Life of Pennzane and 815Z–Lubricated Instrument Bearings Cleaned With Non-CFC Solvents

By
Stuart Loewenthal[*], William Jones[†], and
Roamer Predmore[‡]

SUMMARY

Bearings used in spacecraft mechanisms have historically been cleaned with chlorofluorocarbon CFC-113 (Freon) solvents and lubricated with a perfluorinated polyalkylether (PFPE) oils like 815-Z. Little full-scale bearing life test data exists to evaluate the effects of the newer class environmental-friendly bearing cleaners or improved synthetic hydrocarbon space oils like Pennzane.

To address the lack of data, a cooperative, bearing life test program was initiated between NASA, Lockheed Martin and MPB. The objective was to obtain comparative long-term, life test data for flight-quality bearings, cleaned with non-CFC solvents versus CFC-113 under flight-like conditions with two space oils. A goal was to gain a better understanding of the lubricant surface chemistry effects with such solvents. A second objective was to obtain well-controlled, full-scale bearing life test data with a relatively new synthetic oil (Pennzane), touted as an improvement to Bray 815Z, an oil with considerable space flight history.

Test Matrix

The lubricants selected for study included Bray-815Z oil, a perfluorinated polyalkylether (815Z) fluid and a Multiply alkylated cyclopentanes (Pennzane) oil. PFPE oils have more flight history than any other class of space lubricant, while the Pennzane fluids are just beginning to enter space service.

The test bearings were selected to be representative of the type that would be used for a space scanner bearing application. The bearings were better than a class 7T torque tube instrument bearing. Angular contact, ball bearings were hard preloaded back to back with 45 + 5 lb. hard preload resulting in a maximum Hertz stress of 163 ksi (or mean stress of 108 ksi). This preload is approximately 3 x higher than what might be expected for this bearing in a typical long-lived scanner application.

The test bearings were cycled ± 12 degs at a speed of 2.5 cycles per sec under a 10^{-6} torr vacuum installed into Lockheed's computer controlled, vacuum bell jar life testers and pumped down to range. Bearing torque and torque ripple were continuously monitored over the simulated scanner. To improve the statistical significance of the results, each solvent - lube combination was tested twice in repeated test bearings. Thus a total of 16 test bearings were life tested for the 4 solvents and 2 oils.

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This paper add data to the attached paper that was published

Summary of Results

Life test torque history data for the various solvent-lubricant combinations have been collected over the past 15,000 hours. Example torque traces for the baseline Freon-cleaned bearings at both test start and 26 M cycles appears in Fig. 1. At 26M cycles the 815Z bearings show a clear failure torque signature while the Pennzane bearing torque signature is unchanged.

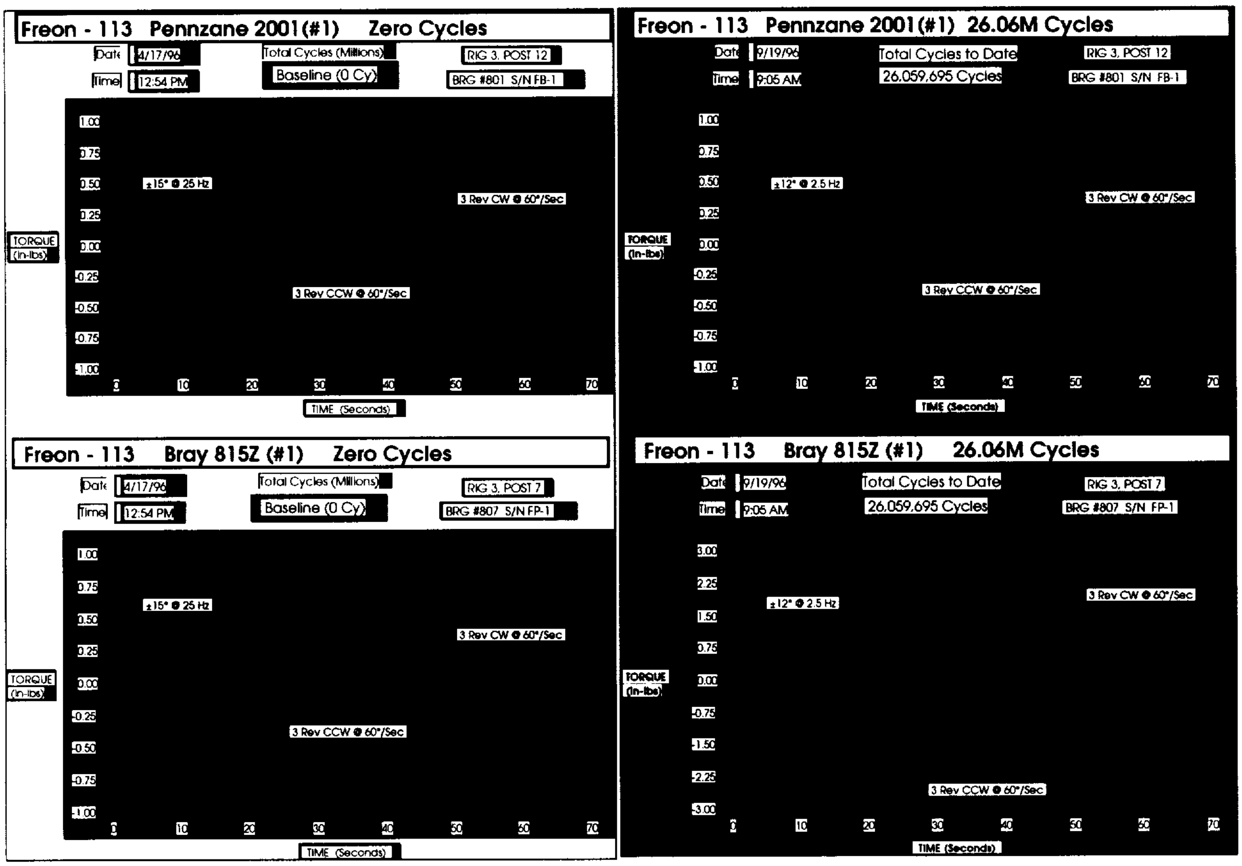

Fig. 1 Freon 113 Traces at Start & 26 M Cycles

A summary of approximate cycles to failure can be found in Fig. 2. The alternate cleaning solvent bearings shows lives equal to or better than the Freon baseline bearings. An indication that no deleterious effect can be expected with the switch to environmentally friendly bearing solvents.

Fig. 2 shows that seven of the eight 815Z- lubricated bearings had failed by about 50 million cycles while all but one of the Pennzane-lubricated bearings have survived 170 million cycles with 6 test bearings still sowing good torque performance. This represents a 3 to 7X life advantage relative to the Bray 815Z bearings, depending on the particular solvent.

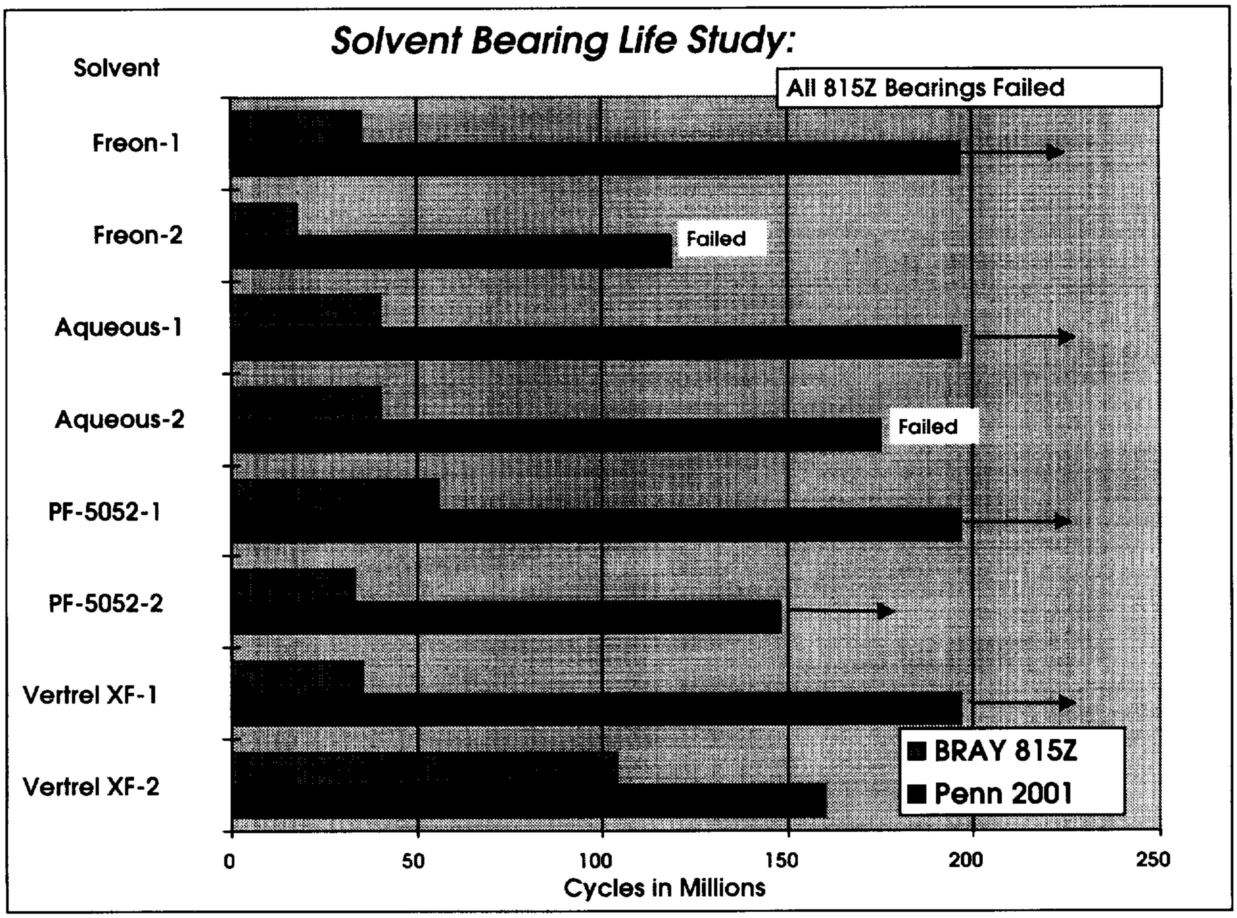

Fig. 2 Test Life Summary

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ATTACHMENT

Instrument Bearing Life With Non-CFC Cleaners

by

Stuart Loewenthal*, William Jones†, Jeffrey Grout‡,
Roamer Predmore§ and Robert Thom**

SUMMARY

Accelerated bearing life tests were conducted to evaluate the effects of ODC-free bearing cleaning solvents as a replacement to CFC-113. Three chemically different, ODC-free cleaning solvents were tested against the CFC-113 baseline. Test bearings were representative of the type that would be used for a space scanner bearing application. The bearings were lubricated with two space flight oils.

Lives with the replacement solvents exceeded those obtained with CFC-113 baseline. Pennzane-lubricated bearings enjoy a 2 to 6X life advantage over those lubricated with Bray 815Z oil.

BACKGROUND

Bearings used in spacecraft mechanisms have historically been cleaned with a chlorofluorocarbon CFC-113 (Freon) solvent. Most space bearing applications are very sensitive to lubricant surface chemistry. This is not only due to the harsh environment of space, but because of the need to provide low, consistent torque for many years of service while operating primarily in the boundary lubrication regime. Oscillatory scanner, chopper and pointing mechanism bearings exemplified such demanding requirements. Although environmentally friendly, non-CFC solvent replacements have shown their ability to clean as well as CFC-113, little well-controlled life test data is available to judge their long term effect on bearing life. Oddly, the concern is not that these replacement solvents fail to clean well enough, but rather that they may clean too well and thus increase the lubricant's chemical reactivity with the bearing surfaces.

To address these concerns, a cooperative, bearing life test program was initiated between NASA, Lockheed Martin and MPB. The objective was to obtain comparative long-term, life test data for flight-quality bearings, cleaned with non-CFC solvents versus CFC-113 under flight-like conditions with two space oils. A goal was to gain a better understanding of the lubricant surface chemistry effects with such solvents. A second objective was to obtain well-controlled, full-scale bearing life test data with a relatively new synthetic oil (Pennzane), touted as an improvement to Bray 815Z, an oil with considerable space flight history.

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Test Matrix

Three chemically different, ODC-free cleaning solvents were tested against the CFC-113 baseline (see Table I). These included an MPB proprietary aqueous based wash based on Brulin 815GD, a perfluorinated hydrocarbon solvent from 3M (PF-5052) and a hydrofluorocarbon solvent from Dupont (Vertrel-XF).

The lubricants selected for study included Bray-815Z oil, a perfluorinated polyalkylether (PFPE) fluid. PFPEs have more flight history than any other class of space lubricant, used in a multitude of space mechanisms over the past 25 years. They have outstanding cold temperature performance with extremely low outgassing. However, they lack the ability to accept antiwear additives (Refs. 1,2). They also have a tendency to polymerize under the presence of high shear stress and temperature with ferrous based bearing materials (Refs. 3-5) at levels that are uncommon for most space applications. However, this chemical reactivity eventually limits their life for demanding boundary lubrication applications, such as scanner bearings.

Multiply-alkylated cyclopentanes (MAC) are a relatively new class of space oils that are candidates to replace PFPE space oils. These oils also enjoy excellent vapor pressure characteristics, moderate cold temperature performance and, unlike PFPE's, can accept anti-wear additives (Ref. 6). Since the current additives (phosphates) formulated with these oils are quickly (days) depleted in the presence of a space vacuum, it is not clear as to their long term benefit. A number of accelerated wear test studies have been published (Refs. 7, 8) comparing the wear rates obtained with MAC and PFPEs. However, the authors are unaware of full scale bearing tests that directly compare their lives under the same test conditions. Furthermore, it was suspected that the MAC oil would be less sensitive to solvent-surface chemistry since it didn't have the PFPE's chemical reactivity. On the otherhand, MAC's were found in Ref. 9 to be unable to properly wet 440-C bearing steel as used in our test bearings. Therefore, because of these questions, a MAC oil, generically referred to Pennzane 2001, manufactured by Nye, Inc under the trade name Rheolube 2001, was added to the test matrix.

To improve the statistical significance of the results, each solvent - lube combination was tested twice in repeated test bearings. Thus a total of 16 test bearings were life tested for the 4 solvents and 2 oils.

Table I Test Matrix

SETS	SOLVENT	OIL
2	Freon-113	Bray 815Z
2	Aqueous	Bray 815Z
2	PF-5052	Bray 815Z
2	Vertrel-XF	Bray 815Z
2	Freon-113	Pennzane 2001
2	Aqueous	Pennzane 2001
2	PF-5052	Pennzane 2001
2	Vertrel-XF	Pennzane 2001

All of the test bearings were processed by MPB per a standard LMMS specification typical for space flight bearings. Cleaning and lubrication was done at MPB rather than LMMS in order to better represent what a space bearing user might expect.

All bearing components were pre-cleaned through MPB's normal process where maching oils were removed with either mineral spirits or aqueous cleaning. The 440-C components were then acid passivated, and washed with their respective test solvent. Those bearings cleaned by the aqueous method were first ultrasonicaly cleaned in Brulin 815GD, then ultrasonically rinsed in high purity deionized water and finally dried with NEPA filtered hot air. Those cleaned in the other solvents were first sloshed in the specified solvent and then ultrasonically cleaned. Bearings cleaned in PF-5052 and Vertrel-XF were initial pre-cleaned in reagent grade Heptane since these solvents don't adequately remove many organic contaminants such as machining oils.

A wettability check was performed to identify any beading problems. The bearings were than assembled, given a final test solvent wash until cleanliness level of better than 200 per MIL-STD-1246A was achieved.

All bearings were given a 10X to 20X visual examination prior to lubrication. The bearings were lubricated with either 60 to 80 mgs of Bray 815Z oil or 30 to 50 mgs of Pennzane 2001 oil to provide the same volume oil fill amounts on the order of 3.5%. This fill amount was deliberately selected to be meager to help accelerate the tests. A predicted oil film thickness for these bearings are about 300 micro inches based on wetted area.

Test Bearings

The test bearings were selected to be representative of the type that would be used for a space scanner bearing application. The bearings were better than a class 7T torque tube instrument bearing. Their geometry is given in Table II. Angular contact, ball bearings were hard preloaded back to back with 45 + 5 lb hard preload resulting in a maximum Hertz stress of 163 ksi (or mean stress of 108 ksi). This preload is approximately 3 x higher than what might be expected for this bearing in a typical long-lived scanner application.

The bearing races are fabricated from AISI-440-C steel. The ball separators are alternating PTFE toroids. The races are finished to a rms roughness of less than 3 micro-inch.

Vendor acceptance tests include:
- preload
- actual bore/OD measurements
- surface finish
- race transverse curvatures
- lubricant weight
- running torque

Table II Bearing Geometry

• Angular Contact, Duplex
• 2532 size
•1.563 x 2.00x 0.25 inch
• Class 7T Precision
• 20 ° Contact Angle
• 34 balls (0.125 in)
• Conformity 0.525

Test Conditions

The bearing pair were mounted into a bearing cartridge and then hard preloaded. The cartridges were then installed into Lockheed's computer controlled, vacuum bell jar life testers and pumped down to 10^{-6} torr range. Twelve pairs of bearings were tested concurrently. Bearing torque and torque ripple were continuously monitored over the simulated scanner cycle of ± 12 degs. The stroke of ± 12 degs is slightly greater than the inner race ball track overlap but less than one complete ball rotation. This provides a harsh lubrication condition of 4 inner race ball contacts per cycle but no benefit of wide sweep - rewetting of the contact. A test cycle speed of 2.5 cycles per second was selected as a compromise between test time and operation primarily in the boundary lubricating mode (that is a lambda ratio of less than one where lambda is the ratio of elastohydrodynamic film thickness to composite surface roughness.

The bearings were continuously tested in this oscillatory mode. Periodic functional tests were performed as health checks. During these functionals, the bearing oscillation was stopped and the bearing immediately rotated 3 revolutions in each direction at 60 deg/sec. Normally the first sign of torque degradation occurs during the transition from oscillation to continuous rotation due to debris that has formed at end of stroke. This debris gives rise to a noticeable torque bump. Failure is considered to occur when a significant rise in torque occurs of between 3 to 4X the bearings starting torque.

Discussion of Results

Examples of functional bearing torque traces appear in Figs. 1 through 3. These traces were taken at approximately 2.5 million cycle intervals early in the test and later

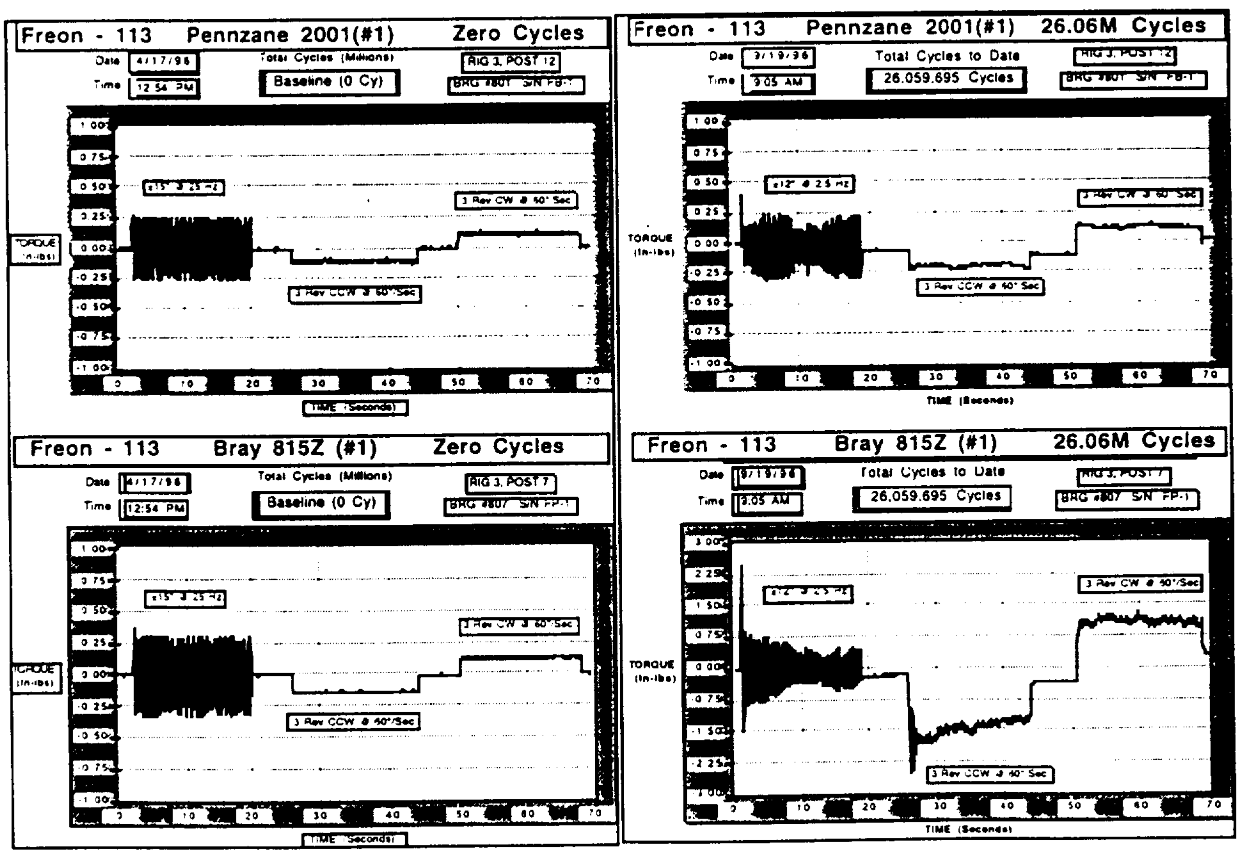


Fig. 1 Freon 113 Traces at Start & 26 M Cycles

at 5 million cycle intervals. As illustrated in Fig. 1, the torque trace consisted of a 15 to 20 second period of the oscillatory life test cycle followed by 3 revs of the bearing at 60 deg/sec in each direction.

Starting and 26 M cycle torque traces for the baseline-based Freon cleaned bearings with Bray 815Z oil appears in Fig. 1. Large (2.25 in-lb) failure torques for the 26 M cycle 815Z bearings are apparent from the lower right hand plot. (Note that the Y-scale has been increased by a factor of 3X). The dramatic torque rise immediately following oscillations are characteristic of degraded lubricant gimbal bearings. This torque "bump" is an artifact of the balls rolling over the debris that has accumulated at the end of stroke. One can also see that the torque levels (neglecting the small zero offset) with the Freon-Pennzane bearing are relatively still well-behaved at the 26 M cycle point.

In the case of the Aqueous and PF-5052 solvents, torque is elevated for the 815Z bearings at the 45 to 50 M cycle point (see Fig. 2), but once again stable for the Pennzane bearings. It is worth noticing that PF-5052/815Z bearing trace is not seriously degraded at 45 M cycles unlike the Freon cleaned bearing at 26 M cycles as discussed in Fig. 1.

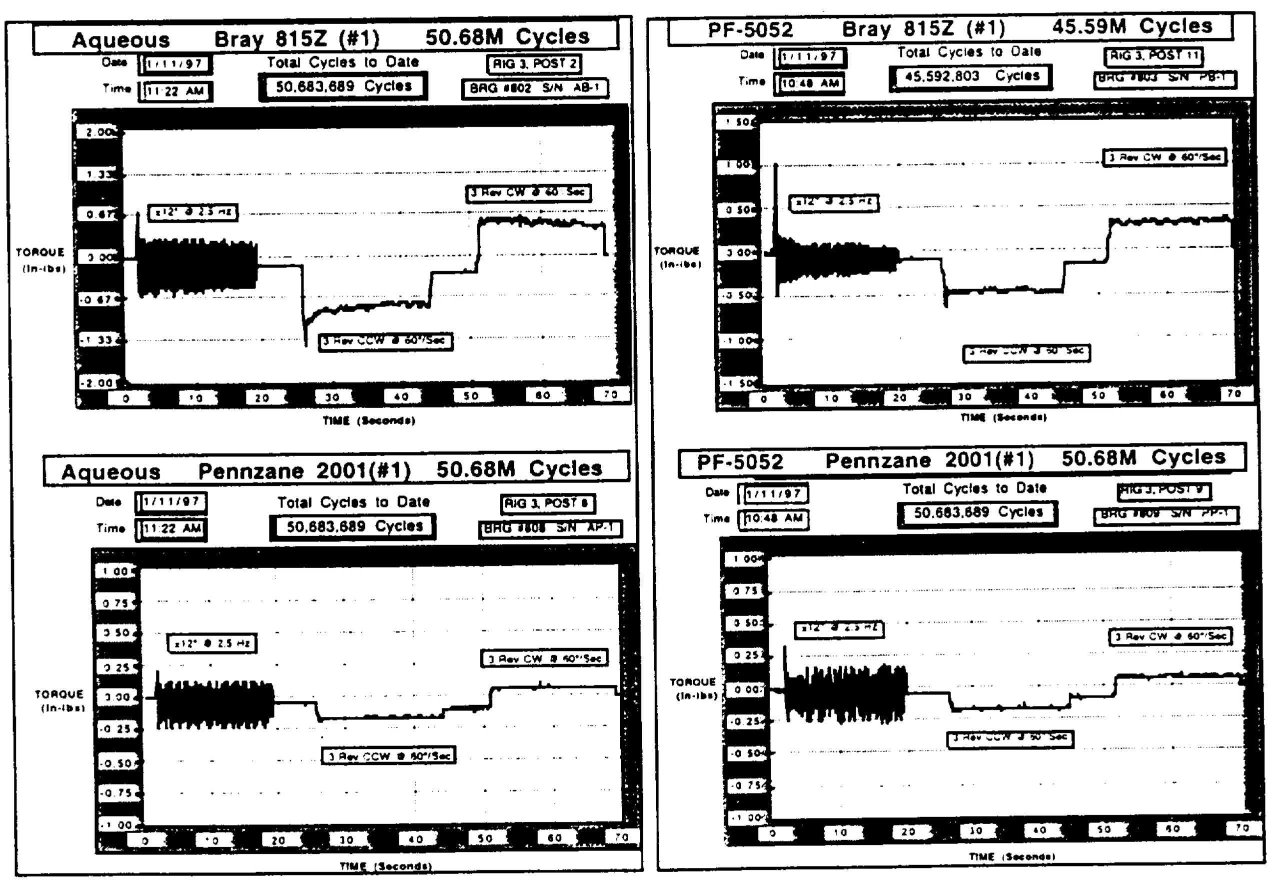


Fig. 2 Aqueous & PF5052 Traces at 50 M Cycles

The excellent performance of the Pennzane lubricated bearings in this harsh test is clearly evident from the torque traces taken at 71 M cycles at the time of this writing (Fig. 3). The Pennzane bearings cleaned with the four test solvents exhibit torque traces with little or no degradation after a year of accelerated testing.

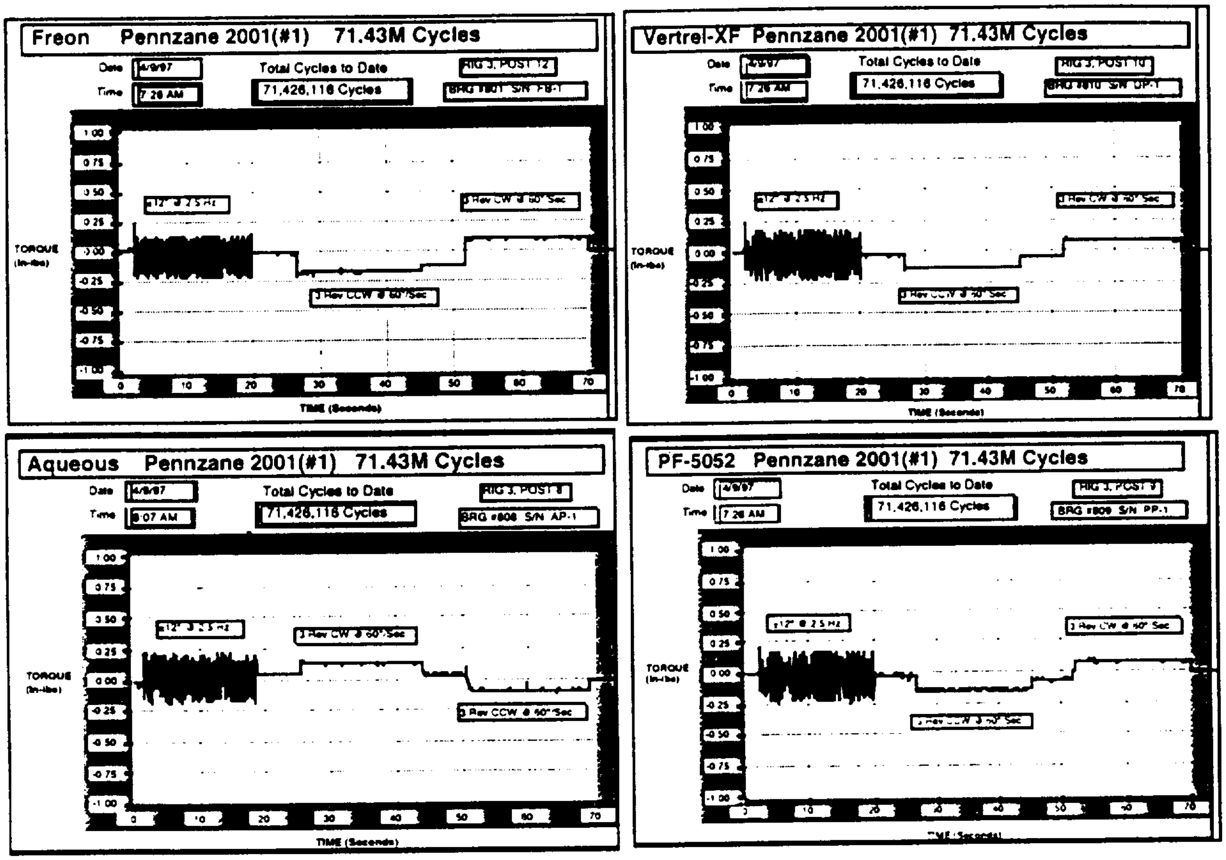


Fig. 3 Four Solvents at 71 M Cycles with Pennzane 2001

Torque History

Plotting the peaking running torque for the 8 pairs of 815Z bearings as a function of cycles can help rank the performance of the various solvents as shown in Fig. 4. Running torques for all the bearings were in the 0.l to 0.15 in-lb range at the beginning of the test. The two Freon cleaned bearings appeared to fail in the 10 to 15 M cycle range. This was followed by the aqueous and Vertrel-cleaned bearings and then those cleaned in the PF-5052 solvent. A summary of approximate cycles to failure can be found in Fig. 5. (Note that at the time of this writing the replicate #2 Vertrel and #2 PF-5052 bearings were still running at about the 18 million cycle point) As can be seen from Fig. 5, all of the alternate solvents had bearing lives at least as good as Freon and, in the case of PF-5052, up to approximately 3x better.

In the case of the Pennzane-lubricated bearings, the torque traces have been stable through life, although a slight upward trend is evident from Fig. 6. Although mid-life torques observed with the Freon-prepared bearings are slightly higher than the rest, the torques with all the bearings are still quite good after 70 million cycles. The best

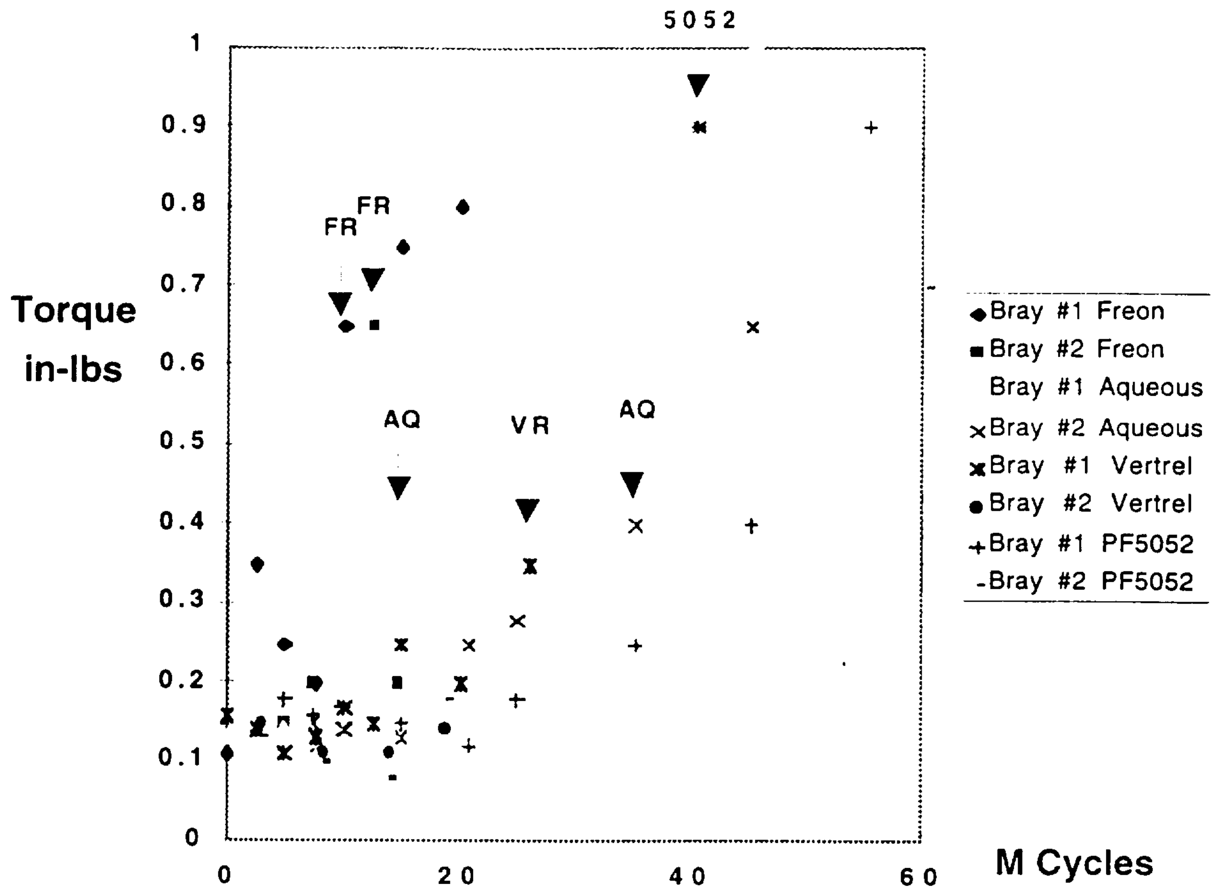


Fig. 4 Torque History - Bray 815Z Oil

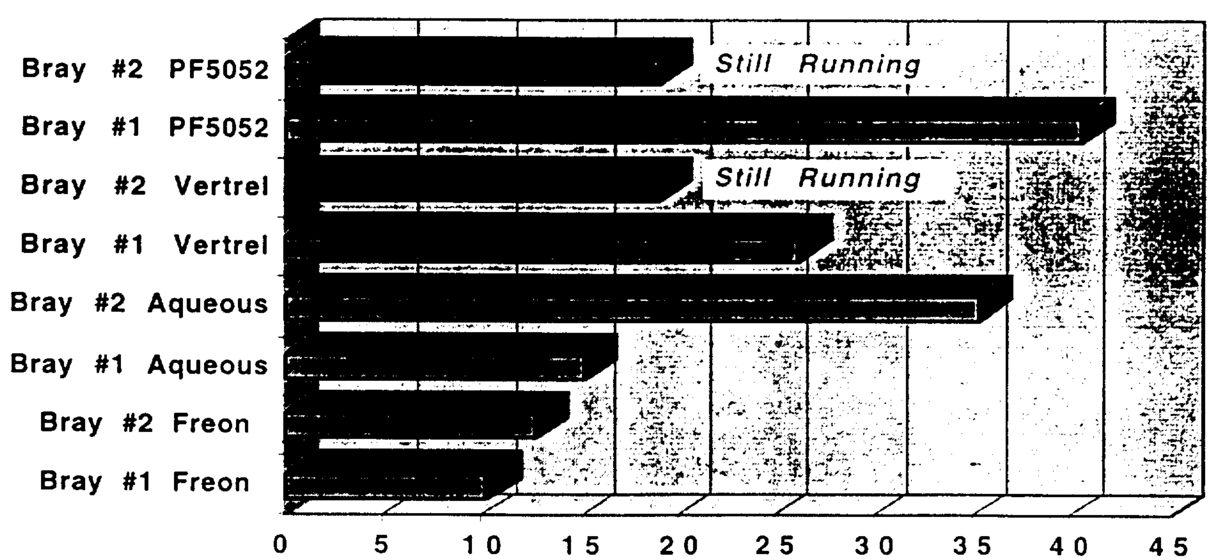


Fig. 5 Test Life Summary - Bray 815Z Oil

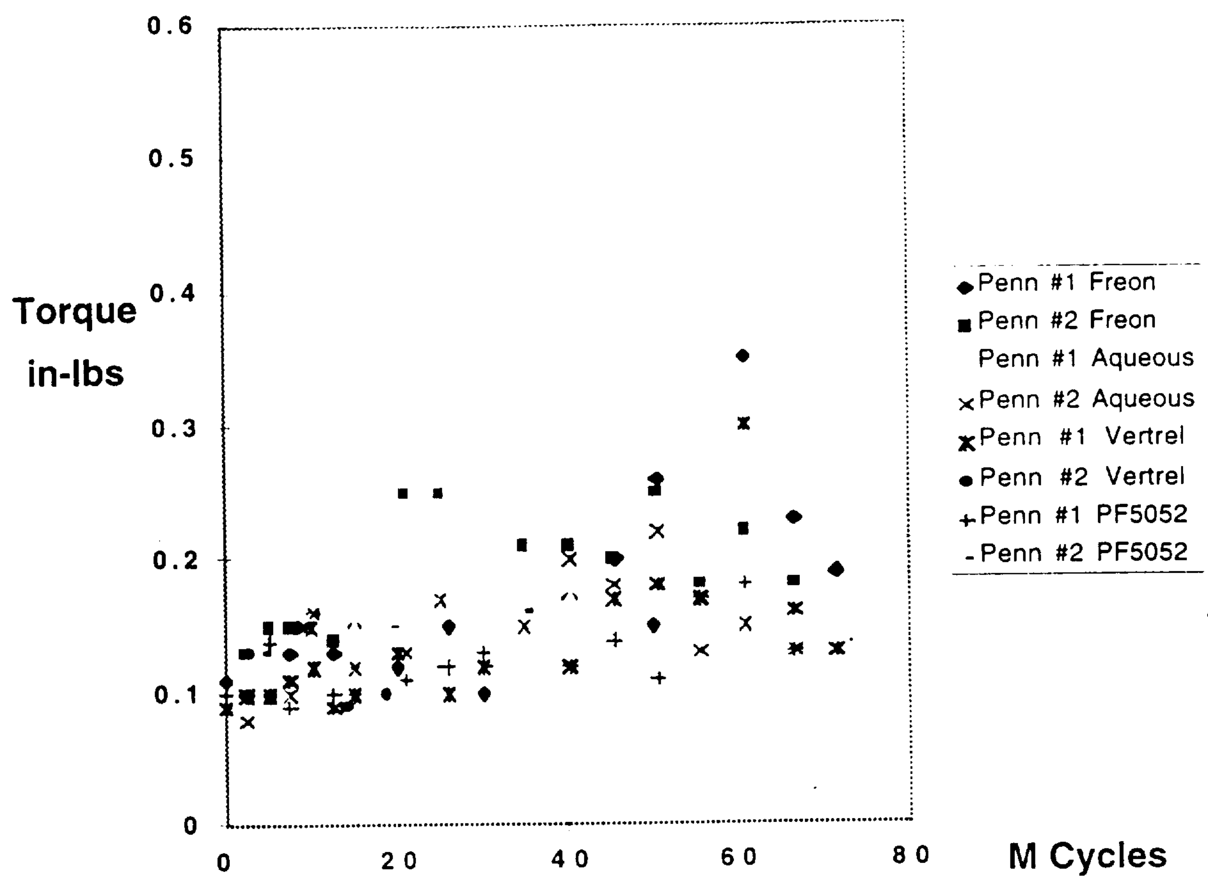


Fig. 6 Torque History - Pennzane Oil

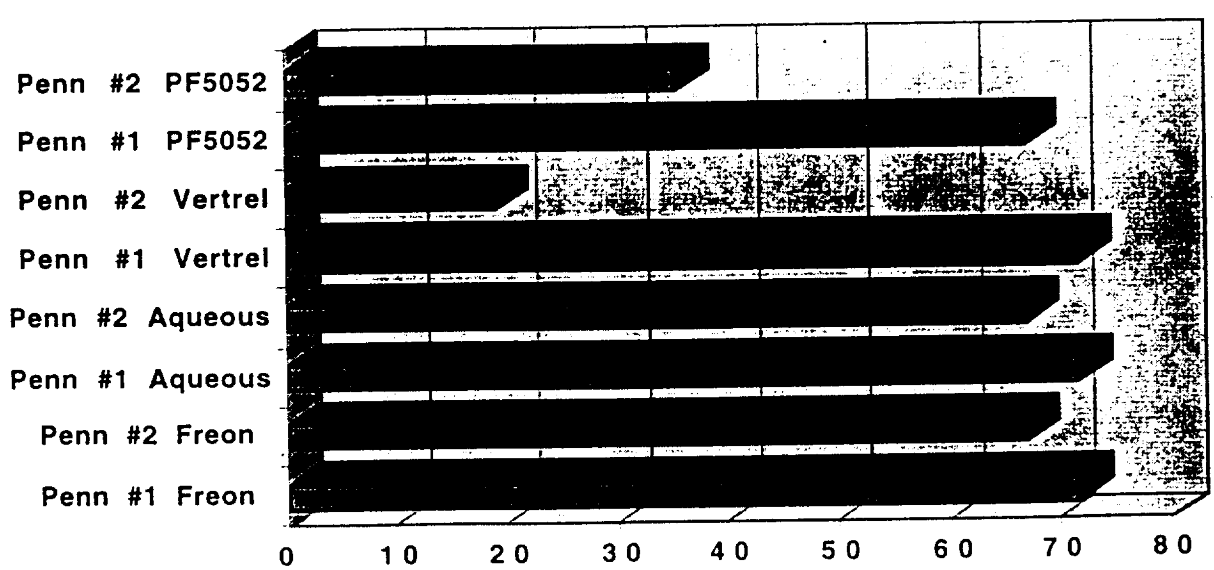


Fig. 7 Test Life Summary - Pennzane Oil

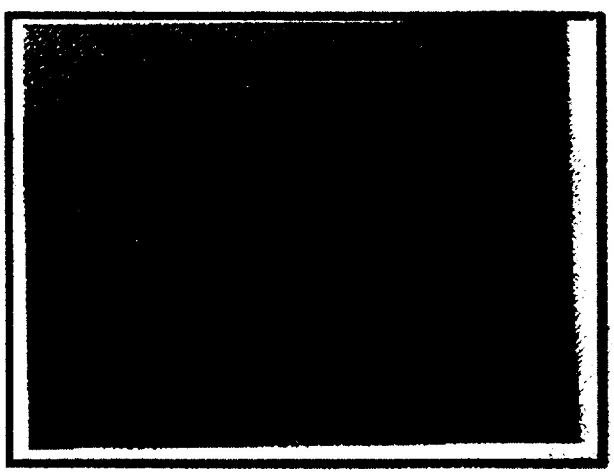
performers at this point are the PF-5052 solvent bearings followed by those that were Vertrel and Aqueous cleaned.

As summarized in Fig. 7, six of the Pennzane bearings are in the 65M plus range with no sign of trouble. This represents a 2 to 6X life advantage relative to the Bray 815Z bearings, depending on the particular solvent, at the time of this writing.

Post Test Exam

Five pairs of the failed Bray 815Z lubricated bearings were examined. The photomicrographs in Fig 8 of the Freon and Vertrel bearings at 35M cycles are typical of the appearance of the failed 815Z bearings. In general, copious amounts of black sludge like debris was apparent. The amount of debris is probably exaggerated since the bearings pictured here received 10 to 20 M cycles of additional testing after failure. The bearings were generally not dry but still contained some free oil at this point. This degraded lubricant debris was undoubtedly a major contributor to the degraded torque signatures observed. It is worth noting that torque levels were approximately 2 and 1.2 in-lbs at this state of failure for the Freon and Vertrel bearings, respectively.

Fig. 9 shows similar photos of the aqueous bearing and the uncleaned inner race. Note the debris pushed-out of the track or scrapped up on the toroids and redeposited on the bearing lands.



- Bray 815Z Oil
- 35.3 M Cycles
- Heavy Black Sludge
- Much Debris

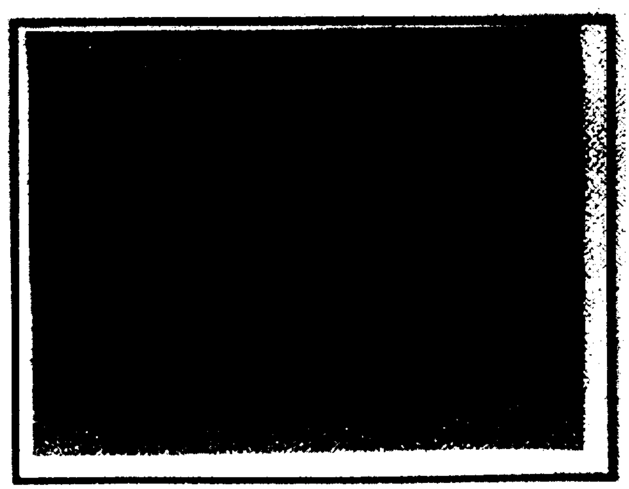
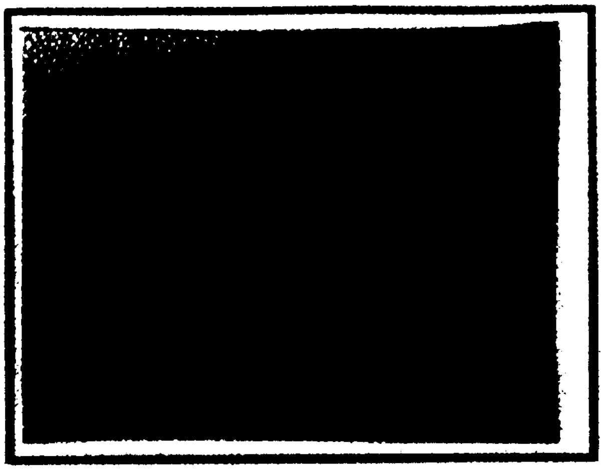


Fig. 8 Comparison of Freon & Vertrel Cleaned Bearings at Failure



Aqueous /Bray 815Z

- 40.5 M Cycles
- Free-oil visisble
- Heavy Black Sludge
- Debris Push Out of Track

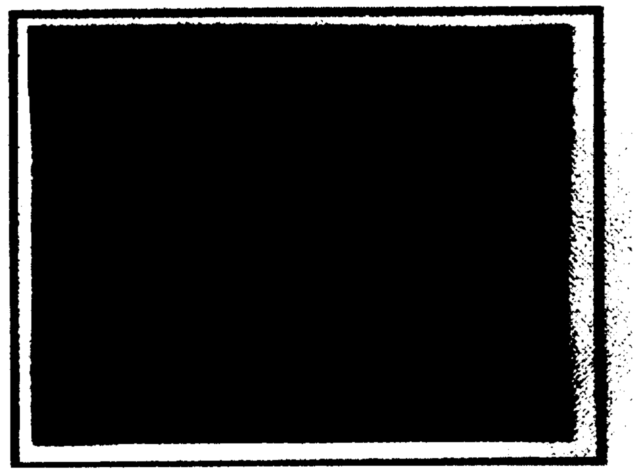


Fig. 9 Typical Appearance of Bearing & Race

The PTFE toroids also showed evidence of ball wear although the wear was not gross (Fig. 10). It is likely that most of this toroid wear occurred after the oil in the bearing was nearly consumed. This would be consistent with the hypothesis that little wear would be expected from a smooth ball pressed against a slippery, oil-coated teflon toroid.

The races of the failed bearings were examined for wear, and as shown in Fig. 10, adhesive wear was present but not severe. This is consistent with the writer's previous experience with scanner instrument bearing failures where degraded lubricant debris gives rise to anomalous torques considerably before the bearing becomes dry and begins to wear.

The results of the visual inspection of the failed 815Z oil bearings is given in Table III. The lubricant/bearing degradation with the Freon cleaned bearings appears greater than the bearings cleaned with the other solvents bearings.

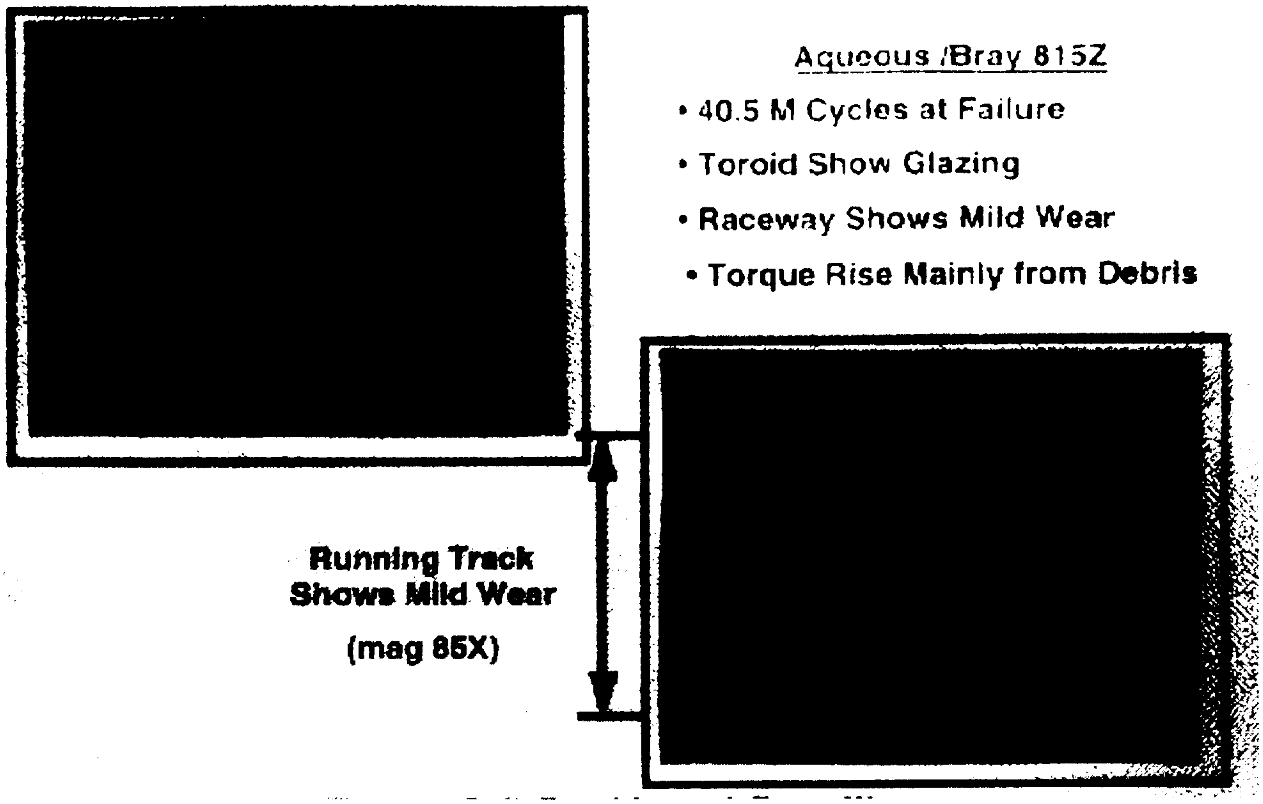


Fig. 10 Ball Toroids and Race Wear

Table III Post Test Failed Bearing Inspection with Bray815Z

Solvent	Brg #	Cycles	Lube	Debris	Ball Track	Toroids
Freon-113	#2	17.8 M	Heavy-Sludge	Copious Black	Mild Wear	Mild Wear
Freon-113	#1	35.3 M	Tar-Like	Copious Black	Med/Severe Wear	Medium Wear
Vertrel	#1	35.3 M	Sludge	Medium Black	Med/Severe Wear	Medium Wear
Aqueous	#1	40.5 M	Sludge	Medium Black	Medium Wear	Medium Wear
Aqueous	#2	40.5 M	Heavy-Sludge	Medium Black	Medium Wear	Medium Wear

CONCLUSIONS

The bearing life test results evaluating ODC-free bearing cleaning solvents versus Freon with two space oils indicate:

1. Replacement solvents provide longer bearing lives than Freon with Bray 815Z oil. Lack of failures prevent ranking relative life with Pennzane oil.

2. Pennzane lubricated bearings enjoy a 2 to 6X life advantage over those lubricated with Bray 815Z oil thus far. Little torque signature degradation was observed at 71 million cycles while failures with 815Z ranged from about 12 M cycles with Freon to about 40 M cycles with the PF-5052 solvent.

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Test Matrix

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This paper add data to the attached paper that was published

Summary of Results

Life test torque history data for the various solvent-lubricant combinations have been collected over the past 15,000 hours. Example torque traces for the baseline Freon-cleaned bearings at both test start and 26 M cycles appears in Fig. 1. At 26M cycles the 815Z bearings show a clear failure torque signature while the Pennzane bearing torque signature is unchanged.

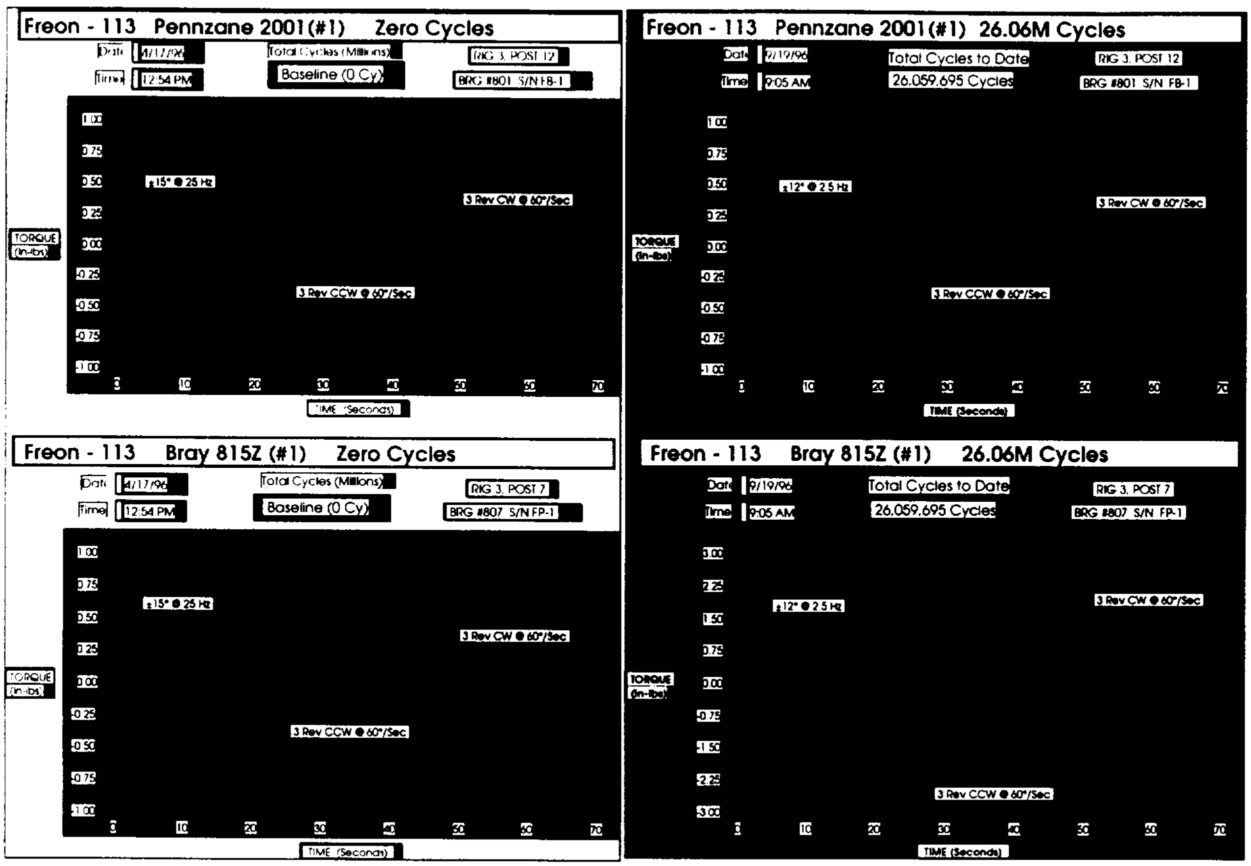

Fig. 1 Freon 113 Traces at Start & 26 M Cycles

A summary of approximate cycles to failure can be found in Fig. 2. The alternate cleaning solvent bearings shows lives equal to or better than the Freon baseline bearings. An indication that no deleterious effect can be expected with the switch to environmentally friendly bearing solvents.

Fig. 2 shows that seven of the eight 815Z- lubricated bearings had failed by about 50 million cycles while all but one of the Pennzane-lubricated bearings have survived 170 million cycles with 6 test bearings still sowing good torque performance. This represents a 3 to 7X life advantage relative to the Bray 815Z bearings, depending on the particular solvent.

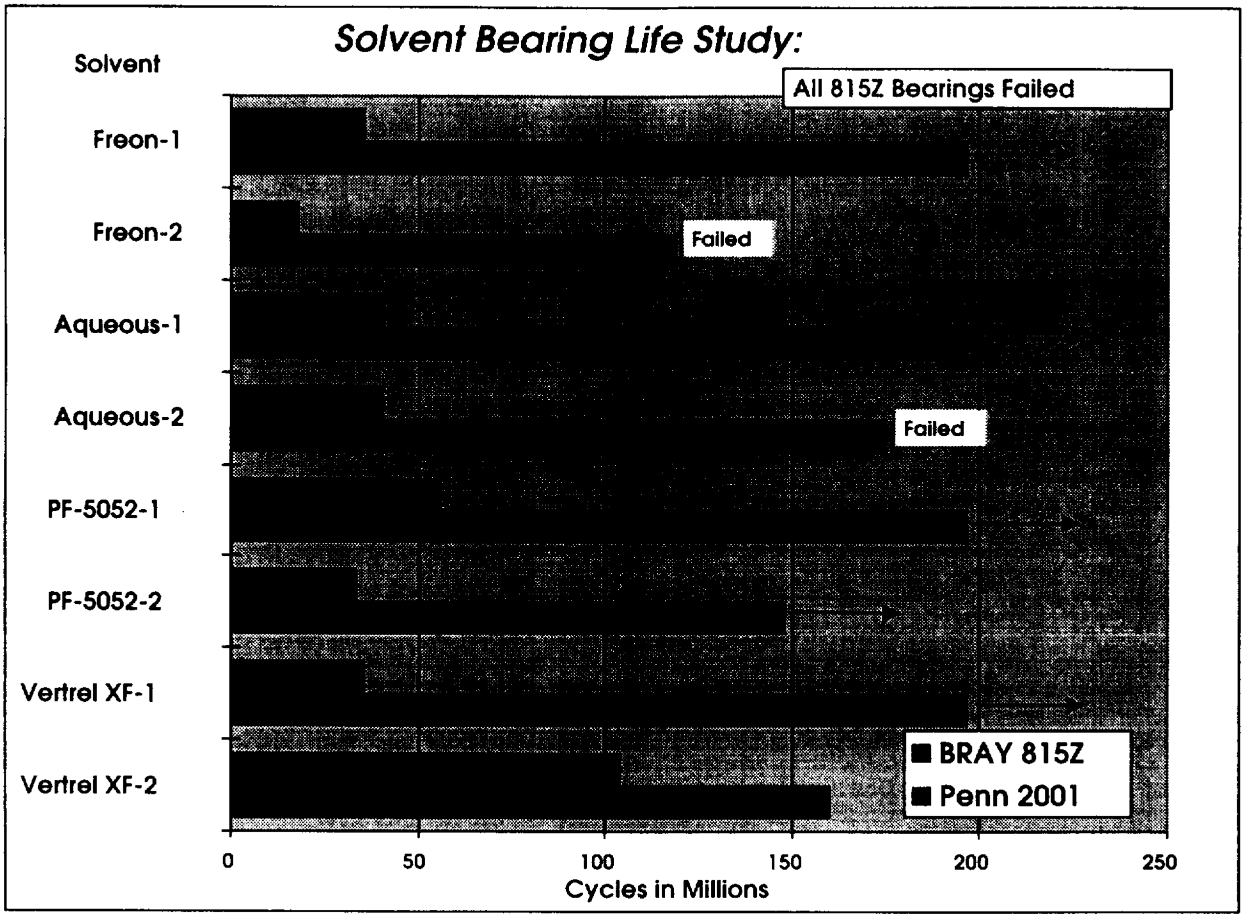

Fig. 2 Test Life Summary