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# Tribological Properties of a Pennzane®-Based Liquid Lubricant (Disubstituted Alkylated Cyclopentane) for Low Temperature Space Applications

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## Abstract

The tribological properties of a disubstituted alkylated cyclopentane, Pennzane® Synthesized Hydrocarbon Fluid X-1000, are presented. This compound is a lower molecular weight version of the commonly used multiply alkylated cyclopentane, Pennzane® X-2000, currently used in many space mechanisms. New, lower temperature applications will require liquid lubricants with lower viscosities and pour points and acceptable vapor pressures. Properties reported include: friction and wear studies and lubricated lifetime in vacuum; additionally, typical physical properties (i.e., viscosity-temperature, pour point, flash and fire point, specific gravity, refractive index, thermal properties, volatility and vapor pressure) are reported.

## Introduction

All spacecraft utilize mechanisms contain moving mechanical assemblies (MMAs) that require some form of lubrication to function properly [Jones and Jansen, 2000]. Lubricants include liquids, greases, and solids. These materials normally operate in ultrahigh vacuum. Therefore they must possess extremely low vapor pressure [Nguyen et al, 2001]. Most spacecraft are thermally compensated so that these lubricants only experience temperatures in the narrow range of 0 to +60°C. This allows conventional liquid and grease lubricants to be used. However, new spacecraft mechanisms are being designed that will operate at much lower temperatures (i.e.,–50 to 0°C). Most standard liquid lubricants possess very high viscosities in this temperature range, which would necessitate the use of large motors with high power requirements to maintain design torque margins. Therefore, lower viscosity liquid lubricants that still possess low volatility are needed.

Pennzane® Synthesized Hydrocarbon Fluid X-2000 (usually called Pennzane® fluid) is a multiply alkylated cyclopentane hydrocarbon that has desirable tribological properties for many space applications [Venier and Casserly, 1991; Venier, et al., 1992; Carré et al., 1995, Casserly and Venier, 1999]. A six year life test of a CERES bearing assembly using Pennzane® fluid has yielded excellent results [Brown et al., 1999]. Accelerated and operational life tests on bearings for the MODIS instrument have also been completed using a Pennzane® fluid formulation [VanDyk et al., 2001] and showed excellent results. Full scale bearing tests conducted at Lockheed Martin compared the performance of a formulated Pennzane® fluid X-2000 to Bray 815Z, a standard space lubricant, and showed Pennzane® fluid to have at least a 7 times life advantage over 815Z [Loewenthal et al., 1999]. Relative lifetime tests [Jansen et al., 2001; Jones et al., 2000] using the Spiral Orbit Tribometer (SOT) have also shown that unformulated Pennzane® fluid (X-2000) yielded the greatest relative lifetime compared to a series of space lubricants. Despite the excellent performance of Pennzane® X-2000, its high viscosity at low temperature (i.e., 80,000 cP at – 40°C) precludes its use under these conditions.

Pennzane® X-2000 is a member of the chemical class of multiply alkylated cyclopentanes or MACs [Venier and Casserly, 1991; Casserly and Venier, 1999]. It is predominately the tri-alkylated cyclopentane product prepared from 2-octyldodecanol, namely, tri-2-octyldodecyl cyclopentane. The disubstituted

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product (commercially called Pennzane® Synthesized Hydrocarbon Fluid X-1000, or simply X-1000) has now been produced. It has a more useful low temperature viscosity (29,000 cP at -40°C) and yet retains relatively low vapor pressure at room temperature.

The objective of this work is to compile some of the physical and tribological properties of interest to space mechanism designers for this disubstituted product (X-1000). Properties reported include: wear rates and relative lifetime in ultrahigh vacuum and typical physical properties (i.e., viscosity-temperature, pour point, flash and fire point, specific gravity, refractive index, thermal properties, vapor pressure and volatility).

## Physical Properties

The measured physical properties of bis(2-octyldodecyl)cyclopentane, Pennzane® X-1000, are given in Table 1 along with the corresponding properties of tris(2-octyldodecyl)cyclopentane, Pennzane® X-2000, and a linear perfluropolyalkylether (PFPAE). For the hydrocarbons, the properties reported were obtained by ASTM test procedures at the Pennzoil-Quaker State Technology Center, The Woodlands, TX, except that thermal conductivity, specific heat, and autoignition temperature were obtained from Phoenix Laboratories, Chicago, IL, and outgassing data from Ball Aerospace, Boulder, CO. The data for a linear PFPAE are from the literature.

Vapor Pressure

The vapor pressure of Pennzane® SHF X-1000 was calculated from the rate of effusion through a small orifice in a Knudsen cell. At 125°C, the vapor pressure is 6 x $10^{-6}$ Torr. Knudsen cell measurements [Nguyen and Jones, 2001] on a previous lot of X-1000 yielded a somewhat higher vapor pressure of 2.5 x $10^{-5}$ Torr at 100°C. However, extrapolated to 25°C, the vapor pressure is only about 3 x $10^{-9}$ Torr.

The very low vapor pressure and pour point (-52°C) of bis(2-octyldodecyl)cyclopentane, Pennzane® X-1000, are the same combination of properties that have made Pennzane® X-2000 so useful for lubrication in spacecraft. Taken together they define a wide, useful temperature range for X-1000 for vacuum applications.

Viscosity

The viscosity index of Pennzane® X-1000 is high (131) and the kinematic viscosity of 9.4 cSt at 100°C is less than might be expected from such a non-volatile fluid. In line with the low vapor pressure, bis(2-octyldodecyl)cyclopentane has a high flash point of 290°C (550°F).

Thermal Properties

The specific heat of bis(2-octyldodecyl)cyclopentane is 0.46 cal/gm at 30°C, about 10% lower than that of tris(2-octyldodecyl)cyclopentane. For temperatures between 30°C and 100°C, the specific heat is nicely linear with temperature, following the equation,

$$\text{Specific heat} = 0.453 + (0.155(^\circ C) \times 10^{-3})$$

The thermal conductivity of bis(2-octyldodecyl)cyclopentane at 30°C is 0.165 W/(m)(°K), very nearly the same as that of tris(2-octyldodecyl)cyclopentane, and about twice that of perfluoropolyether. The thermal conductivity of bis(2-octyldodecyl)cyclopentane at 100°C is 0.144 W/(m)(°K),

Optical Properties

The infrared spectrum of bis(2-octyldodecyl) cyclopentane is typical of a saturated hydrocarbon (Figure 1). It is colorless in the visible region and virtually transparent down to 300 nm in the ultraviolet region.

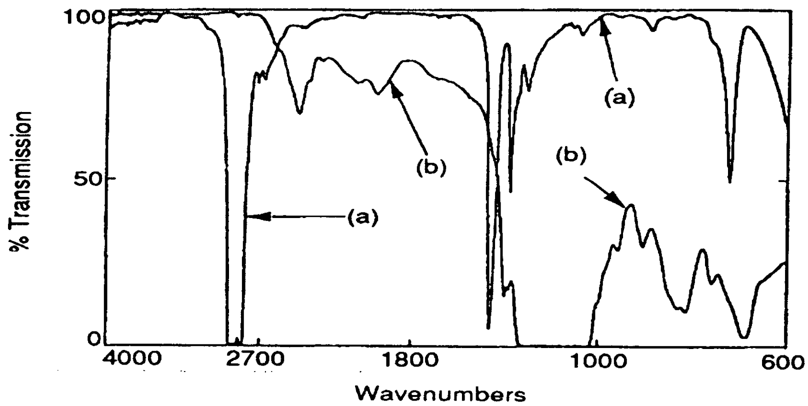


**Figure 1. Infrared Spectra of (a) bis(2-octyldodecyl)cyclopentane, and (b) perfluoropolyether**

## Tribological Properties

Vacuum Four Ball Tribometer

Figure 2 shows a tribometer developed at NASA Glenn Research Center based upon a four-ball configuration. It is designed to test the ability of liquid lubricants to reduce wear under pure sliding conditions at room temperature under a vacuum of at least $10^{-6}$ Torr. The system consists of a rotating ball sliding against three stationary balls that are immersed in a lubricant. The system is loaded though a pneumatic cylinder, which pushes the lubricant cup and stationary balls against the rotating ball. The lubricant cup is held in position by a flex pivot.

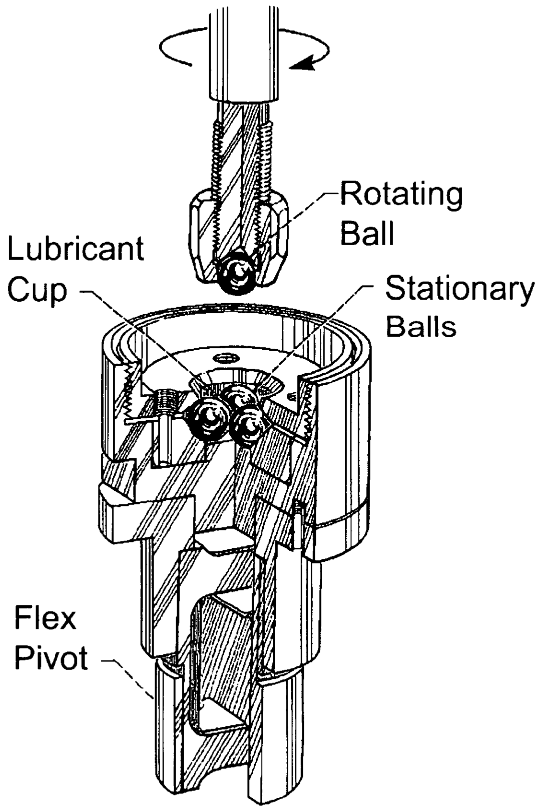


**Figure 2. Detail of four-ball apparatus**

Typical tests are run with 9.82 mm (3/8 in) diameter balls, 100 RPM, room temperature, and an initial Hertzian stress of 3.5 GPa. This stress drops as a function of test time as a wear scar develops on the stationary balls. The test is stopped every hour and the wear scar diameters measured. A special platform allows for the measurement of the wear scars without removing them from the cup [Masuko et al., 1994]. This allows the test to resume exactly where it was stopped. A full test takes 4 hours. Upon completion, the wear volume is plotted as a function of sliding distance and the wear rate is calculated from the slope of the line. This rig provides quick information about the wear characteristics of lubricants and additive packages to reduce metallic wear.

<u>Spiral Orbit Tribometer</u>
The spiral orbit tribometer (SOT), first introduced by Kingsbury [1989], is essentially a thrust bearing with flat races (plates) and a single ball (Figure 3). The tribometer simulates rolling, pivoting, and sliding as seen in an actual angular contact bearing. Accelerated tests are achieved by only using microgram quantities of lubricant on the ball. During the test, the lubricant is completely consumed by tribochemical attack, resulting in short test durations. The advantage of this type of acceleration is that operational test parameters, such as contact stress, speed, and temperature can mimic those in the actual application. Long lubricated lifetimes imply low lubricant consumption or low tribochemical degradation rates.

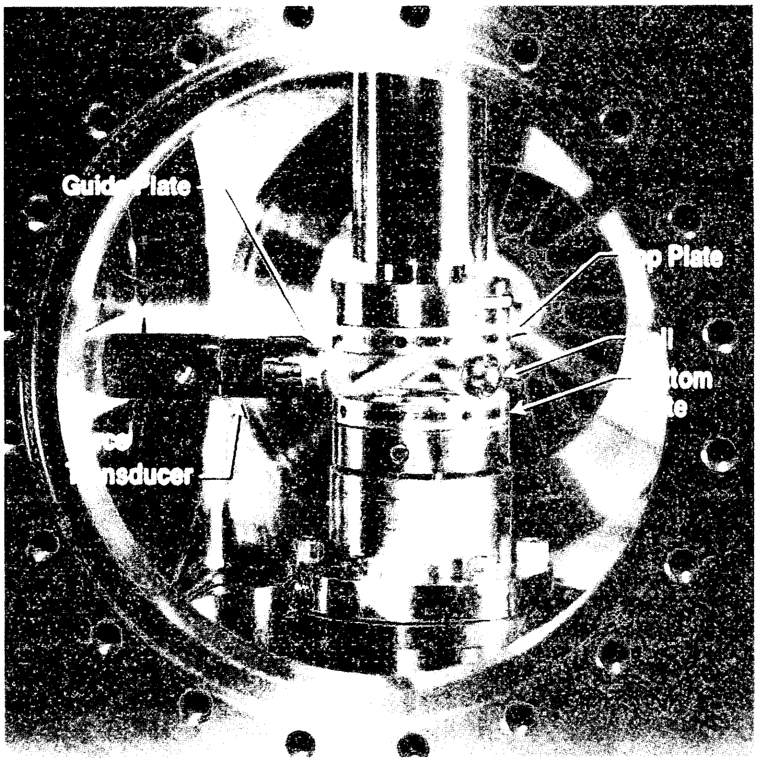

**Figure 3. The Spiral Orbit Tribometer**

The tribological elements of the system appear in more detail in Figure 4. 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. During every orbit, the ball contacts the vertical guide plate, which returns the ball to the original orbit radius. The straight-line region where the ball contacts the guide plate is denoted as the "scrub". The force the ball exerts on the guide plate during the scrub is measured and the coefficient of friction can be calculated. After leaving the scrub, the ball's spiral orbit begins again. The spiral orbit and scrub constitute a track 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 by Kingsbury, 1989 and Jones et al., 2000.

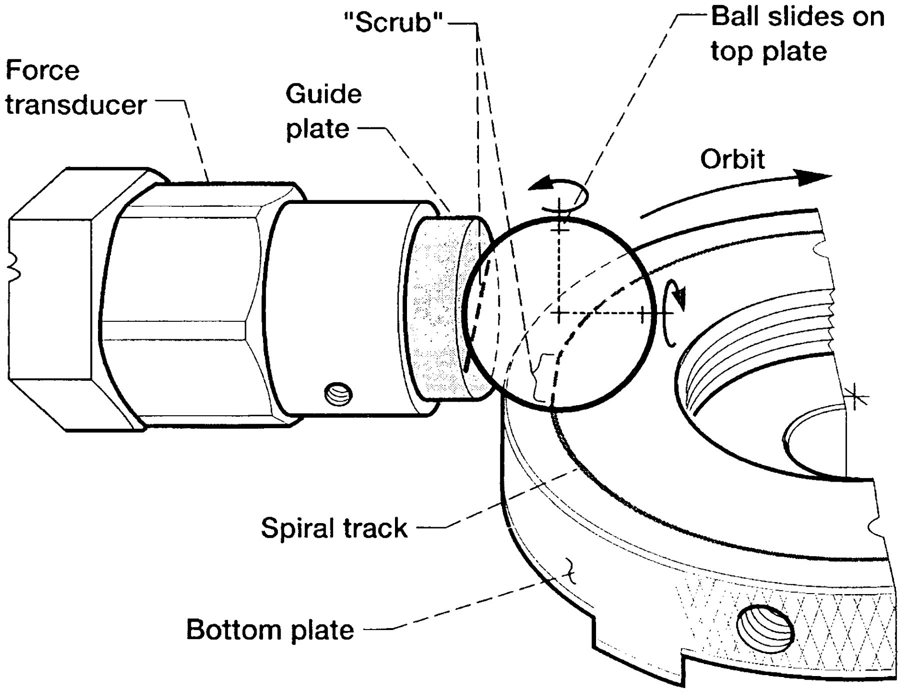


**Figure 4. Detail of the SOT**

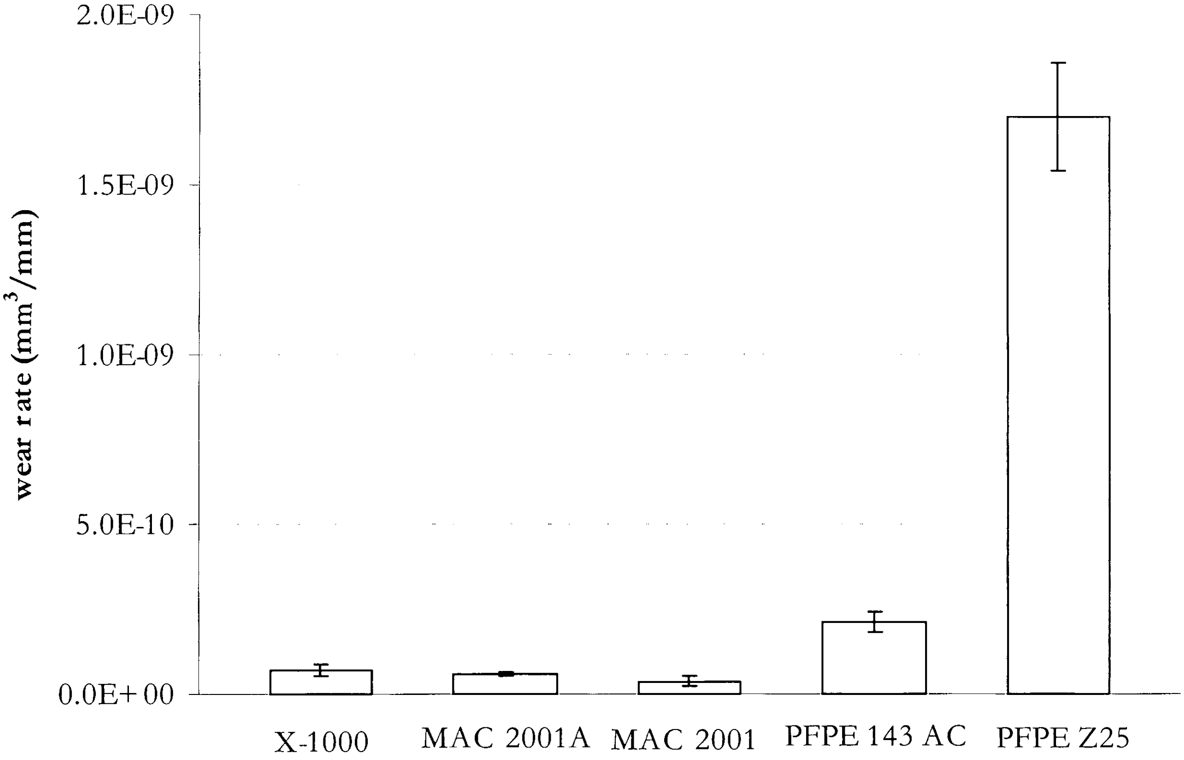


**Figure 5. Four-Ball Wear Rates for Several Lubricants**

**Table 1 - Comparative properties of Pennzane® SHF X-1000, Pennzane® SHF X-2000, and PFPAE**

| | Bis(2-octyldodecyl)-cyclopentane (X-1000) | Tris(2-octyldodecyl)-cyclopentane (X-2000) | PFPAE[(a)] 815Z |
|---|---|---|---|
| **Specific Gravity** | 0.85 | 0.85 | 1.85 |
| **Pour point** (°C) | -52 | -45 | -72 |
| **Refractive Index** (20°C) | 1.4682 | 1.4671 | 1.294 |
| **Vapor Pressure** | | | |
| 125°C (Torr) | $6 \times 10^{-6}$ | $4 \times 10^{-7}$ | $8 \times 10^{-8}$ |
| 40°C (Torr) | | $1 \times 10^{-12}$ | $3 \times 10^{-12}$ |
| **Vacuum Outgassing** (125°C, 24 hr, $10^{-5}$ Torr) | | | |
| **Total Wt. Loss** (%) | <0.4% | <0.2% | |
| **Condensables** (%) | 0.2% | <0.1% | |
| **Flash Point** (°C) | 290 | 315 | None |
| **Viscosity** | | | |
| 100°C ($mm^2$/sec) | 9.4 | 15.0 | 45 @ 99°C |
| 40°C ($mm^2$/sec) | 60 | 110 | 148 @ 38°C |
| -20°C (mPa•sec) | 3000 | 6200 | 1900 |
| -30°C (mPa•sec) | 8000 | | |
| -40°C (mPa•sec) | 29,000 | 80,000 | 6500 ($mm^2$/sec) |
| **Viscosity Index** | 131 | 135 | 350 |
| **Autoignition Temp** (ASTM E659) | | | |
| **Hot-flame** (AIT) | 750°F | | |
| **Cool-flame** (CFT) | 610°F | | |
| **Reaction threshold temp** | 485°F | | |
| **Thermal Conductivity** | | | |
| W/(m)(°K)@ 30°C | 0.165 | 0.16 | 0.08 |
| W/(m)(°K)@ 100°C | 0.144 | | |
| **Specific Heat (cal/gm)** | | | |
| @ 30°C | 0.458 | 0.52 | 0.20 |
| @ 100°C | 0.469 | | |

(a) Data from Castrol Industrial North America, Downers Grove, IL

## Results

Vacuum Four Ball Tribometer

The wear rate obtained with the unformulated X-1000 fluid appears in Figure 5 along with reference data for unformulated and formulated X-2000, as well as two commonly used unformulated perfluoropolyalkylethers (Krytox 143AC and Fomblin Z-25). The Z-25 is chemically identical to Brayco 815Z. The X-1000 has a similar wear rate compared to the X-2000 and significantly lower than the two perfluoropolyalkylether fluids.

Spiral Orbit Tribometer

The normalized lifetime for X-1000 at a mean Hertzian stress of 1.5 GPa appears in Figure 6. For comparison, results obtained previously with 440C steel specimens [Jones et al., 2001] are shown for unformulated and formulated X-2000, Krytox 143AC, and Brayco 815Z As can be seen, the X-1000 fluid performs better than the unformulated X-2000 fluid and is comparable to the formulated X-2000. In addition, its normalized lifetime is two orders of magnitude greater than 815Z and 30 times greater than Krytox 143AC.

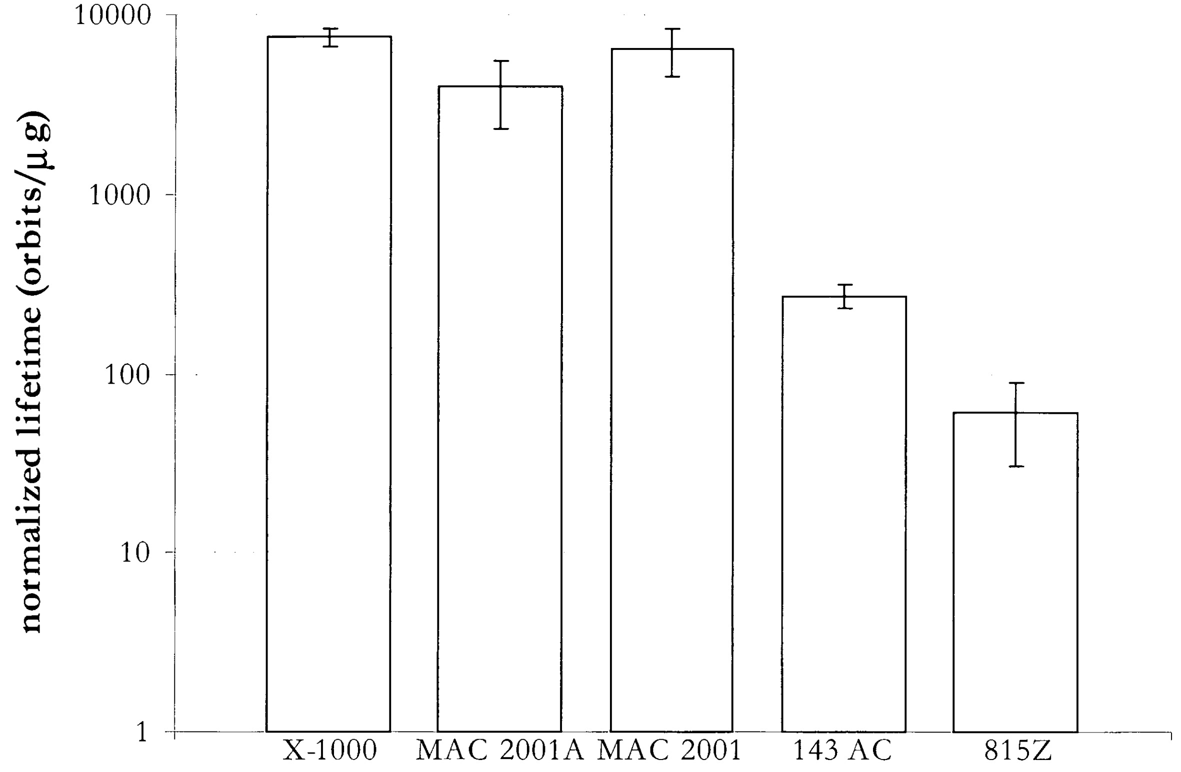


**Figure 6. Normalized lifetimes (orbits/μg) from the SOT**

## Conclusion

Pennzane® Synthesized Hydrocarbon Fluid X-1000, a lower molecular weight relative of Pennzane® SHF X-2000, has the expected lower viscosity and lower pour point. Although the volatility is greater, it still exhibits vacuum outgassing of less than 0.5%. In addition, it performs equally as well as X-2000 as a boundary lubricant in tribological testing (i.e., low metallic wear rates in pure sliding and low degradation rates in rolling contact).

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