Life of Scanner Bearings with Four Space Liquid Lubricants

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Abstract

The results of a life test program to evaluate bearing life with different space lubricants and cleaning solvents is presented. Thirty pairs of flight-like scanner bearings were tested over a period of seven years. Lubricants included two well known perfluorinated space oils (Brayco 815Z™ and Krytox 143AB™), a more recent synthetic hydrocarbon oil (Pennzane 2001™), and one yet to be in space service (silahydrocarbon oil). Bearings lubricated with Pennzane 2001 oil were found to have the longest lives. Life improvements up to 18X relative to perfluorinated oils and 3X relative to the silahydrocarbon oil were measured. No statistically significant life improvement was found with TiC-coated balls relative to standard plain steel balls for Penzanne 2001 bearings. Bearing life was generally longer when the bearings were cleaned with ozone-safe aqueous or hydrofluorocarbon (HFC) solvents as alternates to the discontinued CFC-113.

Introduction

Bearings for space applications have historically been cleaned with a chlorofluorocarbon CFC-113 (Freon) solvent until the early 1990's when the production of this ozone-depleting solvent was banned. The need arose to qualify alternate cleaners since bearing lubricant life was considered to be very sensitive to surface chemistry. A full-scale bearing life test program was initiated for NASA in April 1996 to evaluate three environmental-friendly cleaning solvents. The solvents included in this study were an aqueous-based cleaner (Brulin 815GD), a perfluorinated hydrocarbon (morpholine) solvent (3M PF-5052), and an HFC solvent (DuPont Vertrel XF). Intermediate test results previously reported [1, 2] showed bearing lives with these alternate cleaners were at least as long as those cleaned with the traditional CFC solvent. This was not consistent with earlier tests using a transient elastohydrodynamic apparatus in air, which indicated that bearing lifetimes might be compromised by some of the new cleaning techniques [3]. Later accelerated tests using a Spiral Orbit Tribometer in vacuum, however, yielded no detrimental effects on lubricant lifetime [4].

An equally important objective of the tests was to evaluate potential life improvements attended with improved space vacuum lubricants. Although extended mission lifetimes of many new space systems have driven the need to evaluate new flight lubricants, their acceptance is contingent on establishing an adequate life test database. The lubricants included in this study were traditional perfluorinated oils, which were compared with a relatively new multiply-alkylated cyclopentane oil (Pennzane 2001). At the time the intermediate test results were reported, the Pennzane 2001 bearing lives were much longer than those with the baseline perfluorinated oils and six of the eight Pennzane-lubricated bearings were still running. The present investigation reports the final life test results, with the addition of a new silahydrocarbon oil which has a good vapor pressure and good low temperature viscosity properties [5, 6]. The use of titanium carbide (TiC) coated balls as a means to increase bearing life over that of standard 440C stainless steel balls was also evaluated with Pennzane 2001.

Thirty pairs of flight-like scanner ball bearings were tested in a 10^{-6} Torr vacuum at ambient temperature in this current study. Periodic bearing health torque checks were performed, consisting of oscillations and

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continuous rotation patterns. Test acceleration factors included increasing the preload of each bearing pair by roughly a factor of three times from typical scanner bearings, reducing the amount of the lubricant to about one-third, and continuously cycling the bearings at a small stroke such that complete rewetting of the ball contact does not occur. At the time of this report, all but one pair of bearings had been tested to failure.

Test Description

Test Matrix

The original test series evaluated three different ODC-free bearing cleaning solvents against the CFC-113 (Freon) baseline. These consisted of an aqueous-based wash (Brulin 815GD), a perfluorinated hydrocarbon solvent (morpholine) from 3M (PF-5052), and a hydrofluorocarbon solvent from DuPont (Vertrel XF). A fourth solvent, heptane, was used in preparing the silahydrocarbon-lubricated bearings.

The baseline lubricant was Brayco 815Z™ oil, a perfluorinated polyalkylether (PFPE) linear fluid, currently distributed by Castrol Industrial North America. This oil has more flight history than any other class of space lubricant. The second test lubricant was a formulated multiply-alkylated cyclopentane (MAC) oil, generically referred to as Pennzane 2001™ and distributed by Nye Lubricants. This lubricant contained a triphenyl phosphate antiwear additive along with an antioxidant. The third test lubricant was a branched PFPE oil (Krytox 143AB™) manufactured by DuPont. The fourth and final test lubricant, a late addition to the test program, was a silahydrocarbon oil formulation. The molecular formula for this unimolecular silahydrocarbon base oil was $CH_3Si(CH_2CH_2Si(C_6H_{13})_3)_3$, with a molecular weight of 976 amu. This oil was synthesized and formulated by Nye Lubricants, with the same formulation as used in the Pennzane 2001. Originally developed by the Air Force for high temperature aircraft bearing applications, it has low vapor pressure and relatively low cold temperature viscosity making it a potentially good candidate for future space applications [5, 6]. Approximately one-third the normal amount of lubricant (60 to 80 mg of Brayco 815Z and 30 to 50 mg of the other test lubricants) was used in all test bearings, in order to provide for accelerated test results.

With the exception of the three pairs of silahydrocarbon-lubricated bearings, all of the solvent – lube combinations were tested in duplicate to provide greater confidence in the results. All test bearings were processed by the Miniature Precision Bearing (MPB) division of Timken, in order to represent end user application, again with the exception of those lubricated with silahydrocarbon oil. These latter test bearings were cleaned with heptane and lubricated at the Lockheed Martin facility with oil supplied by the Air Force Research Labs.

Test Bearings

The angular contact ball bearings used for test (Figure 1) were selected as representative of the type that would be used for a space scanner bearing application. The test bearings are 39.6-mm (1.56-in) bore by 50.8-mm (2.0-in) OD containing 34 balls of 3.2-mm (1/8-in) diameter. They were manufactured from AISI 440-C steel and hard preloaded back to back with 200 $\pm$ 22 N (45 $\pm$ 5 lb), resulting in a peak mean Hertz stress of 0.75 GPa (109 KSI). This preload provided additional test acceleration, in that it is approximately three times greater than that normally specified for this size bearing in a typical long-lived scanner application. The ball separators are alternating PTFE toroids. The races are finished to rms roughness of less than 0.08 microns (3 micro-inch). The test bearings had plain steel balls, except for a limited test series for two pairs of Pennzane-lubricated bearings where TiC-coated balls were tested. Further bearing specifications, including a highlight of differences between typical flight bearings and those used for life test are presented in Table 1.

Figure 1. Test bearing with toroid ball separators

Table 1. Angular Contact Ball Bearing Parameters

Parameter	Typical Flight Bearing	Life Test Bearing
Type	Angular Contact, Duplex, Tube Type	Same
AFBMA Precision	ABEC Grade 7 or Better	Same
Mount	Back-to-Back	Same
Bore x OD x Width	39.6875 x 50.8 x 6.35 mm (1.5625 x 2.000 x 0.250 inch)	Same
Preload	**67 ± 9 N (15 ± 2 lb)**	**200 ± 13 N (45 ± 3 lb)**
Max. Contact Stress	**758 MPa (110 ksi)**	**1130 Mpa @ 200 N (164 ksi @ 45 lb)**
Ball Number / Diameter / Grade	34 balls / 3.175 mm (0.125 inch) diameter / Grade 3	Same
Contact Angle	20 ± 3 deg	Same
Race Conformity	52 to 53%	Same
Lubricant	**Grease**	**Oil**
Angular Runout, pair	< 20 arcsec	Same
Radial Runout, pair	< 152 nm (60 microinch) (non-repeat < 100 (40))	Same
Lube Weight per Row	**160 – 190 mg (≈15% fill)**	**30 – 50 mg[1]**
Race Material	AISI 440-C per AMS 5630 (ESR)	Same
Ball Material	AISI 440-Cper AMS 5618 (CEVM)	Same
Ball Treatment	**Passivated**	**Same & TiC Coating**
Toroids	PTFE, alternating	Same
Running Torque Variation	± 20% max.	Same
Max. Weight per Pair	54 g (0.12 lb)	Same

[1] 60 to 80 mg for Brayco 815Z

Test Conditions

The bearing pairs were mounted into a cartridge and then hard preloaded, with the inner bearing races clamped on a geared shaft (Figure 2). The cartridges were then installed into one of Lockheed Martin's 45.7-cm (18-inch) diameter vacuum bell jar life test stations (Figure 3), which was then pumped down to 10^{-6} Torr range. A computer controlled motor located external to the bell jar drives a central bull gear, which in turn drives up to twelve test bearing pairs concurrently. The outer bearing cup is mounted in flexures, so that the bearing's torque can be measured via the test computer using a strain gaged torque reaction element.

The bearings were continuously cycled at a stroke of ± 12 degrees at a speed of 2.5 cycles per second. The stroke does not allow for complete rewetting of the contact, being slightly greater than the inner race ball track overlap but less than one complete ball rotation. Periodic functional tests were performed approximately every five million cycles, in order to ascertain bearing health. During these functional tests, the bearing oscillation was stopped and the bearings were immediately rotated three revolutions in each direction at a rate of 60 deg/s. The resulting torque signature was plotted for comparison with prior health check results.

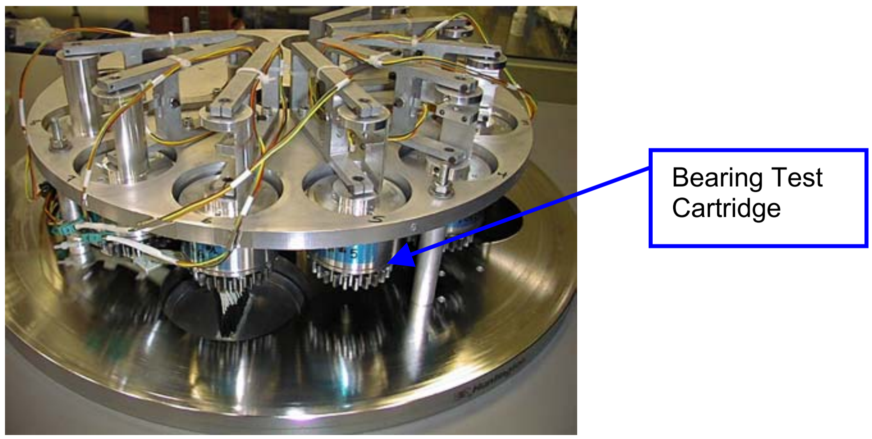

Figure 2. Bearing life test fixture with individual strain gaged bearing cartridges

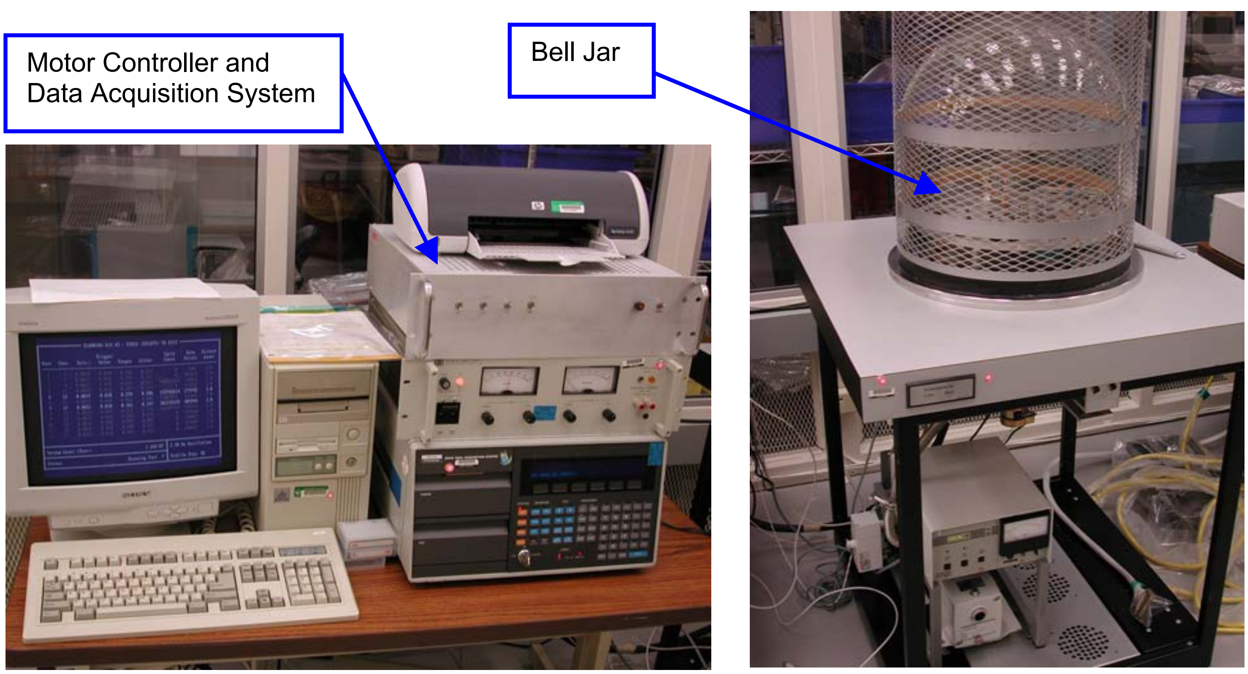

Figure 3. Bearing Life Test Setup

Results

The torque was observed to be extremely stable for typically more than 90% of the life for each pair of bearings. As an example, the torque trace of a Pennzane-lubricated bearing just after being installed into the fixture (Figure 4) is nearly identical to the trace measured after 453 million cycles (Figure 5). Note the transition from the constant test oscillation to the constant rotation pattern used only during health checks.

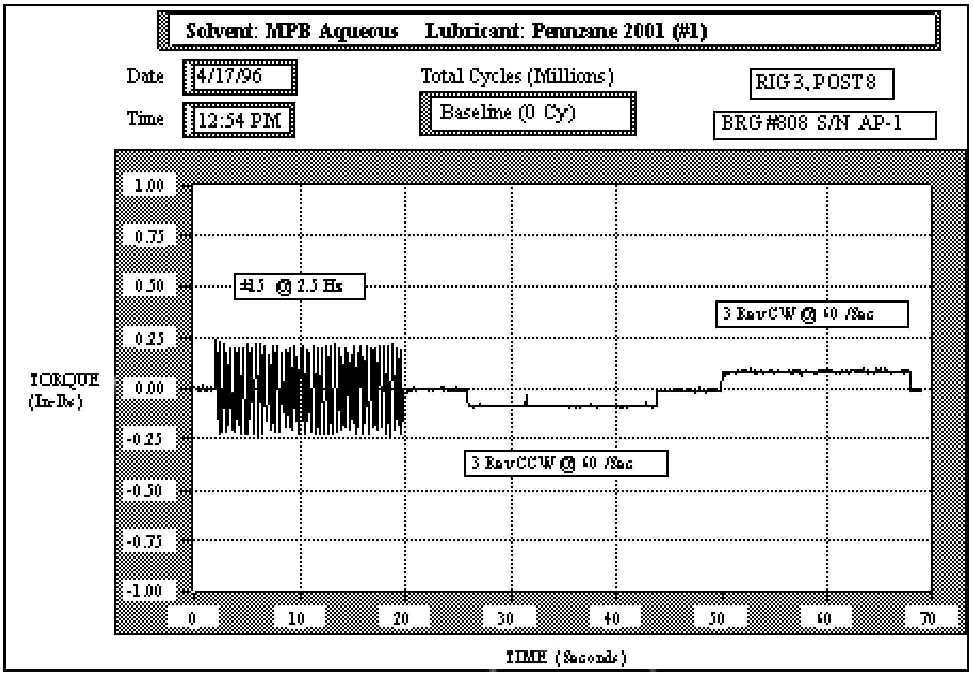

Figure 4. Pennzane 2001 Bearing Torque Trace at 0 cycles

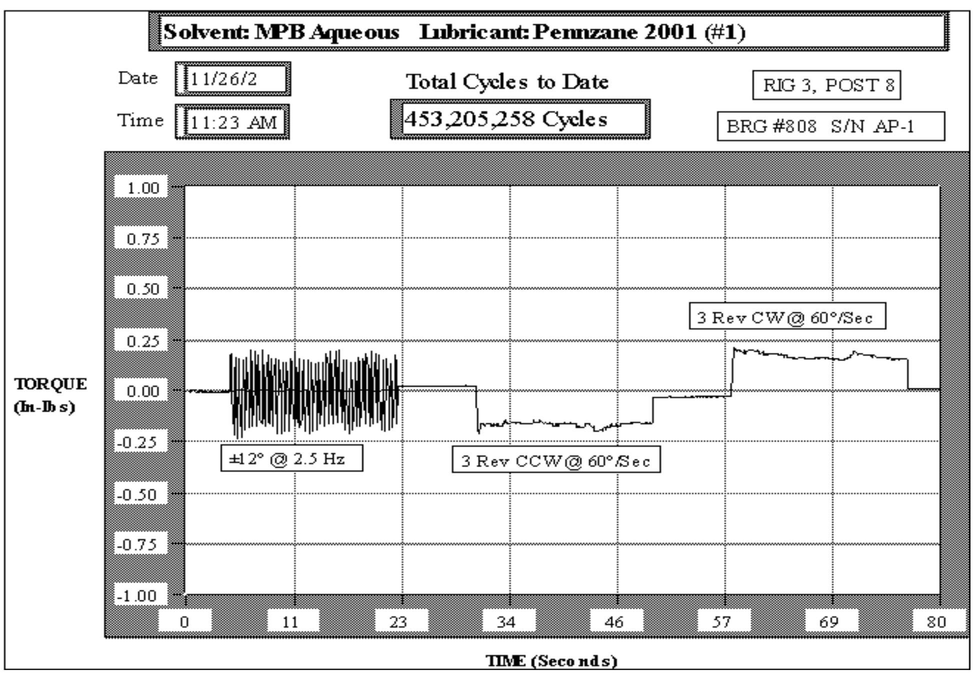

Figure 5. Pennzane 2001 Bearing Torque Trace at 453M cycles

There are two indicators of lubricant degradation observable in a bearing health check torque signature. The first, and more noticeable, is the development of torque bumps during the transition from oscillations to continuous rotation (Figure 6). This is an early indicator of lubricant breakdown for bearings operating in a gimbaling motion. Debris mounds form at the end of each stroke as the back and forth motion over one spot on the bearing race continuously stresses the lubricant without the ability to bring “fresh” oil into contact. The result is small amounts of lubricant being degraded into a sludge-like friction polymer (Figure 7). Eventually this leads to torque bumps, when the stroke is increased. Subsequent roll-overs cause the balls to break through this buildup, which helps smooth out the torque. Bearing failure is considered to occur when the torque reaches three to four times the starting steady state torque. The other indicator of bearing degradation is increased average torque and torque hash (high frequency noise) during the constant rotation portion of the torque test. This occurs in a later stage of lubricant degradation. Note the marked change in torque signature between Figures 5 and 6 in just 20 million cycles (5% life).

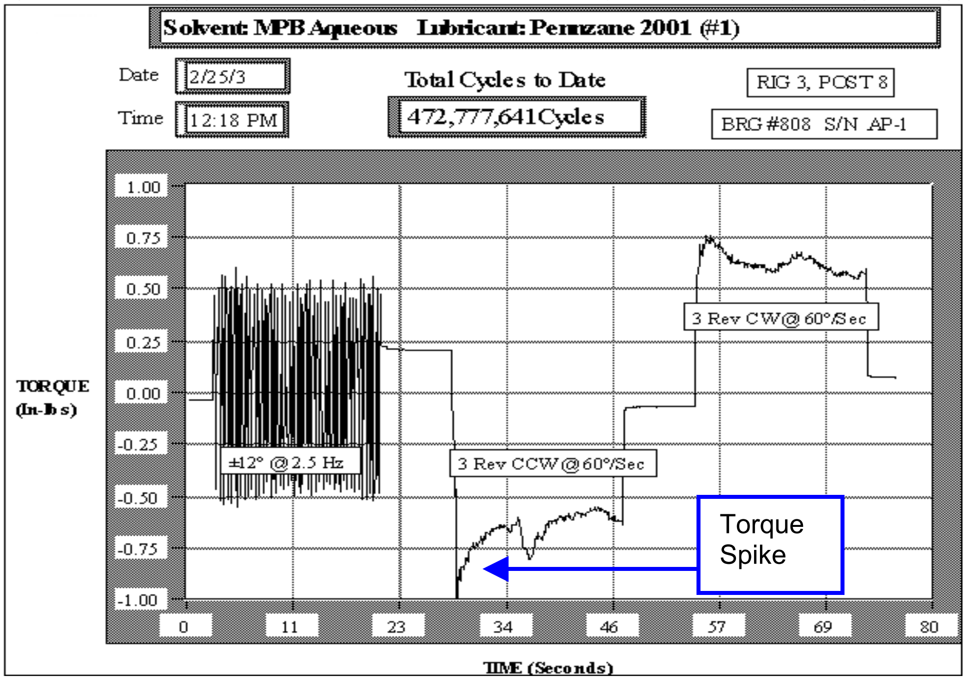

Figure 6. Pennzane bearing torque trace approaching failure. Note torque spike of > 1 in-lb from debris bump at transition to 3 revs of continuous rotation

Figure 7. Typical Bearing Lubricant, Post-Failure

Summary of Results

The cumulative test results are summarized in Table 2. These results show that bearings lubricated with Pennzane 2001 oil had the longest life. It is clearly superior to the other lubricants, independent of solvent cleaner. Average life was extended by a factor of approximately 9X when compared to those bearings lubricated with Brayco 815Z. The results also show that Krytox 143AB offered no life improvement relative to Brayco 815Z. The silahydrocarbon lubricant extended average life by 2.8X. A similar ranking of lubricants was obtained using a Vacuum Spiral Orbit Tribometer [7] where a silahydrocarbon relative lifetime was much greater than Brayco 815Z or Krytox 143AC lubricants but clearly not as good as Pennzane 2001.

The introduction of TiC-coated balls showed no statistical significant life improvement relative to the standard 440C stainless steel balls for the Pennzane-lubricated bearings (note that one of the TiC test bearings is still under test, currently at 386 million cycles). Similar results were found by Jansen et. al [8].

As shown in Figure 8, the three environmental-friendly cleaning solvents performed generally better than Freon 113. Heptane was used to re-clean the bearings prior to lubricating with the silahydrocarbon lubricant. It also showed performance as good or better than Freon 113. The variations in life are mainly due to the test lubricant.

Table 2. Summary of Results – Bearing Life, Million Cycles

	Lubricant				
Solvent	Brayco 815Z	Krytox 143AB	Pennzane 2001	Pennzane TiC Balls	Silahydro-carbon
Freon -113	10.1	9.0	265.5	-	-
Freon -113	12.6	40.0	118.5	-	-
Brulin 815GD	15.0	30.2	481.5	385.8 SR[2]	-
Brulin 815GD	35.6	60.0	165.8	141.0	-
3M PF-5052	40.5	29.4	409.0	-	-
3M PF-5052	33.1	-	372.0	-	-
DuPont Vertrel XF	26.1	-	360.0	-	-
DuPont Vertrel XF	108.2	-	349.0	-	-
Heptane	-	-	-	-	131.0
Heptane	-	-	-	-	110.9
Heptane	-	-	-	-	62.8
Average Life	**35.2**	**33.7**	**315.2**	**263.4**	**101.6**
Ave. Life Factor	**1.0**	**1.0**	**9.0**	**7.5**	**2.9**
L10 Life	**7.3**	**8.2**	**131.0**	**-**	**47.0**
L10 Life Factor	**1.0**	**1.1**	**17.9**	**-**	**6.4**

[2]SR = Still Running

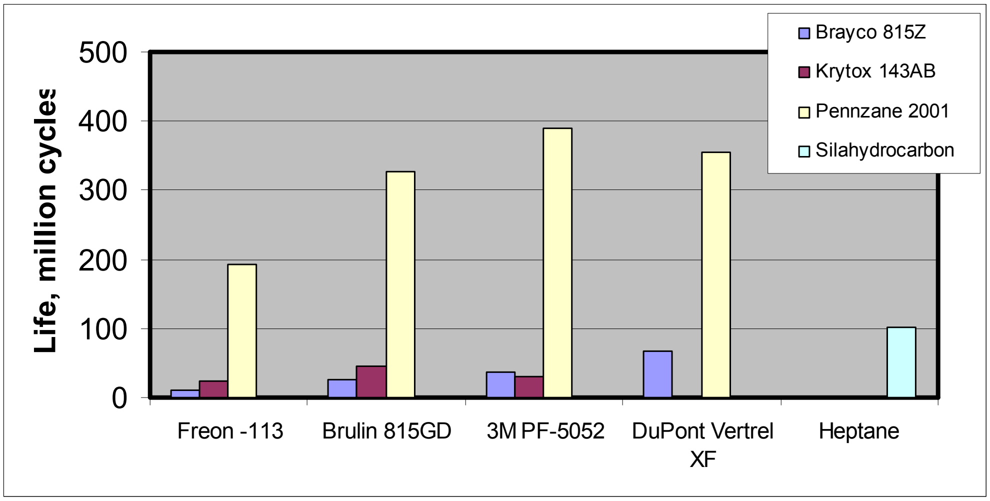

Figure 8. Effect of Cleaning Solvent on Average Bearing Life

Weibull analysis was performed on the test bearings to show the effects of reliability on measured life, Figure 9. The L10 lives (90% reliability) of the four test lubricants are shown in Figure 9. At the L10 level the life advantage of Pennzane 2001 relative to Brayco 815Z or Krytox 143AB is approximately 16 to 18 fold (see Table 2). The silahydrocarbon-lubricated bearings enjoyed about a 6X life advantage at 90% reliability.

Bearings lubricated with the four test oils exhibited similar failure distributions, i.e., Weibull slope. Life differences between Krytox 143AB and Brayco 815Z lubricated bearings are not statistically significant.

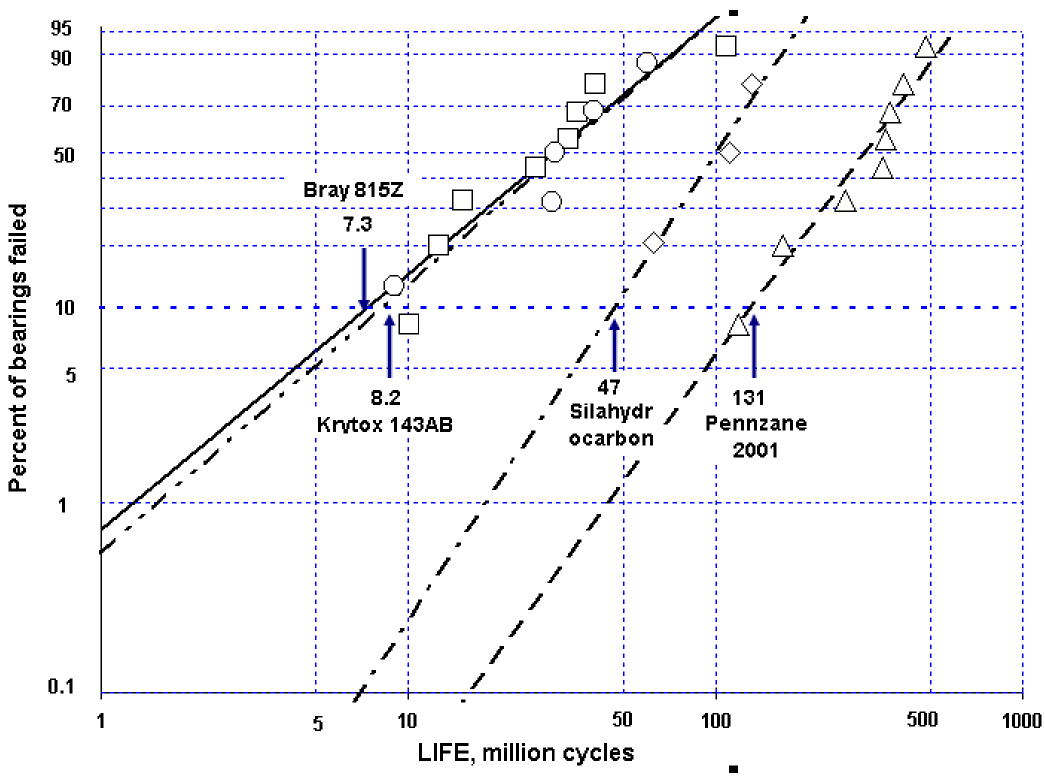

Figure 9. Weibull Analysis of Bearing Life

The life results presented above were affected by bearing test acceleration factors as noted. These factors include higher than normal preloads, less lubricant than normal, and nearly continuous dither over the same spot on the raceway. Flight bearing life under less severe conditions may actually be greater than that reported in this study.

Conclusions

The seven-year bearing life test program supports the following conclusions:

1. Pennzane 2001 lubricated bearings provided a 9X average life improvement relative to either the Brayco 815Z or Krytox 143AB lubricated bearings. The L10 life improvement was 16 to 18 times.

2. Krytox 143AB showed comparable life to the baseline Brayco 815Z lubricated bearings.

3. A silahydrocarbon lubricant produced an L10 bearing life that was about 6X greater than that with Brayco 815Z or Krytox 143AB.

4. TiC-coated balls did not offer a life advantage over 440C stainless steel balls for the Pennzane 2001 lubricated bearings.

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