BALL BEARING TESTING IN SUPPORT OF MTG IRS INSTRUMENT

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ABSTRACT

ESTL carried out a ball bearing life test programme in support of the development of the Metosat Third Generation Infrared Sounder (MTG IRS) instrument [1]. Two ball bearing pairs were tested simultaneously in the same vacuum chamber. One pair was solid lubricated (sputtered MoS_2 applied to the balls and raceways) and the second fluid lubricated using Fomblin Z60 oil.

The test results indicated that the torque performance of the fluid lubricated ball bearings was superior to that of the solid lubricated bearings. It was concluded that the fluid lubrication represented the most appropriate solution provided any potential contamination risk resulting from oil evaporation was acceptable.

1. INTRODUCTION & OBJECTIVES

ESTL carried out a ball bearing life test programme in support of the MTG IRS instrument proposal activities conducted by Astrium, Germany.

The objectives of the life test programme were:

- To carry out a representative life test programme to evaluate the lifetime performance of the two lubricant options baselined for the IRS instrument. The programme comprised ground simulation, vibration testing and thermal vacuum testing.
- To characterise bearing frictional torque as a function of operational life for two lubricant options.
- To compare the performances of a fluid-lubricated and a solid-lubricated ball bearing pair.

2. TEST ITEMS

The test items were FAG XCB71916 T P4S angular contact ball bearing pairs manufactured from Cronidur 30 steel and fitted with silicon nitride balls. One ball bearing pair was lubricated with sputtered MoS_2 applied to the raceways and balls and fitted with vacuum heat-treated PGM-HT cages. The second pair was lubricated with Fomblin Z60 oil, which has an exceptionally low vapour pressure of $1.1x10^{-16}$ mbar at room temperature, and fitted with Z60-impregnated cotton-phenolic cages. The ball bearings were hard-preloaded (1400N for MoS_2 and 1200N for oil). Table 1 provides additional bearing details.

Table 1: Bearing details

Parameter	XCB71916
Manufacturer	FAG
Ring material	Cronidur 30
Ball material	Silicon nitride
OD (mm)	110
ID (mm)	80
Width (mm)	16
Free contact angle (degrees)	25
Inner/outer ring conformities	1.07/1.05
Ball diameter (mm)	9.525
Ball complement	25
Mounting configuration	Back-to-back
Housing and shaft materials (baseline)	Ti-alloy
Ball overlap angle at inner ring (deg)	26.4
Ball overlap angle at outer ring (deg)	22.7

3. TEST DETAILS

Two ball bearing test stations were installed in a 60cm diameter thermal vacuum chamber to allow parallel testing to be carried out. To enable the potential contamination risk associated with testing fluid-lubricated and solid-lubricated bearing pairs in the same chamber to be minimised, a cold finger (held at -20 deg C) was installed in the test chamber. Labyrinth seals were used on both sets of bearings to minimise oil loss and to prevent oil ingress to the MoS_2 lubricated bearings. Witness plates were also installed in the test chamber to assist in the evaluation of potential oil contamination.

The ball bearings were subjected to accelerated scan profiles comprising 8.4 deg movements with larger angle regeneration cycles carried out over ±30 degrees. The accelerated life test and regeneration profiles are illustrated in Figures 1 and 2, respectively. The regeneration cycle was carried out to help minimise the effects of a localised build-up of wear debris at the limits of the 8.4 deg movement. During the accelerated test phase, a slow speed scan profile was also carried out every hour, followed by a single large angle sweep

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of ±30 deg (regeneration cycle, movement from -30 deg to +30 deg, followed by return).

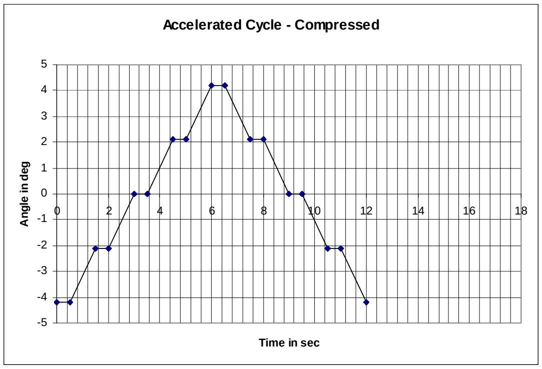

Figure 1: Life test profile

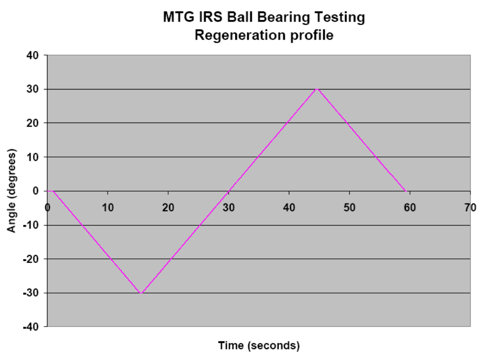

Figure 2: Regeneration profile used in life test programme

The Ground Simulation Test was carried out in nitrogen gas for 168,642 cycles (includes safety factor of four) at laboratory ambient temperature. The data was logged continuously by LabView software, which recorded the mean torque output, the peak torque, standard deviation, test temperature, angle of movement and also stored the raw data on hard disk.

For the vacuum phase, the bearings were tested at +55 deg C and a thermal gradient of less than 1 deg C maintained during testing (original target was 0.5 deg C). The housing and shaft temperature sensors were monitored and recorded continuously during the test.

The bearings was driven by means of a stepper motor and a 100:1 reduction harmonic drive gearbox located externally to the vacuum chamber. The accelerated motion profile comprised an outward movement of 8.4 deg followed by a return movement, also of 8.4 deg. After the ground cycles, the bearings were exposed to thermal vacuum cycles, representing the orbit conditions. The number of test cycles carried out is provided in Table 2. Based upon these numbers, there are two ball passes every time the bearing moves 30 deg, ie four ball passes per movement from zero to 30 deg and hence four ball passes every regeneration cycle.

Table 2: Vacuum cycles

Type	Number of predicted cycles	Factor	Test Cycles
In -orbit	10	10	100
	990	4	3960
	99000	2	198000
	616727	1.25	770909
Total orbit	716727		**972969**

4. RESULTS

1.1. Vibration Testing

Vibration testing was successfully carried out and the conclusions from the vibration tests are as follows:

- All testing was completed as required and the pass criteria were satisfied. No damage or unexpected volumes of debris were produced. A minor quantity of fine MoS_2 particles was observed from the MoS_2 lubricated ball bearing assembly.
- Little evidence of settling was observed and all natural frequencies remained within 1.2% of their initial values during testing.
- In the intended flight configuration gapping as predicted was not observed. However, the vibration test would still have pre-conditioned the lubricants for the subsequent life test programme.

1.2. Ground Testing in Nitrogen

The following table provides a summary comparing the peak-to-peak torque trends taken from the accelerated scan profiles in nitrogen during the simulated ground test.

Table 3: Summary of peak-to-peak torque trends in nitrogen from accelerated scan profile. All torques in units of Nm

	Start	**Maximum**	**Minimum**	**Finish**
MoS_2, nitrogen	0.35	1.0	0.3	0.75
Oil, nitrogen	0.23	0.28	0.2	0.23

1.3. Thermal Vacuum Test at +55 deg C

The test results revealed that relatively large peak torques occurred at the ends of the 8.4 deg movement, particularly for the MoS_2 lubricated ball bearings, consistent with effects arising from debris accumulations at the ends of travel. Figures 3 and 4 provide typical measurement results during regeneration cycles.

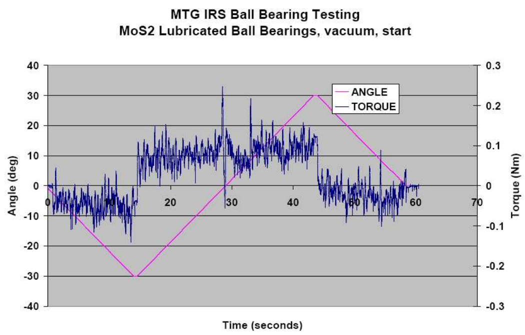

Figure 3: Baseline regeneration profile for MoS_2 lubricated ball bearings in vacuum at the start of vacuum test phase (255 cycles)

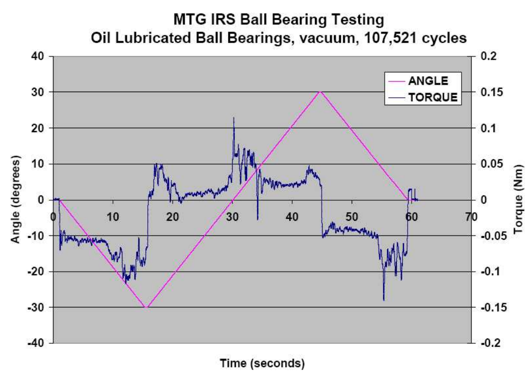

Figure 4: Regeneration profile for oil lubricated ball bearings in vacuum (107,521 cycles)

The following two graphs provide a summary of the mean and 0-peak torque data taken from regeneration graphs at weekly intervals.

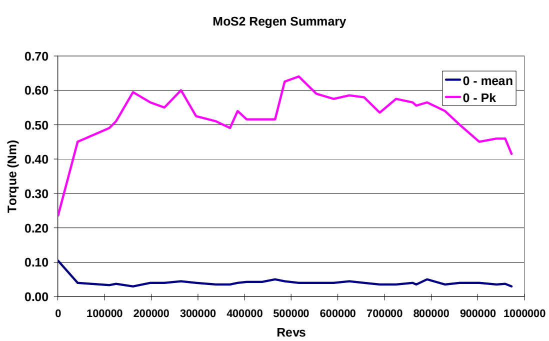

Figure 5: Summary of mean and 0-peak torques during regeneration cycles

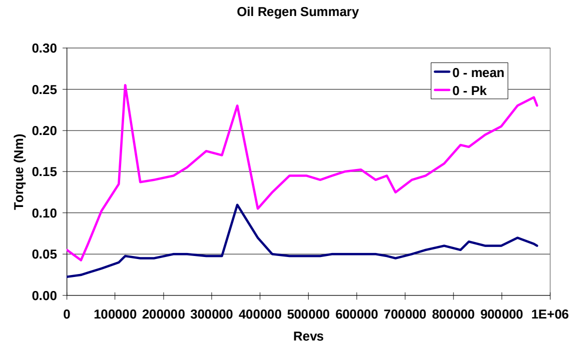

Figure 6: Summary of mean and 0-peak torques during regeneration cycles

Figures 7 and 8 provide examples of the scan profiles at the start of accelerated testing.

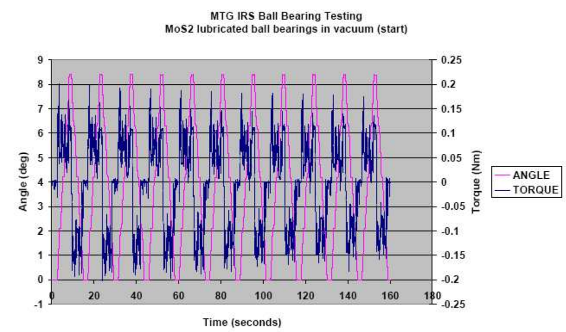

Figure 7: Baseline life test profile for MoS_2 lubricated ball bearings in vacuum

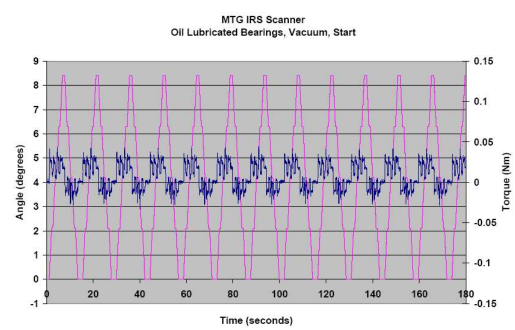

Figure 8: Baseline life test profile for oil lubricated ball bearings in vacuum

1.4. Transient peaks - oil-lubricated ball bearings

For the oil-lubricated ball bearings and during the life test in vacuum, torque trips were observed at 61,000 cycles and also intermittently between 110,000 and 526,000 cycles, where peaks could exceed 0.3Nm and a maximum value of 0.81 Nm was measured. The most likely cause was attributable to a particle on a ball or in the lubricant which occasionally resulted in a high transient peak (Note: the presence of such particles was confirmed during the post-test inspection). If the particle was present on a raceway, then peaks would have been expected to have been visible continually, instead of intermittently on a particular motion profile. Carrying out 10 regeneration cycles after a trip either reduced or eliminated the transient peak and the test was continued. The torque trip level was reset to 0.7Nm for 5 peaks and 0.75Nm for a single peak. Examples of the torque traces are provided in the following Figure and its appearance is consistent with a transient torque increase resulting from the presence of a hard particle.

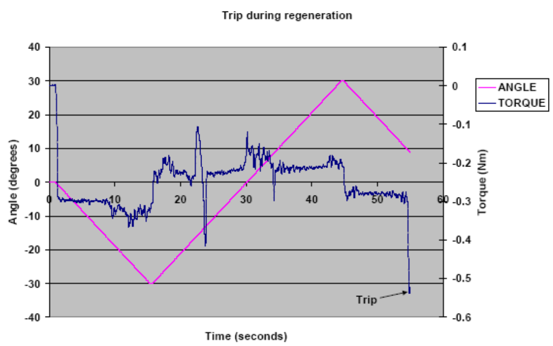

Figure 9: Trip during regeneration at 136,066 cycles (oil-lubricated ball bearings). Transient at approx -15 deg attributable to presence of hard particle in the bearing.

1.5. Post-test inspection: MoS_2-lubricated bearings

Raceways – The raceways exhibited marks corresponding to the 8.4 degree movement (Figure 10), although the ball running track was clearly defined. The MoS_2 film was worn and patchy, although there was still some lubricant film present. However, it is not clear at this stage if this film is residual MoS_2 or if it is primarily due to transfer from the PGM-HT cage. The raceway is illustrated in the following Figure.

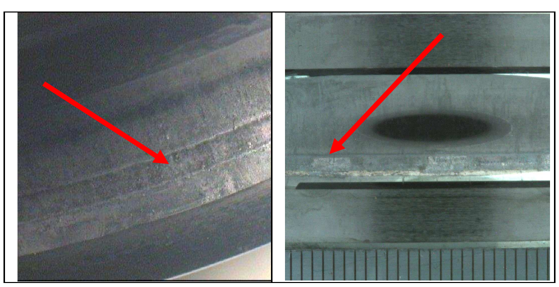

Figure 10: Inner raceway showing ball track

Cages – The PGM-HT cages were in good condition with marks in the ball pockets corresponding to contact with the balls during normal operation.

Balls – The balls were in good condition, although the MoS_2 film appeared patchy and it also appeared that material has been transferred from the cages to the balls.

1.6. Post-test inspection – oil-lubricated bearings

The Fomblin Z60 oil appeared darkened, being brown in colour in the ball track and upon the balls, although the lubricant was still wetting the raceways (Figure 11).

This darkening of the oil is not necessarily detrimental as the torque had not increased significantly and similar effects are normally observed in ball bearing tests with PFPE oils.

Raceways – marks corresponding to the 8.4 degree movement were present on the inner and outer raceways as illustrated in the following Figure.

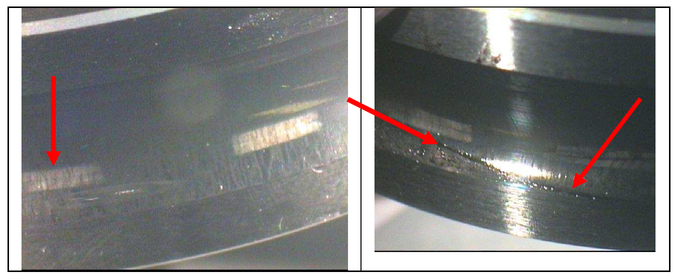

Figure 11: Left: Ball groove showing marks on ball track. Right: raceway, showing discoloured oil

Cages – The cages were in good condition, with some darkened patches visible in the ball pockets as illustrated in Figure 12.

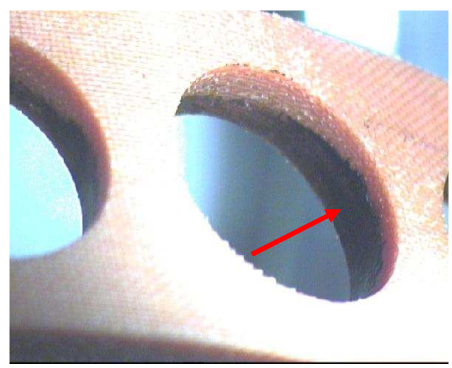

Figure 12: Darkened patch in ball pocket

Balls – The balls appeared to be in good condition and were wetted by the discoloured oil. However, of some concern were some small compressed shiny flakes present upon the surfaces of a few balls. These features are consistent with a compressed metallic particle and an example is shown in Figure 13.

Figure 13: Compressed flake on ball surface indicated by red arrow. Note that the two other highlights are reflections from the microscope lighting

The origin and nature of this flake were not clear from visual inspection. It seems feasible that these particles gave rise to the high transient peaks which were observed at some stages of the oil test. The transient peaks then reduced as the particle was compressed during operation.

Analysis using EDAX identified the particle as comprising aluminium (Figure 14), the most probable source being the Al-alloy housing and shaft initially used to characterise the test bearings prior to installation in the Ti-alloy housings.

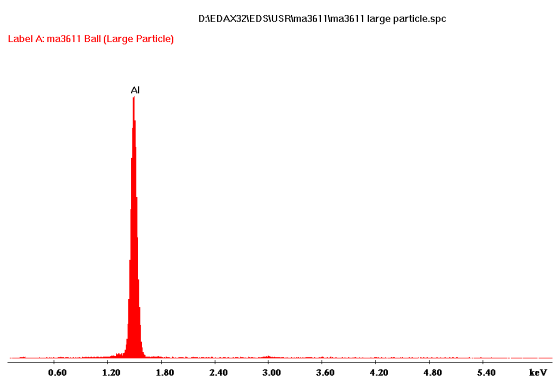

Figure 14: EDAX spectrum from metallic particle on ball showing Al-peak

5. DISCUSSION

5.1 Ground testing in nitrogen:

The mean torque in nitrogen was higher than expected for MoS_2-lubricated ball bearings, most likely as a result of the convoluted labyrinth path to the bearings for the nitrogen purge. The nitrogen purge was probably not fully effective and purge holes in the housing are recommended for this type of set-up. Note also, that the bearings were not run-in and solvent rinsed prior to operation. Carrying out these steps in vacuum normally reduces torque noise and peaks in subsequent torque testing and could have been of benefit in this test.

The oil-lubricated ball bearings exhibited similar levels of mean torque to the solid-lubricated bearings, although the 0-peak values were approximately one-third of those of the solid-lubricated ball bearings.

5.2 Life testing in vacuum:

The mean torque values for the oil and solid-lubricated ball bearings were approximately 0.05Nm, although the peak values for the solid-lubricated bearings were greater. Values of 0.5 to 0.6Nm were measured for the 0-peak data during the regeneration cycles for the MoS_2-lubricated ball bearings and 0.1 to 0.25Nm for the oil.

5.3 Residual Gas Analysis (RGA)

A mass spectrometer was used to assist in identifying gaseous species present in the vacuum chamber. If there were contaminants produced by oil degradation or evaporation, peaks could be expected at mass numbers 47, 66, 69 [2] and possibly at higher molecular masses as well. Note that the MoS_2 bearing test station was also foil wrapped to prevent contamination by oil. Any oil which escaped from the oil station would therefore have been released into the test chamber.

Figure 15 was obtained at the start of testing and the peaks present correspond to hydrogen, water, oxygen and nitrogen, all of which are normal in a vacuum chamber. Note that the chamber had been subject to a bake-out at approximately 80 deg C prior to testing to improve cleanliness.

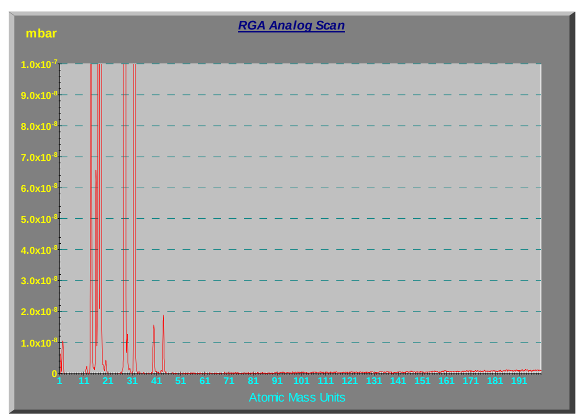

Figure 15: Start of testing (room temperature)

Figure 16 illustrates the constituents present in the chamber after testing and cooling back to 20 deg C. Note that the peaks present are consistent with the normal atmospheric gases, except for a minor peak at

60. It is not clear if this peak results from an outgassed contaminant at the higher temperature or if it does actually result from the Z60 oil. However, it should be noted that this peak is small and barely detectable thus representing a very minor contaminant source.

Figure 16 represents the final measurement at RT and no unusual peaks are evident.

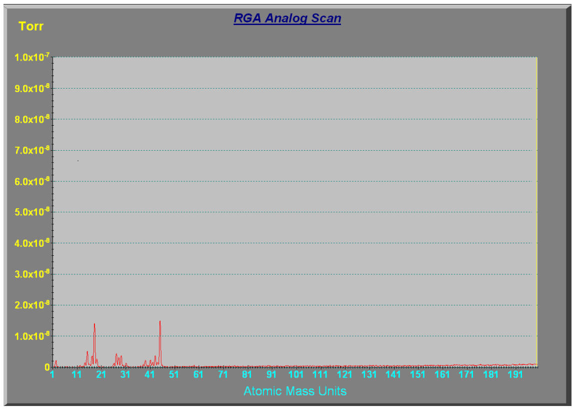

Figure 16: End of test, 20 deg C

PFPE fluids are limited by their tendency to degrade when used in conjunction with bearing steels. The failure mechanism can be summarised as follows:

- Fluorine is released from the oil by the action of repeated shearing under high contact stresses which leads to reactions with the iron in steel to form FeF_3.
- PFPE oils then suffer catalytic attack by FeF_3 which leads to the breakdown of further molecules and the release of more F.
- The ensuing chain reaction results in rapid oil degradation.

The following figure from [2] provides results from a study of Fomblin Z25 degradation products, with CFO at 47 being the most prominent, none of which were identified in the IRS ball bearing tests.

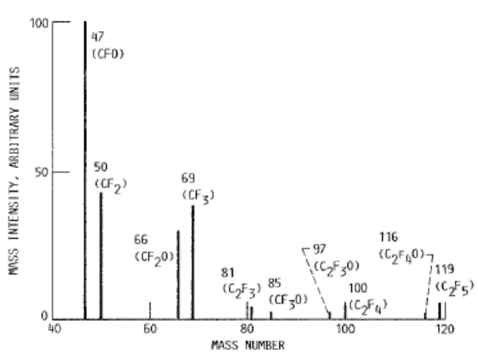

Figure 17: Mass spectrum of gaseous species evolved during testing Fomblin Z25 against 440C steel[2]

6. CONCLUSIONS

<u>MoS_2-lubricated Ball Bearings</u>

- The mean torque in the ground simulation test carried out in nitrogen was higher than predicted for MoS_2, most likely as a result of the convoluted path to the bearings for the nitrogen purge. The nitrogen purge was probably not fully effective and purge holes in the housing are recommended for this type of set-up. The mean torque for the oil-lubricated ball bearings was consistent with predictions.
- In vacuum, the mean torque for the MoS_2-lubricated ball bearings was approximately 0.02Nm and the maximum peak-to-peak torques were up to 2.6 times greater than the maximum peak-to-peak values for oil.
- The MoS_2-lubricant film was depleted on the balls and raceways and transfer from the PGM-HT cages occurred.

<u>Oil-lubricated Ball Bearings</u>

- On the basis of the torque measurements, oil lubrication provided better overall torque performance and the required lifetime (plus ECSS margin) was also achieved. The mean and 0-peak torques (if the transients due to contaminant particles are ignored) were also within the criteria defined by Astrium for this application. For the oil-lubricated bearings, the torque behaviour was as expected/predicted except for the transient peaks caused by contaminant particles.
- Z60 oil was still wetting the raceway and ball surfaces, although the oil was discoloured.
- However, the remaining lifetime which could ultimately have been achieved with the oil lubricated ball bearings is not clear from this test programme.
- Although the oil-lubricated bearings successfully completed lifetime cycles with respect to torque and lubricant condition, oil can only be used if the contamination levels are also acceptable.

7. RECOMMENDATIONS & LESSONS LEARNED

Z60 oil lubrication is considered more appropriate to comply with the torque performance requirements than MoS_2 due to absence of large peaks, although the consequences of potential contamination from the oil have to be carefully assessed.

Locating the nitrogen purge closer to the MoS_2-lubricated ball bearings may have allowed a more efficient purge to have been carried out which may have been beneficial in reducing the torque during simulated ground testing. In addition, running-in the bearings in vacuum and then solvent rinsing with isopropyl alcohol would also have been of benefit in reducing torque noise.

8. REFERENCES

1. M J Anderson et al (2011), MTG IRS Ball Bearing Life Testing, MTG-ESTL-TR-0067 01A

2. S Mori & W Morales (1989). Reaction of PFPE's with 440C ss in vacuum under sliding conditions at RT, NASA TP-2883