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# Lubricated Bearing Lifetimes of a Multiply Alkylated Cyclopentane and a Linear Perfluoropolyether Fluid in Oscillatory Motion at Elevated Temperatures in Ultrahigh Vacuum

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## ABSTRACT

Bearing life tests in vacuum with three space liquid lubricants, two multiply alkylated cyclopentanes (MACs) and a linear perfluoropolyether (PFPE) were performed. Test conditions included: an 89 N axial load (mean Hertzian stress 0.66 GPa), vacuum level below 7 x $10^{-4}$ Pa, and a ±30° dither angle. Dither rate was 75 cycles per minute. Higher (110° to 122° C) and lower temperature tests (75°C) were performed. For the higher temperature tests, the PFPE, Fomblin® Z25 outperformed Pennzane® X-2000 by more than an order of magnitude. Lubricant evaporation played a key role in these high temperature results. At 75°C, the order was reversed with both Pennzane X-1000 and X-2000 outperforming Fomblin Z25 by more than an order of magnitude. Most Pennzane tests were suspended without failure. The primary failure mechanism in these lower temperature tests was lubricant consumption in the tribocontacts.

## 1.0 INTRODUCTION

Historically, lubricants were chosen for space mechanisms based upon previous usage in space rather than the latest technology. This strategy was highly successful with the limited mission lives and minimal duty cycles of the early space program; however, with improvements in other spacecraft components and increases in mission lives, tribological systems have become a main factor in limiting spacecraft reliability and performance and often represent single point failures that cripple or debilitate expensive spacecraft [1].

In past decades, many different liquid lubricants have been used in space applications, including mineral oils, esters, silicones, polyalphaolefins, and perfluoropolyethers (PFPE). In the past decade, a synthetic hydrocarbon (Pennzane) has been replacing many older lubricants. This study focused on comparing these synthetic hydrocarbons and a PFPE because most modern spacecraft mechanisms use one of these lubricant classes.

Three lubricants were tested; two multiply alkylated cyclopentanes (MAC) and a linear perfluoropolyether. MAC oils are synthesized by reacting cyclopentadiene with various alcohols in the presence of a strong base. The reaction products are then hydrogenated to produce the final product, which is a mixture of di-, tri-, tetra-, or penta- alkylated cyclopentanes. Varying reaction conditions controls the distribution [2]. MACs, first introduced in the 1990s, offer low vapor pressure, long life, and good lubricity – effectively combining the best traits of perfluoropolyethers and synthetic hydrocarbons. The fluid tested was Pennzane synthesized hydrocarbon fluid (Shell's trade name) fortified with an amine and a phenolic based antioxidant package. Two viscosity grades, X1000 and X2000, were run. Pennzane X2000 is the most commonly used form of Pennzane; however, Pennzane X1000 has lower viscosity, but higher volatility and was introduced for lower temperature applications.

Perfluoropolyethers are composed entirely of carbon, fluorine, and oxygen. They have been widely used in space applications since the late 1970s [3]. PFPEs are colorless, odorless, and completely inert to almost all chemical agents including oxygen and are compatible with nearly all plastics. PFPEs are also resistant to chemically aggressive environments and are unaffected by sulfuric acid, hydrochloric acid, alkalis, halogens, and petroleum solvents. Additionally, some PFPEs have very low vapor pressures. For these tests, Fomblin Z-25, a linear PFPE was used. Properties for the test fluids are listed Tab. 1.

Several studies have shown MAC oils provide superior performance over perfluoropolyether oils in vacuum environments under room temperature conditions [4-8]. In bearing life tests, Bazinet et. al show approximately a 9x life increase using a formulated Pennzane compared to Brayco® 815Z [5]. These bearings oscillated ±12° and every 5 million cycles a torque signature was taken by rotating the bearing three full revolutions in each direction. Testing was performed at a mean Hertzian stress of 0.75 GPa, at room temperature, and a vacuum less than $10^{-6}$ Torr. Failure criteria was a 4X increase in torque compared to the starting torque.

*Table 1 - Lubricant properties*

| **Lubricant** | **Average Mol. Weight** | **Viscosity at 20°C (cSt)** | **Viscosity Index** | **Pour Point (°C)** | **Vapor Pressure (Pa)** | |
|---|---|---|---|---|---|---|
| | | | | | **25°C** | **150°C** |
| Z25 | 9500 | 255 | 355 | -75 | $1.2x10^{-11}$ | $1.1x10^{-5}$ |
| X1000 | 630 | 160 | 140 | -63 | $3.6x10^{-7}$ | $6.0x10^{-1}$ |
| X2000 | 910 | 330 | 137 | -55 | $3.1x10^{-10}$ | $2.3x10^{-3}$ |

Testing using a vacuum Spiral Orbit Tribometer (SOT) also showed a large life improvement (50X) of Pennzane compared to Brayco 815Z (a fluid chemically similar to Fomblin Z-25) [6]. The SOT is an accelerated test tribometer that accurately depicts the rolling and pivoting motions seen in an angular contact bearing and measures lubricant degradation rates (i.e. consumption rates) under boundary lubrication conditions. Testing was performed at a mean Hertzian stress of 1.5 GPa, room temperature, and a vacuum less than $10^{-6}$ Pa.

Long term vacuum bearing tests (1,000 hours) showed a greater formation of degradation products in bearings lubricated with a branched PFPE (Krytox® 143AC) compared to bearings lubricated with Pennzane [7]. Testing was done using Timken Super Precision 1219 bearings (440C stainless steel) at elevated temperatures (75°C), a mean Hertzian stress of ~0.66 GPa, and a vacuum of less than $10^{-5}$ Pa.

Testing using a vacuum 4-ball tribometer showed that a formulated Pennzane yielded an 18x lower wear rate compared to Brayco 815Z [8]. Testing was performed over a four hour period, measuring an average wear scar every hour. These results were converted to wear volume and plotted to yield a wear rate. Testing was done at room temperature and at a vacuum of less than $10^{-4}$ Pa.

The objective of this work was to compare two Pennzane base fluids and Fomblin Z-25 in vacuum bearing tests under oscillatory motion at elevated temperatures.

## 2.0 EXPERIMENTAL

### 2.1 Apparatus

The apparatus used for these experiments, shown in Fig. 1, isolates a single angular contact bearing. The system operates at a vacuum level better than 7.0 x $10^{-6}$ Pa, from 1 to 1000 RPM or a precise dither angle, up to 130°C, and loads to 89 N. The system uses dead weight loading and either a heat lamp or band heater. The system also measures cross bearing electrical resistance, which is used to monitor the operating regime. Bearing torque, load, chamber pressure, and cross bearing resistance are recorded using a data acquisition system.

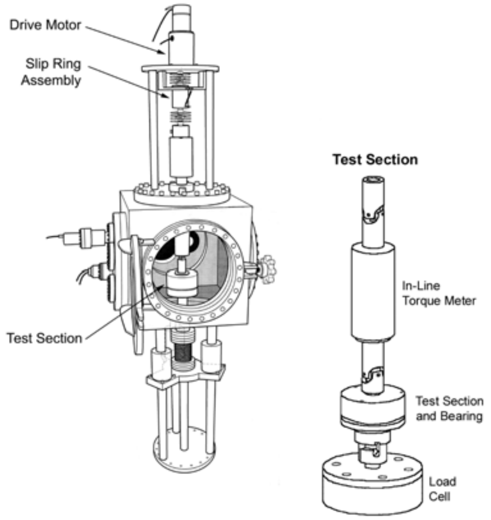

*Figure 1 - Bearing test facility*

The system uses a single Timken Super Precision 1219 (440C stainless steel) angular contact bearing. The bearing has an outside diameter of 30.16 mm, a bore of 19.05 mm, eighteen 3.175 mm balls, and a cotton phenolic retainer. The bearing is mounted in a fixture that holds the outer race and rotates the inner race. Temperature information is gathered from a thermocouple mounted just below the inner race. The apparatus if fully described in Ref. 9.

### 2.2 Test Procedure

Before each test, a new bearing was prepared. The bearing was received from the manufacturer unlubricated. First, the bearing was separated and the retainer underwent a three day sohxlet extraction in hexane. The retainer was dried in a vacuum oven at 100°C for 24 hours. The heat was turned off and the retainer allowed to cool to room temperature under vacuum. It was then immediately removed from the vacuum and placed in the desired lubricant where it was allowed to soak for three days at 100°C. At the conclusion of three days, the retainer was removed, excess oil wiped off and weighed. The bearings were reassembled and stored in a dry chamber until they were ready to be tested.

Before testing, each bearing was lubricated with oil using a micro liter syringe. Several small lubricant drops were deposited directly onto the balls. The bearing was rotated and the weight increase noted. The target weight increase for Pennzane was ~1.3 mg and for Fomblin was ~2.6 mg, yielding similar lubricant volumes added to the bearing.

After assembly, the bearing was installed in the system and an 89 N axial load applied. This corresponds to a mean Hertzian stress of approximately 0.66 GPa. The chamber was evacuated and the test started when the vacuum level dropped below $7 \times 10^{-4}$ Pa. The bearing was set to dither ±30°. At the beginning of the test, the dither rate was 15 cycles per minute. The bearing was heated and then the speed was increased to 75 cycles per minute. Cross bearing resistance was monitored to ensure the bearing continuously operated in the boundary lubrication regime.

Tests were divided into two groups, high and low temperature. For the high temperature (110 to 122ºC) tests, a heat lamp was used to elevate the temperature. Test temperature variation was much greater (± 5ºC) than at 75ºC, since there was no active control. For the low temperature (75ºC) tests, a band heater was used. The band heater controlled within ±1°C.

Tests were run until the torque exceeded a pre-defined limit. For the high temperature tests, the torque limit was ±7.1 N-cm and for the low temperature tests, the torque limit was four times the bearing’s starting torque. Due to time limitations, some tests were suspended if, at least, 1.4 million cycles were completed. At least two tests at each condition with each lubricant were performed. Upon test conclusion, the bearing was removed and reweighed.

## 3.0 RESULTS

### 3.1 High Temperature Tests

Results are summarized in Tab. 2. For the high temperature tests, the average life for the Pennzane X2000 was $2.6 \times 10^4$ cycles while the average life for the Fomblin Z25 bearings was $3.1 \times 10^5$ cycles and one test was suspended.

### 3.2 Low Temperature Tests

For the low temperature tests, two X2000 tests were suspended after $1.4 \times 10^6$ cycles, one test after $4.9 \times 10^6$ cycles, and one failed at $3.6 \times 10^6$ cycles. The average lifetime of the Z25 lubricated bearings was $6.2 \times 10^5$ cycles. One X1000 bearing failed after $1.5 \times 10^6$ cycles and one was suspended after $7.2 \times 10^6$ cycles.

## 4.0 DISCUSSION

For the high temperature tests, the Fomblin Z25 lubricated bearings exhibited an order of magnitude longer life than the Pennzane X2000 lubricated bearings. Since the test bearings were not sealed, evaporation played a key role in the observed lifetime at the elevated temperatures. This was confirmed by reweighing the bearings at test conclusion. One X-2000 test yielded an anomalous (8%) weight loss. Visual inspection of this bearing indicated little free oil remaining. It is assumed that this is the result of a weighing error. Tribological degradation was also taking place at this test condition.

In the 110ºC to 122ºC range, X-2000 exhibits a vapor pressure approximately two orders of magnitude greater than Z-25. Taking into account the longer run times for Z-25, lubricant evaporation calculations indicate that X-2000 will exhibit about 10 times the loss exhibited by Z-25.

In contrast, at 75ºC, both Pennzane X1000 and X2000 outperformed the Fomblin Z25 lubricated bearings by more than an order of magnitude. Almost all Pennzane tests were suspended without failure. At this temperature, tribological degradation (consumption) of the lubricant was the operative failure mechanism. Evaporation was a minor factor. These results correlated well with room temperature Spiral Orbit Tribometry tests previously reported [10].

One method of estimating the lifetime of a ball bearing/lubricant combination is to calculate the number of ball crossings or passes at a given race location. In addition, since higher Hertzian stresses result in increased lubricant consumption (i.e. decreased bearing lifetime), this must be factored into the analysis. Although stress is not a linear factor, most instrument bearings operate in a narrow stress range, typically 60 to 80 ksi mean. Therefore, a linear relationship is normally assumed. In order to determine a Cumulative Degradation Factor (CDF), the mean Hertzian stress is multiplied time the number of ball passes, yielding units of ball passes-psi (bp-psi). This factor can then be compared to similar calculations from the field or from bearing life tests [5]. For example, PFPE lubricants such as Fomblin Z-25 or Brayco 815Z tend to fail in the CDF range of 2 to 8 x $10^{12}$ ball passes-psi. Pennzane based lubricants usually fail in the CDF range of 2 to 9 x $10^{13}$ ball passes-psi. These ranges are for room temperature tests. Very little data is available at elevated temperatures. A rule of thumb that is often used to estimate the effect of temperature on reaction rates is that these rates will approximately double for every 10ºC rise in temperature. For room temperature tests (25ºC) to 75ºC, a reaction or degradation rate of 32 times greater could be estimated.

Adjusting these CDF values for temperature would yield an expected failure range for X-2000 of 6 to 28 x $10^{11}$ bp-psi and for Z-25, 6 to 25 x $10^{10}$ bp-psi. Assuming one ball pass per cycle, the single X-2000 failure occurred at a CDF of 3.4 x $10^{11}$ bp-psi. The three Z-25 failures occurred in the CDF range of 4 to 7 x $10^{10}$ bp-psi. This compares favorably to the predicted failure ranges.

## 5.0 CONCLUDING REMARKS

Pennzane based lubricants can be used for higher temperature applications for space mechanisms. At some point in the temperature range (75ºC to 110ºC), evaporation will limit their lifetime. However, properly sealed systems may extend this temperature limit.

Temperature adjusted Cumulative Degradation Factors yield a reasonable prediction of bearing lifetimes at elevated temperature.

*Table 2 - Summary of Test Results*

| **Lubricant** | **Temp (°C)** | **Lifetime (Cycles)** | **Start Lube Wt (mg)** | **End Lube Wt (mg)** | **% Wt Loss** | **Start Torque (in-oz)** | **End Torque (in-oz)** |
|---|---|---|---|---|---|---|---|
| *High Temperature Tests* | | | | | | | |
| X2000 | 110±5 | 2.4e4 | 15.9 | 5.3 | 67 | 3.2 | 20 |
| X2000 | 112±5 | 2.8e4 | 15.7 | 14.4 | 8 | 4.0 | 20 |
| Z25 | 115±5 | 2.7e5 | 21.6 | 6.3 | 71 | 2.0 | 20 |
| Z25* | 122±5 | 3.4e5 | 23.3 | 8.8 | 62 | 2.0 | 5.5 |
| *Low Temperature Tests* | | | | | | | |
| X2000* | 75±1 | 1.4e6 | 12.4 | 8.5 | 31 | 2.5 | 5.0 |
| X2000* | 75±1 | 1.4e6 | 11.2 | 8.8 | 21 | 3.0 | 2.0 |
| X2000 | 75±1 | 3.6e6 | 10.3 | 5.9 | 43 | 2.5 | 12 |
| X2000* | 75±1 | 4.9e6 | 11.5 | 8.5 | 26 | 2.5 | 3.0 |
| Z25 | 75±1 | 6.7e5 | 22.4 | 11.0 | 51 | 2.5 | 12 |
| Z25 | 75±1 | 7.5e5 | 30.8 | 17.7 | 43 | 2.5 | 12 |
| Z25 | 75±1 | 4.5e5 | 22.5 | 14.8 | 34 | 2.5 | 12 |
| X1000 | 75±1 | 1.5e6 | 10.5 | 5.6 | 47 | 2.2 | 12 |
| X1000* | 75±1 | 7.2e6 | 15.1 | 10.9 | 28 | 2.4 | 1.5 |

** Test suspended*

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**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

Bearing life tests in vacuum with three space liquid lubricants, two multiply alkylated cyclopentanes (MACs) and a linear perfluoropolyether (PFPE) were performed. Test conditions included: an 89 N axial load (mean Hertzian stress 0.66 GPa), vacuum level below $7\times10^{-4}$ Pa, and a ±30° dither angle. Dither rate was 75 cycles per minute. Higher (110 to 122 °C) and lower temperature tests (75 °C) were performed. For the higher temperature tests, the PFPE, Fomblin (Ausimont SpA) Z25 outperformed Pennzane (Shell Global Solutions) X-2000 by more than an order of magnitude. Lubricant evaporation played a key role in these high temperature results. At 75 °C, the order was reversed with both Pennzane X-1000 and X-2000 outperforming Fomblin Z25 by more than an order of magnitude. Most Pennzane tests were suspended without failure. The primary failure mechanism in these lower temperature tests was lubricant consumption in the tribocontacts.

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