Level C)

The properties of oil used in the lubricating system degrade with time as the MGB operates. Degradation can be observed as changes in physical properties, chemical/ molecular structure and/ or behaviour, impurity, etc. Variation of oil properties due to degradation will prevent the lubrication system from operating adequately at the required design rates. For instance, gear contact friction ratios will deviate from the designed specifications if the oil properties such as viscosity or impurity values changed due to degradation.

System cooling function (Level C)

The working heat dissipation capability of the oil flowing through the MGB at a given time is significantly influenced by the actual temperature rating of the oil itself at that time. Continuous adequate cooling of the oil plays vital role in the efficiency at which the heat dissipation function of the lubrication system is being provided. Oil viscosity is also affected by the working oil temperature at a time, thus affecting the lubricating effect of the oil on the moving MGB parts.

System pumping function (Level C)

The quality of oil within the lubrication system is also shaped by the flow rate (which in turn influence the heat carrying capacity of oil) and by the flow nature (single phase or multi-phase flows). Both flow rate and nature are significantly influenced by the working pumping capacity of the system at a given time. Accordingly, the pumping function of the system greatly influences the overall oil quality.

B.2 Inadequate oil quantity (Level B):

This main failure is influenced by the following main influential factors:

Initial oil quantity (Level C)

The initial oil quantity available within the MGB lubrication system before the MGB operation is vital. Lower (or higher) quantity of oil than the design-specified amount will directly lead to the occurrence of the 'inadequate oil quantity' event.

Oil leak from the system (Level C)

Oil leakage from the system is the most critical event that can influence the 'inadequate oil quantity' main factor. The severity of influence of an oil leak on the overall system reliability depends on the leakage rate i.e. whether it is slow, moderate, or fast.

Redundant oil/ coolant supply (Level C)

The event of 'inadequate oil quantity' also depends on both the availability and usability of redundant oil or coolants supply to the system in emergency situations, when the main oil system fails. If redundant supply of oil or coolant is available, then this main failure of inadequate oil quantity will not be a cause of risk to the MGB lubrication system regardless of any other defects that might occur. This redundant oil/ coolant is a major vital arrangement that can restore the reliability of the lubrication system in emergencies. However, some of the three main functions of the lubrication system may be adversely affected to various extents during such emergency sequences.

B.3 Inadequate oil pressure (Level B):

This main failure is influenced by the following main influential factors:

Oil cooling function (Level C)

The working oil temperature has a direct influence on the oil flow pressure within the lubrication system. Higher oil temperatures than the design – specified range will adversely influence the flow pressure. This, for instance, is observable in the generation of excessive vapours within the MGB enclosure, and the tendency of the flow to become a multi-phase flow with deviated pressure reading from the specified range.

Oil leak out of system (Level C)

Again, oil leak out of the system critically influences the working oil pressure. Lower oil quantity than the specified amount adversely influences the efficiency of pumps (usually immersed in oil tanks /reservoirs). This can directly introduce a multi-phase flow into the system (bubble formation). Again, the severity of influence of an oil leak on the oil flow pressure depends on the rate of that leak where it is slow, moderate, or fast.

Oil passage blockage (Level C)

Evidence showed that oil flow pressure can be influenced if the oil passages / galleries embedded within the MGB structure are fully or partially obstructed or blocked. This is also true for other oil ways through internal or external pipes, hoses, etc. A passage obstruction or blockage will produce higher flow pressures upstream and lower flow pressures downstream of it, thus greatly influencing the overall pre-specified flow pressure arrangement through various valves and other system components.

Pressurised oil system opens (Level C)

The helicopter pressurized MGB lubrication system is a closed system where oil flows under specified pressures in a closed cycle arrangement. If the system opens at any of its parts to the ambient conditions, then the whole system collapses due to loss of pressure. This is more critical if the system opens at an early higher pressure stage such as the high pressure line normally delivering output of the pumping facility to the oil cooler.

Pumping function (Level C)

This is again a vital influencing factor. The core components of any pressurized system are the pumps that produce the working circulation motive force of the flow. Any malfunctioning of these pumps will have a direct influence on the overall reliability of the system.

B.4 Inadequate provision of oil system operation monitoring (Level B):

This main failure is influenced by the following main influential factors:

Oil leak out of system (Level C)

As discussed before, oil leakage from the system can lead to only ambient temperature within MGB cavity being read, and not the actual oil temperature. Accordingly, the monitoring function (regarding oil temperature) will be influenced regardless whether the physical structure of the monitoring facilities is still being in adequate working order (Note: oil leakage can lead to oil pressure drop, but this will not adversely influence the monitoring function (regarding oil pressure) since the exact oil pressure value can still be read even if this value drops to zero if the oil system is totally opened.

System monitoring, warning, alarm facility failure (Level C)

The oil system operation monitoring provision main failure (Level B) will occur if the monitoring, warning, and alarm facility (Level C) failed. This facility is the collection of physical mechanical structure and electronic devices (sensors, switches, valves, transmitters, indicators, displays, etc.), logic circuits, software codes, and many other components. Failure of any of these components will totally or partially render the facility unserviceable, thus greatly influencing the monitoring function provision. The simplest example provided by the collected evidence is the case if the oil system low pressure warning indicator bulb failed, the reliability of the whole oil system will thus be influenced.

4.2.8.3 Justification of Level C:

In a similar manner, evidence showed that the 10 main influencing factors of (Level C) are in turn generated / influenced by sets of sub-influential factors (from Level D below them). The model in Figure 30 indicates that the collective (Level C) main influential factors (or any one of them) are triggered through *AT LEAST* one of 31 influences that are exerted by the 15 sub-influential factors of (Level D) below. The presentation of these 31 influential relations is based on collated evidence. For report brevity, the significance of these influences and their partial and collective impacts on the overall system reliability will not be discussed here in detail; however, they will be thoroughly discussed later during model application analysis.

4.2.8.4 Justification of Level D

Level D of the model lists 15 sub-influential factors. These are the initial triggers of failures (basic events) that propagate through 31 influences to 'activate' their corresponding main influential factors in Level C above. Level D sub-factors are the input events to the model. Each sub-factor either exists (as a cause of risk to the lubrication system) or does not exist. This input, as will be discussed in the following sections, is introduced to the model in form of a given probability.

4.2.9 Types of input to model

The sub-influential factors are represented at any given time by 15 different initial weights (counted as initial test probabilities) expressing either the positive or negative influence of each of the sub factors on the relevant main factors of Level C. For this model, there are three methods for providing initial input:

i. Historical data of previous events involving MGB lubrication system failures:

   Referring to such historical data, exact input values can be introduced into the model such that an exact number indicating the reliability of the lubrication system can be reached. Unfortunately, such historical data is not readily available in the current instance.

ii. System of experts:

   Expert opinion can be used to designate suitable input values to the model. However, this method readily faces the limitations usually associated with experts systems.

iii. Computer-generated data:

   This method is the focus of the following sections of this study. The idea is to enter a very large number of randomly generated test probabilities to generate very large number of various 'exists/ does not exist' scenarios of each of the 15 sub-influence factors. This will produce a large number of pairs of 'success' and 'failures' for the model main event, then:

   a. The set of 15 input values corresponding to the maximum 'success' value will describe the optimum setting of the MGB to operate without failure,

b. The set of 15 input values corresponding to the minimum ‘failure’ value will describe the worst setting of the MGB that is most vulnerable to failure.

   Similarly, by using such computer-generated data, the model can further provide for other detailed analyses of the lubrication system as will be discussed in the following sections.

4.2.10 Model recognition of input

The input to the model must be introduced in a specific format as answers to certain explorative questions that investigate existence of each of the sub-influential factors.

Table 21 lists relations between input and the model recognition of that input as a cause of risk to the MGB lubrication system.

Table 21 - Relation between input and the model recognition of that input as a cause of risk

No	Questions guiding input to model	Input value descriptor	Model mathematical processing of input as cause of risk	Remarks	Relation between input and risk recognition
1	Maintenance Procedures: What is the suggested test probability of maintenance procedures as a cause of risk to the MGB lubrication oil system?	High	High	Higher is the value of probability of inadequate maintenance procedures, higher is the expected risk on system	Proportional
		Low	Low		
2	Human Error: What is the suggested test probability that a human error, if committed, will form a cause of risk to the MGB lubrication oil system?	High	High	Higher is the probability of human error occurrence (during maintenance, pre-flight check, etc.), higher is the expected risk on the system	Proportional
		Low	Low		
3	Oil filtration: What is the suggested test probability of the oil filtration process as a cause of risk to the MGB lubrication oil system?	High	High	Higher is the probability of defects or inaccuracy of the filtration function, higher is the expected risk on the system	Proportional
		Low	Low		
4	Oil cooler: What is the suggested test probability that the oil cooler can be a cause of risk to the MGB lubrication oil system?	High	High	Higher is the probability of defects, inaccuracy, or failure of the oil cooler, higher is the expected risk on the system	Proportional
		Low	Low		
5	Drive to oil cooler: What is the suggested test probability that the drive to oil cooler can be a cause of risk to the MGB lubrication oil system?	High	High	Higher is the probability of defects, inaccuracy, or failure of the oil cooler, higher is the expected risk on the system	Proportional
		Low	Low		
6	Internally -stored redundant oil: What is the suggested test probability that internally-stored redundant oil within the MGB can be a cause of risk to the MGB lubrication system?	High	High	Higher is the probability that the MGB contains internally-stored redundant oil (for use in emergency), lower is the expected risk on the oil system. In other words, a low input value to the model	Inverse
		Low	Low		

				implies that the MGB contains large amount of usable redundant oil	
7	Auxiliary oil /coolant external supply: What is the suggested test probability that an auxiliary oil /coolant external supply can be a cause of risk to the MGB lubrication system?	High	High	Higher is the probability that the MGB is provided with auxiliary oil /coolant external supply (for use in emergency), lower is the expected risk on the oil system. In other words, a low input value to the model implies that the MGB is backed with effective auxiliary oil /coolant external supply.	Inverse
		Low	Low		
8	MGB case provision for cooling: What is the suggested test probability that MGB case design/ structure provision for cooling can be a cause of risk to the MGB lubrication oil system?	High	High	Higher is the probability that the MGB case is well designed to support the cooling function (heat dissipation), lower is the expected risk on the oil system. In other words, low input to the model implies the excellence of the MGB case structure as a cooling agent.	Inverse
		Low	Low		
9	MGB case resistance to leaks/ cracks: What is the suggested test probability that MGB case design/ structure can be a cause of risk to the MGB lubrication oil system?	High	High	Higher is the probability of defects, cracks, fractures, or leak resistance deficiency of the MGB case, higher is the expected risk on the system	Proportional
		Low	Low		
10	Debris from internal parts: What is the suggested test probability that debris from MGB internal parts can be a cause of risk to the MGB lubrication oil system?	High	High	Higher is the probability of existence of debris from internal rotating parts of the MGB, higher is the expected risk on the system	Proportional
		Low	Low		
11	Mechanical parts/ connections: What is the suggested test probability that the mechanical parts and connections of the oil system can be a cause of risk to the MGB lubrication oil system?	High	High	Higher is the probability of defects, cracks, or fractures of the mechanical parts / connections of the system, higher is the expected risk on the system	Proportional
		Low	Low		
12		High	High	Higher is the probability that the pump	

	Pump as leak accelerator: What is the suggested test probability that the pump, as leak accelerator, can be a cause of risk to the MGB lubrication oil system?			works at high oil pressure, higher is the potentiality for leaks from cracks/ seals, thus higher is the expected risk on the oil system. In other words; low input to the model implies that either the pump is actually designed to provide low pressure range, or the MGB is designed to resist leaks at high working pressure.	Inverse
		Low	Low		
13	Pump: What is the suggested test probability that the pump of the oil system can be a cause of risk to the MGB lubrication oil system?	High	High	Higher is the probability of defects, cracks, or fractures of the pump, higher is the expected risk on the system	Proportional
		Low	Low		
14	Drive to pump (mechanical): What is the suggested test probability that the mechanical drive to pump can be a cause of risk to the MGB lubrication oil system?	High	High	Higher is the probability of defects, cracks, or fractures of the mechanical drive to pump, higher is the expected risk on the system	Proportional
		Low	Low		
15	Electrical/ electronic components: What is the suggested test probability that the electrical/ electronic components can be a cause of risk to the MGB lubrication oil system?	High	High	Higher is the probability of defects, cracks, or fractures of the electrical/ electronic components, higher is the expected risk on the system	Proportional
		Low	Low		

4.2.11 Application: Computer-based analysis of helicopter MGB lubrication system

4.2.11.1 Strategy and method of MGB component-based reliability analysis

The strategy of model application is built on the use of complicated mathematical model, explained elsewhere (Hokstad et. al. 1999, 2001, Howard and Matheson 2005, Krakenes et al. 2009, Herrera et. al. 2010), to use various scenarios of input values (each assigned, within a given scenario, to one of the 15 sub-influential factors, or to one of the 10 main influencing factors) such that certain unconditional probability of failure is obtained for each of the 4 main failure types of the lubrication system, and for the overall system function failures (main event of the mode). Detailed description of the mathematical model used to calculate probabilities of failures within the ID model is given by **Appendix F**. Very large numbers of scenarios variants are introduced, through computer generated random input test probabilities, such that accurate probabilities of system failures are obtained.

The tests are carried by adopting two major procedures:

i. Component-based reliability analysis

The effects of occurrence of a failure to any one of the MGB oil lubrication system components or other influential triggers (the 15 sub-influential factors) are studied individually by varying its input test probability from P= 0.0 (no failure) to P=1.0 (failure is definitely to occur to that component) while keeping probabilities of failure of all other components to a P= 0.0 value. In this manner, all the internal mutual interactions between all events of the model at all its levels would be the direct impact of that component's failure only.

ii. System functional failure-based analysis.

This is a more holistic approach. 15 various input test probabilities of failure are assigned randomly each to one of the 15 sub-factor triggers of Level D. such arrangement represents only one scenario of test. One scenario (15 random input values between P= 0.0 to P= 1.0) is considered at a single given run of test. A single output representing the probability of failure of the system and its components is obtained for each scenario. Avery large number of these test scenarios will indicate the overall functional behaviour of the system in a collective manner.

4.2.11.2 Factual information on application

The mathematical model supporting the Influence Diagram in Figure 25 is implemented in software to carry out the analysis tests. The following factual data indicates the extent of the analysis:

- 19 spread sheets
- Over 370 graphical illustrations
- 15,220,000 (over 15 M) randomly generated input test probabilities

4.2.12 Results and analysis of the ID model application

The numerical and graphical results of the computer based application of the ID model are extensive, thus only the most important results are presented and illustrated in this report. Results will be discussed for the two test procedures as follows:

4.2.12.1 Component–based MGB lubrication system reliability analysis

Samples of effects of risk sub- influencing factors on MGB lubrication system

Only three sub-influencing factors will be presented here; the maintenance procedures, human errors, and mechanical parts/ components of the system. These three sub-factors will respectively cover the organizational, individual, and physical MGB structure impacts to the overall MGB lubrication system reliability.

Maintenance procedures

The sequence of testing is carried out as follows::

i. All input test probabilities for the 15 sub-influencing factors are put at zero value except for the 'maintenance procedures' influence factor which is assigned a value for input test probability varying from P = 0.0 to P=1.0, with increment of 0.1.

ii. Values of main factors (Level C), main failures (Level B), and main reliability problem (Level A) are calculated at each of the input values for 'maintenance procedures' sub-factor.

iii. Only events directly influenced by the 'maintenance procedures' sub-factor will change values (of probability of failure) as its input test probability is gradually increased. Other events are not influenced and continue to be represented at zero values.

iv. Influences on levels C, B, and A are described by Figures 26, 27, and 28 respectively.

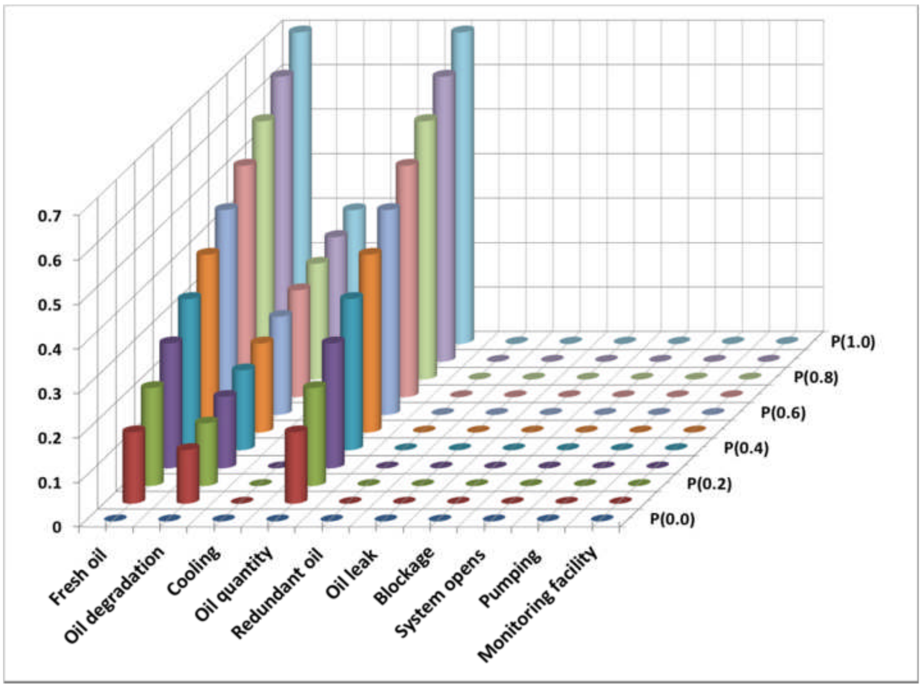


Figure 26 - Influence of 'maintenance procedures' on main influencing factors

The maintenance procedures greatly influence both the fresh oil properties and the oil quantity main factors. Figure 26 indicates that the influences are of high amplitude that starts at (0.0) and ends at (0.7) failure probabilities as the input test probability is varied between (0.0) and (1.0). The maintenance procedures also influence the oil degradation main factor but at lower amplitude and following more flat behaviour. This is logical since the oil degradation even occurs due to many factors other than the maintenance procedures as indicated by Figure 25.

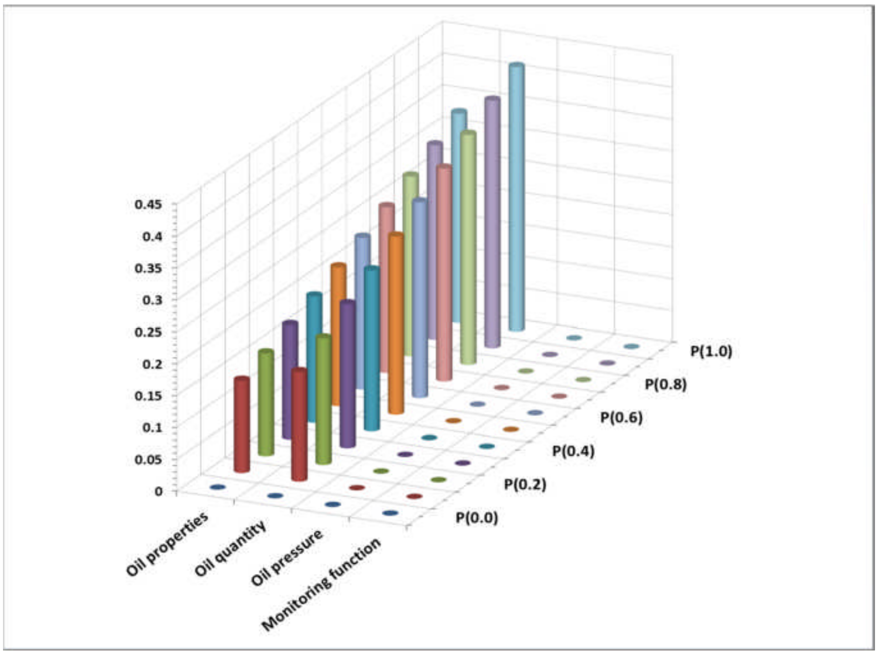


Figure 27 - Influence of ‘maintenance procedures’ on main failures

Figure 27 shows that maintenance procedures influence two main failures, namely the oil properties and, to a higher degree, the oil quantity. Both the oil pressure and monitoring functions are free of any direct influences from the maintenance procedure.

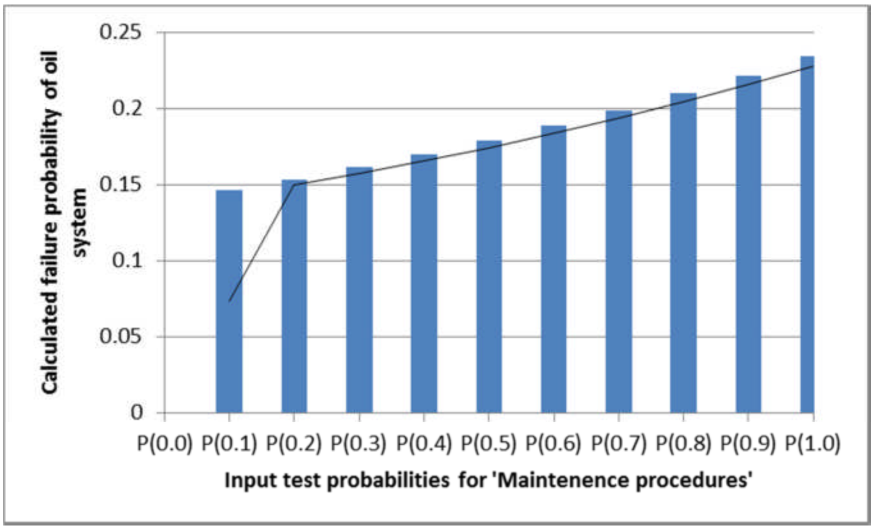


Figure 28 - Influence of ‘maintenance procedures’ on oil system reliability

Figure 28 indicates the increasing influence of the maintenance procedures on the overall lubrication system reliability. As the input test probability of maintenance procedures (as cause of risk) is varied from (0.0) to (1.0), the overall lubrication system failure probability increases from (0.0) to (0.23). The moving average line thus shows a steep increment, although the amplitude is generally of moderate values.

Human error

The human error sub-influential factor has one of the most critical impacts on many main influential factors. Figure 29 shows that human error significantly influences the fresh oil properties and the oil quantity main factors. These two impacts actively increase from (0.0) to (0.28) probability of failure as result of varying the human error occurrence input test probability from (0.0) to (1.0). This logically corresponds with the fact that human error during oil change or top-up processes is frequently observed. Human error also influences the possibility of getting the oil passage way obstructed or even totally blocked. Collected evidence previously showed that such occurrences, although possible ((0.0 to 0.22 probability of occurrence), but they are generally less in frequency than the oil fresh properties or quantity factors. A fourth main factor that is influenced by human errors is the oil degradation event, though at lower, almost flat, mode of behaviour.

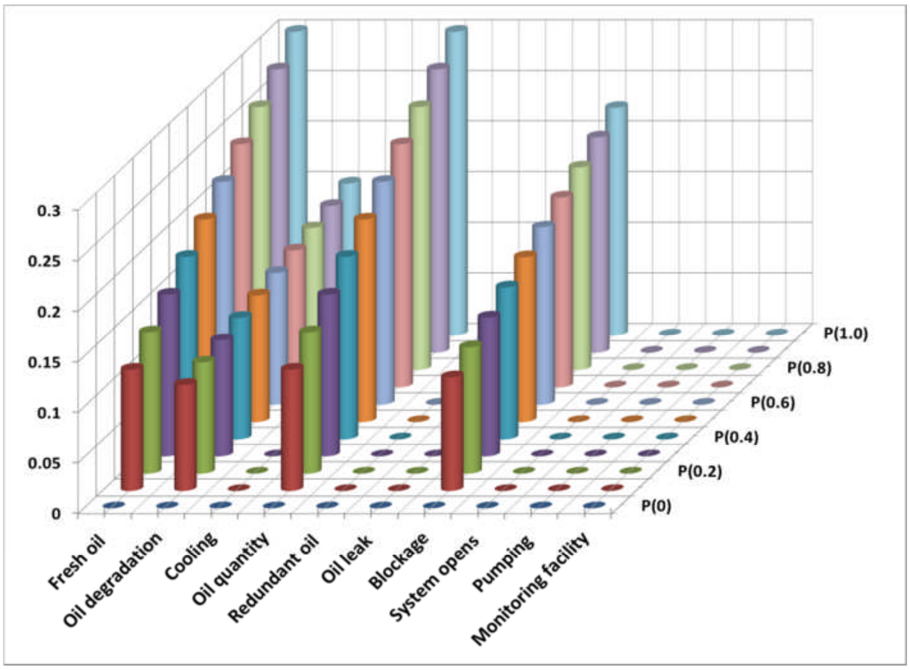


Figure 29 - Influence of 'human error' on main influencing factors

It can be observed from Figure 30 that the human error has lesser severe impacts on the main failure types if compared to these influences from the maintenance procedures. Human error has steep increasing adverse influence on the MGB oil quantity, an increasing effect on the oil properties, but a constant lower influence on the oil pressure as the probability of human error occurrence is increased. This is again of logic since the oil quantity event is more vulnerable to be triggered by human error, starting from a wrongly-read oil level and up to more complex cases where oil leaks occur as result of inadequate adjustment of oil filters studs for instance. The influence of human error on the working system pressure is fixed in amplitude since the human error can only directly influence the pressure is in the case if the oil passage is obstructed or blocked; a single event that has a constant impact on the pressure distribution of the working oil within the system.

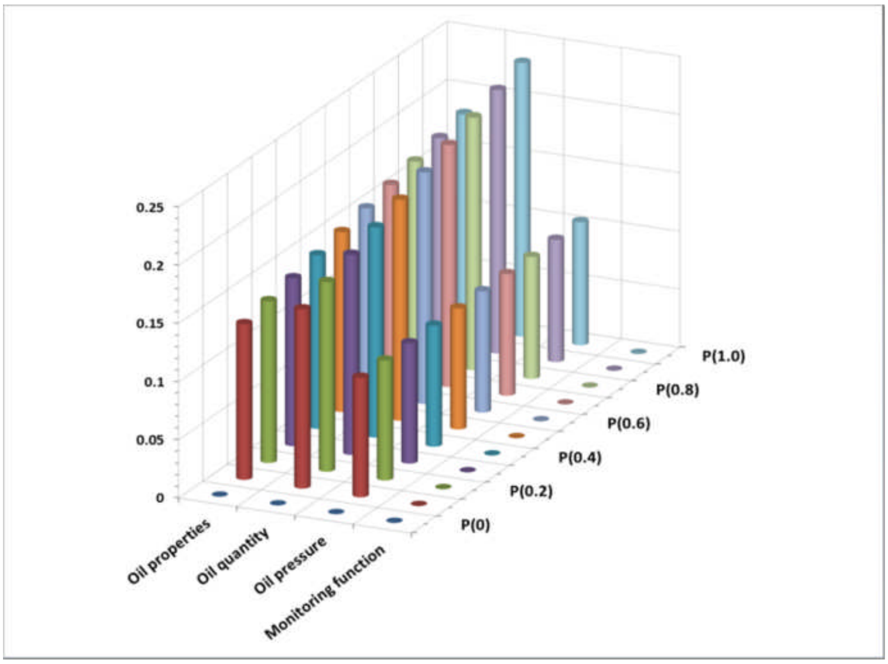


Figure 30 - Influence of 'human error' on main failures

Again, the overall adverse impact of human error on the overall reliability of the lubrication system (Figure 31) is of lesser value when compared the maintenance procedures sub factor. The maintenance procedures chances to cause risk to the lubrication system are greater since they cover large spectrum of risk initiators when observed as a group of organizational attitudes. The maintenance procedures in fact start firstly with design practices and continue to cover all aspects of the maintenance programme during operation.

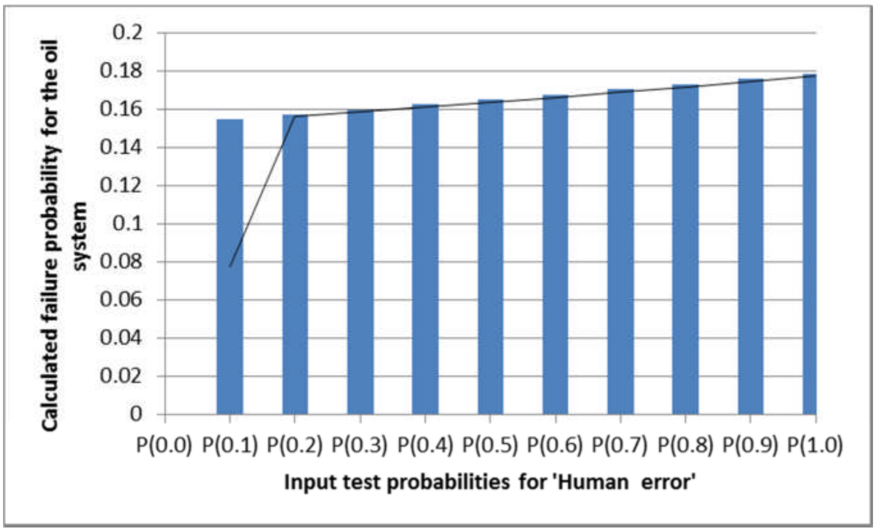


Figure 31 - Influence of 'human error' on oil system reliability

Mechanical parts/ connections

Mechanical parts and connections are the physical structure of the lubrication system save the pump, cooler, and filter. These mechanical parts thus include tanks/ reservoirs, hoses, pipes, oil galleries, oil sprayers, joins, plugs, valves, bowls, studs, etc. As Figure 32 indicates, mechanical parts influence both redundant oil availability and usability within system, oil leak, oil passage blockage, and they can cause depressurization if the system is rendered opened through any of these parts. These influences are of steady low to medium amplitudes ranging from (0.0) to (0.28) maximum probability of failure for oil leaks and depressurization, and down to (0.18) maximum failure probability for the redundant oil availability and oil passage blockage. However, mechanical parts also plays vital role in the reliability of the monitoring function of the oil system. The probability of failure in monitoring provision reaches high rate (0.685) if one of the mechanical parts is to face 100% probable failure. In fact, it is quite challenging to draw definite borders that can totally separate the monitoring 'mechanical physical facility' from the mechanical parts group. Consequently, the impact of these mechanical parts on the monitoring function is significant.

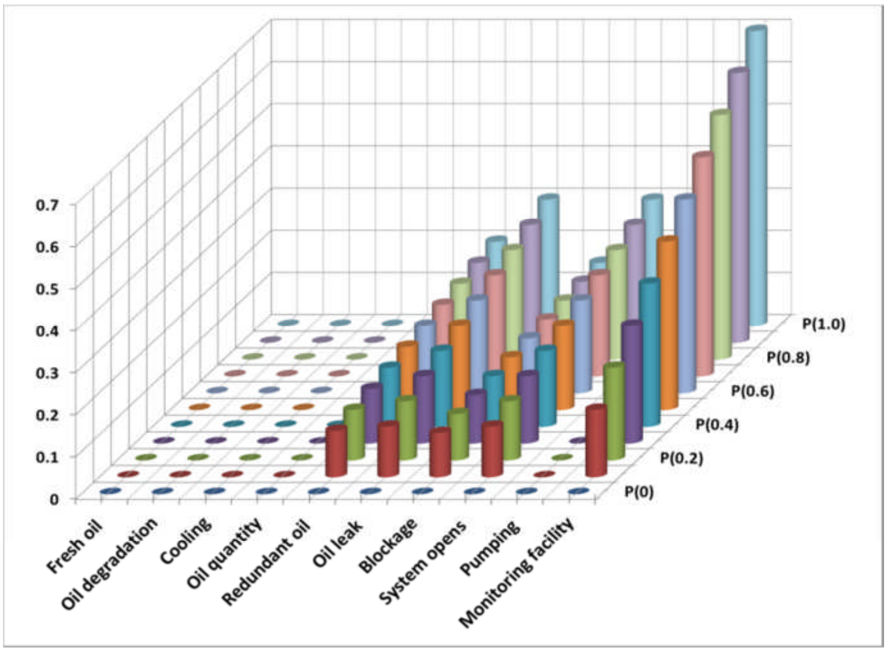


Figure 32 - Influence of 'mechanical parts/ connections' on main influencing factors

Figure 33 shows that the mechanical parts failure cause higher risks to the lubrication system than other sub-factors including organizational and individual impacts. The rates of failure probabilities for the oil quantity and oil pressure are constant (flat) with low amplitudes ranging from (0.0) to (0.16) in result to increment of failure probabilities of the mechanical parts group. Oil properties are not influenced by this group of parts, however significant influence caused by them is observed on the monitoring provision of the system. This is again because most of the monitoring facility physical structure is in fact totally coupled with some or all of these mechanical parts of the system.

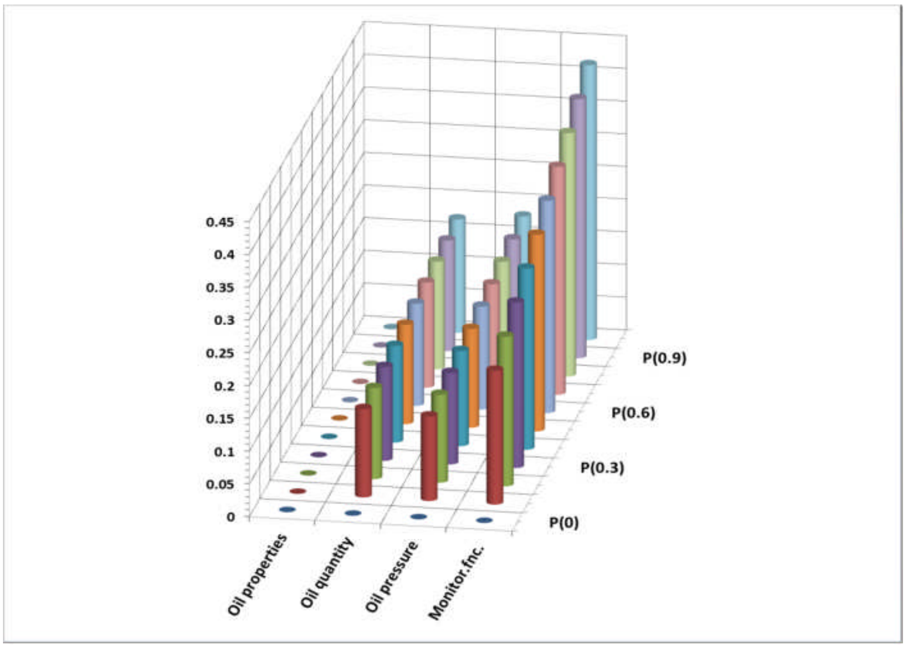


Figure 33 - Influence of 'mechanical parts/ connections' on main failures

Mechanical parts linearly and increasingly influence the overall lubrication oil reliability, though at moderate inclination of graph of Figure 34. A 100% definite occurrence of a failure event to one or more of these mechanical parts will cause a risk of failure to the integral lubrication system that slightly exceeds the (0.2) probability of occurrence. A (0.1) probability of mechanical parts failure still threatens the overall system by a (0.16) probability of failure.

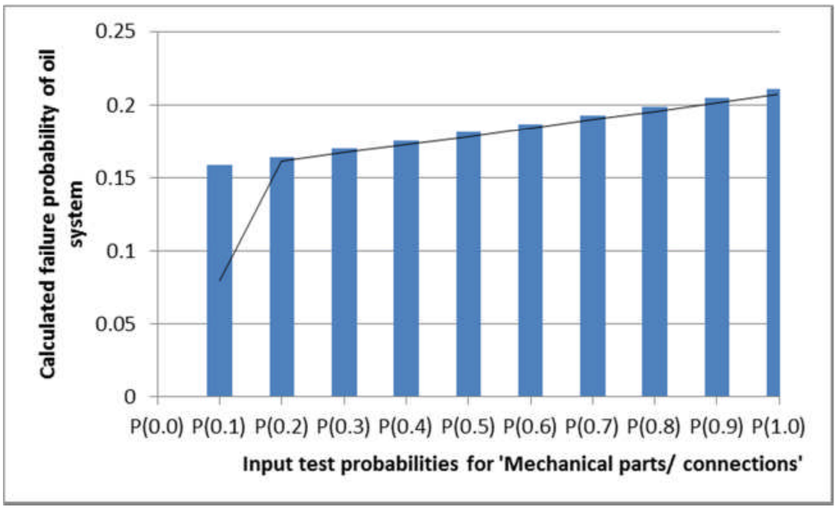


Figure 34 - Influence of 'mechanical parts/ connections' on oil system reliability

Similar sets of calculations are carried out for the rest of the 15 sub-factors, thus exact behaviour of each of them is identified in details. Accordingly, designers can be more aware of the precise behaviour of MGB lubrication oil system components, as triggers of system failures, when each component is considered in isolation.

4.2.12.2 System functional failure – based analysis of MGB lubrication system

This is the second part of analysis carried on the lubrication system, where the collective influences of the input test probabilities of the 15 sub factors of Level D of the model are varied randomly in very high number of scenarios.

The sequence of testing is carried out as follows:

i. 15 various randomly generated input test probabilities are assigned to the 15 sub-factors the first scenario of possible failures that can occur collectively in a given time to the MGB lubrication system. These input probabilities are introduced between two pre-specified values of (P= 1.00E-6 and P=1.00E-3).
ii. Influence of this scenario is obtained on the 10 main influencing factors (Level C), the 4 main failure types (Level B), and the overall system failure behaviour (Level A). A certain failure probability is obtained for each of these events.
iii. The model is recalculated again with new set of 15 random input test probabilities (second scenario). New sets of failure probabilities of events of the model are thus obtained.
iv. The process is then repeated for 10,000 cycles.
v. A large matrix (30x10000) of output is obtained for each single test. Results are sorted descending from scenarios producing highest probability of failure of the whole lubrication system (Level A) to those scenarios producing lowest probability of failure of the system (Level A).
vi. The highest 1% scenarios of the test output (first upper 100 scenarios of the matrix) are then considered. Averaging these, a final single set of highest probabilities of failure are obtained for each of the events in Levels C, B, and A.
vii. Next, the lowest 1% scenarios of the test output (last bottom 100 scenarios) are then similarly considered. Averaging these, a final single set of lowest probabilities of failure are obtained for each of the events in Levels C, B, and A.
viii. The full assessment of the functional reliability of the MGB lubrication system is thus reached.

The following sections present sample results of MGB lubrication system at only very low limits of input test probabilities:

<u>Sample Run 1 (low input test probabilities of failure**)**</u>

Lower test input probability = 0.000001
Higher test input probability = 0.001
Total number of iterations = 10,000
Total number of runs = 100
Total number of the randomly generated input test probabilities= 15,000,000 (15M)

<u>Considering the Top 100 scenarios (Higher 1% of random sample):</u>
Mean highest obtained probability of oil system failure (Level A) = 0.206687224

The 15M+ randomly generated input test probabilities assigned to the 15 sub-infuencial factors are governed between (0.000001 to 0.001). Accordingly, the highest input test probabilities of failure of the sub-influencing factors that produced the highest overall system failure probability of (0.206687224) are shown in Figure 35.

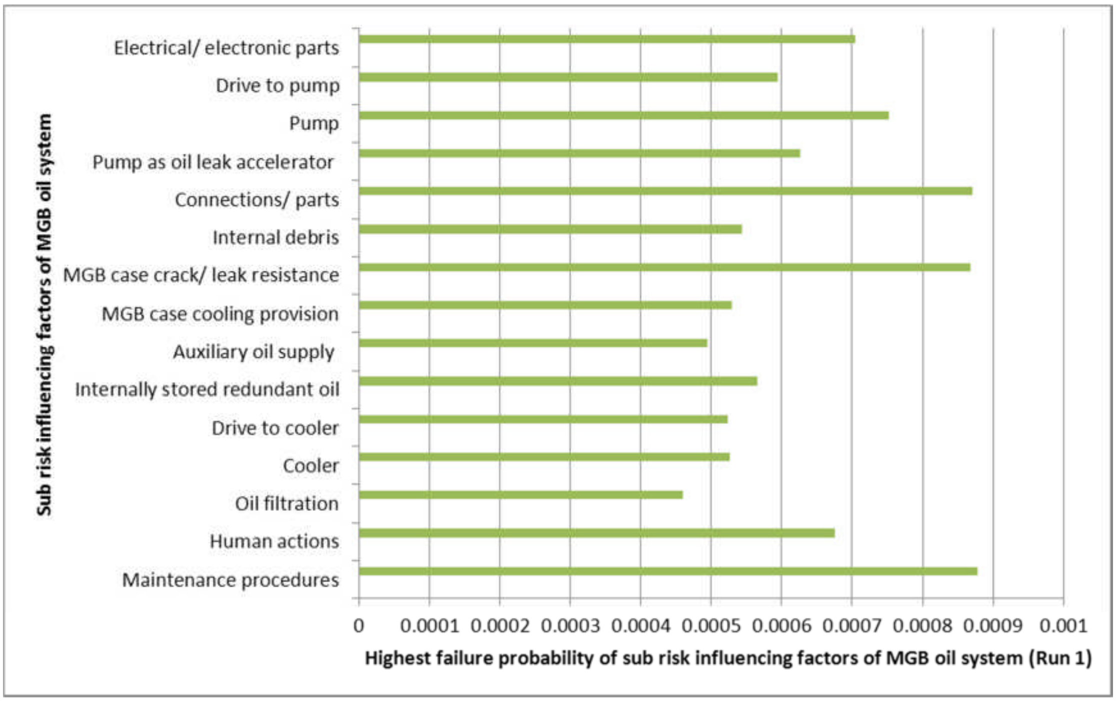


Figure 35 - Highest input test failure probabilities of sub influencing factors (input P= 0.000001 to 0.001) that produced the highest overall lubrication system failure probability of (0.206687224)

Three sub-factors represented the main threats to the lubrication system overall reliability; these are:

- The mechanical parts/ connections
- The MGB case crack/ oil leak resistance
- The maintenance procedures.

The first two sub-factors listed above are found to attain a probability of (0.00086) each, as events to occur in order to cause the overall system failure probability indicated above. Maintenance procedures are of more probability as a cause of risk reaching to 0.000875). A pump, at an occurrence probability of (0.00076), is the next serious threat, followed by the group of electric/ electronic parts at (0.000705) and human error at (0.00068) probabilities of occurrence. Oil filtration is the least threat to the oil system functional integrity with only (0.00045) probability of occurrence.

The distribution of sub-factors as direct causes to risk of system failure greatly dictates the distribution of main factors failure probabilities as well. This is detailed by Figure 36. For instance, the mechanical parts' failure dictates the system depressurization event to be the highest probable main factor of failure at a probability of (0.100685) as well as the monitoring facility failure at (0.10066). Similarly, maintenance procedures failures directly triggered the failures of the fresh oil properties, initial oil quantity each at (0.10066) probabilities. It can also be noted that the leak main failure of probability (0.10063) is caused through joined influences of MGB case oil leak resistance and the mechanical parts group.

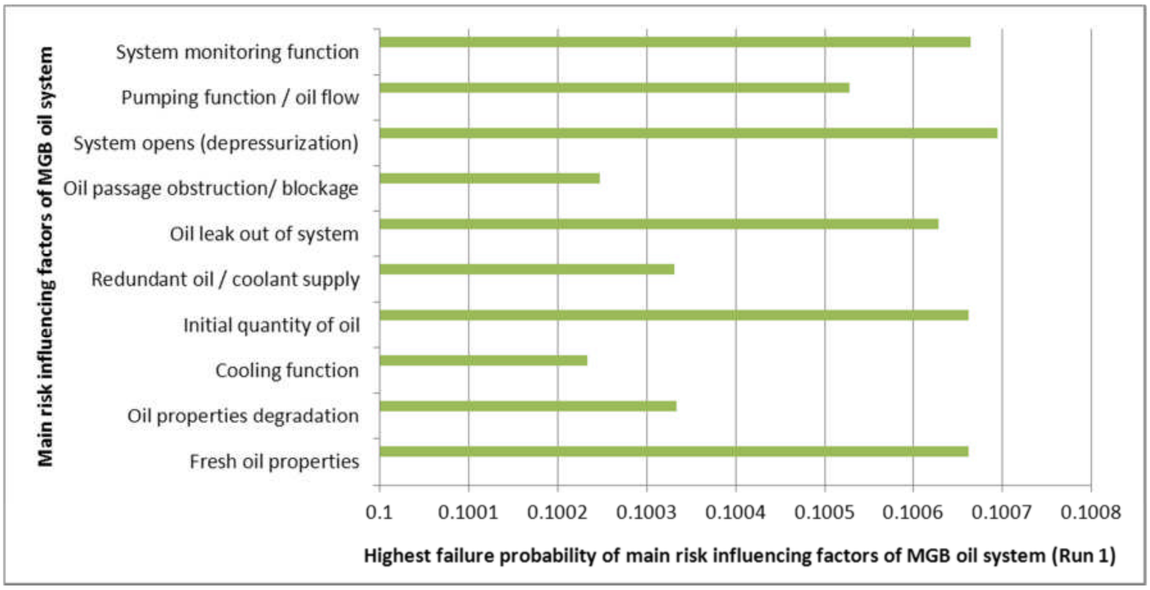


Figure 36. Highest obtained failure probabilities of main influencing factors (input P= 0.000001 to 0.001) corresponding to the highest overall lubrication system failure probability of (0.206687224)

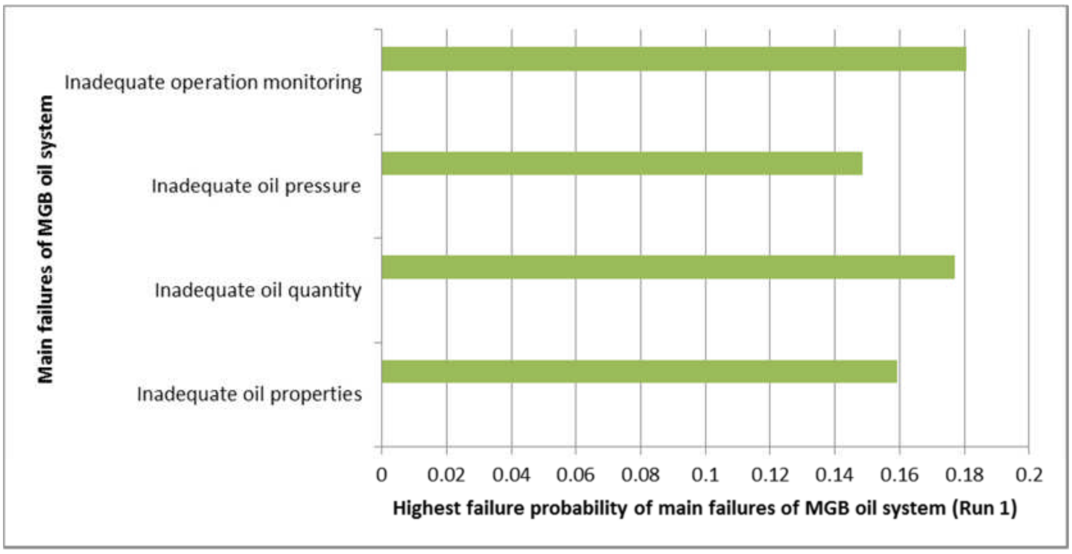


Figure 37 - Highest obtained failure probabilities of main failure types (input P= 0.000001 to 0.001 corresponding to the highest overall lubrication system failure probability of (0.206687224))

The main failures types that led to the highest probability of oil system failure are also investigated as given by Figure 37. Again, the influence of the mechanical parts is tangible on the inadequate provision of the monitoring function, as well as inadequate pressure event both at (0.18) and (0.149) failure probability respectively. The impact of the maintenance procedures shortages are best indicated through the inadequate oil quantity and the inadequate oil properties main failure types at (0.177) and (0.1595) probabilities of failure respectively as well. This broad description of these factors is just a brief representation of complicated sets of internal interaction of influences between events within the four levels of the influence diagram as identified in Figure 25.

To conclude, the ID approach is a powerful investigating technique that provides deep insights to the mutual influencing interactions between various factors shaping the overall reliability of the MGB lubrication system. Analysis can cover both the overall holistic reliability of the system, as well as the exact influence of each of its internal components or external factors (organizational/ human). Industry is highly recommended to make use of such an approach to better explore the reliability of the MGB lubrication system, and other systems of the aircraft as well.

PART THREE

Deliverables of HELMGOP TASK 3

5 THIOETHER MIST LUBRICATION TESTING FOR GEARBOX RUN DRY CAPABILITY EVALUTION

5.1 Introduction to Tests

The loss of lubrication in transmission systems is a key cause of failure in rotorcraft accidents. As part of airworthiness requirements, CS 29.927 requires that the drive system operate for at least 30 minutes once the primary lubrication system has failed. In view of this requirement, NASA has proposed a thioether-based mist lubrication (Handschuh et al. 2007b) which showed promising results of thermal stability and low gear wear after the gearbox has run dry. In their method, the thioether liquid is misted and delivered in an airstream to gears operating at such high temperatures that the molecules react on the wearing surfaces to generate a lubricious deposit which provides effective lubrication. In this experiment, a similar experimental setup is proposed to ratify the effectiveness of such thioether based mist lubrication.

5.2 Objective

The experiment's objective is to test the performance of a mist lubrication system using commercially available thioether compared to conventional oil dip lubrication.

5.3 Performance Measure

The performance measure to evaluate effectiveness of the mist lubrication system are the temperature profile of the gears after the gearbox has run dry and the physical condition of the gears itself.

5.4 Test Rig Description

The overview of the experimental setup is depicted in Figure 38 and the physical laboratory setup shown in Figure 39. The rig consists of the gearbox setup and the mist lubrication setup. The gearbox arrangement is shown in Figure 40. The gear set employed in this test is made of case carburized steel with specifications shown in Table 22. An AC three-phase electrical motor (1.1 KW) with speed of 690 rpm was employed to drive the gearbox. A simple mechanism that permitted a pair of coupling flanges to be rotated relative to each other, thereby applying a pre-torsional load, was employed to apply torque load onto the gears. The lubricating oil used in the gearbox was Aeroshell 555 which is a common aerospace lubricant for helicopter gearboxes in accordance with DOD-L-85734 and DEF STAN 91-100. The technical specification for Aeroshell 555 is shown in Enclosure 1. The instrumentation for the experiment is shown in Figure 41. Type K thermocouples are placed as close as possible to the gear teeth to measure the temperature profiles with connection via slips rings in the shaft to an analog to digital converter. Five thermocouples are arranged radially as shown in Figure 42 to obtain the temperature profile across the gear face. In addition, 2 additional thermocouples are used to monitor the ambient temperature within the gearbox and the gearbox temperature itself.

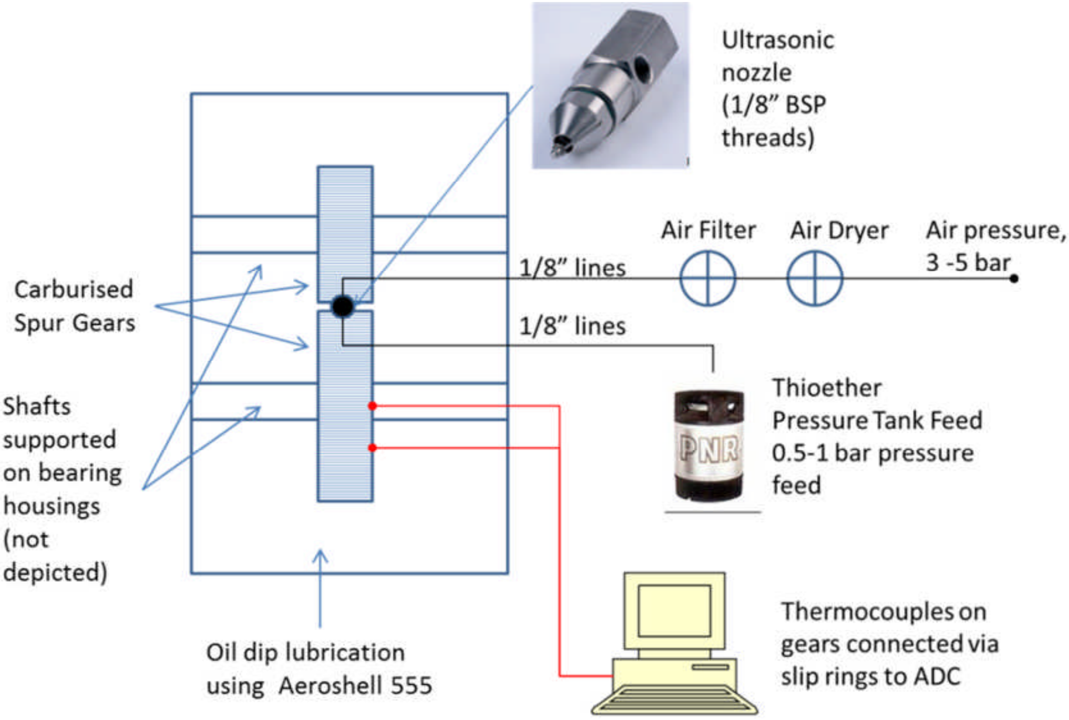


Figure 38 - Experimental rig overview

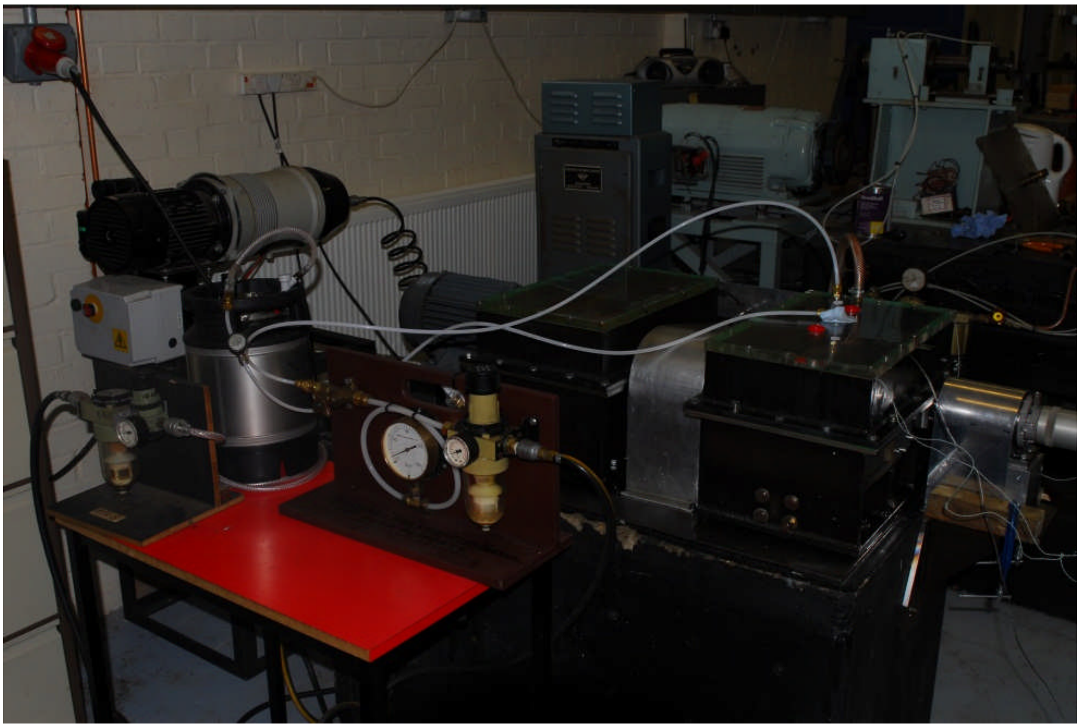


Figure 39 - Laboratory setup

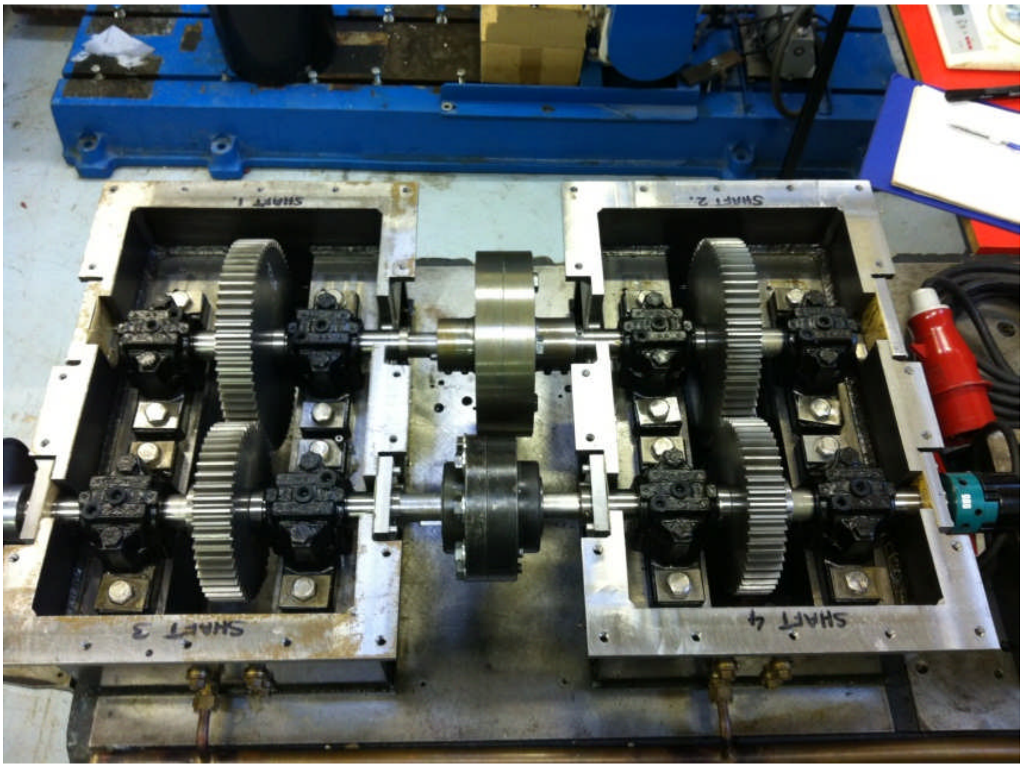


Figure 40 - Gearbox back-to-back arrangement

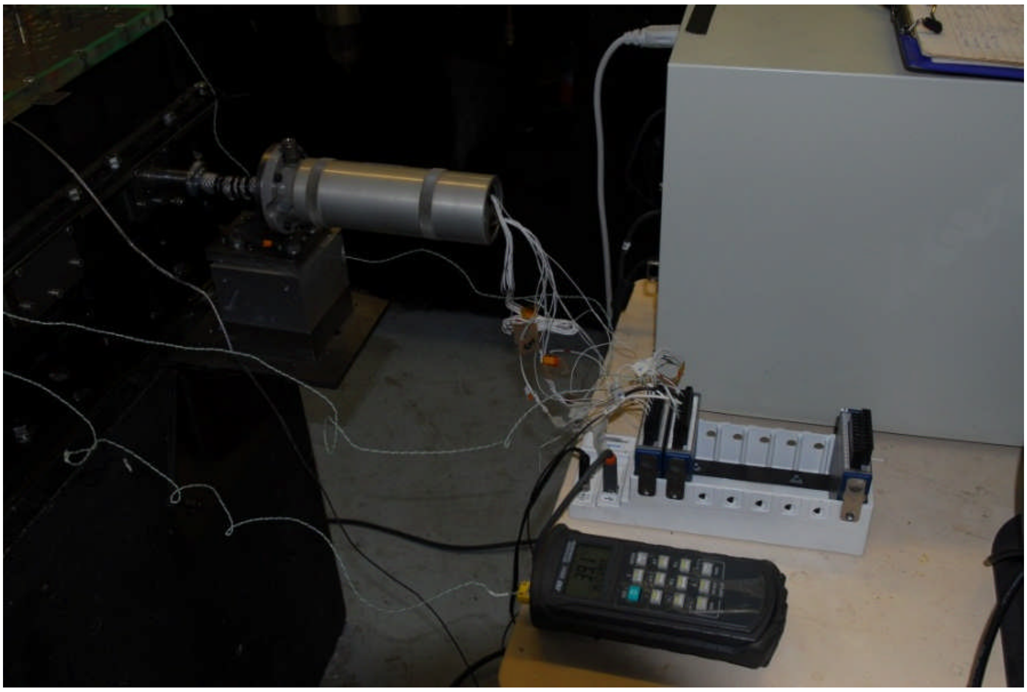


Figure 41- Instrumentation Setup

For the thioether mist lubrication system, ultrasonic nozzles are used to dispense the lubricant so that a low flow rate and fine misting can be achieved. The specification for the nozzle used is shown in Enclosure 2. The system consists of a liquid pressure tank for the lubricant and requires filtered and dry air pressure supplied through a compressor as shown in Figure 43. In

(Handschuh et al. 2007b), the thioether used is a blend of 4 compounds, (a) 1,1-thiobis [3-phenoxybenzene]; molecular weight, (b) 1-phenoxy-3-[[3-(phenylthio) phenyl]thio]benzene, (c) 1,1-thiobis [3-(phenylthio) benzene] and (d) 1,3,-bis (phenylthio) benzene. In this experiment, the thioether used is Poly(oxy-1,2-ethanediyl), α-butyl-ω-hydroxy-,mixed ethers with 2-ethyl-1-hexanol and 2,2'-thiobis[ethanol] or its product name Vulkanol OT, a commercially available compound. The technical specification for Vulkanol OT is shown in Enclosure 3.

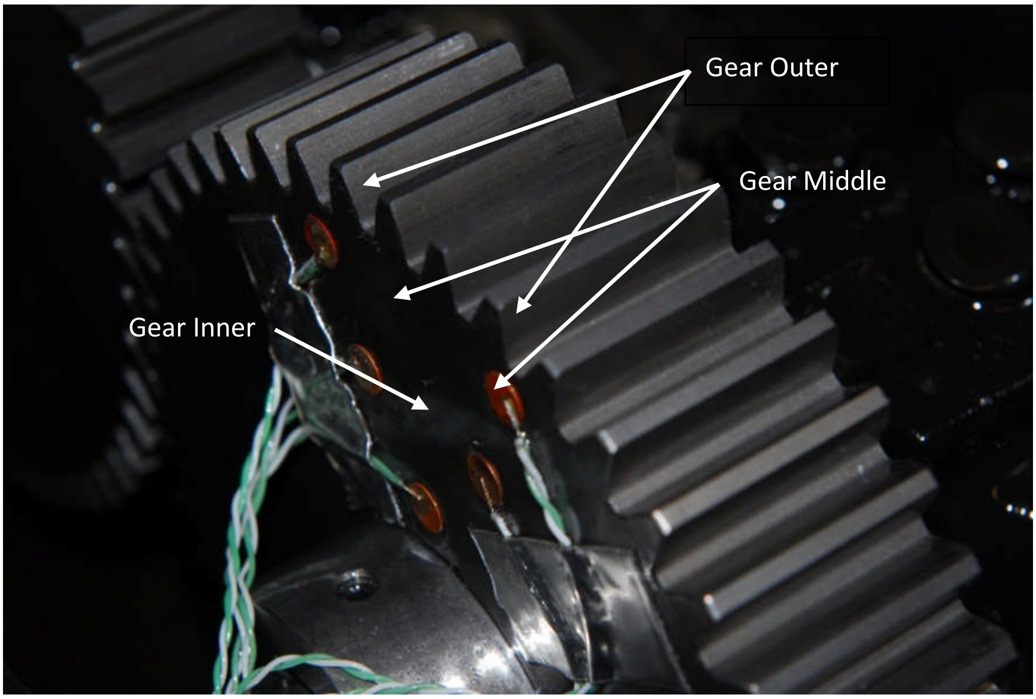


Figure 42 - Thermocouple arrangement on gear face

Table 22 - Pinion and Gear Specification

	Spur
Number of teeth, pinion: gear	49: 65
Base diameter, pinion: gear (mm)	138.13: 183.24
Pitch diameter, pinion: gear (mm)	147: 195
Tip diameter, pinion: gear (mm)	153: 201
Root diameter, pinion: gear (mm)	139.5: 187.5
Contact Ratio	1.33
Module (mm)	3
Addendum modification coefficient	0
Surface roughness, Ra (μm)	0.8, 2.00
Face width (mm)	15,30
Pressure Angle (degree)	20
Helix Angle (degree)	0
Modulus of Elasticity (Gpa)	228

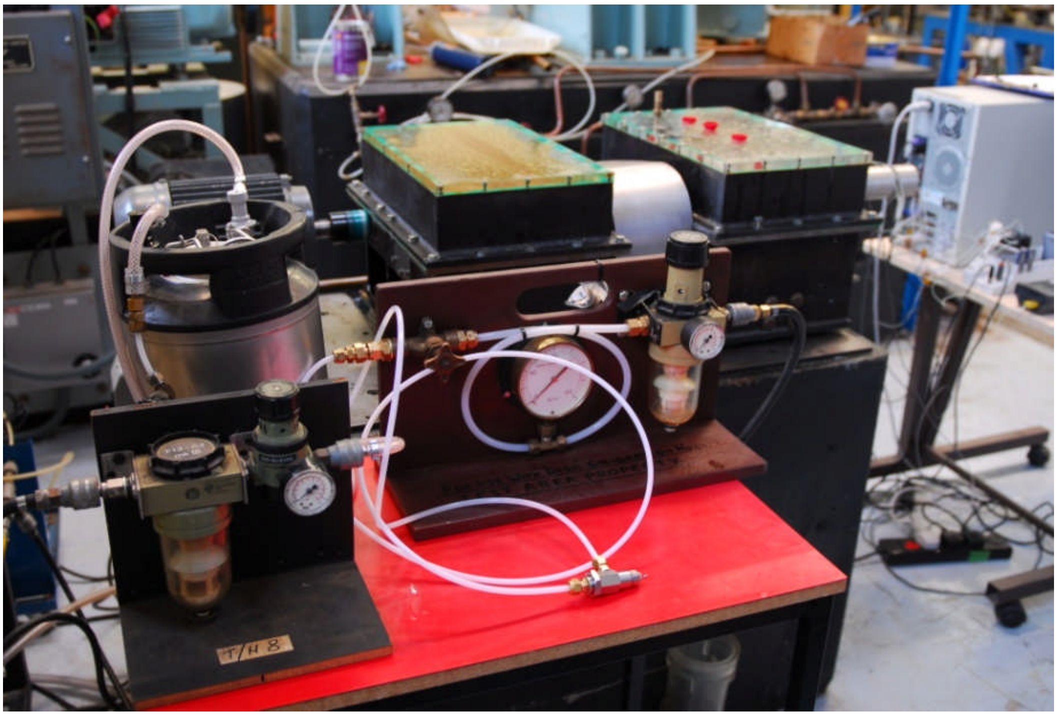


Figure 43 - Mist lubrication setup

5.5 Test Plans and Sequences

The gearbox is run under different conditions of lubrication, torque load, speed and rotation direction as shown in Table 23. The rotational direction of the gears used in the experiment is defined in Figure 44. In each run, the temperatures and time taken for the gear temperatures to stabilize are measured with the gears inspected for damage after the run. In this experiment, the gear temperature is considered to be stabilized when the rate of temperature rise is <1°c/5min (<12°c/hour). For all the tests with mist lubrication, the liquid pressure and air pressure system is adjusted to deliver thioether or oil at an approximate rate of 12-15 ml/hour which is similar to the rate employed in (Handschuh et al. 2007b).

Table 23 - Test Runs and Conditions

Test	RPM	Torque Load	Lubrication	Mist Rate	Gear Rotation
1	690	100Nm	Oil Dip	NA	CW
2	690	100Nm	Thioether Mist	12-15ml/hr	CW
3	690	100Nm	Thioether Mist	12-15ml/hr	CCW
4	1420	100Nm	Thioether Mist	12-15ml/hr	CCW
5	1420	100Nm	Oil Dip	NA	CCW
6	1420	280Nm	Oil Dip	NA	CCW
7	1420	280Nm	Thioether Mist	12-15ml/hr	CCW
8	1420	280Nm	Oil Mist	12-15ml/hr	CCW
9	1420	280Nm	Pressurised Air	NA	CCW

By comparing Test 1, 4 and 6 against Test 3, 5 and 7, the performance of oil dip lubrication against thioether mist lubrication under increasing speed and torque load conditions are evaluated. When comparing Test 1 against Test 3, it is assumed that gear rotation direction does not affect the temperature profile in oil dip lubrication. Test 2 and 3 would compare the effects of gear rotation direction on thioether lubrication. Test 7, 8 and 9 will compare the performance of thioether mist lubrication against oil mist lubrication and pressurized air cooling.

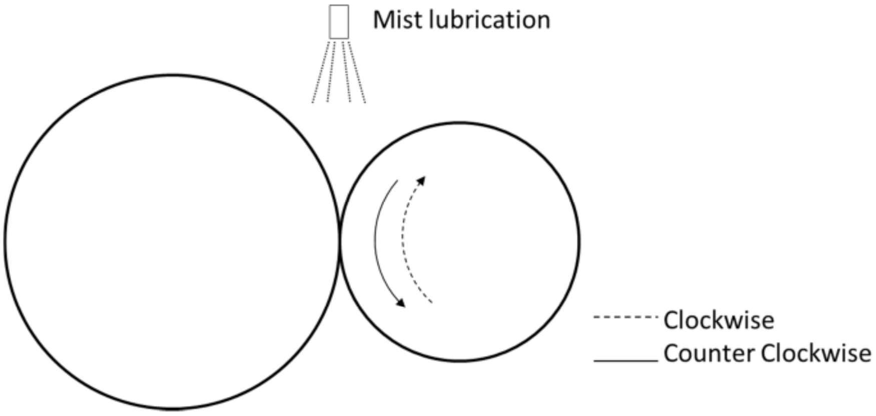


Figure 44 - Gear Rotation Direction

6 EXPERIMENTAL EVALUATION OF GEARBOX RUN DRY CAPABILITY

6.1 Main Findings of Experimental Tests

A summary of the test results is shown in Table 24 and the detailed plot for each test is shown in **Appendix G**. From the tests, the key observations made are:

i. Thioether mist lubrication does provide adequate lubrication for the gears to achieve stabilization temperatures although the stabilization temperatures reached will be higher compared to oil dip lubrication.
ii. The rotational direction of the gears has a significant impact on the performance of the mist lubrication. The mist lubrication is not effective when it is sprayed after the gear teeth meshing (CCW in the experiment) and this could be due to the thioether being "fling off" the gear surface.
iii. When oil is applied as a mist-lubrication, the rate of temperature rise of the gears is slower but it stabilizes at temperatures higher compared to thioether mist lubrication.
iv. The use of mist lubrication can significantly reduce gear wear by providing either thioether or oil lubricant at very low flow rate. This allows the lubricant reservoir of an emergency or backup lubrication system to be kept small.

Table 24 - Test Runs Result Summary

Test #	*Duration*	*Stabilization Temperature (°c)*				
		Gear Inner	*Gear Middle*	*Gear Outer*	*Gearbox Air*	*Gearbox Casing*
1	*4.90 Hrs*	*43.6*	*43.3*	*45.5*	*53.1*	*41.1*
2	*0.90 Hrs*[1]	*55.3*	*56.6*	*64.4*	*43.3*	*27.3*
3	*2.56 Hrs*	*56.0*	*56.8*	*62.6*	*56.5*	*38.4*
4	*1.54 Hrs*	*78.9*	*80.3*	*81.5*	*81.6*	*51.7*
5	*2.99 Hrs*	*59.4*	*59.7*	*59.0*	*68.6*	*48.3*
6	*1.82 Hrs*	*64.3*	*64.8*	*64.5*	*69.7*	*47.2*
7	*1.50 Hrs*	*90.9*[2]	*95.0*	*95.9*	*87.5*	*51.6*
8	*2.37 Hrs*	*98.5*	*104.4*	*103.7*	*99.4*	*59.8*
9	*0.17 Hrs*[1]	*71.7*	*119.7*	*121.4*	*63.7*	*22.8*

[1] Test terminated to prevent gear damage

[2] Last temperature shown after thermocouple dislodged at 1.36 hours

6.2 Comparison of Thioether Mist Lubrication Against Oil Dip Lubrication

The comparison of the outer gear temperature and temperature change rate between thioether against oil lubrication is shown in Figure 45 and Figure 46 respectively. It should be noted that gear temperatures will rise rapidly in the absence of lubrication as shown in Test 9. It can be seen that the thioether mist lubrication is effective in lubricating and cooling the gears to allow the gear temperatures to stabilize. The stabilization temperatures however are higher compared to oil dip lubrication. With higher speeds and torque loads, the stabilizing temperature rises thioether lubrication is still effective in allowing the gear temperature to stabilize. From Figure 46, it can also be observed that thioether mist lubrication stabilizes at a faster rate than oil dip lubrication. The temperature profile normalized to the thioether mist lubrication stabilization temperature is shown in Figure 47. It is shown that the stabilization temperature for oil lubrication is approximately 30% lower compared to thioether mist lubrication. Inspection of the gears after the tests showed minor scuffing on the gear teeth surfaces as shown in Figure 48 but there were no significant damage. A brownish lubricious layer of residue is found on the gear teeth surface after the test with thioether mist. This further ratifies that thioether mist lubrication is effective as there were no excessive wear on the gears after operating for duration > 30mins.

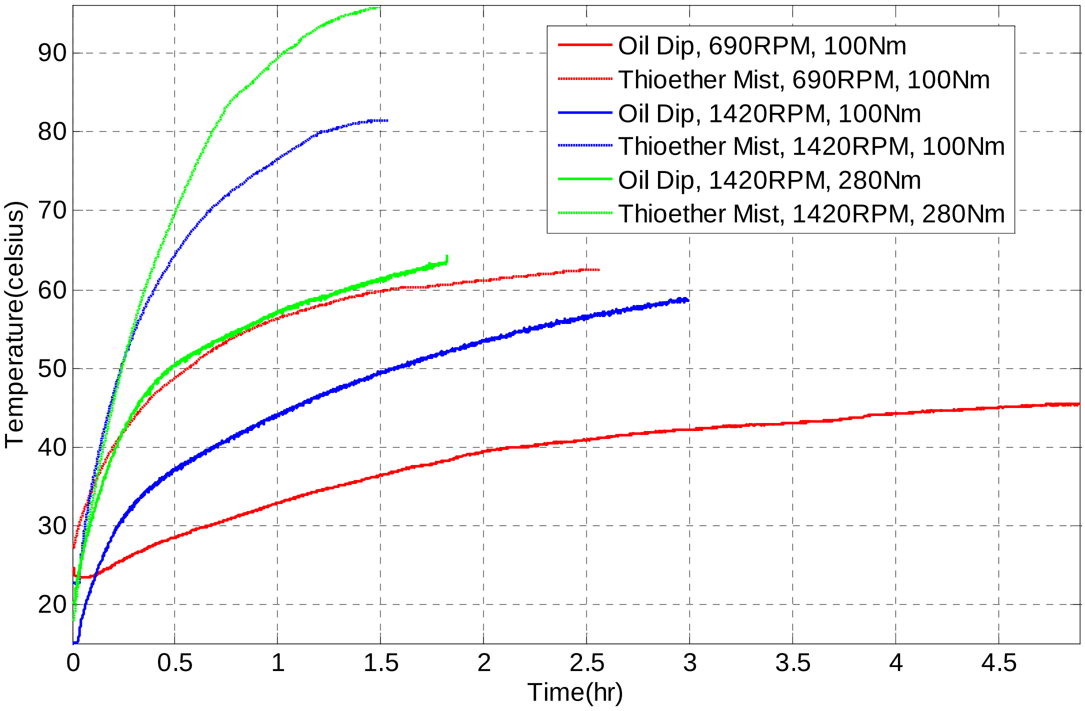


Figure 45 - Normalised Temperature profile of oil dip against thioether mist lubrication under different speed and torque load conditions (Gear outer temperature shown)

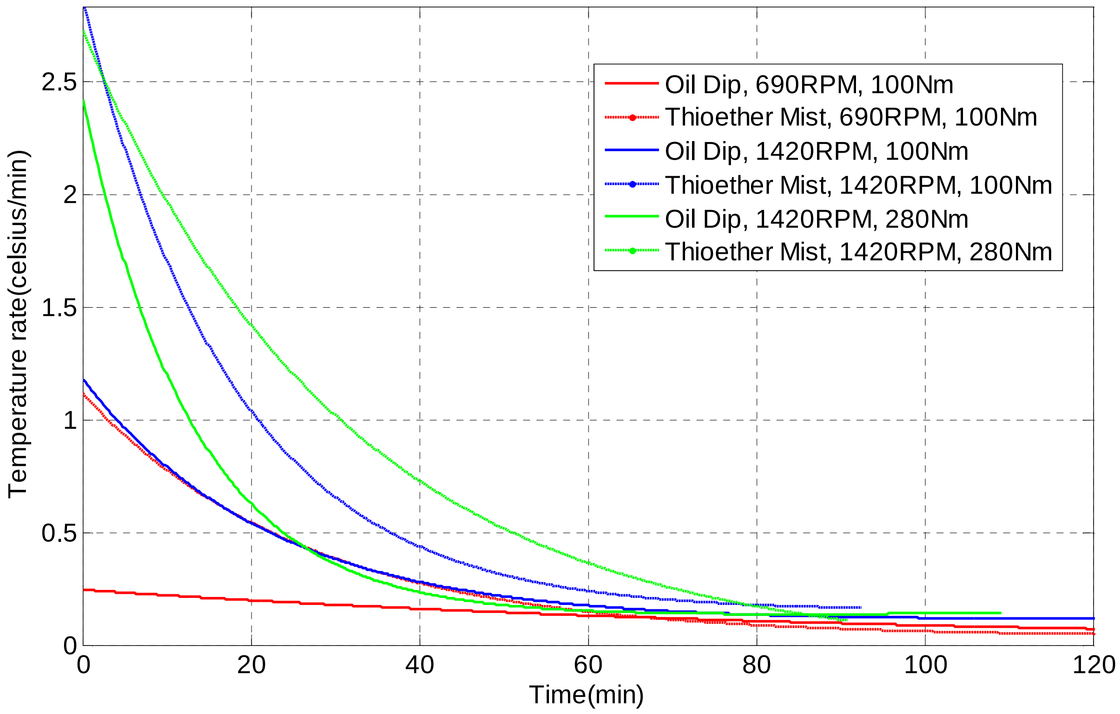


Figure 46 - Temperature rate comparison (Gear outer temperature rate shown)

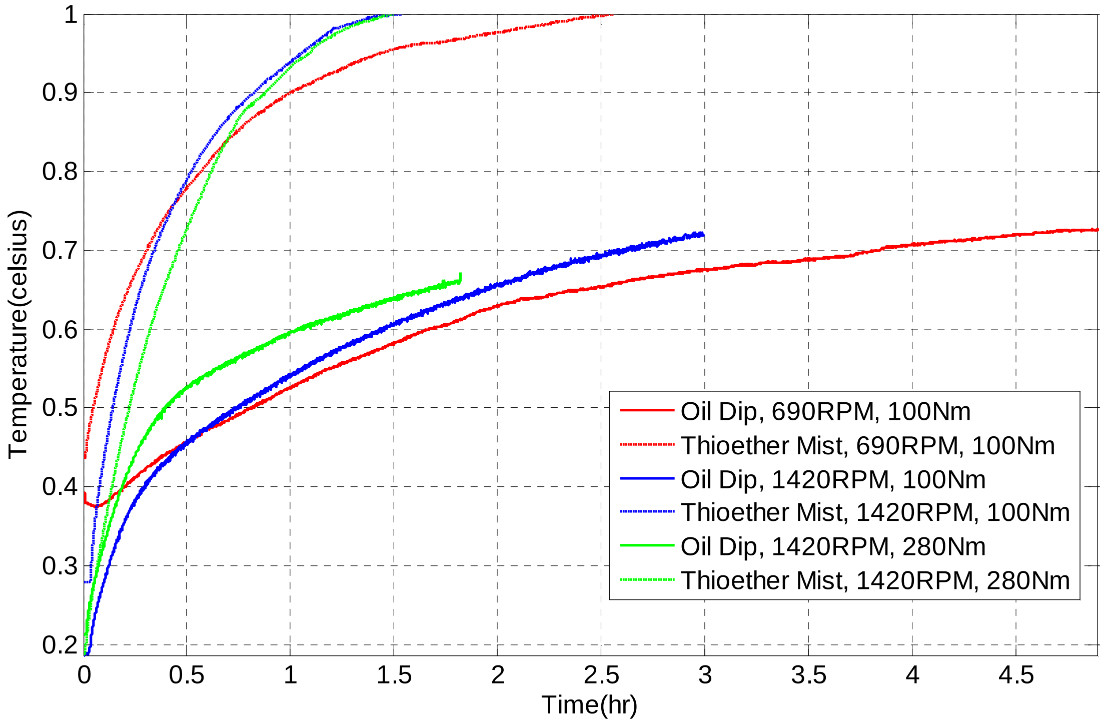


Figure 47. Normalised Temperature profile of oil dip against thioether mist lubrication under different speed and torque load conditions (Gear outer temperature shown)

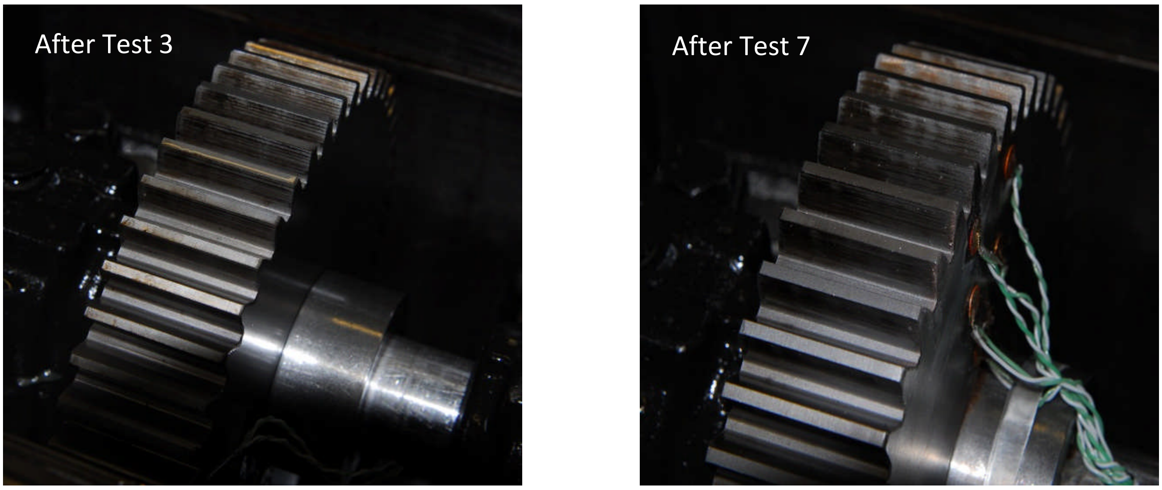


Figure 48. Undamaged gear with lubricious residue on teeth surface after Test 3 and Test 7

6.3 Comparison of Gear Rotation Direction on Thioether Lubrication

The effect of gear rotational direction when using thioether lubrication is shown in Figure 49. It is clearly seen that the mist lubrication is not effective when it is sprayed on after the gear teeth meshing as the temperature rises sharply and steadily. When the rotational direction is changed, the mist lubrication improves significantly and the temperature rise rate decreases and stabilizes. As mentioned previously, the poor performance of the mist lubrication when it is sprayed on after the gear teeth meshing could be attributed to the fling off of the thioether lubricant as the gear teeth emerges from the mesh. This can be a disadvantage for a mist lubrication based system as the spray nozzle has to be placed before the gear teeth meshes.

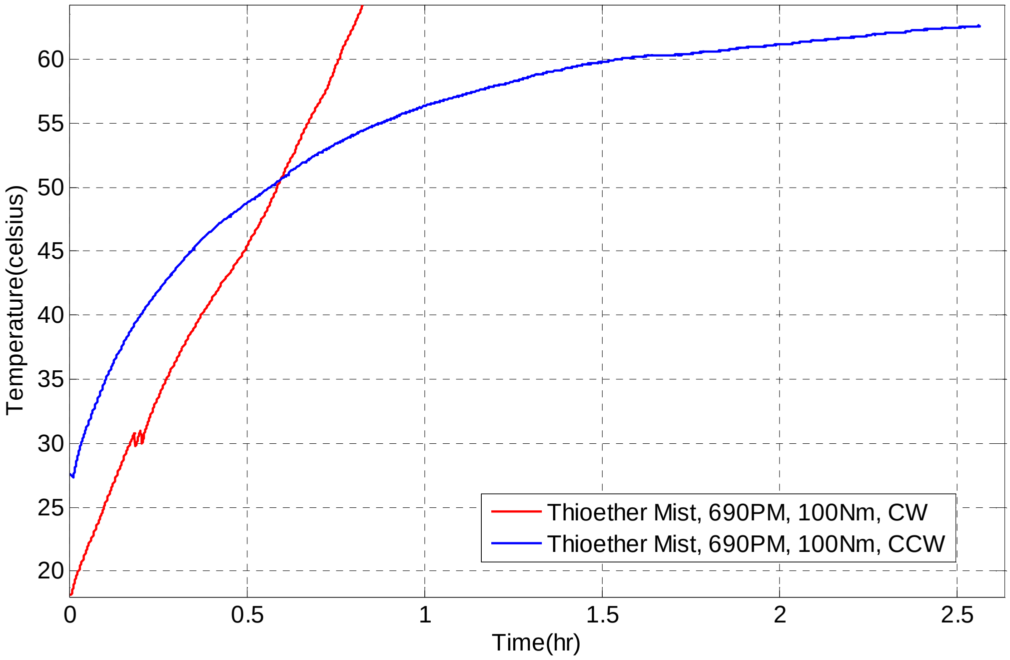


Figure 49 - Effect of gear rotation direction on Thioether mist lubrication (Gear outer temperature shown)

6.4 Comparison of Mist Lubrication Using Oil and Thioether with Air Cooling

The effect of using the Aeroshell 555 lubricating oil as a mist lubricant is also investigated in this study. This is to evaluate if the mist lubrication would be effective if an alternative lubricant is used. Like the thioether, a low flow rate of 12-15ml/hour of oil is used in Test 8 under similar speed and torque load conditions from Test 7. The temperature profile comparison between oil and thioether mist lubrication is shown in Figure 50. It can be seen that the temperature rise rate is slower for oil mist lubrication. However, thioether mist lubrication stabilizes at a lower temperature of 95.9°c compared to 103.7°c for the oil mist. This shows that oil is a viable candidate for use in mist lubrication as well. As a comparison, the temperature profile of the gears subjected to only pressurized air cooling is also shown in Figure 50 where it rises very rapidly. For a 30mins requirement for the gearbox to operate safely after loss of primary lubrication as per CS 29.927, the gear mesh in the test requires only approximately 6 – 8 ml of oil or thioether lubricant to prevent the gears from overheating and excessive wear.

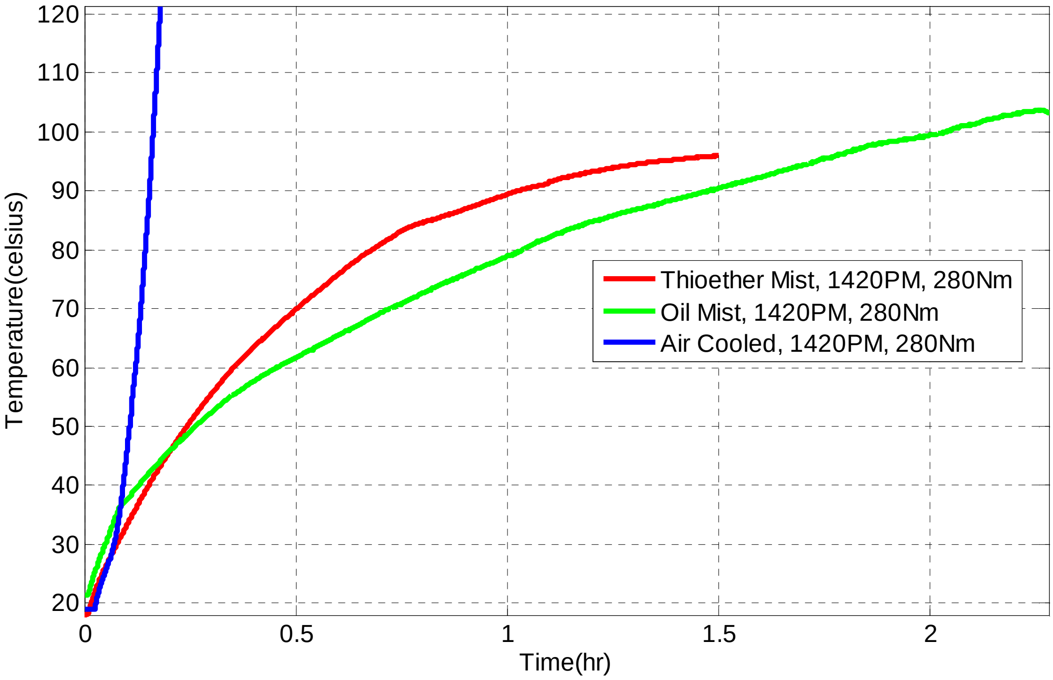


Figure 50 - Temperature profile for mist lubrication using oil, thioether and air cooling (Gear outer temperature shown)

6.5 Tests Conclusions

From this study, it can be concluded that thioether-based mist lubrication can adequately lubricate gears to achieve stabilization temperatures in a gearbox run-dry situation. The lubricant to be used is not restricted to thioether however as oil can be applied with mist lubrication as well. From the test, oil mist lubrication shows a slower rate of temperature rise but with stabilizes at temperatures higher compared to thioether mist lubrication. With the very low lubricant flow rate of a mist lubrication system, the lubricant reservoir can be kept small which is ideal for an emergency or backup lubrication system. A drawback of the mist lubrication system is that the rotational direction of the gears has a significant impact on performance. The mist lubrication is not effective when it is sprayed after the gear teeth meshing and this may complicate the design of the spray system.

PART FOUR

MGB Lubrication System Optimization

7 DISCUSSION OF RESEARCH FINDINGS

7.1 General

This report summarizes the activities carried out for the HELMGOP project. These may be summarised under the headings Lubrication Technologies, Safety and Reliability assessment and Airworthiness requirements. The following Table able lists all possible intervention techniques that can be considered for MGB oil loss optimization target.

Overall intervention options of HELMGOP

Optimization Area	Main Failures Areas	Intervention Options
Lubrication System Reliability Enhancement	Oil Quality Oil Quantity Oil Flow Pressure	SRK errors / Memory errors (Human) Design for maintenance Internal oil pockets / Pools Oil absorbent materials Auxiliary non pressurized oil dropping source Auxiliary oil-air mist Auxiliary pressurized oil system Oil system re-configuration Material modification Prevention of Internal parts failures. External input prevention
MGB Run-Dry Capability Enhancement	MGB Components MGB Manufacturing	Parts heat expansion clearance enhancement MGB heat dissipation capacity enhancement Parts mechanical strength enhancement Material heat resistance enhancement Material wear resistance enhancement Material self-lubrication property enhancement Advanced parts machining Parts coating Parts super-finishing Parts chemical treatments Manufacturing procedures enhancement (including human input)

In addition to literature review, the work has been informed and assisted by contact with operators and maintainers of large helicopters. The MOD Project Teams have been consulted (with manufacturer support) as well as the Royal Navy Flight Safety Centre (Yeovilton) and 1710 Naval Air Squadron at Portsmouth. Bristow Helicopters Ltd, operator of category A helicopters, have also supported the project.

7.2 Lubrication Technologies

The concept for vapour/mist phase lubrication (VMPL) involves the delivery of organic molecules, via a carrier gas such as air, to rubbing components such as ball bearings or gear teeth.

In application of certain lubrication schemes a disadvantage of the hydrocarbon option is that aircraft must carry cylinders of compressed hydrocarbons and nitrogen. The nitrogen is needed to avoid combustion of the hydrocarbon. VMPL only requires compressed air and a small misting unit containing an organophosphate. The organophosphate reacts with the gear surfaces to form a lubricious deposit that possesses excellent load carrying capacity however continued reaction will eventually lead to gear surface wear. The unanswered question is how long such a lubricating system will last before severe wear develops on the gear faces.

Handschuh and Morales (2000) investigated the use of VMPL by undertaking comparisons of baseline tests, using a synthetic lubricant that would be typically employed in operation, with an organophosphate mist lubrication system. Temperatures were measured for both test cases and the gear teeth inspected using an X-ray photoelectron spectroscopy (XPS).

Key results from these tests (Handschuh and Morales 2000) showed that mist lubrication caused a reduction in gear temperature from 28 minutes of operation whilst no-mist lubrication caused the gear temperature to continually increase. The decrease in temperature from the mist is attributed to a reduction in coefficient of friction since the relative sliding speeds remain unaltered. There was some evidence that the surface geometry was altered though it was stated (Handschuh and Morales, 2000) this effect on the magnitude of heat generation should be minimal. It was noted that the rate of mist flow was stated as low – what is low and what effect of mist rates have on the on durability of gears is under investigation.

The majority of studies in mist/vapour phase lubrication have employed liquid phosphate ester. Whilst this lubrication method works well, its continuous use can lead to unacceptable wear rates. Handschuh et al. (2007b) investigated some of the properties of a polyphenyl thioether liquid. Polyphenyl thioethers are derivatives of polyphenyl ethers where one or more of the oxygen atoms in the polyphenyl ethers are replaced by sulphur atoms. An initial investigation into the use of a thioether as a VMPL lubricant was conducted using a high temperature reciprocating pin-on-plate tribometer (Handschuh et al. (2007b). The tests showed that the thio-ether was able to lubricate a ceramic pin and plate pair, at temperatures greater than 450 °C, with a coefficient of friction less than 0.05 with minimal wear of the substrates.

The lubricant was then tested on case-carburized and ground AISI 9310 spur gears. The mister was filled with thio-ether and delivered at 15ml/hour in a flowing air stream of 400l/hour. (Handschuh et al. 2007b). The results from this study clearly showed a dramatic improvement over the results from investigations that employed synthetic paraffinic oil and a phosphate ester oil (Handschuh and Morales 1999, 2000, 2005). For instance, the primary evidence that good lubrication was provided, using the thioether, was the observed minimal gross wear on the gear teeth even after 35 hour of operation at 10,000 rpm speed and gear tooth force of 516 N. Gear tooth wear, however, was observed using the paraffinic oil and phosphate ester after only 10 min of operation in other investigations. The results of this test are a significant advance in the use of VMPL.

The use of VMPL shows significant promise as a potential option to operate gearboxes after the loss of the principal lubrication system. Of particular significant is the performance of the Thioether liquid as a vapour/mist lubricant. However there are still unanswered questions that need to be addressed such as:

i. What is the influence of gear surface finish on the effectiveness of VMPL
ii. Limit on material operating temperatures
iii. Where is the optimal positioning for the mist jets and mist supply rate
iv. Are there even better performing organosphosphates?
v. Temperature measurements reported as in the vicinity of the 'fling off' and not actually on the gear metal.

Such a back-up lubrication system would not have a significant weight penalty, but would provide a valuable safety feature to assist in the case of a main lubrication system failure.

In addition to the above technique, considerable merit may be seen in the Type C lubrication system. This consists of a dual redundancy system with each system consisting of an oil sump, an oil pump and oil cooler - see Figures D9 and D10 in **Appendix D**.

Notably, the Type C features a unique safety measure where 'wicks' are located at key gears and bearing locations. These wicks retain and store oil during normal operation, and can then release lubricant during a run-dry situation. This will continue to lubricate components through capillary action. Although this does not improve the reliability of oil and oil pressure loss, it does improve the run-dry capability of the transmission significantly. It worth highlighting here that the 'wicks' system by itself can be considered reliable as its design is very simple with no moving parts involved, however, currently there are no measures that set definite quantification for such reliability.

7.3 Safety and Reliability Assessment

Monte Carlo Simulation has been applied to the reliability analysis for the Type B gearbox lubrication system. It has a number of benefits which include the ability to cope with uncertainty in the data. This was followed by the Influence diagram (ID) approach which addresses the reliability investigation and reliability of the MGB lubrication system. This is analysed as an independent system from the MGB, though some connections are always present. For instance, the MGB case is the main structure of the MGB, but the model here only focusses on it as a means for oil cooling (heat dissipation) or as a leak-free structure (for oil leak resistance).

The reliability of the lubrication system is significantly influenced by human and organizational inputs. Thus the overall system reliability calculations must accommodate for such inputs.

The model only handles the direct influences between the lubrication system components and functions; indirect influences are not considered. For example, the MGB case influences the cooling function directly (heat dissipation to external ambient environment), however, the MGB case only influences the initial oil quantity indirectly (through human error in reading oil level if the oil level glass in poorly designed). Thus the first direct relation is expressed by an influence arrow while the second indirect relation is not represented.

The model works on the assumption that the lubrication system adequately receives the designed motive forces from external sources. For instance, it is always assumed that adequate dynamic power (input from engines) and electrical supply are secured during the MGB lubrication system operation.

The concept of risk in preparing this model is taken as ‘the case when the given component of lubrication system operates or behaves or exists in deviated manner other than the designed ranges or conditions’. The model thus calculates the probability of such risk (event failure) to occur regardless of the severity of that event on the system.

The ID model is widely applicable for studying the reliability of the MGB lubrication system in either collective functional behaviour, or focused component-based orientation.

It can be seen that the ID approach is a promising powerful technique that can readily be applied by researchers as well as practitioners to deeply investigate the reliability of helicopter MGB lubrication system and all other systems as well. The unseen interdependency between various factors influencing that reliability can widely be uncovered. The numerical manipulation of input is a freely available strategy that can help investigate focal influences of the 15 listed initial triggers of failure. For instance, in the first application of the model as covered by this report (the component-based reliability investigation), only one sub- influential factor is varied while freezing influences from all other triggers. This is ideal for exploring the behaviour of the whole system while only one input is varied. However, the model can further freely accept any variations of combinations of sub-factors input. For example, the model can adequately explores the joined effect of combinations like filtration and internal debris impurities, human error and electrical/ electronic components, pumps failure and drive to cooler failure if occurred simultaneously. The model is thus promising for holding countless numbers of situations of things that can go wrong individually and in combinations. It can thus resample all actual historical events of MGB lubrication system failures as an investigative tool, as well as predicting critical scenarios that can occur in the future as results of multi-input triggers.

Another readily available feature of the approach is the possible estimation of the ‘safe ranges’ of failure probabilities of system or its main components. In other words, the model can be utilized to identify or estimate the maximum ‘permissible’ probability of failure for a given component, or a selected set of components, before the targeted governing failure probability of the whole lubrication system is reached. This may be of interest for designers and manufacturers in a practical sense.

7.4 Airworthiness Requirements

The current certification standards were described briefly in Section 2.5.2, and are worthy of further discussion here. The comparison of civil and military Certification standards has proved to be valuable, and it would seem useful to review the former to make the requirements more detailed and prescriptive. A number of different sources have been consulted, which are taken from both European and US civil and military sources. The various standards are quoted in **Appendix C**:

EASA CS29, Subpart E – “Powerplant” (**Appendix C.1**)
FAR 29.927 “Additional tests” and AC 29.927 (**Appendix C.2**)
UK Def-Stan 00-970 Part 7 Rotorcraft, Section 7 “Installations” (**Appendix C.3**)
DoD, MIL-HDBK-516C Airworthiness Certification Criteria
JSSG-2009 Joint Services Specification Guide: Air Vehicle Subsystems (**Appendix C.4**)

7.4.1 Civil approach to certification of lubrication system

The civil route to obtain a Type Certificate is quite well established and the approach of the FAA and EASA is similar in many respects. The lubrication system is certificated as part of the MGB, and as such does not have to meet explicit safety targets.

Although quoted in **Appendix C.1**, CS29.901 – Installation and CS29.903 do not apply to the lubrication system. The certification of the latter is covered by CS29.917 Rotor drive system Design, which applies to “any part necessary to transmit power from the engines to the rotor hubs”. The safety requirements are to be met by Design assessment (CS29.917b) which should analyse all functions over the complete range of operation. This failure analysis does not contain any numerical safety targets. It requires that all potentially catastrophic failure conditions are identified together with the means to “minimise the likelihood of their occurrence”.

The testing of the lubrication system is explained in CS29.927 “Additional Tests” Part (c) which gives the requirement for 30 minutes continued operation after “perception by the flight crew of the lubrication system failure or loss of lubricant”. However, this requirement may be “bypassed” if it is shown that such a failure is extremely remote, i.e. 1×10^{-7} per hour or better. It is this caveat that is under scrutiny after the S-92 crash, see TSB Report **A09A0016,** Recommendation **A11-01.** There are few conditions placed on the operation during the 30 minute period at a “torque and rotational speed prescribed by the applicant for continued flight**”.** This is in contrast to the military specifications which are more prescriptive regarding this test.

Of additional interest is the CS29.1309 which covers “Equipment, systems, and installations”. Unlike the equivalent standard for fixed wing aircraft (CS25.1309), this does not require that there are no “single point” failures. It does however stipulate quantitative safety targets that must be met, which (for category A helicopters) are:

> Any failure condition which would prevent the continued safe flight and landing is **extremely improbable [1 x 10^{-9} per FH or better];** and
> Any other failure conditions which would reduce the capability of the rotorcraft or the ability of the crew to cope with adverse operating conditions is **improbable [1 x 10^{-5} per FH or better]**

However, despite the use of the word “system”, the above requirement is not applied to the Lubrication system. The lubrication system of the transmission is covered by CS29.917. If CS29.901(c) were used, this would ensure that no single point failures could occur, as it states “For each power-plant and auxiliary power unit installation, it must be established that *no single failure or malfunction or probable combination of failures will jeopardise the safe operation of the rotorcraft…”*

In **Appendix C.2**, the FAA equivalent of CS29 is shown to be largely similar with regard to lubrication system failure. The Advisory circular that accompanies the requirement, AC 29.927 gives additional information regarding the test, and EASA CM-RTS-001 (2012) also refers. The recommended test procedure is to cause an oil leak and test the gearbox for 15 minutes after illumination of low oil pressure warning, at reduced torque for simulated auto-rotation. It was not clear if the 30 minutes oil system test includes 15minutes for the oil to drain prior to low oil pressure warning. The actual run-dry time of the gearbox within the 30 minute test period is therefore not well defined.

7.4.2 Military approach to certification of lubrication system

The UK standard for certification of military helicopters is Def-Stan 00-970 Part 7 (see **Appendix C.3**). Section 7 of this document set refers to Installations, which includes transmission systems. In the same way as the civil standard, the requirements states that the transmission should continue to function for at least 30 minutes following loss of oil. The latter is defined as “the reduction in the volume of oil from any self-contained oil system below the permitted minimum, for whatever reason”.

It is useful to note that the standard gives clear definitions of a number of relevant terms, for example "Flight Endurance Following Loss of Oil" and "Test Endurance Following Loss of Oil". Section 6 of the standard is entitled "Oil System Integrity" and gives additional guidance as to the safety-critical nature of the lubrication system. It emphasises that loss of oil or failure to provide load capacity or cooling could lead to catastrophic failure. In this case it is suggested that "the lubricant containment and supply systems should be treated as **Grade A Parts**". These are parts which should be specified, designed an333d manufactured to higher standards "if there is a probability that its failure will result in the malfunction or failure of another Grade A part or assembly" [**Def-Stan 00-970 Part 7, Section 4 Leaflet 400 Grading of Parts and Assemblies, 2007**]

It continues to emphasise that if a lubrication system lacks redundancy e.g. only one reservoir exists, the components of the system should be treated as **Vital Parts**. This category is a subset of Grade A Parts above, the standards for which may be even more stringent.

The Sea King helicopter may be described as a useful case study. After many years of service, and occasions of MGB lubrication failure, the aircraft was retro-fitted with an Emergency Lubrication System (ELS). Although two main oil pumps are used as standard on the MGB, there is a lack of redundancy elsewhere in the system. Hence the ELS uses a third pump which operates from a second sump (below the main). This then feeds an independent distribution system **[Hyde, 1992**]. If failure of the main lubrication system occurs in flight, the backup system takes over and can provide an hour at minimum cruise power. In this mode, oil does not pass through the cooler, but temperatures were within limits, demonstrated by a two hour rig test **[Hyde, 1992**].

In the US military, standards are published by the Department of Defense (DoD), parts of which are given in Appendix C.4. As well as Mil-Std-516C, there are requirements contained in the Joint Services Specification Guide, JSSG-2009. As mentioned earlier, the requirements here are more prescriptive, stating *"the gearboxes shall function for at least 30 minutes after <u>complete loss of the lubricant</u> from the primary lubrication system".* The military load spectrum is well defined as follows [JSSG-2009]:

> *a. Two minutes at rated power to simulate hover.*
> *b. Twenty six minutes at a power condition to simulate cruise.*
> *c. Two minutes at a power condition simulating vertical landing.*

8 RESEARCH CONCLUSIONS AND RECOMMENDATIONS

8.1 Lubrication Technologies

i. The use of Vapour/Mist Phase lubrication (VMPL) shows significant promise as a potential option to operate gearboxes after the loss of the principal lubrication system. Of particular significant is the performance of the Thioether liquid as a vapour/mist lubricant.

ii. Further investigation should be carried out to measure the performance of “wicks” located at key gears and bearing locations. These wicks retain and store oil during normal operation, and can then release lubricant during a run-dry situation. This will continue to lubricate components through capillary action.

8.2 Safety and Reliability Assessment

i. Monte Carlo simulation can be used as an effective technique to represent the reliability of the lubrication system. This is useful when the parameters in question are either unknown or only based on limited test data.

ii. The Influence Diagram (ID) approach is a promising powerful technique that can readily be applied to investigate the reliability of helicopter MGB lubrication system and other parts of the Rotor Transmission system. The model can be used to accept input data from a variety of sources, including manufacturer, operator and maintenance staff.

iii. The ID model can be used to explore the behaviour of the whole system while only one input is varied. However, the model can further freely accept any variations of combinations of sub-factors input.

iv. The ID model can be used to represent situations that can go wrong individually and in combinations. It can also be applied to estimate the ‘safe ranges’ of failure probabilities of system or its main components. In other words, the model can be utilized to identify or estimate the maximum ‘permissible’ probability of failure for a given component, or a selected set of components.

v. The ID approach, when built resting on concrete evidence from historical events and research output, can open wide scopes for investigating as well as predicting numberless cases of failure mechanisms of the lubrication oil system or its components.

8.3 Airworthiness Requirements

i. The start and duration of the lubrication system failure test should be defined more clearly. The two criteria currently used are:

    a. *"at least 30 minutes after perception by the flight-crew of the lubrication system failure or loss of lubricant"*
    b. *"auto-rotative conditions for 15 minutes after illumination of low oil pressure warning".*

ii. It is suggested that the lubrication system test should be more tightly defined, as per military standards, for example:

    > "*the gearboxes shall function for at least 30 minutes after <u>complete loss of the lubricant</u> from the primary lubrication system"* [JSSG-2009]

iii. The expected torque spectrum required for safe recovery after enunciated loss of lubrication should be defined for the lubrication system failure test. A useful start point would be that of JSSG-2009, namely "*Time 1 at rated power to simulate hover, Time 2 at power condition to simulate cruise, Time 3 at a power condition simulating vertical landing / auto-rotation."*

iv. Certification standards for civil types could be modified to reflect the safety-critical nature of the lubrication system, as shown in Def-Stan 00-970. If a catastrophic failure can be caused by a single failure, steps could be taken to provide back-up lubrication systems, as exemplified by the Sea-King ELS.

v. Safety assessment requirements should be applied to the lubrication system as a distinct part of the transmission system. This could be done in a similar manner to CS29.901(c), for example "*Within the MGB lubrication system, it must be established that no single failure or malfunction or probable combination of failures will jeopardise the safe operation of the rotorcraft"*

vi. The exemption clause "Unless such failures are extremely remote…" should be removed, as there are common cause failures which will prevent such a target being met in practice.

vii. The duration of the lubrication system test should be increased to one hour. This will reflect the extended operating range of helicopters, plus the improved techniques currently available for operating after failure of the MGB lubrication system.

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- MOD Merlin Project Team
- MOD Sea King Project Team
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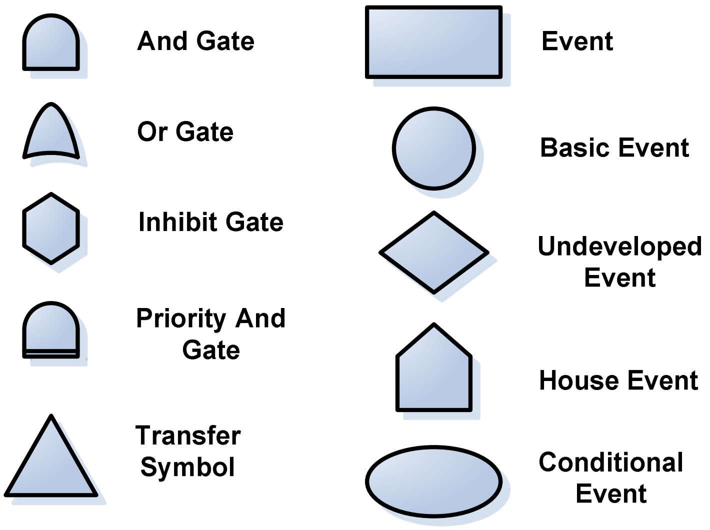
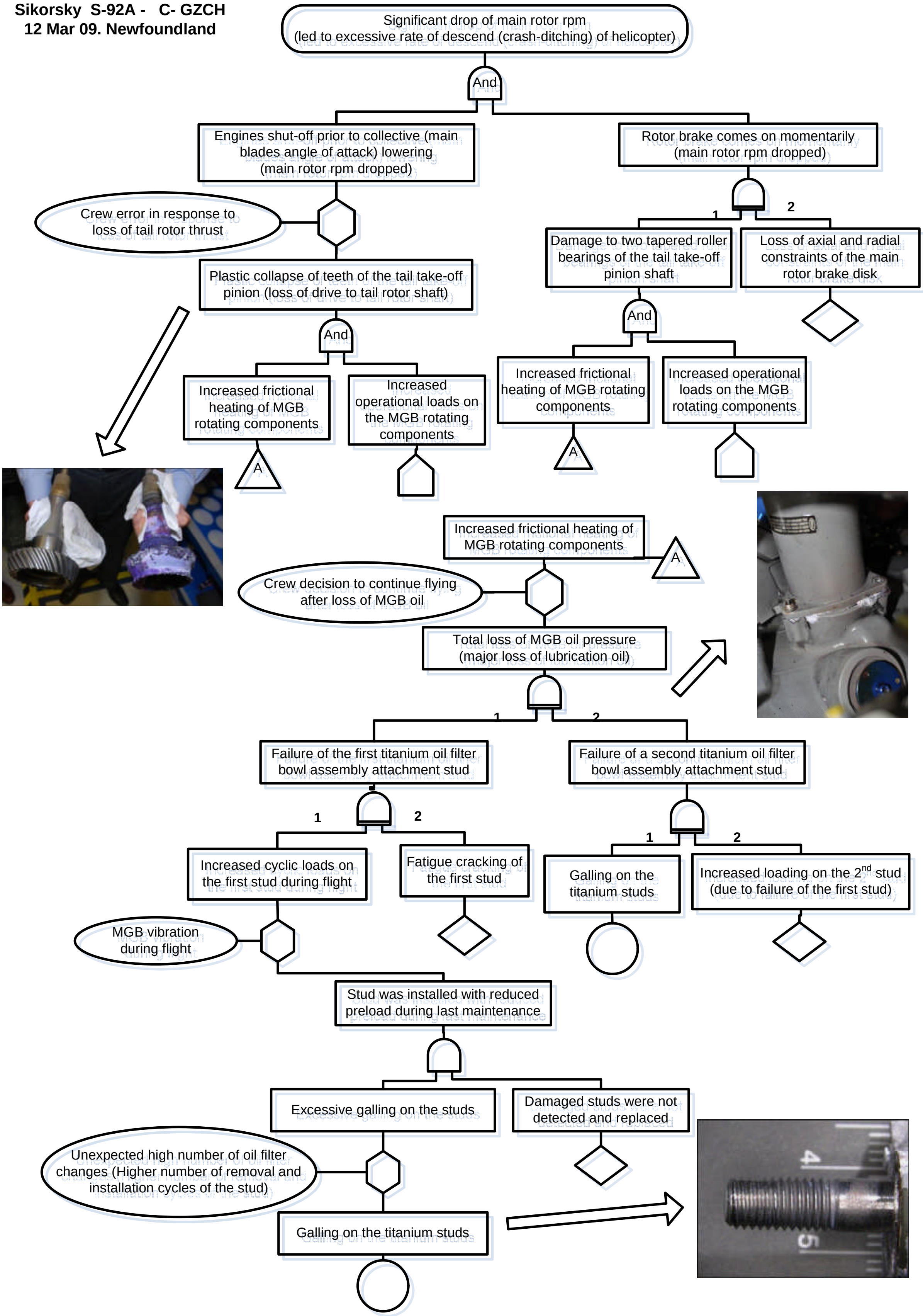
Appendix A

Fault Tree Analysis Diagrams of Sample Helicopter MGB Lubrication System Failures

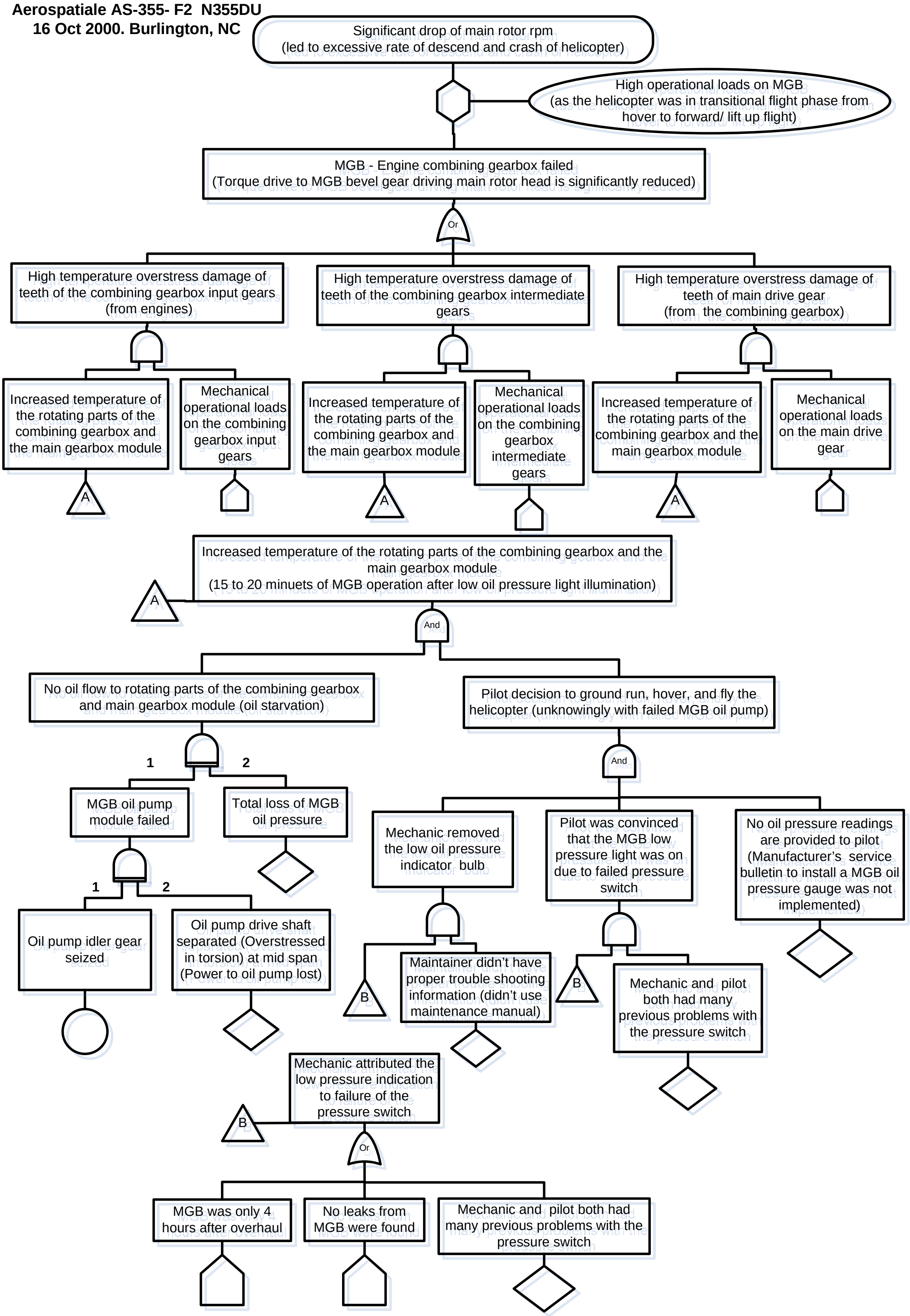
Key For Fault Tree Analysis



Sikorsky S-92A - C- GZCH
12 Mar 09. Newfoundland



Aerospatiale AS-355- F2 N355DU
16 Oct 2000. Burlington, NC



Schweizer 269C-1 C-FZQF
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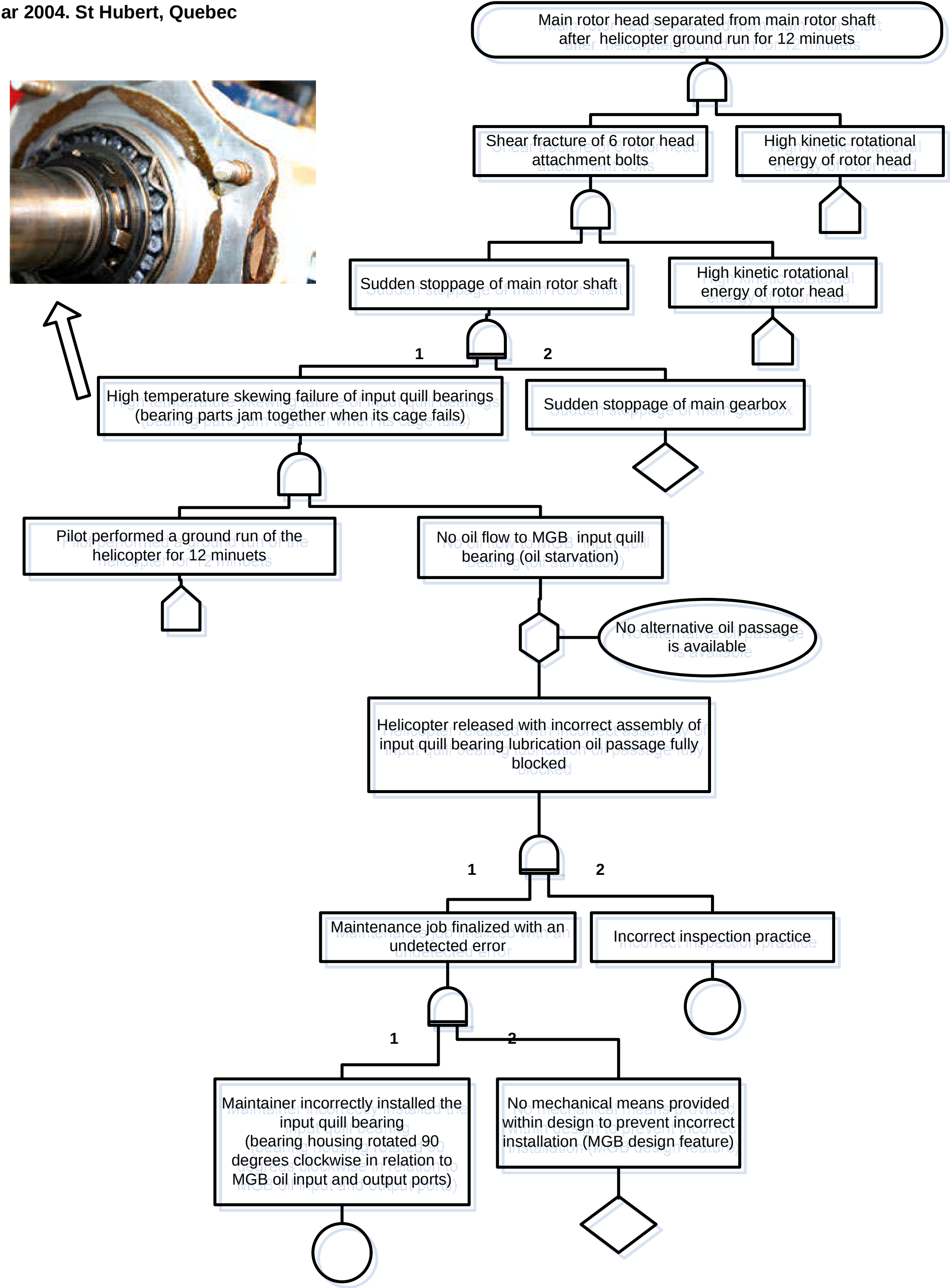

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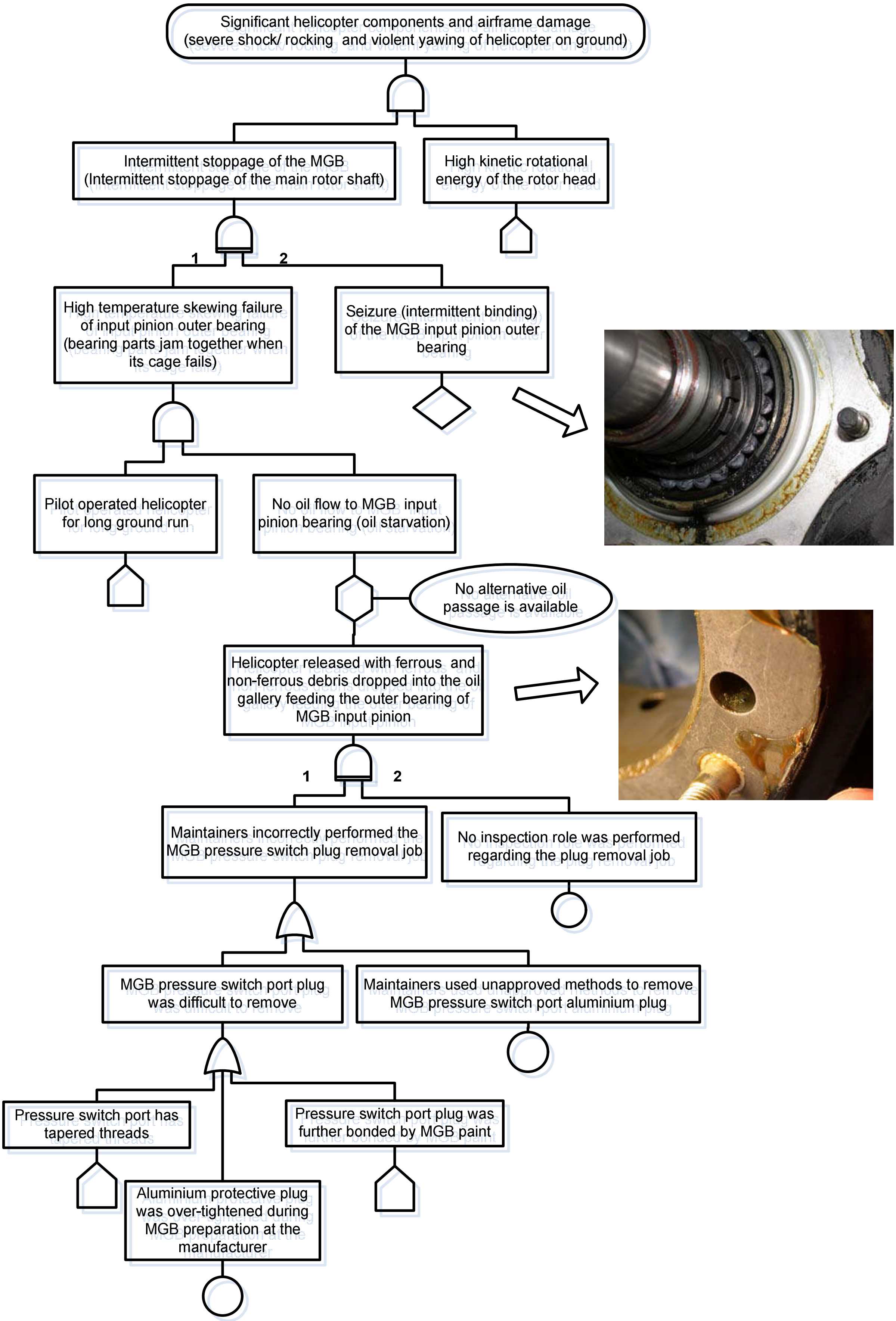
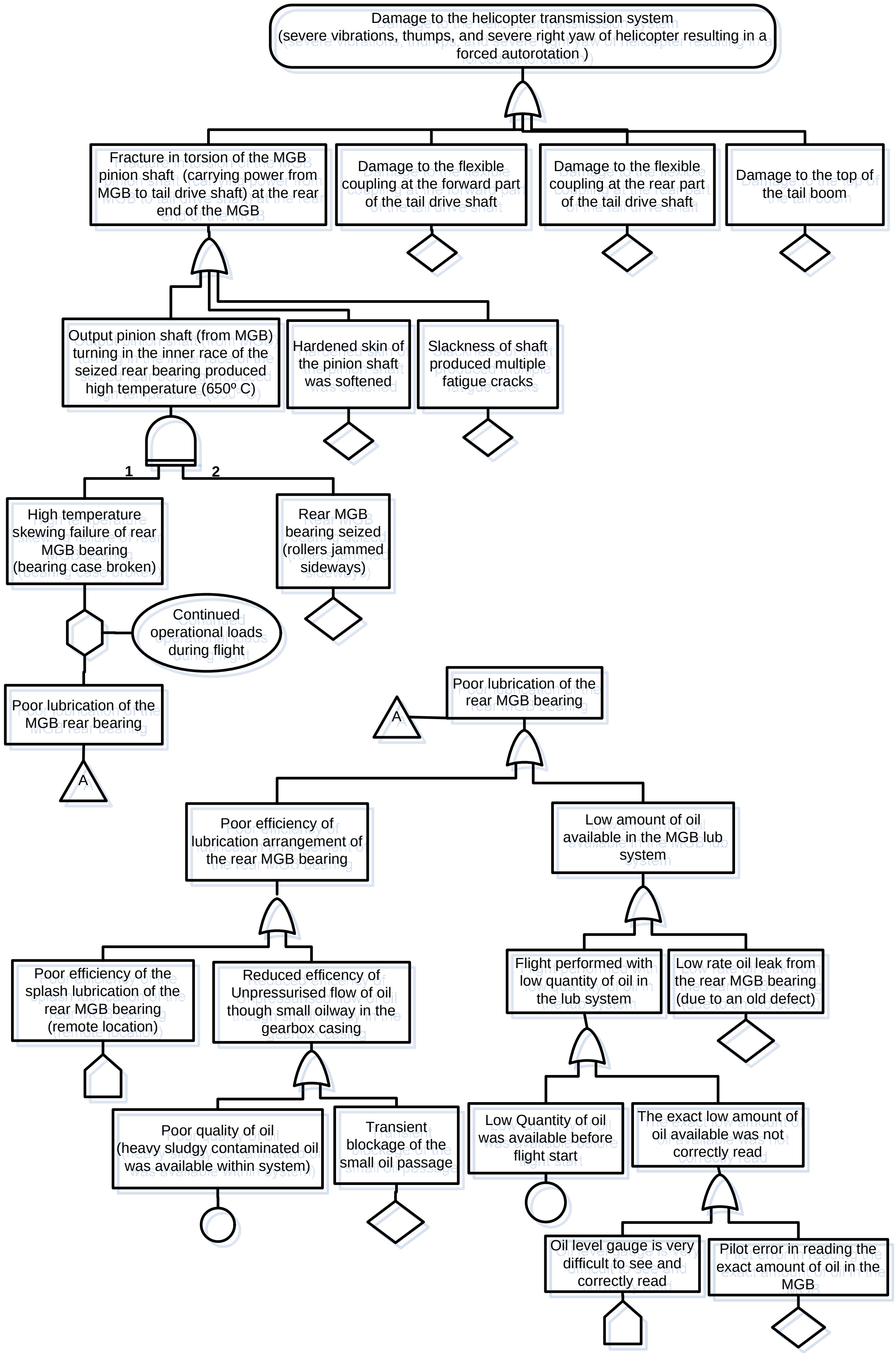


Enstrom F- 28F Falcon G- BXXW
06 Aug 2003. Wellesbourne, UK



Appendix B

Common Helicopter Lubrication System Components

SN	Component	Functional Description
1	Oil Sump	To store the oil
2	Temperature Sensor	To monitor the oil temperature in the sump
3	Debris Detector	To monitor the oil returning from the transmission for metallic chips.
4	Oil Pump	To scavenge oil from the reservoir and deliver it at the required flow rate and pressure to the Oil Cooler and Oil Gallery
5	Oil Pump Pressure Relief Valves	To drain the oil back into the reservoir if the oil pressure is too high.
6	Oil Filters	To remove particles whose size can cause distress to contacting surfaces.
7	Oil Filter Bypass	To bypass the Oil Filter when the pressure is too high.
8	Oil Cooler	To maintain the gearbox oil-in temperature below the maximum allowed
9	Oil Cooler Pressure & Temperature Bypass	To bypass the oil cooler when the pressure to the heat exchanger is too high or when the oil temperature is too low.
10	Oil Passageway	To channel the oil between the lubrication subsystems. (Includes all pipelines and connectors between the oil sump and the oil gallery)
11	Pressure Sensor	To monitor the oil pressure in the Oil Gallery
12	Check Valves	To prevent backflow of oil from the Oil Jet if the oil pressure drops.
13	Oil Gallery	To direct pressurised oil at gears and bearing locations.
14	Pressure Regulator	To regulate the pressure of the Oil Jet screen by draining excessive oil back into the reservoir.

1	Oil Sump
2	Temperature Sensor
3	Debris Detector
4	Oil Pump
5	Oil Pump Pressure Relief Valves
6	Oil Filters
7	Oil Filter Bypass
8	Oil Cooler
9	Heat Exchanger Pressure & Temp. Bypass
10	Oil Passageway
11	Pressure Sensor
12	Oil Gallery
13	Pressure Regulator

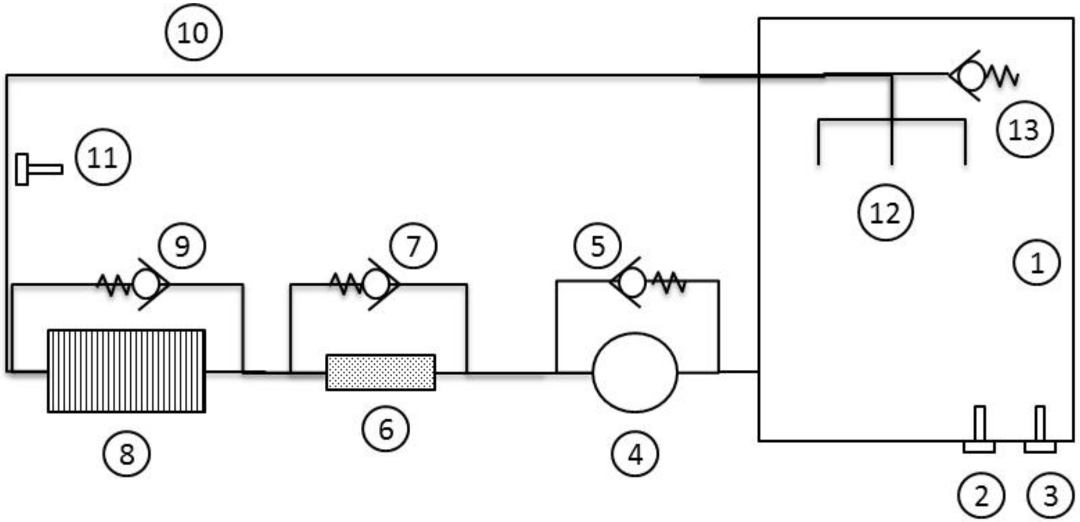


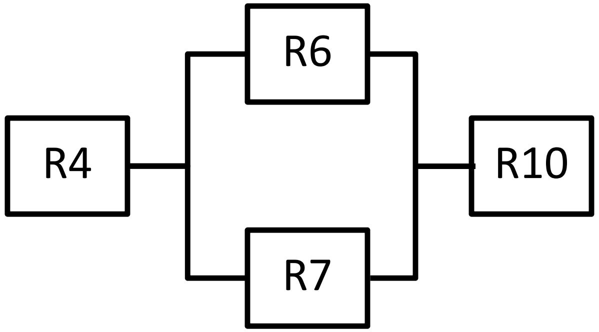
Fig B1 Basic Lubrication System

	Components	MTBF (hours)	Reliability at 5 hours
R1	Primary Oil Reservoir	10000	0.9995
R10	Oil Passageway	10000	0.9995
System Reliability, Rsys			0.9990

Probability of loss of oil (at 5 hours) = 9.995E-04

Fig B2 Basic Lubrication System RBD for Loss of Oil

	Components	MTBF	t=5
R4	Oil Pump	2000	0.9975
R6	Oil Filter	2000	0.9975
R7	Oil Filter Bypass	2000	0.9975
R10	Oil Passageway	10000	0.9995
System Reliability, Rsys			0.9970
Prob. of loss of oil pressure			3.005E-03



Rsys = R4*(1-(1-R6)*(1-R7))*R10

Fig B3 Basic Lubrication System RBD for Loss of Oil Pressure

FMEA WORKSHEET

SYSTEM	Transmission System	DATE	
INDENTURE LEVEL	Transmission system → Basic Lubrication System	SHEET	
REFERENCE	[5]	COMPILED BY	

ID NO	ITEM DESCRIPTION	FUNCTION	FAILURE MODE	POTENTIAL CAUSES	LOCAL EFFECT	END EFFECT	DETECTION METHOD	SEVERITY CLASS
1	Lubrication System	To lubricate and cool transmission bearings and gears	Complete loss of lubricating oil	Oil passageway fracture	Massive Oil leakage	Transmission runs dry leading to severe and rapid wear of gears and bearings	Oil pressure sensor detects drop in oil pressure	Catastrophic
				Oil Sump fracture				
			Complete loss of Oil Pressure	Pump Failure	No oil distributed to the oil gallery			
				Oil passageway blocked				
				Oil Filter blocked & Oil filter bypass failure				
			Oil Overheating	Oil Cooler Failure	Increasing oil temperature	Higher wear rate due to reduced lubricant film	Oil temperature sensor detects rise in oil temperature	Critical

Appendix C

Current Regulations for Certification of Lubrication Systems

The following sections are ***verbatim*** extracts from the relevant regulations that cover MGB lubrication systems for large Category A helicopters.

Appendix C.1 - EASA CS29, SUBPART E – POWERPLANT

General

CS 29.901 Installation

(a) For the purpose of this Code, the powerplant installation includes each part of the rotorcraft (other than the main and auxiliary rotor structures) that:

(1) Is necessary for propulsion;
(2) Affects the control of the major propulsive units; or
(3) Affects the safety of the major propulsive units between normal inspections or overhauls.

……

(c) For each power-plant and auxiliary power unit installation, it must be established that no single failure or malfunction or probable combination of failures will jeopardise the safe operation of the rotorcraft except that the failure of structural elements need not be considered if the probability of any such failure is extremely remote.

CS 29.903 Engines

This does not specifically address lubrication system.

ROTOR DRIVE SYSTEM

CS 29.917 Design

(a) General. The rotor drive system includes any part necessary to transmit power from the engines to the rotor hubs. This includes gearboxes, shafting, universal joints, couplings, rotor brake assemblies, clutches, supporting bearings for shafting, any attendant accessory pads or drives, and any cooling fans that are a part of, or attached to, or mounted on the rotor drive system.

(b) Design assessment. A design assessment must be performed to ensure that the rotor drive system functions safely over the full range of conditions for which certification is sought. The design assessment must include a detailed failure analysis to identify all failures that will prevent continued safe flight or safe landing, and must identify the means to minimise the likelihood of their occurrence.

CS 29.927 Additional tests

(c) Lubrication system failure. For lubrication systems required for proper operation of rotor drive systems, the following apply:

Category A. Unless such failures are extremely remote [1 x 10-7 per FH], it must be shown by test that any failure which results in loss of lubricant in any normal use lubrication system will not prevent continued after operation, although not necessarily without damage, at a torque and rotational speed prescribed by the applicant for continued flight, for at least 30 minutes after perception by the flight crew of the lubrication system failure or loss of lubricant.

CS 29.1309 Equipment, systems, and installations

(a) The equipment, systems, and installations whose functioning is required by this CS –29 must be designed and installed to ensure that they perform their intended functions under any foreseeable operating condition.

(b) The rotorcraft systems and associated components, considered separately and in relation to other systems, must be designed so that –

(2) For Category A rotorcraft:

(i) The occurrence of any failure condition which would prevent the continued safe flight and landing of the rotorcraft is **extremely improbable [1 x 10^{-9} per FH or better];** and

(ii) The occurrence of any other failure conditions which would reduce the capability of the rotorcraft or the ability of the crew to cope with adverse operating conditions is **improbable [1 x 10^{-5} per FH or better]**.

Appendix C.2 - FAR 29.927 Additional tests

(c) Lubrication system failure. For lubrication systems required for proper operation of rotor drive systems, the following apply:

(1) Category A. Unless such failures are extremely remote, it must be shown by test that any failure which results in loss of lubricant in any normal use lubrication system will not prevent continued safe operation, although not necessarily without damage, at a torque and rotational speed prescribed by the applicant for continued flight, for at least 30 minutes after perception by the flightcrew of the lubrication system failure or loss of lubricant.

AC 29.927. § 29.927 (Amendment 29-13) ADDITIONAL TESTS [07/06/2012]

c. Section 29.927(c):

(1) Explanation.

(i) This section prescribes a test to demonstrate that any failure resulting in the loss of lubrication pressure to the rotor drive primary oil system will not impair the capability of the rotorcraft to operate under autorotative conditions for 15 minutes.

(ii) The regulation is intended to apply to pressurized lubrication systems and has not been applied to splash lubricated gearboxes since historically their design has not been as critical or complex when compared to pressurized systems. The likelihood of loss of lubrication is significantly greater for transmissions that use pressure lubrication and external cooling. This is due to the increased complexity of the lubrication system and the external components that circulate oil outside the gearbox. A pressure lubrication system is more commonly used in the rotorcraft's main transmission but may also be used in auxiliary transmissions or gearboxes.

(iii) The lubricating system has two primary functions. The first is to provide lubricating oil to contacting or rubbing surfaces and thus reduce friction losses. The second is to dissipate heat energy generated by friction of meshing gears and bearings, thus maintaining surface and material temperature. Accordingly, a loss of lubrication leads to increased friction between components and increased component surface temperatures. With increased component surface temperatures, component surface hardness can be lost, resulting in the inability of the component to carry or transmit loads. Thermal expansion in transmission components can eventually lead to the mechanical failure of bearings, journals, gears, shafts, and clutches that are subjected to high loads and rotational speeds. A loss of lubrication may result from internal and external failures. Failures include, but are not limited to, oil lines, fittings, seal plugs, sealing gaskets, valves, pumps, oil filters, oil coolers, accessory pads, etc. A leak caused by a crack in the transmission outer case need not be considered as a source of a loss of lubrication provided the outer case has been structurally substantiated to satisfy the requirements of §§ 29.307, 29.923(m), and 29.571.

(2) Procedures. Conventionally, a bench test (transmission test rig) is used to demonstrate compliance with this rule. Since this is essentially a durability test of the transmission to operate with residual oil, typically the worst case failure (i.e., the undrainable oil or the oil remaining after a severe pressure leak, whichever results in a greater loss of oil in the transmission's normal lubrication system) is used as a critical entry point for the test. The transmission should be stabilized at the torque associated with maximum continuous power (reacted as appropriate at main mast and tail rotor output quills) at a normal main rotor speed, oil temperature that is at the highest limit for continuous operation, and oil pressure that is within the normal operating range. A vertical load should be applied at the mast, equal to the gross weight of the rotorcraft at 1g. Once the transmission oil temperature is stabilized, simulate the worst case failure in the normal use lubrication system. Upon illumination of the low oil pressure warning device (required by § 29.1305), reduce input torque to simulate an autorotation and continue transmission operation for 15 minutes. To complete the test, apply an input torque to the transmission for approximately 10 seconds to simulate a minimum power landing. A successful demonstration may involve limited damage to the transmission, provided it is determined that the autorotative capabilities of the rotorcraft were not significantly impaired.

Appendix C.3 - UK Def-Stan 00-970 Part 7 Rotorcraft, Section 7 Installations

Leaflet 705 TRANSMISSION SYSTEMS

3 SYSTEM DESIGN

3.2 System Safety

Para 3.2.9 Safety of Lubricated Parts

(i) Each independent assembly shall where practical have its own oil supply suitably filtered; independent of the engine lubrication system(s), with a suitable level indicator or contents gauging means that shall not be rendered ineffective by obscuration or staining.

(ii) Transmission systems shall continue to function for a period of **30 minutes minimum** following loss of oil*. Compliance shall be demonstrated by rig tests at loads and time factors to be agree with the Rotorcraft Project Director.
(* See Leaflet 705/1 para 2.7 for definitions)

4 DESIGN OF COMPONENTS

4.3 Lubrication Systems

4.3.1 Functioning.

(i) Lubrication, free from leakage, shall be provided to all components subjected to rolling and/or sliding contact, and shall be effective over the range of temperatures, attitudes, and manoeuvres for which the rotorcraft is designed.

(ii) Consideration shall be given to the provision of redundancy in oil supplies to critical areas of the transmission systems to enhance survivability in emergency conditions. (See Leaflet 705/1, para 6.1)

(iii) All lubrication systems shall be tested in accordance with Leaflet 705/2, para 4.3-4.5, and 7.2.

Leaflet 705/1 TRANSMISSION SYSTEMS SAFETY CONSIDERATIONS

Definitions

2.7 OIL LOSS TOLERANCE (Leaflet 705, para 3.2.9)

2.7.1 Loss of Oil. The term here means the reduction in the volume of oil from any self-contained oil system below the permitted minimum, for whatever reason.

2.7.2 Total Loss of Oil. The term here means the reduction in oil level below that necessary for recirculation by oil pumps, dipping gears, or other rotating parts with a gearbox, for whatever reason.

2.7.3 Flight Endurance Following Loss of Oil. The term here means the time interval following an indication from whatever source, of loss of oil, during which the rotorcraft can achieve a cruise flight followed by a power-on landing or autorotative landing.

2.7.4 Test Endurance Following Loss of Oil. The term here means the duration of test of the complete transmission or its components measured from the time whilst running when oil loss is apparent from normal instruments and indicators, following initiation of Total Loss of Oil from a gearbox or other lubricated component. The definition implies the simulation of rapid oil loss from the region of highest pressure in a pressure-recirculating system, or by drainage from the lowest practical point from a splash-lubricated gearbox.

6 OIL SYSTEM INTEGRITY (Leaflet 705, para 3.2.9, and 4.3.1)

6.1 The importance of the lubricant should be recognised in terms of:

(i) specification, brand, and product control.

(ii) adequacy and continuity of supply to lubricated components especially to relevant VITAL PARTS.

(iii) freedom from contamination and degradation.

To this end the term PART in connection with Transmission Systems is extended to include the lubricant. It should be noted that the loss of lubricant or failure of the lubricant either in respect of load capacity or cooling function could lead to the loss of control or of motive power. Where this is the case the lubricant containment and supply systems should be treated as GRADE A PARTS. In Transmission Systems components having only one reservoir the lubrication system cannot be considered to have redundancy, unless adequate tolerance to TOTAL LOSS OF OIL is obtained, and the components of the system should therefore be treated as VITAL PARTS. Only the practical difficulties relating to the traceability of lubricant charges and changes prevent this requirement being applied to the lubricant also, in respect of items (i) and (iii) above.

Appendix C.4 - MIL-HDBK-516C and JSSG-2009

MIL-HDBK-516C Airworthiness Certification Criteria, Department of Defense

7. PROPULSION AND PROPULSION INSTALLATIONS

7.3 Alternate propulsion systems.

7.3.2 Rotary wing systems.

7.3.2.13 Verify that, during a loss of the primary lubrication system, the gearboxes continue to function and transmit required power until appropriate pilot action can be accomplished.

JSSG-2009, Department of Defense Joint Services Specification Guide: Air Vehicle Subsystems

Section 3 is the Requirement and Section 4 is Verification

K.3.4.11.8 Loss-of-lubricant operation [Requirement]

The gearboxes shall function for at least 30 minutes after complete loss of the lubricant from the primary lubrication system and shall be in a condition such that the gearbox is still capable of transmitting the required power and that no components shall be in a state of imminent failure. The operational conditions shall be such that the loss of lubricant occurs at the most severe power condition and that the air vehicle can transition to cruise and land vertically at the end of the thirty minute period. Also, the power drive subsystem shall be capable of safe operation in the overrunning mode for at least 30 minutes with complete loss of gearbox lubricant. The running mechanism shall be permitted to be non-repairable after 30 minutes of loss-of-lubricant operation.

REQUIREMENT RATIONALE (3.4.11.8)
The requirement is necessary to provide the capability to egress the hostile area in the event that the lubricant is lost from ballistic or fragment damage to exposed oil lines. Oil lines are particularly vulnerable to damage because of the extensive lubrication system connecting various components (pumps, heat exchangers, filters). The 30 minutes of operation is considered within the state-of-the-art without imposing an undue weight and volume burden on the system.

REQUIREMENT GUIDANCE (3.4.11.8)
Should an emergency lubrication system be used to meet this requirement, any resulting attitude limitations during loss of lubricant operation should be defined.

K.4.4.11.8 Loss-of-lubricant operation [Verification]

Verification shall be by bench testing each gearbox and transmission in its production configuration.

VERIFICATION RATIONALE (4.4.11.8)
Testing is needed to verify this requirement.

VERIFICATION GUIDANCE (4.4.11.8)
Two thirty minute tests should be conducted. A teardown inspection should be conducted following each thirty minute test. Testing should be conducted after completion of the system level verification test described in “VTOL-STOL power drive subsystem” in this appendix. Test article dimensions and clearances should be recorded prior to test and should be representative of a production configuration.

Transmission and gearbox lubrication systems should be starved at the system's supply side (downstream from the pump) and continue to scavenge. Operation should be demonstrated for a thirty minute period, typically, as follows:

a. Two minutes at rated power to simulate hover.
b. Twenty six minutes at a power condition to simulate cruise.
c. Two minutes at a power condition simulating vertical landing.

Creditable run time should start at the point at which the cockpit low oil pressure warning would be displayed. For non-pressurized gearboxes, creditable run time should start when the oil being drained from the gearboxes ceases to flow in a steady stream. The transmission should be configured in an air vehicle attitude simulating the cruise power condition. For a VTOL air vehicle, the test spectrum and attitudes should be commensurate with expected field use. Inspection of components should not indicate a condition of impending failure. However, the components need not be in a condition suitable for further service.

A thirty minute loss-of-lubrication overrunning test consistent with the loss-of-lubricant test spectrum above should be conducted. The residual lubricant trapped in the clutch need not be separately drained for this test.

Appendix D

Reliability Assessment of MGB Lubrication Systems of Types A, B, and C Helicopters

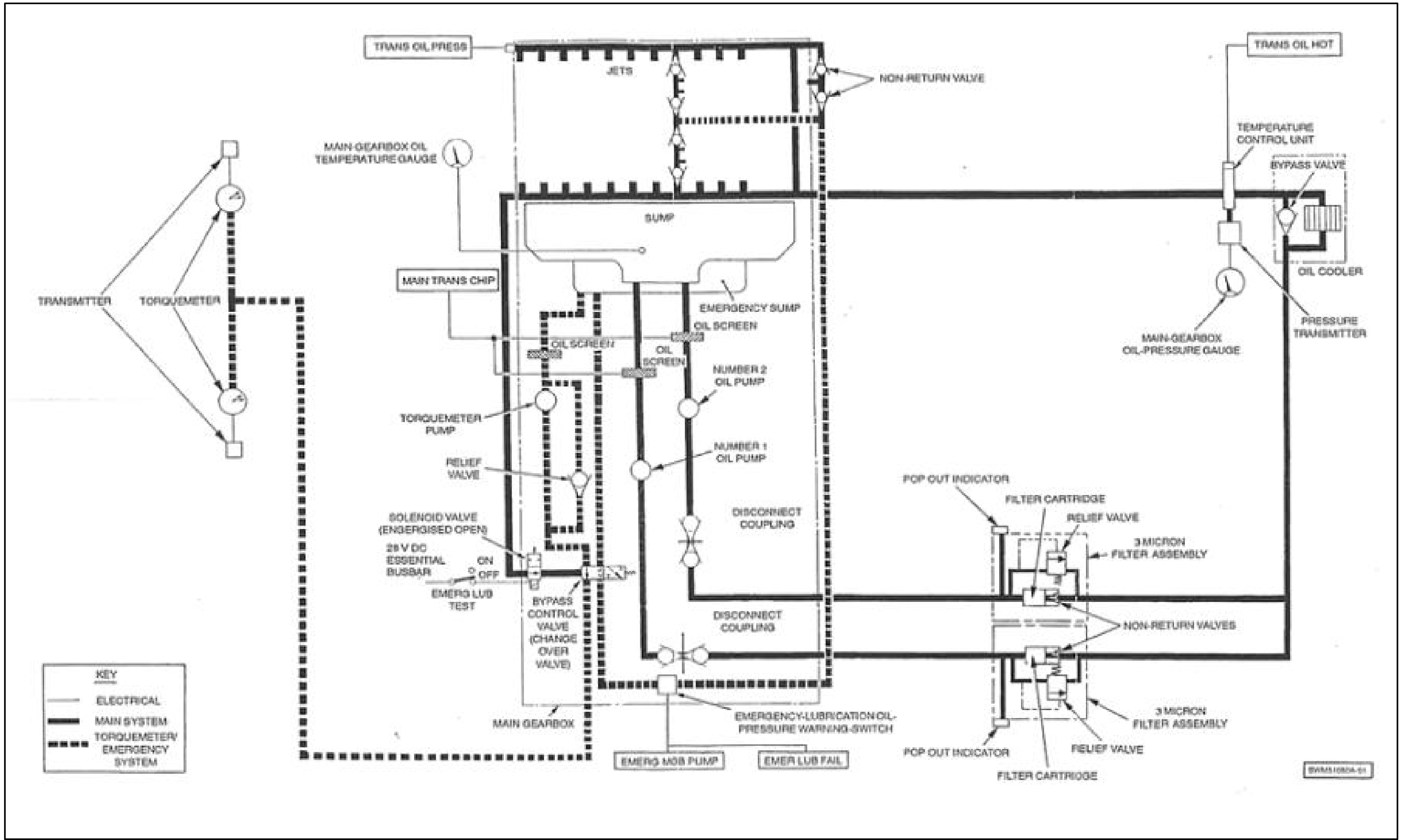


Fig D1 Type A Lubrication System

1	Primary Oil Sump
2	Oil Temperature Gauge
3	Debris Detector
4	Oil Pump
5	Disconnect Coupling
6	Oil Filter
7	Oil Filter Bypass
8	Oil Cooler
9	Oil Cooler Bypass
10	Oil Passageway
11	Oil Pressure Gauge
12	Oil Gallery
13	Emergency Oil Sump
14	Emergency Oil Pump
15	Emergency Oil Relief Valve
16	Change Over Valve (Emergency)

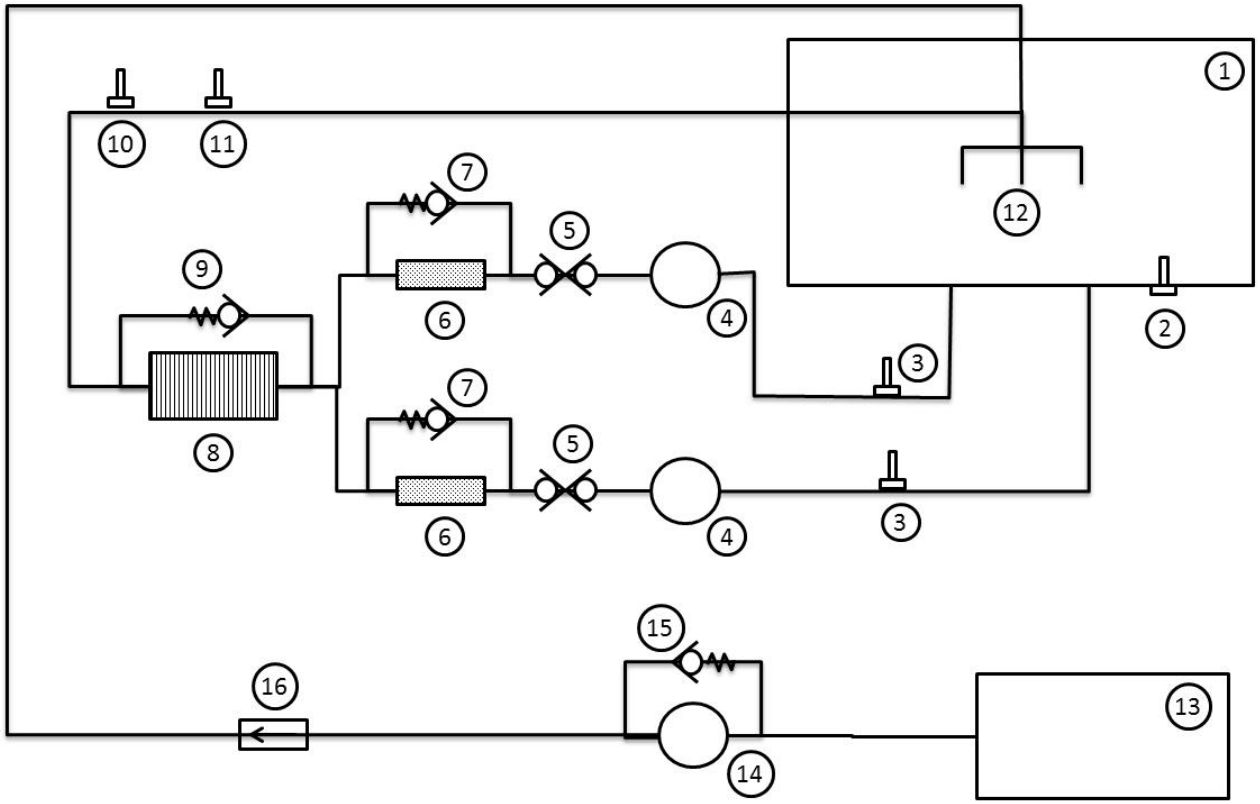


Fig D2 Type A Lubrication System Components

	Component	MTBF (hours)	Reliability at 5 hours
R1	Primary Oil Reservoir	10000	0.9995
R10	Oil Passageway	10000	0.9995
R13	Emergency Oil Reservoir	10000	0.9995
System Reliability, Rsys			0.9995
Prob. of loss of oil			5.001E-004

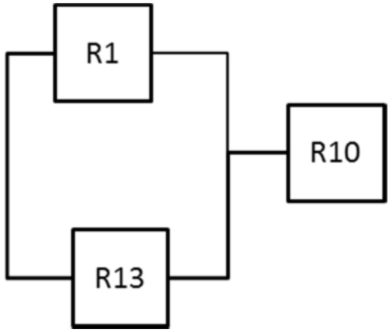


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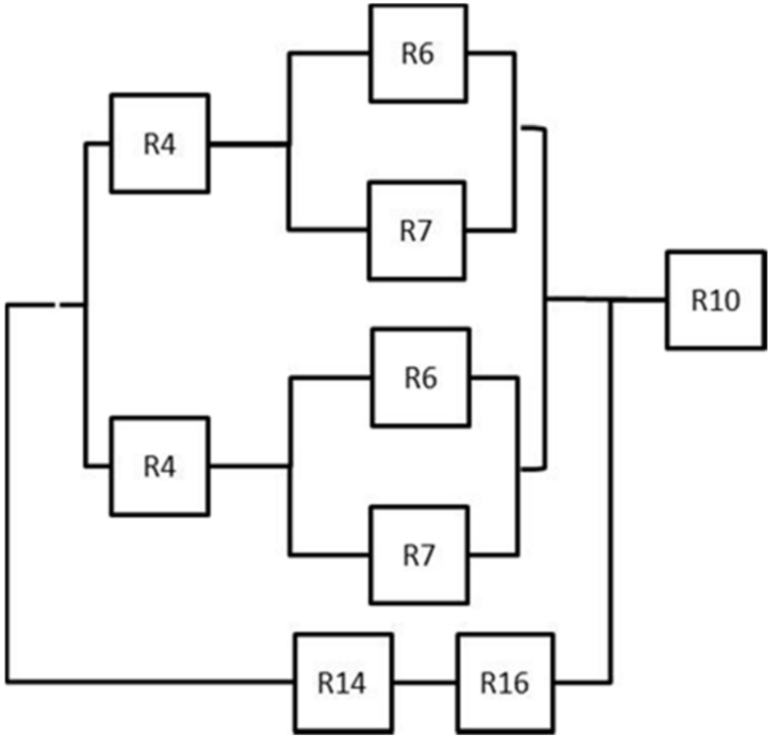
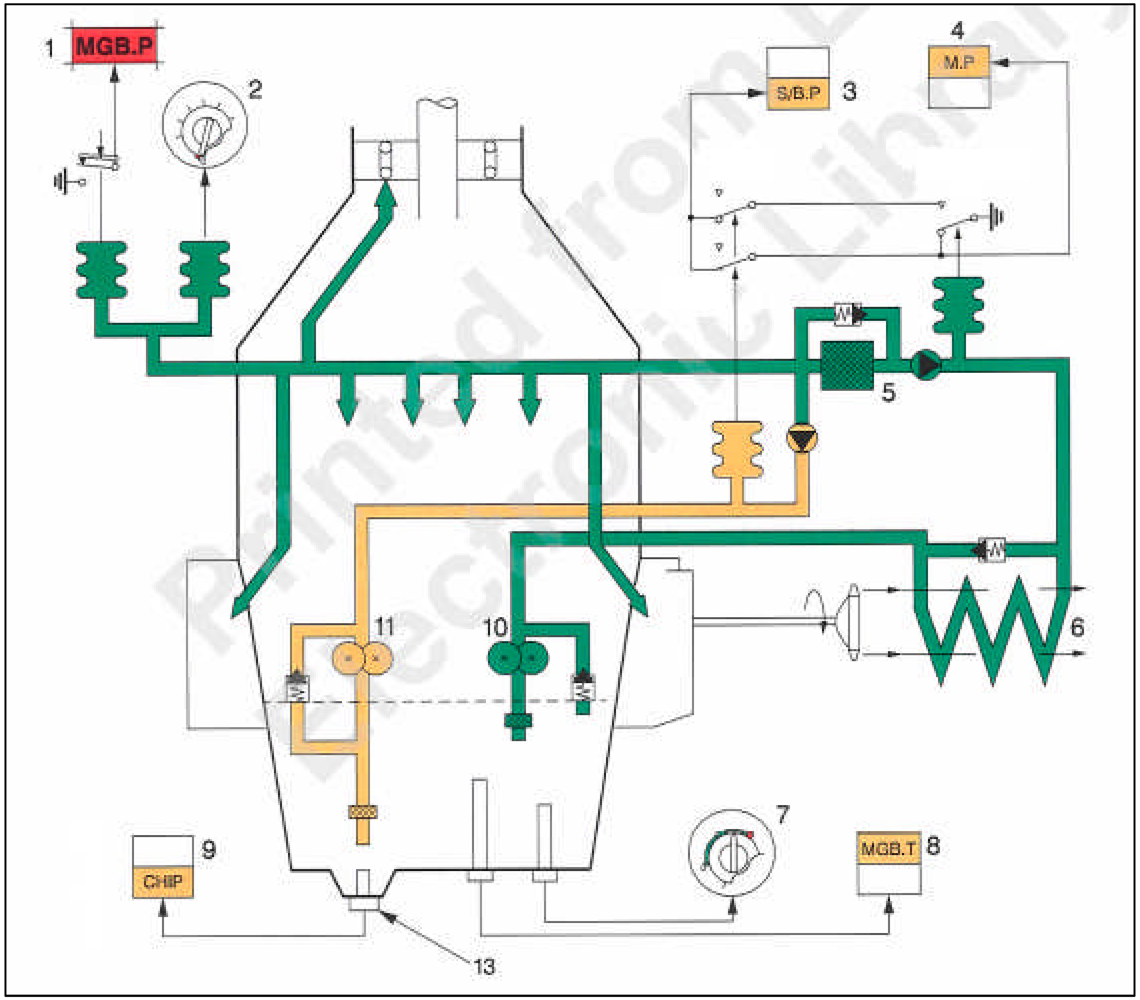
Fig D3 Type A RBD for complete loss of oil

	Component	MTBF (hours)	Reliability at 5 hours
R4	Oil Pump	2000	0.9975
R6	Oil Filter	2000	0.9975
R7	Oil Filter Bypass	2000	0.9975
R10	Oil Passageway	10000	0.9995
R14	Torquemeter Pump	2000	0.9975
R16	Change Over Valve (Emergency)	2000	0.9975
System Reliability, Rsys			0.9995
Prob. of loss of oil pressure			4.999E-004



$$\mathrm{R10} \times \left[1-\left\{(1-\mathrm{R14}.\mathrm{R16})(1-(1-([1-\mathrm{R}4(1-(1-\mathrm{R}6)(1-\mathrm{R}7))]^{2})\right\}\right]$$

Fig D4 Type A RBD for Loss of Oil Pressure



<u>Fig D5 Type B Lubrication System</u>

1	Oil Reservoir
2	Temperature Sensor
3	Debris Detector
4	Oil Pump
5	Oil Pump Pressure Relief Valves
6	Oil Filters
7	Oil Filter Bypass
8	Oil Cooler
9	Oil Cooler Pressure & Temperature Bypass
10	Oil Passageway
11	Pressure Sensor
12	Pressure Regulator
13	Oil Gallery
14	Emergency Oil Pump
15	Low oil pressure switch

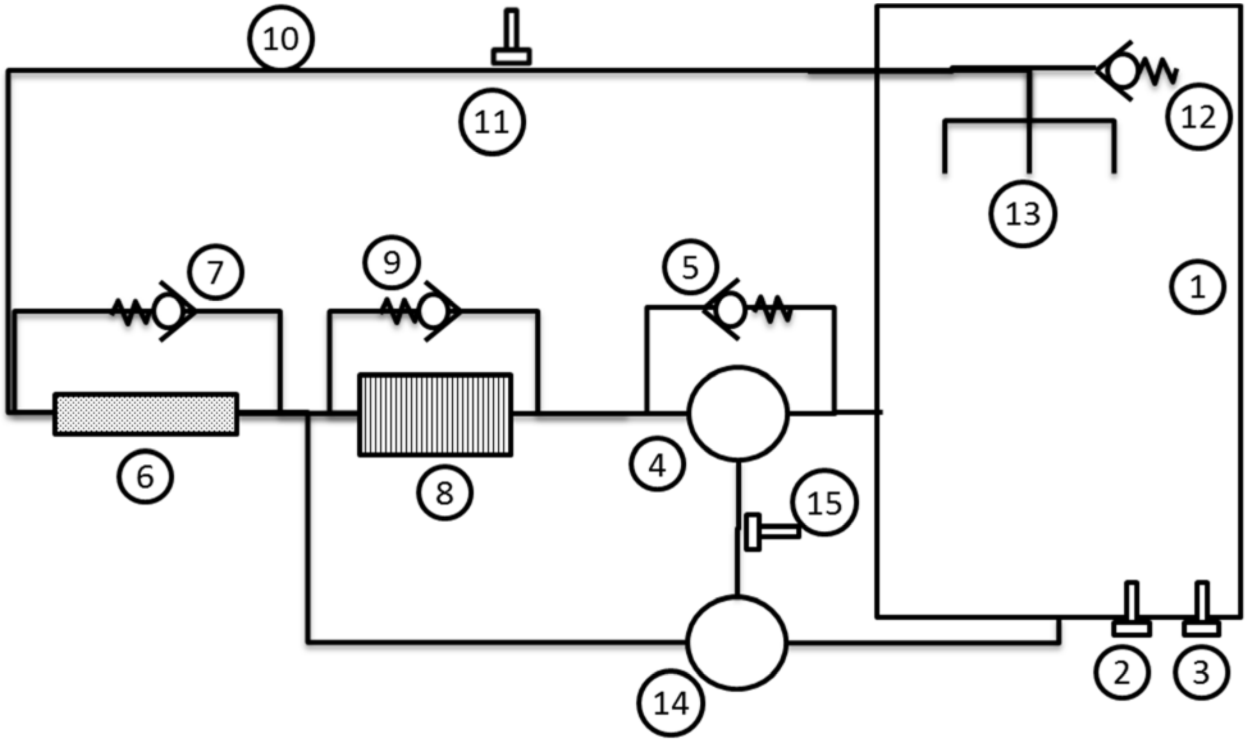
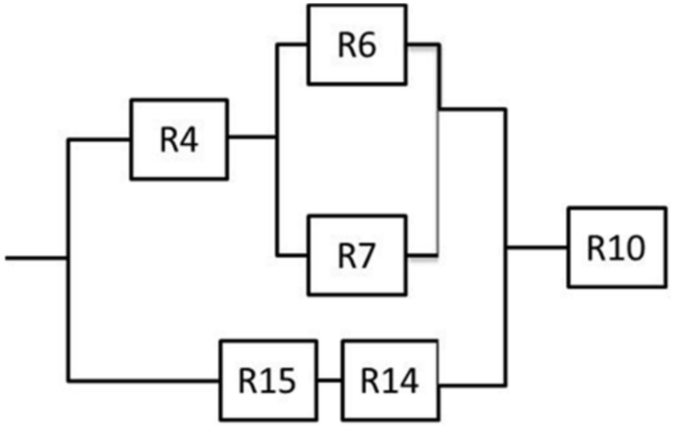


Fig D6 Type B Lubrication System Components

	Components	MTBF (hours)	Reliability at 5 hours
R1	Primary Oil Reservoir	10000	0.9995
R10	Oil Passageway	10000	0.9995
System Reliability, Rsys			0.9990
Prob. of loss of oil			9.995E-004

Fig D7 Type B RBD for Loss of Oil

	Components	MTBF	Reliability at 5 hours
R4	Oil Pump	2000	0.9975
R6	Oil Filter	2000	0.9975
R7	Oil Filter Bypass	2000	0.9975
R10	Oil Passageway	10000	0.9995
R14	Emergency Pump	2000	0.9975
R15	Low Oil Pressure Switch	2000	0.9975
System Reliability, Rsys			0.9995
Prob. of loss of oil pressure			5.124E-004



$$R10 \text{ x } \left[1-\{[1-R4(1-(1-R6)(1-R7))].[1-R14.R15]\}\right]$$

Fig D8 Type B RBD for Loss of Oil Pressure

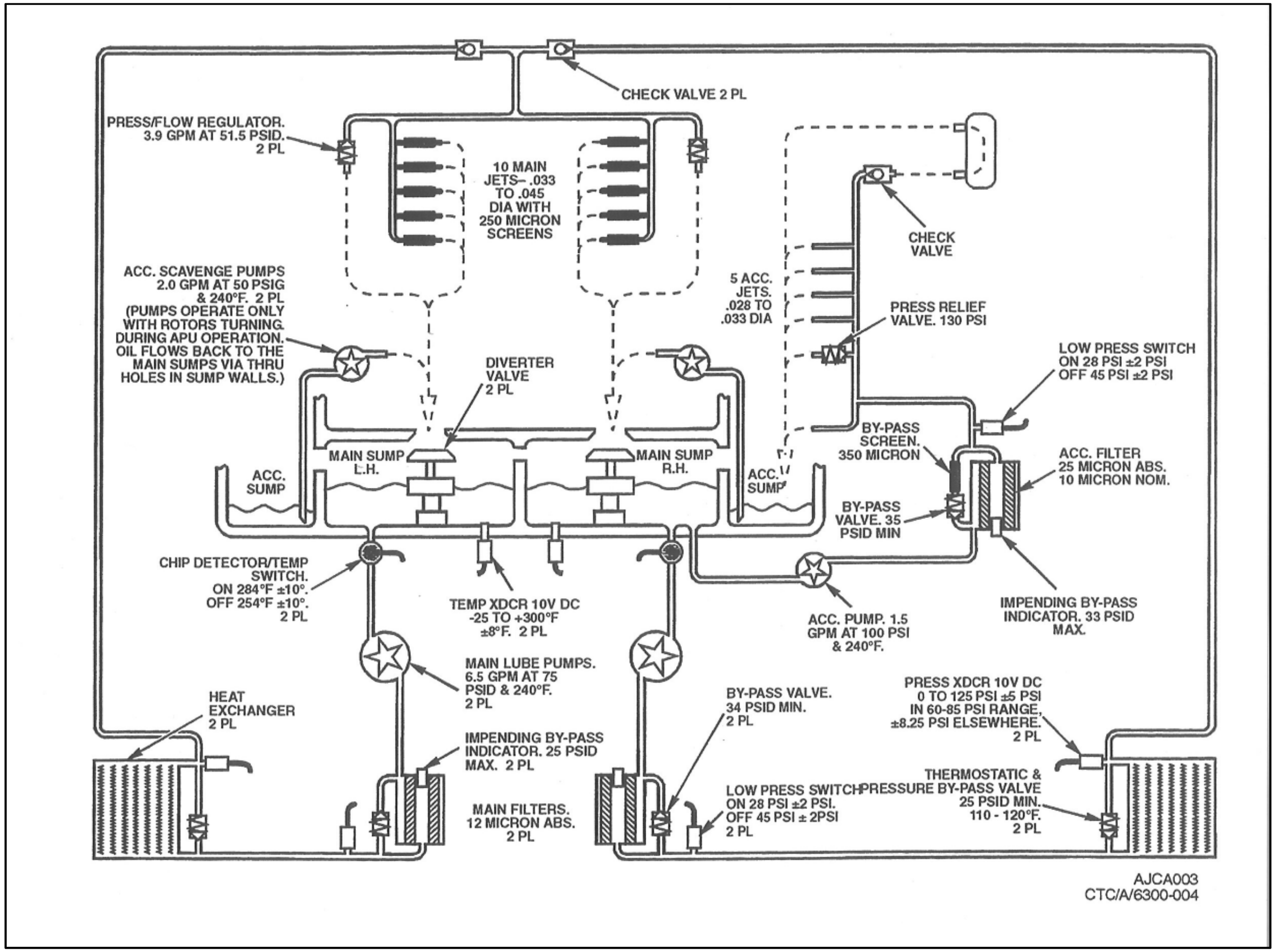


Fig D9 Type C Lubrication System

1	Oil Reservoir
2	Temperature Sensor
3	Debris Detector
4	Oil Pump
5	Oil Pump Pressure Relief Valves
6	Oil Filters
7	Oil Filter Bypass
8	Oil Cooler
9	Oil Cooler Pressure & Temperature Bypass
10	Oil Passageway
11	Pressure Sensor
12	Check Valves
13	Oil Gallery
14	Pressure Regulator

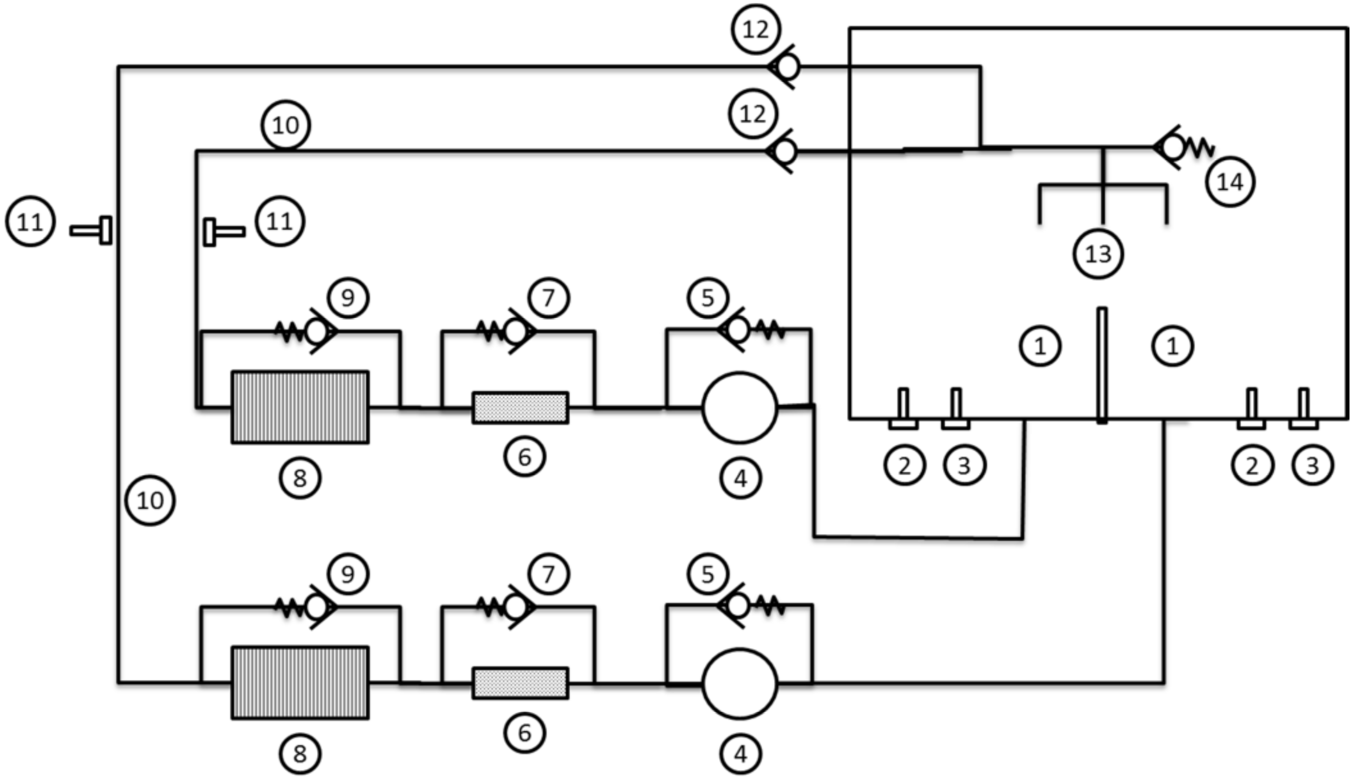


Fig D10 Type C Lubrication System Overview

	Component	MTBF	t=5
R1	LH Primary Oil Reservoir	10000	0.9995
R1	RH Primary Oil Reservoir	10000	0.9995
R10	Oil Passageway	10000	0.9995
System Reliability, Rsys			0.9995
Prob. of loss of oil			5.001E-004

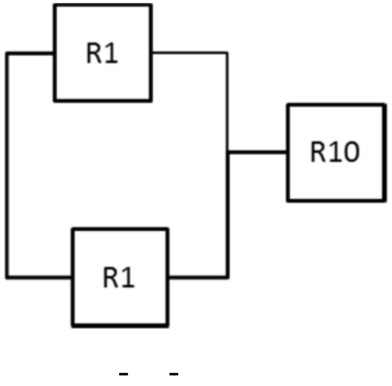
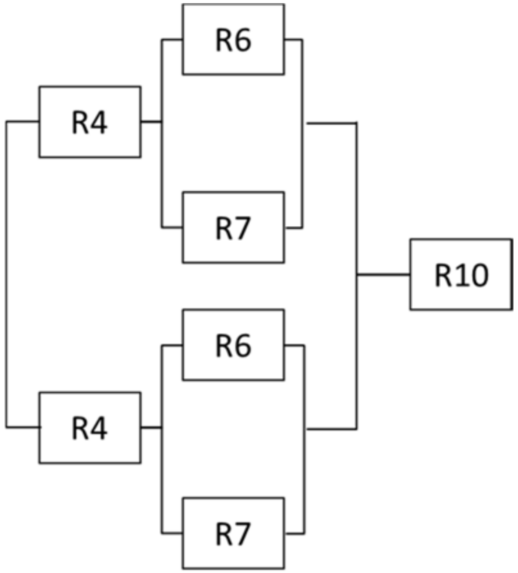


Fig D11 Type C RBD for complete loss of oil

	Component	MTBF	Reliability at 5 hours
R4	Oil Pump	2000	0.9975
R6	Oil Filter	2000	0.9975
R7	Oil Filter Bypass	2000	0.9975
R10	Oil Passageway	10000	0.9995
System Reliability, Rsys			0.9995
Prob. of loss of oil pressure			5.061E-004



$$R10 \text{ x } \left[1-\{1-R4[1-(1-R6)(1-R7)]\}^2\right]$$

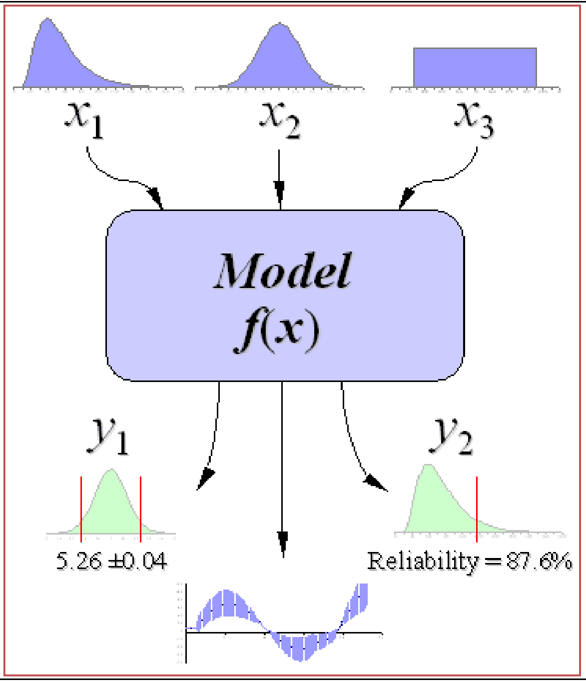
Fig D12 Type C RBD for complete loss of oil pressure

Appendix E

Monte Carlo Simulation

This is a widely used technique which is employed when it is required to model variability of the parameters in a model. Principles and applications of the technique are described in (**Andrews & Moss, 2002)**. Often the values of parameters are known and can be applied to a straightforward formula, for example Pressure = Force / Area. However, it is sometimes the case that input parameters are variable and/or unknown, so a model may be used based on stochastic (random) inputs for the parameters, rather than fixed.

Monte Carlo simulation uses random number generation coupled with known or assumed probability distributions to produce artificial “data”. This is then used in a series of simulated tests where the output is based on simulated results. This is portrayed in Figure E.1, where the inputs x1, x2 and x3 are taken from probability distributions which are defined at the start. These are then used in the model f(x) to calculate values for y1 and y2. These values are saved, and the process repeated many times (iterations) to produce many values of y1 and y2. The relative frequency of the values of y1 and y2 are then measured in order to plot a statistical distribution for the output values.



The steps are expanded here to give additional explanation.

- Create a parametric model, y = $f(x_1, x_2, ..., x_q)$.
- Use random number generator and uniform distribution to generate numbers between 0 and 1.
- Apply to probability curve to get parameter value.
- Use these values in the formula in question.
- Repeat steps 2 to 4 many times.
- Plot distribution of results.

Figure E- 1 Visualisation of Monte-Carlo Simulation (Wittwer, 2004)

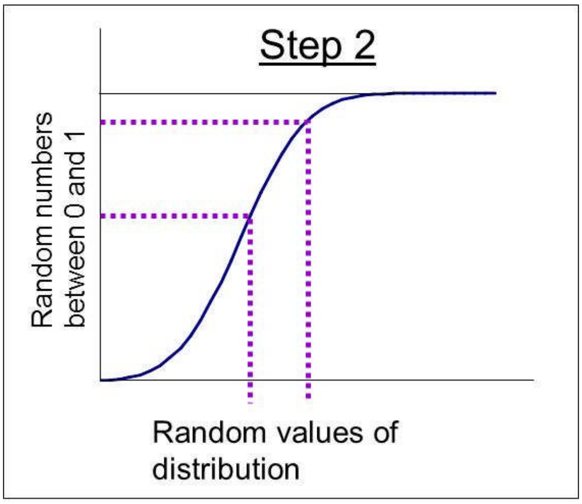


Figure E - 2 Example distribution for input variable

As shown in Appendix D, Figure D-8, the reliability block diagram for “Loss of oil pressure” is analysed using various values for the reliability of each component.

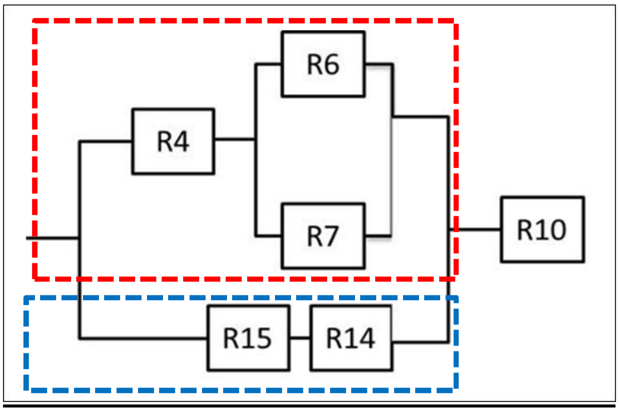


Figure E – 3 Type B RBD for loss of oil pressure (as per Figure D-8)

<u>The applied method</u>

1. *Select random numbers and use to generate simulated TTF for all components, R4, R6, R7, R10, R14 and R15*
2. *Apply failure logic to work out the time to failure for the SYSTEM:*

    a. *Take larger of T6, T7 (parallel network), and compare with T4*
        i. *If T4 is lower value than (T6, T7) then use T4, else use larger of (T6, T7) – part ‘A’ (MAIN)*

    b. *Take lower of T14, T15 (series network) – part ‘B’ (STANDBY)*

    c. *Add A and B value = MAIN + STANDBY time to failure.*

    d. *Compare with T10; If T10 is lower then this is the SYSTEM time to failure. If not then use A + B = MAIN + STANDBY*

3. *Repeat many* times, then plot as histogram to get PDF.*

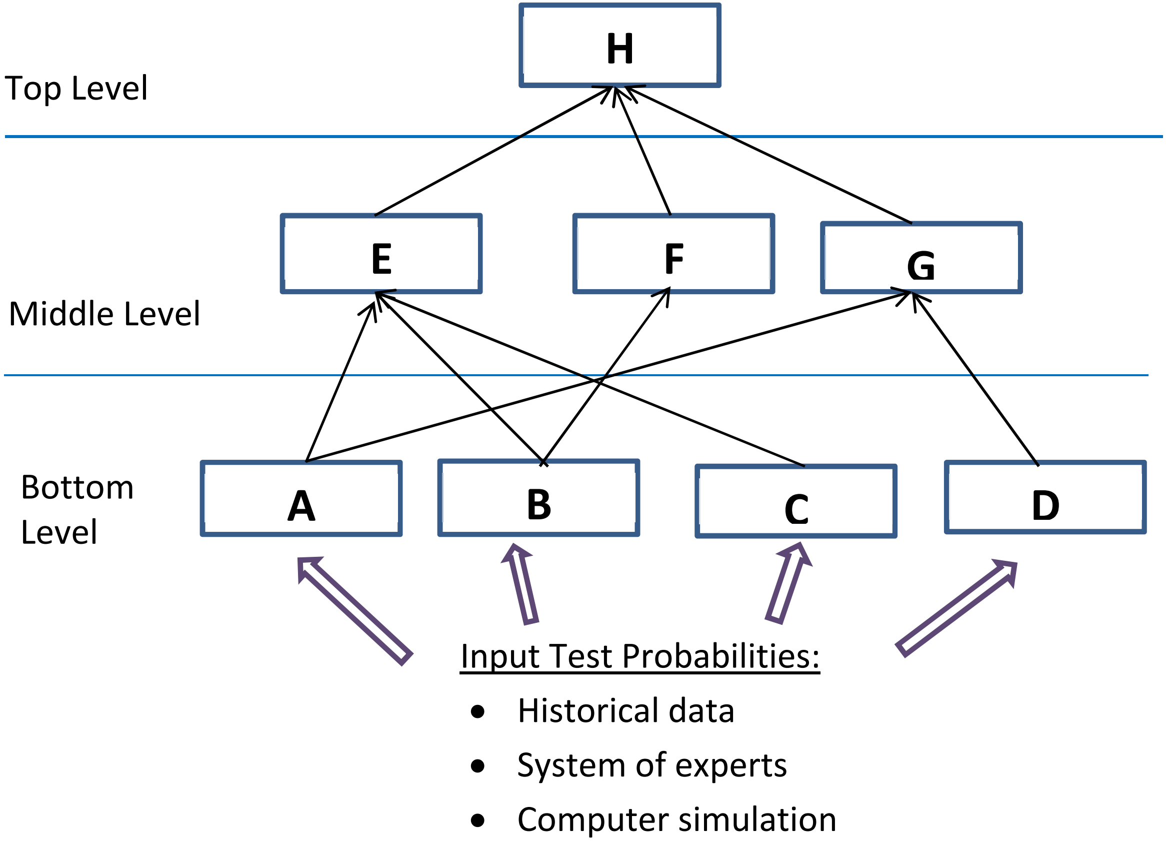
    ** The simulation was run for 10000 iterations in this case, but could be increased*

Appendix F

Mathematical Model of Influence Diagrams

Probability of occurrence of an event under influence of associated sub-level events

The typical influence diagram shown is composed of events A, B, C, …, H. Relations between these events are described through the shown influences. Influences exerted by events at each level shape the probabilities of occurrence of events at the upper levels. For illustration, the following sequence calculates the probability of occurrence of event E under influences of events A, B, and C.



Typical influence diagram with options for input test probabilities

Calculating probability of occurrence of event E under influences of events A, B, and C:

1. *Assigning input probabilities for relevant events (A, B, and C) from the bottom level*

Let input test probability of A as a cause of occurrence of E = $\mathbf{P_{AY}}$

Let input test probability of A not being a cause of occurrence of E = $\mathbf{P_{AN}}$

Where $\mathbf{P_{AN}} = 1.0 - \mathbf{P_{AY}}$

Let input test probability of B as a cause of occurrence of E = $\mathbf{P_{BY}}$

Let input test probability of B not being a cause of occurrence of E = $\mathbf{P}_{\mathbf{BN}}$
Where $\mathbf{P}_{\mathbf{BN}} = 1.0 - \mathbf{P}_{\mathbf{BY}}$

Let input test probability of C as a cause of occurrence of E = $\mathbf{P}_{\mathbf{CY}}$
Let input test probability of C not being a cause of occurrence of E = $\mathbf{P}_{\mathbf{CN}}$
Where $\mathbf{P}_{\mathbf{CN}} = 1.0 - \mathbf{P}_{\mathbf{CY}}$

2. *Matrix of total combined influences of events A, B, and C on occurrence of E*

(n) scenarios of combined influences*	Influence of A as a cause of E occurrence	Influence of B as a cause of E occurrence	Influence of C as a cause of E occurrence	(n) combined influences of events A, B, C to cause occurrence of E ($\mathbf{I}_{\mathbf{Tj}}$, j=1,2,3,…, n)
1	$\mathbf{P}_{\mathbf{AY}}$	$\mathbf{P}_{\mathbf{BY}}$	$\mathbf{P}_{\mathbf{CY}}$	$\mathbf{I}_{\mathbf{T1}} = \mathbf{P}_{\mathbf{AY}} * \mathbf{P}_{\mathbf{BY}} * \mathbf{P}_{\mathbf{CY}}$
2	$\mathbf{P}_{\mathbf{AY}}$	$\mathbf{P}_{\mathbf{BY}}$	$\mathbf{P}_{\mathbf{CN}}$	$\mathbf{I}_{\mathbf{T2}} = \mathbf{P}_{\mathbf{AY}} * \mathbf{P}_{\mathbf{BY}} * \mathbf{P}_{\mathbf{CN}}$
3	$\mathbf{P}_{\mathbf{AY}}$	$\mathbf{P}_{\mathbf{BN}}$	$\mathbf{P}_{\mathbf{CY}}$	$\mathbf{I}_{\mathbf{T3}} = \mathbf{P}_{\mathbf{AY}} * \mathbf{P}_{\mathbf{BN}} * \mathbf{P}_{\mathbf{CY}}$
4	$\mathbf{P}_{\mathbf{AN}}$	$\mathbf{P}_{\mathbf{BY}}$	$\mathbf{P}_{\mathbf{CY}}$	$\mathbf{I}_{\mathbf{T4}} = \mathbf{P}_{\mathbf{AN}} * \mathbf{P}_{\mathbf{BY}} * \mathbf{P}_{\mathbf{CY}}$
5	$\mathbf{P}_{\mathbf{AY}}$	$\mathbf{P}_{\mathbf{BN}}$	$\mathbf{P}_{\mathbf{CN}}$	$\mathbf{I}_{\mathbf{T5}} = \mathbf{P}_{\mathbf{AY}} * \mathbf{P}_{\mathbf{BN}} * \mathbf{P}_{\mathbf{CN}}$
6	$\mathbf{P}_{\mathbf{AN}}$	$\mathbf{P}_{\mathbf{BN}}$	$\mathbf{P}_{\mathbf{CY}}$	$\mathbf{I}_{\mathbf{T6}} = \mathbf{P}_{\mathbf{AN}} * \mathbf{P}_{\mathbf{BN}} * \mathbf{P}_{\mathbf{CY}}$
7	$\mathbf{P}_{\mathbf{AN}}$	$\mathbf{P}_{\mathbf{BY}}$	$\mathbf{P}_{\mathbf{CN}}$	$\mathbf{I}_{\mathbf{T7}} = \mathbf{P}_{\mathbf{AN}} * \mathbf{P}_{\mathbf{BY}} * \mathbf{P}_{\mathbf{CN}}$
8	$\mathbf{P}_{\mathbf{AN}}$	$\mathbf{P}_{\mathbf{BN}}$	$\mathbf{P}_{\mathbf{CN}}$	$\mathbf{I}_{\mathbf{T8}} = \mathbf{P}_{\mathbf{AN}} * \mathbf{P}_{\mathbf{BN}} * \mathbf{P}_{\mathbf{CN}}$

* The number of different scenarios of joined influence combinations (n) depends on the number of the influencing events.

3. *Initially-predicted probabilities of E occurrence under influences of A, B, and C*

Referring to the of matrix of step 2, the maximum predictable initial probability for occurrence of E, let be identified as ($\mathbf{P}_{\mathbf{EPYmax}}$), corresponds to scenario 1, where all influences from events A, B, and C are acting as causes for occurrence of E.

Similarly, referring to matrix of step 2, the minimum predictable initial probability for occurrence of E, let be identified as ($\mathbf{P}_{\mathbf{EPYmin}}$), corresponds to scenario 8, where no influences from events A, B, and C are acting as causes for occurrence of E.

Thus, the initially predicted probabilities of E occurrence under influences of A, B, C for the different scenarios is given by:

$$\mathbf{P}_{\mathbf{EPYj}} = \mathbf{P}_{\mathbf{EPYmax}} - \sum \quad ((\mathbf{P}_{\mathbf{EPYmax}} - \mathbf{P}_{\mathbf{EPYmin}})/(n - 1.0))*(j - 1.0)$$

Thus, the initially predicted probabilities of E non-occurrence under influences of A, B, C for the different scenarios can be given by = $\mathbf{P}_{EPNj}$, j = 1,2,3, …, n
Where $\mathbf{P}_{EPNj} = 1.0 - \mathbf{P}_{EPYj}$, j = 1,2,3, …, n

4. *Probability of occurrence of E for each possible scenario of A, B, C influences combination*

(n) scenarios of combined influences	(n) calculated probability of E occurrence for a given scenario of A, B, C influences combinations ($\mathbf{P}_{EYj}$)	(n) calculated probability of E non-occurrence for a given scenario of A, B, C influences combinations ($\mathbf{P}_{ENj}$)
1	$\mathbf{P}_{EY1} = \mathbf{I}_{T1} * \mathbf{P}_{EPYj}$	$\mathbf{P}_{EN1} = \mathbf{I}_{T1} * \mathbf{P}_{EPNj}$
2	$\mathbf{P}_{EY2} = \mathbf{I}_{T2} * \mathbf{P}_{EPY2}$	$\mathbf{P}_{EN2} = \mathbf{I}_{T2} * \mathbf{P}_{EPN2}$
3	$\mathbf{P}_{EY3} = \mathbf{I}_{T3} * \mathbf{P}_{EPY3}$	$\mathbf{P}_{EN3} = \mathbf{I}_{T3} * \mathbf{P}_{EPN3}$
4	$\mathbf{P}_{EY4} = \mathbf{I}_{T4} * \mathbf{P}_{EPY4}$	$\mathbf{P}_{EN4} = \mathbf{I}_{T4} * \mathbf{P}_{EPN4}$
5	$\mathbf{P}_{EY5} = \mathbf{I}_{T5} * \mathbf{P}_{EPY5}$	$\mathbf{P}_{EN5} = \mathbf{I}_{T5} * \mathbf{P}_{EPN5}$
6	$\mathbf{P}_{EY6} = \mathbf{I}_{T6} * \mathbf{P}_{EPY6}$	$\mathbf{P}_{EN6} = \mathbf{I}_{T6} * \mathbf{P}_{EPN6}$
7	$\mathbf{P}_{EY7} = \mathbf{I}_{T7} * \mathbf{P}_{EPY7}$	$\mathbf{P}_{EN7} = \mathbf{I}_{T7} * \mathbf{P}_{EPN7}$
8	$\mathbf{P}_{EY8} = \mathbf{I}_{T8} * \mathbf{P}_{EPY8}$	$\mathbf{P}_{EN8} = \mathbf{I}_{T8} * \mathbf{P}_{EPN8}$

5. *Total unconditional probability of E occurrence/ Non–occurrence under influences of A, B, and C*

The total unconditional probability of E occurrence under influences of A, B, and C can thus be given as ($\mathbf{P}_{EYT}$)
Where,

$$\mathbf{P}_{EYT} = \sum \mathbf{P}_{EYj}$$

Consequently, the total unconditional probability of E non-occurrence under influences of A, B, and C is given as ($\mathbf{P}_{ENT}$)
Where,

$$\mathbf{P}_{ENT} = \sum \mathbf{P}_{ENj}$$

6. *Identification of probabilities of occurrence, or non-occurrence, for the whole middle level events*

The above sequence of calculation is repeated to determine unconditional probabilities of occurrence, or non-occurrence, for each of the remaining events of the middle level (i.e.

events F and G in the given model). The initial input test probabilities required for these can be listed as:

For calculating probability of occurrence, or non-occurrence, for event F:

Input influence from bottom event B is used.

For calculating probability of occurrence, or non-occurrence, for event G:

Input influences from bottom events A and D are used.

7. *Identification of probabilities of occurrence, or non-occurrence, for the whole middle level events*

These calculated probabilities of occurrence, or non-occurrence, of events E, F, and G are then used as initial input probabilities to calculate the overall targeted total unconditional probability of occurrence, or non-occurrence, of the main event H at the top level, which is the main problem of the model.

Appendix G

Thioether Mist Lubrication Tests Plots

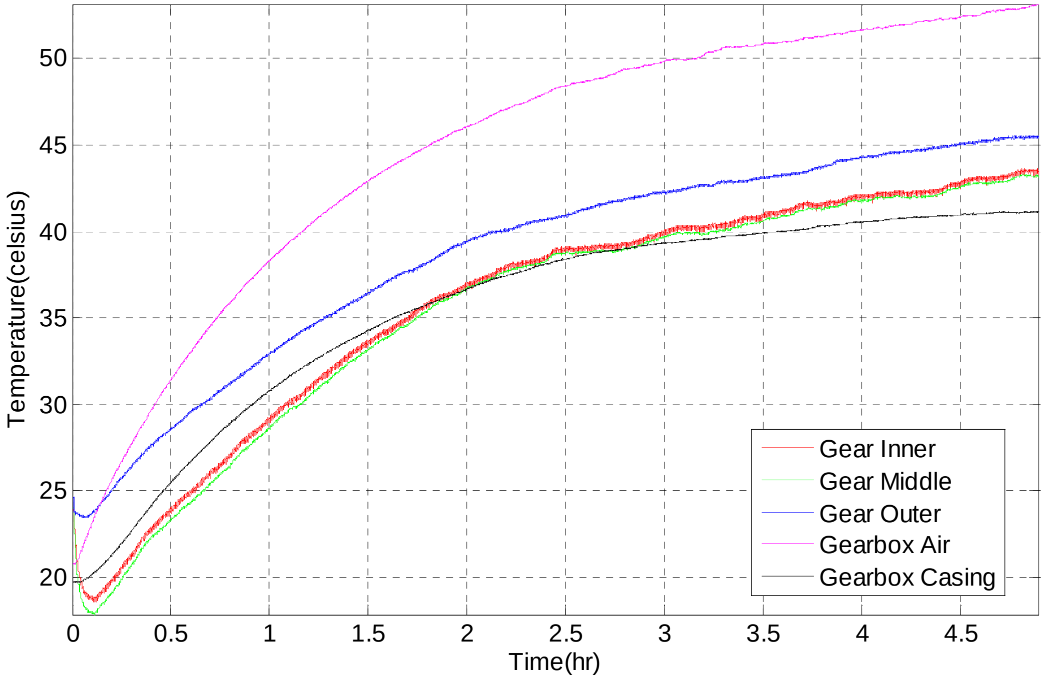


Figure G-1: Test Run 1: Oil Dip lubrication at 690 RPM, 100 Nm torque and CCW rotation

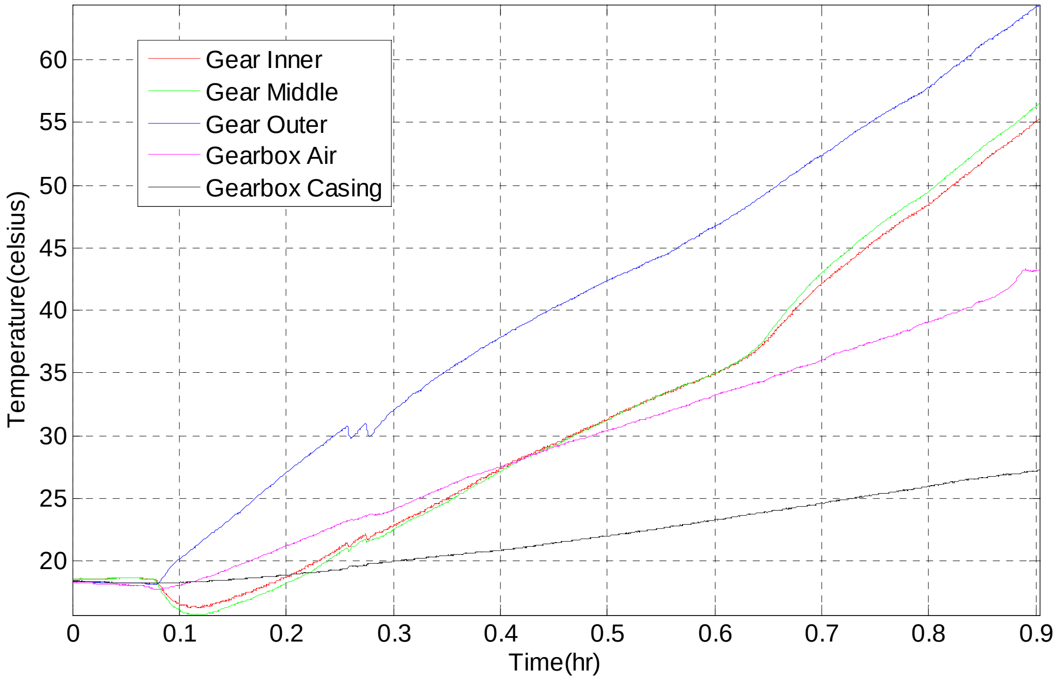


Figure G-2: Test Run 2: Thioether mist lubrication at 690 RPM, 100 Nm torque and CCW rotation

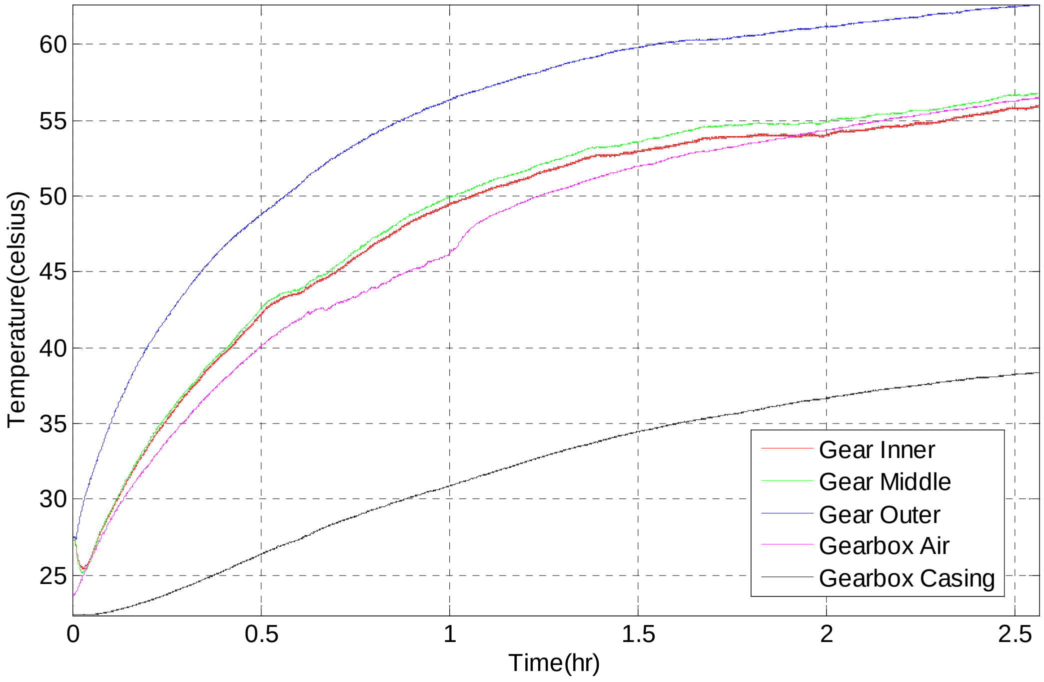


Figure G-3: Test Run 3: Thioether mist lubrication at 690 RPM, 100 Nm torque and CW rotation

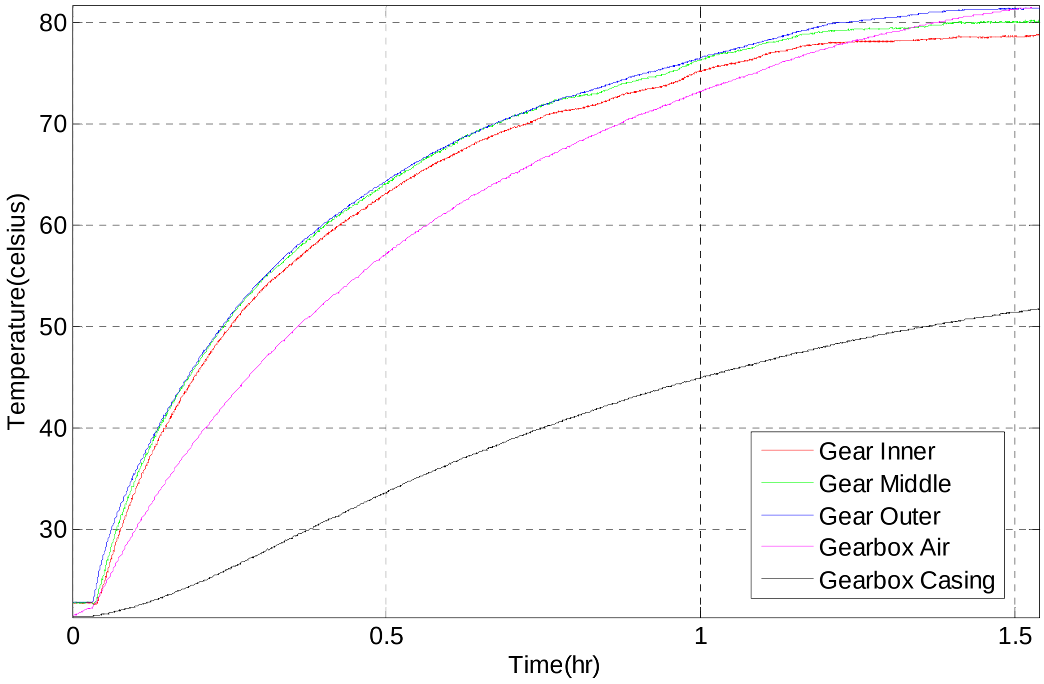


Figure G-4: Test Run 4: Thioether mist lubrication at 1420 RPM, 100 Nm torque and CW rotation

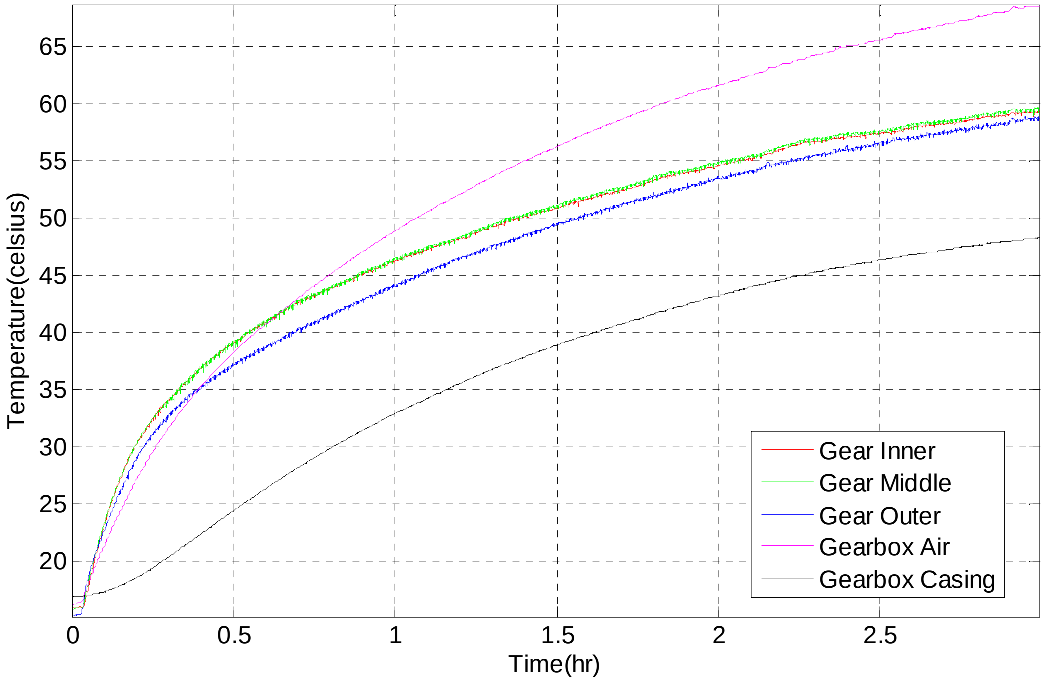


Figure G-5: Test Run 5: Oil lubrication at 1420 RPM, 100 Nm torque and CW rotation

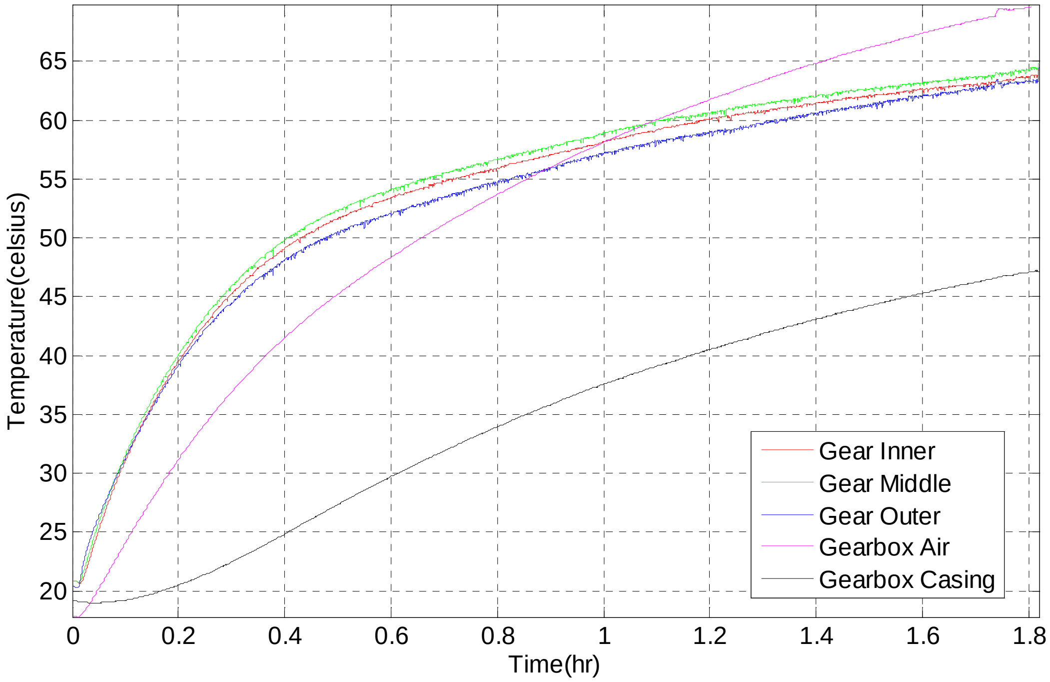


Figure G-6: Test Run 6: Oil lubrication at 1420 RPM, 280 Nm torque and CW rotation

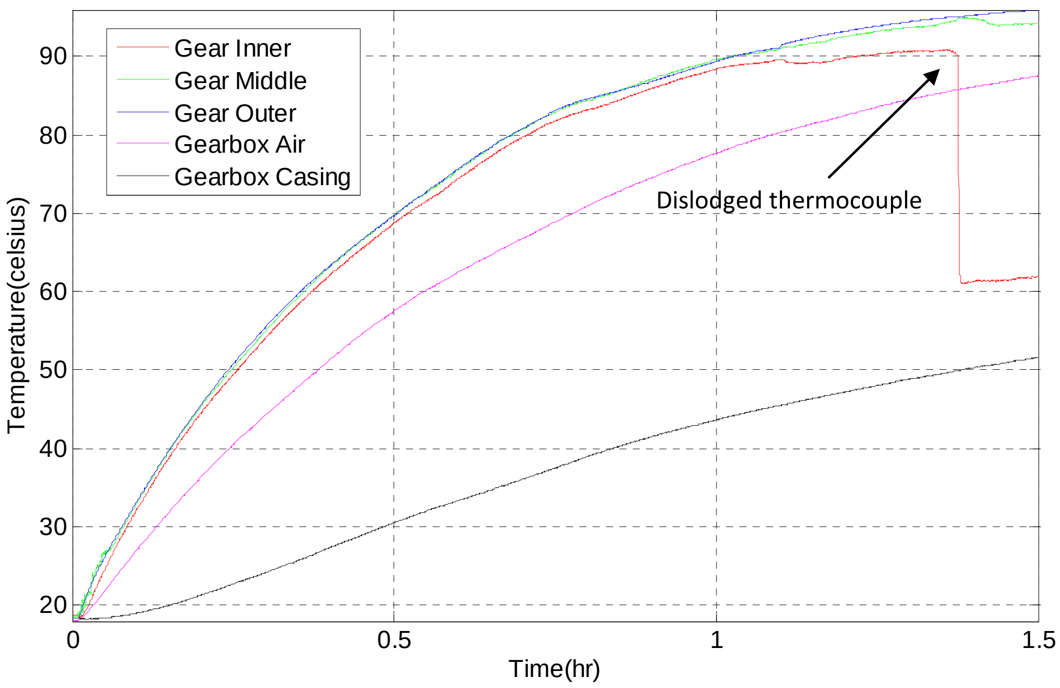


Figure G-7: Test Run 7: Thioether Mist lubrication at 1420 RPM, 280 Nm torque and CW rotation

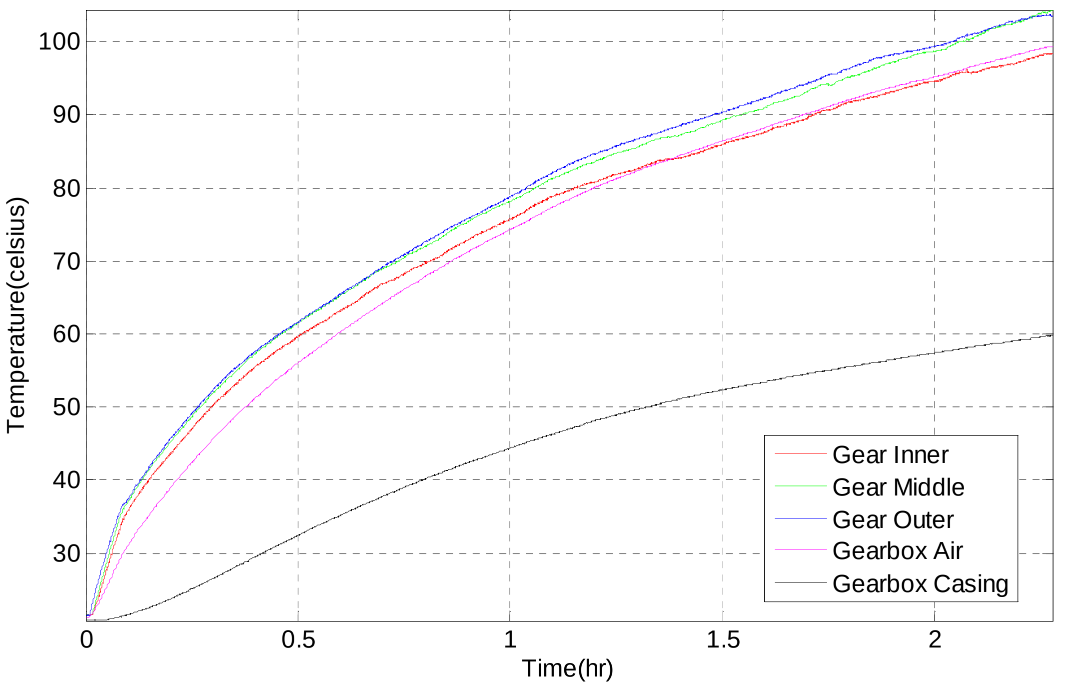


Figure G-8: Test Run 8: Oil Mist lubrication at 1420 RPM, 280 Nm torque and CW rotation

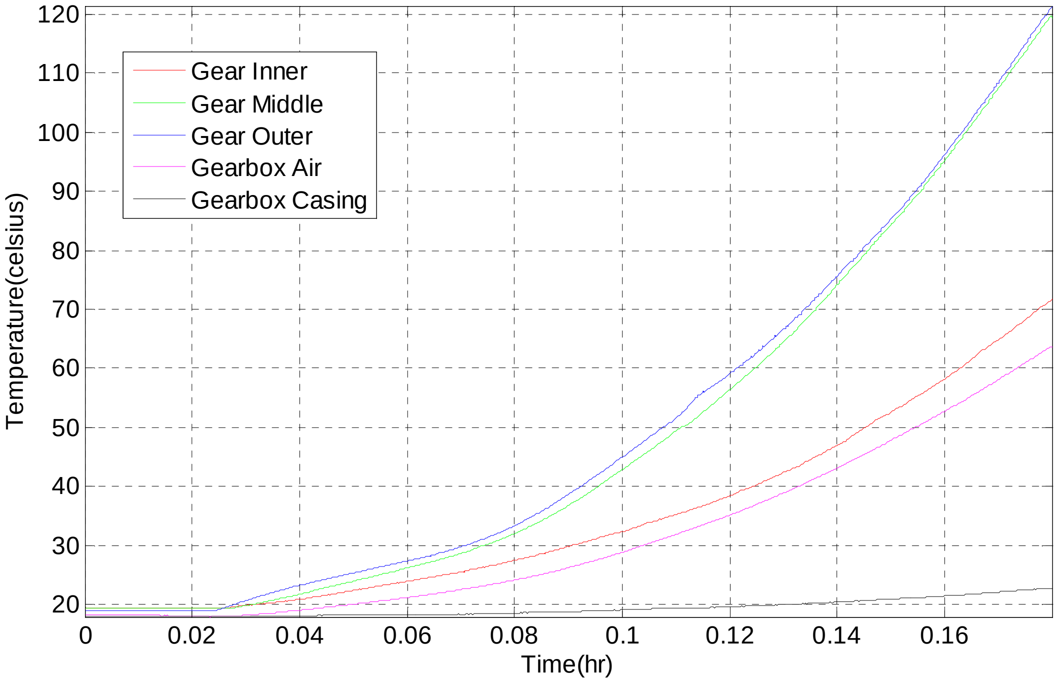


Figure G-9: Test Run 8: Compressed Air at 1420 RPM, 280 Nm torque and CW rotation

Enclosure 1

AeroShell Turbine Oil 555

Used for Thioether Mist Lubrication Tests

AEROSHELL TURBINE OIL 555

AeroShell Turbine Oil 555 is an advanced 5 mm^2/s synthetic hindered ester oil incorporating a finely balanced blend of additives to improve thermal and oxidation stability and to increase the load carrying ability of the base oil.

APPLICATIONS

AeroShell Turbine Oil 555 was specifically developed to meet the high temperatures and load carrying requirements of SST engines and the DEF STAN 91-100 (formerly DERD 2497) and XAS-2354 specifications. AeroShell Turbine Oil 555 was also designed to give enhanced performance in current engines.

More recently with the need to transmit more power and higher loads through helicopter transmission and gearbox systems (many helicopters use a synthetic turbine engine oil in the transmission/gearbox system) it has become apparent that the use of a very good load carrying oil, such as AeroShell Turbine Oil 555 is necessary. This in turn has led to the development of a U.S. Military Specification, DOD-L-85734, which covers a helicopter transmission oil against which AeroShell Turbine Oil 555 is fully approved.

AeroShell Turbine Oil 555 contains a synthetic ester oil and should not be used in contact with incompatible seal materials and it also affects some paints and plastics. Refer to the General Notes at the front of this section for further information.

SPECIFICATIONS

U.S.	Approved DOD-L-85734
British	Approved DEF STAN 91-100 Note: both UK and US production are manufactured to the same formulation.
French	–
Russian	–
NATO Code	O-160
Joint Service Designation	OX-26
Pratt & Whitney	Approved 521C Type II
General Electric	Approved D-50 TF 1
Allison	Approved EMS-53 (Obsolete)

EQUIPMENT MANUFACTURER'S APPROVALS

AeroShell Turbine Oil 555 is approved for use in all models of the following engines:

Honeywell	Auxiliary Power Units GTCP 30, 36, 85, 331, 660 and 700 series
General Electric	CT58, CT64, CF700, CJ610
Motorlet	MD601D, E and Z
Pratt & Whitney	JT3, JT4, JT8, JT9, JT12, PW4000
Pratt & Whitney Canada	ST6, PW200
Rolls-Royce	Trent, Adour, Gem, Gnome, M45H, Olympus 593, RB199
Turbomeca	Makila
IAE	V2500 Series, all marques

EQUIPMENT MANUFACTURER'S APPROVALS – HELICOPTER TRANSMISSIONS

AeroShell Turbine Oil 555 is approved for an increasing number of helicopter transmissions, whilst details are listed below, it is important that operators check latest status with the helicopter manufacturer. In all cases it is important to check compatibility with seals used in the transmission/gearbox.

US Military	Approved for helicopter transmission specification DOD-L-85734
Eurocopter	Approved for Super Puma, for other helicopters check with Eurocopter
Agusta	Approved for A109 and A129 models, for other models check with Agusta
Bell Helicopter Textron	Approved for all Bell turbine engined powered helicopters
Boeing Vertol	Approved for Chinook
McDonnell Douglas	Approved
MBB	Approved
Sikorsky	Approved for S-61N (note other types such as the S-70 and S-76 do not use synthetic turbine oils in the transmission)
Westland Helicopters	Approved for some models

PROPERTIES	**DOD-L-85734**	**TYPICAL**
Oil Type	Synthetic ester	Synthetic ester
Kinematic Viscosity mm ^{2}/s		
@ 98.9°C	5.0 to 5.5	5.4
@ 37.8°C	25.0 min	29.0
@ –40°C	13000 max	11000
Flashpoint, Cleveland Open Cup °C	246 min	>246
Pourpoint °C	–54 max	Below –54
Total Acidity mgKOH/g	0.5 max	0.3
Evaporation Loss 6.5 hrs @ 204°C % m	10.0 max	2.6
Foaming	Must pass	Passes
Swelling of Standard Synthetic Rubber		
SAE-AMS 3217/1, 72 hrs @ 70°C swell %	0 to 25	14
SAE-AMS 3217/4, 72 hrs @ 204°C swell %	0 to 25	14
Thermal Stability/Corrosivity 96 hrs @ 274°C		
– metal weight change mg/cm^2	4 max	–0.97
– viscosity change @ 37.8°C %	5 max	–1.2
– Total Acid Number Change mgKOH/g	6 max	2

Table continued

Table continued

PROPERTIES	**DOD-L-85734**	**TYPICAL**
Corrosion & Oxidation Stability		
72 hrs @ 175°C	Must pass	Passes
72 hrs @ 204°C	Must pass	Passes
72 hrs @ 218°C	Must pass	Passes
Ryder Gear Test, Relative Rating Hercolube A %	145	>145
Bearing Test Rig Type 1½ conditions		
– Overall deposit demerit rating	80.0 max	22
– viscosity change @ 37.8°C %	–5 to +30	21
– Total Acid Number change mgKOH/g	2 max	0.83
– filter deposits g	3 max	0.5
Sonic shear stability – viscosity change @ 40°C %	4 max	NIL
Trace metal content	Must pass	Passes
Sediment mg/l	10 max	Passes
Ash mg/l	1 max	Passes

AeroShell Turbine Oil 555 is also approved for use in the industrial and marine versions of the Rolls-Royce RB211-22 and Olympus engines, General Electric LM 100, 250, 350, 1500 and 2500 engines.

A viscosity/temperature chart is shown at the end of this section.

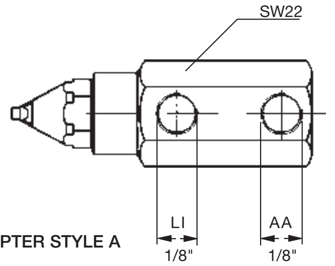
NOTES

Enclosure 2

Ultrasonic Atomizers

Used for Thioether Mist Lubrication Tests

ATOMIZERS AND FITTINGS



ADAPTER STYLE A

Ultrasonic atomizers produce the finest sprays available with air assistance for industrial processes, with a narrow angle full cone jet.
Water and air do not mix in a confined volume before leaving the nozzle and therefore their feed pressures can be adjusted independently without influencing each other: this allows for a very wide regulation range on the liquid capacity and makes it easier to reach the desired operating conditions.

Please note that the code given in the table only refers to the atomizing head and must be completed with the identification for one of the four connection adapters available, as shown below in the page.
The drawing beside shows an atomizing head assembled onto one A type adapter.

Materials	Atomizing head	B1 AISI 303 Stainless steel
	Adapter	B1 AISI 303 Stainless steel
		T1 Brass

WM = Water capacity (l/min)
AH = Air capacity (Ncm/h)

IDENTIFICATION CODES

ATOMIZING HEAD
The codes given in the table refer to the atomizing head only, and can be used to order the head as a separate part.

ADAPTERS
Can be ordered separately using the codes below, please replace
XX = B1 for AISI 303
XX = T1 for brass

COMPLETE ATOMIZERS
To identify a complete atomizer, please add to the head code the three suffix letters describing the adapter material and the adapter style according to the information below.

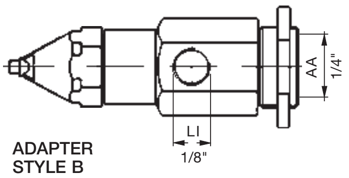
MAD 0801 B1 X Y Z

Adapter Material
A = T1 Brass
B = B1 AISI 303

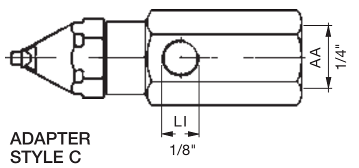
Adapter style
A = XMA 0103 xx
B = XMA 0101 xx
C = XMA 0102 xx
D = XMA 0100 xx

Connection
B = BSP F
N = NPT F

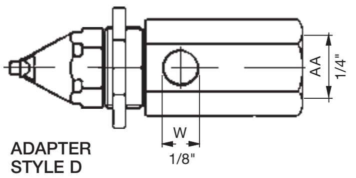
	Set-up Code	Air pressure (bar)	WM	AH	WM	AH	WM	AH	WM	AH	WM	AH
25°	**MAD 0331 B1**	2	0,10	3,1	0,12	3,0	0,15	3,1	0,27	2,7	-	-
		3	0,05	3,7	0,10	3,1	0,12	3,6	0,20	3,7	0,32	2,9
		4	0,02	4,7	0,05	4,8	0,08	4,4	0,18	4,4	0,25	4,2
		5	-	-	0,02	5,3	0,05	5,3	0,13	5,5	0,22	5,2
		6	-	-	-	-	0,02	6,1	0,12	6,0	0,18	5,8
	MAD 0801 B1	2	0,23	2,7	0,28	2,9	0,37	2,7	0,72	2,2	-	-
		3	0,22	3,6	0,27	3,6	0,32	3,5	0,52	3,2	0,82	2,7
		4	0,18	4,5	0,22	4,4	0,28	4,6	0,45	4,6	0,62	4,7
		5	0,12	5,4	0,18	5,3	0,25	5,6	0,40	5,4	0,53	5,4
		6	0,07	6,2	0,13	6,3	0,22	6,2	0,35	6,3	0,50	6,2
	MAD 1131 B1	2	0,50	7,3	0,60	6,6	0,73	6,9	1,15	5,6	-	-
		3	0,40	9,7	0,50	9,5	0,65	9,4	0,96	9,3	1,35	7,9
		4	0,27	11,6	0,37	11,9	0,55	11,8	0,93	12,1	1,20	11,5
		5	0,13	13,9	0,23	13,8	0,38	14,0	0,87	14,1	1,15	13,8
		6	0,07	18,6	0,13	18,7	0,27	8,7	0,72	18,9	1,10	19,0
40°	**MAL 0800 B1**	2	0,18	2,7	0,23	2,7	0,32	2,9	0,73	2,1	-	-
		3	0,15	3,7	0,18	3,9	0,25	3,5	0,50	3,7	0,85	2,6
		4	0,10	4,5	0,17	4,6	0,22	4,9	0,33	4,8	0,53	4,4
		5	0,03	5,4	0,10	5,6	0,18	5,4	0,30	5,4	0,45	5,3
		6	-	-	0,03	6,2	0,12	6,3	0,27	6,2	0,38	6,3
	MAL 1130 B1	2	0,46	7,3	0,52	7,2	0,68	6,8	1,13	5,7	-	-
		3	0,38	9,5	0,47	9,7	0,65	10,2	0,95	9,4	1,27	7,7
		4	0,23	11,8	0,35	11,8	0,50	11,9	0,88	12,1	1,15	11,8
		5	0,13	13,5	0,23	13,9	0,37	14,0	0,82	14,1	1,10	14,2
		6	0,07	16,0	0,13	16,2	0,27	16,2	0,63	16,2	1,03	16,3
	MAL 1300 B1	2	0,95	14,6	1,12	16,5	1,40	16,3	2,42	10,4	-	-
		3	0,80	19,3	1,00	20,0	1,26	22,2	1,90	19,2	2,87	14,5
		4	0,60	24,7	0,80	24,7	1,08	25,0	1,80	25,0	2,40	23,2
		5	0,42	29,9	0,60	30,3	0,90	30,4	1,70	30,5	2,27	29,9
		6	0,23	35,6	0,40	36,0	0,67	35,6	1,55	36,2	2,15	35,2
	Liquid pressure (bar)		***0,5***		***0,7***		***1,0***		***2,0***		***3,0***	



ADAPTER STYLE B



ADAPTER STYLE C



ADAPTER STYLE D

LOCKNUT FITS BOTH FRONT AND REAR THREADED BODIES.

B and D adapter style allow for mounting the atomizer through a wall or the side of a duct.
In this case do not forget to order the VAC 0021 B1 locknut, which fits both, to hold the adapter in place.

Enclosure 3

Properties of Thioether Liquid

Used for Thioether Mist Lubrication Tests

Vulkanol® OT

Product Description ether thioether
Supply Form nearly colorless to yellow liquid

Product Characteristics

Property	Nominal Value	Unit	Test Method
Refractive index (at 20 °C)	1.474 ± 0.003	---	DIN 51 423
Density (at 20 °C)	0.960 ± 0.020	g/cm^3	DIN 51 757 (Method 4)
Viscosity (at 20 °C)	24 ± 5	mPa·s	DIN 53 019

Other Product Features

Property	Typical Value
Volatile matter (at 150 °C)	6.0 %
Packaging	50 kg metal hobbocks, 180 kg rolling channel drums and 950 kg IBC
Storage Life/Conditions	2 years from date of production, keep cool (approximately 25 °C) and dry in closed original packaging

Vulkanol® OT

Vulkanol® is a Registered Trademark of LANXESS Deutschland GmbH

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