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

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Summary

Life tests were conducted on instrument scanner ball bearings cleaned with 3 types of non-ozone depleting solvents and compared with those cleaned with a conventional CFC-113 (Freon) solvent. The test bearings were lubricated with a standard space oil (Bray 815Z, Fomblin Z25) and a more recent synthetic space oil (Pennzane 2001). Lives with replacement solvents equaled or exceeded those obtained with CFC-113 baseline, indicating that alternate cleaning solvents were acceptable. Pennzane lubricated bearings enjoyed a significant life advantage (>5X) over those lubricated with Bray 815Z oil in these oscillatory gimbal bearing tests. Many of the Pennzane bearings are still exhibiting acceptable torque traces after more than 25,000 hr. of tests.

Background

Bearings used in spacecraft mechanisms have historically been cleaned with a chlorofluorocarbon CFC-113 (Freon) solvent. A considerable flight heritage database has been generated. Most space bearing applications are very sensitive to lubricant surface chemistry. With the ban in the use of these ozone-depleting chemicals, there was a concern that replacement environmental-friendly solvents may adversely affect bearing life in previously space-qualified, long-lived mechanisms (ref. 1). Oddly, the concern is not that these replacement solvents may fail to clean well enough, but rather clean too well and hence, accentuate the chemical reactivity of the bearing surface, leading to a higher rate of lubricant degradation and thus, lower bearing lifetimes. To address these concerns, the authors conducted a bearing life test program as reported in reference 2 to obtain comparative long-term life test data for flight-quality bearings, cleaned with and without CFC solvents. A second objective was to compare the life performance of a relatively new hydrocarbon-based space oil (Pennzane) against the space flight "standard" Bray 815Z, a perfluoropolyether. Published full-scale bearing life test data with these oils and solvents was scarce at the time of these tests and has remained so. The previous work in reference 2 captured the first year of testing in which none of the Pennzane lubricated bearings had failed. This current paper reports on these bearings with an additional 2 years of test time.

Test Description

Test Matrix

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

The baseline lubricant was a Bray 815Z oil. This perfluorinated polyalkylether (PFPE) fluid has more flight history than any other class of space lubricant. It has been used in a multitude of space mechanisms over the past 25 years. PFPE's are characterized by outstanding cold temperature performance with extremely low outgassing. However, they exhibit a tendency to polymerize in the presence of ferrous-based bearing materials under high shear stress and temperature (refs. 3 to 6). Such conditions are normally beyond most applications, judging by their prior long-standing use. However, this chemical reactivity eventually limits their life for demanding applications such as for particularly long-lived bearings and those that operate primarily in boundary lubrication, such as oscillatory 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 antiwear additives (ref. 7). 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 to 10) comparing the life obtained with MACs and PFPEs. However, the authors are unaware of any long term, full scale bearing tests that directly compare their lives. Furthermore, it was suspected that the MAC oil would be less sensitive to solvent-surface chemistry since it did not have the PFPE's chemical reactivity. Additionally, MACs have been observed to dewet bearing steel surfaces (refs. 10 and 11) and it was wondered if this represented a long-term life threat. Therefore, a MAC oil, generically referred to Pennzane 2001, manufactured by Nye, Inc under the trade name synthetic oil 2001, was added to the test matrix. This formulated oil contained a triphenyl phosphate antiwear additive along with an antioxidant.

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 (see Table I). All of the test bearings were processed by Miniature Precision Bearing Company (MPB) per a standard Lockheed Martin Missiles and Space Company (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 precleaned through MPB's normal process. The 440 bearing components were then acid passivated, rinsed with deionized water and washed with the respective test solvent. A wettability check was performed to identify any beading problems. The bearings were then assembled and 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 mg of Bray 815Z oil or 30 to 50 mg of Pennzane 2001 oil to provide the same volume oil fill amounts, on the order of 3.5 percent. This incomplete fill amount was deliberately selected to help accelerate the tests.

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. These angular contact ball bearings were hard preloaded back to back with 200±22 N (45±5 lb) load resulting in a maximum Hertz stress of 1.1 GPa (163 KSI). This preload provided additional test acceleration, being ~3 times greater than that normally specified for this size bearing in a typical long-lived scanner application.

The bearing races are fabricated from AISI-440-C stainless steel. The ball separators are alternating PTFE toroids. The races are finished to a RMS roughness of less than 0.08 μm (3 μm–in.). Table II identifies the test bearing geometry.

Test Conditions

The bearing pairs were mounted into a bearing cartridge and then hard preloaded. The cartridges were then installed into Lockheed Martin'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°.

In the interest of shortening test time, the stroke of ±12° was selected. This 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. A test cycle speed of 2.5 cycles/sec was selected as a compromise between test time and operation primarily in the boundary lubrication 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°/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.

Summary of Results

Torque Traces

Life test torque history data for the various solvent-lubricant combinations has been collected over the past 25,000 hr. Examples of beginning and 26M cycle torque traces for Pennzane and Bray lubricated bearings cleaned with the baseline Freon solvent appear in Figure 1. At 26M cycles, the 815Z bearings show a clear failure torque signature while the torque signature of the Pennzane bearing is unchanged. Large failure torques (0.25 Nm or 2.25 in.-lb) are apparent for the 26M cycle, 815Z bearings from the lower right hand plot. (Note that the Y-scale on this plot has been increased by a factor of 3X). The dramatic torque rise immediately following oscillations are characteristic of degraded lubricant in the gimbal bearings. This torque "bump" is an artifact of the balls rolling over the debris that has accumulated at the end of stroke. In comparison, the torque trace with the Freon-Pennzane bearing is still well behaved at the 26M cycle point. In the case of the Aqueous and PF-5052 solvents, torque is elevated for the 815Z bearings at the 45 to 50M cycle point (see Fig. 2), but again stable for the Pennzane bearings. The excellent performance of the Pennzane lubricated bearings in this harsh test is clearly evident from the torque traces at 215M cycles with the four different test solvents (Fig. 3). These Pennzane bearings exhibit little if any torque degradation after 3 years of accelerated testing.

Torque History Summary

The peak running torque for the 8 pairs of 815Z bearings as a function of cycles is plotted in Figure 4. All of the bearings having either reached or are approaching the 3X failure torque levels. Running torques for all the bearings were in the 0.011 to 0.017 N-m (0.1 to 0.15 in.-lb) range at the beginning of the test. The two Freon cleaned bearings failed 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. It is instructive to note that none of the bearings experienced a sharp torque rise or hard jam. Bearing torque generally rose gradually, often taken many millions of additional cycles before reaching failure levels. This gradual rise in torque occurs concurrently with the steady breakdown of the 815Z oil as it is converted a sludge-like polymer as documented in the post-test inspection section which follows. It appears that a small amount oil is converted to a "friction" polymer each cycle giving rise to a relatively linear torque increase with cycling. Having more oil in the bearing to start with may extend bearing life.

At the time of this writing only two of the 8 Pennzane-lubricated bearings have failed as shown in Figure 5. One of the Freon-cleaned bearings failed at 119M cycles and one of the aqueous bearings failed at 175M cycles. The torque traces of the other 6 Pennzane lubricated bearings are still remarkably good as illustrated by the 4 that have reached 215M cycles in Figure 3. At this point in the test program, the Pennzane bearings enjoyed approximately a 5X average life factor advantage over those lubricated by the Bray oil. These results are consistent with the results reported by Jones et al. in (ref. 10) where an order of magnitude lower wear rate was observed with Pennzane than with Fomblin Z25 using a vacuum 4-ball tribometer.

It is also clear from Figure 5, that all of the bearings cleaned with alternate solvents have lives at least as long as those cleaned with the baseline Freon wash. Thus, the concerns that bearing life may be jeopardized with these environmentally friendly solvents were unfounded.

Post Test Exam

Five pairs of the failed Bray 815Z lubricated bearings were examined. The photomicrographs in Figure 6 are typical of the appearance of the failed 815Z bearings. In general, copious amounts of black sludge-like debris was apparent on failed bearings. The bearings were generally not dry, but still contained some free oil. As shown in Figure 6, degraded lubricant debris is pushed-out of the track and also scrapped off the balls on to the toroids to be redeposited on the bearing lands. This degraded lubricant debris was undoubtedly a major contributor to the degraded torque signatures observed.

The PTFE toroids also showed evidence of wear although it was not severe. 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 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 surface becomes dry and begins to wear.

A summary of the results from 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.

Conclusions

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

1. Replacement cleaners provided bearing lives that were at least as long as those obtained with the baseline Freon-113.
2. Pennzane lubricated bearings enjoyed an average 5X life advantage over those lubricated with Bray 815Z oil with 6 of the 8 Pennzane bearings still under test. Four of these bearings have reached 215M cycles at 25,000 test hours and continue to show excellent torque performance.

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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

TABLE II.—BEARING GEOMETRY

Angular contact, duplex
2532 size
39.7×50.8×6.35 mm (1.563×2.00×0.25 in.)
Class 7T precision
20° contact angle
34 balls 3.06 mm diameter (0.125 in.)
Conformity 0.525

TABLE III.—POST TEST FAILED BEARING INSPECTION WITH BRAY 815Z

Solvent	BRG number	Cycles	Lube	Debris	Ball track	Toroids
Freon 113	2	17.8 mil	Heavy sludge	Copious black	Mild wear	Mild wear
Freon 113	1	35.3 mil	Tar-like	Copious black	Medium/ severe wear	Medium wear
Vertrel	1	35.3 mil	Sludge	Medium black	Medium/ severe wear	Medium wear
Aqueous	1	40.5 mil	Sludge	Medium black	Medium wear	Medium wear
Aqueous	2	40.5 mil	Heavy sludge	Medium black	Medium wear	Medium wear

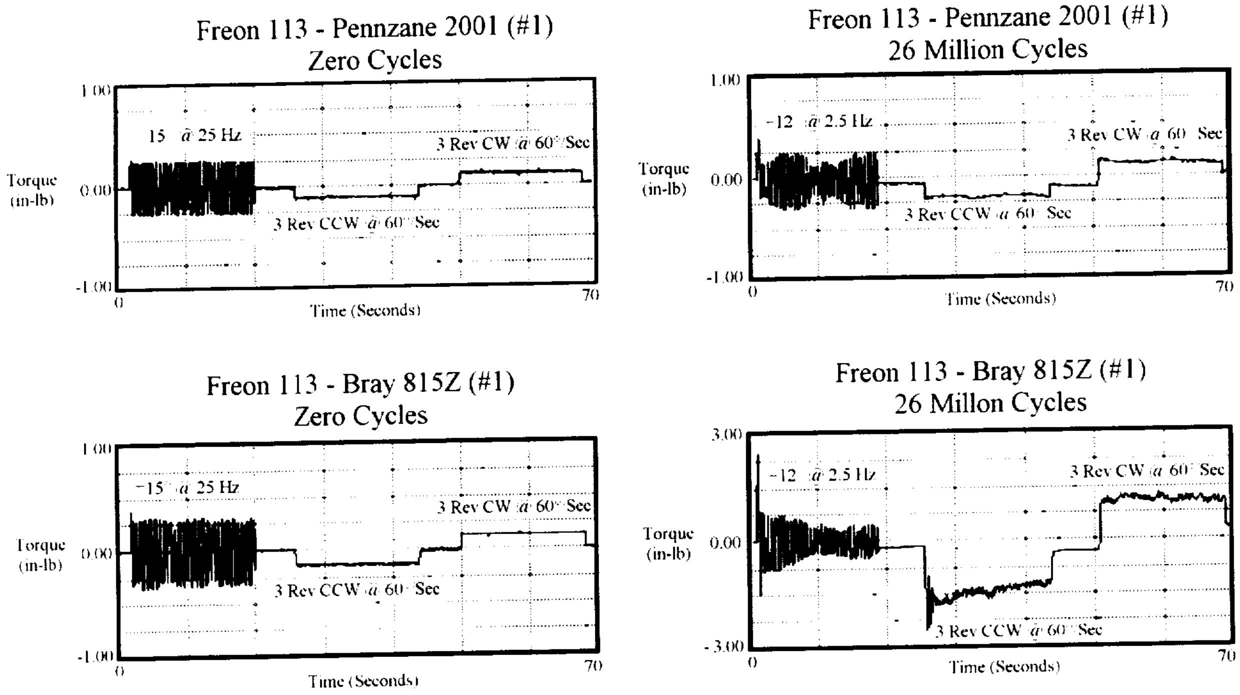

Figure 1.—Freon 113 traces at 0 and 26 million cycles.

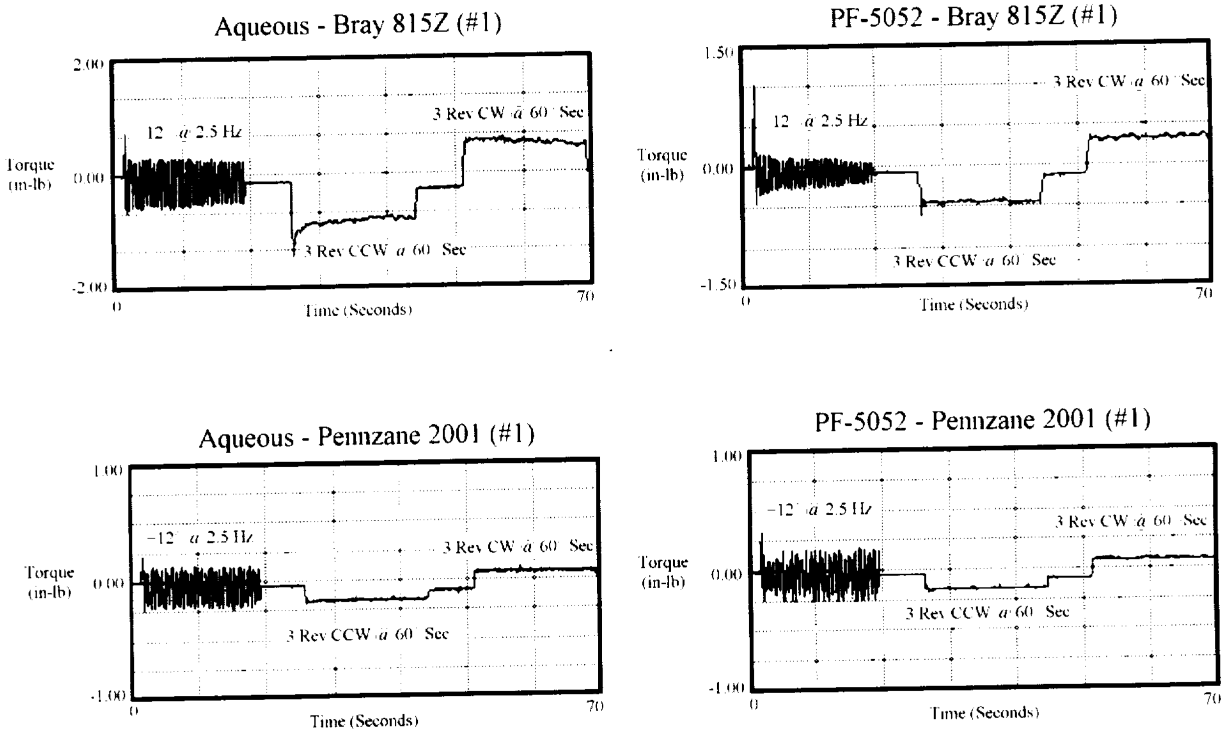

Figure 2.—Aqueous and PF5052 traces at 50 million cycles.

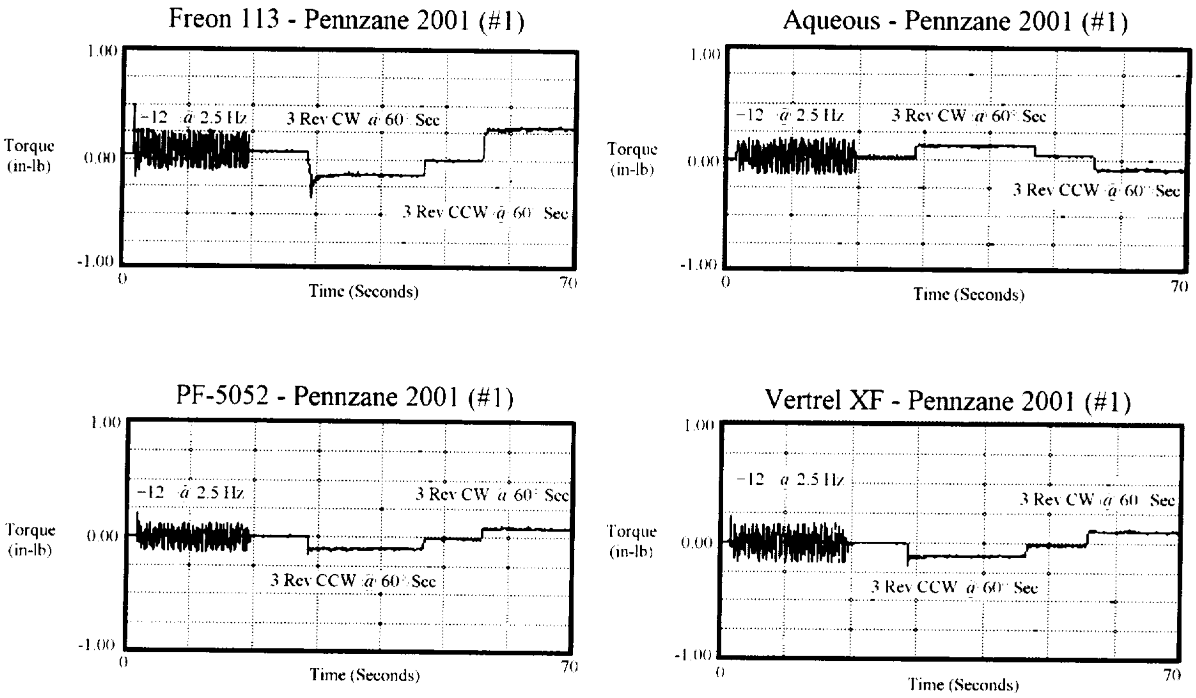

Figure 3.—Four solvents at 215 million cycles with Pennzane 2001.

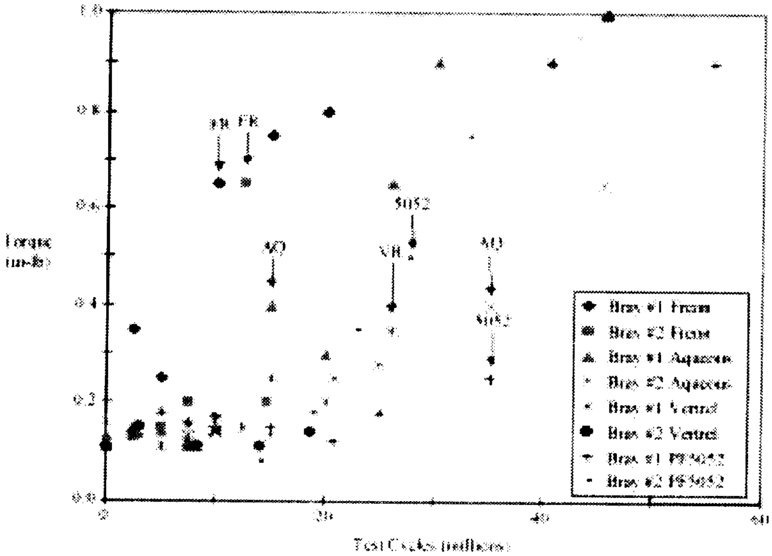

Figure 4.—Torque history of Bray 815Z oil.

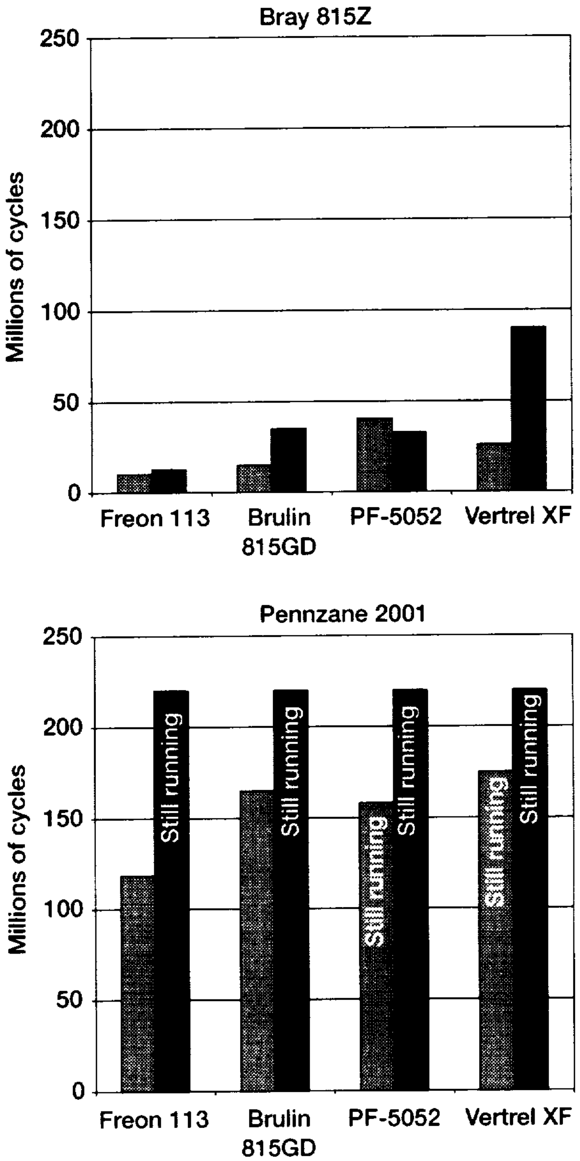

Figure 5.—Life test summary.

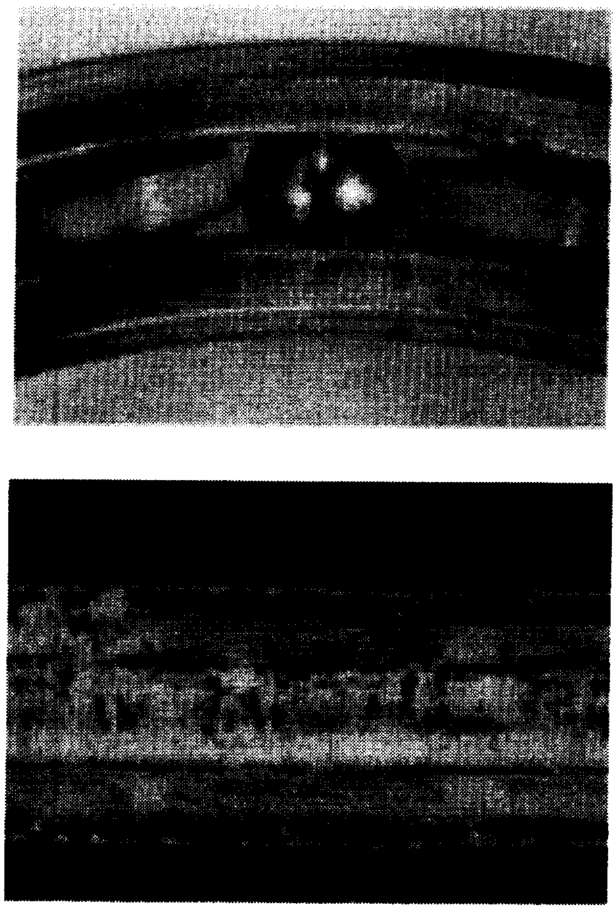

Figure 6.—Typical appearance of failed Bray 815Z bearing and race. Aqueous cleaned bearing at 40.5 million cycles. Note copious black debris on balls and heavy black sludge pushed outside of running track.

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13. ABSTRACT *(Maximum 200 words)*

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