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Research Project:

# HELMGOP II
# Helicopter Main Gearbox Loss of Oil Performance Optimisation

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# HELicopter Main Gearbox loss of Oil Performance optimisation – HELMGOP II

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# 1. INTRODUCTION

The helicopter Main Gearbox (MGB) is responsible for converting the engine power from high speed and low torque to low speed and high torque in order to drive the main and tail rotor systems during flight. It also drives other accessory systems that are essential to the safe operation of the helicopter. During operation, MGBs generate a significant amount of frictional heat and often require a forced oil circulation lubrication to minimise physical wear and defects.

The oil lubrication system is a critical part of the helicopter MGB and is evident in the many accidents and incidents over the last 30 years. This led to the regulatory requirement of the MGB to sustain operation for at least 30 mins on a category "A"[1] rotorcraft, in the event of failures leading to the loss of the primary oil lubrication pressure.

To improve the capability of the helicopter to continue operation after loss of oil and also to help meet this regulatory requirement, helicopter manufacturers have chosen to introduce secondary or emergency MGB oil lubrication systems on a number of helicopter types. These may be categorised into active or passive systems. The active system that involves an independent oil lubrication source can offer different levels of reliability improvement and capability for continued operation of the MGB when compared to the controlled degradation of the MGB gears and bearings usually experienced in a passive system.

The Vapour Mist Phase Reaction Lubrication (VMPL) investigated in the research programme utilises thioether as an independent lubricant, which offers an alternative method of gearbox emergency lubrication. Being lightweight in design and capable of lubrication at elevated temperatures, it has been the focus of researchers in the aerospace industry. VMPL differs from other vapour and mist lubrication techniques such as vapour lubrication and regular oil-mist lubrication, in terms of its delivery means as well as its thermal decomposition and chemical reaction properties.

Thioether is a derivative of Polyphenyl Ethers (PPEs) in which one or more of the oxygen atoms in the polyphenyl ethers molecules are replaced with sulphur atoms. PPEs compounds are viscous, light yellow liquids with outstanding resistance to thermal degradation, oxidation, radiation, hydrolysis and chemical attacks, and are compatible with most metals and elastomers employed in high temperature applications. Because these compounds are non-halogenated, they are non-toxic and require no special precautions when being handled [11].

PPEs can remain in their liquid state at low temperatures due to their flexible molecule structure, a physical characteristic given the location of the oxygen atoms amongst the benzene rings. The benzene rings of these compounds possess high resonance energy, which accounts for their high boiling points and strong resistance to thermal degradation and oxidation. The thermal stability of

[1] A multi-engine helicopter design with independent engines, fuel systems, and electrical systems. This category of rotorcraft requires no single failure that can cause loss of more than one engine.

PPEs coupled with their properties of low vapour pressure led to their first major use as high temperature lubricants in the engines of the SR-71 supersonic strategic reconnaissance aircraft. At altitudes above 60,000 feet and with operating bearing surface temperatures of 316°C, a 5-ring polyphenyl ether (5P4E) could provide lubrication unmatched by no other lubricants [12].

When compared to other hydrocarbon fluid lubricants, PPEs also possess high surface tension. Upon application to a surface, the PPE molecules are more attracted to one another than the surface, and readily form a stationary field of microscopic droplets instead of a continuous film. The droplets are densely packed and tend to stay where they have been applied. The high surface tension of PPEs, together with its high thermal stability and low vapour pressures made them useful in satellites, where the lubricated surfaces are close to other surfaces such as solar cells and heat dissipaters that must be kept clean.

Appendix A provides additional information on the function of the MGB and the criticality of its oil lubrication system. It also details the VMPL method and the possible MGB defects under inadequate oil lubrication.

Thioether mist lubrication experiments in the past, including HELMGOP I by EASA and Cranfield University, have produced promising results that indicate its possible application as an MGB emergency lubrication system. However, these experiments were performed on a simple single-stage gearbox at a speed of up to 10,000 RPM to study the effectiveness of thioether mist lubricant. There has yet to be any documented research into the performance of a mist lubrication system on a commercial helicopter gearbox

## 2. AIM AND OBJECTIVES

The aim of the HELMGOP II is to investigate the performance of a mist lubrication system using commercially available thioether lubricant (MCS-293$^{TM}$) on a helicopter main gearbox as compared to a conventional oil jet lubrication system.

The objectives of the project are as follow:

a) Design of Test Rig to Drive and Load a Helicopter Gearbox

A test rig complete with a high-speed input drive and an absorption or passive dynamometer is necessary to power the MGB and to subject it the necessary loading conditions for the lubrication tests. Coupling input and output drive shafts have to be designed and manufactured to mechanically connect the MGB to the high-speed drive and the dynamometer. Lubrication and cooling requirements for the helicopter gearbox, external speed increase gearbox and the dynamometer must also be met.

b) Design of Mist Lubrication System for a Helicopter Gearbox

A mist lubrication system capable of delivering a controlled flow rate of the thioether lubricant and the pressurised air has to be designed and built for the experiment. The routing of the thioether mist must be achieved with adequate lubrication to the MGB gears and bearings, and with minimal impact to the original lubrication system.

c) Instrumentation of a Helicopter Gearbox for Performance Analysis

For precise and accurate monitoring of the MGB during the lubrication tests, the correct type and location of the temperature and vibration sensors must be considered. The instrumentation wiring shall be routed in a manner that facilitates the identification of the sensors as well as the strip down of the MGB.

d) Conduct Lubrication Tests on Helicopter Gearbox

A progressive test plan is necessary for the safe operation of the MGB lubrication tests. This ensures that maximum instrumentation data can be acquired while advancing the MGB towards its temperature limit in a controlled environment.

e) Compare and Analyse Lubrication Test Results

Lubrication tests data for the MGB under normal oil jet lubrication, oil-off conditions as well as thioether mist lubrication shall be compared and analysed to determine the performance of the thioether mist lubrication.

The performance measures used to evaluate the effectiveness of the mist lubrication system using thioether lubricant are the temperature profile of the gears and bearings, the vibration signature of the helicopter gearbox as well as the physical condition of the gears and bearings.

# 3. HELICOPTER MAIN GEAR BOX TEST RIG

A commercial category "A" helicopter main gearbox was used to investigate the performance of a mist lubrication system using commercially available thioether lubricant. It comprises of 5 reduction gear modules: LH and RH Input Reduction Gear Modules, Aft Reduction Gear Module, Main Reduction Gear Module and a 2-Stage Epicyclic Reduction Gear Module. The MGB assembly was set up on a test rig (Figure 3.1) complete with a DC electric drive motor, a speed-increasing gearbox, an absorption dynamometer and a thioether misting system. The electric drive motor together with the speed-increasing gearbox provides a maximum input drive speed of 17,842 RPM to the MGB. The absorption dynamometer provides resistance proportional to the desired loading on the MGB. In the lubrication tests, the dynamometer was set to deliver a level of resistance that is equivalent to 293 kW loading at the MGB LH input module. This represents the required loading at one input drive of the MGB during the loss of the primary oil lubrication system. At this loading, the equivalent frictional heat generated by its internal gears and bearings is approximately 16 kW.

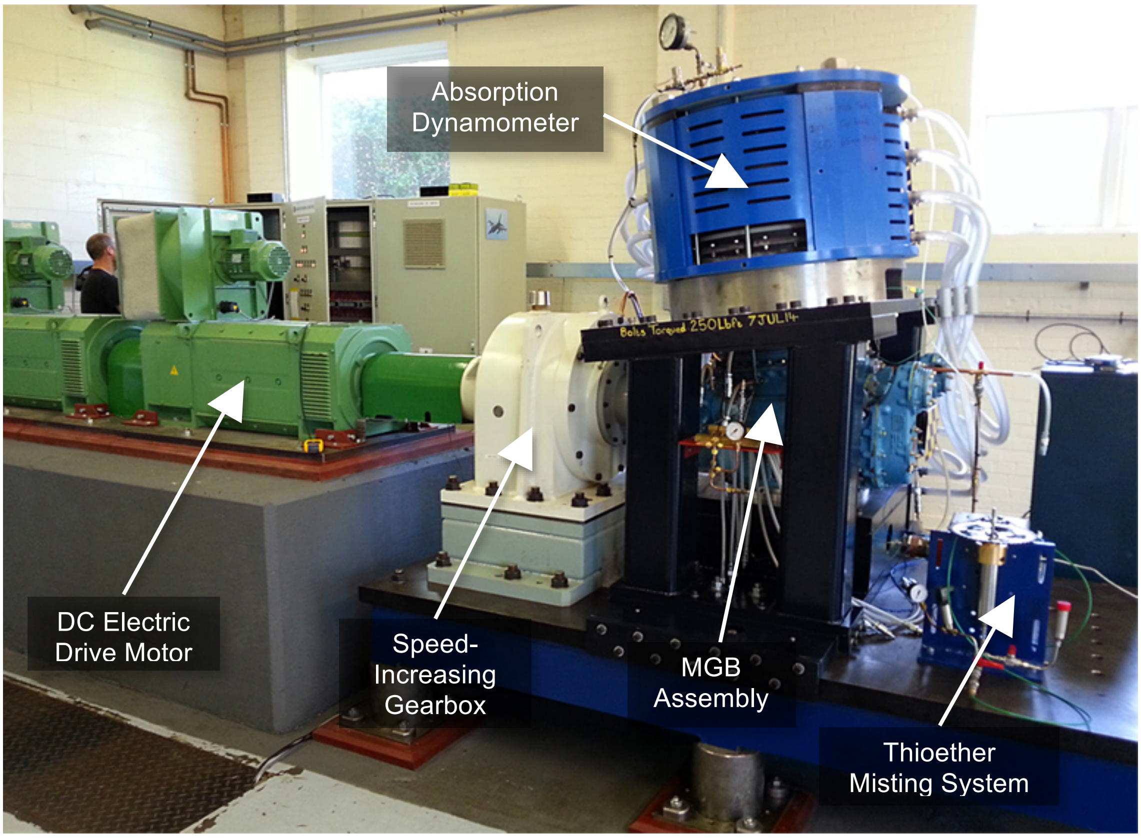


Figure 3.1 The MGB Test Rig

A thioether misting system was set up to deliver 165 mL/hr of thioether through 11 commercial misting nozzles. The thioether lubricant is channelled through 11 access ports located around the MGB assembly. The MGB test rig is instrumented to provide temperature, pressure, flow, power and speed readings during the tests. Appendix B details the design of the MGB test rig and the thioether misting system as well as its instrumentation.

# 4. HELICOPTER MAIN GEAR BOX TEST PLAN

## 4.1 Description of Progressive Test Phases

The test plan for the MGB test rig is progressive in nature and comprises three main phases. The aim is to ensure a safe and proper build-up of the MGB test rig systems while preserving the integrity of the MGB before conducting the actual load tests.

The first phase involves the partial commissioning of the test rig under no load condition to ensure the safe and proper operation of the driving electric motors, the speed-increasing gearbox, the lubrication and cooling systems, the thioether misting system as well as the instrumentation system. In this phase, the temperature profiles of the MGB gears and bearings, as well as the associated vibration signatures, would be determined at full speed in the absence of load for the three lubrication conditions: Normal lubrication, "oil-off" condition and thioether mist lubrication. The "oil-off" condition is intended to simulate MGB operation with residual oil that is representative of a rapid loss of oil event. The tests would be carried out under a restrictive operating envelope (duration less than 30 mins and an abort temperature limit of 150°C). This is for the purpose of safety and preserving the integrity of the MGB for the actual load tests. The captured data will provide a basis of comparison for MGB lubrication under no-load condition.

The second phase covers the full commissioning of the MGB test rig, including the loading system (dynamometer complete with water cooling and air pressure systems). It aims to verify the functionality of the complete MGB test rig under load condition. Unlike the partial commissioning phase, the temperature profile of the MGB gears and bearings, as well as the associated vibration signatures, would only be determined for the normal lubrication condition under actual test load. In this single test, there would be a progressive build up of test speed and load on the MGB and would last until thermal equilibrium of the MGB has been established at full speed and load. <u>Thermal equilibrium is defined as the condition in which the rate of change of bearing and gear temperature is less than two degrees centigrade per five minutes of operation (<2°C/5mins)</u>. The progressive test conditions will be split into six test sets and are listed in <u>Table 4.1</u>. The operating envelope would be expanded to allow MGB operation of up to 120 mins (or more) in duration and with an abort temperature limit of 150°C. Data from the full commissioning test would form the baseline thermal map to conduct the lubrication tests in the final phase.

The final phase builds on the results obtained in the full commissioning phase. It involves two separate tests, each operating the MGB at full speed and load under normal lubrication condition till thermal equilibrium before switching over to the "oil-off" condition and the thioether mist lubrication respectively. <u>Prior to subjecting the MGB to these conditions, short bursts of compressed air will be delivered through the MGB inlet port and the flexible tubes to purge out remnants of lubrication oil within the internal galleries and the tubes</u>. This ensures restriction-free routing of the thioether mist while allowing a fair comparison to be made between the two lubricating conditions.

As the temperature profile of the MGB gears and bearings under normal lubrication condition has been established in the second test phase, there is no need for a progressive build up of test speed and load. Instead, the MGB can be quickly brought up to full speed and load to achieve thermal equilibrium before the start of the "oil-off" and thioether mist conditions. Data from the tests would allow comparison of the MGB thioether mist lubrication under actual load against the conventional oil lubrication and the "oil-off" condition. The operating envelope would be the same as that of the full commissioning phase until thermal equilibrium has been established. Operating duration under "oil-off" and thioether mist conditions would be set at 10 mins and 30 mins respectively. Under the "oil-off" condition with load, the temperature of the MGB gears and bearings are expected to reach 200°C rapidly. Highlights of the three test phases are summarised in Table 4.1.

It is important to note that prior to the start of each test, it is necessary to have a common MGB reference temperature of 40°C and below to facilitate the comparison of temperature profiles between the different test phases and across different lubrication conditions. A conservative temperature limit of 200°C is also defined for the final phase in order to preserve the integrity of the MGB for future tests. This allows for a margin of safety between the actual and the measured bearing temperature. A detailed MGB test procedure for each of the test phase is listed in Appendix C.

| Test Phase /Set | Motor Speed/ Load Conditions | Lubrication Conditions | Duration | Abort Temperature Limit | Remarks |
|---|---|---|---|---|---|
| 1 | 3000 RPM/ No Load | Normal, "Oil-Off" and Thioether | 30 mins | 150°C | MGB test rig to cool to 40°C and below before the start of each test and under a different lubrication condition |
| 2/1 | 500 RPM/ 25 kW | Normal | 10 mins | 150°C | |
| 2/2 | 1000 RPM/ 50 kW | | 10 mins | | |
| 2/3 | 1000 RPM/ 100 kW | | 10 mins | | |
| 2/4 | 1500 RPM/ 150 kW | | 10 mins | | |
| 2/5 | 2000 RPM/ 200 kW | | 10 mins | | |
| 2/6 | 3000 RPM/ 293 kW | | Till thermal equilibrium* | | |
| 3 | 3000 RPM/ 293 kW | "Oil-Off" and Thioether | 10 mins and 30 mins | 200°C (to preserve MGB integrity) | |

* Duration of up to 120 mins or more may be necessary to achieve thermal equilibrium.

Table 4.1 Duration and Abort Temperature Limits for Test Phases/Sets
(Source: Author)

A gearbox teardown inspection would be performed after the completion of the last test to scrutinise the gears and bearings for the presence of surface wear.

## 4.2 Operating Conditions and Limits

| Category “A” Helicopter MGB | | |
|---|---|---|
| **Parameter** | **Operating Value (unit)** | **Limit (unit)** |
| Input Drive Speed | 17,842 (RPM) | 22,841 (RPM) |
| Output Drive Speed | 207 (RPM) | 265 (RPM) |
| Power Input | 293 (kW) | 1300 (kW) |
| Oil Supply Feed Pressure | 1.5 to 1.7 (bars) | 1.0 (bar) |
| Oil Supply Flow Rate | 30 (LPM) | 27 (LPM) |
| Oil Supply Temperature | < 80 (°C) | 80 (°C) |
| Oil Return Temperature | < 125 (°C) | 125 (°C) |
| Bearing and Gears Temperature | < 300 (°C) | See Table 4.1 |
| **SICMEMOTORI Tandem Drive DC Electric Motor (P/N: NP225 KS5 PVA/B3)** | | |
| **Parameter** | **Operating Value (unit)** | **Limit (unit)** |
| Rotational Speed | 3000 (RPM) | 3000 (RPM) |
| Power Available | 293 (kW) | 750 (kW) |
| Driving Torque | 933 (Nm) | 2387 Nm |
| Voltage Drawn | 605 (V) | 605 (V) |
| Current Drawn | 260 (A) | 663 (A) |
| **Speed-Increasing Gearbox (P/N: F5030)** | | |
| **Parameter** | **Operating Value (unit)** | **Limit (unit)** |
| Input Drive Speed | 3000 (RPM) | NA |
| Output Drive Speed | 17,842 (RPM) | |
| Oil Supply Feed Pressure | 2.8 (bars) | |
| Oil Supply Flow Rate | 30 (LPM) | |
| Oil Supply Temperature | < 40 (°C) | 40 (°C) |
| **Absorption Dynamometer – Wichita Clutch and Brake System (P/N: 7-325AM-B-1300)** | | |
| **Parameter** | **Operating Value (unit)** | **Limit (unit)** |
| Rotational Speed | 207 (RPM) | 935 (RPM) |
| Available Power to Absorb | 277 (kW) | 895 (kW) |
| Frictional Torque Required | 12,778 (Nm) | 55,950 (Nm) |
| Air Pressure Required | 1.24 (bars) | 9.0 (bars) |
| Water Supply Temperature | < 49 (°C) | 49 (°C) |
| Water Return Temperature | < 77 (°C) | 77 (°C) |
| Water Supply Pressure | NA | 2.7 (bars) |
| Water Supply Flow Rate | 141 (LPM) | 454 (LPM) |
| **Thioether Misting System** | | |
| **Parameter** | **Operating Value (unit)** | **Limit (unit)** |
| Thioether Delivery Rate | 165 (mL/hr) | NA |
| Thioether Delivery Pressure | 7.6 (bars) | |
| Air Delivery Pressure | 7.0 (bars) | |

Table 4.2 MGB Test Rig Operating Conditions and Limits (Source: Author)

Table 4.2 summarises the operating conditions and limits of the various systems in the MGB test rig. They provide the guidelines on the expected measurements and readings to infer the safe and proper functioning of the MGB test rig during the conduct of the lubrication experiments. The limits also provide an indication of the margins that are available to support MGB operation in the dual-drive mode in the future.

The MGB test rig would also be measured in accordance with the vibrational limits stated in ISO 8579-2: 1993 [26], as shown in Tables 4.3 to 4.5. The MGB is categorized under "Vibration Rating B" given its high-speed Forward Reduction Module. With this vibration category and its rated power of 293 kW, the MGB has a conservative vibration Velocity Rating (VR) of "5". This implies that housing vibration measurements of 5 $mms^{-1}$ and below are deemed acceptable for the safe operation of the MGB.

| Vibration Rating | Typical Applications |
|---|---|
| A | Navy |
| B | High-Speed (over 3600 RPM) |
| C | Industrial, Merchant Navy |
| D | Mill |

Table 4.3 Vibration Rating Categories for Gearboxes (Source: [26])

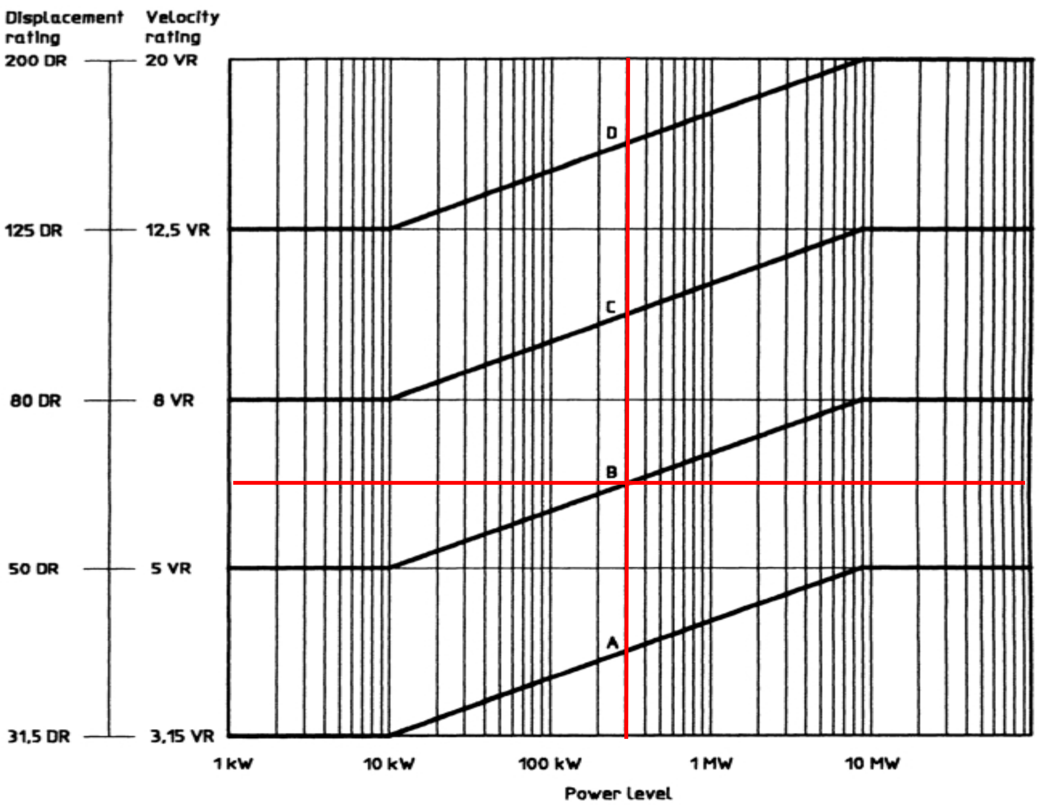


Table 4.4 Subjective Vibration Ratings (Source: [26])

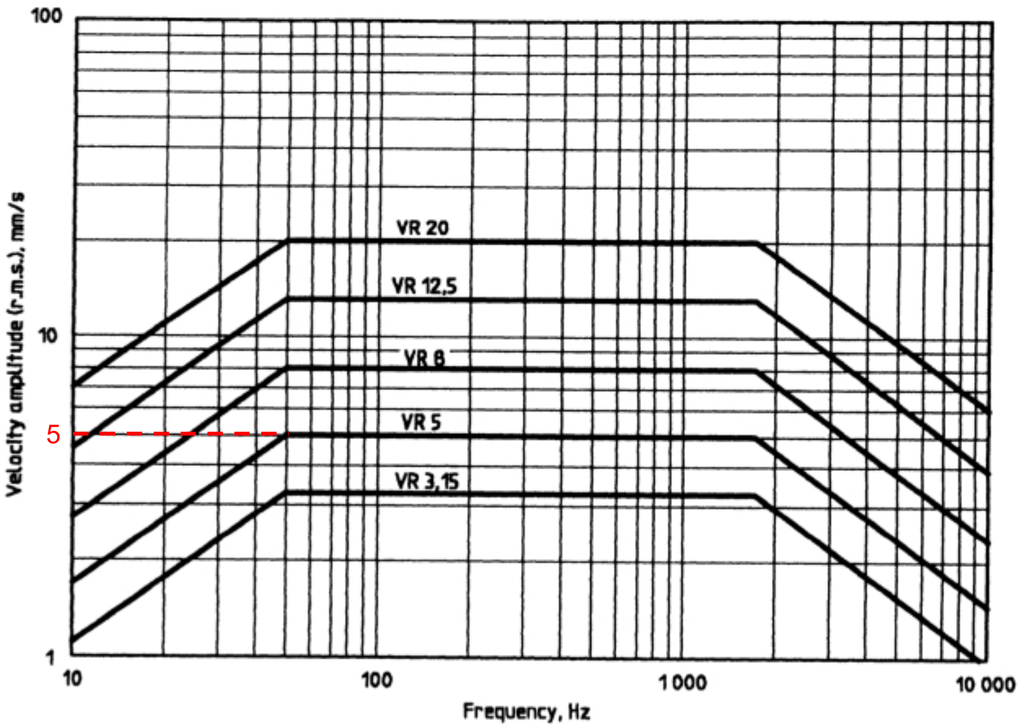


Table 4.5 Rating Curves for Housing Vibration (Source: [26])

## 5. HELICOPTER MAIN GEAR BOX TEST RESULTS AND ANALYSIS

The temperature profiles of the MGB gears and bearings are grouped into four different modules: Input reduction module, aft reduction module, main module and the epicyclic reduction module. This provides an overview of the temperature rise of the gears and bearings in each of the modules. From these temperature profiles, the corresponding rates of temperature change (Δ°C per min) are computed. For MGB locations where dual temperature profiles are present (redundancy instrumentation for critical bearings), the representative temperature profile would be the average of both readings (Table 5.1). Refer to Appendix D for the temperature profiles and rates of temperature change of all the tests carried out on the MGB test rig.

| Thermocouple # | Description | Thermocouple # | Description |
|---|---|---|---|
| 1 | Fwd Brg LH Aft Red | 17 | Sump Plate |
| 2 | Fwd Brg LH Aft Red | 18 | Oil Feed Supply |
| 3 | Fwd Brg Cen Aft Red | 19 | Brg Bevel Plate |
| 4 | Fwd Brg Cen Aft Red | 20 | Brg Bevel Plate |
| 5 | Fwd Brg RH Aft Red | 21 | Epi Case 2nd |
| 6 | Fwd Brg RH Aft Red | 22 | Epi Case Ring |
| 7 | Brg Bevel | 23 | Epi Case 1st |
| 8 | Brg Bevel | 24 | Aft Brg LH Fwd Red |
| 9 | Aft Brg LH Fwd Red | 25 | Fwd Brg LH Fwd Red |
| 10 | Aft Brg LH Fwd Red | 26 | Fwd Brg LH Input |
| 11 | Aft Brg RH Aft Red | 27 | Output Brg |
| 12 | Aft Brg Cen Aft Red | 28 | Output Brg |
| 13 | Aft Brg LH Aft Red | | |
| 14 | Aft Brg LH Input | | |
| 15 | Aft Brg LH Input | | |
| 16 | Oil Out Sump | | |

Table 5.1 Label Names of Thermocouples on MGB – Shaded Zones Denote Instrumentation Redundancy (Source: Author)

To compare and analyse the performance of the MGB under the three different types of lubricating conditions: (1) normal lubrication, (2) "oil-off" condition and (3) thioether mist lubrication, the temperature profiles and the corresponding rates of temperature change of identified thermocouple locations (based on highest temperature reached in normal operation) are plotted on the same graph. In addition, to account for variations in the test rig start-up timing as well as the initial temperature for each lubrication condition, both time and temperature corrections were performed on the data collected. The graphs for comparing the various lubricating conditions are discussed in Sections 5.1 to 5.3.

## 5.1 Phase 1 – Partial Commissioning Test Results (No Load)

The thermal maps of the MGB subjected to Phase 1 tests have identified four thermocouple locations, each corresponding to a particular MGB module that witnessed the highest temperature recorded within that module. The thermocouple locations are listed in Table 5.2. Each of them serves as the location for representing the temperature profile for each MGB module under the various lubricating conditions and in the absence of load.

| MGB Module | Thermocouple # | Description |
|---|---|---|
| Input Module | 14/15 (Avg) | Aft Brg LH Input |
| Aft Module | 5/6 (Avg) | Fwd Brg RH Aft Red |
| Main Module | 19/20 (Avg) | Brg Bevel Plate |
| Epicyclic Module | 23 | Epi Case 1st |

Table 5.2 Location of Highest Temperature in MGB Modules in Phase 1 Tests (Source: Author)

The comparison of the temperature profile for each of the MGB modules, across the various lubricating conditions and based on the representative thermocouple locations are shown in Figures 5.1 to 5.4.

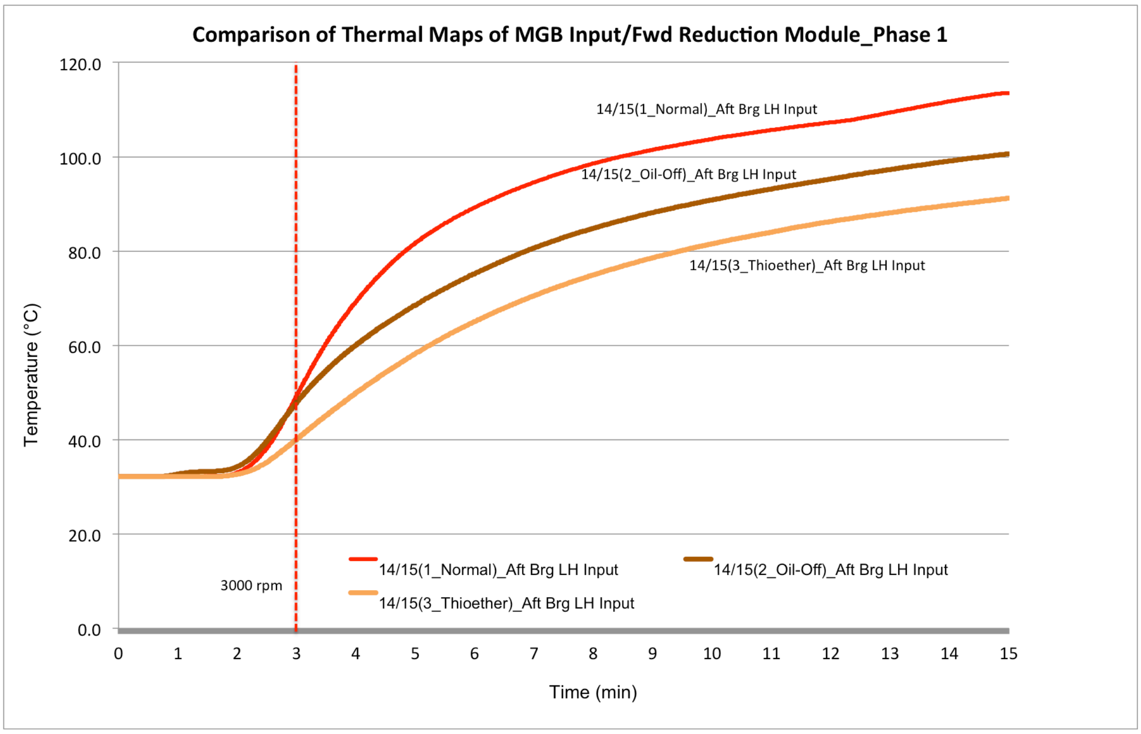


Figure 5.1 Temperature Profile of Fwd Reduction Gear Module at Aft Brg LH Input under Different Lubricating Conditions and No Load (Source: Author)

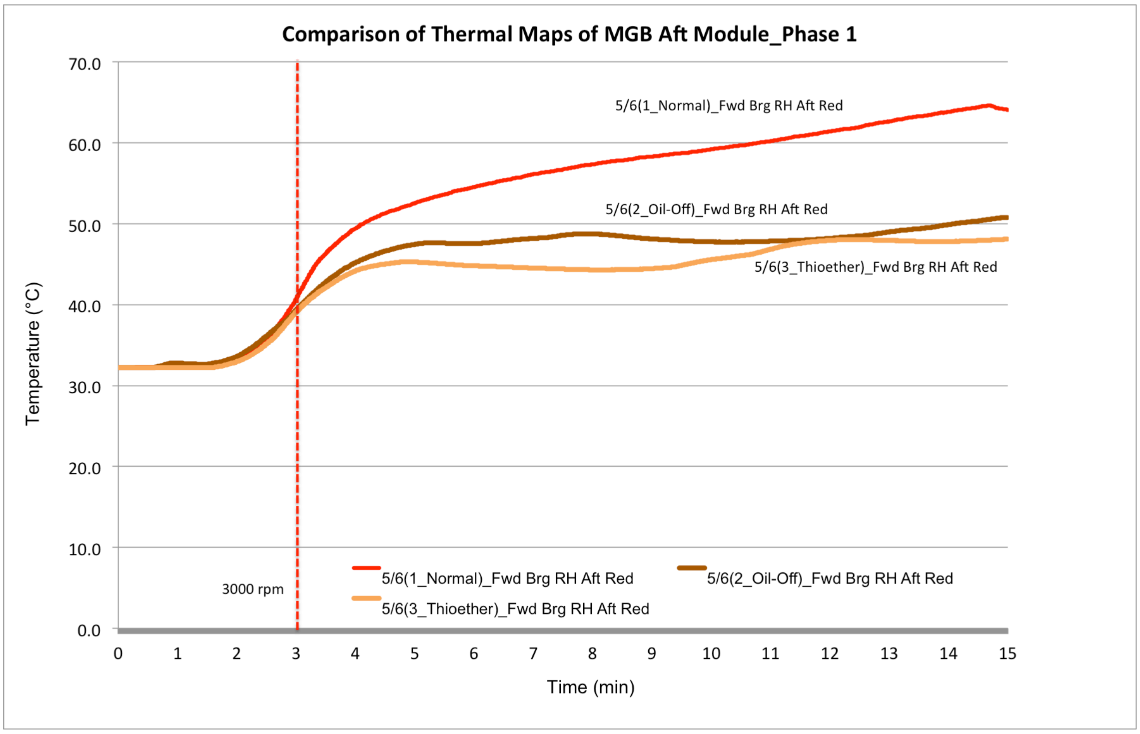


Figure 5.2 Temperature Profile of Aft Reduction Gear Module at Fwd Brg RH Aft Red under Different Lubricating Conditions and No Load (Source: Author)

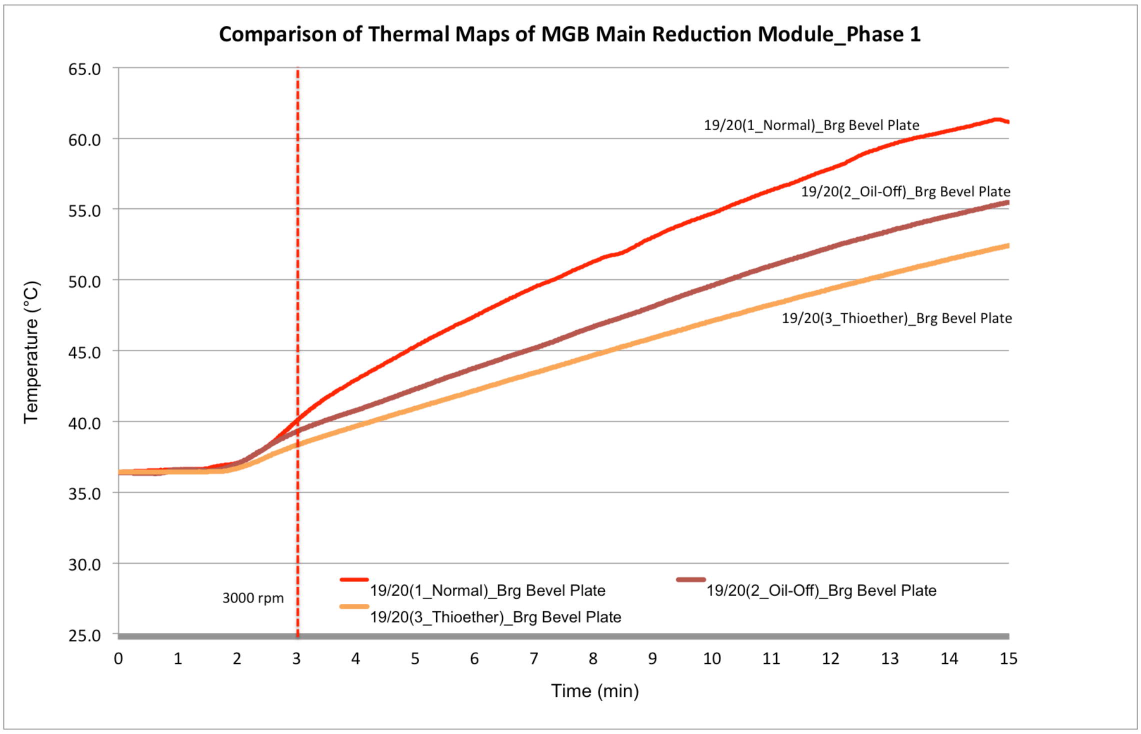


Figure 5.3 Temperature Profile of Main Reduction Gear Module at Brg Bevel Plate under Different Lubricating Conditions and No Load (Source: Author)

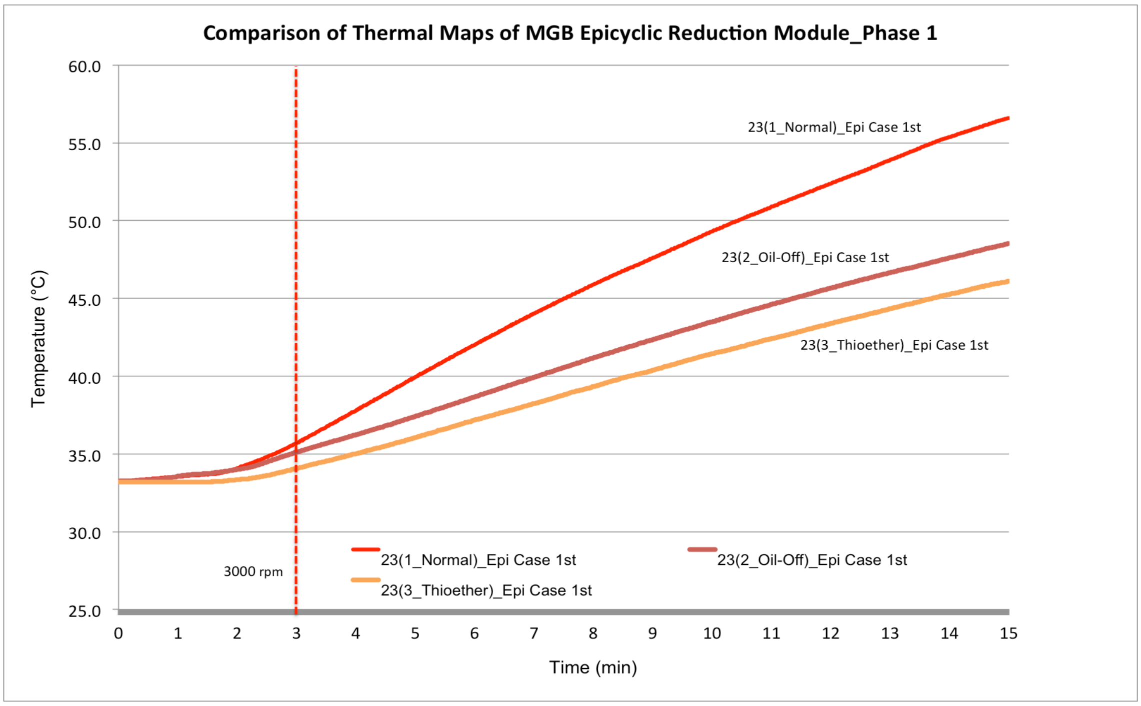

Figure 5.4 Temperature Profile of Epicyclic Reduction Gear Module at Epi Case 1st under Different Lubricating Conditions and No Load (Source: Author)

From the temperature profiles recorded at representative locations across the MGB modules, it is evident that the rise in temperature of the MGB is the highest under normal lubrication and the lowest under thioether mist lubrication. The reason for the highest rise in MGB temperature under normal lubrication as compared to "oil-off" condition or thioether mist lubrication is attributed to the loading conditions of Phase 1 tests. During these tests, the MGB is subjected to no external load.

In a typical gearbox, 50 per cent of the total power losses can be attributed to bearings, 40 per cent to gear meshing and the remaining 10 per cent to windage and churning losses [27]. Windage power loss is defined as the power loss due to the fluid drag when the gear is running in air. Churning power loss is the power loss due to the acceleration of the oil by the gear teeth and the pumping of the oil trapped between the gear meshing (also known as air-oil pocketing loss). This implies that the power losses, in the form of frictional heat generation within the MGB, due to sliding and rolling of gears and bearings becomes less significant as compared to other forms of load-independent losses, such as windage and churning losses.

In a study by NASA and Japanese engineers [28], it was found that windage losses increase with speed (Figure 5.5) while churning losses increase with both speed and lubrication oil pressure (Figure 5.6) and is more affected by air-oil pocketing loss. Hence during Phase 1 test with normal lubrication, the churning losses of the MGB dominate over the other tests with no lubrication or with thioether mist lubrication. The windage losses of all three tests would be comparable as the motor drive speed is kept at 3000 RPM. Interestingly, the lowest rise in MGB temperature under thioether mist lubrication could not be due to its level of churning losses. Instead, the authors are of the view that the mist form of the lubricant contributed favourably to the heat removal from the MGB gears and bearings. This suggests that thioether mist lubrication may be suitable as a means of gearbox lubrication.

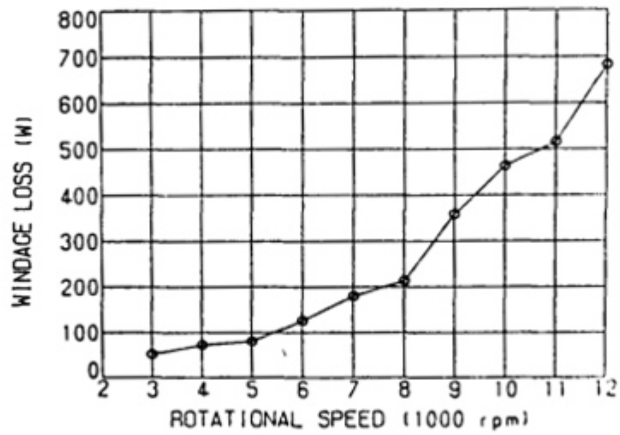


Figure 5.5 Windage Losses of Gearbox Against Speed (Source: [28])

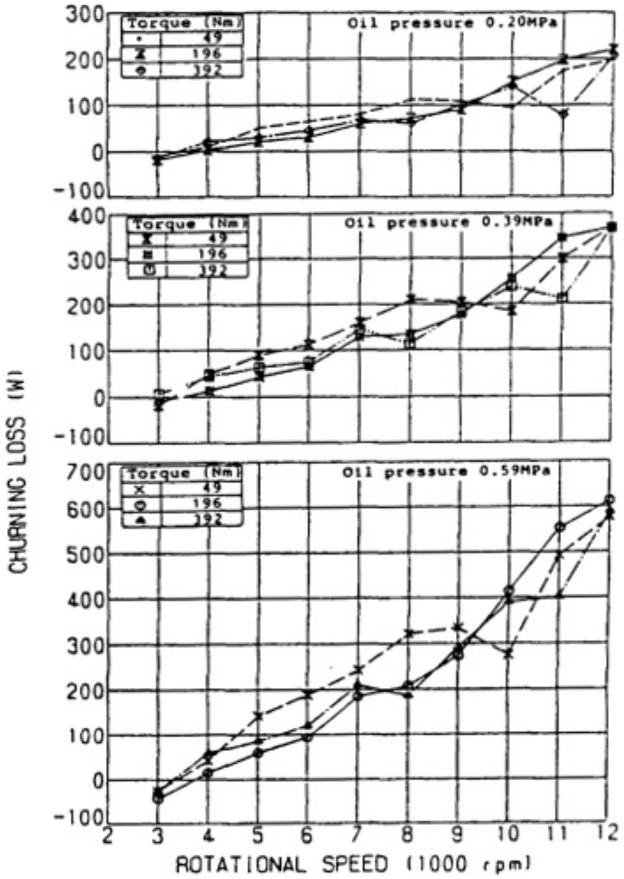


Figure 5.6 Churning Losses Against Speed and Lubrication Pressure (Source: [28])

## 5.2 Phase 2 – Full Commissioning Test Results (Normal Lubrication)

The temperature profiles of the MGB subjected to Phase 2 test, which involved operation under normal lubrication and progressive load levels until thermal equilibrium are shown in Figures 5.7 to 5.12.

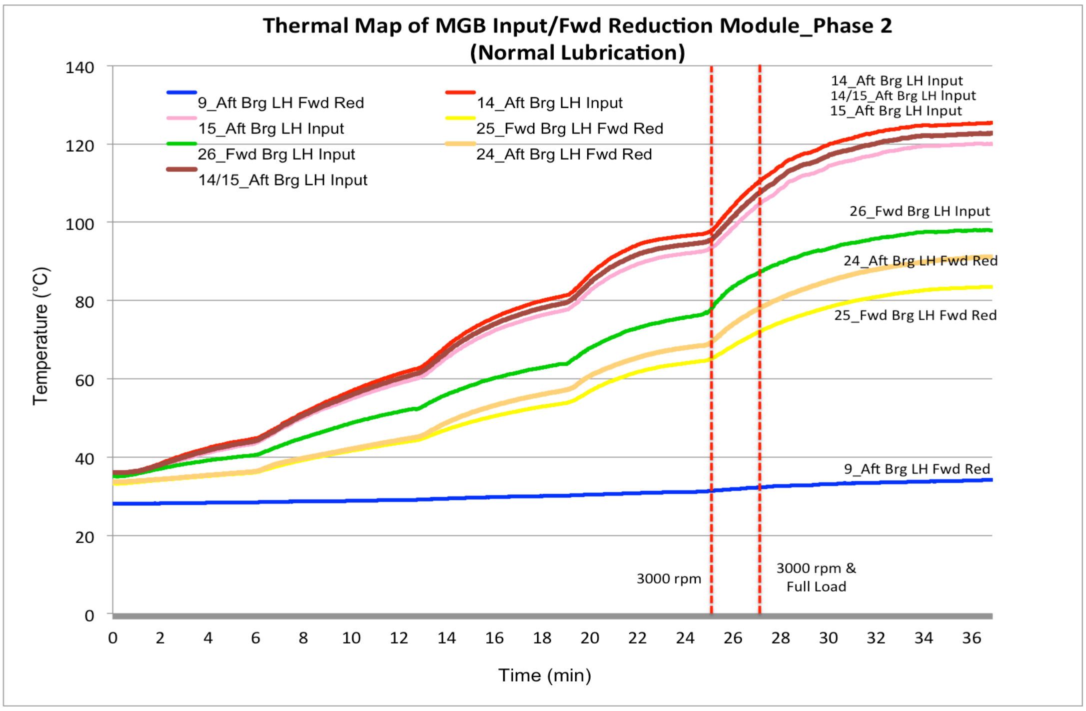


Figure 5.7 Temperature Profile of Fwd Reduction Gear Module under Normal Lubrication and Progressive Loads (Source: Author)

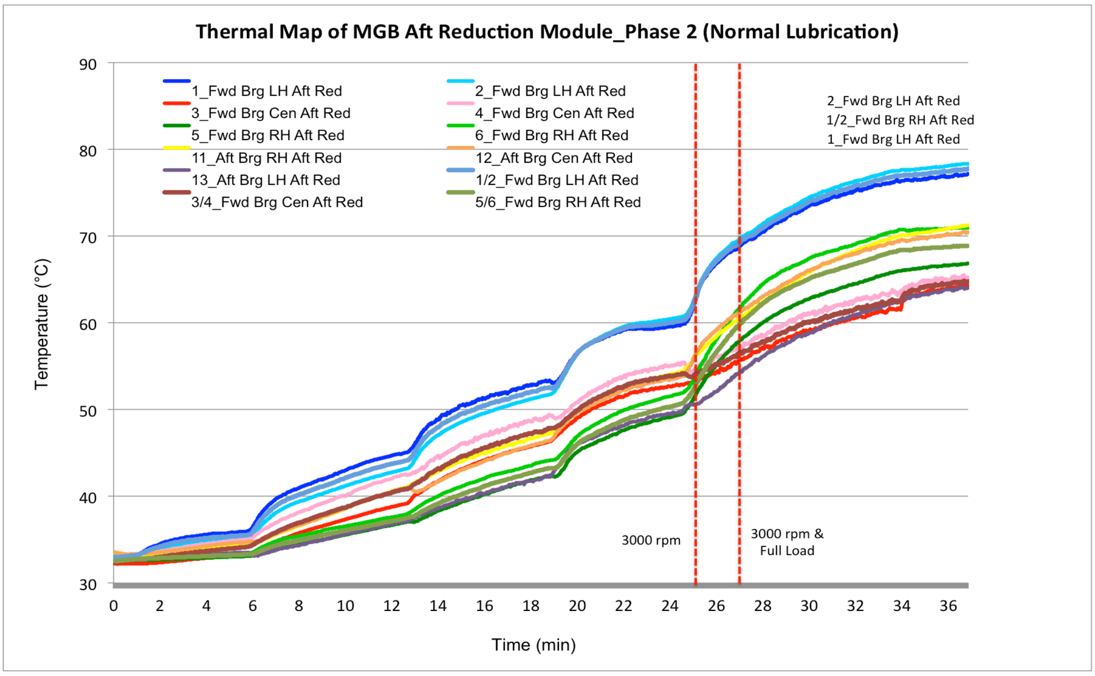


Figure 5.8 Temperature Profile of Aft Reduction Gear Module under Normal Lubrication and Progressive Loads (Source: Author)

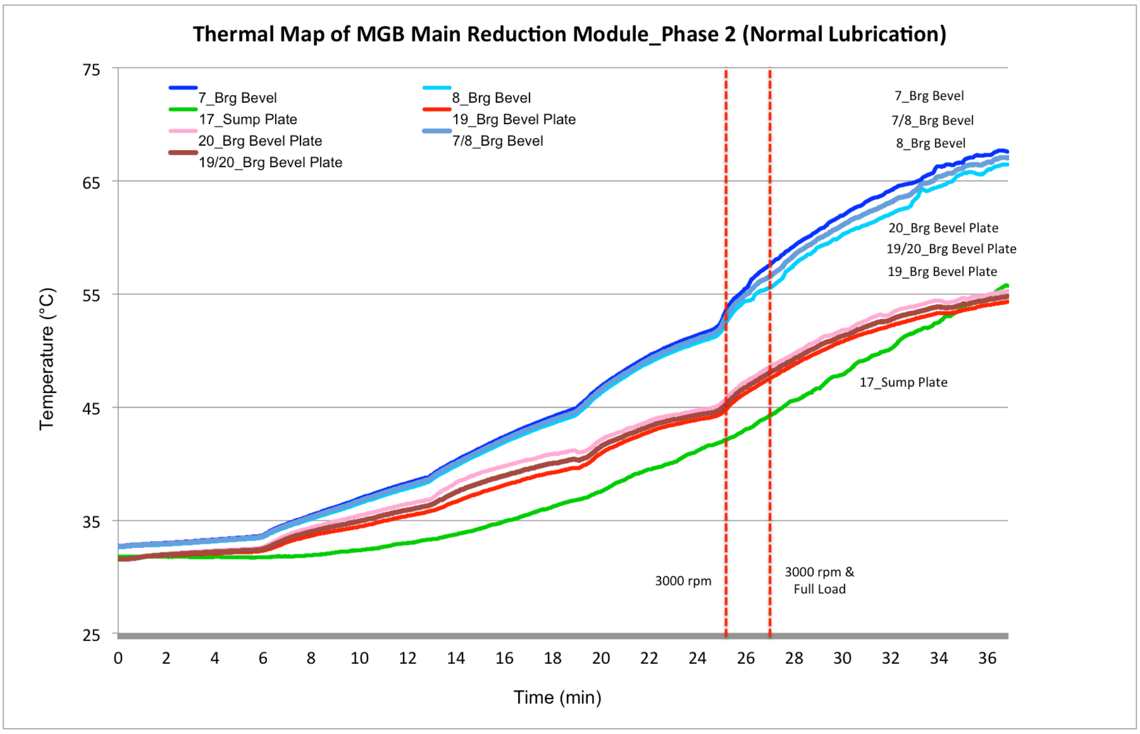


Figure 5.9 Temperature Profile of Main Reduction Gear Module under Normal Lubrication and Progressive Loads (Source: Author)

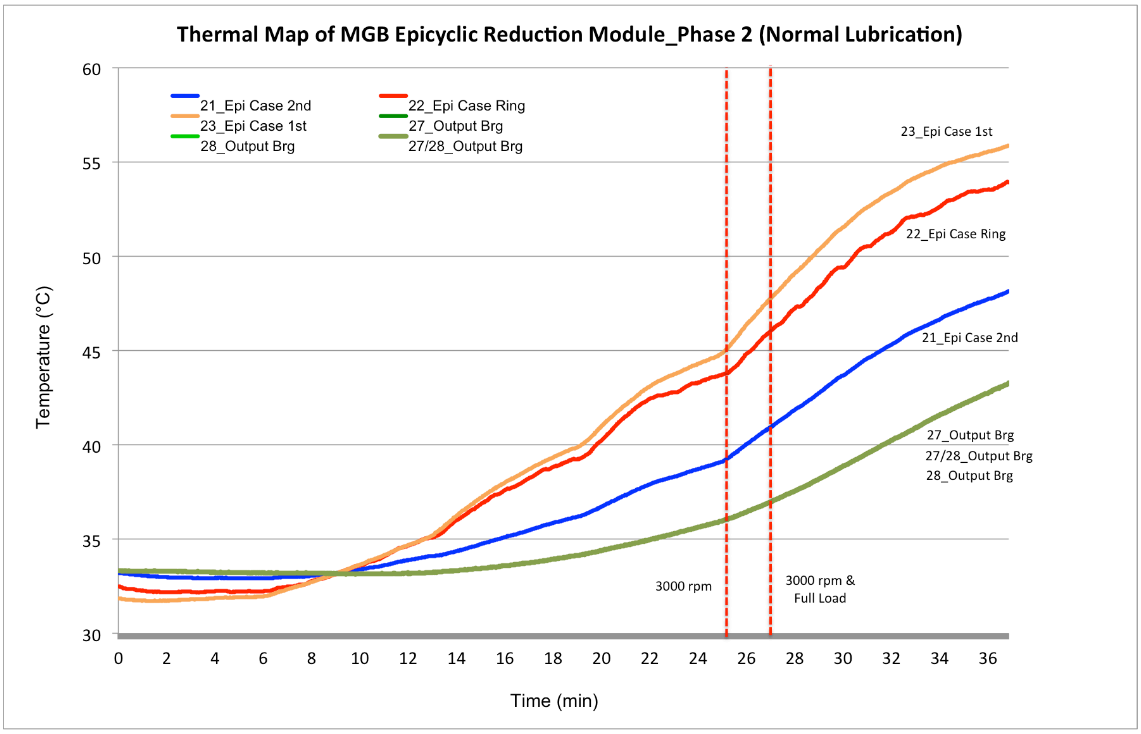


Figure 5.10 Temperature Profile of Epicyclic Reduction Gear Module under Normal Lubrication and Progressive Loads (Source: Author)

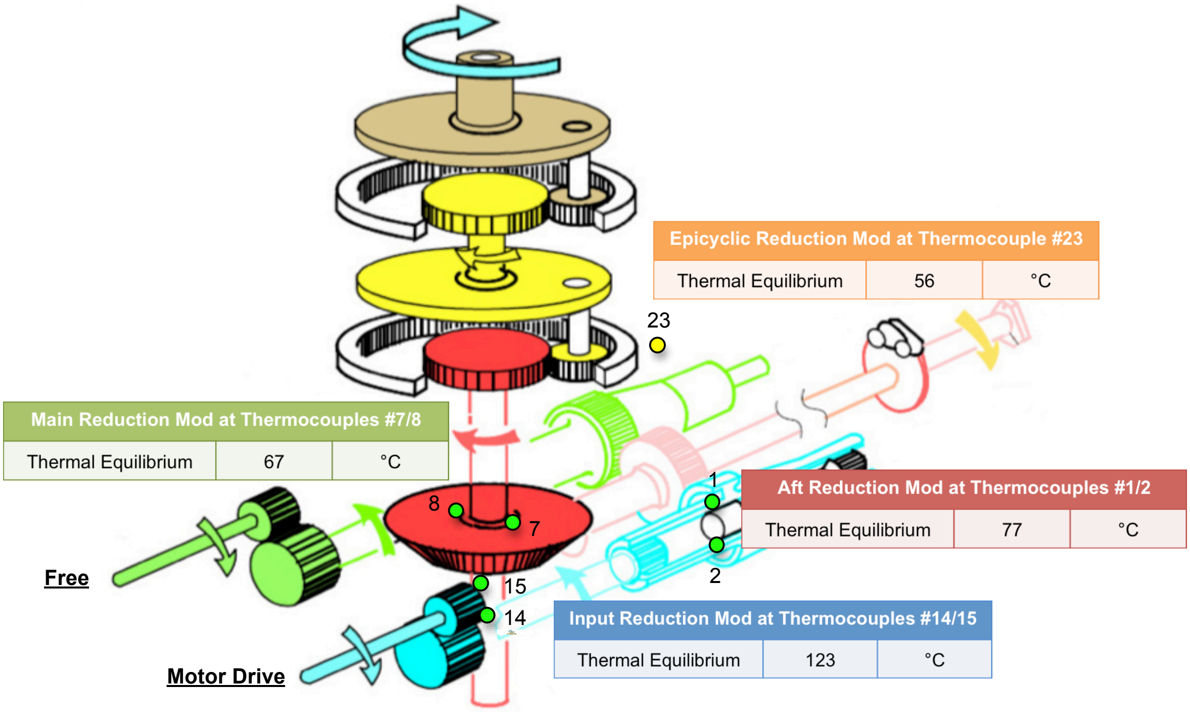


Figure 5.11 Overview of Highest Temperatures Attained across the MGB Modules at Thermal Equilibrium under Normal Lubrication (Source: Author)

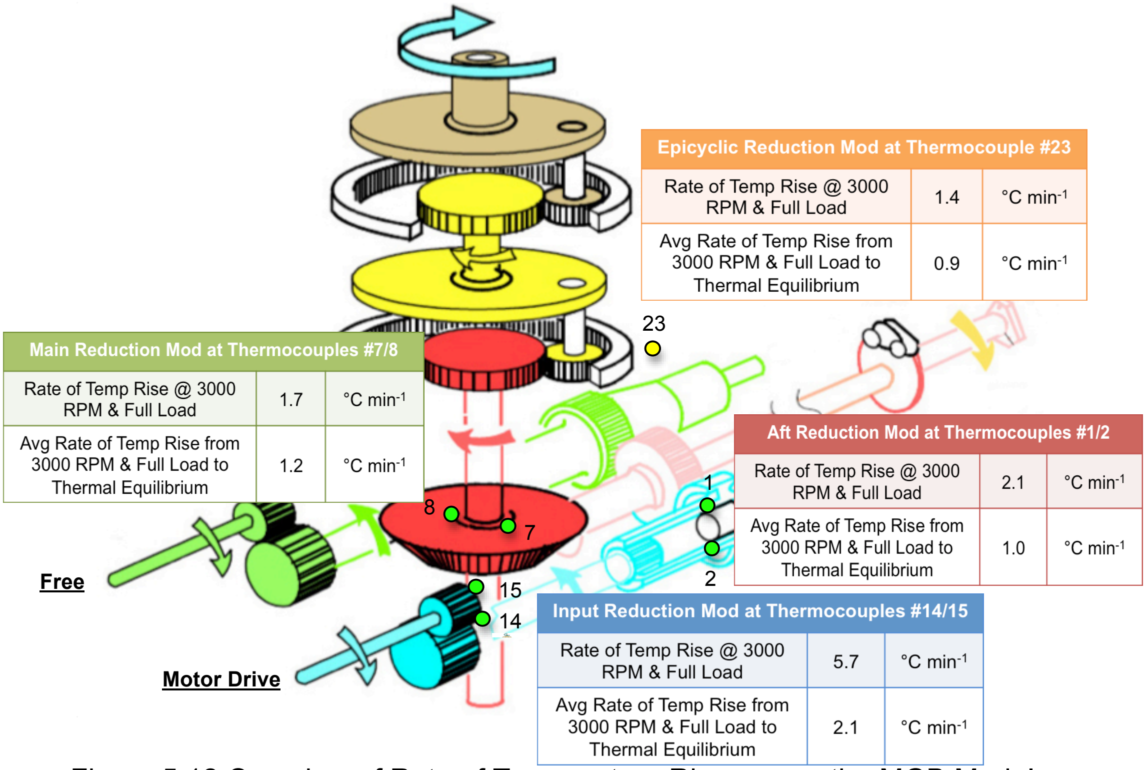


Figure 5.12 Overview of Rate of Temperature Rise across the MGB Modules at 3000 RPM and Full Load under Normal Lubrication (Source: Author)

The thermal maps of the MGB subjected to Phase 2 test have highlighted a different set of thermocouple locations (Table 5.3) that witnessed the highest temperature recorded in each of the MGB modules. They would be used to compare the temperature profile and rate of temperature rise of the respective MGB module under different lubricating conditions during Phase 3 Tests.

| MGB Module | Thermocouple # | Description |
|---|---|---|
| Input Module | 14/15 (Avg) | Aft Brg LH Input |
| Aft Module | 1/2 (Avg) | Fwd Brg RH Aft Red |
| Main Module | 7/8 (Avg) | Brg Bevel Plate |
| Epicyclic Module | 23 | Epi Case 1st |

Table 5.3 Location of Highest Temperature in MGB Modules in Phases 2 and 3 Tests (Source: Author)

From Figure 5.11, it is evident that the different MGB modules attained different temperature readings when operating at thermal equilibrium. The temperature reading was the highest at the Input Reduction Gear Module and the second lowest at the Main Reduction Gear Module. This suggests that the dominant frictional losses for the MGB under load, as manifested by the temperature of the modules, are more influenced by the shaft's rotational speed than its transmission torque. In other words, the losses resulting from the rolling and sliding of the gears and bearings within the MGB are directly related to their rotating speeds. This inference was based on the direct temperature measurements of the bearing assemblies located in the Input, Aft and Main Reduction Gear Modules (Table 5.4). For the Epicyclic Reduction Gear Module, the temperature reading taken at the 1st stage case gear provides an indirect measurement of the 1st stage planetary gear bearing assembly. Although the 1st stage planetary gear shaft rotates at a higher speed than the bevel wheel, the lower temperature reading could be attributed to the thermal gradient resulting from the heat conduction process between the bearing assembly to the case gear.

| MGB Module | Thermocouple # | Temperature (°C) / Means | Shaft Speed (RPM) |
|---|---|---|---|
| Input Module | 14/15 (Avg) | 123 / Direct | 17842 |
| Aft Module | 1/2 (Avg) | 77 / Direct | 6218 |
| Main Module | 7/8 (Avg) | 67 / Direct | 1867 |
| Epicyclic Module | 23 | 56 / Indirect | 3404 (1st Stage Planet) |

Table 5.4 Correlation of Temperature against Shaft Speed in the MGB Modules for Phases 2 Test (Source: Author)

Figure 5.12 summarises both the instantaneous rate of temperature rise when the MGB has attained full speed and load (27 mins into the experiment), as well as the average rate of temperature rise between the attainment of full speed and load till thermal equilibrium (27 to 36 mins of the experiment). The latter is computed by taking the average the rates of temperature rise determined at every minute of the MGB operation. The instantaneous rate of temperature rise was the highest for the Fwd Reduction Gear Module and the lowest for the Epicyclic Gear Reduction Module. They were aligned with the temperatures reached at thermal equilibrium across the MGB modules. This trend was however not observed when the rates of temperature rise were averaged over the duration of interest.

## 5.3 Phase 3 – Full Commissioning Test Results ("Oil-Off" Condition, Thioether Mist Lubrication and "Dry Gears" Condition with Full Load)

Phase 3 test results provided a comparison of the temperature profile and rate of temperature rise of each MGB module under different lubricating conditions upon attaining thermal equilibrium at full speed and load: (1) "oil-off" condition, (2) thioether mist condition and (3) "dry gears[2]" condition. A third set of "dry gears" condition was introduced as a new test after data collected from the first two conditions suggested the possibility of residual oil that may impede the performance of the thioether mist lubricant, especially during the short operating duration of 6 to 7 mins, prior to the MGB reaching its abort temperature limit.

The abort temperature limit for the Phase 3 tests was set as 200°C. During the first test involving the "oil-off" condition, the maximum temperature of the MGB reached 198°C. Temperatures at the aft bearing of the LH input pinion (thermocouples #14 and #15) were observed to creep from an average reading of 183°C, when the load was taken off the MGB (Figure 5.13). In comparison, the temperatures at the fwd bearing of the LH aft reduction gear (thermocouples #1 and 2) fell, while those of the bevel bearing (thermocouples #7 and 8) and the 1st stage epicyclic case gear tapered off before receding.

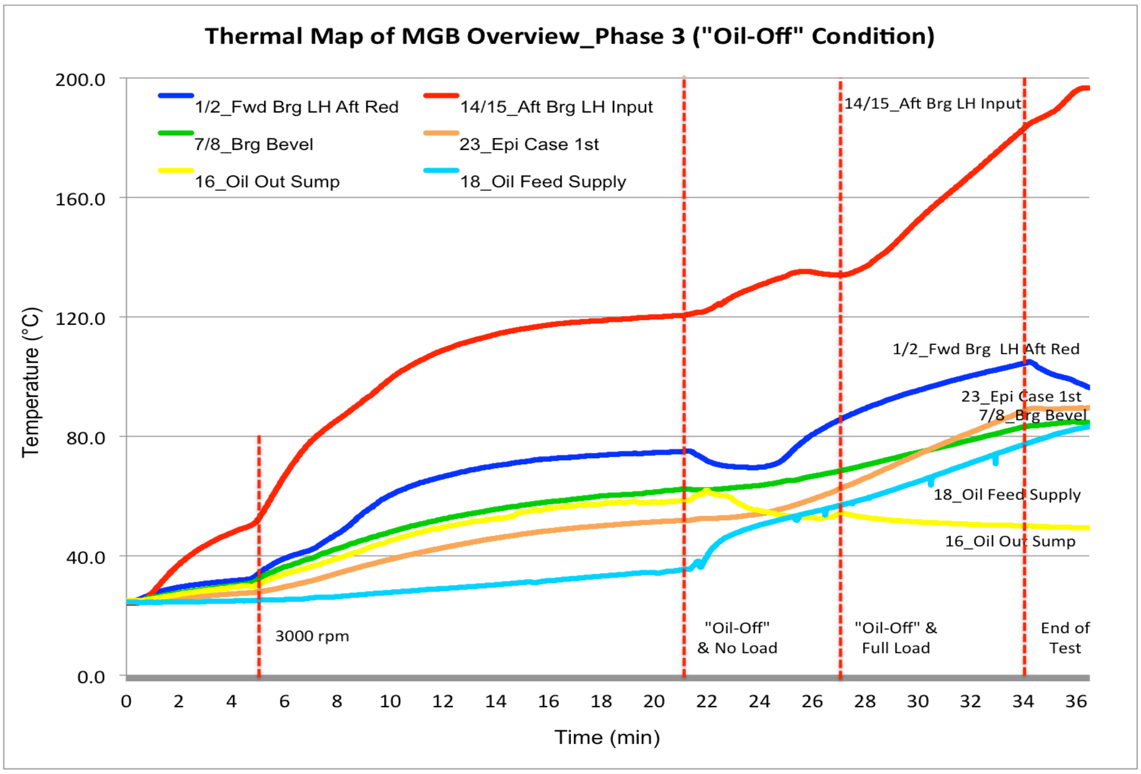


Figure 5.13 Temperature Profile of MGB under "Oil-Off" Condition (Source: Author)

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[2] The MGB is operated under no load and full speed to attain thermal equilibrium before subjected to full loading of 293 kW. This allows the gears and bearings to fling off any residual oil that may provide some form of boundary lubrication for the contacting metal surfaces. This results in a condition of reduced residual oil within the MGB.

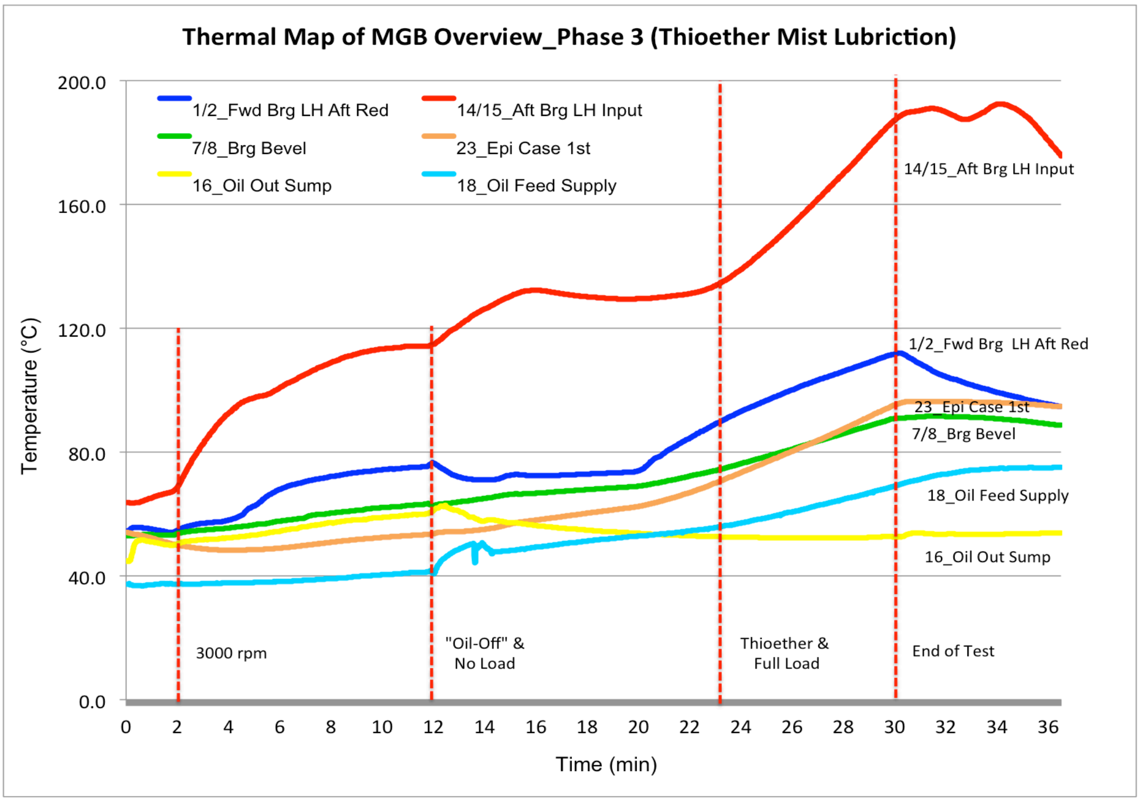


Figure 5.14 Temperature Profile of MGB under Thioether Mist Lubrication (Source: Author)

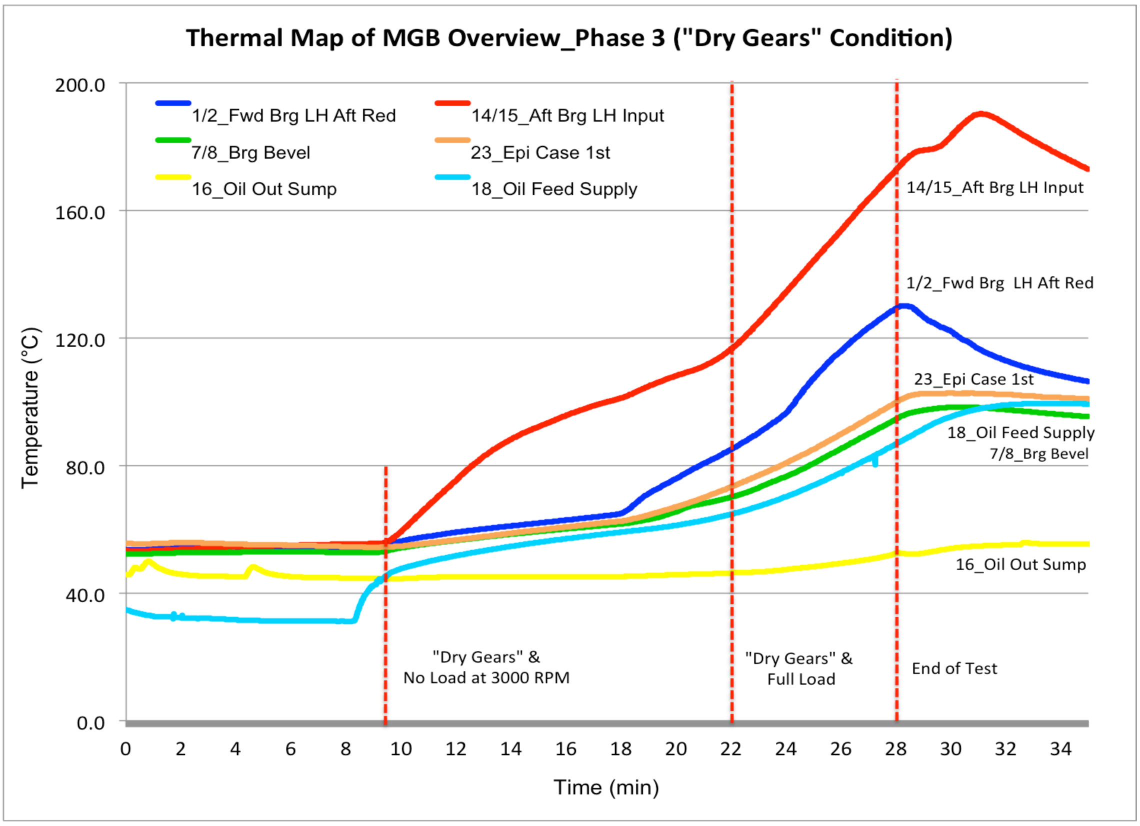


Figure 5.15 Temperature Profile of MGB under “Dry Gears” Condition (Source: Author)

From Figure 5.14, it was interesting to note that when the load was taken off the MGB under thioether mist lubrication, temperatures at the aft bearing of the LH input pinion (thermocouples #14 and #15) tapered off before receding. They did not continue rising unlike that of the "oil-off" and "dry gears" (Figure 5.15) lubricating conditions. This observation was aligned with the suggestion of the lubricating characteristic of the thioether mist lubricant in Chapter 5.1. In all the three lubricating conditions, the shape of the temperature profiles for the LH aft reduction gear fwd bearing, the bevel bearing and the 1st stage epicyclic case gear were found to be similar.

The comparison of the MGB performance under the different lubricating conditions were based on the temperature profiles and rates of temperature rise across the MGB during the short operating duration of 6 to 7 mins, following a state of thermal equilibrium at full load. Results of this comparison are shown in Figures 5.16 to 5.24.

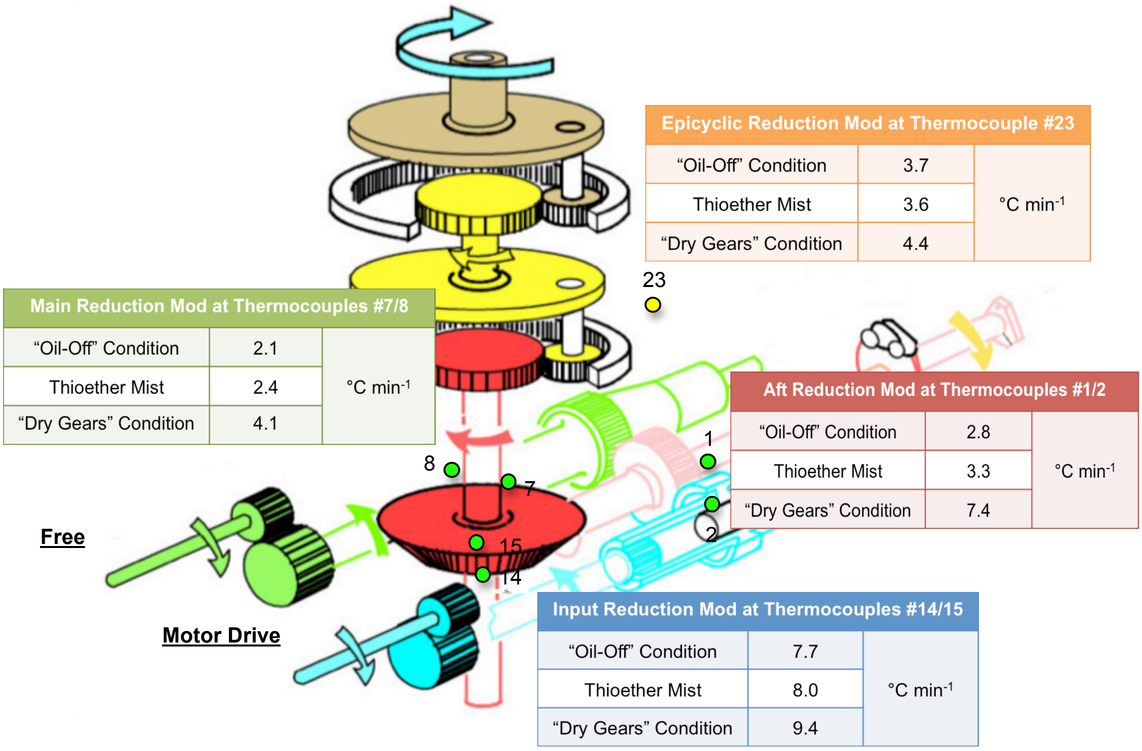


Figure 5.16 Overview of Rate of Temperature Rise across the MGB Modules under Various Lubricating Conditions and Full Load (Source: Author)

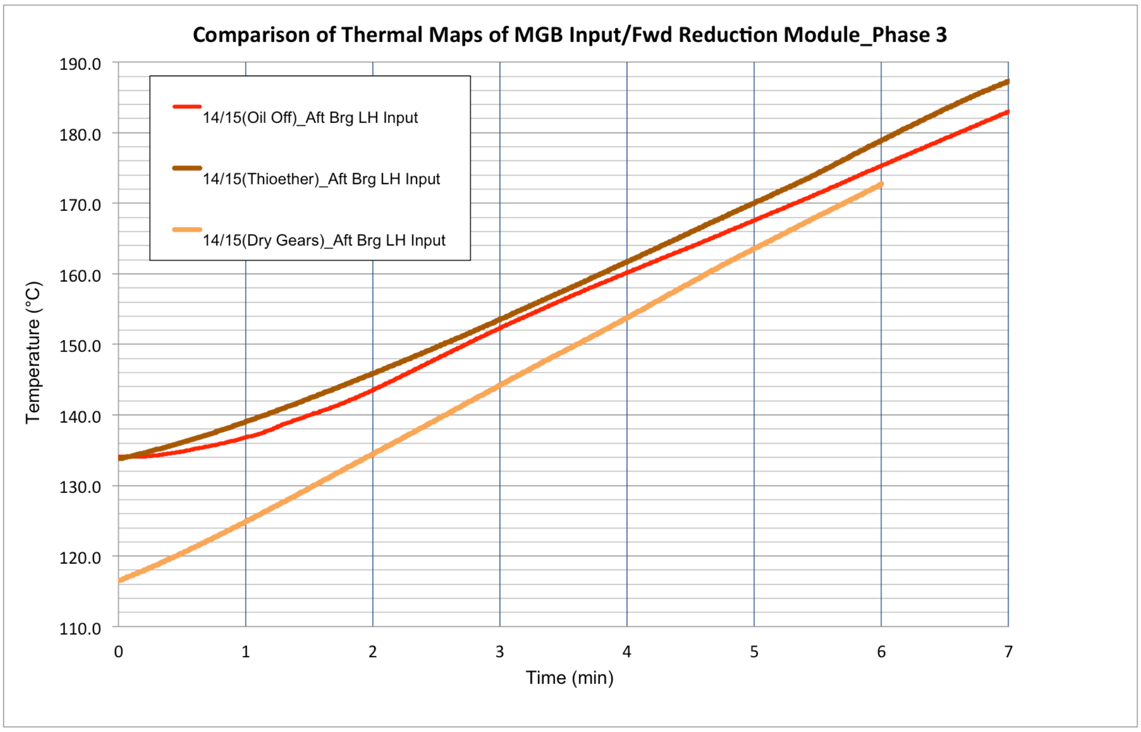


Figure 5.17 Temperature Profile of Fwd Reduction Gear Module at Aft Brg LH Input under Different Lubricating Conditions and Full Load (Source: Author)

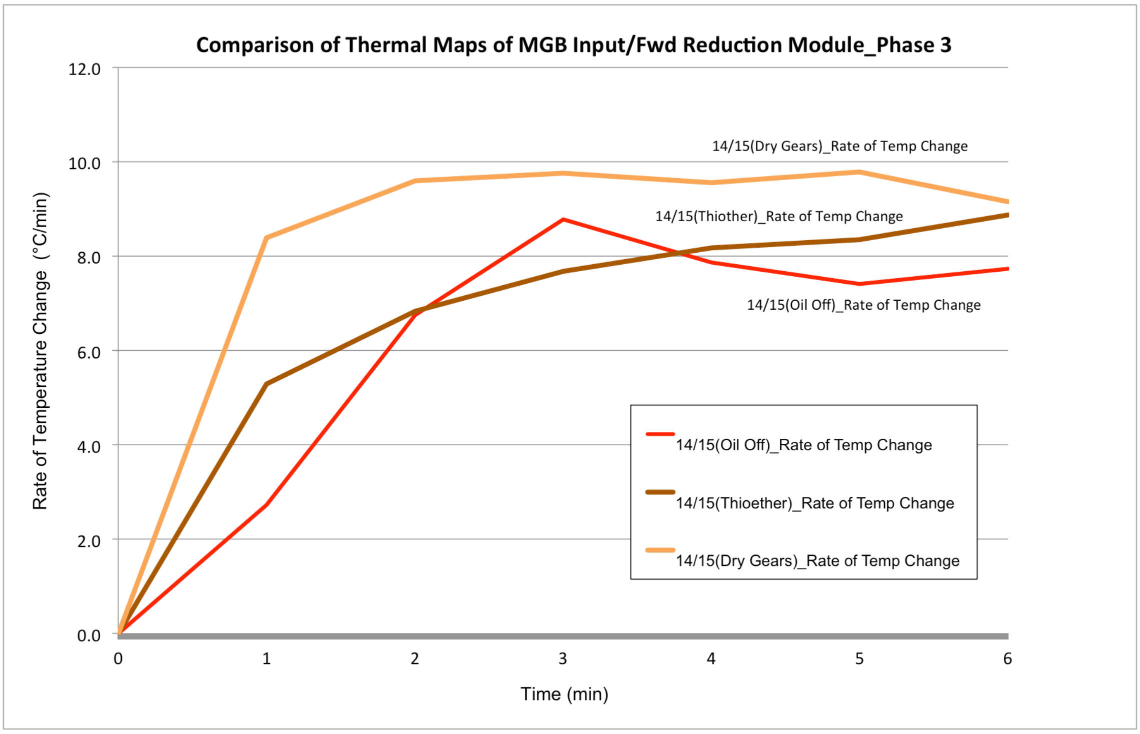


Figure 5.18 Rate of Temperature Rise of Fwd Reduction Gear Module at Aft Brg LH Input under Different Lubricating Conditions and Full Load (Source: Author)

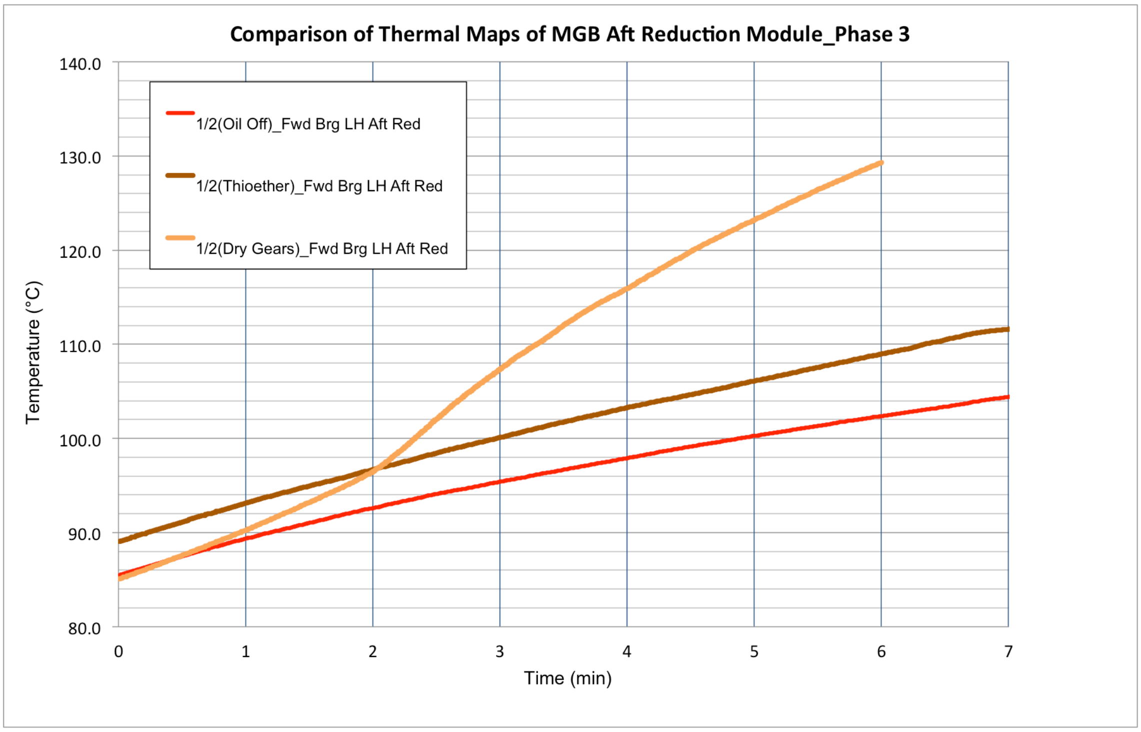


Figure 5.19 Temperature Profile of Aft Reduction Gear Module at Fwd Brg LH Aft Red under Different Lubricating Conditions and Full Load (Source: Author)

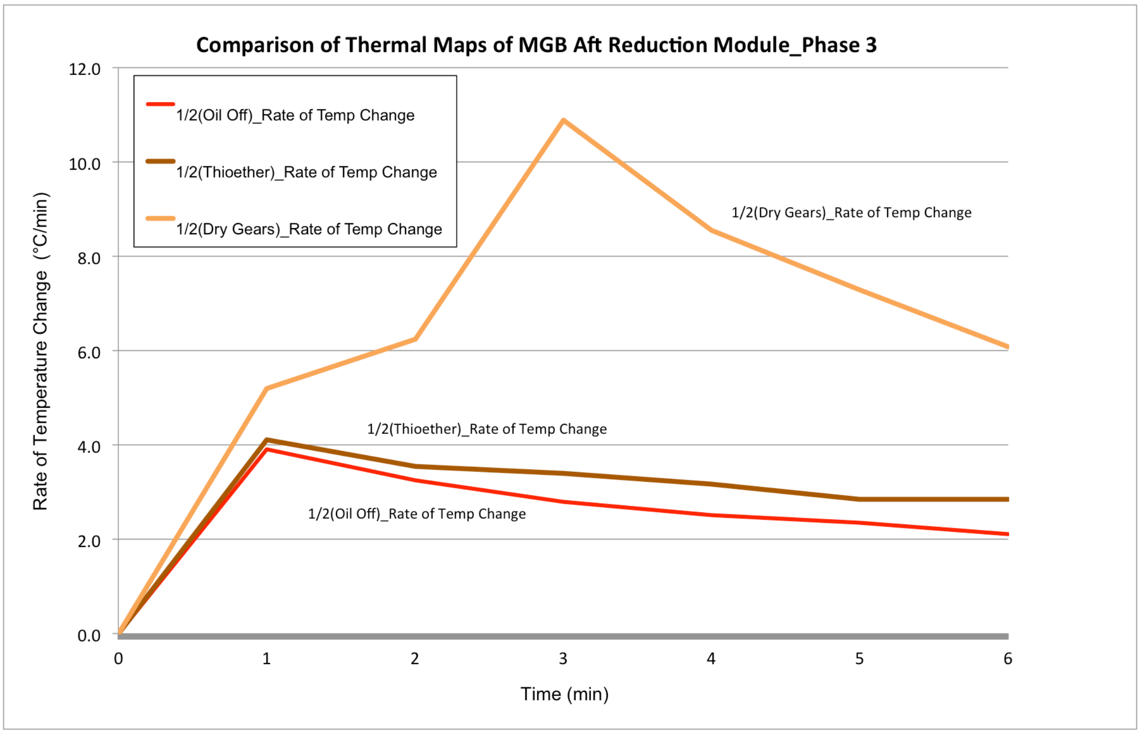


Figure 5.20 Rate of Temperature Rise of Aft Reduction Gear Module at Fwd Brg LH Aft Red under Different Lubricating Conditions and Full Load (Source: Author)

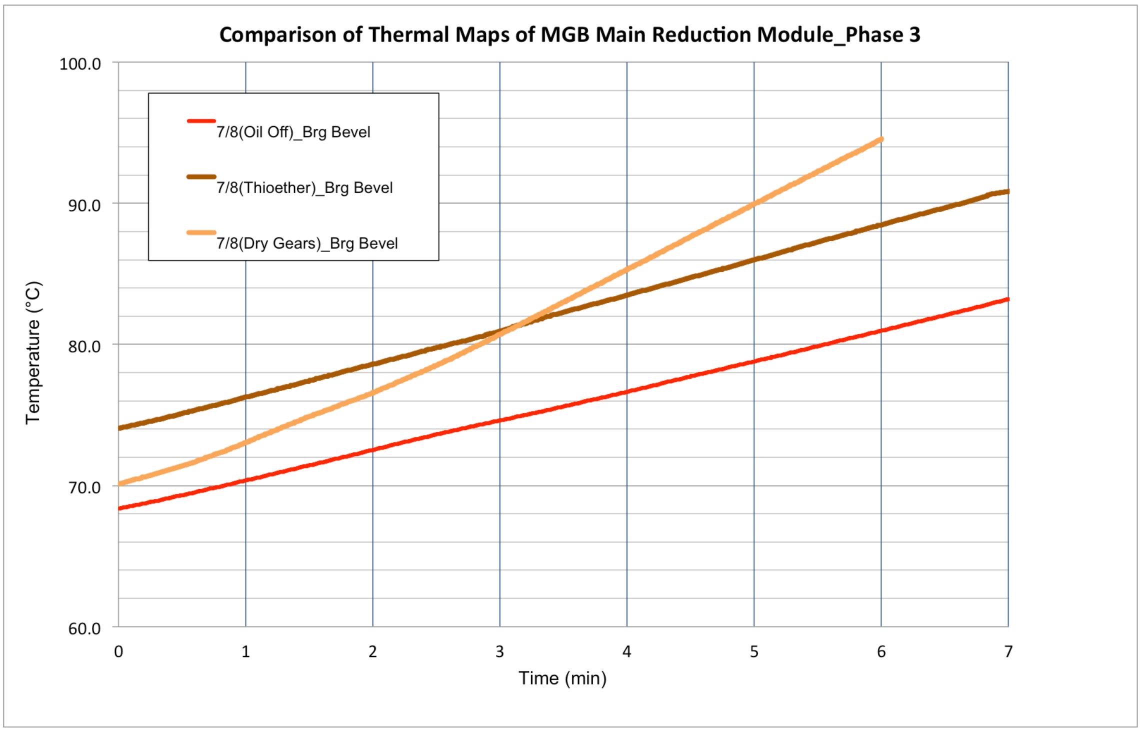


Figure 5.21 Temperature Profile of Main Reduction Gear Module at Brg Bevel under Different Lubricating Conditions and Full Load (Source: Author)

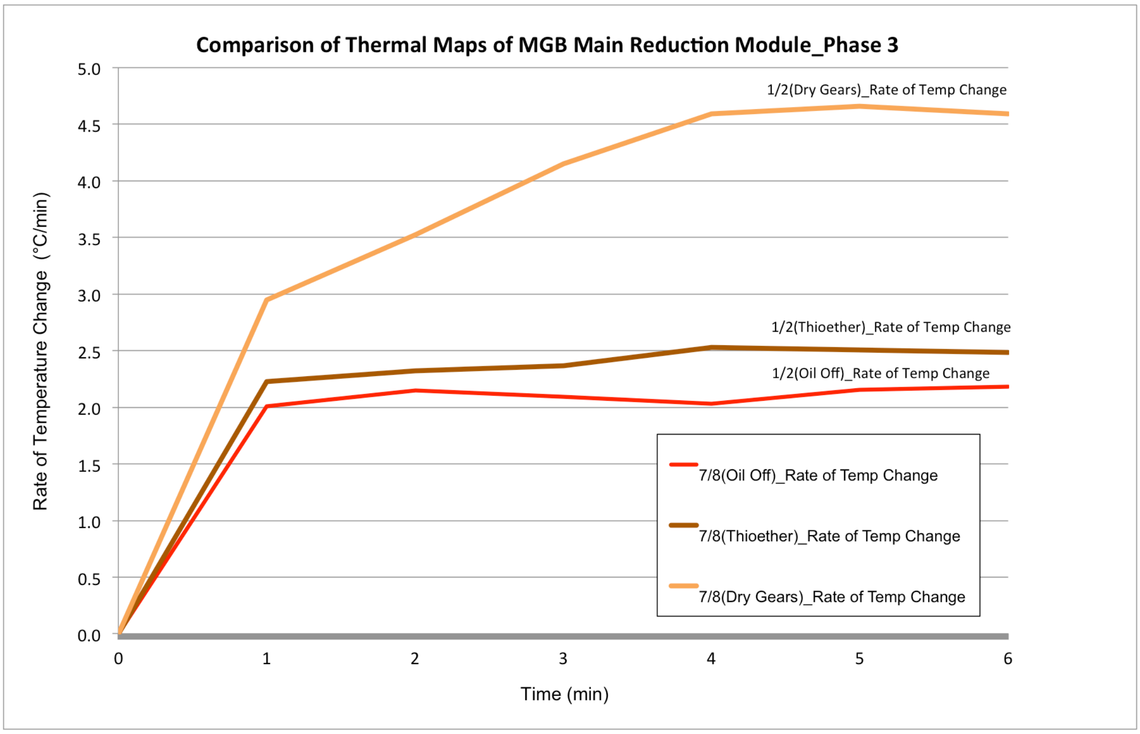


Figure 5.22 Rate of Temperature Rise of Main Reduction Gear Module at Brg Bevel under Different Lubricating Conditions and Full Load (Source: Author)

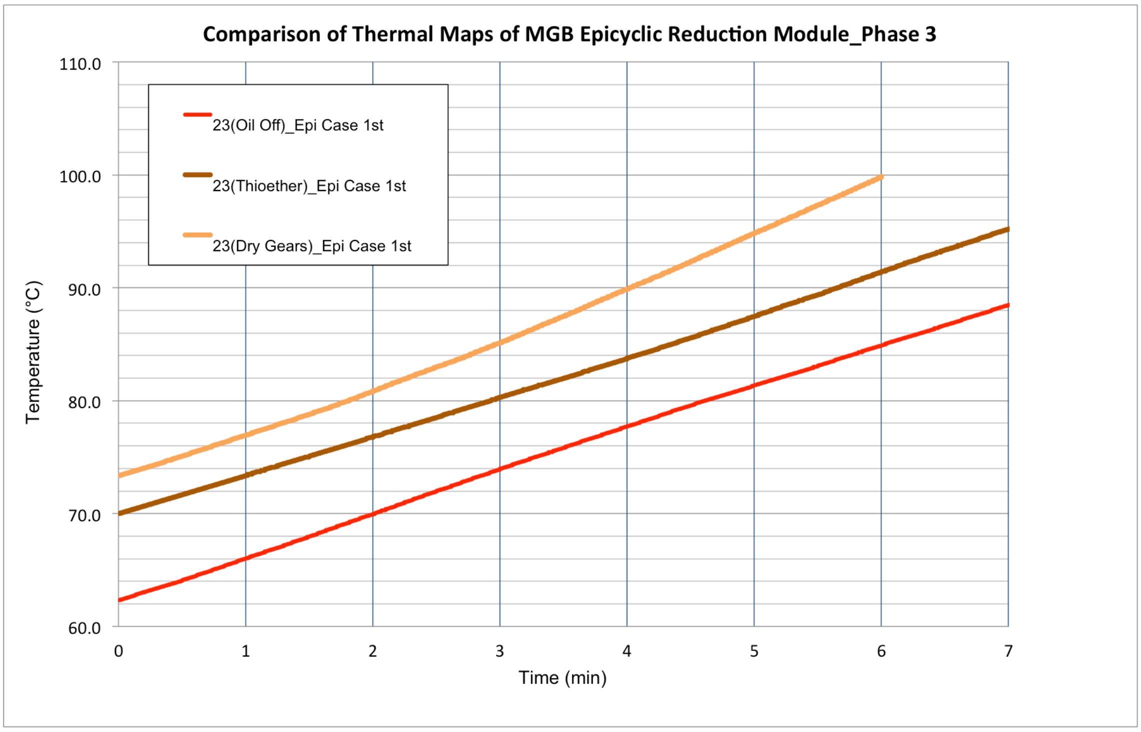


Figure 5.23 Temperature Profile of Epicyclic Reduction Gear Module at Epi Case 1st under Different Lubricating Conditions and Full Load (Source: Author)

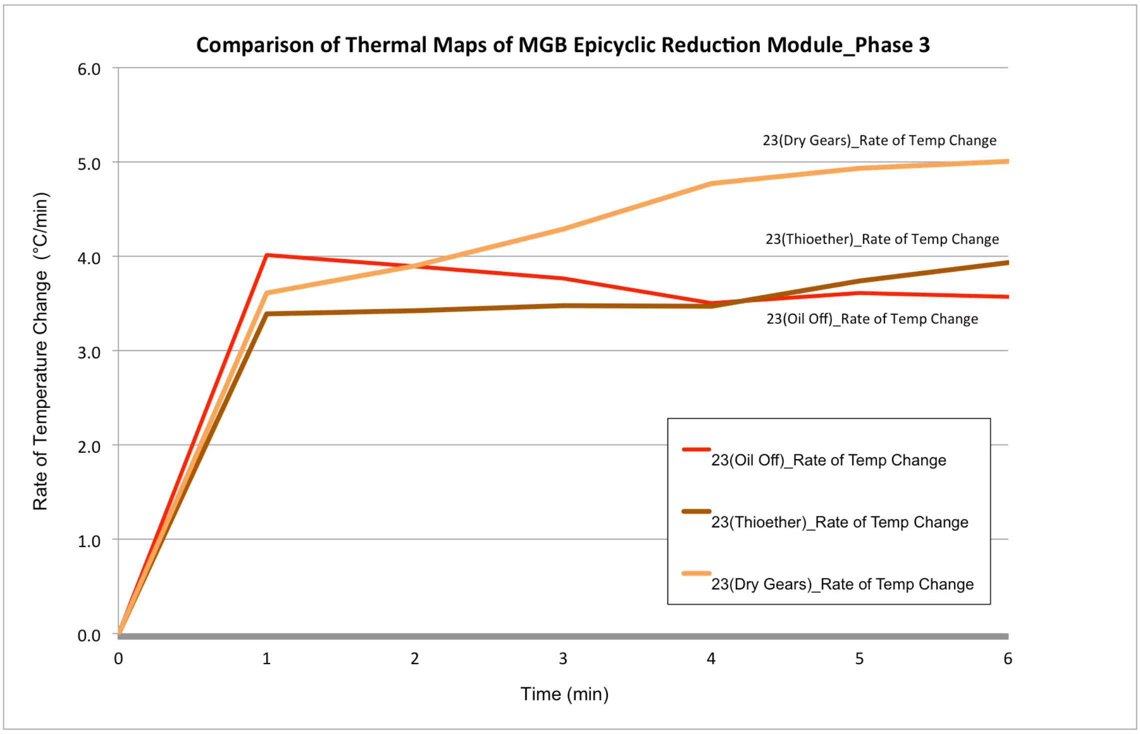


Figure 5.24 Rate of Temperature Rise of Epicyclic Reduction Gear Module at Epi Case 1st under Different Lubricating Conditions and Full Load (Source: Author)

The temperature profile and the rate of temperature rise of all the MGB modules revealed an increase in frictional losses when the gears and bearings are operated in the presence of reduced residual oil or under “dry gears” condition. Similar to the temperature readings obtained during thermal equilibrium, the rate of the temperature rise was the highest at the Input Reduction Gear Module when compared to the rest of the modules.

The rate of temperature rise, for each of the MGB modules, under thioether mist lubrication was comparable to that of “oil-off condition”. However, it is important to note that the observations were made over a short operating duration of 6 to 7 mins, following the MGB operation at thermal equilibrium. The duration resulted from the abort temperature limit that was reached by the Input Reduction Gear Module during the Phase 3 tests. As the MGB was operating under normal lubrication at thermal equilibrium, the short duration under the “oil-off” and thioether mist conditions might have involved residual lubrication oil instead. This implied that the similar rate of temperature rise during both tests was attributed to the boundary lubricating conditions from the residual oil. It also suggests that if the MGB was operated in these two conditions for a prolonged duration, which is currently not possible for the purpose of this test given the thermal limitations of the MGB Input Reduction Gear Module, one might observe a different rate of temperature rise for each of the test condition. This hypothesis was supported by the higher rate of temperature rise under the “dry gears” condition, which was akin to operating the MGB over a prolonged duration to reduce the presence of residual lubrication oil in gear meshes and bearings.

To verify the hypothesis, an attempt was made to lubricate the MGB gears and bearings with thioether at low rotational speeds following the test under “dry gears” condition, before operating at full speed and load. The low speeds would help the thioether mist lubricant to overcome the effects of windage within the MGB, which is prominent at high speeds. The thioether mist lubrication system was also modified to operate with a single misting nozzle connected to the MGB oil inlet port (Figure 5.25), utilising the same flowrate as per the earlier test. This allowed the entire volume of thioether mist to be directed to the internal gears and bearings using the existing oil galleries within the MGB casing instead of splitting into multiple delivery channels. Comparing the rate of temperature rise across each MGB module, under the “dry gears and improved thioether mist” condition against that of the “dry gears” condition, would provide a better evaluation of the performance of thioether mist lubrication in the MGB.

Unfortunately, during the running-up phase of the final test to 3000 RPM in the absence of load, periodic “screeching” noises were heard from the MGB assembly. In the interest of safety and to avoid extensive damage to the MGB, the lubrication experiment was aborted and the test rig brought to a stop. A decision was made to teardown the MGB to identify the cause of the noise and the extent of damage before further actions could be considered.

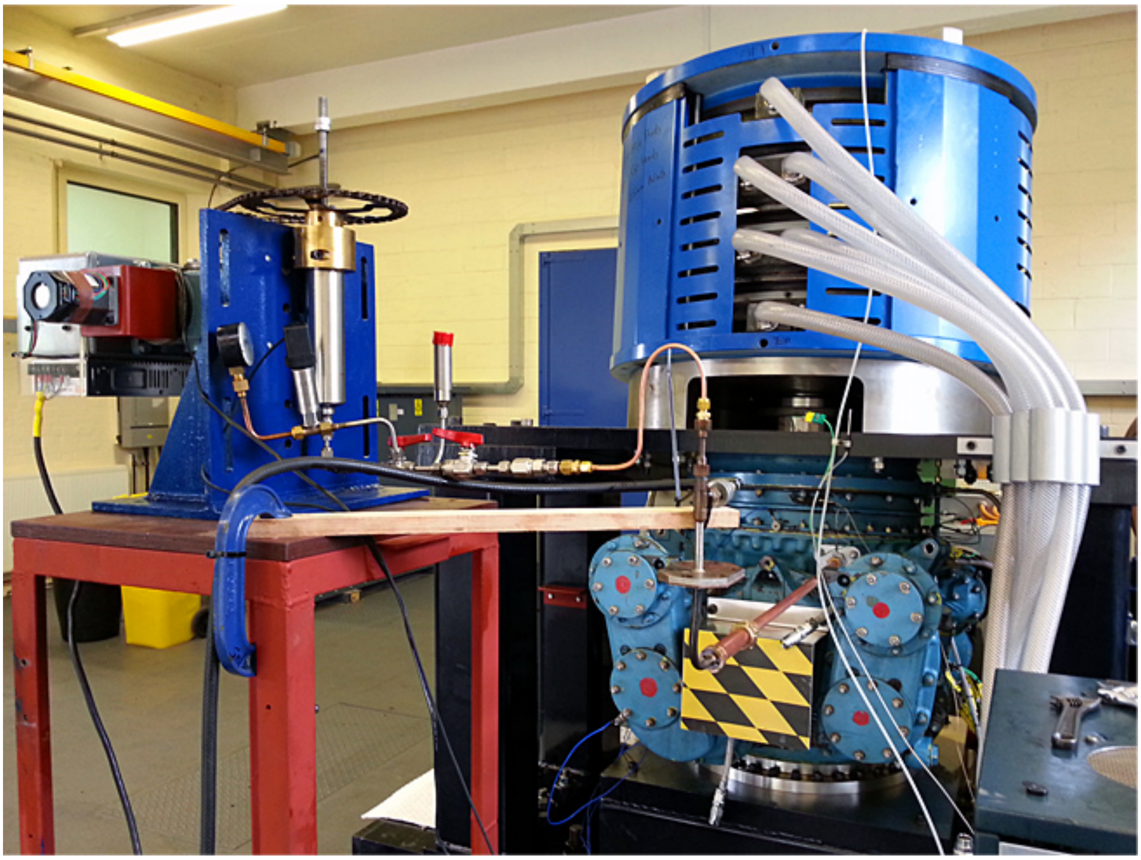

Figure 5.25 Modified Thioether Mist Lubrication System (Source: Author)

Upon tearing down the MGB assembly, a visual inspection revealed no observable surface damage to the internal gears and bearings (Figures 5.26 to 5.30) following the conduct of the lubrication tests. The bearings were found to rotate freely by hand. The absence of surface damage validates the inert properties of thioether and promotes its potential usage as a MGB emergency lubricant. The periodic “screeching” noise was attributed to the aft bearing of the LH high-speed input pinion (Figure 5.31), where it was believed that the bearing outer race has lost its location pins and was free to rotate within the bearing.

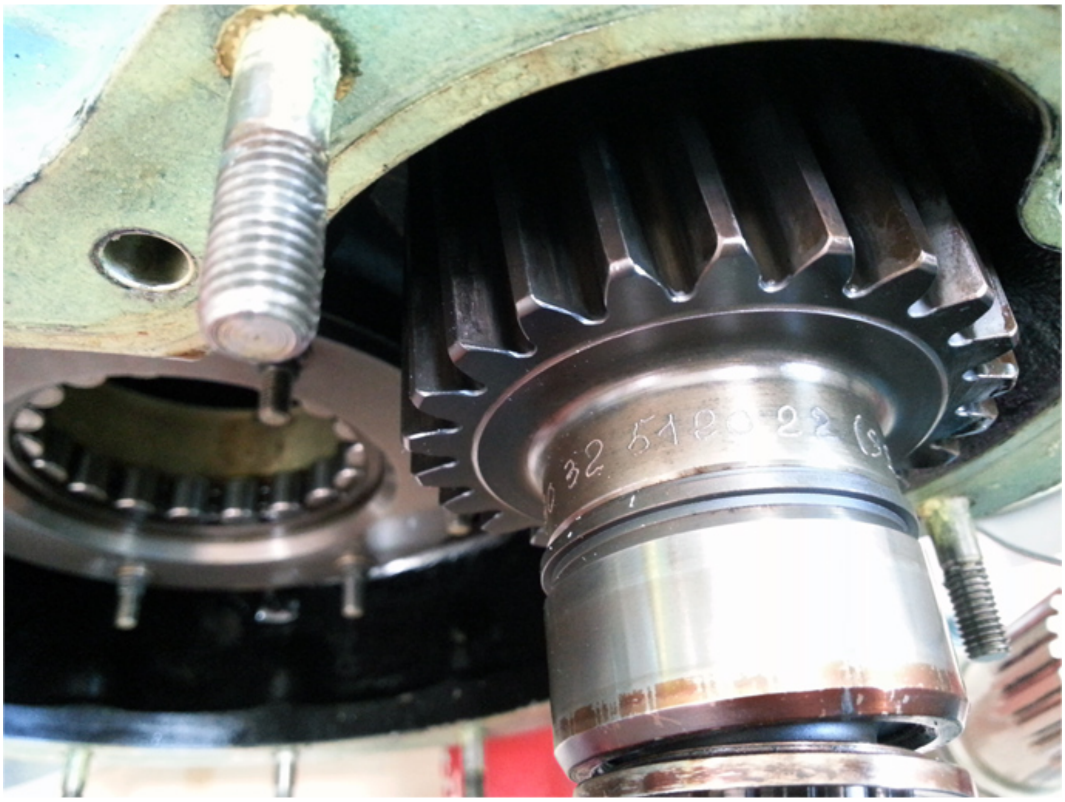

Figure 5.26 LH High-Speed Input Pinion (Source: Author)

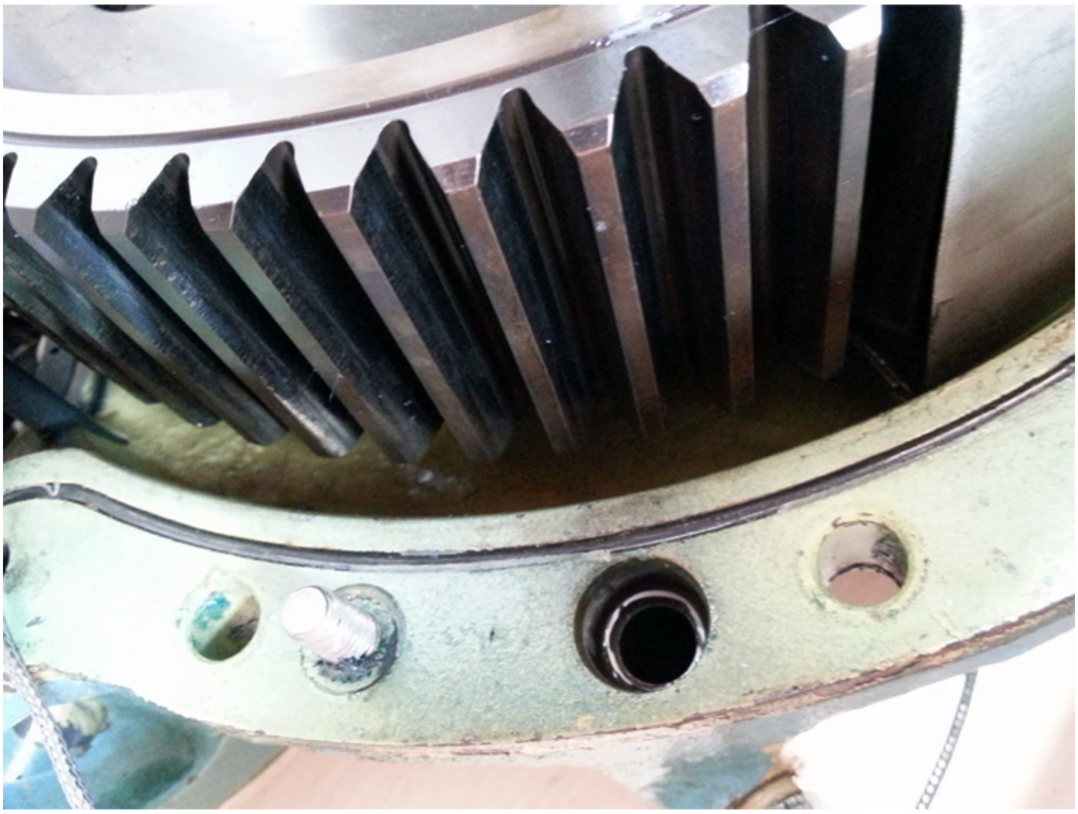

Figure 5.27 LH Input Reduction Gear (Source: Author)

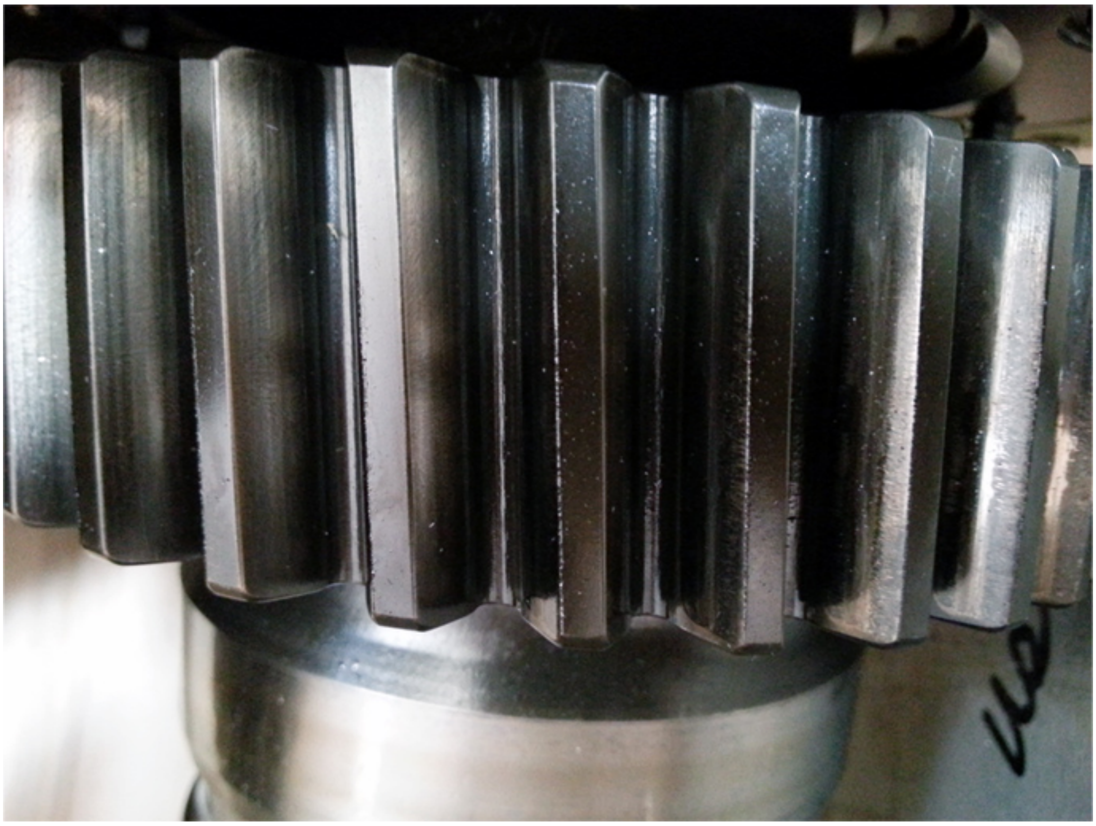
Figure 5.28 LH Aft Reduction Gear (Source: Author)

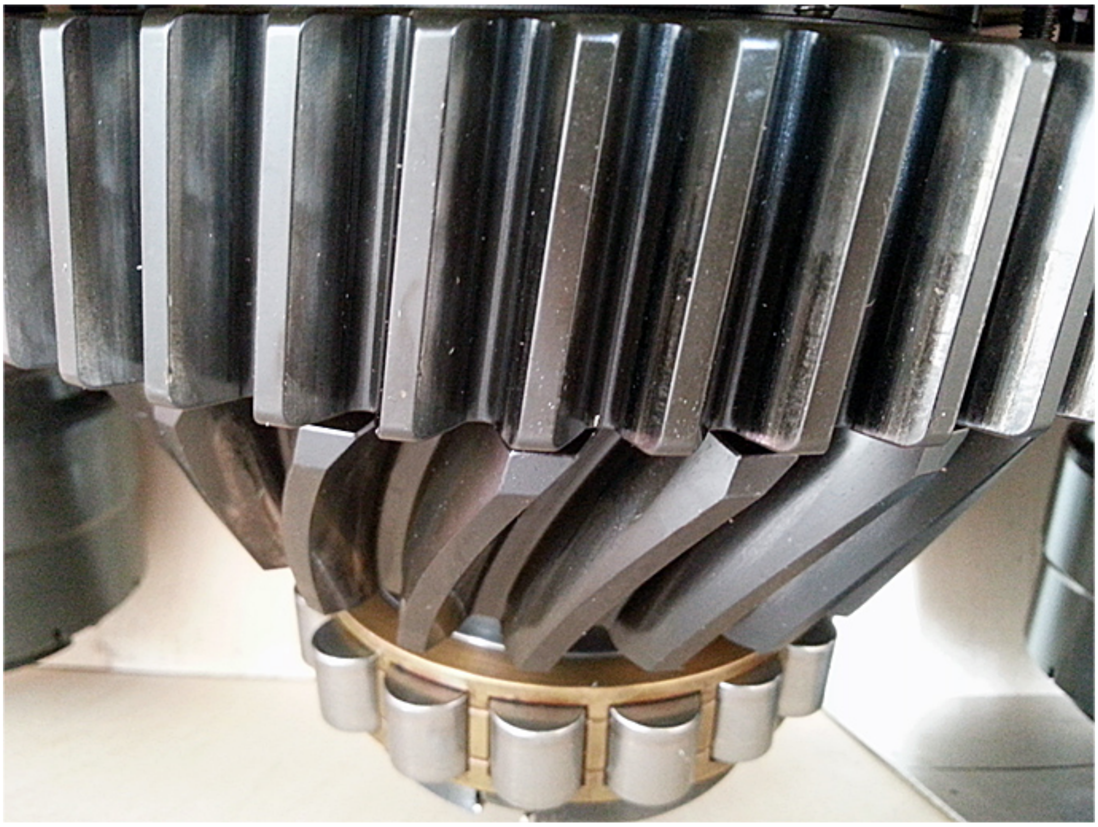
Figure 5.29 Main Reduction Gear (Source: Author)

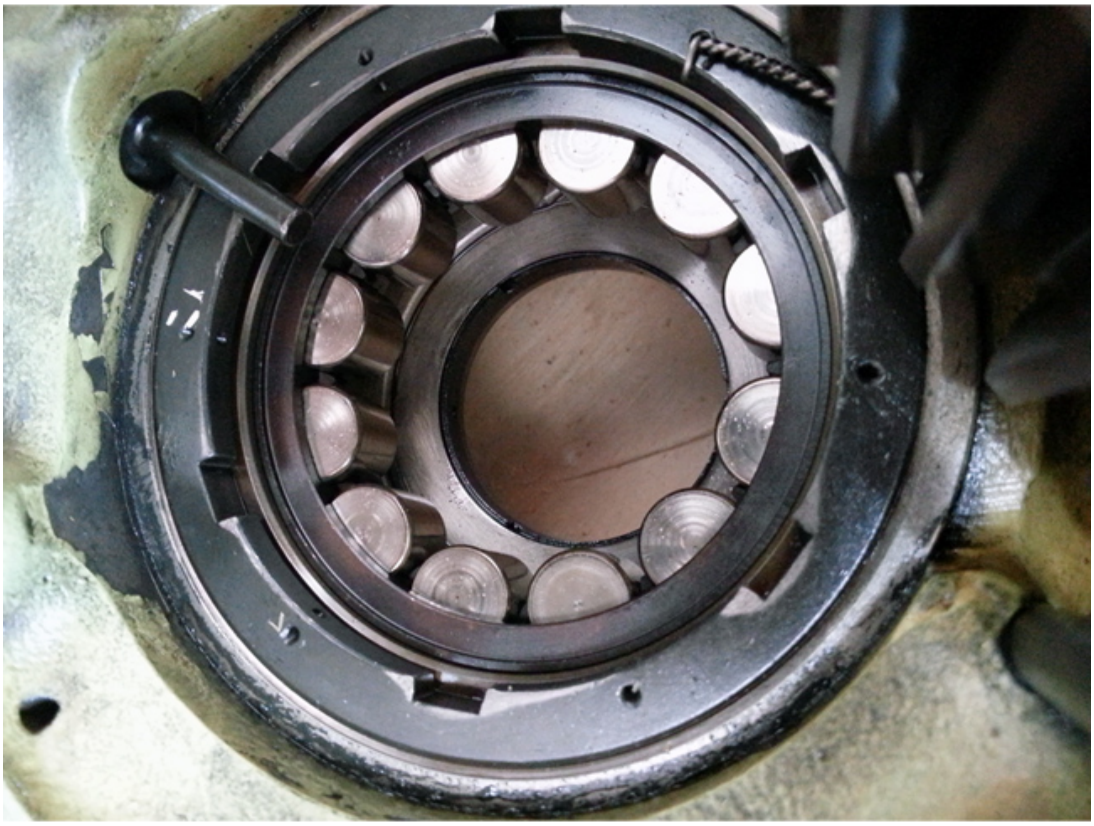

Figure 5.30 LH High-Speed Input Pinion Fwd Bearing (Source: Author)

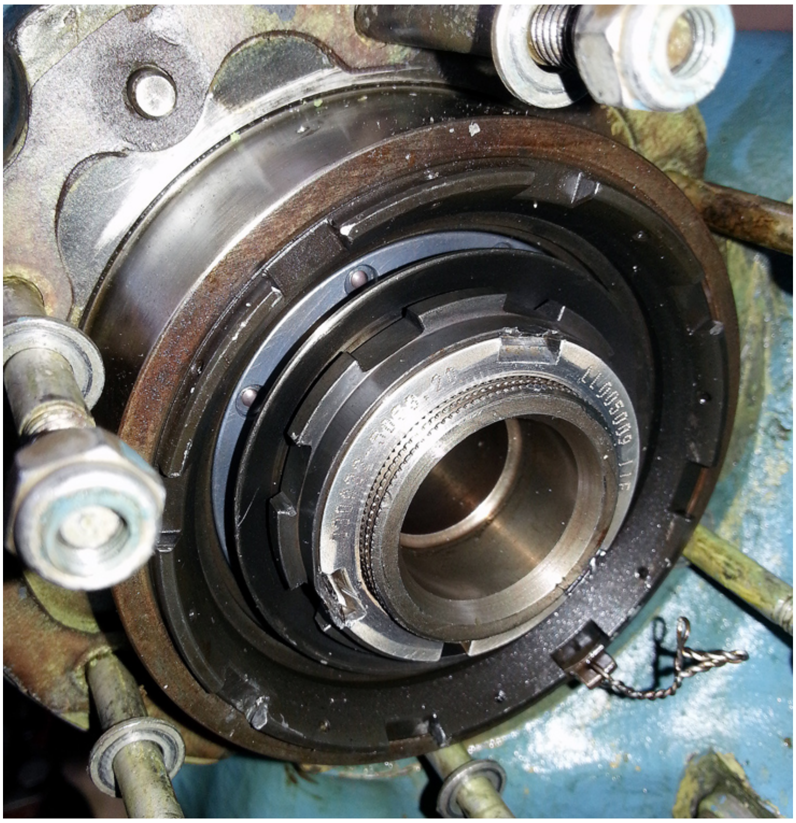

Figure 5.31 LH High-Speed Input Pinion Aft Bearing (Source: Author)

## 6. CONCLUSION

This project has met its objectives regarding the lubrication and vibration analysis of a Helicopter Gearbox, notably the design of a MGB test rig and the thioether mist lubrication system, as well as the instrumentation of the MGB test rig for performance analysis. A known limitation of this programme was the destructive nature of running an MGB under degraded lubrication conditions. Unfortunately the MGB suffered a failure prior to making a full assessment of the capability of thioether when used in an emergency lubrication system. However from the research and lubrication experiments conducted, several technical conclusions could be drawn:

a) The physical properties of thioether, notably its thermal stability and and high surface tension, support its usage as an emergency lubricant in a helicopter MGB.

b) The existing oil galleries within the MGB casing serve are able to serve as effective distribution channels for thioether mist lubrication to the vicinity of the internal gears and bearings.

c) It is believed that thioether mist lubrication in a helicopter MGB has lower churning losses as compared to normal oil lubrication under no-load condition.

d) The high-speed input module of a helicopter MGB attains the highest temperature during normal operation. It is clear that rotational speed is a limiting factor in the thermal performance of a MGB.

e) The highest temperature attained across the MGB modules at thermal equilibrium with a given input power of 293 kW is summarised in Table 6.1.

| MGB Module | Thermocouple # | Temperature (°C) |
|---|---|---|
| Input Module | 14/15 (Avg) | 123 |
| Aft Module | 1/2 (Avg) | 77 |
| Main Module | 7/8 (Avg) | 67 |
| Epicyclic Module | 23 | 56 |

Table 6.1 Temperatures Across MGB at Thermal Equilibrium with 293 kW Input Power (Source: Author)

f) It is believed that helicopter MGB frictional losses are more influenced by the shafts rotational speed as compared to its transmission torque.

g) The instantaneous rate of temperature rise across the MGB modules upon first reaching 3000 RPM and with an input power of 293 kW is summarised in Table 6.2.

| MGB Module | Thermocouple # | Instantaneous Rate of Temp Rise (°C min$^{-1}$) |
|---|---|---|
| Input Module | 14/15 (Avg) | 5.7 |
| Aft Module | 1/2 (Avg) | 2.1 |
| Main Module | 7/8 (Avg) | 1.7 |
| Epicyclic Module | 23 | 1.4 |

Table 6.2 Instantaneous Rate of Temperature Rise across the MGB Modules at 3000 RPM and with 293 kW Input Power (Source: Author)

h) The average rate of temperature rise across the MGB modules during the period between first reaching 3000 RPM and thermal equilibrium with an input power 293 kW is summarised in Table 6.3.

| MGB Module | Thermocouple # | Average Rate of Temp Rise (°C min$^{-1}$) |
|---|---|---|
| Input Module | 14/15 (Avg) | 2.1 |
| Aft Module | 1/2 (Avg) | 1.0 |
| Main Module | 7/8 (Avg) | 1.2 |
| Epicyclic Module | 23 | 0.9 |

Table 6.3 Average Rate of Temperature Rise across the MGB Modules between 3000 RPM and Thermal Equilibrium at 293 kW Input Power (Source: Author)

i) During the loss of oil tests, thioether mist lubrication provides observable cooling on the LH input pinion aft bearing upon the removal of the load from the MGB as compared to "oil-off" or "dry gears" conditions.

j) The average rate of temperature rise across the MGB modules under different lubricating conditions, following the attainment of thermal equilibrium at 3000 RPM and an input power of 293 kW is summarised in Table 6.4.

| MGB Module | Thermocouple # | Average Rate of Temp Rise (°C min$^{-1}$) | | |
|---|---|---|---|---|
| | | "Oil-Off" | Thioether | "Dry Gears" |
| Input Module | 14/15 (Avg) | 7.7 | 8.0 | 9.4 |
| Aft Module | 1/2 (Avg) | 2.8 | 3.3 | 7.4 |
| Main Module | 7/8 (Avg) | 2.1 | 2.4 | 4.1 |
| Epicyclic Module | 23 | 3.7 | 3.6 | 4.4 |

Table 6.4 Average Rate of Temperature Rise across the MGB Modules between Under Different Lubricating Conditions, 3000 RPM and 293 kW Input Power (Source: Author)

k) It is believed that the presence of residual oil in a helicopter MGB supports boundary lubrication condition at the MGB gears and bearings for a limited time duration. This period was shown to be around 6 to 7 mins following an "oil-off" condition for the gearbox design under test at the test conditions used.

l) Gearbox windage, which is dependent on the shaft rotational speed, poses a potential barrier to the effective use of thioether mist lubrication in a helicopter MGB.

m) Thioether has no observable detrimental effect on the gear tooth and bearing surfaces, as well as elastomeric seals when used in a helicopter gearbox.

n) The periodic “screeching” noise heard during the last lubrication experiment, which involved the use of a modified thioether mist lubrication system, was attributed to the aft bearing of the LH high-speed input pinion, in which the bearing outer race has lost its location pins and was free to rotate within the bearing.

# 7. RECOMMENDATIONS

The design of the MGB test rig and the testing of the lubrication experiments have identified areas of improvement that would enhance the capability and the accuracy of the test rig system, as well as the scope for future research into thioether mist lubrication for gearboxes. These are summarised in the list of recommendations below:

a) Dual input drive at full design speed for the MGB.
An upgrade of the existing speed-increasing gearbox to a new assembly that supports dual output drive with a speed of to 22,841 RPM, would enable lubrication tests that are representative of the “oil-off” conditions on the SA330 MGB. This would imply the ability to introduce a sum of input power of 750 kW to both the LH and RH input modules of the gearbox, and to study the effects of different lubricating conditions on the temperature profile of the gearbox.

b) Upgrade of MGB Oil Lubrication System

An upgrade of the existing oil lubrication system for the MGB would be necessary to support the installation of the new speed-increasing gearbox assembly. In particular, both feed and supply pumps should support an oil flow rate of 67 LPM to replicate the actual flow rate on the SA330 helicopter.

c) Power Measurements using Torque Transducer for MGB

A more accurate measurement of the input power applied to the MGB can be achieved with the use of a torque transducer installed at the coupling of the speed-increasing gearbox to the MGB input drive. This measurement can be used as a feedback signal to control the air pressure line for the dynamometer to maintain constant input power to the MGB.

d) MGB Test Rig Thermography

The incorporation of a thermal imaging device to capture the temperature profile of the MGB during the lubrication tests would provide a live overview of the hot spots generated on the MGB and would allow easy monitoring of the temperatures reached at various locations within the gearbox.

e) MGB Test Rig Videography

A video camera set up for the MGB test rig allows the filming of the lubrication experiments for future playback and observations, especially following the occurrence of a defect on the test rig such as a leak, excessive vibration or an unusual noise.

f) Instrumentation for Gear Oil “Fling-Off” Temperatures

The existing instrumentation setup provides accurate temperature measurements of the stationary bearing assemblies within the MGB. The use of a thermal probe to measure the gear oil “fling-off” temperature would allow the monitoring of the gear temperature profile. Having an accurate temperature measurement of the gears and bearings within the MGB enables the use of a higher abort temperature limit for the lubrication tests since the margin of uncertainty is reduced.

g) Individual Testing of MGB Modules

The physical properties of thioether enable its operation at high temperatures up to 400°C, which is above the thermal limits of the modern helicopter gearboxes. One solution is to carry out lubrication tests on the MGB modules separately, and with the necessary modifications (such as replacing elastomeric seals with metal ones and using shims that can withstand higher temperatures) to sustain operation at high temperatures. With the ability of the individual modules to operate at elevated temperatures, a higher abort temperature limit can be introduced and the performance of thioether mist lubrication can be better compared against convention lubricants.

h) Research on Gearbox Windage on Thioether Mist Lubrication

The effect of gearbox windage on the application of thioether mist lubrication for bearing assemblies can be further studied into. Dedicated bench tests may provide insights to the techniques for introducing thioether mist onto the contact surfaces of the roller elements and raceways.

i) Reconvene Thioether Mist Lubrication Experiment

Owing to the safety abort of the final lubrication experiment, which involved the use of a modified thioether mist lubrication system, the influence of residual oil on thioether performance was not verified. It is highly recommended that this final experiment be reconvened to conclude the performance of thioether mist lubrication on a helicopter gearbox, together with the results of the HELMGOP II Project.

**APPENDICES**

A. Literature Review of Helicopter Main Gearbox Lubrication

B. Helicopter MGB Test Rig Details

C. Operating Procedures for MGB Test Phases / Sets

D. Temperature Profiles and Rates of Temperature Change for MGB Test Phases / Sets

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