FOMBLIN Z25: A NEW METHOD FOR ITS DEGRADATION ASSESSMENT & PROPOSAL FOR SAFE OPERATION IN SPACE

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ABSTRACT

We present an overview of the studies of the past two years performed by the Mechanisms Section of the European Space Research and Technology Centre (ESA-ESTEC), the European Space Tribology Laboratory (ESTL) and Aerospace & Advanced Composites GmbH (AAC) on the tribological and chemical degradation mechanisms of PFPE oil Fomblin Z25.

Tests have been performed using a spiral orbit tribometer (SOT), demonstrating the susceptibility of the lifetime of this lubricant to a range of variables (including load and temperature). A residual gas analyser was implemented, demonstrating a technique for detecting the failure of a PFPE lubricant independent of the friction coefficient through in-situ monitoring of selected volatile gases throughout the tests. To the authors knowledge this work is the first demonstration of the failure of Fomblin Z25 oil independent from friction, torque, or motor current increase.

In addition, SOT and pin-on-disc (POD) research efforts have been aimed at identifying the so called auto-catalytic effect during lubricant degradation.

1. BACKGROUND

Z-type perfluoropolyether (PFPE) oils and greases are produced in Europe, and used extensively in spacecraft applications thanks to their good properties, such as low outgassing, large viscosity index, and a wide operating temperature range. However, contrary to multiple alkyl cyclopentane (MAC) type of greases, whilst their evaporation 'lives' are long, the period of operation over which they remain effective as lubricants is relatively short. This is because their lives under boundary lubrication conditions are limited as a result of degradation initiated by chemical reaction between components within the oil and bearing steels.

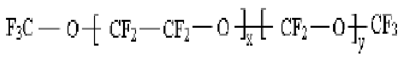
This problem is a particular concern for modern satellite mechanisms, designed for up to 18 years of operating life and relying on properly designed lubrication.

1.1. Degradation Behaviour

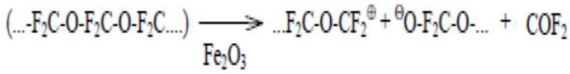
The mechanism that gives rise to this degradation is believed to be as follows [1]:

- Fluorine is released from the oil by the action of repeated shearing under high contact stresses.
- The released fluorine reacts with iron in the steel to form iron fluoride FeF_3 (supported by XPS in [2]).
- Although PFPEs in general are regarded as chemically inert they suffer catalytic attack by FeF_3 which causes further breakdown of oil molecules, resulting in the release of yet more fluorine, whereupon a chain reaction occurs.
- In consequence the rate of oil degradation is accelerated and, tribologically, this results in higher torque, torque noise, and wear.

The formation of FeF_3 and the degradation of the lubricant can be described also with the following 4 schemes [1]:

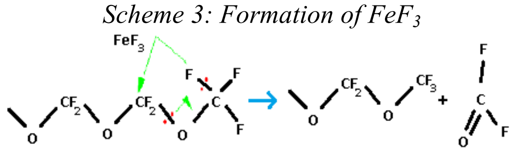


Scheme 1: Molecular structure of Fomblin Z25



Scheme 2: Initial degradation

Scheme 3: Formation of FeF_3



Scheme 4: Fomblin Z25 Degradation by FeF_3

There is therefore a significant desire to understand and characterise this mechanism further, particularly with regard to variables which may change the rate of this reaction, and subsequently affect the operation life of PFPE lubricated components.

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2. SOT TEST PLAN

Numerous spiral orbit tribometer (SOT) tests were performed under varying conditions.

All tests were performed with Fomblin Z25 (40-50µg), and took place under high vacuum (<1.3x10^{-6} mbar).

2.1. Evaporation Test

A single SOT test was performed under conditions designed to cause minimal tribo-degradation of the oil, in an attempt to measure the evaporation life at 100°C. To this end the test was performed at relatively low contact stress, and slow rotation speed.

This test was intended to give some confidence in the second stage of testing, by demonstrating that the evaporative life of the Z25 oil was not so short as to compromise the tribo-degradation life at high temperature.

Table 1. Fomblin Z25 evaporation test

Temperature (°C)	Peak contact stress (GPa)	Ball speed (RPM)
100	1.50	10

2.2. Variable Testing

The matrix below details the test parameters of the oil degradation tests, selected to allow investigations into the effect of temperature, load, and rotation speed on the lifetime and friction coefficient of the oil.

Ball rotation speeds were 114RPM (red) and 10RPM (blue).

All tests were run until failure, defined as a rapid increase in friction (typically above 0.3).

Table 2. Test matrix for lifetime testing on Fomblin Z25

		Peak contact stress (GPa)			
		0.81	1.05	1.50	2.25
Temperature (deg.C)	25	✓		✓ / ✓	✓
	60		✓		
	80	✓		✓ / ✓	✓
	100	✓	✓	✓ / ✓	✓

3. APPARATUS

The Spiral Orbit Tribometer (SOT) is essentially a thrust bearing, with an individual ball held between two interchangeable flat plates, located within a vacuum chamber. A load is applied to the top plate via a spring-loaded linear translator. The lower plate rotates via a motor located outside the chamber, causing the ball to move in a spiral path with a radius ~21mm.

This configuration causes the ball to spiral outwards, and a fixed guide plate is positioned to keep the ball within the flat plates and to produce a repeatable orbit. A force transducer behind the guide plate measures the force exerted by the ball onto the guide plate. From this a friction coefficient value is found, once per orbit. The SOT is controlled using a LabVIEW-based data acquisition program.

The arrangement of the SOT allows the ball to experience rolling, sliding and pivoting – all motions experienced by a ball in an angular contact bearing. This allows for a more representative testing of a lubricant than conventional pin-on-disc testing, which only recreates sliding motion.

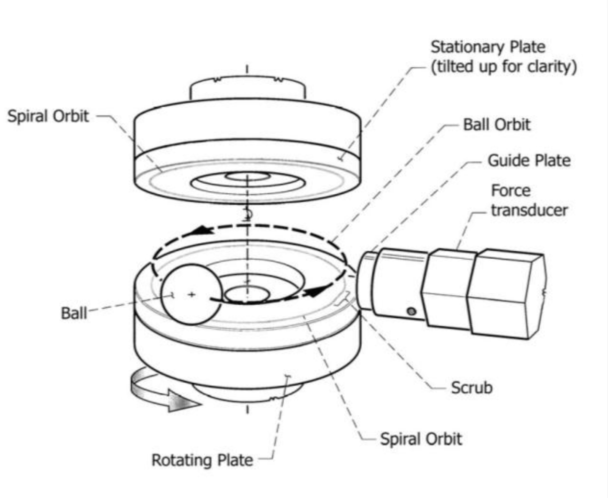

Figure 1. Internal arrangement of SOT

Lifetimes are given in units of oribts/micrograms, allowing for normalization of results should varying lubricant amounts be used.

Heating of the SOT was achieved through the implementation of an IR heating lamp directed through the front window of the SOT, controlled via an active control system. A mid-IR bulb, with wavelengths suited for transmittance through glass, was selected to minimise heating to the external surfaces.

In addition, an AccuQuad Kurt J. Lesker residual gas analyser (RGA) was attached to the SOT to allow identification of gaseous species within the chamber during tests. The RGA was operated only up to 140AMU with a resolution of 0.1AMU. The RGA was operated in analogue scan mode, with a full scan recorded every ~57 seconds. Prior to each test the RGA was degassed, re-calibrated, and tuned to maximise the signal-to-noise of each test.

3.1. Samples

SOT flat samples were manufactured from non-passivated 440C steel, polished to a roughness of Ra<0.05 micron. Balls used were manufactured from 440C steel, of 12.7mm (1/2 inch) diameter, with the exception of the TiC tests which used 5.556mm (7/32 inch) 440C balls.

Prior to lubrication, all balls and plates were solvent cleaned using Lenium ES solvent in accordance with standard ESTL procedure.

3.2. Lubrication procedure

Lubrication was achieved through the preparation of a solution of lubricant diluted in an appropriate solvent to give a known concentration. This solution was applied directly to a rotating ball. The solvent was allowed to evaporate from the ball's surface, leaving the desired lubricant amount. This method allows for the application of very small lubricant amounts, typically 50µg. This minuscule amount of lubricant allows for reduced test times, and ensures all tests take place under boundary conditions.

4. SOT RESULTS

SOT results shall now be presented separately.

4.1. Evaporation Test

The Langmuir equation (Eq. 1) predicts that in a perfect vacuum the oil amount that was used during this test would have fully evaporated at 100°C in less than 10hrs.

$$\frac{dm}{dt} = \frac{0.58}{133.3} P_v \left(\frac{M_m}{T} \right)^{0.5} \text{ kg/m}^2\text{s} \qquad (1)$$

Where T is the temperature (K)
P_v is the vapour pressure at temperature T (Pa)
M_m is the molecular weight of the oil (g/mol)
m is the mass of oil (kg)

This was not the case, with this test continuing to display evidence of oil capable of lubricating 90hrs into the test. Beyond this point degradation was artificially initiated by increasing the rotation speed, verifying the presence of good oil. However as (Eq. 1) could be used to estimate the required lubricant amount in a space mechanism, it is important to discuss in more detail this difference between the predicted and measured results.

The full Langmuir equation for loss by evaporation may be expressed as:

$$\frac{dm}{dt} = (P_v - P_p) \left(\frac{M_m}{2000 \pi R T} \right)^{0.5} \text{ kg/m}^2\text{s} \quad (2)$$

Where P_p is the partial pressure of the oil vapour in the gas phase
R is the gas constant (8.31441 $J \cdot mol^{-1} \cdot K^{-1}$)

Essentially the equation calculates the net loss (or gain) of liquid resulting from the difference between the evaporation rate and condensation rate. It is important to grasp that, in a vacuum chamber, P_p is not the vacuum pressure (e.g. ~ 10^{-6} mbar in the SOT) but the partial pressure of oil molecules.

When calculating the loss of oil in space applications P_p is normally assumed to be zero as it is expected (especially in an open system) that oil molecules evaporating from the oil surface would diffuse away without colliding with other molecules (the mean free path (MFP) being extremely long). Hence the long equation (Eq. 2) reduces to the form shown in (Eq. 1).

In a vacuum chamber operating with a background pressure of 10^{-6} mbar the MFP of gas molecules will be comparable to the chamber dimensions so again molecular collisions are unlikely. In this case evaporating oil molecules will strike (and condense on) the chamber wall or other surfaces within their line of sight rather than collide with other molecules. On this basis the assumption that P_p is negligible also under high-vacuum conditions appears reasonable.

The large difference in the calculated and measured lifetimes on the SOT are likely to result from:

- The prediction of evaporation rate by the Langmuir equation is erroneous when applied to large, non-spherical molecules (the theory was developed in consideration of the evaporation of metal atoms and subsequently extended to 'simple' gas molecules – N_2 O_2 etc.)

- The Langmuir equation is inapplicable to ultra thin oil films. The amount of Z25 oil applied to the SOT ball is equivalent to about 30 mono-molecular layers. This oil is then spread over a larger area by transfer to the ball tracks. As the oil layer becomes thinner there will come a point when the loss of oil by evaporation will be governed not by the bulk properties of the oil but rather by the bonding of oil molecules to the steel substrate.

Despite these difficulties in prediction of the lifetime of the lubricant, the evaporation experiment showed that for a considerable amount of time (at least 90 hours) the degradation of the oil on the SOT in high temperature results from wear rather than evaporation.

4.2. Variable Testing

Following the evaporation test the lifetests described in Tab. 2 were performed. Individual results for each variable are given below (Fig. 2).

Considering load, these results clearly demonstrate a reduction in lifetime with increasing contact stress, irrespective of temperature and rotation speed. These results are in-line with those previously demonstrated on liquid lubricants at room temperature [3, 4]. In addition, friction coefficients were demonstrated to reduce with increasing contact stress.

Tests also demonstrated reductions in lifetime with increasing temperature for all loads and all rotation speeds. The results of our evaporation test rule out the potential for loss of oil by evaporation to be the cause of this reduction, strongly suggesting that the environment temperature plays a significant role in the degradation of Fomblin Z25 oil.

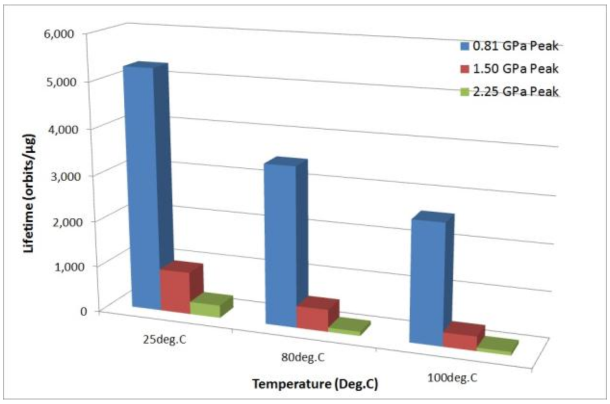

Figure 2. Lifetime results of SOT, showing dependence of life on contact stress for all temperatures

Plotting the lifetimes of all tests at 114RPM together this relationship appears to be linear within the temperature range measured. This observation is curious given that the Arrhenius equation (Eq. 3) suggests an exponential relationship. However this discrepancy may simply be a result of the limited temperature range tested, and with a greater range of temperatures a true exponential relationship may become apparent.

$$k = Ae^{\left(\frac{-E_a}{RT}\right)} \qquad (3)$$

Where k is the rate constant
A is a pre-exponential factor
E_a is the activation energy
R is the gas constant
T is the temperature (K)

Fig. 3 plots the normalized lifetimes relative to the lifetime at room temperature for each load. From this plot we can see the high sensitivity of the lifetime of Fomblin Z25 to temperature. When loaded to 0.81GPa the lifetime at 373K is reduced to 49% of the room temperature lifetime, whilst at 2.25GPa the lifetime at 373K is reduced to only 27% of the room temperature lifetime. Therefore, it is also shown that the sensitivity of lifetime to temperature increases with increased loading.

Considering friction coefficient we see a decrease with increasing temperature. This result is fairly well understood, and is related to the viscosity decrease (easier shear) of the oil with increasing temperature. We would expect to see a significant increase in friction should the ambient temperature be reduced to below 0°C [5].

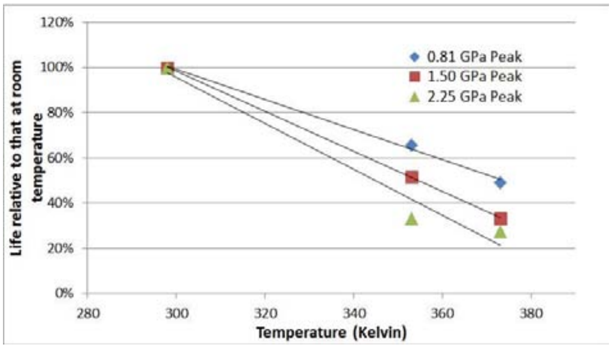

Figure 3. Lifetimes relative to room temperature lifetimes with added trend lines

Regarding speed, the results (Fig. 4) showed no significant difference in the lifetime between 114RPM and 10RPM for Fomblin Z25 oil. This would suggest that it is the ambient temperature of the test (i.e. the chamber temperature) rather than the temperature in the contact zones (influenced by speed) which affects lubricant lifetime.

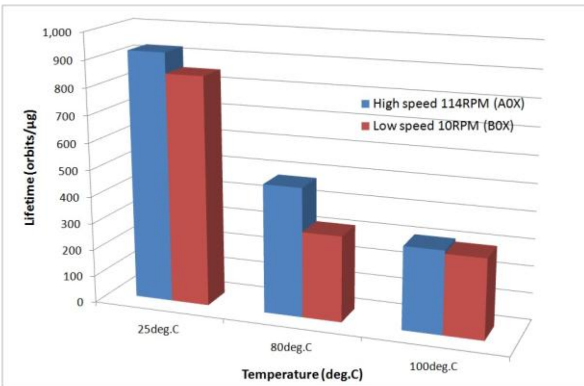

Figure 4. Lifetime comparison of tests performed at 1.50GPa peak, at varying speed

If we consider friction coefficient we see reduced values for lower rotation speeds. This behaviour is expected, and is due to the reduced shear strength of the oil as the rate of shear is reduced.

5. RESIDUAL GAS ANALYSIS

5.1. Degradation at High Temperature

To provide an insight into the relationship between temperature and PFPE degradation a sublimation test was performed in which a sample of 362mg of Z25 oil was placed within a vacuum chamber [2]. The sample was then heated at a rate of 1°C/min, measuring the weight loss of the sample throughout. In addition an RGA was operated throughout the test, to identify at what temperature the Z25 begins to outgas and/or crack.

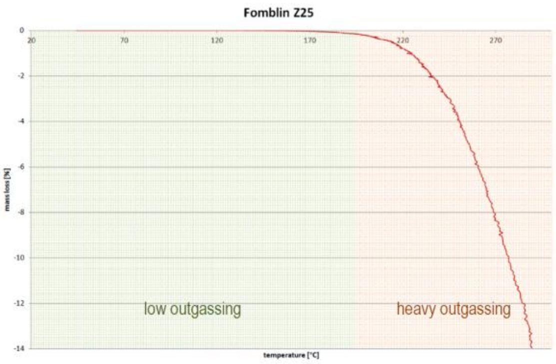

Figure 5. Mass loss of Fomblin Z25 in thermal vacuum. Temperature increased at 1°C/min

These tests demonstrated significant mass loss of the oil between 180°C to 250°C, due to degradation of the oil (occurring when stationary, and non-loaded conditions). This degradation is shown through increases in the partial pressures of certain gas species (Fig. 6).

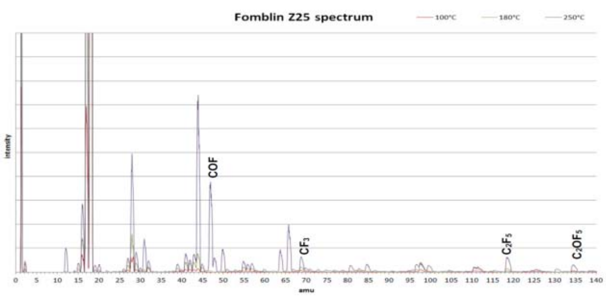

Figure 6. RGA spectrum of Z25 during sublimation test, taken at various temperatures

This allowed us to highlight a number of gas species believed to be related to the degradation of the PFPE oil, which could be observed in-situ. These findings are consistent with experimental work performed at NASA GRC on the degradation of PFPE lubricants (Table 3).

Table 3. Volatile gas species measured in SOT tests

AMU	28	44	47	66	69	119	135
Species	CO	CO_2	COF	COF_2	CF_3	C_2F_5	C_2OF_5

In addition, preliminary POD tests demonstrated that when subjected to contact stress and sliding motion, degradation of the PFPE was observed at much lower temperatures (e.g. 25°C, in comparison to 180°C – 250°C).

5.2. SOT RGA Results

To aid analysis, specific gas species (as partial pressures) were plotted along with friction coefficient, against time [6]. An example is given as Fig. 7. A summary of the progression is given as Tab. 4.

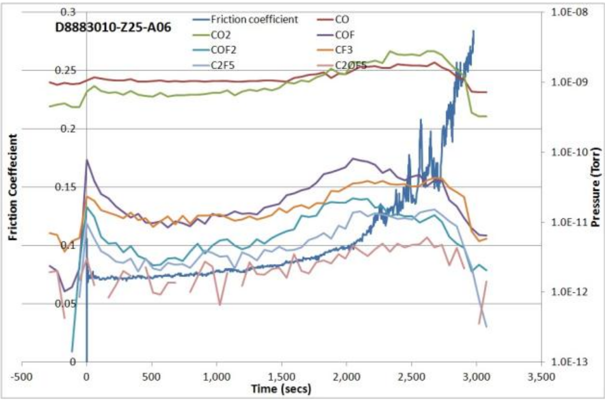

Figure 7. Friction and volatile gas evolution at 80°C, 2.25GPa

Table 4. Evolution of gas species during SOT test (Fig. 7 used as reference)

Time in Fig. 7 (secs)	**Observation**	**Proposed explanation**
-300 - 0	Low pressure prior to motion	No degradation occurring before rolling
0	Initial peak when rolling begins	Degradation begins upon starting motion.
100 - 1,800	Flat readings during 'steady-state'. Peaks most likely 'noise'	
1,800 - 2,000	Increase of the partial pressure values **before significant increase in the friction coefficient**	Majority of oil has been degraded, but enough still present to prevent significant increase in friction.
~2,000	Partial pressures peak.	Maximum creation of volatile gas species as remaining oil degrades.
2,000 - 2,900	Pressures reduce while friction coefficient increases	No un-degraded oil remaining. Volatile gas species being cleaned by the constant pumping of the chamber
2,900 - 3,200	A return to the steady, low values once motion is stopped.	No further oil degradation once motion has stopped

This progression demonstrates that the degradation state of the lubricant can be determined from the volatile gas partial pressures alone, and that the Z25 oil is fully degraded and no longer providing lubrication significantly prior to the friction increasing to our trip limit.

In addition, this work demonstrates that through the monitoring of certain gas species released as the oil degrades, failure of the test can be predicted **before significant increase in friction**. Should this prediction method be used to assess lubricant failure in a mechanism, we would not expect significant wear to have taken place at the time the mechanism test is halted.

6. THE AUTO-CATALYTIC EFFECT (ACE)

It has previously been observed that when exposed to extended periods of dwell under vacuum, following a period of running, some mechanisms that have used PFPE-based lubricants have displayed significantly higher torque on re-start [7]. One possible explanation for this is that once degradation of PFPE oil has begun, this reaction continues even when rotation is halted. Several studies were performed to investigate the existence of this so called auto-catalytic effect (ACE).

6.1. Heating Tests (Impact of FeF_3 on Z25)

As discussed above, the degradation of PFPE oils is believed to be catalysed by FeF_3 reacting with the fluorine released from the oil.

To assess the effect of the FeF_3 to the triggering temperature for the PFPE degradation, a series of heating tests were performed at ESTEC [8]. A Netzsch Simultaneous Thermal Analyser (STA) fitted with a Fourier Transform Infra-Red (FTIR) and Mass Spectrometer was used for these tests, providing precise temperature control and in-situ monitoring of changes in the environment resulting from the PFPE/FeF_3 powder mixture. Tests were performed under atmospheric pressure N_2 gas (chamber previously purged to 10^{-2} mbar) [7].

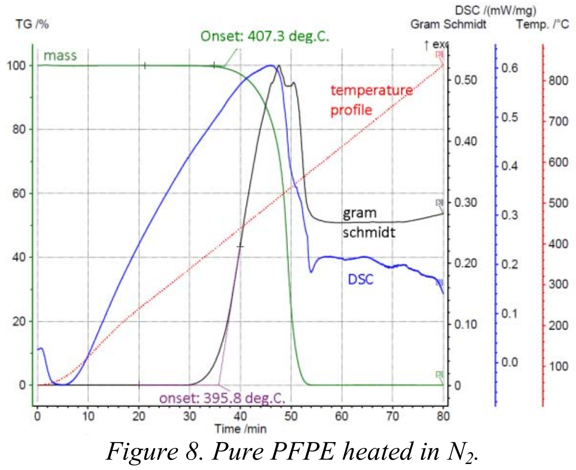

Figure 8. Pure PFPE heated in N_2.

Firstly, the pure lubricant was heated to determine the thermal degradation onset temperature of the Fomblin Z25 oil at atmospheric pressure. This is shown in Fig. 8, presenting the temperature profile (red curve), the total mass loss of the oil (green curve), the Differential Scanning Calorimetry (blue curve), and the FTIR Gram-Schmidt reconstruction (black curve). We observe that thermal degradation occurs at ~407°C, though as this test was performed at ambient pressure, we would expect sublimation to occur below 400°C (Fig. 5).

For the second test, approximately 5 mg of FeF_3 powder were mixed with ~100mg of Fomblin Z25 in an ceramic crucible. These quantities of FeF_3 were intentionally high to ensure results would be measurable during a reasonable timespan. The mixture was heated to 300°C in an N_2 environment. During this test evidence of degradation was observed at a lower temperature, approximately 220°C (Fig. 9).

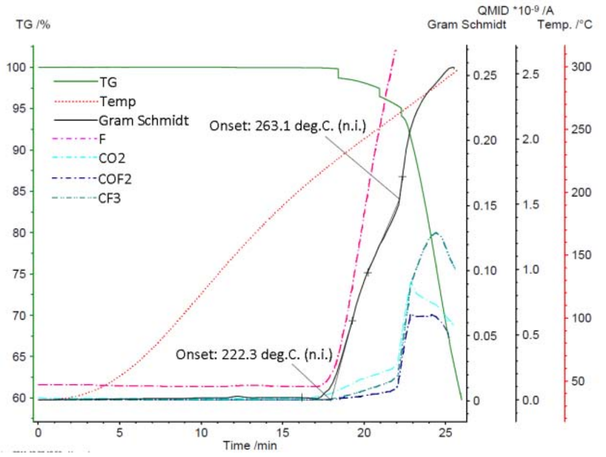

Figure 9. PFPE/FeF_3 heated in N_2.

These tests clearly demonstrate that the presence of FeF_3 affects the degradation of the PFPE, and the temperature at which this degradation is triggered.

A third test was performed in which the PFPE/FeF_3 mixture was first heated to 230°C, and then held at that temperature for the remainder of the test duration (Fig. 10). A mass loss of approx. 75% of the lubricant occurred at ~213°C, but remained constant at 25% following this time. However at 80mins a sudden increase is observed in the RGA readings (especially fluorine) [8].

This behaviour resembles the results that were observed during the SOT tests when the lubricant was failing (Fig. 7), and is interpreted as evidence of the ACE.

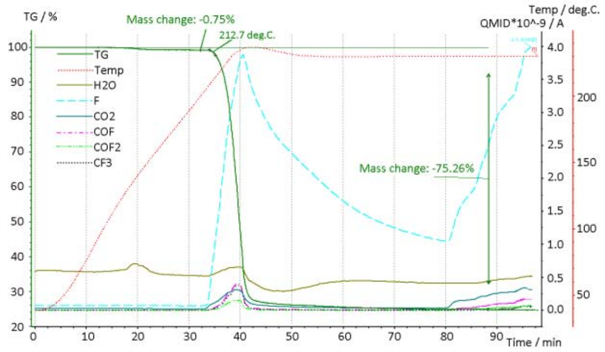

Figure 10. PFPE + FeF_3 heated from 40°C to 230°C with 1 hour of isothermal step.

6.2. ACE on the SOT

As the tests described above were not entirely representative of a realistic scenario due to the artificially induced FeF_3, the ACE was further studied on the SOT through periodic pausing of the motion once degradation of the oil had begun to occur. Tests were performed at 2.25GPa peak contact stress, up to 100°C, under vacuum, with a maximum dwell time of 65hours (Fig.11). The RGA was operated throughout.

In all instances no evidence was seen of continued degradation of the oil during the dwells (only time dependant phenomena), expected to be shown by an increase in the partial pressures read by the RGA. Instead a slow pressure reduction was observed whilst in dwell, consistent with the constant running of the chamber turbo pump.

In addition no friction increase was observed upon restart of motion, and the total rolling lifetimes were comparable to those gained in tests without dwell periods.

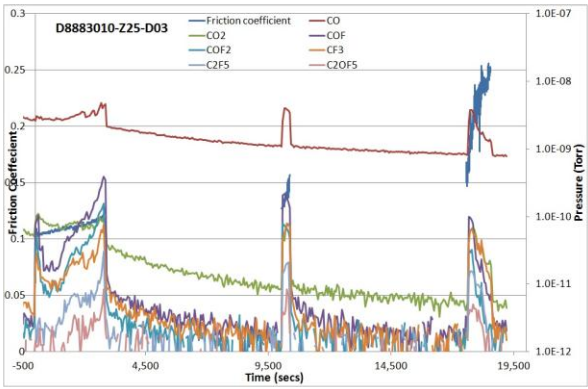

Figure 11. Dwell test on SOT (80°C, 2.25GPa, each dwell 2-hours). No evidence of ACE

6.3. ACE on the POD

In addition, a series of POD tests were carried out at ESTL to further investigate the ACE. Tests were performed in which ~400µg of Z25 oil was applied to a 440C disc using a similar technique to that used for the SOT tests described above, and run at low speed ($0.01ms^{-1}$), 1.80GPa peak contact stress, at 100°C under vacuum. An RGA was used to monitor the degradation of the oil during the test. After a pre-defined period of running, defined as the period required to begin degradation of the oil by sliding, motion was halted and the test subjected to an extended dwell of 144hrs under vacuum at temperature.

Upon restart the friction coefficient was noticeably higher than prior to the dwell, in contrast with the observation from the SOT tests (Fig.11). The friction did not display signs of recovery with subsequent shorter dwells. It is worth commenting that this test was under high temperature dwell for considerably longer than the previous SOT test, perhaps suggesting a time-dependence factor in the onset of the ACE. We can also rule out oil evaporation during this 144hr dwell, as a subsequent test with an identical dwell performed before the onset of motion did not display increased friction (Fig. 12).

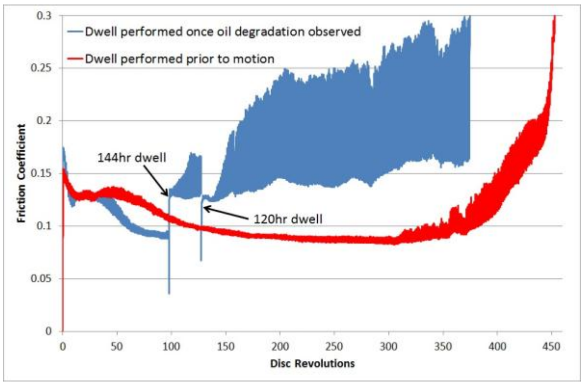

Figure 12. Dwell test on POD, showing increase in friction following 144hr dwell, once degradation of oil initiated through sliding

7. APPLICATION AND GUIDELINES ON USE

Space mechanisms are commonly lubricated with greases that use Fomblin Z25 as the base oil. The lifetimes of two of such greases (Braycote 601 EF Micronic and Maplub PF100-b) were compared on the SOT in [3]. The results showed that on the SOT the lifetimes were similar to the lifetimes of the base oil.

The same greases were also tested by bearing tests in similar conditions as on the high vacuum, and 1.5GPa peak contact stress). Fig. 13 shows that against expectations PF100-b outperformed Braycote by providing a better friction coefficient and lifetime.

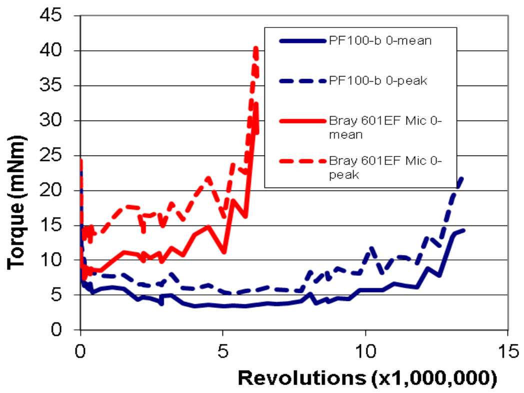

Figure 13: PFPE grease comparison on ball bearing

These conflicting results indicate how difficult it is to predict a lifetime in operation for the PFPE based lubricants in the boundary lubrication regime. The degradation properties of Fomblin Z25 have even made the manufacturer of Braycote to add a note on the datasheet of the lubricant stating that it should not be used continuously in over 0.7GPa (100,000 psi) contact stresses. This is clearly inconvenient for space applications where mechanisms are commonly operated in higher contact stresses. Thus, based on the results presented in Fig. 2 (effect of temperature and contact stress to degradation) it is recommended that for applications having to operate under high temperature 80 to 100°C) it is recommended to keep the contact stresses as low as possible.

Another way to prolong the lifetime of Fomblin Z25-lubricated bearings is to use Titanium carbide (TiC) coated 440C balls. An ESTL study on angular contact bearings [9] has demonstrated that an order of magnitude increase is possible using this coating. A rough comparison extrapolating from available 440C data from [3] and TiC data from [10] as presented in Tab. 5 supports this finding and suggests that TiC balls can prolong the lifetime of Z25 by a factor of 4x in comparison to uncoated 440C steel balls – a conservative agreement with previous findings [9].

Table 5. Comparison of Fomblin Z25 lifetimes, using test and extrapolated data

Peak Hertzian contact stress	Lifetime (orbits/μg)
1.50GPa 440C	1,535
1.88GPa 440C	650
2.25GPa 440C	239
3.00GPa (extrapolated 440C)	**~50**
3.00GPa TiC	**199**

However this increase in life may not solely be related to the ceramic coating protecting the PFPE from reacting with the steel. An independent test program on hybrid ceramic contacts (Silicon Nitride and Zirconia against 440C steel) demonstrated reduced lifetimes of Fomblin Z25 in comparison with pure 440C steel [11].

It is thought that this surprising behaviour might be related to the differing surface roughness between steel and ceramic balls and their ability to restrict the flow of lubricants, but this has yet to be verified. Such an investigation is also preferable for TiC coatings.

8. CONCLUSIONS

The main conclusions of the work presented here are:

- The tribological behaviour of the PFPE Fomblin Z25 oil is affected as tabulated below.

Table 6. Summary of factors affecting the tribological performance of Fomblin Z25

	Increase contact stress	Increase temperature	Increase speed
Degradation lifetime	Decrease	Decrease	No change
Friction coefficient	Small increase	Decrease	Increase

- The method of PFPE degradation through the release and reaction of FeF_3 proposed in [1] appears to be correct.

- It has been shown that (on the SOT at least) failure of the lubricant can be predicted before significant increase in friction, through the monitoring of certain gas species released as the oil degrades.

- Evaporative tests on the SOT and POD suggest that the Langmuir equation for loss by evaporation may not be applicable in these environments.

- Our evidence shows that that as soon as the oil is sheared under mechanical stress (i.e. upon commencement of SOT rotation) high-vapour-pressure degradation products are generated and that this evolution continues until the oil is fully consumed. This means that the amount of non-degraded oil available for effective lubrication is continuously reducing and that, as such, the calculation of evaporation life based on the amount of oil initially applied is too optimistic.

- Extrapolation of the oil consumption rate under given conditions from the SOT to bearings is not trivial, and further work is required before this can be successful.

- Evidence of auto-catalysis has been observed during both stationary heating tests where the catalyst FeF_3 is artificially introduced to the system, and in POD tests in which FeF_3 is produced through shearing of the oil. This point is particularly important with respect to the way we qualify our mechanisms today (no time depending phenomena considered).

This study demonstrates that the degradation mechanisms of PFPE type lubricants are difficult to predict due to the dependence upon many parameters. In light of this, we can only recommend today that mechanism engineers be mindful of the factors affecting lubricant degradation (particularly high contact stress and temperature) with respect to the required duty of their applications.

8.1. Further Work

Future work is anticipated in this field, likely in the following areas;

- Continuation of investigation into the applicability of SOT data to bearing applications. This will include both bearing tests, and SOT testing on more applicable ball sizes.
- Further investigations into factors affecting PFPE lubricant degradation (e.g. passivation of steels, surface roughness investigation).

9. REFERENCES

[1] Marchetti M. hesis "*Aspects globaux et locaux de la mise en oeuvre de la lubrification fluide en ambiance spatiale*" 7 Novembre 000

[2] Merstallinger, A. & Holzbauer, R., '*PoD-QMS*', AAC-77/2011-12, 2012

[3] Buttery, M., '*Spiral Orbit Tribometer Assessment of Space Lubricants*', Proc. 1 th ESMATS Vienna, 2009

[4] Buttery, M., '*Further Spiral Orbit Tribometer Assessments of Space Greases*', E A-ESTL-TM-0089 02-, 2012

[5] unningham, J. M. & Rimmer, A., '*Evaluation of the In-Vacuo Torque Performance of a Range of Space Compatible Oils in Bearing Tests, and a Function of Temperature, Speed, and Oil Quantity*', E A-TM-227, 1998

[6] Buttery, M., '*Characterisation of Degradation of PFPE Based Lubricants*', E A -ESTL-TM-0102 01-, 2012

[7] Gaillard, L. et al, '*FeF_3 Catalytic Influence on PFPE Lubricant's Lifetime under Loaded Conditions*', Proc. 41st AMS Jet Prop. Lab., 2012

[8] Erdogan, A., '*Investigation on the degradation of PFPE based lubricants*', E - MSM/2012/120/ln/AE, 2012

[9] Gill, . & Price, W. B., '*In-Vacuum Performance of Fomblin Z25-lubricated, 52100 Steel Bearings with TiC-coated Balls (Final Report)*', E L-TM-107, 1991

[10] Buttery, M., '*TiC Coating Assessment*', E A-ESTL-TM-0088 01-, 2012

[11] Buttery, M., '*Hybrid Ceramic Bearing Characterisation*', E A-ESTL-TM-0099 01-, 2012

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