# INTERIM RESULTS FROM ESTL STUDIES ON STATIC ADHESION & THE PERFORMANCE OF PENNZANE SHF X-2000 IN BALL BEARINGS

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## ABSTRACT

This paper describes the results from two long term test programmes which have been performed at the European Space Tribology Laboratory (ESTL). The first involves the measurement of separation forces between surfaces which have been clamped together for extended periods in vacuum, and the second relates to the performance of Pennzane SHF X-2000 oil in bearings over extended running periods in vacuum.

In the long term storage test work thirty samples of various material/lubricant types were clamped together, at stress levels up to the yield strength of the base material, for a period of one year in vacuum. On separation in vacuum measurable stiction forces were recorded for only the annealed aluminium couple and for TiC-Coated balls against $MoS_2$ sputter coated 440C.

In long term bearing tests, Pennzane SHF X-2000 performed over $10^9$ revolutions at 1400 rpm and some $1.5\times10^8$ revolutions at 200 rpm. On inspection it has been noted that there has been no degradation of the oil, but there has been oil loss due to evaporation resulting in metallic wear in the worst cases.

*Keywords: Static Adhesion, Pennzane SHF X-2000, Ball Bearings, Vacuum.*

## 1. INTRODUCTION

This paper reports on two ongoing extended test programmes which are being performed by the European Space Tribology Laboratory (ESTL). Studies have been performed regarding the adhesion of materials clamped together for one year in vacuum. Also bearings lubricated with Pennzane SHF X-2000 have been run continually for a period in excess of one year to provide long term performance data to supplement that which ESTL has previously provided to the industry.

The two topics will be reported separately, starting with the long term storage test campaign.

## 2. LONG TERM STORAGE TESTING

*Introduction*

A concern of spacecraft mechanism designers is the possibility of cold welding at interfaces which have been clamped together for long periods in the vacuum environment of space. There are an increasing number of European missions in development which require the flawless separation of this type of interface after extended dormant periods in space.

ESTL has researched the literature and found little engineering data to aid designers in their choice of materials and contact stresses (Ref 1.).

*ESTL Test Facility*

ESTL has designed and built a test facility which incorporates thirty test stations, arranged radially around the central access port of a Ø60 cm vacuum chamber.

Figure 1 shows the general arrangement of the test facility. The test stations are all mounted on a single baseplate suspended from the roof of the chamber. A gate valve is incorporated to form a small vacuum lock at the top of the chamber. This allows the actuation pushrod with its measuring force transducer to be rotated into position above each of the samples in turn without threatening the integrity of the vacuum in the main testing chamber.

Figure 2 shows a test station in more detail. The samples are loaded against a flat static disc by a preload spring. The spring acts on the sample carrier via a load arm which rotates on a Bendix flexural pivot, thus ensuring consistent losses over the duration of the test. When the time arrives to separate the samples **in vacuum** the loading arm is lifted by pushing down on the extension rod. Since the loading pin is engaged in a slot in the loading arm, then the first stage of actuation purely measures the load in the preload spring by offloading the samples. Only when the loading pin has traversed the slot does the loading arm act to separate the samples and at this stage is the

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separation force registered by the force transducer. By utilising a displacement transducer on the top of the pushrod outside the vacuum chamber, a simple X-Y plot showing both the preload and the adhesion force can be obtained.

*Test Samples Chosen*

The test facility has thirty test stations as already described, and as an initial screening test it was decided to use ten different material combinations at three levels of contact stress, in order to investigate the effect of this particular parameter. A further variation was introduced in that six sets of three samples were configured as flat on flat (three pins of Ø0.75mm) whilst the other four sets were ball (three off Ø7.14mm) on flat to simulate the conditions in rolling element bearings.

Table 1 shows the material types chosen, the type of interface barrier applied if any, and the contact type configuration. Load levels were then chosen for each test station, in the case of the flat on flat specimens the yield stress of the weakest bulk material in each pair was set as a reference level and loads were chosen to apply an apparent contact stress of 0.4×, 0.8× & 1.0× this reference level. For the ball on flat samples loads were chosen to apply Hertzian mean contact stress levels of 1, 2 & 2.5 MPa, being the maximum range which would normally be envisaged for a bearing application. Table 2 shows the measured surface roughnesses of the disc samples and the induced contact stresses.

The samples were loaded into the test chamber in October 1993, and were left statically loaded under ambient temperature vacuum until actuation in October 1994. During this period the vacuum pressure level fell continually from $10^{-6}$ torr at the early stages of the test to below $10^{-7}$ torr on completion.

*Test Results and Sample Inspection*

On taking the measurements, only two sets of data showed measurable adhesion forces, these being the annealed aluminium couple (included as a control set) and the TiC-Coated balls versus $MoS_2$ sputter coated 440C steel discs. The measured results are tabulated in Tables 3 & 4. As can be seen from the Tables, in the case of the flat on flat aluminium samples the ratio of the pull-off load to the initial preload is the same for the three different loads, whereas for the TiC-Coated balls on flat when the pull-off load is divided by the calculated Hertzian contact area the pull-off stress is fairly consistent.

Inspection of the samples has shown that all contacts have been under load, however no gross adhesion has taken place for any of the samples. The most striking effect is where the $MoS_2$ has been plucked from the surface by the TiC-Coated balls, as shown in Figure 3.

## 3. PENNZANE LUBRICATED BEARING TESTS

*Introduction*

Over the years since its formation ESTL has regularly performed and reported on the performance of oils in long term vacuum bearing tests. The most recently published test data refers to the performance of the PFPE oil Fomblin Z25 when lubricating bearings fitted with TiC-Coated balls. The results were very encouraging and showed that almost $10^9$ revolutions could be performed before the classic degradation of the PFPE oil resulting in failure (Ref 2.).

The series of tests reported here were to show the effectivity of the Multiply Alkylated Cyclopentane oil Pennzane SHF X-2000 under the same test conditions for similar durations.

*ESTL Test Facility*

A diagram of the test rig used for ESTL tests on liquid lubricants is shown in Figure 4. Two variants of test were performed, one at 1400 rpm under theoretically full elastohydrodynamic (EHL) conditions, and the other at 200 rpm simulating boundary/partial EHL conditions (ie when asperity interaction occurs, as calculated by standard EHL formulae, neglecting any shear thinning or other effect on oil viscosity). The tests were performed at ambient laboratory temperature conditions.

Torque measurements were taken from a strain gauge force transducer. Mean torques were ascertained by periodic reversal of the direction of rotation, and torque noise was defined as the "hash width" (approx ±3 standard deviations) of the torque trace as measured by a potentiometric chart recorder. These measurements are directly comparable with results from previous ESTL tests.

*Test Configuration*

Both the test bearings and the support pair were standard SNFA separable angular contact type (ED20), manufactured from SAE 52100 bearing steel. The test bearings were 'hard' preloaded to 40N in a face-to-face configuration. Other size data is tabulated in Table 5.

In each case the cages employed were one piece outer race riding phenolic, vacuum impregnated with Pennzane SHF X-2000 oil. On assembly each of the bearings were lubricated with 50µl of oil.

The oil was supplied to ESTL by Pennzoil, and was certified as being from batch number 371-57.

*Test Results*

There were two tests performed at each of the sets of conditions and the measured torque results are shown in Figures 5 & 6. As in previous tests the torque levels decreased to low levels, showing low torque noise throughout. Test 2 gave a consistently higher mean torque, believed to be due to inaccurate preload setting.

*Discussion*

The tests were halted in April '95, having performed more revolutions than the previously reported Fomblin Z25 lubricated bearings fitted with TiC-Coated balls. The torque traces showed no sign of any misbehaviour from any of the bearings, however there were aspects of the testing which gave cause for concern. Firstly the pressure in the vacuum chambers was never low enough to allow the ion-pump systems to be activated, and the complete test was performed using a turbopump connected to a common manifold. Secondly in previous tests it has been noted that if the bearings are stopped for a short period then the torque recovers back towards the starting value. This was true early in the test of these bearings, however a final check on completion revealed absolutely no torque recovery at that stage, implying that the bearings were now starved of oil or had alternatively lost preload.

On inspection of the bearings it was noted that the condition of the bearings was apparently directly related to the housing in which it had been tested. The test rigs pre-date ESTL, and various variations in housing style have been generated over the years. Where the ends of the housings were fitted with simple close clearance labyrinth seals then oil was still present on the bearings, however where no seal was present the bearings and cages were visually dry. One cage for instance was dry on one side where it faced the chamber and still wet on the opposite face which was inside the housing. The bearings themselves showed heavy wear in the positions where the molecular seals were absent, and it is assumed that the preload was totally relieved.

There was **no** sign of degradation of the oil in any of the bearings, however there was discolouration due to the wear products from both race and cage. In areas where the cages were dry, there were dark deposits which are assumed to be "burnt" phenolic. Further analysis of the residues will be carried out in due course.

Initial conclusions are therefore that the Pennzane oil does not degrade in the same manner as the PFPE oils (indeed there are no chemical constituents which would lead to this expectation), however the vapour pressure, at least of this particular batch, is significantly higher than that of the PFPE oils. The duration of this test has therefore been set not by the lubrication abilities of the oil, but by the pumping speed, conductance and oil quantities in the test facility. It should be noted that in the many previous tests at ESTL, using the same test hardware, the PFPE oils have never failed due to starvation caused by oil evaporation losses.

## 4. CONCLUSIONS

Adhesion between contacted preloaded surfaces under purely static loading has not been registered in ESTL test work with the exception of two cases. Firstly annealed aluminium samples, and secondly for the case of TiC-Coated balls versus $MoS_2$ coated 440C discs (where the $MoS_2$ was plucked from its substrate by the TiC). It is believed that the influence of surface oxide layers and contaminants is critical here, and ESTL is now looking at incorporating a fretting motion into the test facility which can work the surfaces prior to their storage in vacuum.

The multiply alkylated cyclopentane oil Pennzane SHF X-2000 has been shown not to suffer from the classic degradation suffered by PFPE oils when lubricating bearings operated in vacuum for long periods. However the bearings eventually suffered from oil starvation due to oil evaporation losses, a problem which has never been encountered by ESTL in tests of PFPE oils. The conclusion is therefore that oil quantity, sealing efficiency and the effects of condensing oil on other spacecraft components are the prime aspects to consider if SHF X-2000 is to be used as a mechanism lubricant. ESTL is to undertake further studies using a newly procured batch of oil to investigate if this effect is batch dependent, and will use a soft preloading system in order that the wear process will be registered by the torque transducer.

## 5. REFERENCES

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| Test | Pin Material | Disc Material | Disc Coating | Interface Barrier | Contact Type |
|---|---|---|---|---|---|
| 1 | Vespel SP3 | 7075-T6 Aluminium Alloy | Sulphuric Anodised* | None | Flat on Flat |
| 2 | 722M24 Plasma Nitrided | Ti-6AL-4V Annealed | Sulphuric Anodised~ | MoS2 ' | Flat on Flat |
| 3 | Densimet W | Ti-6AL-4V Annealed | Sulphuric Anodised~ | MoS2 ' | Flat on Flat |
| 4 | 722M24 Plasma Nitrided | Ti-6AL-4V Annealed | Hard Chrome# | MoS2 ' | Flat on Flat |
| 5 | Densimet W | 7075-T6 Aluminium Alloy | Hard Anodised^ | MoS2 ' | Flat on Flat |
| 6 | 6082-O Aluminium Alloy | 6082-O Aluminium Alloy | None | None | Flat on Flat |
| 7 | TiC Coated 440C Ball | 440C Hardened | None | MoS2 ' | Ball on Flat |
| 8 | 52100 Hardened Ball | 52100 Hardened | None | MoS2 ' | Ball on Flat |
| 9 | 52100 Hardened Ball | 52100 Hardened | None | Lead " | Ball on Flat |
| 10 | 52100 Hardened Ball | 52100 Hardened | None | PTFE ''' | Ball on Flat |

Table 1: Table of Materials Under Investigation & their Contact Types

NOTES:

| | | Nom Thickness (microns) |
|---|---|---|
| * | Sulphuric Anodise to Def Stan 03-25 | 10 |
| ~ | Tiadise to Def Stan 03-25 | 0.1 |
| # | Tichrome 100T | 2.5-3.5 |
| ^ | Hard Anodise 300N to Def Stan 03-26 | 38-50 |
| ' | MoS2 sputter coating by ESTL | 1 |
| " | Lead Ion Plating by ESTL | 1 |
| ''' | Spray Bonded Emralon 823 (Acheson Colloids) | ~2-5 |

| Sample | Force/pin (N) | Total Force (N) | Preload (N) | Pull-Off Ratio |
|---|---|---|---|---|
| 6A | 2.3 | 6.9 | 78 | 0.088 |
| 6B | 4.5 | 13.5 | 156 | 0.087 |
| 6C | 5.6 | 16.8 | 195 | 0.086 |

Table 3 Adhesion Measurements for Annealed 6082 Aluminium versus Itself

| Sample | Force/ball (N) | Total Force (N) | Contact Area/ball ($mm^2$) | Pull-Off Stress ($N/mm^2$) |
|---|---|---|---|---|
| 7A | 3 | 9 | 0.00874 | 343 |
| 7B | 9.6 | 28.8 | 0.035 | 274 |
| 7C | 19.2 | 57.6 | 0.0547 | 351 |

Table 4 Adhesion Measurements for TiC-Coated Balls versus Sputtered $MoS_2$

| | |
|---|---|
| OD | 42mm |
| ID | 20mm |
| Width | 12mm |
| Ball Number | 10 |
| Contact Angle | 15° |
| Conformity | 1.14 |
| Preload Shim Height | 16μm |
| Precision | ABEC 7 |

Table 5 Ball Bearing Parameters

| Test Identity | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Sample |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Measured Ra (microns) | 0.38 | 0.18 | 0.26 | 0.66 | 1.03 | 0.24 | 0.05 | 0.07 | 0.08 | 0.06 | A |
| | 0.34 | 0.2 | 0.2 | 0.62 | 0.69 | 0.39 | 0.05 | 0.06 | 0.07 | 0.06 | B |
| | 0.41 | 0.2 | 0.21 | 0.59 | 0.87 | 0.21 | 0.07 | 0.05 | 0.06 | 0.05 | C |
| Contact Stress (N/mm^2) | 14 | 260 | 208 | 260 | 202 | 59 | 1000 | 1000 | 1000 | 1000 | A |
| | 28 | 520 | 416 | 520 | 404 | 118 | 2000 | 2000 | 2000 | 2000 | B |
| | 35 | 650 | 520 | 650 | 505 | 147 | 2500 | 2500 | 2500 | 2500 | C |

Table 2: Table of Disc Surface Finishes & Applied Contact Stresses

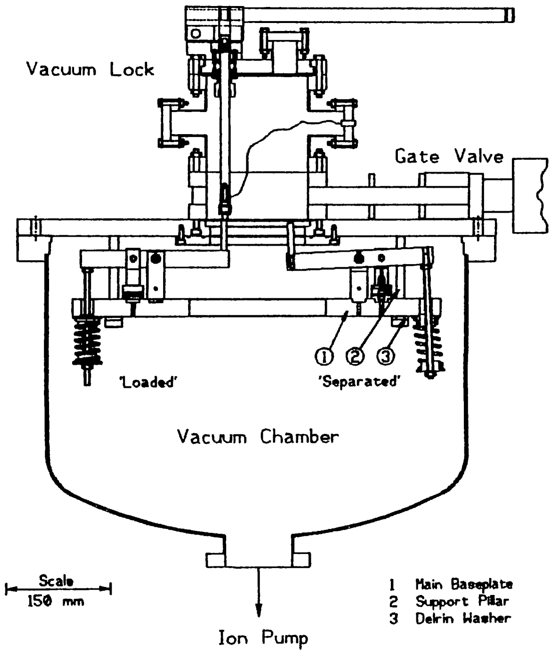


Fig 1 Long Term Storage GA

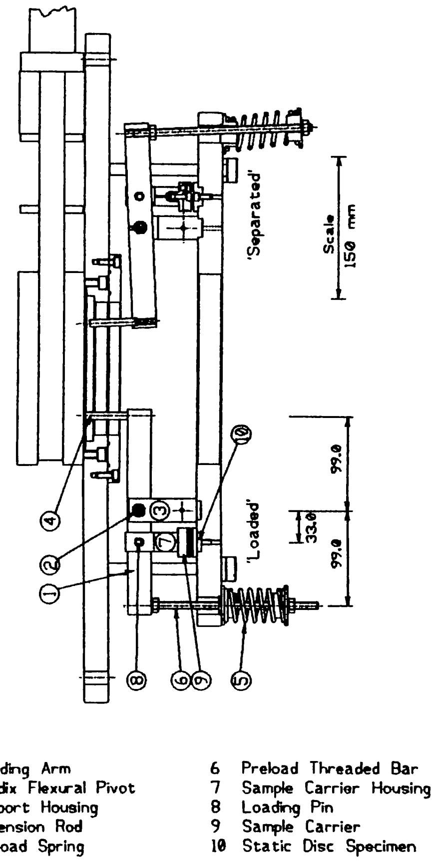


Fig 2 Long Term Storage Test Station

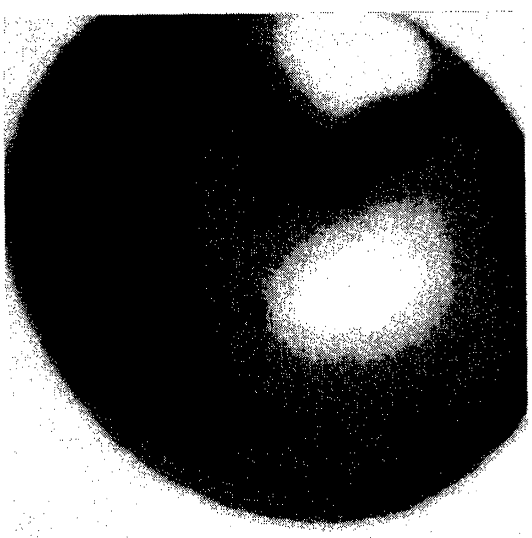

Fig 3 TiC-Coated Ball with $MoS_2$ Pick-Up

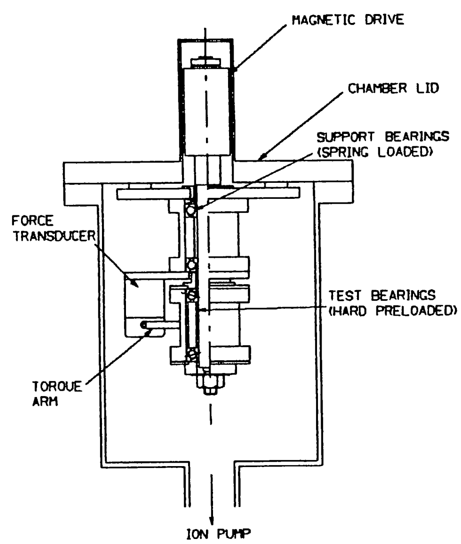


Fig 4 ESTL Oils Test Facility GA

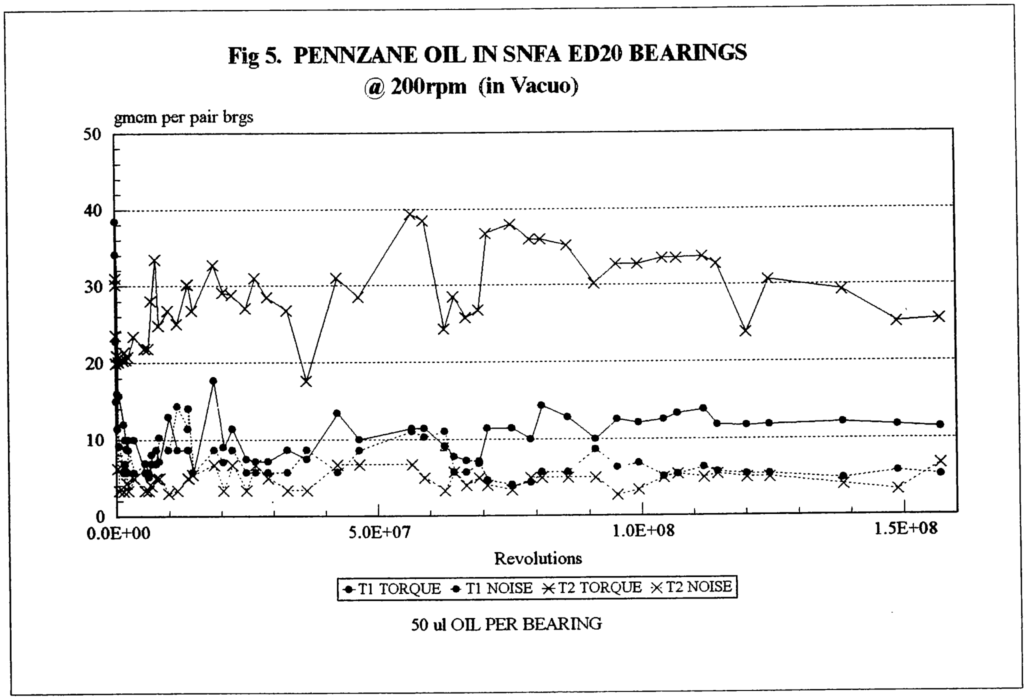

Fig 5. PENNZANE OIL IN SNFA ED20 BEARINGS
@ 200rpm (in Vacuo)
gmcm per pair brgs
50
40
30
20
10
0
0.0E+00
5.0E+07
1.0E+08
1.5E+08
Revolutions
T1 TORQUE
T1 NOISE
T2 TORQUE
T2 NOISE
50 ul OIL PER BEARING


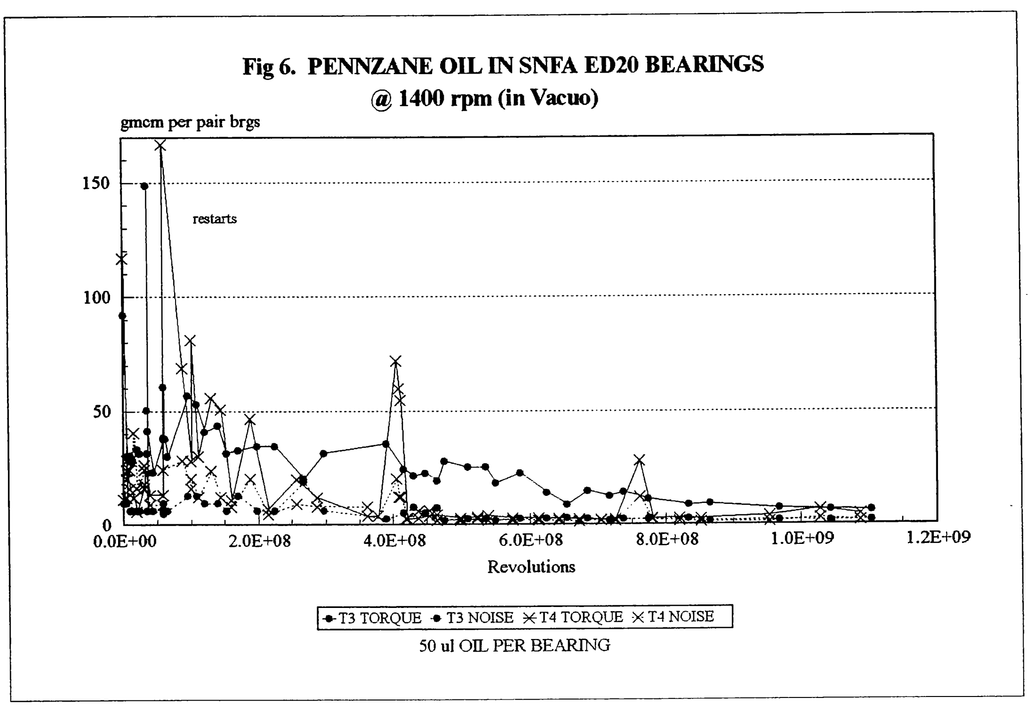

Fig 6. PENNZANE OIL IN SNFA ED20 BEARINGS
@ 1400 rpm (in Vacuo)
gmcm per pair brgs
150
100
50
0
restarts
0.0E+00
2.0E+08
4.0E+08
6.0E+08
8.0E+08
1.0E+09
1.2E+09
Revolutions
T3 TORQUE
T3 NOISE
T4 TORQUE
T4 NOISE
50 ul OIL PER BEARING