IN-VACUUM PERFORMANCE OF FOMBLIN Z25-LUBRICATED, 52100 STEEL BEARINGS WITH TiC-COATED BALLS.

S Gill[1], W B Price[1], R A Rowntree[1], H J Boving[2], H -E Hintermann[2]

European Space Tribology Laboratory (ESTL)[1]
Centre Suisse d'Electronique et de Microtechnique SA (CSEM)[2]

ABSTRACT

The effectiveness of TiC-coated AISI 440C stainless steel balls in preventing the in-vacuo degradation of Fomblin Z25 oil has been evaluated. The balls were incorporated into SAE 52100 steel 20mm bore angular contact ball bearings, and run in an ESTL vacuum bearing test facility. One pair of bearings was run at 200rpm for $1.4x10^8$ revolutions, whilst the second pair performed $9x10^8$ revolutions at 1400rpm. In both tests the bearing preload was 40N.

In both tests, use of the TiC-coated balls led to a substantial increase (by a factor of nine or more) in the life of the Fomblin Z25 lubricant, compared to that found in all SAE 52100 steel bearings.

Keywords: Ball Bearing, Fomblin Z25, TiC, Perfluorinated Oil, Degradation, Vacuum

1. INTRODUCTION

Low vapour pressure fluid lubricants continue to find many applications in spacecraft mechanisms and components, in particular ball bearings. With the advantage of low torque noise and their potential long life, they continue to be used in momentum transfer devices e.g. momentum and reaction wheels, despin mechanisms etc. The testing of liquid lubricants at ESTL, under similar conditions, has been widely reported and recent reviews are available (Refs. 1 & 2).

Because of its unique properties, Fomblin Z25, a perfluorinated oil, remains a very popular choice for space lubrication, despite its well-known shortcomings (Refs. 3-5). This paper reports the results of a pair of tests performed to investigate whether the polymerisation of Fomblin Z25 in steel bearings would be delayed or inhibited by the incorporation of a set of TiC-coated balls.

2. BEARING SPECIFICATION

The test pair of bearings were standard SNFA separable angular contact type (ED20), with SAE 52100 steel raceways and Grade 3 TiC-coated AISI 440C stainless steel balls. To be comparable with earlier work (Refs. 3-4), the bearings were 'hard' preloaded to 40N in a face-to-face configuration. The balls were coated by CSEM. Other relevant data are summarized below:

OD	42 mm
ID	20 mm
Width	12 mm
Ball Number	10
Ball Diameter	7.14mm
Contact Angle	15 degrees
Conformity	1.14 (inner & outer)
Surface Finish	0.03 microns (cross groove)
(R_a)	0.01 microns (along groove)
Precision	ABEC 7

The cages employed were one piece phenolic (outer race riding), vacuum impregnated with Fomblin Z25 lubricant. On assembly the bearings were lubricated with 50 microlitres of Fomblin Z25.

3. TiC BALLS

3.1 Background

Ideally, in a ball bearing the lubricant film carries the load and avoids asperity contacts. However, due to insufficient film thickness, surface irregularities or momentary overloads, asperity contacts do take place. The collisions can lead to microwelds which roughen the surface, and which can degrade the liquid lubricant through decomposition, oxidation or polymerisation. When TiC-coated balls are used in a bearing, there are less asperity contacts because coated balls are smoother than conventional steel balls. In addition, since there is practically no microwelding taking place between steel and TiC, lubricant breakdown is retarded. This has been particularly observed in instrument bearing applications (Refs. 6-7).

Proc. 'Fifth European Space Mechanisms and Tribology Symposium', ESTEC, Noordwijk, The Netherlands, 28-30 October 1992 (ESA SP-334, April 1993)

The original development of TiC balls by CSEM was initially aimed at their use without lubricant in space or other vacuum applications. There are many current space mechanisms relying on TiC-coated balls. Currently, however, over 90% of all TiC-coated balls produced end up in earth-bound liquid lubricated bearings. The main application of TiC balls is in bearings for inertial navigation instruments; this application is very similar to reaction/momentum wheels and long life scanner bearings as used in spacecraft. As ESTL has extensively evaluated the in-vacuum performance of liquid-lubricated all steel bearings, there was a strong interest to run tests with steel bearings using TiC-coated balls with a 'space' oil.

A detailed description of TiC balls is given in the literature (Ref. 8); hereafter are only brief reviews of materials, process and geometry-related aspects.

3.2 Materials and Processes

The substrate of TiC-coated balls is the conventional vacuum remelted AISI 440C stainless steel. The titanium carbide (TiC) coating is produced by the CSEM developed Chemical Vapour Deposition (CVD) process, inside a reactor at 900 - 1050 deg C. The main chemical reaction is the following:

$$TiCl_4\ (g) + CH_4\ (g) \text{ -- } TiC\ (s) + 4HCl\ (g)$$

Figure 1 shows a micrograph of a section through a TiC-coated AISI 440C ball. The 3 to 4 micron thick coating is well adhered and forms a good metallurgical bond with the substrate. A complete description of this CVD process can be found in the literature (Ref 9). The as-deposited coating is, in fact, too rough, and needs high precision lapping/polishing before use within a ball bearing.

With its extreme HV microhardness of 35000 N/mm^2, and Young's Modulus of 447 x 10^3 MPa, TiC is a ceramic material. Despite this, the overall elastic properties of the coated ball can be assumed to be identical to those of an uncoated conventional steel ball; therefore the stiffness of a bearing with TiC balls is identical to that of an all steel bearing.

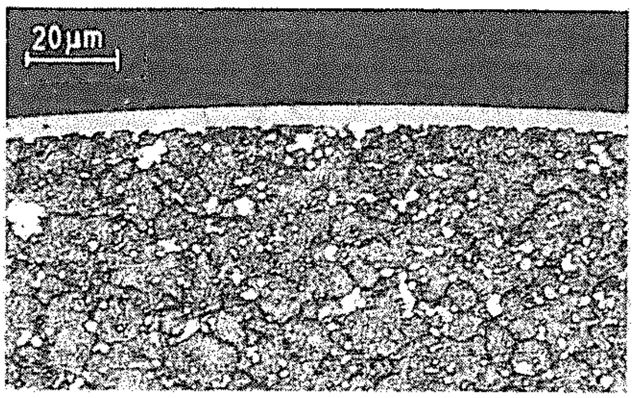

Figure 1. Micrograph of TiC-Coated AISI 440C Ball.

3.3 Geometrical Properties

The TiC-coated balls are polished to Grade 3 - the highest precision level - according to AFBMA (Ref. 10). The corresponding specifications are:

Ball diameter variation	<0.08 microns
Deviation from spherical form	<0.08 microns
Surface roughness	<0.012 microns

4. TEST CONDITIONS

A diagram of the test rig used for ESTL tests on liquid lubricants is shown in Figure 2. Two tests were performed, one at 1400rpm under theoretically full elastohydrodynamic conditions, and the other at 200rpm simulating boundary/partial elastohydrodynamic (EHL) conditions (i.e. 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 laboratory ambient temperature conditions, under a vacuum of better than 10^{-7} Torr. The support bearings were routinely relubricated.

Torque measurements were taken from a strain gauge force transducer. Mean torques were ascertained by periodic reversal of the direction of rotation. Torque noise was defined as the "hash width" (approx. $\pm$ 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.

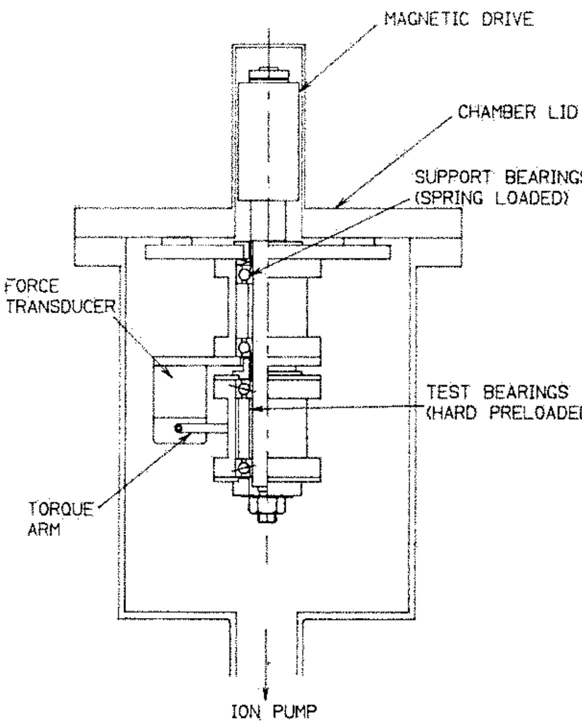

Figure 2. ESTL Bearing Test Rig.

5. TEST RESULTS

5.1 1400rpm

Figure 3 shows the results obtained from the bearing pair rotated at 1400rpm. Also shown are results from an earlier test on standard SAE 52100 steel bearings, which revealed severe lubricant degradation when inspected after 10^8 revolutions (Ref.3, test 5).

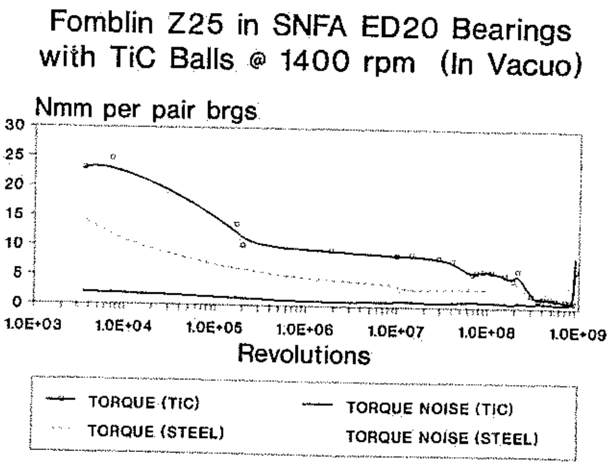

Figure 3

The mean torque fell gradually during the test, almost levelling-out at 2 to 3 Nmm per bearing pair, after about $3x10^8$ revolutions. A similar pattern had been observed in the previous test with SAE 52100 steel balls, except that the mean torque levelled-out after about $5x10^7$ revolutions. The torque noise also fell steadily until it levelled out after about $2x10^6$ revolutions.

As shown in Figure 3, after $9x10^8$ revolutions there was a substantial increase in both the torque and the torque noise, and the test was terminated at this point.

5.2 200rpm.

The mean torque fell steadily throughout most of the test, starting to level-out at 2 to 3 Nmm per bearing pair after 10^8 revolutions (Figure 4). The torque noise remained relatively constant throughout the test. The previous test using SAE 52100 steel balls had behaved in a similar manner to the TiC-coated balls for the first 10^7 revolutions, after which there had been a dramatic increase in torque for the SAE 52100 bearing; this point is thought to coincide with the onset of degradation of the Z25 lubricant, though here there was no corresponding increase in torque noise.

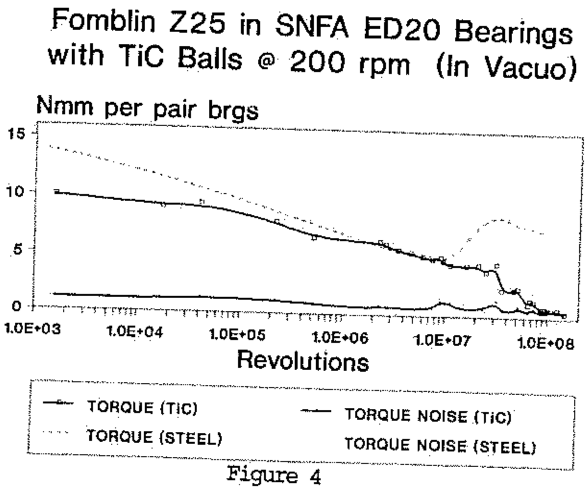

Figure 4

6. BEARING POST-TEST EXAMINATION

6.1 Optical examination

On completion of the extended tests, the bearings were disassembled and examined. The bearings from the 200rpm test remained in pristine condition, with absolutely no evidence of lubricant degradation. However, the bearings from the 1400rpm test showed evidence of extensive degradation of the lubricant. The greatest degradation had occurred on the top bearing, with dark-coloured particles visible on the raceways, balls and cage. Similar, but less extensive debris was visible on the races and balls from the bottom bearing.

Figure 5 shows the balls from the upper bearings after the 200rpm and 1400rpm tests. Balls from the 1400 rpm test were coated with a mainly organic-debris film (i.e. degraded lubricant). This debris could be removed by an implement with a hard point. The underlying TiC coating was intact, but with some indentations. These indentations were attributed to debris on the races deforming the TiC coating, but not causing it to break.

Balls from the 200 rpm test had much less debris adhering, and the polished TiC-coating surface was visible. A few scars and small lap scratches were visible; the latter are quite usual on TiC coatings.

Figure 6 shows the corresponding inner races. The discolouration of the components from the 1400 rpm test is clearly visible.

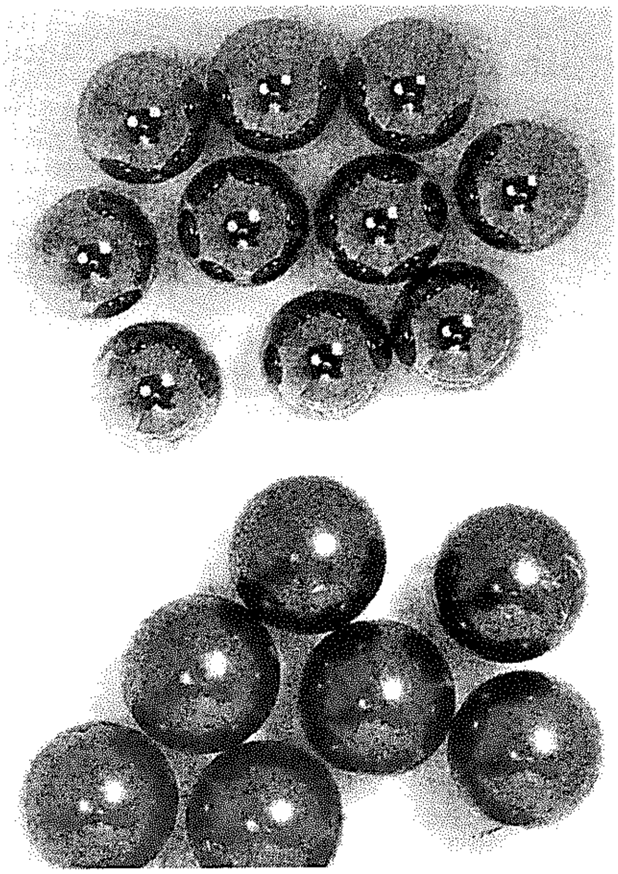

Figure 5. Balls from Test Bearings: 200rpm (top), 1400rpm (bottom).

Figure 6. Inner Races from Test Bearings: 200rpm (top), 1400rpm (bottom).

6.2 EPMA examination

Selected balls were examined by electron probe microanalysis (EPMA). Secondary electron images were obtained from balls tested at 200rpm and 1400rpm; a "new" TiC-coated ball was also examined. Elemental analysis was performed on the debris on one ball from the 1400rpm test.

The secondary electron images showed that the surface of a ball from the 200rpm test appeared smoother than the surface of a "new" TiC ball. Assuming all TiC balls have a similar initial finish, it implies that peaks of the surface asperities were removed during the 1.4×10^8 revolutions of the bearing. No adhered debris, degraded lubricant or damage to the TiC-coating was observed on this ball.

The balls from the 1400 rpm test were coated with solid debris and liquid lubricant residues. Chemical analysis was performed on one ball from the upper race. Figure 7 is a group of X-Ray elemental images of the area around one of the debris particles observed. On each image, the brightest area corresponds to the greatest concentration of the specified element, whilst a dark area indicates that an element is present at a lower concentration than in the surrounding area. Note that the background shade has no chemical or physical significance.

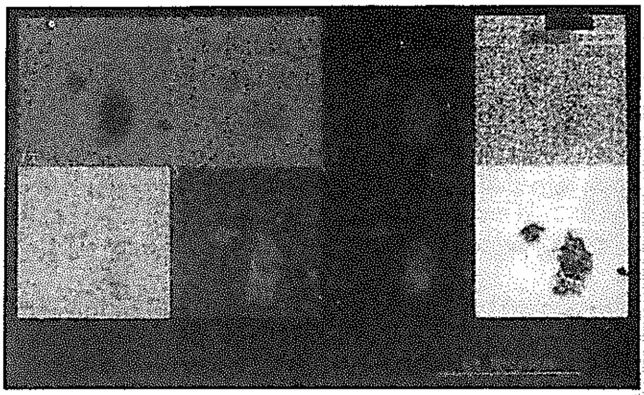

Figure 7. X-Ray Elemental Image, Ball, 1400rpm Test Top Row: Ti, Cr, Fe, Mo; Bottom Row: C, O, F, SEM Image.

The principal elements in the debris particles were Fe, F and O. Carbon could not be identified conclusively in the debris due to presence of carbon in the TiC layer on the balls. The presence of iron, fluorine and oxygen in the debris particles along with the absence of carbon indicates that degradation of the Fomblin Z25 lubricant has occurred.

The inner race of the upper bearing from the 1400rpm test was also examined by EPMA. Debris was present primarily at the edge of the raceway. X-Ray elemental maps showed the presence of two types of debris (Fig.8). The black deposit seen during the optical examination consisted mainly of carbon and fluorine, confirming that there had been degradation of the Z25 lubricant. The lighter-coloured debris particles seemed from the elemental maps to consist mainly of oxygen and fluorine. However, X-Ray spectra confirmed the presence of iron in these particles. Hence, these particles contain a mixture of iron oxides and fluoride. This is in agreement with the results of Carre on the degradation mechanism of PFPE lubricants (Refs. 11 & 12).

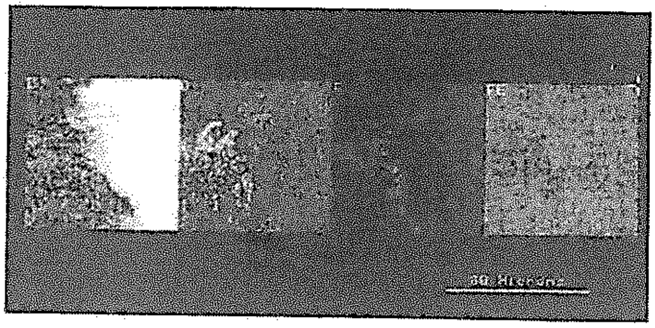

Figure 8. X-Ray Elemental Image, Inner Race, 1400rpm Test. Row: C, O, F, Fe.

There appears to be less iron in the particle than in the surrounding area because the concentration of Fe in iron oxide is lower than its concentration in steel. The spectra also show that traces of titanium have been transferred to the raceway.

7. DISCUSSION

The most widely accepted mechanism for degradation of perfluorinated polyether (PFPE) oils, such as Fomblin Z25, requires the participation of a Lewis acid. In component tests, the Lewis acid is said to be generated by a chemical reaction between "clean" (freshly worn), highly-reactive steel surfaces and the PFPE oil, initially to form FeF_3. This compound is a Lewis acid, which catalyses the degradation of the PFPE oil by way of chemical reactions involving the ether links (-C-O-C-) within the oil (Refs. 11-14). Zehe and Faut have claimed that metal oxides such as Fe_2O_3 can also degrade some PFPE oils (Ref. 15).

Degradation of Fomblin Z25 lubricant was observed only in the test at 1400 rpm, in which the oil is expected to be in the elastohydrodynamic (EHL) regime. In this regime, no ball-to-race contact is expected to occur, and thus "clean", highly-reactive steel surfaces should not be produced.

The identification of iron oxide and fluoride particles in the debris on the races indicates that a "Lewis acid" type of chemical reaction has occurred, and that there must have been some asperity contact with the steel races in the bearings, probably during the latter stages of the 1400 rpm test.

Carre has reported that thermal degradation of PFPE oils can occur in the absence of a Lewis acid (Ref. 13). The presence of the Lewis acid merely serves to lower the temperature at which the degradation has occurred. This led Carre to predict that prevention of the formation of "clean" steel wear surfaces would delay, but not prevent, the onset of degradation of PFPE oils. He predicted that, even if the contacting surfaces were protected by wear-resistant coatings, the maximum possible extension in life of PFPE oils was by a factor of 8. Beyond this point, thermal degradation of the oil would occur.

Carre demonstrated this effect by coating the contacting surfaces with titanium nitride during boundary lubrication tests on thrust ball bearings. Compared with uncoated AISI 440C steel components, the use of TiN-coated components extended the life of the PFPE lubricant (Krytox 143AB) by a factor of 5-10. He found no damage to the TiN-coatings, and hence, no evidence that iron wear debris had initiated the oil degradation. He therefore concluded that thermal degradation of the oil had occurred.

Carre also found that use of silicon nitride balls in contact with AISI 440C races did not extend the life of the lubricant when compared with AISI 440C versus AISI 440C under boundary lubrication conditions. He suggested that this was due to an increase in Hertzian contact stress, due to silicon nitride being harder than steel, cancelling out any benefits gained by reducing the extent of metal to metal contacts. Carre also reported that increasing the applied load reduced the life of the lubricant. The effect of increasing the load would be to increase the number of asperity contacts, and thus to generate additional frictional heat, thereby tending to reduce the life of the lubricant.

If thermal degradation of Z25 oil occurred, the debris particles would contain only carbon, oxygen and fluorine. As noted above, our debris particles contained iron, oxygen and fluorine, which is indicative of degradation catalysed by FeF_3. If Carre's theory about thermal degradation is correct, then coating of the races, as well as the balls, might further extend the life of the Z25 lubricant by at least a factor of ten. However a 10^{10} revolution bearing test at 1400rpm would take over 13 years!

In the 200rpm test, the oil is in a mixed EHL/boundary lubricant regime, with contact between asperities on the balls and races. This would be expected to produce "clean" steel surfaces on the races, leading to formation of FeF_3, and thence to catalytic degradation of the Fomblin Z25 oil. This occurred in the previous test with uncoated steel balls after 10^7 revolutions, but had not occurred with the TiC-coated balls after $1.4x10^8$ revolutions.

This may be because asperity removal was confined to the TiC-coating. Titanium carbide is much less reactive than "clean" iron, and is therefore unlikely to participate in chemical reactions leading to the degradation of the Z25 oil.

If the 200rpm test had been further extended, wear of the races, production of "clean" steel surfaces, and hence Z25 oil degradation, would eventually be expected to occur. However, the duration of the test, 1.4x10^8 revolutions, is adequate for the known life of relevant mechanisms in many satellite applications.

8. CONCLUSIONS

The use of TiC-coated balls in SAE 52100 steel raceways delayed the onset of degradation of Fomblin Z25 lubricant on bearings operating in vacuum. At 1400rpm, there was a substantial increase (at least a factor of nine) of life expectancy over the use of Fomblin Z25 in uncoated SAE 52100 steel bearings. After 9x10^8 revolutions at 1400rpm, the torque and torque noise increased rapidly due to degradation of the Z25. The degradation mechanism involved the participation of iron, resulting in the formation of FeF_3, a Lewis acid, and the consequential catalytic degradation of the lubricant.

At 200rpm, there was also a significant increase (by at least a factor of 10) brought by the TiC coating to the life expectancy of Fomblin Z25 oil, with no evidence of lubricant degradation after 1.4x10^8 revolutions. The balls remained in pristine condition at the end of the test, with no evidence of damage to the TiC-coating.

9. ACKNOWLEDGEMENTS

D Forster & R B Watters of ESTL lubricated the bearings, and assembled & operated the test facility.

10. REFERENCES

1. PRICE W B 1989, Review of ESTL Work on Liquid Lubricants for Space, ESTL/TM/87.

2. ZARETSKY E V 1990, Liquid Lubrication in Space, Tribology International, Vol 23, No 2, 75-93.

3. STEVENS K T 1983, The Performance of Fomblin Z25 Oil in Ball Bearings Operating in Vacuum, Progress Report, ESA(ESTL)56.

4. STEVENS K T 1983, Some Observations of Fomblin Z25 Oil & Braycote 3L-38RP Grease in Ball Bearings & Gearboxes, Proc 1st European Space Mech & Tribology Symp, ESA-SP-196, 109-117.

5. CONLEY P L & BOHNER J J 1990, Experience with Synthetic Fluorinated Fluid Lubricants. Proc 24th Aerospace Mechanisms Symposium, 213-230.

6. McKEE F B 1987, Proc Symp on Ball Bearings Technology., Sponsored by The Charles Stark Draper Laboratory and DoD, Orlando FL, USA.

7. KINGSBURY E 1991, Proc International Rolling Element Bearing Symposium, Sponsored by The Charles Stark Draper Laboratory and DoD, Orlando, FL, USA.

8. BOVING H J & HINTERMANN H E 1987, Thin Solid Films, 153, 253-266.

9. BUNSHAH R F 1982, Deposition Technologies for Films and Coatings, Noyes, Park Ridge, NJ, 335-362.

10. The Anti-Friction Bearing Manufacturers Association, (AFBMA), Metal Balls, Standard 10 1989.

11. CARRE D J & MARKOWITZ J A 1986, ASLE Trans, 28(1), 40.

12. CARRE D J 1990, The use of solid ceramic and ceramic hard-coated components to prolong the performance of perfluoropolyalkylether lubricants, Aerospace Corporation report, SSD-TR-90-32.

13. MORI S & MORALES W 1989, Wear, 132, 111.

14. CARRE D J 1991, The performance of perfluoropolyalkylethers under boundary conditions, Aerospace Corporation report, SSD-TR-91-17.

15. ZEHE M J & FAUT O D 1989, Acidic attack of perfluorinated alkyl ether lubricant molecules by metal oxide surfaces, NASA Technical Memorandum 101962.