EVALUATION OF THE TORQUE PERFORMANCE OF A RANGE OF SPACE-COMPATIBLE OILS & GREASES AS A FUNCTION OF TEMPERATURE, SPEED & LUBRICANT QUANTITY

Josephine Cunningham

European Space Tribology Laboratory, AEA Technology plc, Risley, Warrington WA3 6AT, UK
Tel : +44 1925 25 3215, Fax: +44 1925 25 2415
E-mail: josephine.cunningham@aeat.co.uk

ABSTRACT

Liquid lubricants have been used in spacecraft mechanisms since the earliest satellites were launched. Over the last twenty years the European Space Tribology Laboratory (ESTL) have assessed the torque performance of many space-compatible fluid lubricants and are frequently asked to provide up to date information/practical data on the effects of various parameters including speed (and accelerated life testing), temperature and lubricant quantity on the torque performance of ball bearings for space mechanism applications. The requirement for use highlights the necessity for updating existing data bases and providing more information on the performance of oils and greases qualified or under qualification for use in the space environment.

This paper summarises the results from the most recent series of tests used to evaluate the in-vacuo torque performance of a range of space-compatible oils and greases in bearing tests as a function of:

- **Temperature:** 10°C above the pour point to +60°C
- **Speed:** 0.1, 1, 10 ,100 & 500 rpm
- **Grease Quantity:** Nominally 1, 5 & 15% of the *"free volume"*
  The *"free volume"* is defined as the unoccupied volume between the two races, omitting the volume occupied by the balls & cage.

The lubricants selected for testing were as follows:

- **Oils:** Fomblin Z25 & YVAC 40 (PFPE's), Nye 2001, 179C (PAO-6), 238 (MAC's) & KG80 (Mineral Oil).
- **Greases:** Braycote 601 & 602, Fomblin YVAC 3 & ZNF, Krytox 240AB, Ultratherm 2000 (All PFPE's) & Rheolube 2000 (MAC).

All tests were conducted in pairs of Barden 101H or equivalent SNFA EX12 Bearings with phenolic cages at a pre-load of 190N (1100 MPa mean).

The torque performance of the oils and greases are summarised in **Figures 1 & 2** which show plots of mean torque vs temperature at 10rpm. Each line represents a different lubricant and is the average through the Hysteresis, of the torques generated at 1, 5 & 15% free volume.

The conclusions are summarised briefly below:

General
- Torques increased with decreasing temperatures. Operating close to the pour points produced rapid increases in torque, a feature which must be considered if torque margins are critical.
- At +20 & +60°C, mean torques were marginally lower at 1% free volume. At low temperatures torques increased with increasing lubricant quantity, emphasising the necessity to optimise the lubricant quantity when mechanisms are operating at low temperatures.

Oils
- Oils performed in a similar manner with the exception of Fomblin YVAC 40, the highest viscosity oil where torque values were relatively high. At +20 & +60°C, Nye 179C generated the lowest mean torque. At -60°C, Fomblin Z25 maintained the lowest overall torque.
- The Nye oils were relatively unaffected by rotational speed except at low temperatures and 15% free volume, where the torques increased rapidly, questioning their capability to provide effective lubrication under these conditions.
- Fomblin YVAC40 & KG80 (the highest viscosity oils) both showed general increases in torque with increasing rotational speed.
- KG80 was most sensitive to temperature/rotational speed and oil quantity.

Greases
- The lowest torque values were obtained for Rheolube 2000 & Braycote 602.
- Large increases in mean torque occurred with changes in rotational rate, a feature attributed to possible changes in lubrication regimes and changes in the distribution of grease at the ball-race interface with changes in speed, temperature and grease viscosity.

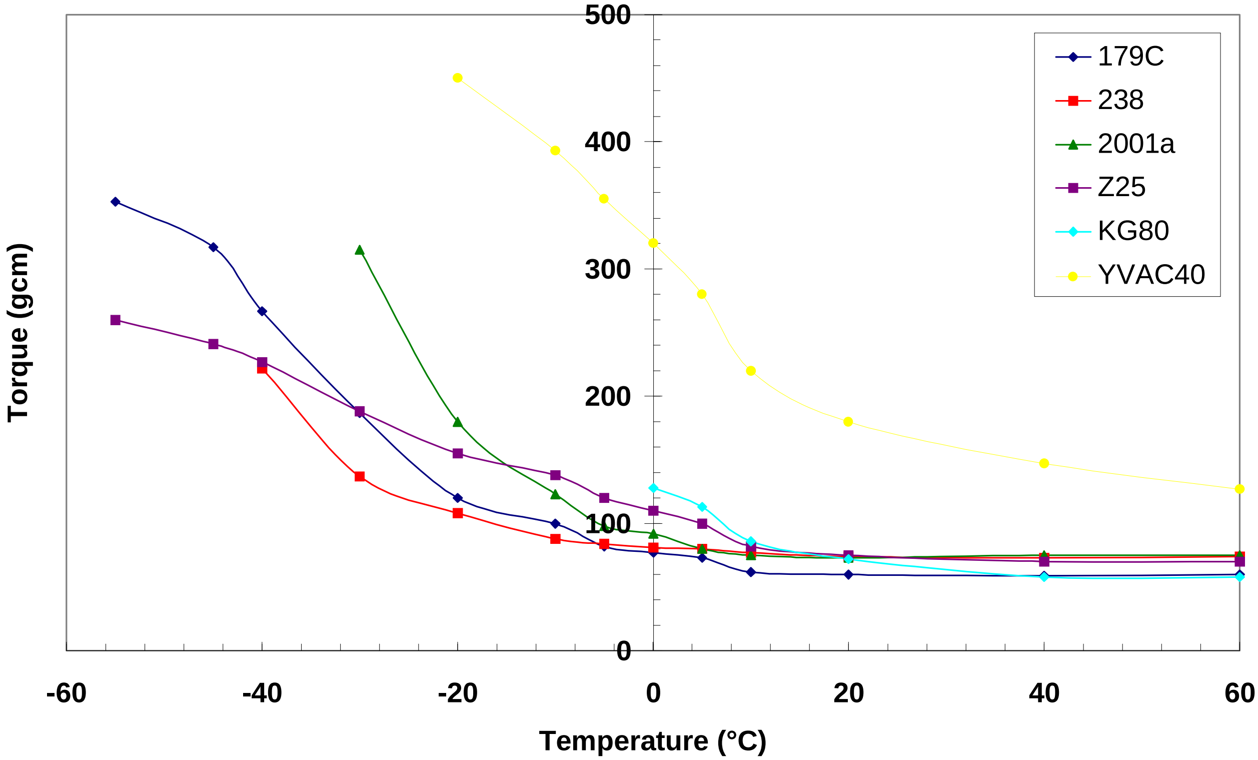

Figure 1 - Oils Data Summary - Mean Torque vs Temperature @ 10rpm

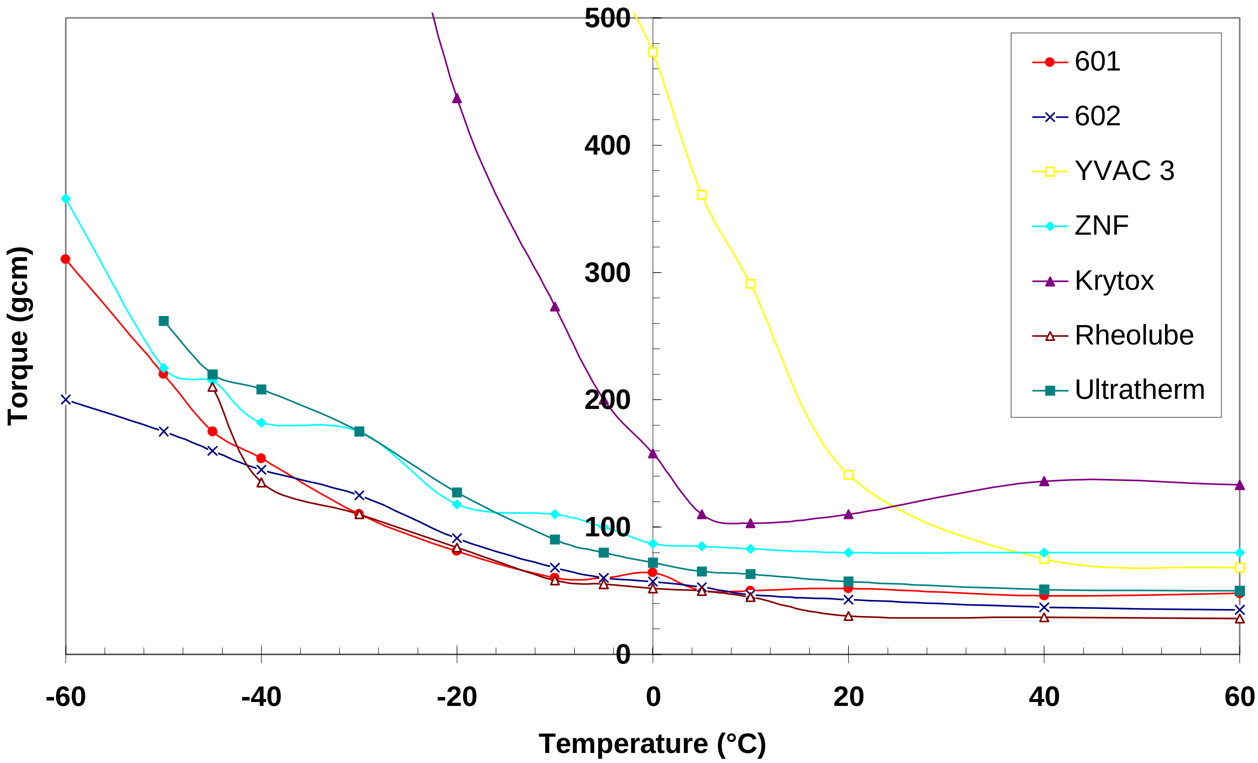

Figure 2 - Grease Data Summary - Mean Torque vs Temperature @ 10rpm

SILVER-BASED BRUSH ELECTRIC CONTACTS PERFORMANCES

C. Fritsch*, J.B. Mondier**

*Laboratoire Central des Industries Electriques
33 avenue du Général Leclerc , 92260 Fontenay-aux-Roses, France
Telephone : 0140 95 63 46, Fax : 01 40 95 89 16, E_mail : clement.fritsch@lcie.fr

**Centre National d'Etudes Spatiales
18 avenue E. Belin, 31401 Toulouse Cedex 4, France
Telephone : 05 61 28 22 15, Fax : 05 61 28 29 85, E_mail : jean-bernard.mondier@cnes.fr

ABSTRACT

A test facility devoted to the study of power sliding electric brushes was realized at the L.C.I.E (Laboratoire Central des Industries Electriques) under CNES (Centre National d'Etudes Spatiales) funding. It has been operated for several test sequences during which the slip-ring assembly material and the brush behaviour were analysed. In 1998, new tests were performed in order to determine the capability upper limit of this technology. Besides, this study had the objective to define the process to be used in order to recover the designed contact performances on brushes stored temporary in damp air.

The article describes the main features of the test bench operated at L.C.I.E and the results of the last test program. The main lessons learned from this research activity are reported and discussed.

1. INTRODUCTION

Since the break through of 3 axes stabilized satellites, the on-board electric power needs to be transferred from the solar arrays by specific systems. This vital function, whatever the in-orbit mission may be, is most often performed by mechanisms comprising slip-ring assembly. The material for brushes is a sintered silver-based alloy including a dry lubricant, the MoS_2, whereas a coin silver alloy is often used for the tracks. These choices were adopted when the CNES (Centre National d'Etudes Spatiales) was starting its national programs such as SPOT for Earth remote sensing and TDF/TVSAT for TV broadcasting.

Despite the continuous progress realized in order to reduce the consumption of on-board systems, the amount of power to be transferred to the board keeps increasing. This may be caused by the growing of platforms and payloads and also by the extension of missions, which requires more margins on solar panels performance. This is why the CNES has conducted a research program on silver-based brush testing in order to come to know their in-service behaviour and thus to allow a better use of their capability in slip-ring assemblies. Owing to the needs increase, these investigations were completed by a set of specific tests for evaluating the in-service capacity and endurance of this brush technology.

2. TESTS AND MEASUREMENTS

After a first successful test program regarding the test bench performance validation, a second test sequence confirmed the initial choice of the brush material and ended in a set of recommendations for the designers. These ones were related to the influence of the contact main features on the brush capabilities. The third test program had to demonstrate the brush ability to work in more severe conditions (ultra-vacuum, thermal, current density) while enduring an extended life.

On board the satellite, the intensity of current to be transferred from the solar panels to the board depends on the power supply sub-system. This current is a major electrical factor in the slip-ring assembly design. One possible way of enhancing the equipment performances is to raise the brush current density. Then, it reduces the brush dimension and the resistive torque generated by the load applied on the brush, thus the drive motorization need is lowered, and so are the slip-rings mechanism overall dimensions and mass. This is why it was interesting to test a current density increased from 0.4 A/mm² (the present design value) up to 1 A/mm². The current is also responsible for the thermal dissipation that occurs inside the mechanism. This contributes to its typically high operational temperature. The maximum slip-ring assembly measured temperatures in the last qualification programs conducted were ranging from 90°C to 100 °C. As these values seemed acceptable, regarding the materials capability, a life test operational temperature of 100°C was specified for the test bench brushes and tracks. Besides, the duration of each test had to be defined. The longest planned missions for this kind of device being Envisat and Metop for ESA, Spot5 and Helios2 for the CNES, the number of revolutions to be done including the ECSS qualification factors were 56,000.

Some other aspects have been studied during these tests. One of them is related to the level of ultra-vacuum obtained in the test chamber. As this level may be suspected to be not enough representative of the in-orbit vacuum, some tests were devoted to the contact performance measurements under a degraded vacuum (from 10^{-5} mbar to 10^{-8} mbar). The purpose was to evaluate the reliability of the ground tests vacuum level. Another point was the study of the brush M_OS_2 particles size influence on the performances measured. The release of M_OS_2 particles within the contact, the lubrication efficiency as well as the electric resistance may be affected by the particle size. One point of interest was to know weather a different distribution of M_OS_2 particles in the brush could change the tribology process in the contact area.

Besides, the in-service behaviour of oxidized brushes was analyzed. This item is linked with the brush lubricant degradation due to the slip-ring assembly use under a typical clean room air. Procedures of contaminated brush refurbishment were studied in order to satisfy the specific operational needs encountered during ground operations before the satellite launch.

The performed test program is summarized in the following table.

Test n°	M_OS_2 size (% of reference value)	Run-in I=current value	Cycles under air	Cycles under vacuum	Chamber pressure (mbar)
1	100	N/A	1,000	56,000	10^{-8}
2	100	N/A	1,000	56,000	10^{-6}
3	100	N/A	1,000	56,000	10^{-5}
4	100	I=0	1,000	0	1,000
5	100	I=nominal	1,000	0	1,000
6	27	N/A	1,000	56,000	10^{-8}

3. TEST BENCH DESCRIPTION

The bench consists mainly of two cylindrical enclosures of 630 mm length, 340 mm diameter. One of them is equipped for ultra vacuum tests, the other one is devoted to atmospheric pressure tests or to pollution of brushes. The slip-rings and brushes to be studied are mounted on the cover, which may be used with both enclosures, so that a test may begin in a gazeous environment and be concluded in ultra vacuum.

The enclosure equipped for vacuum conditions is tied to a vacuum producing system, consisting of a primary pump and a secondary cryogenic pump. Measurements of pressure are fulfilled by a Pirani-gauge (for primary vacuum), and, for the ultra vacuum, by a quadripolar mass spectrometer, which measures the total residual pressure in the enclosure as well as the partial pressures of following gases : H_2O, O_2, H_2, N_2+ CO_2, CO_2, He and Ar, plus an user-selected gas. Measuring range is between 10^{-3} and 10^{-10} mbar. The typical minimum total pressure lies near 2.10^{-8} mbar, depending on the enclosure's content and the pumping time.

Contact set up – The contact is realized between two brushes and a slip-ring system made of three concentric rings, the internal and the external ones being for contact testing, the middle ring being only for potential measurements. In figure 3, all the principal elements are visible.

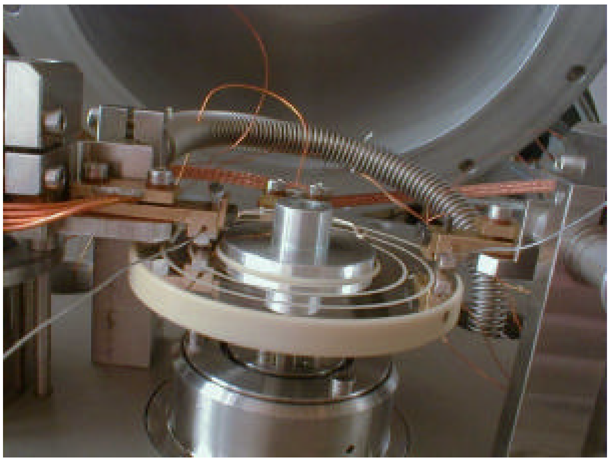

Figure 3 – System equipped with all additional elements for testing

The contact force is created by an electro-dynamic actuator tied to the contact support. Contact force may reach 2.4 N. Rotation of the slip–ring is achieved by a stepping motor mounted externally to the enclosure. The movement is transmitted by a magnetic coupling. The synchronous excitation ensures a smooth, well-controlled movement, between a maximum speed of about 1 turn in 10 seconds and a virtually null minimum speed.

The contact system comprises a heating system, designed to regulate contact temperature between 30 °C and 100 °C, each contact being independently regulated. The temperature is measured by a thermocouple that equips each brush. The heating devices (resistors) are fixed to each brush. Under the slip ring system, an additional heater minimises temperature gradients. This back heater is set to a predetermined point. Overall regulation is better than 3 °C, for each contact, with a set point of 100 °C.

The total residual pressure of the enclosure may be regulated between the minimum obtainable pressure and 10^{-5} mbar. The regulation is obtained through more or less opening of the gate between the cryo-pump and the enclosure. This function is controlled by a microcomputer, the measuring signal being issued from the spectrometer described before.

During the tests, the two closed contacts are submitted to an electrical direct regulated current. Contact resistance of each contact is determined by measuring the potential difference between each brush and the centre slip-ring, which is equipotential with the rings. By this method, one has virtually no parasitic massic contribution, and the measurement concerns only constriction and film resistance of the studied interfaces.

Each brush support is mounted on a Bendix pivot. Deflection induced by the friction during rotation is measured by means of a capacitive position sensor. The frictional coefficient may so be calculated, knowing the contact force, the geometry of the set up and the characteristics of the pivots.

Signal processing – The four signals : potential difference and deflection for both contacts are continuously sampled at a 200 Hz rate. The data is linked to a computer for calculation of means, rms values, etc. Typically, the calculations are done simultaneously with a resolution of 1 value per turn and with 60 values per turn, so as to get precisely localised information about slip-rings.

Beside these signals, the mean temperature of each brush is measured by a thermocouple, at a rate of about 1 measurement every 10 seconds. The pressure (total and partial pressure of gases) is measured at a rate of 1 value each 15 s. For each test, the set of parameters to be measured is the following : vacuum level, temperature of contacts, intensity in the contact, polarities of contact, contact force, rotation speed versus the number of turns.

4. TESTS RESULTS

Every test was performed in a configuration comprising a couple of brushes sliding on two electrically connected coaxial tracks. One of these brushes (polluted brush) was initially stored in an 85% damp air at room temperature during 120 days. The other one was an unused brush that had been stored under dry nitrogen (as new brush). This conditioning was assumed to correspond to the cumulated periods of time for a slip-ring assembly to be integrated on satellite, then stored and finally tested before launch.

4.1 Life Tests

The test n°1 was devoted to the brush life performances. The tracks were heated and thermally controlled in order to obtain the specified and measured brush temperature of 100 °C. At the beginning of the test, a thousand of turns were performed under ambient air in order to simulate the cumulated ground use of a flight slip-rings unit. During this phase, the polluted brush contact electric resistance ($R_{polluted}$) decreased quickly over a few turns, as the brush cleaned up by friction on the track. Then, the wear particle accumulation slowly made the $R_{polluted}$ rise up to its initial value. In the meantime, the as new brush contact electric resistance (R_{ref}) improved by a factor of 3. This result could be caused by a brush wear particle production that merely affects the track electrical conductance. The part of the life test under vacuum is described by the following plot that shows the $R_{polluted}$ and the polluted brush friction coefficient (μ), both versus the number of track turns.

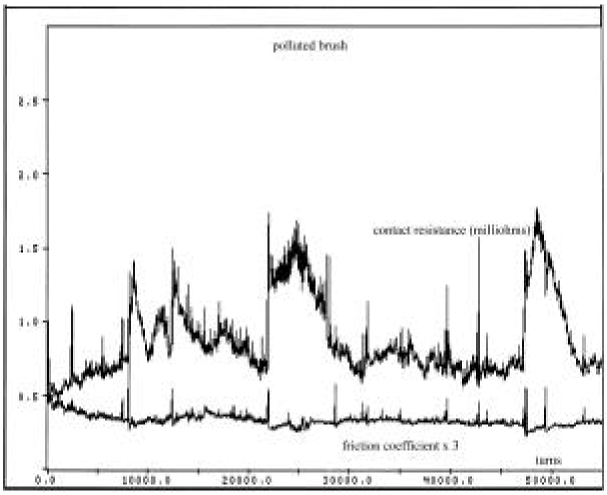

Figure 4.1.1 – Contact resistance and friction coefficient for the polluted brush, Vs number of turns

In the very first revolutions, the $R_{polluted}$ exhibited a quick drop by a factor of 4. The vacuum seemed to have radically changed the tribological behaviour of the brush to track contact. Then, along the life test, the $R_{polluted}$ slowly rose without ever reaching its initial value, but it revealed a few disturbances that are not easy to relate to any external event. The μ plot shows a slowly decreasing profile that could be the result of the M_OS_2 particles gathering on the track. The values of μ and $R_{polluted}$ evolve in the opposite direction. This is in good agreement with the observations made in previous similar tests. At the end of life, the $R_{polluted}$ noise measurement is 0.3 mΩ peak to peak for a mean value of 0.8 mΩ. The measurements done on the as new brush show that the R_{ref} value is almost constant throughout the test.

As a conclusion to the life tests, we can say that the tested polluted brushes performed the assigned life without additional damage regarding its degraded initial state. The end of life electrical and mechanical performance given by respectively $R_{polluted} = 0.8\,m\Omega$ and $\mu = 0.1$ seem acceptable.

4.2 Vacuum Pressure Influence

The influence of the vacuum pressure in the test chamber during the endurance test was studied for 3 values of pressure, as indicated in the table of test program (§2) : 10^{-5} mbar, 10^{-6} mbar and the minimum level obtainable with the bench : 10^{-8} mbar. For all three tests, the contacts were at 100°C. The results at 10^{-5} and 10^{-6} mbar in terms of contact resistance are summarized by the following curves.

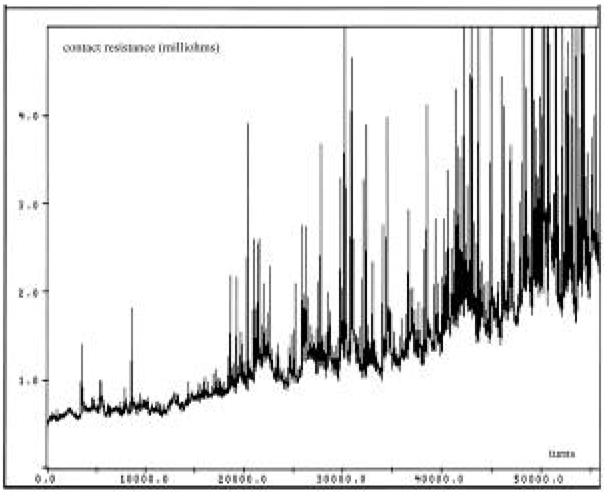

Figure 4.2.1 – Contact resistance of polluted brush at $P = 10^{-6}$ mbar

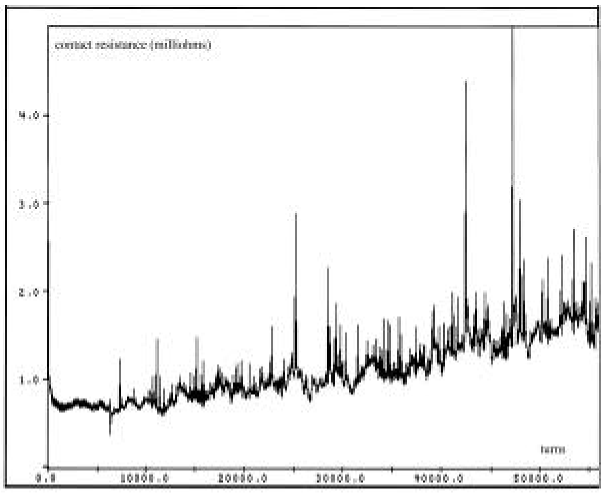

Figure 4.2.2 – Contact resistance of polluted brush at $P = 10^{-5}$ mbar

As a first result, and for the test conditions employed, the overall contact resistance behaviour is dependent on the pressure. At both pressure level of 10^{-5}mbar and 10^{-6}mbar, spikes do occur. But, by higher pressure, they are not as high and they occur later. This statement is valid for both the not polluted and the polluted brush. The number of turns before the mean value of the contact resistance (evaluated over each turn) begins to rise steadily is summarized in the following table.

	10^{-5} mbar	10^{-6} mbar	10^{-8} mbar
As new brush	30,000	17,500	15,000
polluted brush	25,000	15,000	7,500

The sliding distance for the polluted brush is always 1.57 times the one of the not polluted brush. It is therefore normal that in similar conditions, a given particular event occurs earlier on the polluted brush than on the not polluted one. This can be seen in the former table. Besides, these results indicate that a higher level of pressure results in somehow later degradation. The same type of observation could be made considering the first apparition of spikes in the contact resistance.

Based on the previous observations, it appears that tests should be done at the lower end of pressure range. Doing otherwise may result in artificially better contact behaviour.

4.3 MoS_2 Particles Size

The test n° 6 was devoted to the influence of the MoS_2 particle size. The conditions were the same as those for nominal brushes, including the pollution phase. The resistance and friction coefficient are plotted in figures 4.3.1 and 4.3.2. (56000 turns under vacuum).

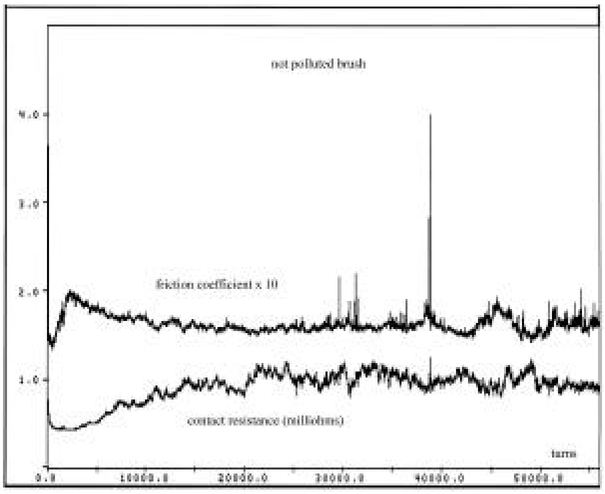

Figure 4.3.1 – Contact resistance and friction coefficient of not polluted brush, Vs number of turns

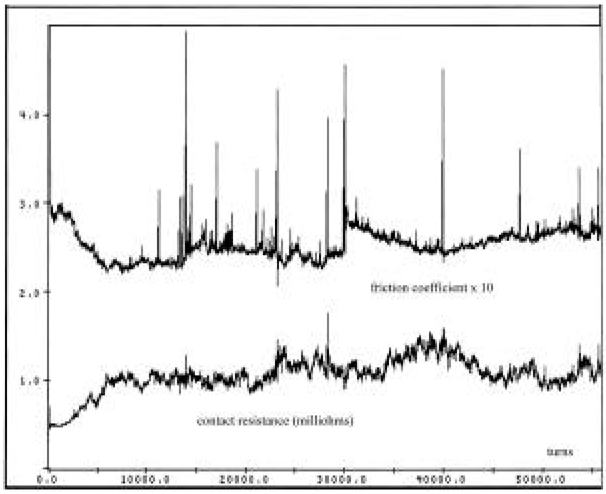

Figure 4.3.2 – Contact resistance and friction coefficient of polluted brush, Vs number of turns

Both contacts behave rather well during the whole test, regarding the contact resistance as well as the friction coefficient. Under air, the resistance begins to decrease, but during a very short time (1 or 2 turns). After this initial decrease, the resistance of the not polluted contact remains stable. It grows for the polluted one, particularly after 750 turns.

In the endurance phase, the two following points should be noted. Firstly, the initial phase of endurance is again very short. After two revolutions, the variations over one turn in contact resistance disappear, and a stable resistance is achieved, for the not polluted brush as well as for the polluted one. Secondly, the friction coefficient of polluted brush exhibits some spikes, whereas, for the not polluted one, it remains more stable.

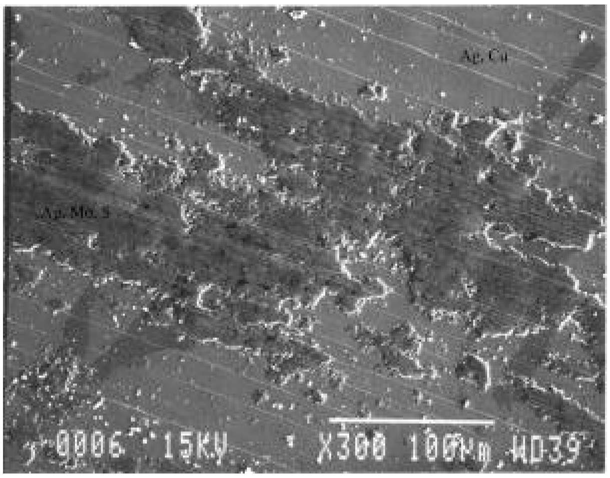

Figure 4.3.3 – SEM observation of the slip-ring under polluted brush, after endurance test (SEI x 300)

A point of interest was the analysis by SEM of the slip-ring surfaces after test. The surfaces of the initially clean slip-rings showed both an abundant but quite homogeneous deposit composed of Ag, Mo and S (see figure 4.3.3) : it is transferred wear material from the brush that is adherent to the track surface. Beside these plates, there are wear particles, originating from the brush as well. Elsewhere, the surface composition is that of the coin silver. On the track under not polluted contact, some deposits of transferred material were found that are both plates and particles (see figure 4.3.4).

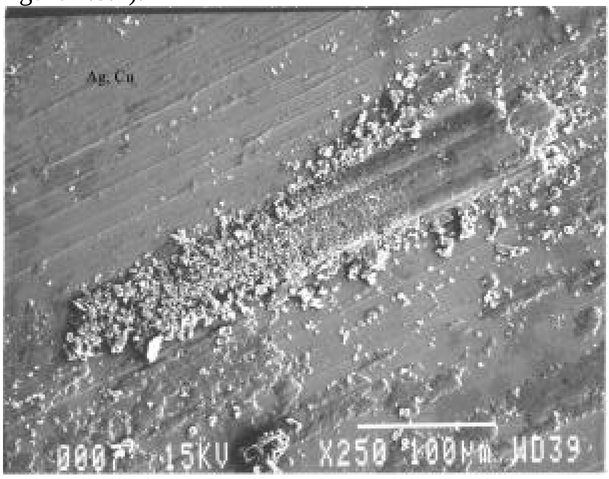

Figure 4.3.4 – SEM observation of the slip-ring under not polluted brush, after endurance test (SEI x 250)

The comparison between the slip-ring surface in case of low-sized MoS_2 particles and nominal-sized MoS_2 (test #1 for example) indicates that the surface is more homogeneous in the former case. This could explain the quite good contact behaviour during the whole test sequence. Considering the global performances of this material, a point of interest could be to further investigate about it. These first results show its lower sensitivity to the pollution, with regards to its contact resistance.

4.4 Run-in Procedures

The test n°4 was a specific sequence performed on polluted brushes. A first run-in test was done under ambient air without the current presence. Actually, a very low current was applied through the contacts in order to permit steady measurements. It was assumed that, in this case, the current had no tribological influence. The purpose was to make a comparison between R_{ref} considered as a reference and $R_{polluted}$, both measured versus the number of track turns. The results presented in the figure 4.4.1 shows that the test begins with a short period of 10 cycles during which R_{ref} and $R_{polluted}$ improve. After that, the average value of $R_{polluted}$ increases continuously while R_{ref} remains almost constant for several hundreds of revolutions. A higher measurement sampling reveals a $R_{polluted}$ periodic profile corresponding to one track round, repeated throughout the test.

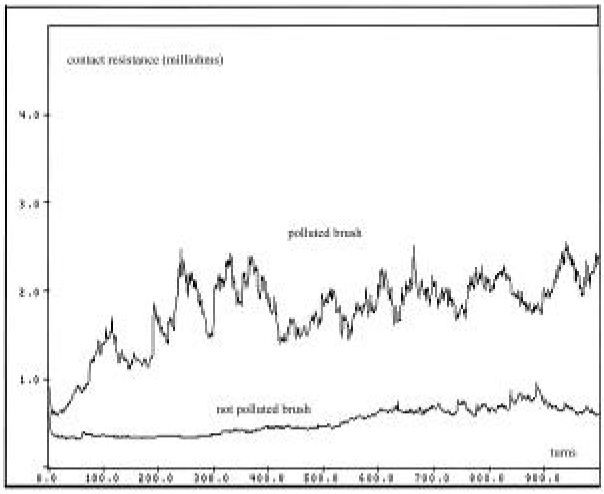

Figure 4.4.1 – Contact resistance of polluted and not polluted brush under air, Vs number of turns

This means that wear particles coming from the polluted brush are likely to remain glued on the track and thus contribute to the steady increase of $R_{polluted}$. The run-in of the brush contact surface pollutes the track without a possible recovery of the R_{ref} value. In these conditions, our procedure failed to refurbish the oxidized brush. Moreover, after several hundreds of cycles, the test room ambient air may be responsible for an additional brush alteration, as it is visible on the R_{ref} evolution. A second similar test has been done with the use of a nominal current during the motion. Preliminary results show that, in such conditions, run-in seems much more efficient than without the presence of current. These promising results are not available for this publication. They will be reported later. After the run-in phase, each couple of brushes were tested under vacuum in order to measure the in-service performance. The results presented in the figure 4.4.2 show that no more than 15 turns are necessary for the $R_{polluted}$ to reach a stable value.

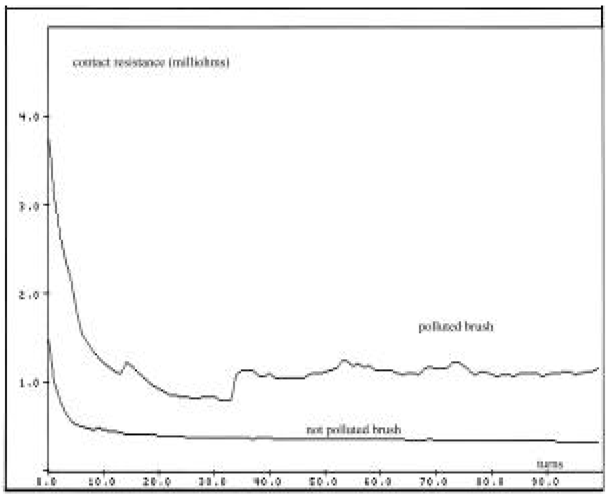

Figure 4.4.2 – Contact resistance of polluted and not polluted brush under vacuum, Vs number of turns

This is a relatively short number of revolutions corresponding to 1 day of an Earth low-orbit flight.

5. FURTHER TESTING

The brush material with low-sized M_oS_2 particles seems to have good properties with regards to its contact resistance considered in endurance tests. It would be interesting to investigate particularly the run-in conditions, because the initial phase of decreasing resistance was found very short.

The test bench, equipped with contact temperature and total pressure regulation, is well adapted to test alternative solutions to M_oS_2 lubrication, for example non-solid lubricants.

In addition to these endurance and run-in tests, the tribological processes could be studied at the very beginning of slipping. The way that the initial lubrication film is formed could play an important role in contact evolution. Such factors could explain partially the performances of the low-sized M_oS_2 material.

6. CONCLUSIONS

The CNES has conducted a power silver electrical contact test program with the help of the L.C.I.E. The results have shown that the increase of current density up to 1A/mm² is compliant with this technology for up to 5 years of low orbit missions. Regarding the tests realised under degraded vacuum pressures, the results have shown a real influence of the vacuum level on the contact performances. But, the results interpretation was not easy, as a non linear behaviour has been observed. Thus, more analysis and tests may be required, on this point, in order to conclude. Besides, the influence of M_oS_2 brush particles has turned out to be a promising test output. Using this material might reduce the brush sensitivity towards damp air. This advantage may be of great interest for slip-rings run-in, with regards to the satellite ground operations before launch. The run-in tests performed have shown that the use of high current could significantly improve the recovery of the initial contact performance. More generally, the database obtained should help the designers for the development of more compact and more performant new slip-ring assemblies.