The Use of Screening Tests in Spacecraft Lubricant Evaluation

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ABSTRACT

A lubricant screening test fixture has been devised in order to satisfy the need to obtain lubricant performance data in a timely manner. This fixture has been used to perform short-term tests on potential lubricants for several spacecraft applications. The results of these tests have saved time by producing qualitative performance rankings of lubricant selections prior to life testing. To date, this test fixture has been used to test lubricants for 3 particular applications. The qualitative results from these tests have been verified by life test results and have provided insight into the function of various anti-wear additives.

INTRODUCTION

Because of the stringent conditions placed on spacecraft lubricants and due to the lack of specific performance information, ground-based testing of lubricants is a major factor in the design of spacecraft mechanisms and in the process of selecting suitable lubricants. In most cases, the approach taken when testing lubricants for space qualification is to perform system level life-tests on actual flight hardware, or to perform simulation life-tests which attempt to duplicate the conditions of operation of the flight system. This approach usually produces useful results but is limited by the length of time necessary to obtain data and by the relatively high cost of testing. In most cases only one or two lubricant candidates can be tested, and their selection is usually based on past experience and not on reliable test information. There is a need for a test procedure which can rapidly screen potential lubricant candidates for applications before system-level life tests are performed.

In the course of our work, we have been confronted by this problem on several occasions. In response to this situation, we have developed a test fixture and a test procedure which can determine relative lubricant performances before lubricant candidates are committed to an application

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life test[1]. The test fixture utilizes low cost components and operates under accelerated conditions in order to reduce the time for lubricant evaluations. The test capability of this apparatus enables us to rank lubricants for suitability for application in life testing. In particular, we have used this test approach to select lubricants for the following application tests: an oscillating scanner mechanism, a harmonic drive actuator, and, recently, for a reaction wheel support bearing. With regard to the oscillating scanner and the harmonic drive, the results of the screening tests have been verified by life tests. In these situations, the results from the life tests have produced a relative lubricant ranking which is identical to the ranking determined by the lubricant screening test facility.

EXPERIMENTAL

The approach developed to evaluate spacecraft lubricants is centered around two different types of lubricant tests. The first step utilizes a lubricant screening test facility, to perform short term accelerated bearing tests on a number of lubricant selections. The results of these tests provide a generalized performance ranking of the selections and indicate the suitability of the lubricants with respect to the intended application. The next step is to perform life tests or simulated life tests in order to evaluate the suitable lubricants under realistic operating conditions. In both cases, post-test surface analyses are performed on the test specimens in order to understand the results of the tests.

SCREENING TEST BEARINGS

The bearings used for the screening tests are INA GT-1 thrust bearings. The primary reason for selecting these bearings was due to their low cost and availability. These bearings have a complement of 12 balls and a raceway diameter of 0.900 in. The balls, like the races, are made of 52100 steel and have a diameter of 0.187 in. For the purposes of our screening tests, the configuration in which the bearings were run during the tests was changed. Instead of using grooved raceways for both the top and bottom, the flat side of the bottom(rotating race) was polished to a 0.25 micron finish and used in place of the raceway. This change in configuration was done so the bearing could be run with a controlled amount of misalignment. The misalignment serves to accelerate the wear process, the implications of which will be described later. In addition, a flat contacting surface operates at higher Hertzian stress than the raceway, which guarantees that more severe tribological conditions will exist on the flat. This situation is crucial to the success of the test because the flat is far easier to analyze than the grooved racetrack.

TEST FIXTURES

The mechanism that was developed to perform the screening tests is represented in Figure 1. This design was based on an earlier design[2], but was changed significantly in order to enhance its capabilities. Similar types of testers, based on the earlier design have been reported in literature[3]. In short, the apparatus consists of a bottom housing, which contains the support bearings for the drive shaft, and a upper housing which is designed to contain the test bearings. On the top of the test fixture is a plate which is used to load the test bearings. This plate is free to slide up and down along four studs which are threaded into the top of the upper housing. The test load is applied to this plate with a set of springs(one for each stud) which are compressed along the studs and against the load plate. This arrangement, in turn, pushes the bottom of the load plate against the stationary race of the test bearing. In order to determine the applied load, a load cell is placed between the load plate and the stationary race of the bearing. The load cell can measure loads from 0 to 100 lbs and has a resolution of 0.1 lbs.

The thrust bearings used for the screening tests are mounted in a housing located in the bottom of the load plate. During a test, these bearings are situated such that the stationary(top) race is mounted in the detachable housing and the rotating flat is on a shoulder of the drive shaft. The apparatus was designed to incorporate the detachable housing in order to vary the degree of ball skidding in the test bearing. As described earlier, the ball skidding is produced by mounting the upper race of the thrust bearing slightly off-center from the rotational center of the rotating flat. The resulting misalignment between the top and bottom races causes balls to skid as well as roll during operation. This type of motion imposes severe stress on the bearing and the lubricant because it forces the bearing to operate in a boundary lubrication regime. Consequently, test lives are greatly reduced in comparison to typical ball bearings. In addition, the eccentric operation of the bearing produces a relatively wide wear zone on the flat disk. This is beneficial because it provides a large area in which to conduct post-test surface analysis. The amount of eccentricity in the test bearing is variable and can be adjusted from dead center to 0.125 in.

In order to measure the reaction torque of the bearing, the upper housing is connected to the lower portion of the test fixture through a set of aluminum flexures. The flexures allow the upper portion of the test fixture to rotate slightly with respect to the bottom housing when a torque is applied to the test bearing housing. The reaction torque of the bearing is thus determined by measuring the amount of rotation of the upper housing with respect to the stationary, lower housing.

This is accomplished by mounting an inductive proximity sensor to the latter and measuring the change in displacement between it and a target plate mounted on the upper housing. The proximity sensor is calibrated by applying known torques to the upper housing and measuring its stiffness coefficient, which is then used to convert measured displacements into bearing reaction torques.

During the tests, the reaction torque of the test bearing is monitored continuously with a data-acquisition computer. A custom Fortran program is used to acquire the data and store it to a disk file. The data are acquired at a relatively high acquisition frequency(100 Hz) and are then time compressed by a data averaging routine. The routine acquires 100 Hz data in ten second intervals and computes a mean value for each interval. The mean values are accumulated in a data array and are stored to a data file on a periodic basis. The averaging routine allows the reaction torque of the test bearings to be monitored continuously throughout the test without storing an excessive amount of data.

In order to simulate the space environment, the test apparatus operates in a vacuum chamber. The chamber is pumped by a 360 l/s turbo-molecular pump and reaches a baseline pressure of $1X10^{-8}$ torr. In addition, the chamber has the capability of being sealed off completely and back-filled with gases (e.g., He for certain reaction wheel bearings). Since the drive motor is external to the vacuum chamber, a rotary (Ferro-Fluidics) feed-through is used to transmit rotary motion to the drive shaft of the apparatus.

In addition to testing thrust bearings, several different sizes of angular contact bearings can be tested with only minor changes in the upper bearing housing and load plate. Recently, the test apparatus was modified to perform pin-on-disk tests. This modification allows data to be obtained on friction and wear of different materials and surfaces.

An accelerated life-simulation test fixture, referred to as the Boundary Lubrication Test Fixture was used to verify some of the results from the screening test. This fixture utilizes modified bearing components as test specimens and operates at speeds and pressures which are very close to those experienced by the bearings in many low-speed oscillatory mechanisms. This test fixture operates in an linear oscillatory manner. The performances of the lubricants are assessed by measuring the wear rate of the test specimens during the testing. This is accomplished with capacitive displacement probes which are mounted directly above the specimens. Figure 2 shows the Boundary Lubrication Test Fixture's bearing and sensor configuration in detail.

RESULTS AND DISCUSSION

CASE #1-OSCILLATING SCANNER BEARINGS

In this particular test program, the goal was to find a suitable replacement lubricant for a pair of R2 bearings which are used to support the shaft of an oscillating optical scanner. The original lubricant used in this application was G.E. Versilube F-50, a chloroarylalkylsiloxane(CAS) oil. This oil has a very low vapor pressure and excellent low temperature properties, but it does not function well under boundary lubrication conditions. In this application, the oil degraded very quickly which resulted in substantial bearing wear and reduced life. The goal of the screening tests was to find a replacement oil which had comparable vapor pressure characteristics and pour point as the CAS oil as well as enhanced boundary wear characteristics. Once identified, the oil was to be tested in a simulated life test in order to qualify it as a space lubricant.

After preliminary investigation, substitute oils were chosen for the tests. These oils, along with some of their physical properties, appear in Table 1. The CAS oil was included in the testing in order to obtain a performance baseline for comparison purposes. The PFPE oil, Brayco 815Z is a perfluoropolyalkylether oil and was selected on the basis of its low vapor pressure and viscosity properties. NYE 188B differs from the other oils because it is a synthetic hydrocarbon oil (poly-alpha-olefin, PAO). It was chosen because of its excellent physical properties and because it could be formulated with the anti-wear additive tricresylphosphate (TCP). The inclusion of an anti-wear additive in the oil was considered to be essential because the bearings operate in a boundary lubrication regime.

In this set of tests, the earlier configuration of the test fixture was used[1]. This version utilized a thrust bearing of the same dimensions as the INA GT1 but incorporated a custom 440C disk and 440C grade 10 balls. The test specimens were run in a vacuum environment at a speed of 1750 rpm and the load ranged between 20 and 50 lbs (229-310 ksi peak contact stress). The motor current of the test fixture was measured in order to get an estimate of the reaction torque of the bearing. Bearing failure was defined to occur when the motor current reached a level 1.5X the starting current.

The wear lives of the screening tests are shown in Figure 3. In this chart, the wear lives of the oils have been normalized with respect to the worst performer. As the chart indicates, the PAO oil had the longest life under these conditions. The primary reason for this result appears to be the superior boundary protection provided by antiwear additive (TCP) in the PAO oil. In the absence of antiwear additives, the CAS and PFPE oils could not protect adequately against direct metal-to-metal contact in the bearing. In addition, both the CAS and the PFPE oils decomposed under use. The CAS oil was the most reactive, forming a hard "sand" like grit which caused significant wear and subsequent failure after only a short period of operation.

After these tests were concluded, the same three oils were tested in a simulated life test of flight grade bearings under conditions which mimicked the operational conditions on orbit. The results of the life testing appear in Figure 4. It is obvious that the PAO oil outperformed the other oils by a wide margin. Both the CAS and PFPE oils exhibited the same failure mechanism in this test as they had in the screening tests. The absence of an anti-wear additive, coupled with lubricant decomposition, was the most likely cause of the early bearing failures. By contrast, the PAO lubricated bearings operated over 3.5 years and did not display abnormal wear upon removal. The bearings still contained an adequate amount of lubricant, and the lubricant did not show any signs of degradation. More details on these test results can be obtained from the literature[4].

CASE #2-HARMONIC DRIVE SUPPORT BEARINGS

Another lubricant evaluation involved testing lubricants for a harmonic drive actuator mechanism. The goal of this study was to obtain comparative performance data between a frequently used neopentylester spacecraft oil(NPT-4), and a new synthetic hydrocarbon oil (Pennzane SHF-2000), a multiply-alkylated cyclopentane (MAC) which has some outstanding physical properties. Additionally, it was desired to gain a better understanding of the role of wear additives in oils and the mechanisms by which they provide protection. The additives of interest are TCP and lead naphthenate (PbNp).

In order to conduct this study, the Boundary Lubrication Test Fixture was used in combination with the Lubricant Screening Test Fixture. The Lubricant Screening Test Fixture was first used to determine the relative performance of the different oils and additives. While the relative ranking of the lubricants was being established, some of the oils were then tested in the accelerated life test fixture to see if the performance trends established by the screening tests were repeated in longer term tests.

The newer version of the Lubricant Screening Test Fixture along with INA GT1 bearings, described earlier, were used to perform the screening tests. These tests were run at a speed of 1800 rpm and were conducted in vacuum at a base pressure of 1×10^{-7} torr. The reaction torque of the test bearing was monitored continuously; failure was defined to occur when the reaction torque of the test bearing exceeded a level 3x the initial run-in torque. For these tests, a 4lb/ball load(288 ksi peak contact stress) was used in the test bearings, and each test bearing was lubricated with 60 μL of oil. This amount was somewhat excessive, but it was used to eliminate lubricant starvation as a failure mechanism. Table 2 lists the oils and oil/additive combinations that were tested in the Lubricant Screening Test Fixture.

While the screening tests were proceeding, the Boundary Lubrication test Fixture was used to conduct longer term wear tests using the same oils and additives. The specimens in these tests were loaded to a stress level of 113 ksi and were run in an oscillatory manner with amplitude of 0.10" and a frequency of 1 Hz. The tests were conducted in a vacuum environment and had durations which ranged from 1000 to 1500 hrs. This time range was chosen because its length was considered sufficient for wear processes to occur.

The test results of the screening tests appear in Figure 5, from which it is clear that oils formulated with wear additives outperformed the base stock oils. The poor performance of the unformulated Pennzane underscores the necessity of using boundary layer additives under these conditions. Of the combinations tested in the screening tests, Pennzane with TCP had the longest life. The addition of Pbnp in Pennzane also improved the life of the oil but not to the extent that TCP did(see later for information on failure modes for the two additives). NPT-4 was not formulated with any of the wear additives because its chemical structure and reactivity causes resulted in the formation of a protective boundary layer. However, the boundary layer produced by NPT-4 is not as effective as those produced by the oil additives. Furthermore, the method by which NPT-4 forms its boundary layer (chemical reaction with the steel surface) may result in damage to the bearing surfaces.

Following these tests, the surfaces of the test specimens were analyzed with energy dispersive x-ray (EDX) and/or Auger electron (AES) spectroscopy. The profiles of the surfaces were also measured using a DecTak 3030 profilometer. These analyses were performed in order to determine the failure mechanisms of the test specimens and to assess the performance of the boundary wear additives.

The post-test analyses revealed that the test bearings lubricated with TCP and PbNp containing oils failed by different mechanisms. The bearings lubricated with Pennzane+TCP appear to have failed by a wear process that involves surface distress and metal removal from the wear track. Figure 6 contains two surface profile scans across the wear track of a Pennzane+TCP lubricated bearing. The graphs in this chart indicate that a significant wear trough, along with increased surface roughness, occurred in this test bearing. The bearing appears to have failed at the point when the additive could no longer provide satisfactory boundary layer protection. The bearings lubricated with Pennzane+PbNp, on the other hand, do not appear to have failed as a result of metallic wear. Instead their increased friction appears to have been caused by the formation of a tough, lead-containing carbon film on the wear surface of the disk. The evidence for the existence of the carbon-lead film was first detected by EDX spectroscopy and later confirmed by profilometry measurements. Figure 7 contains several EDX scans of a test sample containing a carbon-lead film. As the plots show, only the scan of the regions within the wear-zone contain elemental carbon and lead in any quantity. Outside of this area, there is little evidence of these elements on the surface. Figure 8 shows profilometry traces taken across the wear track of the same raceway. The graphs confirm the existence of a film build-up across the wear track and indicate that the film is between 0.1 and 0.5 microns in thickness.

The apparent differences in the performances of TCP and PbNp in Pennzane have suggested that the two additives cannot be directly compared to each other. The test results suggest that TCP and PbNp have different boundary protection modes. Lead naphthenate appears to function by generating a relatively thick film between the contacting surfaces. This characteristic makes PbNp ideally suited to high stress applications where maximum protection against wear is desired and increased friction is not a factor. TCP, on the other hand, seems to function by reacting with the steel and forming a thin, friction reducing film on the contacting surfaces. These characteristics make TCP well suited to light or intermediate loads, where low friction and long life are desired. However, as shown by Figure 6, TCP does not provide the same degree of protection against wear as does PbNp. This is an important consideration, especially in situations where bearing stiffness is crucial to the success of the application.

These results illustrated some of the difficulties of performing comparative screening tests on different lubricants and the need for careful consideration of the end application in making final selections. Many factors, such as load, speed, temperature and material compatibility must be evaluated when determining the test conditions. Post-test analyses of the test components are essential to proper interpretation of the test results. Post test analysis was extremely useful in our case, because it allowed us to reevaluate the ranking established solely by the screening test wear lives. Based on the screening test wear lives, Pennzane with TCP appeared to be the best choice. However, for the purpose of the harmonic drive application, the low friction produced by TCP is not as important as the improved wear protection which PbNp provides. Based on bearing wear as the ranking factor, Pennzane with PbNp is the best combination of those tested.

Due to the length of time necessary to perform the accelerated life tests, not all of the lubricant combinations tested in the screening tests were tested in the Boundary Lubrication Test Fixture. Nevertheless, the results obtained from this test fixture have confirmed most of the findings of the screening tests. Post test analyses, similar to those performed on the screening test samples have given us sufficient data to make this conclusion. Table 3 is a compilation of all of the test results from the screening tests and the low speed oscillatory tests. From these data, it is evident that the lubricant behavior in the screening tests has been replicated in the accelerated life tests. In addition to our findings, life testing performed on actual harmonic drive mechanisms with NPT-4 and Pennzane+PbNp has confirmed these results. Additional tests with Pennzane and PbNp have been planned. These tests will investigate the effects of varying additive concentrations on wear performance and will look for an optimum additive concentration.

CASE #3-REACTION WHEEL SUPPORT BEARINGS

The Lubricant Screening Test Fixture was also used to evaluate lubricants which have been considered for use in reaction wheel support bearings. In this study, the apparatus was used to test a well known spacecraft lubricant SRG-40, a highly refined mineral oil, and two synthetic oils which were considered as replacements for SRG-40. The synthetic oils consist of NYE 179, a PAO oil, and NYE UC-7, a poly-ol-ester oil (POE). All of the oils tested were formulated with TCP. Table 4 lists some of the properties of the oils tested.

Reaction wheel assemblies (RWAs) and gyroscopes often operate in atmospheres of helium or hydrogen gases. The particular RWA of interest uses a He-O_2 mixture (P_{tot} = 0.5 atm with 2% O_2), so it was decided to perform lubricant screening tests in several different environments. These environments consisted of: 1×10^{-7} torr vacuum simulating a worst case scenario of an on orbit leak; 1/2 atmosphere of 98% He 2% O_2, the operating environment used on orbit; and 1/2 atmosphere of pure He. The last environment was chosen because it was desired to see if the inclusion of oxygen was really necessary for the anti-wear additive TCP to function. Many spacecraft designers have included oxygen in the fill gases of reaction wheels based on intuition rather than experimentation. The premise for this has been that TCP will only bond to an oxide surface. Hence the addition of oxygen to the helium fill gas will ensure that all metal surfaces will be covered with an iron oxide film, which can be replenished if worn off. In our experience, however, we have never observed that oxygen is necessary for TCP to function correctly. In fact, our concern here was that the inclusion of oxygen in the fill gas may actually be detrimental to life of the bearing because it could degrade the lubricant. Therefore, several additional tests were run in a 7 torr atmosphere of O_2. This amount represents the equivalent of the 2% O_2 added to the helium, and it was felt that this condition would accentuate both the reactive effect of oxygen on the lubricant and any potential effect of oxygen on TCP.

The test conditions and procedures for the screening tests performed in this study were virtually identical to those performed for the harmonic drive actuator. The only difference, aside from the different environments, was that some of the tests were run with a lighter applied load (3lb/ball).

The wear lives of the screening tests performed in vacuum and 7 torr O_2 appear in Figure 9. In this chart, the wear lives represent the mean values of several tests per oil. As the graph indicates, the synthetic oils outlasted SRG-40 by a wide margin in vacuum. The main factor that accounts for this result seems to be the high vapor pressure of SRG-40. It is felt that this high vapor pressure, combined with the extreme operating environment, led to rapid lubricant loss from the bearings and subsequent failure. The synthetic oils, with their lower vapor pressures, appear to have remained in the bearings for a greater duration which resulted in their longer wear lives. Gas chromatography was later performed on the oil residues of all the test specimens which confirmed that significant lubricant evaporation occurred in the SRG-40 test bearings, while there was much less evaporation in those lubricated with the synthetic oils.

Although not all of the oils were tested in 7 torr of oxygen, the results from those that were tested indicate that the presence of oxygen in the operating environment did not improve the test lives, and, in the case of UC-7, the wear life was significantly decreased. Figure 10 is a plot which compares the bearing reaction torques for UC-7 in vacuum and in the oxygen environment. From this figure it is obvious that the addition of oxygen to the operating environment results in higher torque, more torque noise, and greatly reduced wear life. Visual inspection of the bearings after the tests also revealed extensive lubricant degradation in the case of the oxygen tests and little or no lubricant breakdown in the vacuum tests. This finding was later supported by findings from the 1/2 atmosphere tests.

The wear lives from the tests performed in the 1/2 atmosphere environments appear in Figure 11. In general, these tests ran for a much greater period because the presence of the fill-gas reduced lubricant evaporation and allowed the bearings to operate at a lower temperature, providing a more direct comparison of the respective boundary layer performances of the oils. The tests that were performed with the helium-oxygen mixture (SGR-40 only) confirmed the results obtained from the 7 torr oxygen tests. The test lives in this case were significantly shorter than any of those performed under a helium only atmosphere. In the helium only test condition, UC-7 was the only oil that failed consistently, according to our torque failure criteria. In contrast, the tests performed with the other oils were either terminated before failure, due to time constraints, or were run for a great length of time in order to fail(179). Consequently, post test analyses, similar to those performed in the harmonic drive study were carried out on test specimens from all of the test environments in order to clarify the results

The most notable finding, from the surface analyses(AES and profilometry) is that TCP does not appear to function as an anti-wear additive in UC-7. The Auger spectroscopy performed on the UC-7 wear disks never detected any trace of phosphorus on the steel surfaces. The absence of phosphorus in this case, combined with the detection of a carbon residue on these surfaces, suggests that the reactive nature of ester oils interferes with the normal protective mechanism of TCP. By contrast, all of the samples run with 179 and SRG-40 contained phosphorus in the wear track, indicating that TCP was active in this region and indicating that oxygen is not required for TCP to function.

The profilometry measurements revealed large wear troughs in the wear tracks of the UC-7 test specimens. Measurements made of the other wear disks indicate that SRG-40 operates with less wear than UC-7, and 179 appears to have the lowest wear rate of all the oils tested under these conditions. The presence of this type of wear and its relative absence for the other oils suggest that the reactive boundary layer film, that UC-7 generates under use, is not as effective as TCP in preventing wear. In fact, this method of boundary layer protection may actually damage the steel surfaces of the bearings and cause increased "chemical" wear.

The wear lives of the screening tests and the post test analyses performed on the test specimens, indicate that Nye 179 was the best overall choice for this application. Its performance in vacuum was far better than that of SRG-40, and its performance in helium was considered to be the best of all the oils tested. Furthermore, the use of oxygen as a component in the fill gas of reaction wheels was determined to be unnecessary and generally harmful to the life of the bearing lubricant. These findings have been conveyed to the manufacturer and have been used to determine the configuration of a reaction wheel lubricant validation test which is currently underway.

SUMMARY

The Lubricant Screening Test Fixture and the procedure developed for its use have proven to be quite useful for acquiring performance information for spacecraft lubricants. The chief advantage of this approach is the ability to obtain qualitative rankings of different lubricants through the use of low cost, short duration bearing tests. This is significant, when considering the lengthy test times and high costs associated with most spacecraft lubricant tests. The test fixture and test procedure also can be used to perform more fundamental studies on the interactions of lubricants and additives with bearing surfaces. The case studies described in this paper have demonstrated that this test fixture, in conjunction with the appropriate post-test analyses, can be used to identify different wear protection mechanisms as well as to determine bearing/lubricant chemistry.

The results from the case studies, however, have also demonstrated some of the limitations of this approach. The results have shown that screening tests alone are not sufficient for most lubricant studies. The fact that the test bearings used in these tests are significantly different from the configuration of most satellite bearings makes it almost impossible to predict accurately an application's life based solely on screening test lives. The test results from the case studies have also highlighted the necessity of choosing the appropriate test conditions. The effects of test parameters, such as load, speed, temperature, atmosphere and lubricant quantity, on the test life need to be understood if a valid lubricant ranking is to be established. Even more important is the selection of appropriate post-test analyses. These analyses are often necessary in order to identify performance traits, such as additive surface effects, which may not be discernable in a torque trace or a wear life. This need was most evident in the harmonic drive study, where post-test analysis rearranged the initial lubricant ranking based on wear lives.

If these limitations are understood, however, the proper use of lubricant screening tests can play a major role in the process of qualifying a spacecraft lubricant. They can save considerable time and expense by identifying unsuitable lubricants, thus eliminating unnecessary life tests. In addition, they can often be used to troubleshoot lubricant problems with existing mechanisms, as was most noticeable in the case study involving the reaction wheel lubricants. In this case, with the screening tests, we were able to identify almost all of the lubrication problems associated with the actual flight bearings. Considering their strong points, it seems reasonable to integrate lubricant screening tests into the overall process of lubricant flight qualification.

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TABLES

Table 1. - Oils Tested in Scanner Bearing Case Study

Property	CAS	PFPE	PAO
Viscosity, cS			
-40 °C	640	2600	---
40 °C	52	129	107
100 °C	16	40	14.5
Viscosity index	--	350	145
Pour point (°C)	-73	-73	-55
Specific gravity	1.045	1.866	--

Table 2. - Oils Tested in Harmonic Drive Case Study

Oil	Additive
NPT-4	None
Pennzane SHF-2000	None
Pennzane SHF-2000	PbNP (5%)
Pennzane SHF-2000	TCP (1%)

Table 3. Test Results of Harmonic Drive Case Study

OIL	EDX/AES		PROFILOMETRY	
	SCREENING TESTS	ACCELERATED LIFE TESTS	SCREENING TESTS	ACCELERATED LIFE TESTS
NPT-4	carbon film	carbon film	N.A.	wear patch
PENNZANE	no film	no film	wear trough	wear patch
PENNZANE + PbNp (5%)	carbon + lead film	carbon + lead film	film buildup	film buildup
PENNZANE + TCP (1%)	thin carbon	N.A.	wear trough	N.A.

Table 4. - Oils Tested in RWA Case Study

Oil	VISCOSITY (300K)	POUR POINT	VAPOR PRESSURE (300K)
SRG-40	30.3 cs	-26 °C	~ $1x10^{-4}$ Torr
NYE 179 (PAO)	40.8 cs	<-60 °C	~ $1x10^{-7}$ Torr
NYE UC-7 (POE)	45.8 cs	-57 °C	~ $1x10^{-7}$ torr

FIGURES

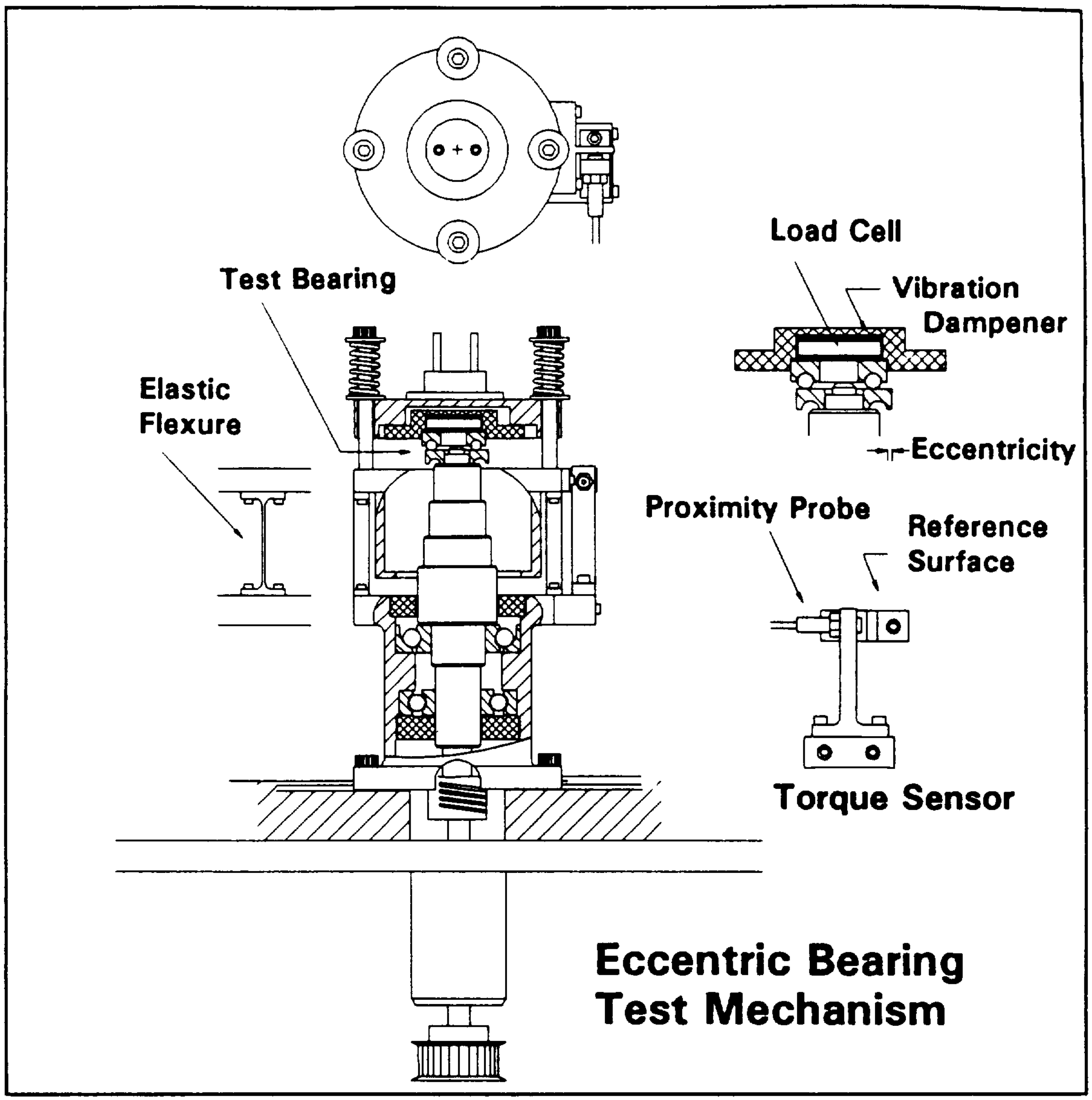

Fig. 1 - Lubricant Screening Test Apparatus

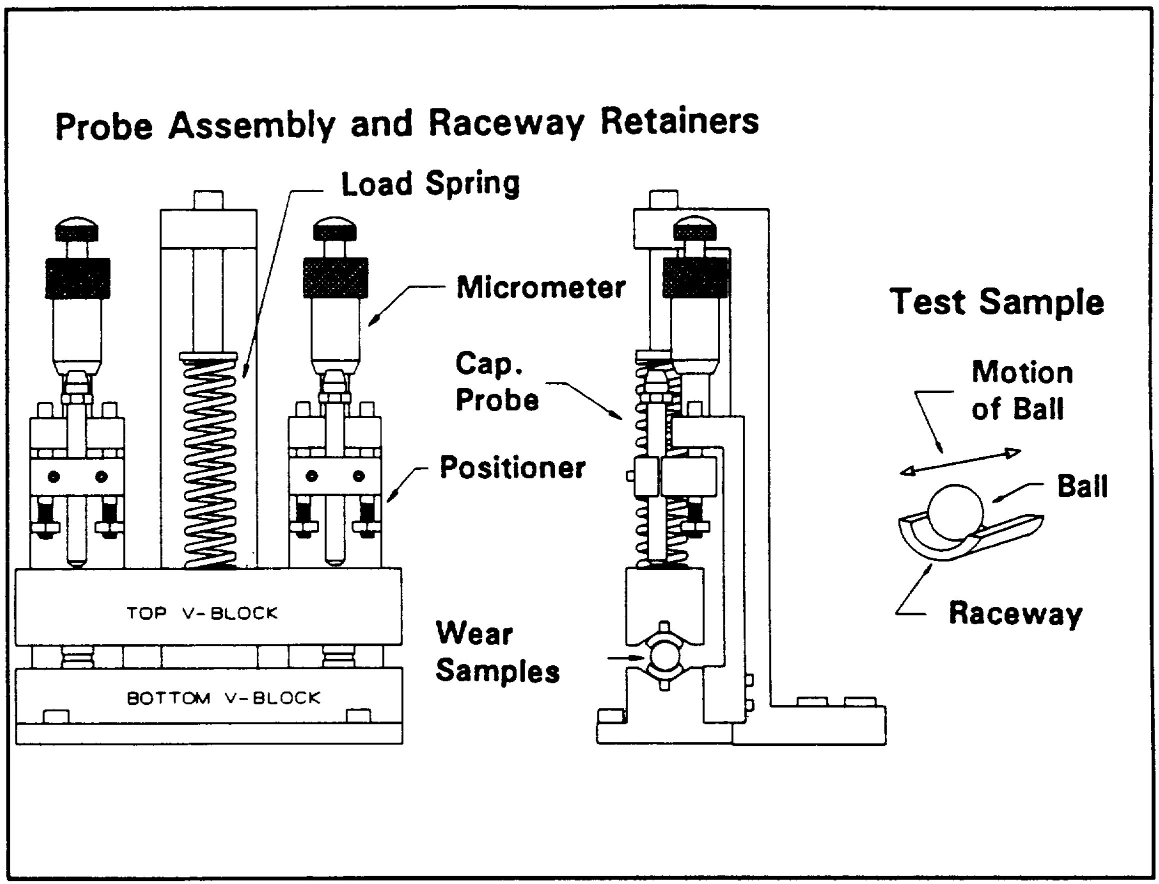

Fig. 2 - Boundary Lubrication Test Fixture, Bearing and Sensor Assembly

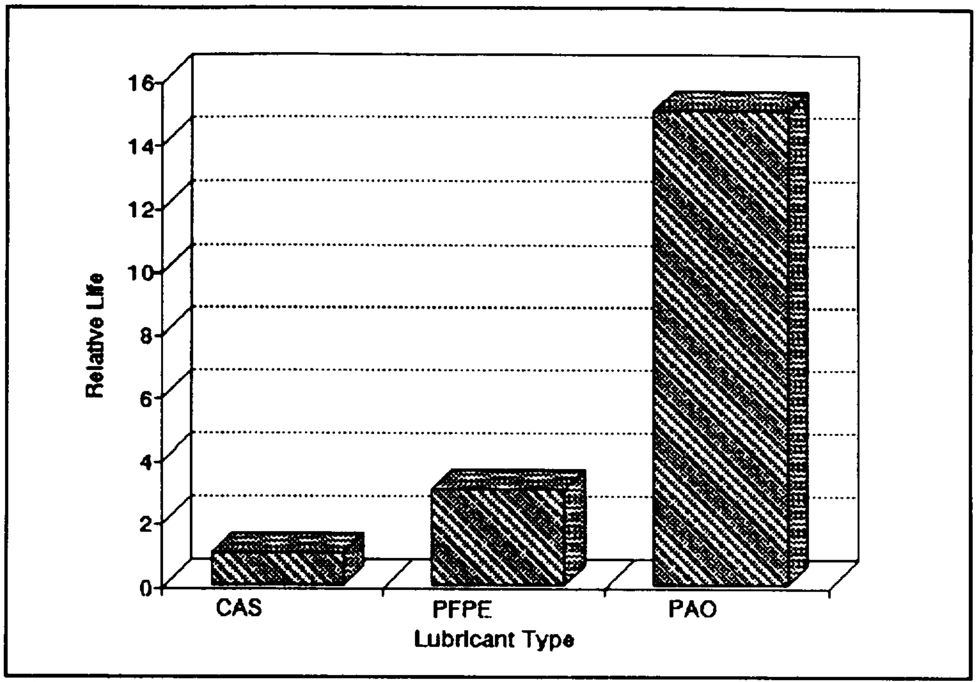

Fig. 3 - Screening Test Results (Scanner Mechanism)

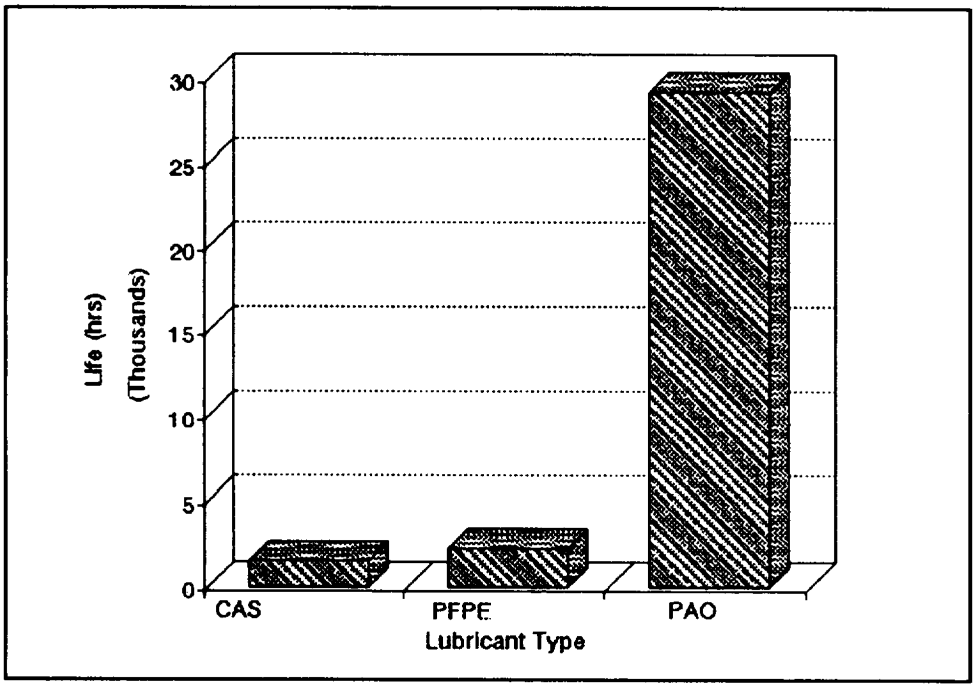

Fig. 4 - Life Test Results (Scanner Mechanism)

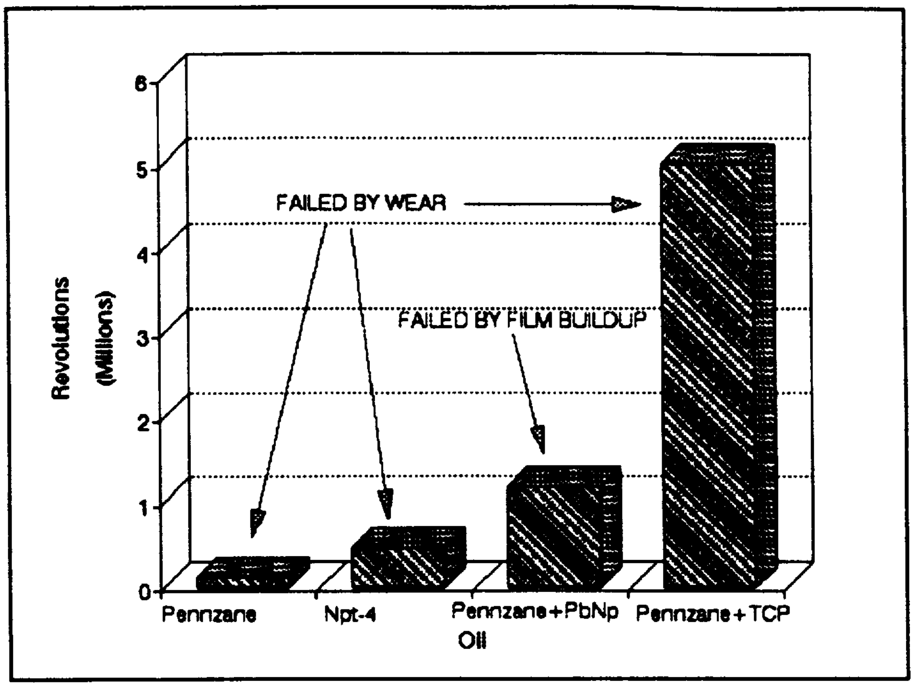

Fig. 5 - Screening Test Results (Harmonic Drive)

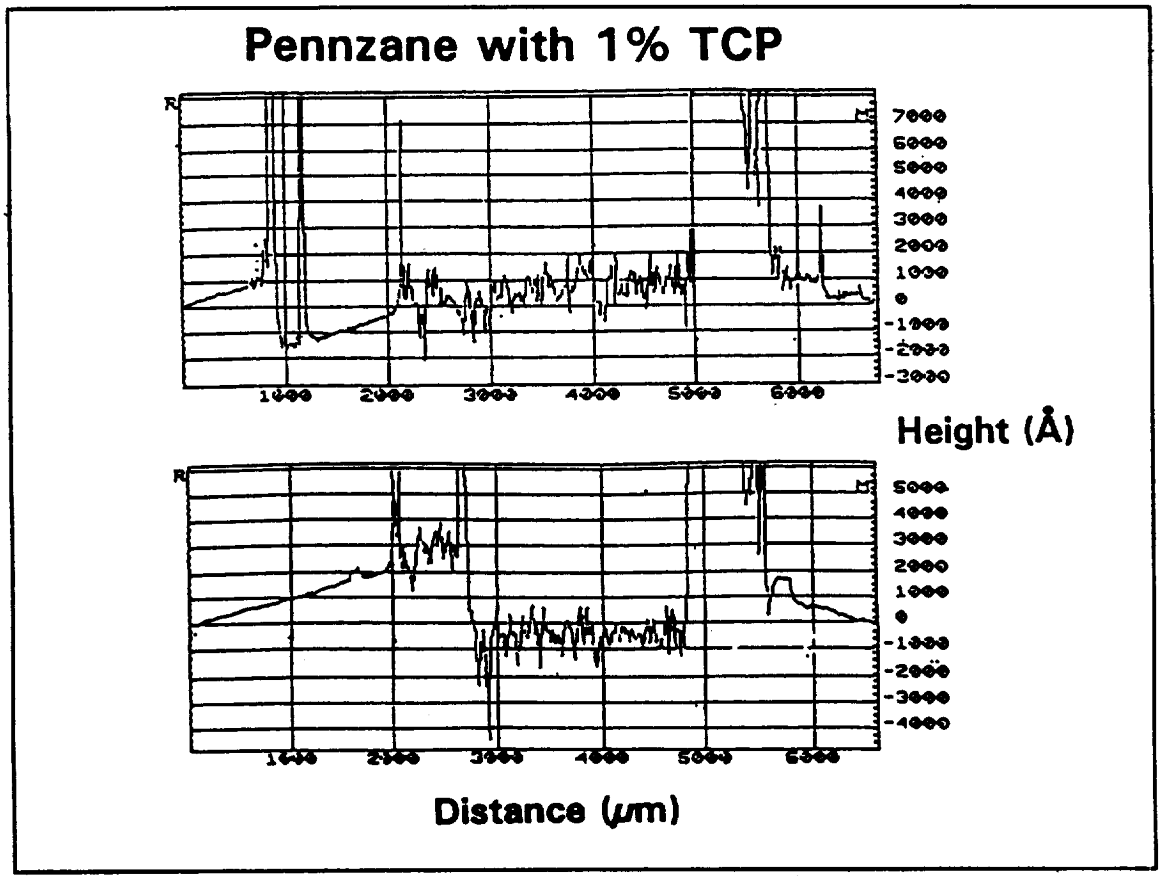

Fig. 6 - Profiles of Pennzane+TCP Wear Disk

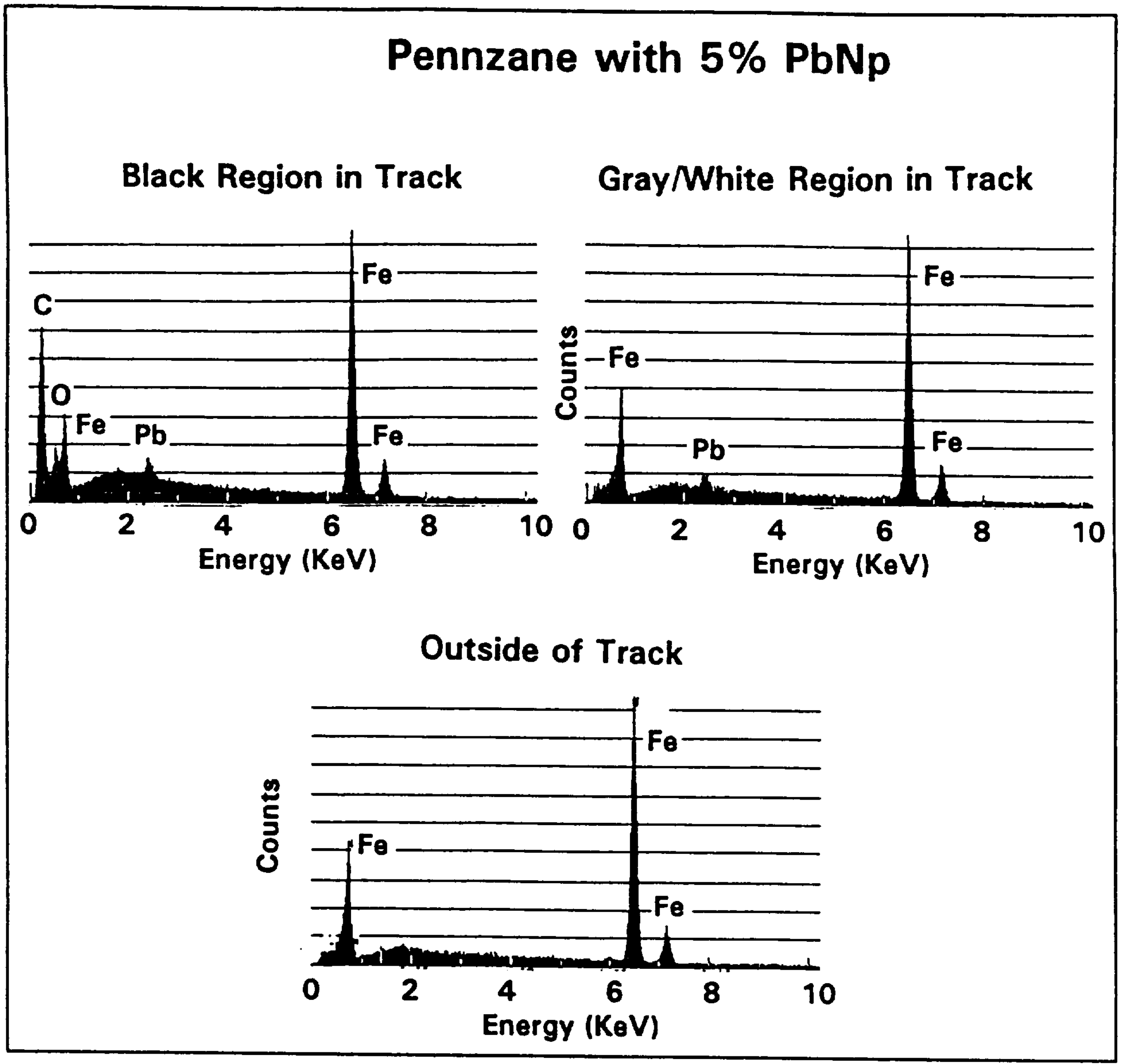

Fig. 7 - EDX Spectra of Pennzane+PbNp Wear Disk

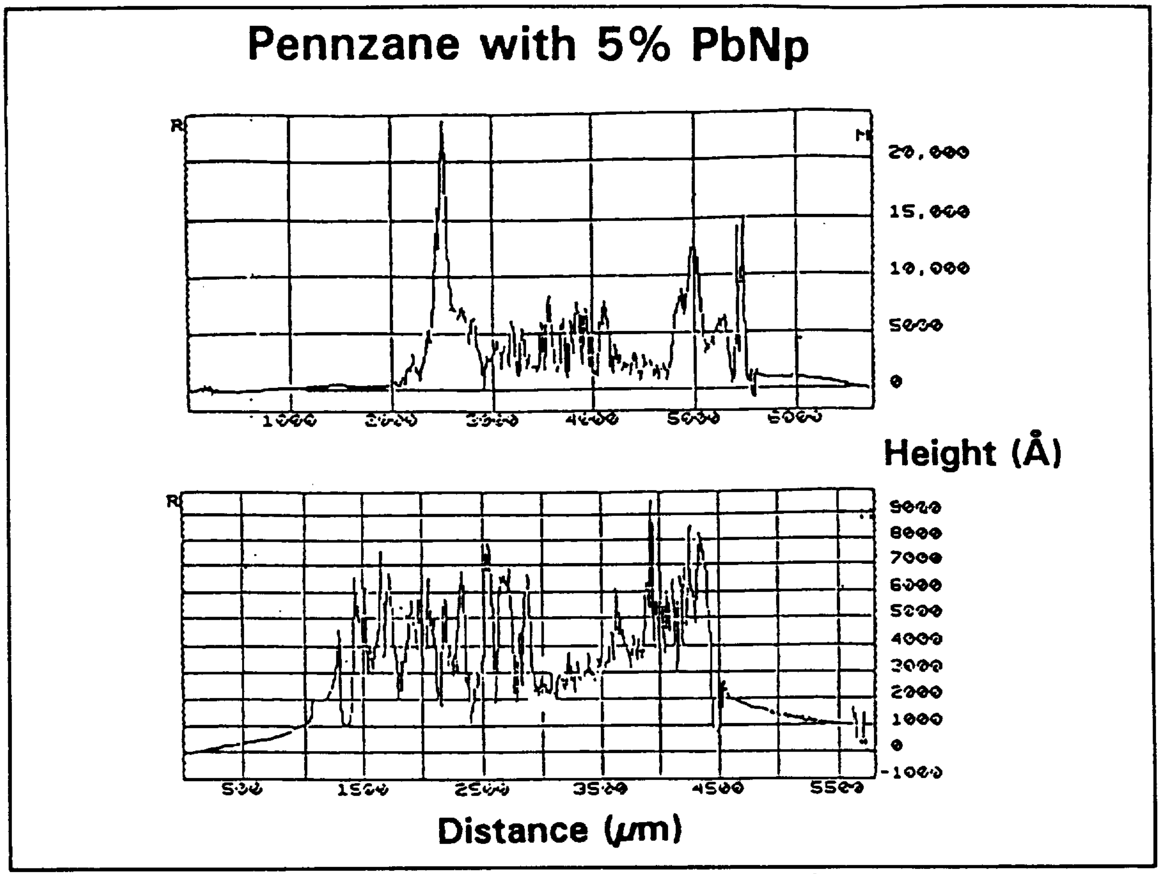

Fig. 8 - Profiles of Pennzane+PbNp Wear Disk

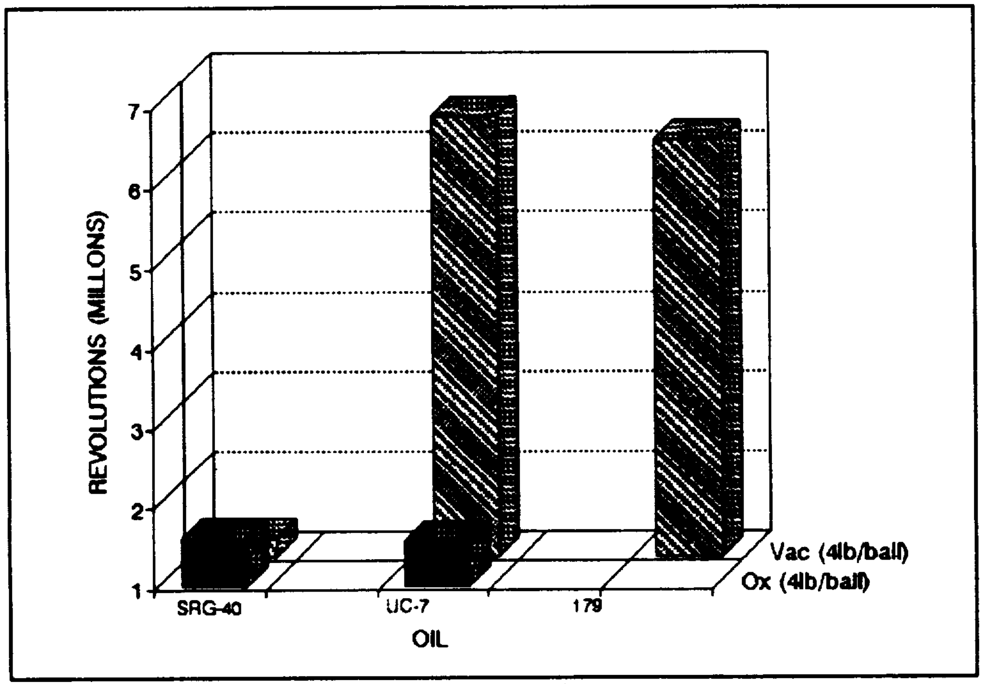

Fig. 9 - Vacuum and O_2 Screening Test Results (RWA)

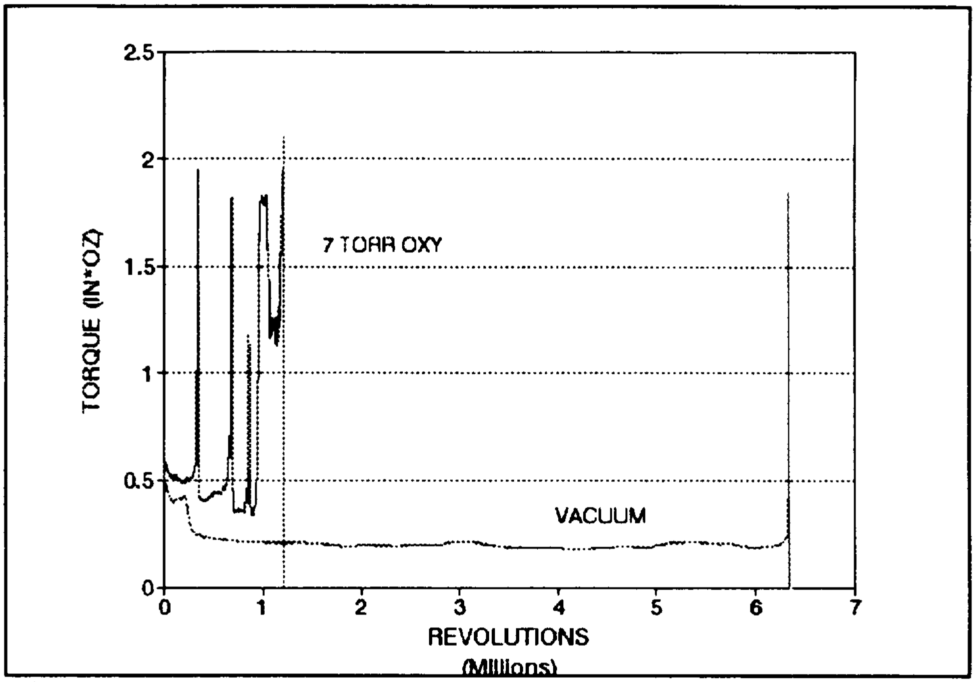

Fig. 10 - Torque Traces of UC-7 in Vac. and O_2 (RWA)

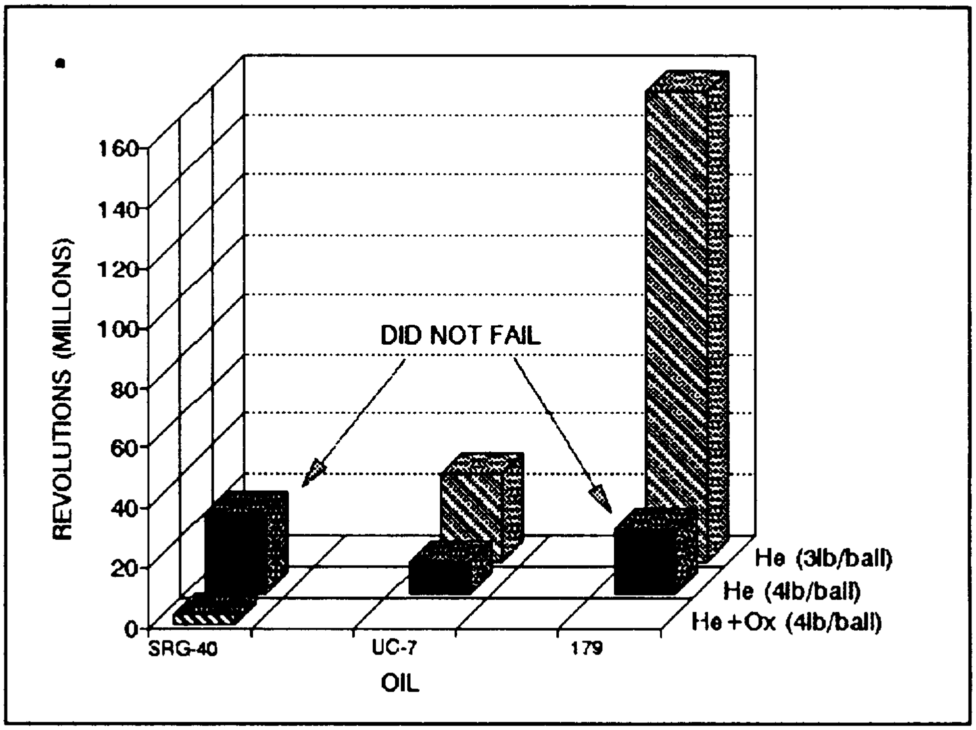

Fig. 11 - 1/2 Atm Screening Test Results (RWA)