An Evaluation of Liquid, Solid, and Grease Lubricants for Space Mechanisms Using a Spiral Orbit Tribometer

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Abstract

We present the findings of the test program performed by The European Space Tribology Laboratory (ESTL) to evaluate the performance (friction and lifetime) of a number of space lubricants under vacuum using a Spiral Orbit Tribometer (SOT). Focus was given to a comparison of various popular space oils, a comparison study between the old and new MAPLUB grease formulations, and the performance of commonly used solid lubricants under various conditions.

Tests demonstrated that the lifetimes of hydrocarbon NYE oils 2001 & 2001A outperformed those of the perfluroropolyalkylether (PFPE) oils Fomblin Z25 & Z60, though these pairs displayed similar behavior. This relationship was also generally seen for greases; with the lifetimes of the multiple alkylated cyclopentane (MAC)-based greases being extended in comparison to the PFPE-based greases. Testing on greases also demonstrated similar performance between the old (-a) and new (-b) formulations when considering PFPE-based MAPLUB greases, and indeed for all tested PFPE-based non-MAPLUB greases, but significantly shorter lifetimes for the new formulations when considering MAC-based MAPLUB greases. MAPLUB MAC greases containing molybdenum disulphide (MoS_2) thickener were also found to display reduced lifetimes.

For solid lubricants, lead displayed significantly extended lifetimes over MoS_2, speculated to be caused by redistribution of lead from the ball onto all contact surfaces during the test. Friction coefficients were seen to be some 2.5x higher for lead than for MoS_2 under similar conditions, a result that corresponds well with conventional bearing tests.

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Introduction

Selection of an appropriate lubricant is a vitally important stage of mechanism design. Due consideration must be given to the lubricant properties such as lifetime, friction coefficient, and vapor pressure to avoid unforeseen mechanism failure, a potentially disastrous consequence. As such there is a great need to accurately understand the behavior of space lubricants, and to comparatively assess their performance under representative test conditions. This paper details the findings of a test program performed by ESTL to assess the performance of a number of space lubricants (liquid, grease and solid), using a Spiral Orbit Tribometer.

Two commonly used space oils are Fomblin Z25, a Z-type PFPE oil, and the MAC oil NYE 2001A. Additionally the oil NYE 2001 is also frequently used; an oil similar in composition to that of 2001A, but containing phosphate ester boundary lubricants and antioxidant additives to improve this oil's boundary lubrication performance.

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During a recent ESA-funded research program, the PFPE oil Fomblin Z60 was highlighted as having exceedingly low vapor pressure, with predicted oil loss by evaporation approximately three orders of magnitude lower than that of Fomblin Z25 at room temperature [1]. Subsequent bearing testing at ESTL found the oil displayed similar lifetimes to those observed with Z25 bearings [2]. Friction coefficients were demonstrated in the range 0.1 – 0.15, with the Z60 displaying slightly higher torque, consistent with the higher viscosity of this oil. During the work described in this paper, a detailed study of these oils was carried out to assess their comparative friction and lifetimes under differing conditions.

In addition to oils, this work program investigated the performance of space-based grease lubricants, focusing upon the MAPLUB grease range. The MAPLUB range provides a series of high performance greases for space applications, developed in collaboration with CNES (Centre National d'Etudes Spatiales). These greases are available under a range of formulations, and are described using a 5-digit reference, e.g. PF100. Grease consistency depends upon both thickener and base oil, and is related to the grease's deformation by an applied force.

- The two letters indicate the base oil
  - PF for Perfluropolyalkylether oil (Fomblin Z25)
  - SH for Synthetic Hydrocarbon oil (NYE 2001A)
- The first two figures correspond to the grease consistency
  - 10 for low consistency
  - 05 for very low consistency
- The final figure specifies the type of additive filler
  - 0 for PTFE only
  - 1 for PTFE and molybdenum disulphide (MoS_2)

Due to a change in laws regarding CFC products, the formulation of these greases has recently changed, resulting in a change in product index (e.g. PF100-a changed to PF100-b). For the old (-a) greases, the PTFE was procured as a powder suspended in a solvent, whilst in the new (-b) formulation the PTFE is procured as a dry powder [3]. It cannot be assumed that the performance of these new greases can be extrapolated from the performance of the old, and thus a comparison study was required. The remaining greases tested included Castrol Braycote 601EF, Braycote 601EF Micronic, and NYE Rheolube 2000. The Braycote greases consist of Brayco 815Z oil suspended within a PTFE thickener, and have strong heritage within the space industry. The Micronic designation indicates the grease has been extruded through a screen pack filter to remove PTFE particles larger than one micron. NYE Rheolube 2000 is a sodium complex-soap-thickened, medium-viscosity MAC grease based upon the oil NYE 2001.

In addition, two commonly used solid lubricants were included within this study. The selected lubricants were sputtered MoS_2, and lead, applied as a thin film. Between them, these two lubricants account for a large majority of solid lubrication for space and have a heritage of successful applications.

Scope of work

This paper covers the friction and lifetime performance of the space lubricants listed in Table 1 under vacuum, assessed with a Spiral Orbit Tribometer.

Table 1. Lubricants covered within the scope of this work

Lubricant	State	Base Oil
Fomblin Z25	Oil	--
Fomblin Z60	Oil	--
NYE 2001 (with additives)	Oil	--
NYE 2001A (without additives)	Oil	--
MAPLUB PF100-a	Grease	Fomblin Z25
MAPLUB PF100-b	Grease	Fomblin Z25
MAPLUB PF101-a	Grease	Fomblin Z25
MAPLUB PF101-b	Grease	Fomblin Z25

MAPLUB SH050-a	Grease	NYE 2001A
MAPLUB SH100-b	Grease	NYE 2001A
MAPLUB SH051-a	Grease	NYE 2001A
MAPLUB SH101-b	Grease	NYE 2001A
Braycote 601EF	Grease	Castrol Brayco 815Z
Braycote 601EF Micronic	Grease	Castrol Brayco 815Z
Rheolube 2000	Grease	NYE 2001
Sputtered MoS_2	Solid	--
Sputtered Lead	Solid	--

Apparatus

Spiral Orbit Tribometer

The Spiral Orbit Tribometer is a test facility developed by NASA Glenn Research Center and recently purchased by ESTL to advance the assessment of lubricants and coatings for space applications. The facility reproduces the kinematics of an angular contact bearing, and allows for the evaluation of friction and degradation rates (i.e. consumption) of lubricants in detail.

The Spiral Orbit Tribometer is essentially a thrust bearing, with a single ball held between two interchangeable flat plates, located within a vacuum chamber. A load is applied to the top plate via a spring-loaded linear translator. The lower plate rotates via a motor located outside the chamber, causing the ball to move in a spiral path with a radius ~21 mm. This configuration causes the ball to spiral outwards, and a fixed guide plate is positioned to keep the ball within the flat plates and to maintain a repeatable orbit. The region of each orbit for which the ball is in contact with the guide plate is denoted as the scrub (see Figure 1). A force transducer behind the guide plate measures the force exerted by the ball onto the guide plate. From this the friction coefficient for each orbit is found, and can be plotted to give the performance of the lubricant over time (Figure 2).

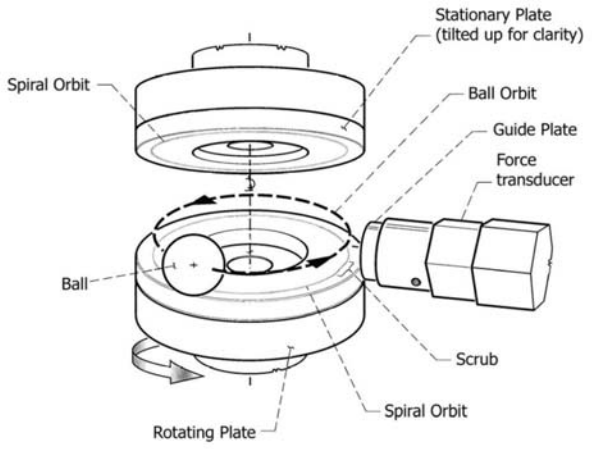

Figure 1. Internal arrangement of SOT, showing flat and guide plates

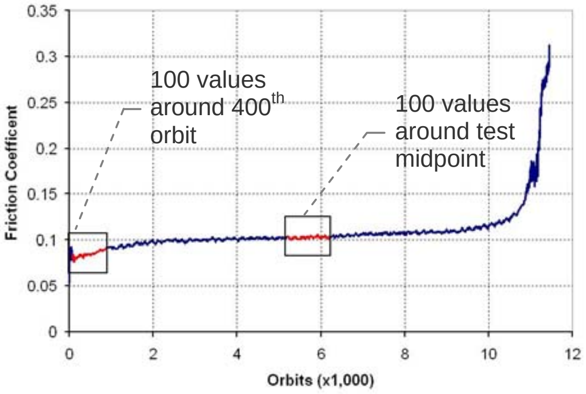

Figure 2. Typical friction plot created with SOT (using grease MAPLUB PF100-b) showing typical regions sampled for friction coefficients

The arrangement of the SOT allows the ball to experience rolling, sliding and pivoting – motions experienced by a ball in an angular contact bearing. This allows for a more representative testing of a lubricant than conventional pin-on-disc testing, which only recreates sliding motion.

Samples

Test plates were supplied along with the SOT by Spiralab LLC, Cleveland, OH. All samples (flat and guide plates) were manufactured from 440C stainless steel, and polished to a surface roughness

R_a <0.05 microns. Balls used were either 12.7 mm (1/2 inch) or 7.14 mm (9/32 inch) diameter, manufactured of 440C and 52100 steel respectively, depending on the requirements of the particular test, explained in more detail below.

Controllers
The SOT is controlled by a supplied laptop PC, running a Labview-based data acquisition program.

Procedures

Sample preparation
Due to the limited number of test specimen sets, it proved necessary to re-prepare used samples for subsequent testing. This was performed by the National Centre of Tribology. Samples were polished using a diamond paste solution mixed with Meta-Di, a water-based diamond suspension solvent, on a 6-micron polishing disc. Samples were cleaned before and after polishing in methanol, and dried using a hot air blower with dry cotton wool. Balls were not reused for multiple tests.

Prior to testing all balls and plates were solvent cleaned in a Kerry cleaning plant using Lenium ES solvent in accordance with standard ESTL practice.

Lubrication
Lubrication was applied to the balls only. Liquid lubrication was achieved through the preparation of a solution of lubricant diluted in an appropriate solvent, of a known concentration. This solution was applied directly to a rotating ball, and the solvent allowed to evaporate from the ball's surface. The amount of lubricant was determined using a high accuracy 6-point microbalance (accurate to 1 μg). A typical lubricant amount of 50 μg was applied for each test.

For grease lubrication, the ball was weighed dry and a minimal amount of grease (less than 1 mm^3) applied directly to the surface. The ball was then rolled successively between three pairs of solvent cleaned Ultra Clean Level 100 Polyethylene tubing, stretched over Petri dishes, to evenly distribute the grease (Figure 4). The ball was subsequently re-weighed, with the weight change being the grease uptake. A typical lubricant amount of 50 μg was applied for each test.

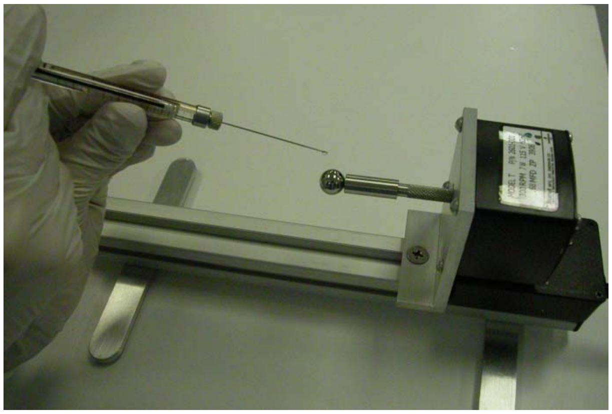

Figure 3. Liquid lubrication – application of oil-solvent solution directly to the ball

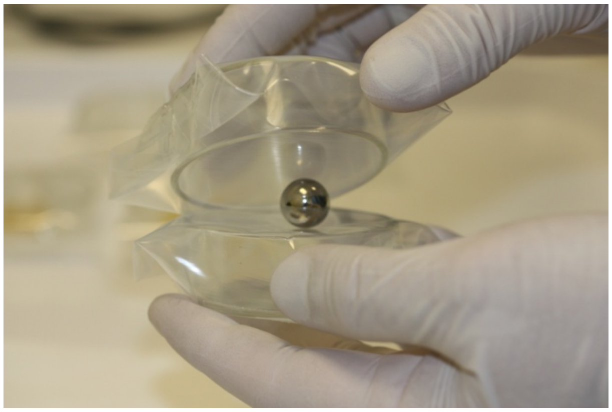

Figure 4. Grease lubrication – grease lubrication through rolling between polyethylene sheets

Solid lubrication was performed with ESTL's sputter coating rig, coating the balls only, to a desired thickness. The coating thicknesses were assessed using a calibrated X-Ray Fluorescence (XRF) measurement system, taking 20 measurements of 60 seconds for each coating run. Coating thicknesses for each test are detailed below.

Test Program

Testing was performed using the SOT under vacuum (<1.3 x 10^{-4} Pa, 10^{-6} torr) at room temperature (~23deg.C). Tests ran until the friction coefficient exceeded 0.3 for three consecutive orbits, and which point the motion was halted by an automatic trigger. Other test details are given in the relevant sections below.

Liquid lubricant assessment

Tests on each liquid lubricant were performed over a range of mean contact stresses (1.00 – 1.75GPa). For all but the highest contact stress, a 440C ball of 12.7-mm diameter was used (a smaller 7.14-mm ball of 52100 steel was used to achieve the higher contact stresses without exceeding the limit of the linear translator). Tests on the Fomblin oils were performed at 30 RPM, and increased to 100 RPM for the NYE oils due to the expected longer lifetimes of these oils. Preliminary testing at ESTL using Z25 demonstrated no apparent dependence of lifetime upon ball size or rotation speed for this lubricant within this range.

Grease lubricant assessment

Grease lubricant tests were performed using a 12.7-mm diameter 440C steel ball, rotated at 100 RPM and loaded to 1.50 GPa mean contact stress. A minimum of three tests were performed for each grease formulation, and results presented in Table 2 show the mean values.

Solid lubricant assessment

For all solid lubricant tests, a 52100 steel ball of 7.14 mm diameter and rotation speed of 100 RPM was used. For MoS_2, the coating thickness was varied with constant mean contact stress. For lead, the mean contact stress was varied with constant coating thickness.

Table 2. Test matrix for solid lubricant tests

Lubricant (thin solid film)	Coating thickness (Angstroms)	Mean contact stress (GPa)
MoS_2	800	1.50
MoS_2	2300	1.50
MoS_2	5300	1.50
Lead	850	1.50
Lead	850	1.75
Lead	850	2.00

Liquid Lubricant Assessment

The frictional behavior of all oils tested was broadly similar. Start-up friction values were typically $\mu = 0.1$. Steady state friction is then maintained until rapidly increasing to above $\mu = 0.3$ (see example Figure 2). This increase in friction is accompanied by a slight increase in chamber pressure, indicating the presence of volatile constituents – an expected observation as the lubricant degrades [4]. Figures 5 & 6 show the lifetime and friction coefficients of the test oils as a function of mean contact stress. Lifetimes are normalized to orbits/microgram of lubricant. Steady state friction coefficients are calculated by averaging 100 readings around the 400th orbit of each test, to allow for comparison with previous results.

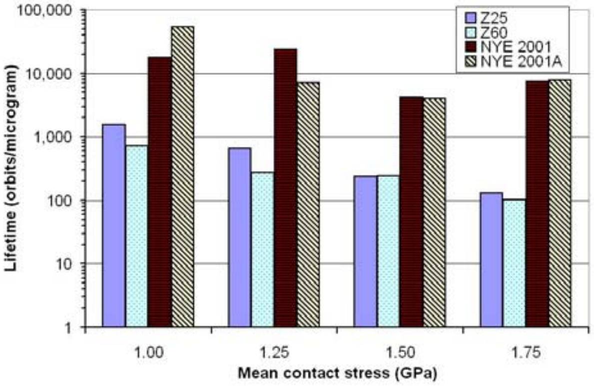

Figure 5. Lifetimes of liquid lubricants as a function of contact stress

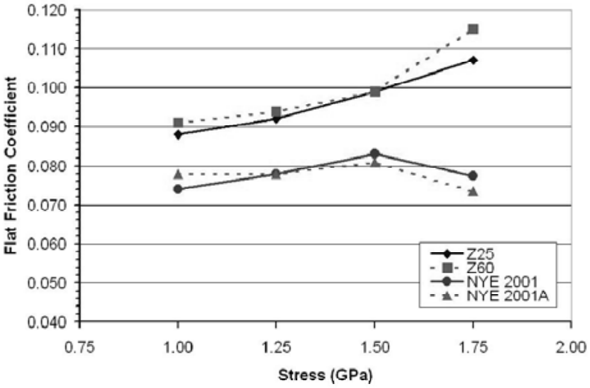

Figure 6. Friction coefficients (assessed at 400th orbit) of liquid lubricants as a function of contact stress

Lifetimes were found to be much reduced for the PFPE oils (Fomblin Z25 & Z60) in comparison to the MAC oils NYE 2001 & 2001A, a result previously seen for these oils under boundary lubrication conditions [5], as well as from past experiences with bearing tests at ESTL, operating in both boundary and mixed lubrication modes [6]. There is also a small but clear distinction in the friction coefficients of the two groups. A comparison of this data with previous studies performed using a SOT by NASA on the lubricants Z25 and 2001A [7, 8] reveals good correlation between the friction and lifetimes of 2001A, but poor correlation when considering the lifetimes of Z25 oil. Lifetimes of Z25 measured by ESTL are some 3x greater than those found in [8]. The likely cause of this discrepancy lies in the differing sample cleaning techniques between the two studies, as surface condition is thought to play a significant role in the degradation rates of PFPEs [9].

The performance of Z60 was very similar to that of Z25, with slightly reduced lifetimes and comparable friction coefficients. Similar results have been observed for these Fomblin oils in non-boundary lubricating conditions [2]. No significant difference was observed between the two NYE oils under the test conditions. This result is curious when we consider that the oil NYE 2001 contains additives to improve this lubricant's boundary performance. However, it is proposed that due to the minimal amounts of oil tested within the SOT (typically 50 µg), resulting in only a few atomic layers of lubricant on the ball's surface, these additives are not replenished once they are removed from the contact zone. Typically there is an oil reservoir present to replace the additives.

All oils displayed a decrease in lifetime, and a corresponding slight increase in friction coefficient, with increasing contact stress, an effect similarly seen in previous studies using a SOT [7]. This behavior demonstrates the sensitivity of these lubricants to contact stress when operating under boundary lubrication conditions. The cause of the potentially anomalous results seen for the MAC oils running at 1.75 GPa is not clear.

Post-test inspection of the samples showed markings on the flat and guide plates from the running of the ball. Inspection with a low powered optical microscope revealed these marks to consist of brown material deposited away from the ball tracks; consistent with the residue of the consumed lubricant.

Grease Lubricant Assessment

Figures 7 & 8 show respectively the lifetime and friction coefficients of the assessed greases. Lifetimes are normalized to orbits/microgram of lubricant, and friction coefficients are taken as the mean of 100 readings around the 400th orbit, and the midpoint of each test (Figure 2). Mean contact stress for all grease tests was 1.50 GPa.

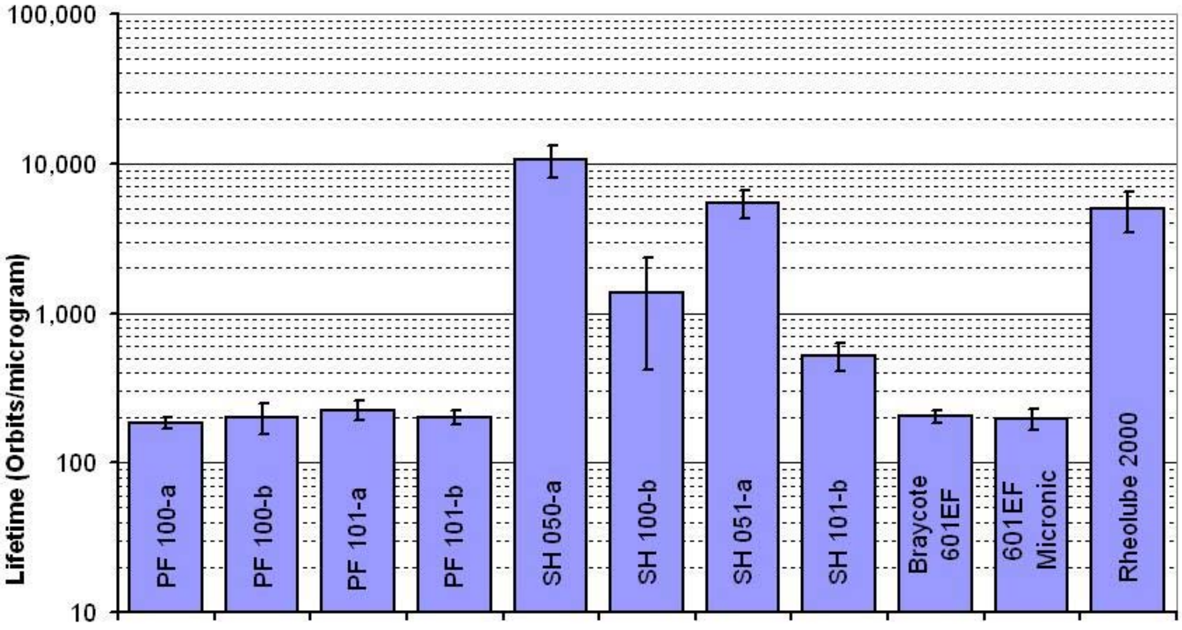

Figure 7. Lifetimes of various greases assessed under vacuum at 1.50 GPa mean contact stress

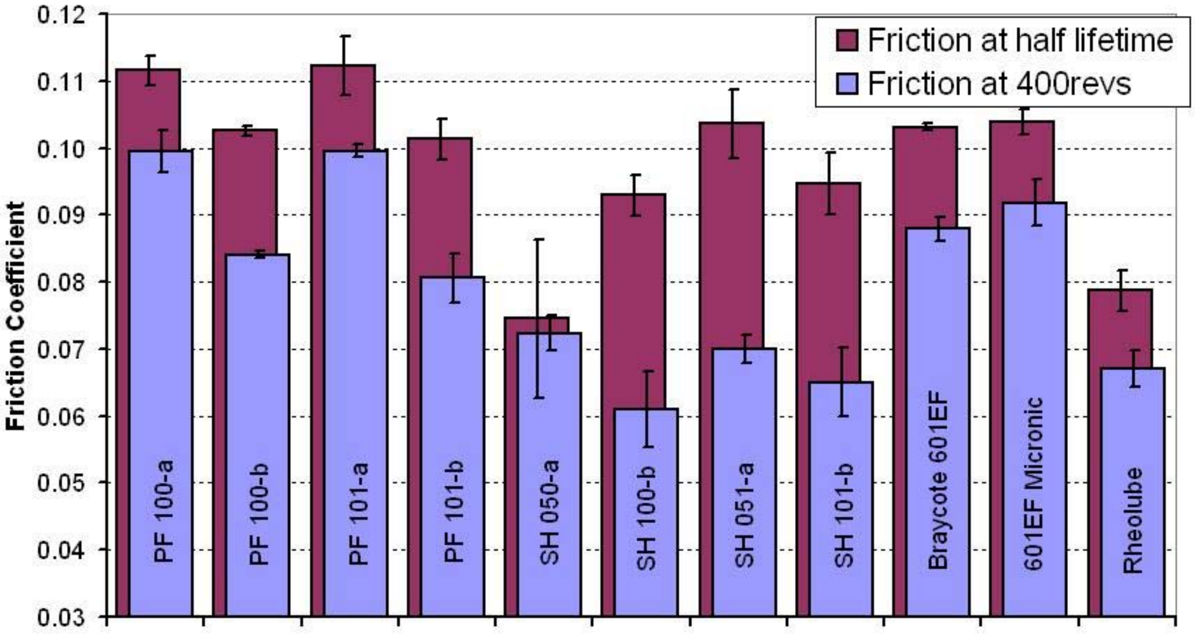

Figure 8. Friction coefficients (assessed at 400th orbit and mid-test) of various greases assessed under vacuum at 1.50 GPa mean contact stress

In general, friction profiles generated from grease lubrication were similar to those of the base oils, with long periods of low friction before a comparatively rapid increase to failure. It was observed that the increase of friction coefficient during the test was more progressive for the MAC greases in comparison to the PFPE-based greases. This effect has been observed previously when testing greases using a SOT [10, 11].

All tested PFPE-based greases showed little variation in lifetime, with a value of ~200 orbits/µg for all greases (Figure 7). This value is significantly increased in comparison to studies performed at NASA under similar conditions (30-40 orbits/µg) [11, 12], and as stated above, this is believed to be a consequence of the differing cleaning techniques implemented. Considering lifetime the inclusion of MoS_2 filler was not found to cause a significant effect, nor was a difference observed between the old (-a) and new (-b) MAPLUB formulations, nor indeed between Braycote 601EF and 601EF Micronic.

Considering the friction coefficients (Figure 8) we find the new MAPLUB PFPE greases display lower friction coefficients than their comparative old formulation greases. This difference is most exaggerated in the early stages of the test. When plotting friction coefficient against orbits, it is seen that the new (-b) greases undergo a change in gradient after a few thousand revolutions (Figure 9), not seen for the old (-a) greases (Figure 10). This difference in the frictional behavior of the greases is the cause of the lower friction coefficients for the new PFPE greases, and is seen when considering greases both with and without MoS_2 filler. The friction coefficients of the Braycote greases fall somewhere between the old and new MAPLUP formulations.

Lifetimes for MAC greases were greatly extended in comparison to the PFPE greases, again in agreement with bearing grease tests at ESTL. Lifetimes for new formulation MAPLUB greases (-b) were seen to be reduced by an order of magnitude in comparison to the old (-a). It is thought this difference can be attributed to the greater viscosities of the new formulations, hampering the re-introduction of grease into the contact surfaces during the tests. In addition, lifetimes for greases containing MoS_2 thickener were found to be less than those containing only PTFE (e.g., SH101/100 and SH050/051). This result is interesting when we consider that the MoS_2 content of these greases is ~1% by volume. Given the minimal amount of grease used per test (~50 µg) it is somewhat surprising to see the addition of such a small amount of MoS_2 apparently effecting the lifetimes to such a degree.

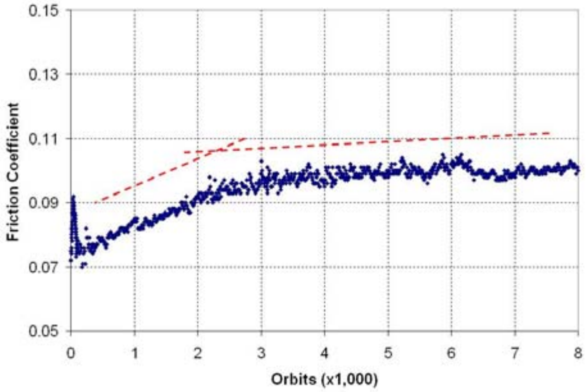

Figure 9. Early stages of PH101-b test, displaying change in gradient around 2,500 orbits

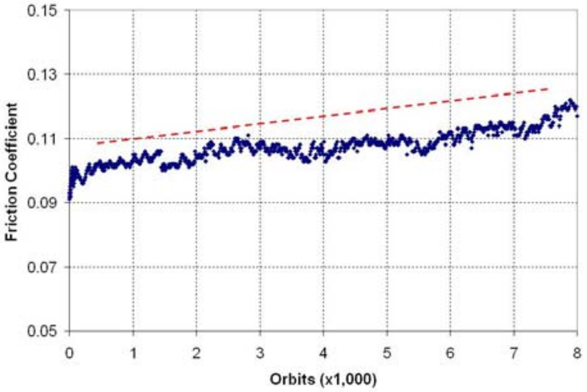

Figure 10. Early stages of PF101-a test, no gradient change

Rheolube 2000 was found to have similar friction to that of the MAC-based MAPLUB greases. This finding is akin to that found in [13], where the performance of low-speed bearings showed comparable torque for Rheolube 2000 and MAPLUB SH050-a & SH051-a. Bearing tests at ESTL have also demonstrated lower torque for Rheolube than Braycote 601 when rotating at low speeds [14], again in accordance with the results generated with the SOT.

Inspection of the samples post-test revealed brown deposits away from the ball track, similar in appearance to those of the base oils, consistent with the degraded lubricants.

Comparison with base oils

The performance of greases in comparison to their base oils is given in Table 3. Values for the oil Castrol 815Z are taken from the SOT commissioning tests performed by ESTL upon delivery of the facility. From the values in Table 3, we see that the performances of the MAPLUB PFPE greases are similar to those of their base oil when considering lifetime, and that the friction coefficients for Z25 fall somewhere between the old and new MAPLUB grease formulations. The change in gradient (demonstrated in Figure 9) is not seen for the base oil. The performance of the Braycote greases is also similar to their base oil Castrol 815Z.

Table 3. Friction and lifetimes of greases and oils assessed at 1.50 GPa mean contact stress under vacuum in the SOT, 100 RPM rotation speed (with the exception of the Z25 oil, performed at 30 RPM)

Grease	Base oil	Lifetime (Orbits/μg)	Friction @ 400th orbit	Friction @ half lifetime
--	Fomblin Z25	239	0.099	0.106
MAPLUB PF 100-a	Fomblin Z25	184	0.100	0.112
MAPLUB PF 100-b	Fomblin Z25	201	0.084	0.103
MAPLUB PF 101-a	Fomblin Z25	225	0.100	0.112
MAPLUB PF 100-b	Fomblin Z25	201	0.081	0.101
--	NYE 2001A	3,937	0.081	0.090
MAPLUB SH 050-a	NYE 2001A	10,653	0.072	0.075
MAPLUB SH 100-b	NYE 2001A	1,376	0.061	0.093
MAPLUB SH 051-a	NYE 2001A	5,492	0.070	0.104
MAPLUB SH 101-b	NYE 2001A	522	0.065	0.095
--	Castrol 815Z	233	0.093	0.104
Braycote 601EF	Castrol 815Z	203	0.088	0.103
Braycote 601EF Micronic	Castrol 815Z	198	0.092	0.104
--	NYE 2001	4,189	0.083	0.090
Rheolube 2000	NYE 2001	4,946	0.067	0.079

MAC MAPLUB greases were varied in comparison to their base oil NYE 2001A when considering both lifetime and friction coefficient. However, friction coefficients were observed to be lower for these greases in comparison to NYE 2001A when considering the early stages of the tests. The grease based on the NYE 2001 oil, Rheolube 2000, gave a similar lifetime, and slightly reduced friction coefficient than that of its base oil. Similar lifetimes of NYE 2001 and Rheolube 2000 (as well as Castrol 815Z and Braycote 601EF) have previously been observed when using the SOT [15].

Solid Lubricant Assessment

Tests on MoS_2 and lead displayed similar behavior to the liquid lubricants, characterized by a long period of low friction before a dramatic increase to failure. In all cases the running-in period to low friction was relatively short in comparison to bearing tests, which can display high torque for many thousands of revolutions. Summaries of lifetimes and friction coefficients for MoS_2 (as a function of coating thickness) and lead (as a function of mean contact stress) are plotted in Figures 11 to 14. Friction coefficients were found from the mean of 100 readings around the 100,000th orbit for MoS_2, and 1,000,000th orbit for lead.

MoS$_2$

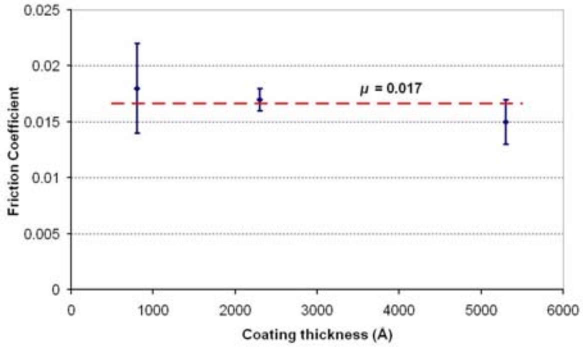

Figure 11. Friction coefficients (assessed at ~100,000th orbit) of MoS$_2$ as a function of coating thickness

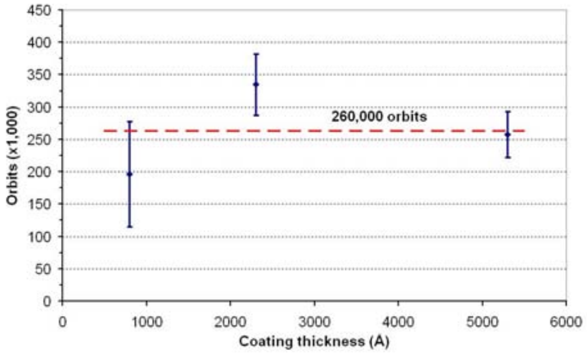

Figure 12. Lifetimes of MoS$_2$ as a function of coating thickness

For MoS$_2$ a mean friction coefficient of μ = 0.017 was found, with little variation across the assessed coating thickness range 850 – 5,300Å (Figure 11). In addition, the lifetime of the coating is also not observed to be dependent upon coating thickness within this range, displaying a mean of 260,000 orbits (Figure 12). It is speculated that a greater initial thickness of MoS$_2$ applied to the ball merely results in greater volumes of lubricant material being lost in the early stages of rolling, with the ball running on a much thinner coating for the majority of its lifetime. X-Ray Fluorescence analysis of the post-test samples revealed no MoS$_2$ remaining on the ball and loose debris pushed clear of the ball track, demonstrating failure in these cases is caused by removal of MoS$_2$ by the actions of rolling, sliding and pivoting.

The frictional performance of thin films of lead was found not to vary with increasing contact stress, with a mean of μ = 0.046 found over the tested contact stress range (Figure 13). This friction coefficient is some 2.5x higher than the value found for MoS$_2$ under similar conditions, a relationship which corresponds well with results from angular contact bearing tests [14]. Lifetimes were seen to decrease with increasing contact stress, an expected behavior, with the lowest stress test (1.50 GPa mean contact stress) being stopped at +3.5million orbits showing no indication of failure (Figure 14).

Lead

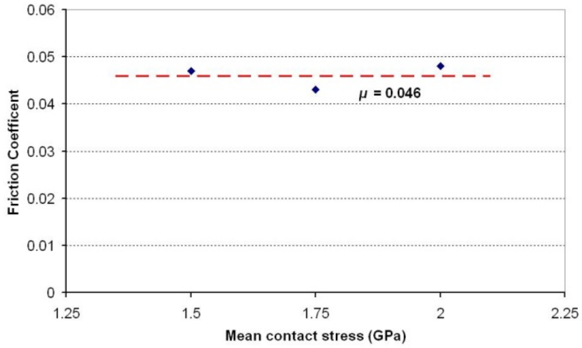

Figure 13. Friction coefficients (assessed at ~1,000,000th orbit) of lead as a function of mean contact stress

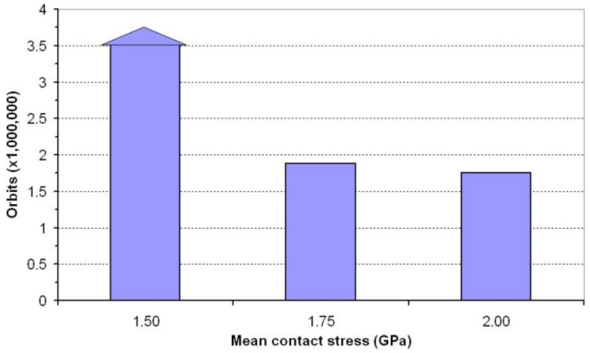

Figure 14. Lifetimes of lead as a function of mean contact stress

Under similar conditions, the lifetimes displayed by thin lead films were extended an order of magnitude in comparison to MoS$_2$. Similar extension of life when using lead lubrication is seen in angular contact bearing tests [14]. This result demonstrates well the ability of the SOT to assess the performance of thin solid film lubricants in comparison to other tribometers, particularly pin-on-disc (POD) tribometers, which are capable of only simulating sliding motion. Figures 15 & 16 demonstrate the difference in lifetime gained from these two methods, with the result from the SOT (Figure 15) being a much more accurate model of the behavior seen in angular contact bearings.

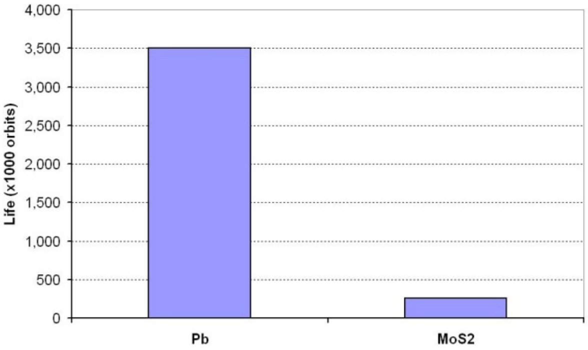

Figure 15. Lifetimes of thin solid films (ball only) as assessed with a SOT

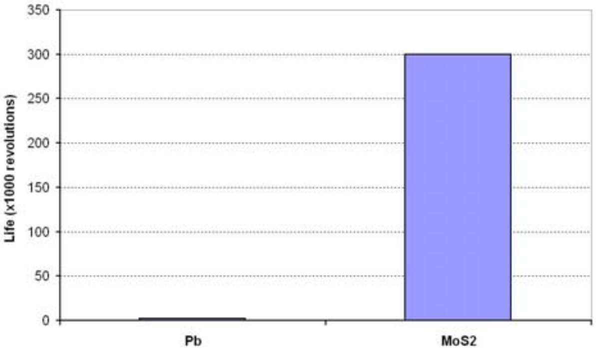

Figure 16. Lifetimes of thin solid films as assessed with a POD tribometer

XRF analysis of the samples used in the 1.50-GPa lead test (+3.5 million orbit lifetime) revealed less than 100 Å of lead remaining on the ball (Figure 17), reduced from the originally deposited 850 Å. Additionally, low but finite lead readings were given in the ball tracks on the flat plates, with the highest readings given in the scrub region (Figure 18). Accurate thickness measurements could not be taken in the ball tracks as the XRF measurement area has a greater diameter than the width of the track (>1 mm). These results lead to the theory that during the test lead is re-distributed from the surface of the ball onto all contact surfaces, promoted by the ductile nature of the lead in comparison to the more friable MoS_2. It is speculated that this process is the cause of the order of magnitude extension in life displayed by lead over MoS_2 running under similar conditions.

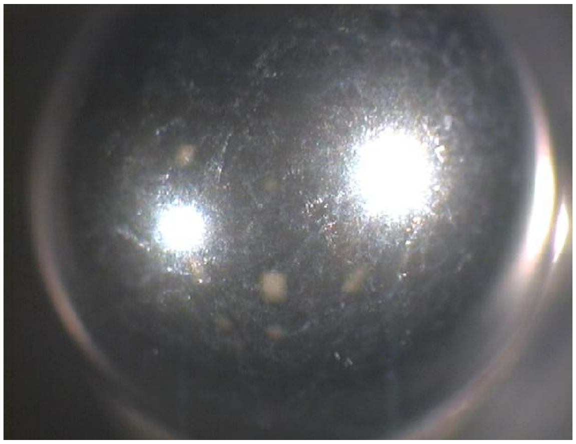

Figure 17. Ball from 1.50-GPa contact stress test on lead, displaying lead mottles on surface. XRF analysis read ~100 Å lead remaining

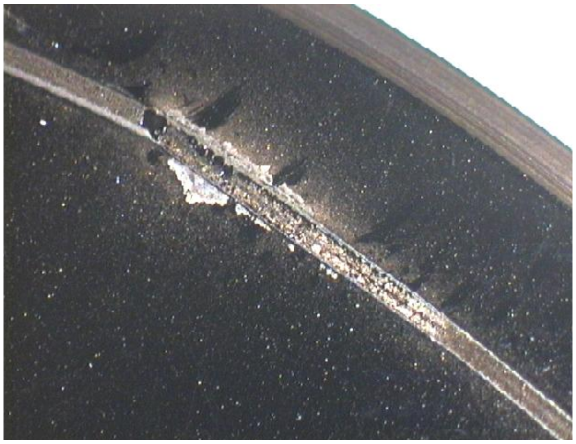

Figure 18. Flat plate (top) from 1.50-GPa contact stress test on lead, displaying lead deposits in scrub region and ball track

Conclusions

The following conclusions are drawn in relation to the tested oils. These conclusions are specific to these lubricants operating under boundary lubrication conditions at ambient temperatures.

- The lifetimes of the hydrocarbons NYE 2001 & 2001A outperform those of the PFPEs Fomblin Z25 & Z60.
- The steady state friction yielded by the tested NYE oils is slightly less than that yielded by the PFPEs at a given contact stress.
- The performance of NYE 2001 is similar to that of NYE 2001A.
- The performance of Fomblin Z60 is similar to that of Z25, with the Z60 oil displaying slightly shorter lifetimes and marginally greater steady-state friction coefficients.
- Increasing contact stress results in decrease in lubricant lifetime.

The following conclusions are drawn in relation to the tested greases.

- Lifetimes are longer, and friction coefficients generally lower for MAC-based greases in comparison to PFPE-based greases under these conditions.
- Little variation in lifetime was found for PFPE-based greases, with all tested greases displaying ~200 orbits/μg
- Friction coefficients were found to be slightly lower for the new (-b) formulation PFPE-based MAPLUB greases in comparison to the old (-a). This difference was observed to be largest in the early stages of running
- Lifetimes of MAC-based MAPLUB greases were an order of magnitude lower for the new formulations in comparison to the old, suspected to be due to the higher viscosities of the new greases.
- MAC MAPLUB greases containing MoS_2 thickener were found to display reduced lifetimes in comparison to those with only PTFE thickener.
- Braycote 601EF and Braycote 601EF Micronic gave virtually identical lifetimes and friction coefficients.
- The performances of the greases were generally similar to those of their base oils, with the exception being the MAC based MAPLUB greases.

The following conclusions are drawn in relation to the tested solid lubricants.

- Lifetimes of lead coatings are greatly extended in comparison with MoS_2 of similar coating thickness, due to the re-distribution of the lubricant over the test surfaces.
- Lead displays a steady state friction coefficient ~2.5x greater than MoS_2, comparable to results from ESTL bearing tests.
- The performance of MoS_2 is not dependent upon coating thickness within the range tested, with no strong relationship when considering lifetime or friction.
- The lifetime of lead decreases with increasing load/contact stress.

The Spiral Orbit Tribometer performs well in such investigations. It enables comparative life and friction assessments to be performed on a variety of lubricants on much shorter timescales than conventional ball bearing tests.

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