SOME OBSERVATIONS ON THE PERFORMANCE OF FOMBLIN Z25 OIL AND BRAYCOTE-3L-38RP GREASE IN BALL BEARINGS AND GEAR BOXES

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ABSTRACT

Fomblin Z25, a perfluoroether fluid, possesses two properties which make it attractive as a space lubricant; namely, a low vapour pressure and a high viscosity index. Its lubricating properties in vacuum require thorough investigation and this paper describes a research programme into the performance of ball bearings lubricated with the Z25 oil. Also described is the outcome of tests on a type of gear box lubricated with the PTFE-thickened grease based on Fomblin Z25.

Results show that there is a problem of polymerisation inherent in the oil that is initiated by active metal surfaces produced by rolling or rubbing. The resulting degradation products and component wear have been observed in ball bearings operating at different speeds (giving both boundary and e.h.d. conditions) and also in a gear box.

Better performance results when there is a trace of hydrocarbon in the oil (for example, when a rust preventative is added to the grease) but this addition increases the vapour pressure.

Keywords: Fomblin Z25, Braycote 3L-38RP, Ball Bearing, Gear box, Perfluoropolymer.

1. INTRODUCTION

A requirement of a liquid lubricant for spacecraft applications is that it should have a low vapour pressure so as to minimise evaporative loss and to avoid contamination of nearby components; particularly optical equipment. Montecatini-Edison (Italy) manufacture a range of fluorinated lubricants (perfluoroalkylethers) principally for use at high temperatures, of which the 'Fomblin Z' series has the lowest vapour pressure. Of particular interest to the space industry is Fomblin Z25 (viscosity 250c/s at 20°C) which has a vapour pressure of less than 10^{-13} torr at 20°C. It also has a high viscosity index (360 compared to near 100 for most space oils) so that its viscosity is less sensitive to temperature than is the case with other oils.

To date, there is only limited knowledge about the lubricating properties of this oil in vacuum. Work has been performed in the USA on an equivalent oil (called Braycote 815Z, Bray Oil Co.) Some of these tests have shown that there may be a problem of oil degradation which could impair the long term lubricating capability. In an investigation by the Materials Science Laboratory at the British Aerospace Dynamics Group (Stevenage, UK) severe degredation of this type of perfluoroether oil has been observed in bearings operating in air. In this case, a brown product, identified as a perfluoro polymer originating from the oil, was generated at the contact between the bearing seals and the races.

Fomblin Z25 is being used in ball-bearings and gear boxes in several European space missions but only at low rotation speeds or for short term, intermittent operation. The applications have so far been limited to the ball bearings and gear boxes in low duty/low speed components such as the Instrument Pointing System and the Space Telescope. Before the lubricant can be recommended for use in mechanisms such as despin assemblies, reaction wheels or momentum wheels, more information is required about its long-term lubricating capabilities.

This paper describes a programme of tests conducted at the European Space Tribology Laboratory (ESTL) designed to assess the lubricating properties of Fomblin Z25 in ball-bearings operating for up to 10^8 revolutions in vacuum at a variety of speeds so as to cover both boundary and elastohydrodynamic lubrication. Also described, is the ESTL experience in the examination of space mechanism gear boxes which have been operated with the PTFE-thickened grease based on the Fomblin Z25 type oil (Braycote 3L-38RP).

2. TESTS TO DETERMINE THE LUBRICATING PROPERTIES OF FOMBLIN Z25 IN BALL BEARINGS

These tests have been aimed specifically at investigating the lubricating properties of Fomblin Z25 in ball bearings under a range of

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operating conditions. The work forms part of the Primary Applications Programme at ESTL and is funded by the European Space Agency.

2.1 Test Bearing Details

The bearings are typical of those used in reaction wheels or momentum wheels. Their details are:

Manufacturer	SNFA (France)
Type	Angular Contact, separable (ED20)
Steel	AISI 52100
OD	42mm
ID	20mm
Width	12mm
Balls No	10
Dia	7.14mm
Cage	One piece phenolic, outer race riding
Contact Angle	15 degrees
Ball/race conformity	1.14
Race Surface Finish	
(across the groove)	0.03 m cla) cut off
(around the groove)	0.005-0.01 ") 0.08mm

Tests were also conducted with close-conformity bearings (ball/race conformity 1.05). These were non-separable angular contact bearings manufactured by RHP (UK) and by SNFA (type EX20).

2.2 Bearing Test Equipment

The majority of the bearing tests reported in this paper were conducted on the apparatus shown in Fig 1. It was designed so that four bearings could be tested at the same time;

(i) A Flexibly-preloaded 'support pair'
(ii) A solid-preloaded 'test pair'

The equipment comprises a stainless steel vacuum chamber with a magnetic coupling between the external motor and the internal drive shaft. The system can be evacuated to better than 10^{-6} torr by an ion pump after initial rough pumping using a sorption pump. A drive shaft is mounted on a pair of angular contact bearings (lubricated with the test oil) which are flexibly preloaded to 40N by wave-washers in a back-to-back configuration. The test pair is mounted on the end of the shaft and solid preloaded to 40N in a face-to face arrangement by choice of suitable spacers for the inner and outer races (the relative offset between the inner and outer race faces of each bearing having been determined before hand). The test pair housing is free-floating and is restrained from rotation by a force transducer. The output from this is then used to determine the frictional torque of the test pair. The torque of the support pair is not measured.

Figure 1 also shows a slip ring and electrical connection arrangement used to monitor the ball-race lubricant thickness. The electrical circuit was identical to that developed by Furey (Ref 1) and used by other workers (eg Tallian (Ref 2) with which individual metallic contact events between the races and balls are monitored on an oscilloscope and their frequency of occurrence is used to detect the breakdown of the elastohydrodynamic film.

Other tests at lower speeds and for only short durations have been conducted in a more simple apparatus. Just two flexibly preloaded bearings are mounted in a housing driven (either continuously or with an oscillating motion) via a ferrofluidic feed-through. Torque is monitored by a torsional transducer.

Experiments to investigate the torque/speed behaviour and elastohydrodynamic film thickness of single bearings in air were conducted on a further test facility. The bearing is mounted in a steel flange supported by a gas bearing. It is driven at speeds up to 5000 rpm by a gas turbine and the torque monitored by a transducer. Lubricant film behaviour is recorded by the same electrical circuit as that mentioned above.

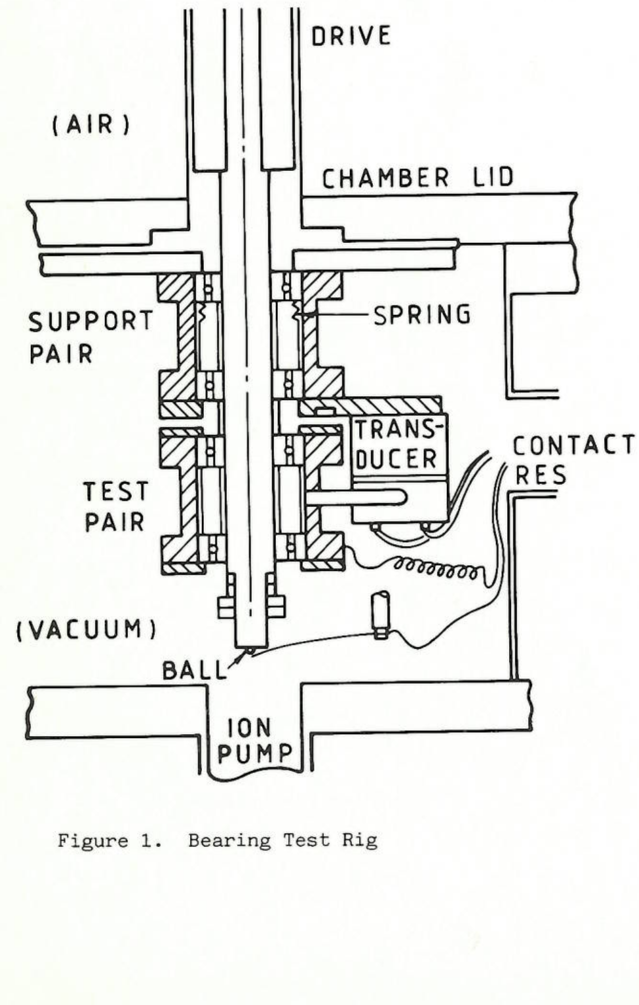


Figure 1. Bearing Test Rig

2.3 Test Specification and Procedure

2.3.1 Specification

Speeds:	20, 100, 200 and 1400 rpm.
Load:	40N axial
Duration:	Up to 10^8 revolutions
Oil quantity:	50 1 with oil also impregnated into the phenolic cage
Temperature:	Laboratory ambient (21°C)
Chamber Pressure:	Less than 10^{-6} Torr.

The conditions were based on the duty which might be expected in spacecraft mechanisms. Typical reaction wheel or momentum wheel speeds are over 1000 rpm, whereas de-spin speeds are in the range 20-100 rpm. In pointing mechanisms the speed is very slow (less than 1rpm) and this condition was covered by the short term tests (up to 10^6 revs) in the simplified test rig. Overall, therefore, the speeds cover a range of oil film thickness giving both boundary lubrication (up to 200rpm) and full elasto-hydrodynamic lubrication (1400rpm). The load (40N) is typical of the light preloads used in actual mechanisms. The test duration (up to 10^8 revs) is similar to that required of a de-spin mechanism but less than would be completed by a reaction wheel or a momentum wheel. However, if successful running under EHD conditions with no bearing deterioration could be established for 10^8 revs, then it would not be unreasonable (provided that the lubricant supply was ensured) to infer that much longer periods of running could be achieved.

50 µl of oil is sufficient to flood a 20mm ball-bearing and any oil in excess of this tends to be expelled and does not lead to any contribution to the viscous torque. Since phenolic tends to absorb oil, the cages were impregnated with Fomblin Z25 so as to minimise the reduction in the available supply of lubricant.

2.3.2 Procedure

The following is the procedure for testing bearings over 10^8 revolutions in vacuum. Similar techniques were used for testing on the more simple apparatus except that the operating periods were shorter.

i. Dismantle the bearings and solvent clean the components separately (ultrasonic and rinse in trichloro-trifluoroethane)

ii. Weigh the components

iii. Impregnate the cage

iv. Assemble the bearings (wearing shed-free gloves) and add 50µl of oil onto the ball surfaces using a syringe.

v. Install the bearings into the rig with spacers to give a 40N preload.

vi. Evacuate the system to better than 10^{-6} torr.

vii. Run the bearings, making a periodic recording of the torque and the torque noise

viii. After 10^8 revs, dismantle the bearings and make further weighings to determine the amount of oil loss and any bearing wear.

ix. record the bearing condition by photography and analyse any wear or degredation products (the technqiues of ferrography and pyrolysis gas - chromatography with mass spectrometry were available).

2.4 Results

2.4.1 1400rpm

10 tests were conducted over 10^8 revolutions at 1400rpm and each gave a similar result. The main features of the bearing performance were as follows.

i. The DC (viscous) torque decreased during each test whilst the torque noise increased. This is demonstrated in Fig 2 which shows that the torque of the open conformity bearings fell to near 30 x 10^{-4}NM, a value similar to the Coulomb torque and implies that little viscous torque has been retained. With close conformity bearings, the overall viscous torque is higher and the deterioration in torque noise occurs later than with open conformity bearings (8 x 10^7 revs compared to 2 x 10^7 revs).

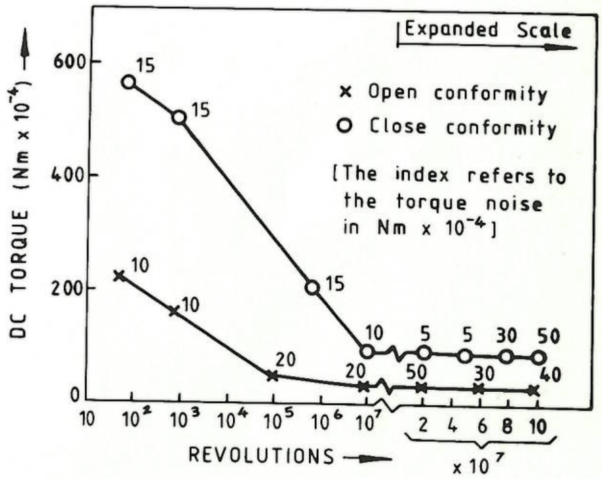


Figure 2. Torque of Fomblin Z25 - Lubricated Bearings at 1400 rpm

ii. The same torque behaviour was observed with two batches of Fomblin Z25 oil and also with the equivalent oil, Braycote 815Z. There was no improvement when Stellite-caged or cageless bearings were used and employing non-chlorinated solvents to clean the bearings made no difference to the result.

ii. The decrease in viscous torque was found to be reversible. Stopping the test for a brief period (up to 1hr) produced, upon restart, a temporary increase in the viscous torque. This was not related to temperature since, with other, more viscous, oils which produced more heating in the bearing, there was no such loss in torque.

iii. The increase in torque noise was found to be caused by a build up of a brown/black deposit on the races and balls. As shown in Fig 3, it accumulated in and near the running track, on the balls and in the cage pockets. This behaviour contrasted with that found with other test oils. For instance, a highly refined mineral oil (BP110), under the same test conditions, gave no loss in viscous torque and the bearings remained clean. With Fomblin Z25, there was more debris present in the open conformity bearings than in the close formity bearings.

A bearing performance of this type is unsuitable for spacecraft mechanisms. Whilst a low DC torque might, from the point of view of power consumption, be considered useful, the erratic torque behaviour could lead to problems in control. When the bearings were examined at British Aerospace, Stevenage (UK), it was confirmed that the debris was the same perfluoro-polymer that had been observed before with the Fomblin Z25 oil. Ferrography showed the presence of metalic and polymer debris. It is argued that the active steel surfaces created during ball/race contact combine with the oxygen atom in the lubricant molecule. Chain scission occurs and a perfluoro-polymer is created. However , with Fomblin Z25 at 1400rpm, EHD lubrication should be firmly established and little ball/race contact should occur. In fact, the decrease in viscous torque gives a clue to the failure mechanism since this suggests that the oil film is collapsing and contacts are occurring. The sequence of events is as follows:

Oil film collapse (loss of viscous torque) — Increasing ball/race contact — Active steel surfaces

Oil Polymerisation — Polymer and metallic debris (increase in torque noise)

In separate tests on single bearings on the high speed rig the fall in DC torque at 1400rpm was confirmed (this time, in air) but electrical contact measurements demonstrated that this was not immediately accompanied by any significant increase in contact events. Fig 4 shows that at the start of the test and after 1.4 x 10^7 revs (when the viscous torque had almost disappeared) EHD lubrication is established at identical speeds.

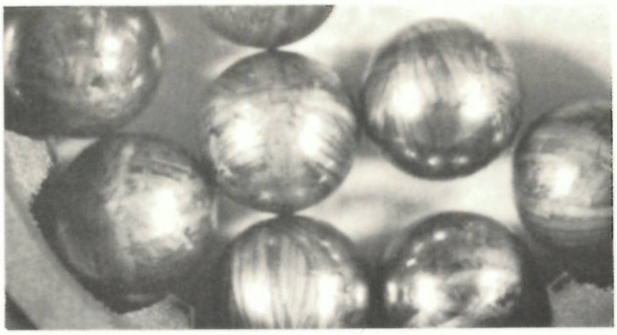


Figure 3a. Balls x3

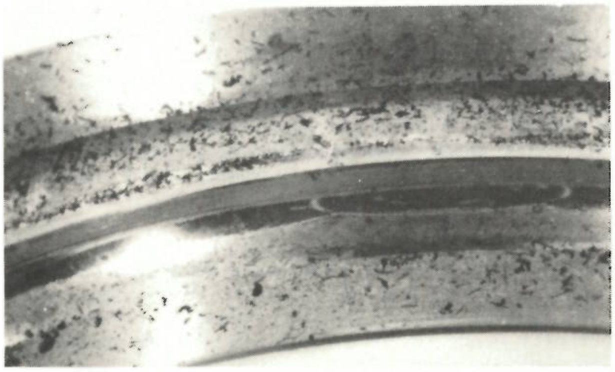


Figure 3b. Outer race x3

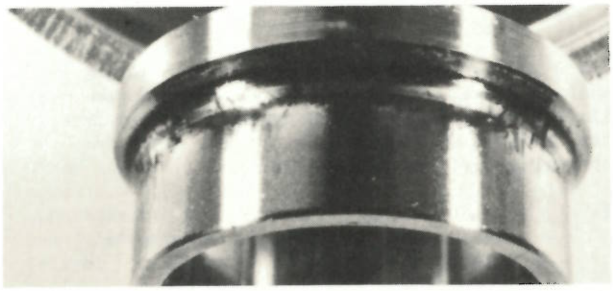


Figure 3c. Inner race x2

Figure 3d Inner race deposit x140

Figure 3 Degradation of Fomblin Z25 in Bearings Operation at 1400rpm.

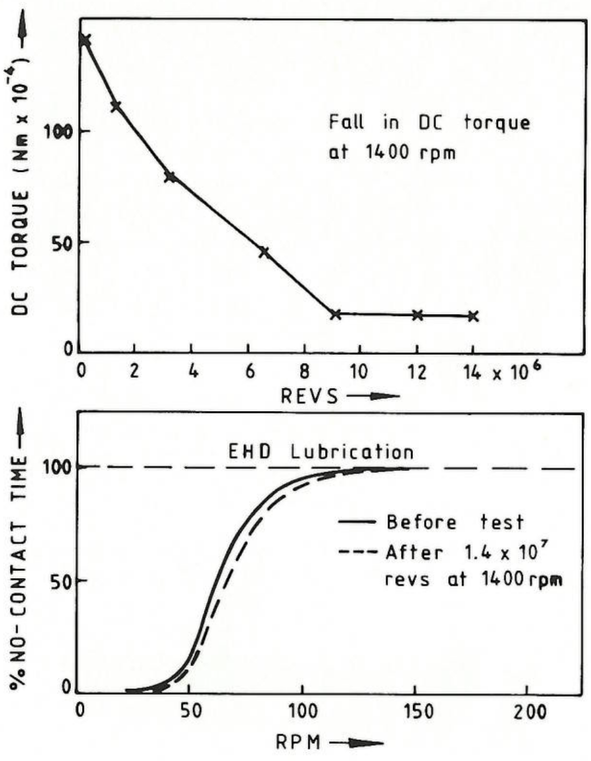


Figure 4. DC torque and Contact Resistance with a Fomblin Z25-Lubricated Bearing at 1400 rpm

Figure 5a Balls, worn to a matt finish x3

Figure 5b Inner race x3

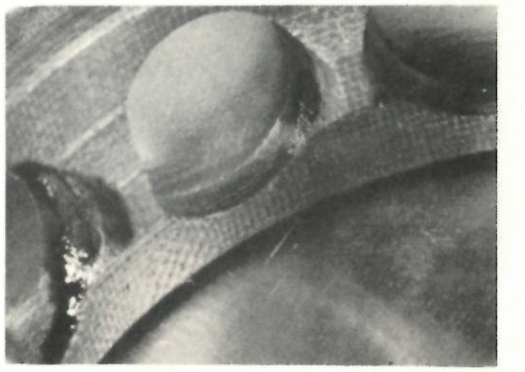


Figure 5c Cage Pockets x3

Figure 5 Degradation of Fomblin Z25 in Bearings Operating at 100rpm.

In a subsequent, longer term test on the main rig using the electrical contact circuit, the same behaviour was observed and 2 x 10^7 revs had been completed before significant contacts occurred. Examination of the bearing at this point revealed that the polymer was just starting to form.

Whilst the mechanism of polymer formation is understood, it is still not clear why there is an initial fall in the viscous torque. The reason may be related to tempory shear thinning or to oil channelling (both would show the recovery observed after the bearings had been stopped) but it seems that the effect is slightly less pronounced in the close conformity bearings. Certainly, the closely conforming ball/race contact will support a larger meniscus of oil and this may maintain an effective film for longer.

During one test at 1400rpm the four bearings performed well, the torque noise remaining low and no debris being formed. Analysis showed that the bearings had been contaminated by a trace of hydrocarbon oil (from incomplete cleaning of the cages) and that this had preferentially wetted the races and balls, excluding the Fomblin oil from the active steel surface and preventing polymerisation.

2.4.2 Speeds of 200rpm and Below

Over 10^8 revolutions at both 200 and 100rpm the same build up of polymer was observed. Fig 5 shows that the debris and wear were even more pronounced than at 1400rpm. The torque behaviour is illustrated in Fig 6; although there was some increase in torque-noise there was no large decrease in the DC torque. This suggests that any mechanism of shear thinning or channelling is absent at low speed but, since the bearings are running in a boundary lubricated condition, ball/race contacts will be occurring continuously and the mechanism for polymerisation will be initiated. It is likely that polymer begins to form from the onset of the test but this has not been proved.

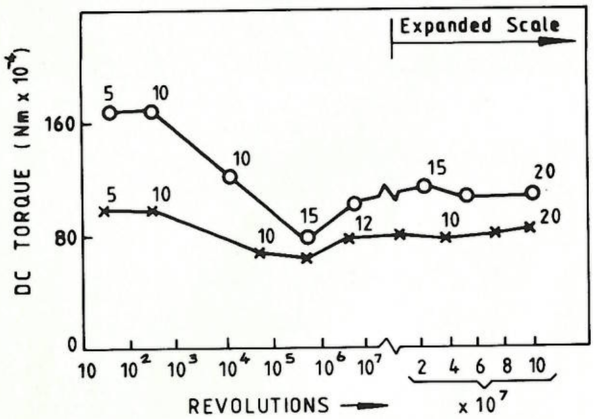


Figure 6. Torque of Fomblin Z25 Lubricated Bearings at 100 and 200 rpm

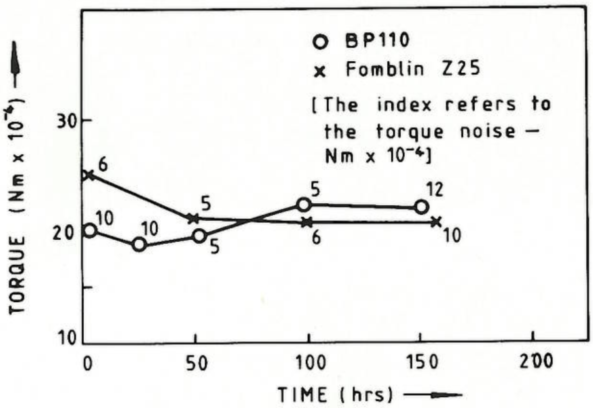


Figure 7. Torque of Fomblin Z25 and BP110 Oil-Lubricated Bearings Operating at 10 rpm

In addition to the work at 200 and 100rpm, some bearings have been tested at 20rpm (a despin type speed) and at even lower speeds (down to 1rpm). At the time of writing, the bearings operating at 20rpm had completed 5 x 10^6 revs without any significant deterioration in the torque and the objective is to determine whether 10^7 revs can be achieved (a de-spin type duty) without serious lubricant polymerisation. At speeds of 1 and 10rpm only limited duty has been completed. Over a period of 10^5 revs no degradation of the Fomblin Z25 oil was observed and the boundary lubricating properties appeared to be no different to those of other space approved oils. For instance, Fig 7 shows the torque results for Fomblin Z25 compared to that of the BP110 mineral oil. There is no significant increase in the torque noise and the appearance of the running track on the respective races is very similar (Fig 8).

More detailed accounts of work on oils at various speeds can be found in the following ESTL (ESA) publications.

Ref 3, ESA (ESTL) 056 Long term (10^8 revs) operation

Ref 4, ESA (ESTL) 051 Slow speed, short term (10^5 revs) operation

Figure 8a BP110 x70

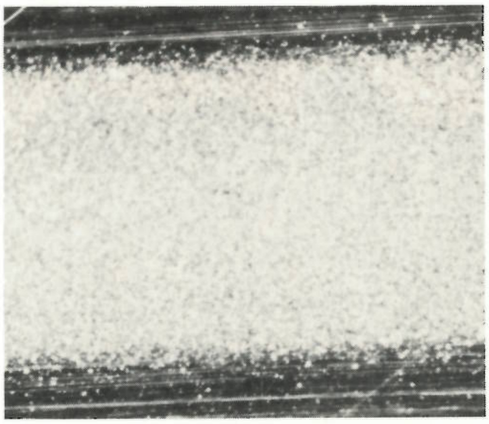


Figure 8b Fomblin Z25 x70

Figure 8 Micro-pitted Wear Track on the Inner Races of Bearings Operated at 10rpm (Dark Field)

2.5 Summary

The ball bearing tests have shown up a problem of polymerisation with the Fomblin Z25 oil. It is initiated by active metal surfaces created during ball/race contacts which react with the oxygen atom in the lubricant molecule. Chain scission occurs and a perfluoro polymer is formed. The problem occurs at speeds giving either boundary or EHD lubrication and after about 10^7 revs (20mm bore ball bearing), enough polymer is created to cause a deterioration in the bearing performance. Better performance resulted when the Fomblin Z25 was accidentally contaminated with a trace of mineral oil.

At the present time, therefore, and until a method of reducing polymerisation can be found, there is a need for caution when using the Fomblin Z25 type of oil in ball-bearings in vacuum. It can certainly be used for low speed, light duty (10^5 - 10^6 revs) but it cannot yet be recommended for despin or momentum wheel type applications.

Some ideas involving the use of inert surface treatments are to be tried in an attempt to avoid the formation of active metal surfaces.

3. SOME OBSERVATIONS ON THE PERFORMANCE OF BRAYCOTE 3L-38RP GREASE RESULTING FROM GEAR-BOX TESTS.

As part of its contractural work on satellite mechanism testing, ESTL has been associated with the testing and inspection of two gearboxes lubricated with the Braycote 3L-38RP grease:

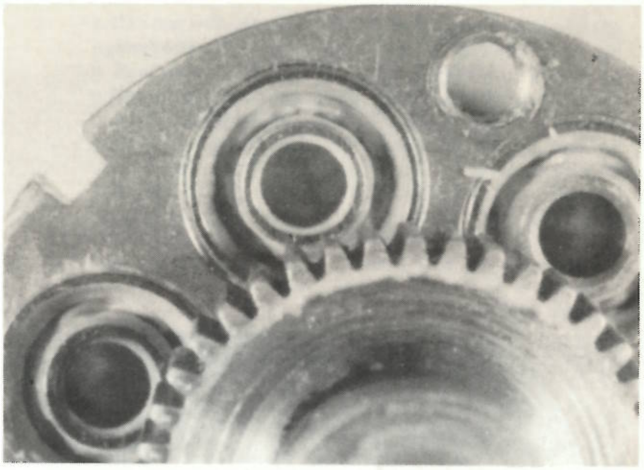
i. A 148:1 reduction instrument size gear box (approximately 15mm dia, 25mm long) containing stainless steel gears and used in a deployment mechanism.

ii. A gear-head motor (30mm dia, 100mm long) comprising a drive motor and a 112:1, three stage epicyclic reduction gear box. Also used in a deployment mechanism and containing gears made in aluminium alloy, aluminium bronze and stainless steel.

3.1 Instrument Gear Box

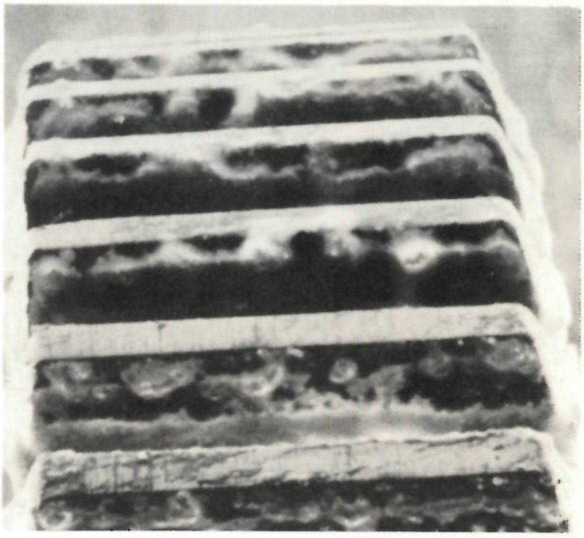
This gear box had been dismantled, cleaned of its original oil, and relubricated with the Braycote 3L-38RP grease. It had then been given a short life test by ESA consisting of 450 deployments over a period of 2 days, each comprising a 180° rotation of the output shaft with 74 revs of the input shaft. Satisfactory operation occurred during the whole test.

Post test evaluation at ESTL was limited to a visual inspection of the gear box components and no lubricant analysis was performed. In fact, all the gears and bearings were found to be in good condition with no evidence of wear or of degradation of the lubricant. Fig 9 shows the clean white grease remaining in the gear shaft support bearing and Fig 10 illustrates one of the gears.



x5

Figure 9 Clean Braycote Grease in Gear Shaft Support Bearings



x20

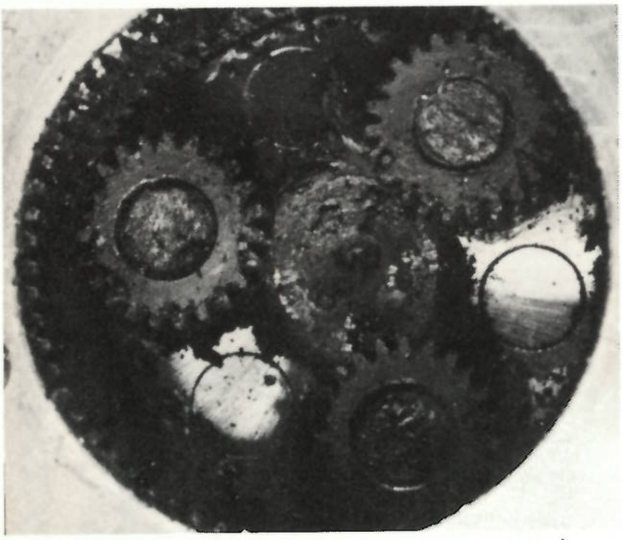
Figure 10 Clean Braycote Grease on Unworn Gear.

Further examinations revealed that the input and output shaft bearings had not been relubricated with the Braycote grease and that traces of the original oil remained. There remains the possibility, therefore, that this oil may have contaminated the Braycote grease and assisted in the lubrication.

3.2 Gearhead Motor

The gearhead motor was life tested in vacuum at ESTL at temperatures between -35°C and +85°C. In total, the motor (gear box input shaft) and the output shaft completed 10^7 and 10^5 revs respectively, half in each direction.

Although this procedure demonstrated the ability of the unit to operate over the range of conditions expected in orbit, there was a deterioration in the performance during the course of the tests. This deterioration was caused by an increase in the friction within the gear box. The result of this was that, at the end of the test, the motor current required to give the same output under identical conditions had virtually doubled. At the end of the tests, very high torque was required to back drive the unit via its output shaft.

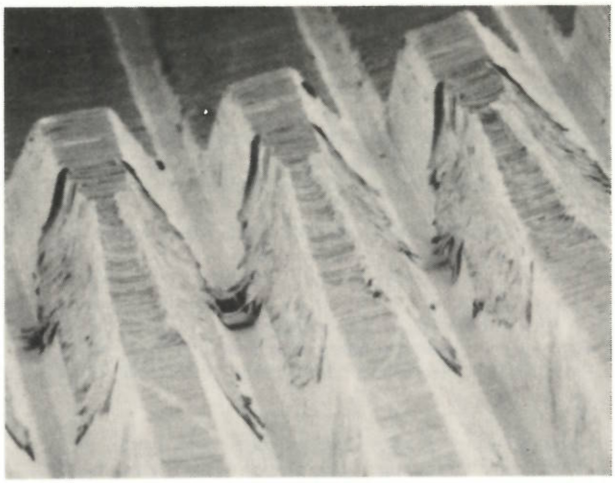


x 4

Figure 11 Third Stage of Gearhead Motor After Test

Examination of the gear box components revealed severe wear of all the gears and showed that, in all three stages, the Braycote grease was black and powdery in appearance. For instance, Fig 11 shows the third stage with severe wear on the stainless steel planet gears (rather less wear was observed on the bronze planet wheels in the first two stages where the loads were lower) and Fig 12 illustrates the tooth wear and flow associated with the corresponding aluminium alloy ring gear.

In contrast to the result obtained at ESTL, an identical gearhead motor also lubricated with Braycote 3L-38RP grease, was life-tested elsewhere and gave a very satisfactory performance, both in terms of torque and component wear.



x40

Figure 12 Wear and Flow on Aluminium Alloy Ring Gear

Examination of the lubricant and components from the two gearhead motors by British Aerospace at Stevenage revealed two important facts;

i. In the gear box tested at ESTL the lubricant had undergone severe degradation. There was a perfluoro-polymer present and the evidence suggested that the PTFE thickener had oxidised (there is inevitably a significant partial pressure of oxygen in the poorly vented gear box, even during tests in vacuum). Since the polymerisation of the lubricant in the presence of wear debris and the oxidation of the PTFE both tend to produce a similar perfluoro-polymer it is not possible to say which was the prime source of the degradation product.

ii. Both gear boxes contained a trace of hydrocarbon (thought to be the rust preventative; an alkylammonium nitrite which carries a long chain hydrocarbon group within its structure) but the level detected in the satisfactory gear box was 10 times higher than that in the ESTL gear box.

3.3 Summary

The evidence from these results strongly suggests significant variations in the grease composition (due, it is thought, to the segragation that tends to occur between the base oil and the filler) and that the hydrocarbon content very much influences the performance. In a similar manner to the ball bearing tests, the lubricant degrades in the presence of active metal surfaces (particularly aluminium, with which the Fomblin Z25 oil is known to be very reactive at high temperatures) whereas, if there is a hydrocarbon oil present to wet the metal surfaces, more effective lubrication results.

4. CONCLUSIONS

1. The tests at ESTL on ball bearings have shown that, after prolonged running, there is a problem of polymerisation inherent in the Fomblin Z25 type of oil whether it is used alone or in a PTFE-thickened grease form. The mechanism is related to the production of active steel surfaces during ball/race contact which react with the oxygen atom in the lubricant molecule and cause chain scission. Build-up of debris in the bearings causes a deterioration in performance so that, at present, the oil cannot be recommended for long term use in critical space satellite mechanisms.

2. The performance was improved by the presence of small traces of hydrocarbon oil in the Z25 but this addition causes an increase in the vapour pressure and impairs the most desirable property of the oil.

3. A similar lubricant degradation has been observed after prolonged running in a Braycote grease-lubricated gear box. The mechanism of polymerisation was the same as in ball-bearings with aluminium alloy gears producing particularly reactive debris. Again, a hydrocarbon additive (this time, the rust preventative in the grease) greatly influenced the performance.

4. It is important that research be continued into the performance of the Fomblin Z25 oil so that the space industry can profit from its unique properties. Research programmes have been announced by the oil manufacturer and these should allow an improvement in its resistance to degradation.

5. ACKNOWLEDGEMENTS

The author wishes to thank Dr B Baxter of the Materials Science Group at British Aerospace Dynamic Group, Stevenage, who formulated the ideas on lubricant degradation. Thanks are also due to Mr J C Anderson at ESTL who performed the work on the gear head motor.

6. REFERENCES

1. Furey M J 1962. Metallic Contact and Friction Between Sliding Surfaces, ASLE Trans, 6.1.

2. Tallian T E 1964. Lubricant Films in Rolling Contact of Rough Surfaces, ASLE Trans 7.2.

3. Stevens K T 1983. The Performance of Fomblin Z25 Oil in Ball Bearings Operating in Vacuum. ESA(ESTL)056.

4. Stevens K T 1981. The Behaviour of Oil Lubricated Angular Contact Bearings Operating at Slow Speed, ESA(ESTL)051.

5. Baxter B H. The Surface-Chemical Investigation of Lubricant Degradation Products Generated by In-Vacuo Life Testing of Bearings Lubricated with Fomblin Z25 Oil: ST25577 July 1981.