DEVELOPMENT OF ADVANCED LUBRICANTS FOR SPACE MECHANISMS BASED ON IONIC LIQUIDS

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ABSTRACT

We present the findings of an ongoing program into the potential use of Ionic Liquid (IL) based lubricants for space mechanisms applications. This multi-stage activity includes assessment of the material properties of the promising candidate ionic fluids, their tribological performances, and vapour pressure measurements.

The activity has highlighted the potential advantages of this family of fluids for vacuum applications; namely impressively low volatilities and favourable tribological behaviours in comparison to conventional vacuum fluids. A down-selection exercise was performed, highlighting the best potential candidate ILs for further study, and validation of these behaviours at component level is planned. However, a requirement for future work is anticipated to mitigate some of the less desirable properties of ILs (namely corrosion).

1. BACKGROUND

Current options for fluid lubrication in vacuum environments are somewhat limited, essentially being a choice between Z-type PFPE polymers (e.g. Fomblin Z25 or Braycote 601EF grease), or MAC type lubricants (e.g. Nye 2001a). However, both lubricant families have their practical limitations – the high susceptibility to chemical degradation of the former [1], and the temperature-limiting evaporative and viscosity properties of the latter. As such there is great desire to demonstrate a new population of lubricants, as any fluid that combines the long life of MACs and the low volatility of PFPEs would prove highly attractive to mechanism engineers. It is considered that Ionic Liquids (ILs), when appropriately formulated, could exhibit these dual properties and as such would be highly favoured for use in space mechanisms.

2. IONIC LIQUIDS

Ionic liquids are salts, consisting of a mixture of negative and positive charged ions in the liquid state, whereas conventional liquids are made up of electrically neutral molecules. Sodium chloride forms an ionic liquid above its melting point of 801°C, but in the context of most studies, the term ionic liquid refers particularly to those materials which are liquid at room temperature (sometimes called room temperature ionic liquids or RTILs). Room temperature ionic fluids typically consist of large organic cations with inorganic anions. The molecular structure of the cations makes crystallisation unfavourable, so that the material remains a liquid [2].

3. SPECIFICATION

To assess the potential of available ILs a requirements specification was prepared, based essentially upon the properties of the popular space oils Fomblin Z25 and Nye 2001a.

Table 1. Requirements specification for ILs

Property / Parameter		**Value**	**Importance**
Vapour pressure (mbar)	20°C	< 4 x 10^{-11}	Mandatory
	20°C	< 2 x 10^{-11}	Preferred
VCM (%)	TML (%)	< 1	Mandatory
	CVCM (%)	< 0.1	Mandatory
	RML (%)	< 0.1	Mandatory
Thermal Stability		Stable to 300°C	Mandatory
Corrosion Inhibition		Good	Mandatory
Kinematic viscosity (cSi)	20°C	100 - 400	Preferred
Viscosity index		100 - 350	Preferred
Pour Point (°C)		< -50°C	Preferred
Max operational temp (°C)		300°C	Preferred
Surface Tension (mNm^{-1})	20°C	18 – 33	Preferred
Solubility		Common solvents	Preferred
Shelf life (years)		Long	Preferred
Chemical inertness		Low toxicity	Preferred
Compatibility with common space materials		Chemically inert	Preferred
Lubricant life (consumption)		Long life	Preferred
Availability		European	Preferred
Cost		Low	Preferred

4. CANDIDATE SELECTION

In the previous two decades, there has been increasing interest in the use of ILs for applications such as lubricants, solvents and electrolytes, including several review articles [2, 3 & 4]. Using this knowledge a preliminary trade-off was performed, highlighting a number of potentially suitable compounds for the current activity.

Given the extremely large number of ILs available, it was not practical to assess every one in detail. An alternative, simplified approach was therefore used, with ILs categorised according to their cation chemistries, and the most promising candidates from each sub-section selected in accordance with the specification. This ensures that the current activity incorporates the range of IL chemistries available. Consideration was also given to those fluids highlighted as having already displayed favourable tribological properties during prior studies.

In terms of cation chemistry, the most commonly used IL types used for tribology research are: imidazolium, phosphonium, ammonium and pyrrolidinium (in order of descending prevalence in relevant research).

- Imidazolium-based cation ILs – One of the more common cation types, with published proof that imidazolium ILs function as lubricants, and have low vapour pressures making them suitable for use in spacecraft applications [5, 6 & 7].

- Phosphonium-based cation ILs – There have been several reports indicating that phosphonium cation ILs are preferable to imidazolium ILs as lubricants due to their anti-wear properties [5], with several ILs highlighted and selected from various literature.

- Ammonium-based cation ILs – This family of ILs has also been suggested to be more effective lubricants than imidazolium cations, with certain fluids performing well in a test campaign including vacuum tribometer and outgassing assessments [6].

- Pyrrolidinium-based cation ILs – Less commonly used than other compound types. However, there have been some promising results, including at SOT level previously performed by ESTL [8].

From these cation chemistries, a list of eight ILs were selected for testing activities, given below. Each IL is given a unique ID number for designation only, and does not refer to the expected performance of the fluids.

It was agreed that all selected fluids would consist of an individual compound (i.e. not consisting of ‘blends’ of several fluids, or an ionic additive to an existing space oil). The sole exception to this is ID1, a formulated product based upon ID5 with an anti-corrosion additive [9]. This fluid has been previously tested at ESTL [8], allowing a direct comparison to demonstrate the effect of the additive.

Table 2. Selected IL candidates for study

Name	Cation type	Anion type
ID1	Pyrrolidinium	Imide
ID2	Ammonium	Imide
ID3	Imidazolium	Sulfate
ID4	Imidazolium	Imide
ID5	Pyrrolidinium	Imide
ID6	Phosphonium	Borate
ID7	Phosphonium	Imide
ID8	Phosphonium	Phosphate

5. PHYSICAL PROPERTIES

The selected eight ILs were assessed for their general physical properties. A brief discussion of each testing activity is given below

5.1. Surface Tension, Wettability & Creep Barriers

Ionic fluids were introduced to common creep barriers (Nyebar LV, 3M Novec 2708 & Dr Tillwich E2 Concentrate) under representative conditions. Results demonstrated poor reactions in several cases, in particular ID6 & ID8, with the creep barriers showing clear evidence of disruption following exposure to the ILs.

In instances where an adverse reaction was not observed, clear beading was apparent for all ILs upon contact with the creep barriers. This demonstrates that existing creep barriers would be successful in impeding the migration of our selected ILs. The use of creep barriers would be required as the surface tension measurements suggested ILs would show comparable wetting effects on untreated steel as conventional vacuum fluids.

5.2. Viscosity

Kinematic viscosity assessments were made of all fluids at 20, 40 and 100°C to ASTM D-445. Viscosity index was measured to ASTM D-2270.

Fluids were found to have a range of viscosity values, with ID6 in particular displaying impractically high viscosity at 20°C (over 6000mm^2/s). Given that this activity was primarily concerned with fluid lubricants for use at room temperature, a ‘working range’ of temperatures for which the ILs provide the desired viscosities was calculated using ASTM D-341. From this it is shown that ID2, ID3, ID7 and ID8 achieve the specification at (or around) room temperature.

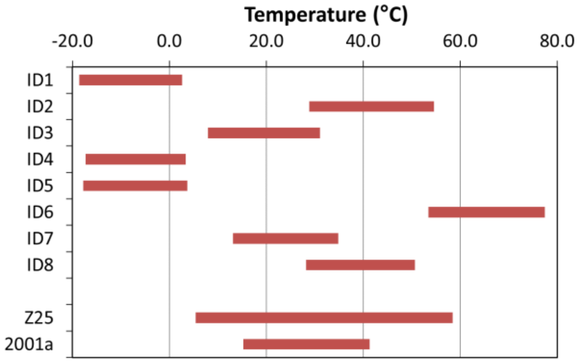

Figure 1. Temperature ranges at which ILs, Z25 and 2001a provide viscosities of 100-400 mm^2/s

5.3. Outgassing properties

An assessment of the outgassing behaviour of all fluids was performed at the ESTEC TEC-QTE laboratory using a µVCM facility to ECSS-Q-ST-70-02C.

Table 3. Outgassing properties of ILs

Name	TML (%)	CVCM (%)	RML (%)
ID1	0.54	0.01	0.54
ID2	0.33	0.01	0.33
ID3	4.3	0.01	-1.53
ID4	0.13	0.07	0.12
ID5	0.07	0.01	0.06
ID6	3.27	0.22	2.48
ID7	0.57	0.02	0.41
ID8	24.93	4.72	0.29
Z25	0.05	0.02	0.04
2001a	0.21	0.05	--

In general, most ionic fluids have reasonable outgassing values in relation to the specification but are significantly poorer than that for Fomblin Z25. ID5 gave the best outgassing values, being the only fluid which gave comparable data to Z25.

ID8 performed particularly badly, with large variance over multiple measurements suggesting this IL was not stable under the test conditions. The same was true of ID3, where a negative RML indicated an elevated level of water absorption after the test, potentially an indication of a permanent change in the composition of the sample (e.g. a replacement of high volatiles in the sample with water, or creation of a gas product as a result of a chemical reaction in vacuum at high temperatures).

5.4. Corrosion

Corrosion tests on all ILs were performed in accordance with ASTM G1 on various metals representative of spacecraft mechanism materials. Tests were performed under accelerated conditions designed to emulate 15-20 years of ambient storage. Following exposure to ILs all samples were cleaned using inhibited acid solutions to remove any corrosion products without attacking the underlying metal. Samples were then weighed and photographed before and after cleaning in a methanol bath.

Results demonstrated the potential for ILs to promote corrosion on metallic surfaces, with corrosion rates on 52100 steel in particular being significantly greater than for unexposed control steel samples. To aid assessment a ranking score was applied to the severity of the corrosion rate for each material/IL combination.

- 1 = Low levels of corrosion
- 4 = High levels of corrosion

Table 3. Severity of corrosion on metallic surfaces

Name	440C steel	52100 steel	17-4PH steel	Al7075 alloy	Ti6Al4V alloy	Total score
ID1	3	2	3	4	1	13
ID2	3	1	3	3	2	12
ID3	4	3	3	4	1	15
ID4	4	4	3	3	1	15
ID5	4	4	3	2	1	14
ID6	3	1	3	3	1	11
ID7	2	1	1	3	1	8
ID8	3	3	3	3	3	15

The performance of the ILs on all materials was then summed to provide a full ranking of corrosion susceptibility.

Table 4. Ranked summary of corrosion rates on ILs

Name	Corrosion score
ID7	8
ID6	11
ID2	12
ID1	13
ID5	14
ID3	15
ID4	15
ID8	15

Doing so highlights ID7 as having the lowest corrosion rates with ID2 and ID6 also performing well. However it must be remembered that (with the exception of ID1) these ILs are not formulated products, and as such do not contain any anti corrosion/oxidation additives. It is therefore perhaps expected that we observe elevated corrosion rates for these ILs. It is known that ionic fluid formulations are miscible with anti-corrosion additives [10], suggesting that this undesirable behaviour could be mitigated in the future.

Fluids were also exposed to non-metallic polymers under identical conditions (PEEK, PTFE, Polycarbonate and Tufnol RLF/2 cotton phenolic cage material). In general no evidence of mass loss or degradation of these polymers were observed, suggesting they are fairly benign to ionic fluid exposure, though there were some exceptions.

5.5. Other Tests

In addition, several other general performance tests were performed on the selected ILs.

- Solvent compatibility – All tested ILs are soluble in common solvents, with ethanol and acetone the most applicable.

- Phenolic impregnation – ID3 reacted negatively with phenolic cage materials during a trial impregnation procedure. All other ILs performed satisfactorily.

- Oxidative stability – ID1, ID6 & ID8 were highlighted as having high susceptibility to oxidation.

- Pour point – Assessed to ASTM D-97. Results demonstrated pour points within the range -45 to -12°C. During the assessment ID1 showed obvious signs of separation of the base IL and the anti-corrosion additive. This separation was also commented upon during the viscosity, outgassing, and oxidative stability assessments.

- Fluid density – Assessed to ASTM-4045. Results demonstrated a range of densities from 1.04 to 1.46 g/ml.

5.6. Down-Selection

As no single ionic fluid performed satisfactorily in every category, a weighted down-selection activity was performed based up the specification requirements. The full details of this down-selection are omitted for brevity, but three ILs were selected for further testing.

- ID2 Ammonium-based cation – A very encouraging IL in all categories, with no major causes for concern.

- ID5 Pyrrolidinium-based cation – Performed very well in outgassing trials, being the only fluid comparable to Fomblin Z25. However also showed potential susceptibility to encourage steel corrosion.

- ID7 Phosphonium-based cation – Provided the lowest corrosion rates and performed very well in all tests. A relatively high pour point of -15°C is a potential cause for concern.

It is potentially interesting to note that our down selected fluids cover unique cation chemistries, but feature a common imide anion.

6. DYNAMIC OUTGASSING

A dynamic outgassing assessment was performed by the ESTEC TEC-QTE laboratory using a VBQC2 facility to ECSS-Q-ST-70-52A with an extended second stage due to the anticipated low volatility of these fluids.

The dynamic outgassing test was performed from 25°C to 125°C in 25°C increments, with the 125°C step extended until the deviation from linearity in the mass loss was less than 1%/hr, with a minimum of 3 days. The vapour pressure at 125°C was then determined from this linear mass loss, along with two lower temperature measurements. These can then be used to determine the vapour pressure of each fluid at a given temperature using the Clausius-Clapeyron relation.

$$\ln \frac{P_1}{P_2} = -\frac{L}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

Figure 2. The Clausius-Clapeyron relation for determining vapour pressure

During the vapour pressure characterisation it was found that fluids of these types may contain dissolved gasses which can form bubbles when subjected to low vacuum (ID2), intermediate vacuum (ID5), or not at all (ID7). It is therefore recommended that all ILs are subjected to a high vacuum degassing treatment of at least 1 hour at RT to prevent this occurring in-flight. However it is also observed that for ID5 such an outgassing procedure may not be effective in fully expelling the dissolved gasses.

Table 5. Vapour pressure performances of ILs

Name	Vapour pressure @100°C (mbar)	Vapour pressure @20°C (mbar)
ID2	2.17×10^{-9}	2.54×10^{-14}
ID5	9.19×10^{-9}	7.68×10^{-14}
ID7	1.95×10^{-8}	7.99×10^{-14}
Z25	3.73×10^{-9}	2.13×10^{-13}
2001a	5.30×10^{-8}	3.00×10^{-11}

Due to issues caused by the bubbling of the fluid, the vapour pressure values for ID5 are likely to be an overestimation, though by less than an order of magnitude.

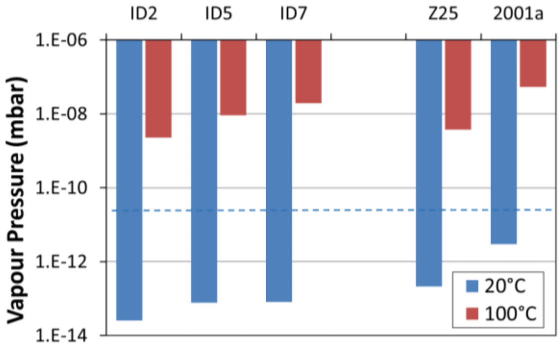

Figure 3. Vapour pressure measurements of down-selected ILs, Z25 and 2001a. Line indicates specification value @ 20°C

Results demonstrated low but measurable vapour pressures for all tested ionic fluids, with our specification met in all cases. At elevated temperatures there is a more marked increase in vapour pressure than for our conventional fluids, perhaps precluding the use of such ILs in hot environments. Nevertheless, the performance at room temperature was very encouraging, with all three ILs taken forward into the tribology phase of the activity.

7. TRIBOLOGICAL PROPERTIES

The tribological performances of the down-selected ILs was assessed using both Pin-on-Disc (PoD) and Spiral Orbit Tribometer (SOT) facilities. Where possible test conditions were selected to allow comparison with pre-existing data on conventional space oils.

7.1. Wear prevention - PoD

PoD tests were performed on all ILs under the following conditions.

- 52100 steel test pieces (standard PoD test items).
- 44±8mg of IL applied directly to the test disc.
- High vacuum ≤ 5 x 10^{-6} mbar.
- 100 RPM (~0.12ms^{-1} sliding speed).
- 100,000 disc revolutions (~7km sliding distance).

Other test conditions are provided below.

All PoD tests ran successfully, with the friction coefficient remaining below 0.3 for the full duration of 100,000 revolutions in all instances. This demonstrates the ability of all three ILs to lubricant steel surfaces under sliding contacts.

During all tests the friction coefficient was observed to increase slightly over the sliding distance. This is interpreted as evidence that the ionic fluids undergo a tribo-chemical reaction induced by sliding, and the product of this reaction is a material with less favourable tribological properties than the 'virgin' fluid (as is the case for PFPE and MAC lubricants). As the test continues this tribo-material builds up within the contact, increasing the friction coefficient marginally.

This also suggests that the failure of the ionic fluids as shearing lubricants is unlikely to be a result of evaporation alone, but rather through tribo-chemical degradation (as with PFPEs [1]), and that the fluids would not have been able to provide lubrication indefinitely, i.e. that failure was inevitable with continued sliding.

Table 6. Results of PoD tests on friction and wear

IL	Peak contact stress (GPa)	Temp (°C)	Mean friction coefficient	Pin SWR (x 10^{-15} m^3/Nm)
ID2	1.50	RT	0.078	130
	1.50	80°C	0.105	237
	0.95	RT	0.076	71
ID5	1.50	RT	0.140	1,737
	1.50	80°C	0.154	2,186
	0.95	RT	0.204	787
ID7	1.50	RT	0.106	204
	1.50	80°C	0.122	1,705
	0.95	RT	0.181	284

Considering friction coefficient, we find that the three ILs provide differing levels of sliding lubrication. ID5 produced the highest friction coefficients during the PoD tests, slightly higher than ID7, which itself was slightly higher than ID2. This is interesting when considering that ID5 features the lowest viscosity at room temperature of these three ILs, demonstrating that the level of friction coefficient is not purely related to the viscous losses of the fluid.

Upon completion of the 100,000 revolutions, post-test inspections showed clear evidence of material wear on both the pin and steel discs. The specific wear rate (SWR) for each test was calculated from the wear scar diameter on the pin. This wear rate was demonstrably greater for ID5 than for the other fluids, suggesting that the wear prevention properties of this fluid are inferior compared with ID2 & ID7.

In addition, some evidence of corrosion was observed on the test items. This corrosion appeared most severe for those tests operated at elevated temperature, and for ID5.

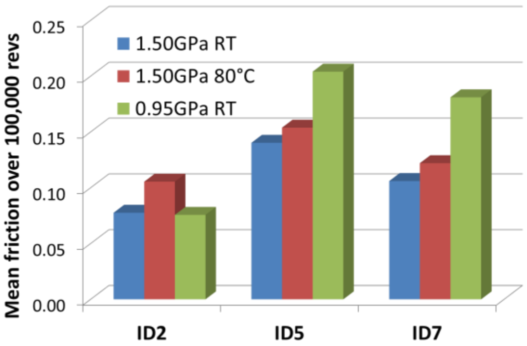

Figure 4. Mean friction over 100,000 revs of IL-lubricated PoD tests under vacuum

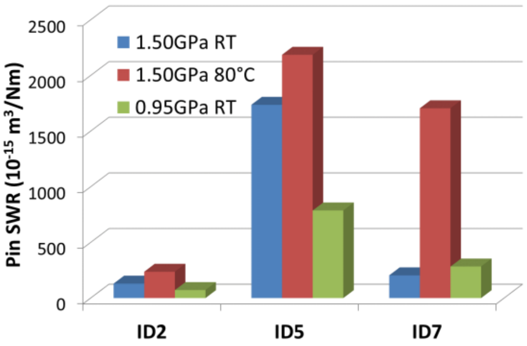

Figure 5. SWRs of test pins lubricated with ILs

7.2. Rolling Friction and Lifetime - SOT

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

The 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. Heating is achieved through an IR heating lamp directed through the front window of the SOT, controlled via an active control system. The lower plate rotates via a motor located outside the chamber, causing the ball to move in a spiral path.

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 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.

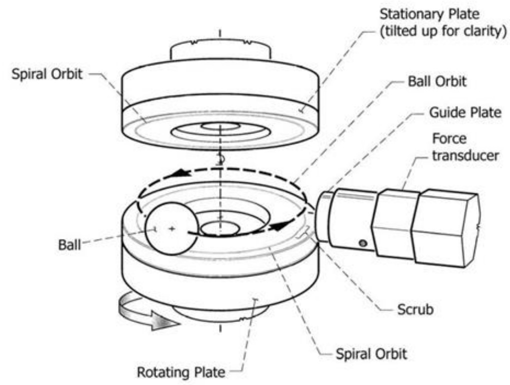

Figure 6. Internal arrangement of SOT

Test items were manufactured of non-passivated 440C steel, polished to a roughness of $R_a \leq 0.05$ micron (standard SOT test items). Lubrication was achieved through the preparation of a solution of IL diluted in an appropriate solvent. This solution is applied directly to a rotating ball. The solvent is 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 per test.

Initial SOT tests were performed under standard conditions (2.25GPa peak, RT, vacuum, 100RPM) to allow direct comparison with pre-existing data on conventional space oils. Under these conditions all IL SOT tests were successful, with friction coefficients remaining low before a rapid increase to failure in a comparable manner to previously observed on PFPE and MAC based lubricants [11]. In general, no evidence of poor vacuum stability or vapour pressure issues displayed themselves during the SOT tests. As for the PoD tests, a slight increase in friction coefficient during the running of the test is observed, prior to the rapid increase indicating failure, attributed to a slow build-up of degraded material within the contact zones.

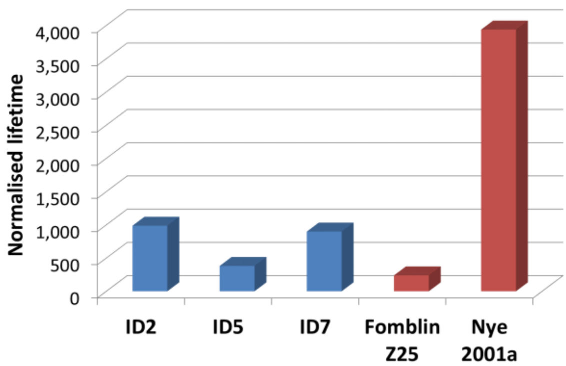

Figure 7. Rolling lifetimes of ILs under vacuum on the SOT

Considering lifetime (Fig. 7), we see that IDs 2 & 7 performed similarly well, with ID 5 performing slightly poorer. In comparison to our conventional vacuum fluids we find that all three fluids provided longer lifetimes than Fomblin Z25 under vacuum, but are still reduced in comparison to Nye 2001a. These results are extremely encouraging, and suggest the potential for ionic fluid lubricant for vacuum applications.

Steady state rolling friction values were comparable to conventional vacuum fluids.

Following this successful demonstration, the susceptibility to contact stress and temperature was assessed. For increasing contact stress a decrease in rolling life and minor increase in friction coefficient was observed for all ILs, comparable to conventional fluids [11]. Increasing temperature produced a lower rolling lifetime and a general reduction in friction coefficient, again comparable to the behaviour observed for Fomblin Z25 [12]. These tests also demonstrated the ability of the ILs to successfully lubricate up to 100°C under vacuum.

Table 6. Summary of factors influencing the rolling tribological performance of ILs

	Increase contact stress	**Increase temperature**
Rolling lifetime	Decrease	Decrease
Friction coefficient	Increase	Decrease

In addition to vacuum performance, the rolling tribological behaviours of our three down-selected ILs were assessed in laboratory air on the SOT. Results demonstrated that the tribological lifetime of the ionic fluids in air are marginally better than in vacuum, with longer lifetimes and lower friction coefficients. This suggests that the ionic fluids are quite robust to operation in ambient conditions, and that operation in air is not expected to severely compromise the performance of the oil. This behaviour contrasts with that observed for PFPE lubricants, in which the lifetime in air is measured to be up to an order of magnitude greater than for the in-vacuum life, with comparable friction [13]. It is also recognised that in-air operation will increase the propensity for corrosion when using these fluids.

Post-test inspections revealed evidence of apparently degraded material deposited upon all surfaces, with greater deposits with the scrub regions and in bandings across the ball. These observations are similar to those typically seen post-test of degraded PFPE lubricants. No evidence of steel wear or corrosion of the contacts was observed from the vacuum-test samples.

Very little observable differences could be seen between the three ILs, indicating similar degradation processes of the fluids. In addition, the test samples appeared similar at elevated contact stresses and temperatures, suggesting that under these conditions the same degradation process occurs, but at an increased rate.

7.3. Residual Gas Analysis

A Residual Gas Analyser (RGA) was operated in-situ for all in-vacuum SOT tests. This has previously been successfully employed for PFPE fluids, where the chemical degradation of the lubricant can be seen through the tracking of volatile gas constituents as the test progresses [12].

A similar assessment method for the ILs highlighted a number of prominent gas species released by the rolling action of the fluid. Many of these compounds (e.g. CF_3 AMU 69, and CO_2 AMU 44) can clearly be identified as fragments of the larger ionic fluid compounds which have been separated during the test, presumably through the action of shearing and/or further reactions.

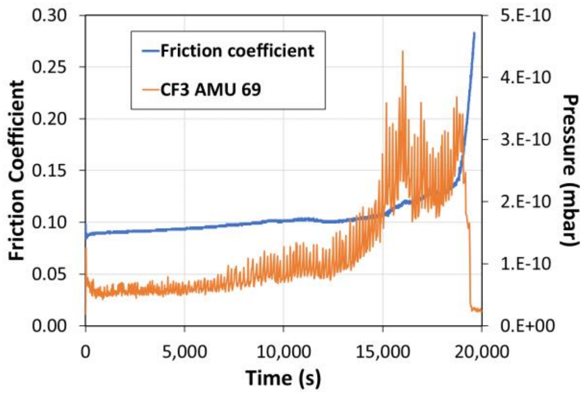

Figure 7. CF_3 behaviour during ID2 test (2.25GPa, RT)

This behaviour is very similar to that seen for PFPE fluids [12] and demonstrates that the tribological failure of these ionic fluids is a result of the (tribo)chemical degradation of the fluid and not evaporation. This theory is consistent with the measured influence of loading and temperature.

What is not known is if this degradation is influenced by substrate material in the same way as PFPEs, whereby reaction with iron within a steel surface can rapidly increase the rate of degradation due to a catalysing influence from the FeF_3 compound [12]. However, given the presence of fluorine within these ionic fluid compounds it is proposed that a similar effect may take place. Such a detailed investigation is beyond the scope of this activity however.

7.4. Down-Selection

The performance of ID5 was either matched or exceeded in all tribological assessments by our other ILs. Given this fact, in addition to the poor corrosion behaviour of ID5, it was agreed to halt testing on this fluid.

The selected ILs from this activity were ID2 and ID7.

8. FUTURE ACTIVITIES

Future testing is planned at ball-bearing level on the remaining two ILs at ESTL. Testing shall be carried out over 10-million revolutions in vacuum and the torque assessment of the bearings monitored.

Given the temperature dependence of the ILs, conditions shall be selected to include elevated and reduced temperatures. The need to perform tests at a range of temperature is clearly demonstrated when we consider the behaviour of existing space lubricants, where a rapid increase in torque is observed as the temperature approaches the pour point of the liquids [14]. Though this is well understood in relation to the increasing viscosities at lower temperatures, it is important that such behaviour be characterised for our selected ILs.

9. CONCLUSIONS

A number of European IL options are available which in general show great promise for use in space applications including:

- Favourable physical properties
- Tribological lifetimes longer than Fomblin Z25
- Lower vapour pressures than conventional vacuum oils

However ILs should not be considered a 'magic bullet' for fluid lubrication, with some critical issues still requiring attention if this family of oils is to be employed. Most significant amongst these issues is their promotion of corrosion on steels, which can be severe with some ILs. Given that it is known that ILs can take up anti-corrosion additives, it is anticipated that this issue may be overcome in the future by the formulation of low volatility anti-corrosion additives and appropriate attention to formulations/blends of such additives with base fluids.

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10. REFERENCES

[1] Carré, D. J. (1986), '*Perfluoropolyalkylether Oil Degradation: Influence of* FeF_3 *Formation on Steel Surfaces under Boundary Conditions'*, Tribology Trans., 29(2)

[2] Somers, A. E. et. al. (2013), '*A review of Ionic Liquid Lubricants'*, Lubricants, 1

[3] Bermudez M-D. et. al. (2009), '*Ionic Liquids as Advanced Lubricant Fluids',* Molecules, 14

[4] Zhou, F. et. al. (2009), '*Ionic Liquid Lubricants: Designed Chemistry for Engineering Applications*', Chemical Society Reviews, 38

[5] Totoli, V. et. al. (2014), '*Tribological Investigations of Ionic Liquids in Ultra-High Vacuum Environment*', Lubrication Science, 26

[6] Holzbauer, R. & Merstallinger, A., (2006), '*Ionic Liquids as New Lubricants for Space*', ARCS-Ionic-Doc02

[7] Morales, W. et. al. (2012), '*Tribological Testing and Thermal Analysis of an Alkyl Sulfate Series of Ionic Liquids for Use as Aerospace Lubricants'*, Tribology Trans., 55(6)

[8] Buttery, M. (2015), '*A Preliminary Evaluation of Ionic Fluid Lubricants for Space'*, ESA-ESTL-TM-0159 01-

[9] Okaniwa, T., Hayama, M., (2013), '*The Application of Ionic Liquids into Space Applications*', Proc. 15th ESMATS, Noordwijk

[10] Liu, W. M. et. al. (2002), '*Tribological Performance of Room-Temperature Ionic Liquids as Lubricant*', Tribology Letters, 13(81)

[11] Buttery, M. (2010), '*Spiral Orbit Tribometer Assessment of Space Lubricants*', ESA-ESTL-TM-0066 01-, 2010

[12] Buttery, M., Gaillard L. et. al. (2013), '*Fomblin Z25: A New Method for its Degradation Assessment & Proposal for Safe Operation in Space*', Proc. 15th ESMATS, Noordwijk

[13] Kent, A., (2016), '*Lifetimes of Space Greases in Air*', ESA-ESTL-TM-0190 01-

[14] Anderson, M. J. & Cunningham, J. M., (2000), '*Evaluation of the In-Vacuo Torque Performance of a Range of Fluid Lubricants for Space Applications*', ESTL-TM-222