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SUMMARY

A vacuum spiral orbit rolling contact tribometer (SOT) was used to determine the relative lifetimes of several unformulated space liquid lubricants. The lubricants tested included a synthetic hydrocarbon (Pennzane 2001A), three perfluoropolyethers (Krytox 143AC, Fomblin Z25, and Brayco 815Z), three silahydrocarbons (a tri, a tetra, and a penta) and a polyalphaolefin (Nye PAO-100). The SOT simulates the ball motions in an angular contact bearing and tribochemically degrades microgram quantities of lubricant. Test failure is determined when a preset friction coefficient is exceeded. Relative lifetime (orbits/µg) is defined as the number of ball orbits to failure divided by the amount of lubricant on the ball. Conditions included: 10 to 200 RPM rotational speed, ~50 µg lubricant, an initial vacuum <1.3x10^{-6} Pa, room temperature (~23°C), a mean Hertzian stress of 1.5 GPa, and 440C stainless steel specimens. Lubricated lifetimes from longest to shortest were: Pennzane 2001A, the silahydrocarbons and the PAO-100, 143AC, Z25, and then 815Z. Relative lifetimes compare favourably to full-scale vacuum gimbal bearing tests. The effect of varying the mean Hertzian stress on the lifetime of some of the lubricants was examined.

INTRODUCTION

Historically, lubricants for space applications have been chosen upon the basis of past experience with the lubricant (heritage) rather than on the latest technology or best lubricant available. This approach worked when mission lifetimes were short and duty cycles were limited, but with recent improvements in many space systems [1], lubrication has become the cause of many mission failures and anomalies [2].

In order to incorporate new lubricants or lubricant additives, evaluation of long-term tribological performance is necessary. Ideally, testing of actual components under realistic conditions would be preferred. However the extended mission lifetimes required for many spacecraft such as deep space probes, weather satellites, and surveillance systems, make these tests unfeasible. Therefore, accelerated tests are required to qualify lubricants before committing them to spacecraft use.

Preferably, as many elements of the accelerated test as possible should mimic those of the final application. Traditional, tribological testing has been designed for terrestrial applications and consists of four-ball, pin-on-disk, Cameron-Plint, and others. These tests measure bulk wear properties or friction in sliding only. Also, they are typically performed in air or nitrogen rather than under vacuum. A notable exception is the eccentric bearing test device developed by Aerospace Corp. [3].

The spiral orbit tribometer (SOT) used for these tests mimics conditions seen in an angular contact ball bearing, a primary component of many space mechanisms. It is essentially a thrust bearing with a single ball. It operates under vacuum and at similar stress levels and speeds as in actual applications. Only microgram quantities of lubricant are used and completely consumed during the test, leading to a finite lifetime. The SOT is more fully described later in this paper.

The objective of this work is to evaluate several current and potential space lubricants using the SOT. The effect of varying the mean Hertzian stress on some of the lubricants was also studied. In addition, results from full-scale vacuum bearing tests are compared to relative lifetimes from the SOT.

EXPERIMENTAL

APPARATUS

The spiral orbit tribometer (SOT) appears in Figure 1. First introduced by Kingsbury [4], the SOT is essentially a thrust bearing with flat races (plates) and a single ball. The tribometer simulates rolling, pivoting, and sliding as seen in an actual angular contact bearing. Accelerated tests are achieved by only using micrograms of lubricant on the ball. During the test, the lubricant is completely consumed, resulting in short test duration. The advantage of this type of acceleration is that operational test parameters, such as contact stress, speed, and temperature are as they will be in the final application.

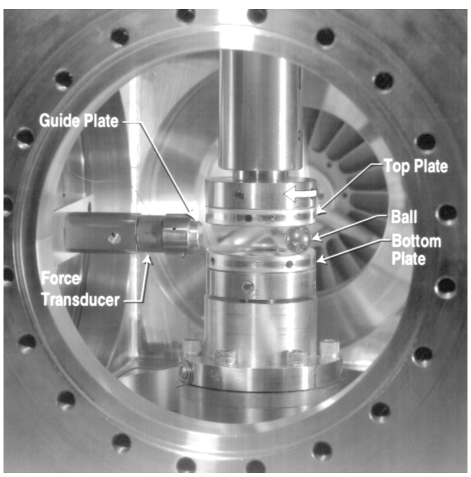

Figure 1 – Vacuum Spiral Orbit Tribometer (SOT)

The tribological elements of the system appear in more detail in Figure 2. The lower plate is stationary while the top plate can rotate at speeds up to 200 RPM. The top plate rotation drives the ball in a spiral orbit. Every orbit, the ball contacts the vertical guide plate, which returns it to the original orbit radius. The straight-line region where the ball contacts the guide plate is denoted as the "scrub". The force that the ball exerts on the guide plate during the scrub is measured from which the friction coefficient can be calculated. After leaving the scrub, the ball's spiral orbit begins again. The spiral orbit and scrub constitute a track (Figure 2) that is stable, repeatable, and is traversed thousands of times by the ball. A detailed description of the tribometer and analysis of ball kinematics appear in References 4 to 6.

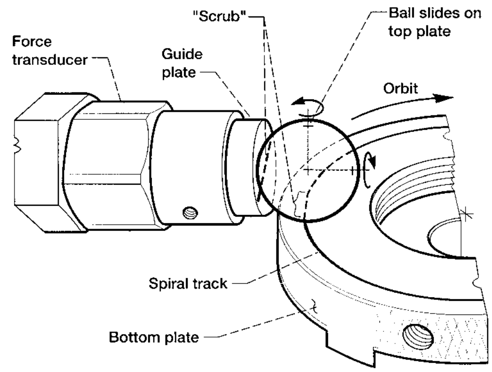

Figure 2 – Detailed view of the SOT components

MEASUREMENT AND CONTROLS

A computer data acquisition (DAQ) and control system developed in LabVIEW™ operates the tribometer. Analog to digital conversion is done using a 16-bit computer card. The DAQ automatically initiates rotation when the vacuum level reaches 1.3×10^{-6} Pa and terminates rotation when a preset friction coefficient is exceeded.

LUBRICANTS

Several classes of lubricants were studied using the SOT. They are fully described below. Lubricant properties appear in Table 1.

<u>Synthetic Hydrocarbons</u>

Polyalphaolephins and multiply alkylated cyclopentane (MAC) make up this group. Polyalphaolephins is made by the oligomerization of linear α-olefins having six or more carbon atoms. MACs are synthesized by reacting cyclopentadiene with various alcohols in the presence of a strong base [7]. Then the products are hydrogenated to produce the final product [2]. This paper focuses on Pennzane 2001A, which is a tri-2-octyldodecyl substituted cyclopentane [8]. Results in other tests [9, 10] have shown this fluid to be a promising new lubricant for space mechanisms.

<u>Silahydrocarbons</u>

These materials, originally developed by the Air Force Materials Laboratory [11], contain only silicon, carbon, and hydrogen. Therefore, they do not exhibit the poor boundary lubricating properties observed with silicones. They are unimolecular, have a wide range of available viscosities, and have excellent volatility characteristics [12]. There are three types (tri, tetra, penta) available based upon the number of silicon atoms present [13, 14].

Perfluoropolyalkylethers (PFPAE)

Perfluoropolyalkylethers are the heritage space lubricants, used since the inception of the space program. They are available in the form of a branched fluid, Krytox, manufactured by DuPont, and a linear fluid, Fomblin Z, manufactured by Montefluous [2]. Brayco 815Z is a linear fluid based on the Z-25 structure, but further processed by the supplier Castrol.

SOT SPECIMEN MATERIALS

The ball, guide plate, and disks were made from hardened (R_c~59), AISI 440C stainless steel. Before each test, the guide plate and disks were polished to an average surface roughness (R_a) of 0.05 microns (2 µin). The ball was grade 25 and had a R_a of 0.05 microns (2 µin).

Table 1 – Properties of Test Lubricants

Lubricant	Viscosity (cS) 40°C	Viscosity (cS) 100°C	Vapor Pressure (Torr at 25°C)
P2001A	108	15	10^{-11}
Trisila	177	24	10^{-8}
Tetrasila	116	18	10^{-8}
Pentasila	143	21	10^{-7}
PAO 100	1350	110	Not Measured
143AC	270	26	10^{-6}
Z25	155	47	10^{-10}
815Z	148	45	10^{-11}

PROCEDURE

PREPARATION

The parts were cleaned using a levigated alumina-polishing compound and rinsed with tap water. The ball, disks, and guide plate were sequentially placed in an ultrasonic bath for five minutes using each of the following solvents: hexane, methanol, and distilled water. They were then rinsed ultrasonically for one more minute in methanol, dried with nitrogen, and placed into the UV-ozone box for fifteen minutes [15]. The ball was rotated every five minutes to ensure that the entire surface had been treated. The samples were removed, the ball was lubricated, and the other parts placed into a vacuum system.

LUBRICATION

The ball was weighed dry. Then, a dilute solution of lubricant was dripped onto the ball while it was held at a point contact and spun. The solvent was allowed to evaporate and then the ball was reweighed using a sensitive balance. This method allowed for a repeatable lubricant charge of approximately 50 micrograms.

TEST SETUP

Once the samples had been cleaned, the guide plate and disks were installed in the tribometer. Then, the ball was inserted so that it was touching the guide plate. This was done to ensure that the ball was always at the same track diameter and there was no 'run-in' time – or revolutions that the ball did not hit the guide plate. The load was applied and the chamber evacuated.

TESTING

The experiment was automatically started after the vacuum level dropped below 1.3×10^{-6} Pa. All tests were performed using a mean Hertzian stress of 1.5 GPa and a top disk rotational speed of 200 RPM. The DAQ constantly monitored guide plate force, load, pressure, revolutions, and contact resistance. The test was terminated when a coefficient of friction of 0.28 was exceeded. For some of the lubricants, tests were performed with the mean Hertzian stress level at 1.0, 1.5, and 2.0 GPa. A typical friction trace appears in Figure 3.

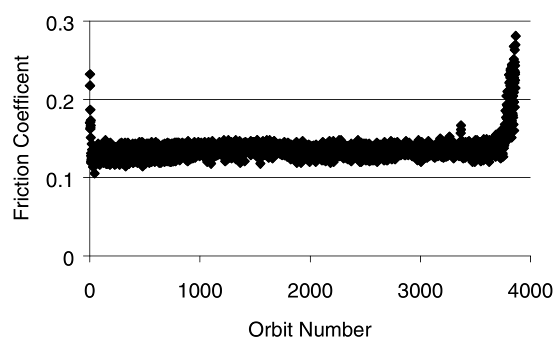

Figure 3 – Typical friction trace from the SOT

RESULTS

LIFETIME RESULTS

Normalized lifetime was determined as the number of ball orbits to failure, determined when the friction coefficient exceeded 0.28, divided by the lubricant charge on the ball. A minimum of four tests with each lubricant were performed. Results are shown graphically in Figure 4. Pennzane 2001A yielded the longest lifetime, followed by the silahydrocarbons and the Nye PAO-100, which statistically yielded the same lifetimes. Of the PFPEs, Krytox 143AC had the longest life, followed by Fomblin Z25, Brayco 815Z. Normalized lifetimes and initial friction coefficients appear in Table 2.

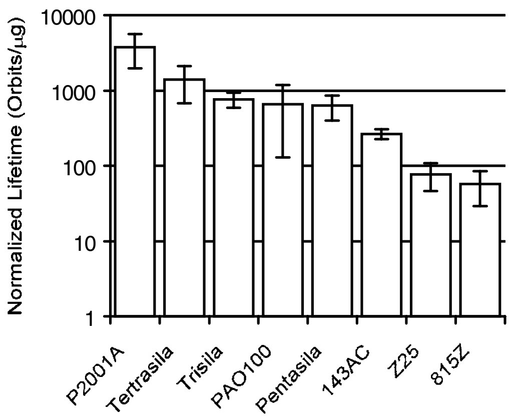

Figure 4 – Relative lifetimes at 1.5 GPa of several space lubricants using the SOT

Table 2 – Normalized lifetimes and initial friction coefficients

Lubricant	Normalized Lifetime (Orbits/μg)	Initial Friction Coefficient
P2001A	3800 ± 1820	0.06
Trisila	770 ± 180	0.14
Tetrasila	1400 ± 720	0.14
Pentasila	630 ± 230	0.15
PAO 100	660 ± 531	0.15
143AC	270 ± 40	0.17
Z25	80 ± 30	0.12
815Z	60 ± 30	0.20

STRESS LEVEL TESTS

The effect of stress on lubricated lifetime using the SOT was previously examined for Krytox 143AC [16] and Pennzane 2001A [17]. Similar tests were performed using Fomblin Z25. Tests were performed at three mean Hertzian stress levels, 1.0, 1.5, and 2.0 GPa. Results are shown in Figure 5.

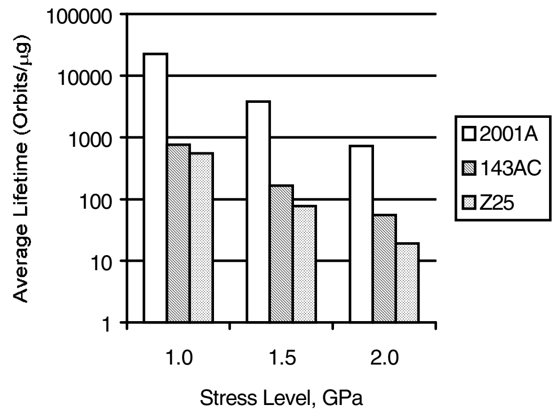

Figure 5 – Relative lifetimes at Pennzane 2001A, Krytox 143AC, and Fomblin Z25 using the SOT

DISCUSSION

STRESS AND LOAD LEVEL

A similar trend with all three lubricants is observed when they are subjected to varying Hertzian stress. There is an exponential decrease in lifetime as stress level is increased. Energy dissipation during the rolling/sliding of the ball against the plates is the driving force behind lubricant degradation in the SOT. The total energy dissipation per unit time is termed severity. A detailed analysis of energy loss in the SOT appears in Reference 6 and of the role of severity in lubricant degradation in Reference 16.

Life varies inversely with load to the 1.3 power for Krytox 143AC and to 1.6 power for the other two oils as shown in Figure 6. This exponent is somewhat higher than unity for simple energy dissipation. However, detailed analysis of the kinematics in the SOT yields an estimated exponent of –1.55. This compares very well with the experimentally measured exponents.

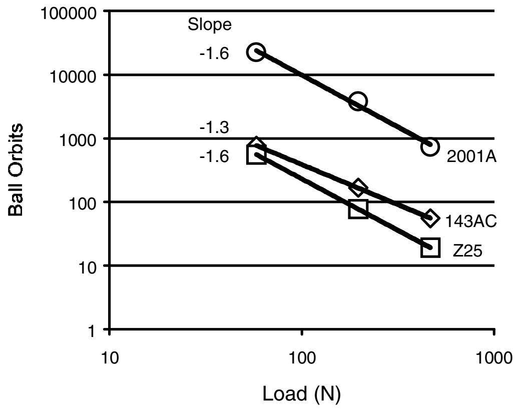

Figure 6 – SOT Life versus Load for Pennzane 2001A, Krytox 143AC, and Fomblin Z25

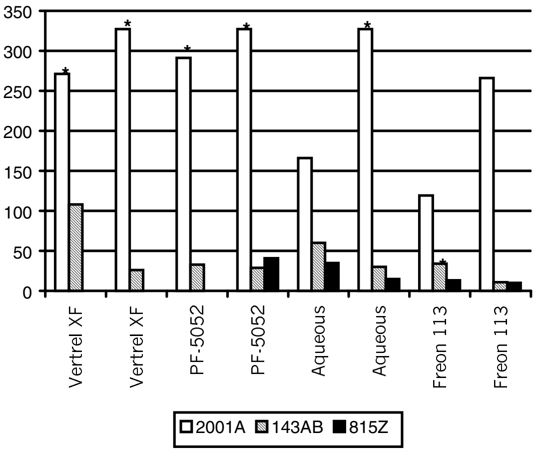

Figure 7 – Relative Life of Scanner Bearing with Various Cleaners and Pennzane 2001, Krytox 143AB, and Bray 815Z oils (* indicates test is still running)

FULL SCALE BEARING TESTS

Instrument scanner bearing life tests with oils similar to those tested in the SOT have been in progress for five years [18]. These tests use hard preloaded (0.75 GPa mean Hertz stress) angular contact, torque tube type, ball bearings. The bearings continuously dither over a simulated scanner cycle of ± 12°. Bearings cleaned with three non-ozone-depleting solvents provided comparable lives to the baseline Freon solvent.

Results for a formulated Pennzane (2001) and Bray 815Z appear in Figure 7 together with five pairs of Krytox 143AB lubricated bearings that were later added to the test. All eight pairs of 815Z and four out of five pairs of 143AB bearings have failed thus far. However, six out of the ten of the 2001-lubricated bearings are still running at nearly 330 million cycles. No apparent trend with cleaner was observed. The lives with alternate solvents often were better than the baseline Freon-113 cleaner.

In keeping with the results from the SOT, the 2001 oil enjoys a significant life advantage over both the 143AB and the 815Z oils. Currently the 2001 test bearings show a seven times higher L_{10} life (90% bearing survival rate) than the 815Z bearings (see Figure 8).

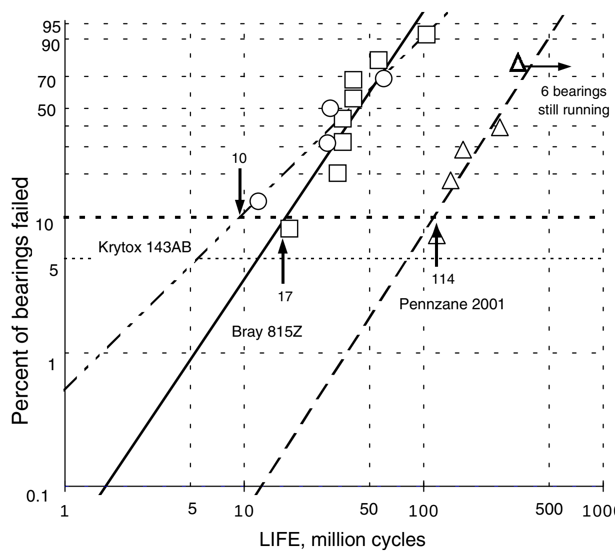

Figure 8 – Life of Scanner Bearings using Weibull Statistics

The lives of the 143AB lubricated bearings were statistically comparable to those lubricated with 815Z oil. This also correlates with the SOT data (see Figs. 4 and 6), which shows that both oils have comparable lives at lower stress levels (below 1 GPa). This is in keeping with the 0.75 GPa mean contact stress level of scanner bearing test [18]. At these lower stress levels, one might expect that the enhanced chemical stability of the branched 143AB PFPE oil over the linear 815Z would not be as apparent as it would be under more severe conditions.

CONCLUSIONS

Synthetic hydrocarbon oils (Pennzane 2001A and silahydrocarbons) provide an order magnitude life advantage over traditional PFPE space oils according to the SOT results. Similar results were obtained with full scale, scanner bearing life tests where a seven times life advantage was obtained between 2001 and 815Z oils. Life was found to vary inversely with load to the –1.3 to -1.6 power following an approximate energy dissipation relationship for lubricant degradation

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