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CONSIDERATIONS ON THE LUBRICATION OF SPACECRAFT MECHANISMS

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1. INTRODUCTION

The wide variety of lubrication techniques now available to spacecraft engineers very often makes the choice of an optimum process for a specific application very difficult to select. The ever increasing demand for the reduction of costs in spacecraft engineering has led to the unthinking application of commercial processes with the minimum of either intellectual or practical justification, and sometimes disastrous results.

The purpose of the paper is, therefore, to try to focus space tribology and to propose a number of precepts to guide designers in its application. Of the many techniques available all, without exception, have limitations in performance. Two European processes will be discussed in more detail and their limitations identified. Some performance results on a recently introduced liquid space lubricant will be given.

2. APPLICATIONS AND REQUIREMENTS

Table 1 is a non-exhaustive list of important space mechanisms with brief details of their lubrication needs in which four broad types of application can be identified.

- low speed sliding contact
- high speed sliding contact
- low speed rolling contact
- high speed rolling contact

For each of these there is a number of solutions but the selection of the optimum will depend wholly on the physical details of the mechanism. Which brings us to the first precept of space tribology.

Precept 1 The optimum lubrication system for a space mechanism is an integral part of the mechanism design and not a process to be added when the design is complete.

Even today when space engineering is more than twenty years old the precept is ignored. The authors have personally experienced two instances during the past year where the lubrication system was expected to make a poor design concept work.

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3. LUBRICANT CLASSIFICATION

They may be categorized as:

DRY

(a) Dichalcogenides (lamellar solids)
(b) Solid lubricant composites and transfer film lubricants
(c) Soft metals

LIQUID

(a) Hydrocarbon oils
(b) Synthetic oils
(c) Greases

It is quite impossible in a short paper to review all available techniques and processes so the authors will concentrate on those available in Europe and with which they are most familiar.

4. DRY LUBRICANTS

4.1 Dichalcogenides

These are a group of metal compounds which exhibit a lamellar structure to which current theory attributes their good lubrication properties. In fact only a limited number may be classed as lubricants, amongst which are WS_2, WSe_2, MoS_2, $MoTe_2$, NbS_2, $NbSe_2$, and $TaSe_2$.

Of these MoS_2 has shown itself to have the best performance in a space environment as a result of years of testing. It has good wear characteristics, low friction and in general performs better in vacuum than in moist air. Its coefficient of friction is load dependent, although some recent work has introduced dispute on this point, and ranges from 0.4 to lower than 0.1. There is a large literature on MoS_2 and ESA is funding a continuous bibliography on its applications to space prepared by A.R. Lansdown. (Ref. 1-5).

MoS_2 may be applied in a number of ways and those of interest to space engineers are reviewed briefly below.

4.1.1 Bonded Films

A bewildering variety of bonded films has been invented, now more than 100, but only a few of them have found general commercial application. The binders may be organic or inorganic, heat cured or simple air drying agents mostly based on cellulose. Some inorganic binders based on ceramics require curing temperatures of 1000°C which limits the materials to which they can be applied.

The thickness of a bonded film may commonly be of the order 10μm which is enough to degrade the precision of many high grade mechanisms. The debris from the film may also lead to very erratic torque, particularly in rolling bearings. The control of such processes is very operator dependent which makes it difficult to achieve consistently uniform results and tends to preclude their use in critical mechanisms. The authors would not now use a bonded film in an application where high precision was a requirement.

4.1.2 Burnished Films

A moderately adherent thin film of MoS_2 may be achieved by burnishing onto a thoroughly degreased and clean metal surface. Rubbing with chamois leather or a wire brush, or tumbling in a ball mill are established methods of burnishing. It is difficult to achieve consistent results even when the process is most carefully controlled, but the process is readily acceptable for very simple single operation devices such as latches, hinge pins and pyrotechnics. It can be applied to rolling bearings where the life is a few thousand revolutions and loads are moderate. Running-in should be an integral part of the process.

4.1.3 Sputtering

The most recent technique for applying MoS_2 films is by sputtering, first developed by Spalvins and Przybyszewski at NASA Lewis Research Centre. Since then a good deal of work on sputtered MoS_2 in ball bearings has been reported in the USA, chiefly by Spalvins (6) and by Christy and Barnett (7) and also in Europe by Bergman (8). In Europe the process has been developed and refined both at the Laboratoire Suisse de Recherches Horlogeres (LSRH) and at the European Space Tribology Laboratory (ESTL) in the U.K.

The very significant advantage to be gained by the process is the achievement of a very thin, about 1μm, film strongly adherent and of controlled composition. However, it has been shown by ESTL that the performance of sputtered films varies widely depending upon the sputtering technique and the stoichiometry of the film. During the past two years films of MoS_2 sputtered by LSRH and ESTL have been compared for performances in 42 mm diameter ball bearings, preloaded to 40N and run at 100 rpm. Results are discussed in para.4.4.

4.2 Solid Lubricant Composites and Transfer Film Lubricants

The number of polymer type materials falling under this heading is now considerable and quite beyond the scope of this paper. In practice only a very few are suitable for use in a space environment and in Europe only PTFE, often filled with MoS_2 and reinforced by glass fibre polyimide and polyacetal (e.g. Delrin) are commonly used for their tribological properties. The disadvantages of polymers in a space environment are:

- high coefficient of expansion
- low load capability
- high wear rate
- limited dimensional stability
- poor thermal conductivity

But these are balanced by the advantages of:

- cheapness and simplicity
- low coefficient of friction
- low outgassing

The lubricating action of these polymers and composites may be by the transfer of a film to the mating material or they may simply provide wear resistant components, but the two actions should not be confused. In consequence they may be used in space either as the base material of one component of a rubbing pair, e.g. gears, or to provide a transfer film to lubricate a rolling or sliding metal pair, e.g. ball bearings.

PTFE + MoS_2 + glass fibre has for many years been used as a cage material in small, lightly loaded, ball bearings. This composite has been studied in detail by Stevens and Todd (Ref.9). Loads must be limited to ensure that the Hertzian contact stress does not exceed 1.2 x 10^3 MN/m^2 at 20°C. The MoS_2 appears to have the function of preventing the transfer film of PTFE becoming too thick. Failure is usually by wear-out of the cage, creating large quantities of debris. In oscillatory motion a build up of transfer film at the end of the arc of travel leads to excessive torque peaks. In addition the thickness of the transferred film can be dependent upon speed of operation.

Both polyimide and polyacetal have been used for lightly loaded gears in a space environment running against stainless steel, titanium or aluminium. Work in progress at ESTL, to be reported in the near future, has shown that Vespel, a polyimide, gives the lowest wear rate of all polymers tested. Polyacetal filled with carbon fibre has also been tested and shows lower wear rate than the unfilled polymer but still greater than the polyimide. Maximum loads for all these materials should be limited to 10 N/mm tooth width for gears of module 1.

4.3 Soft Metals

It has long been known that the soft metals such as Ba, Au, Ag, Pb, In and others are capable of providing lubricating films in certain circumstances. In this paper we shall confine ourselves to the use of lead in rolling bearings and gears in space. The work was initiated by the Royal Aircraft Establishment in the UK in the 1960's and a very extensive test programme was carried out by Marconi Space and Defence Systems on 19 mm diameter bearings at 3000 rpm, some of which ran for eleven years. The programme was extended by ESA to bearings of 90 mm diameter running at 100 rpm and six pairs completed more than 60,000 hours without failure. In all these tests the only limitation was the wear debris from the lead bronze cage, and the search for a better cage material is continuing.

The process used by MSDS Ltd. was vacuum deposition, which made film thickness and adhesion difficult to control, so the Agency undertook the development of an ion plating process at ESTL. (Ref.10, 11, 12).

The pre-eminent advantages of an ion plated film over a vacuum deposited one are excellent adhesion and close control of thickness, 0.35 ± 0.15μm at ESTL. At present only the races of the bearing are plated and the film is transferred to the balls during the running-in period in vacuum, which is an integral part of the process. Ion plating of the balls is now possible but, for most applications seems to offer little advantage.

Lead lubricated bearings are flying in the OTS and MARECS Solar Array Drives and will fly in the SADs of ECS, EXOSAT, L-SAT and the French SPOT. The bearings of the de-spin mechanism of GIOTTO, the European Halley's Comet probe, will also be lead lubricated. The selection of lead in this case was made to take advantage of its immunity from torque changes due to temperature. The torque at -40°C is virtually identical to that at room temperature in a well designed system; a performance which no liquid lubricated bearing can equal. Torque noise, however, will be higher than an equivalent liquid system which was the reason for the final rejection of lead, and all other dry film systems, for the Space Telescope Solar Array Drive, where smoothness of operation is a prime requirement.

Lead lubricated bearings are finding application in scientific instruments and lead lubricated ball screws are flying on Nimbus G. A similar ball screw has performed very well at 4°K and demonstrated the effectiveness of the process at cryogenic temperatures. Ion plated lead is now being applied to gears although it operates better in a rolling than in a sliding contact. Tests have shown it to be a very effective lubricant for gears of nitrided steel on nitrided 440C steel and it has been adopted for the gears of the L-SAT Solar Array Drive. Most importantly the process has been fully established, codified and documented at ESTL to ensure complete repeatability of film parameters and friction and wear characteristics, and it is now offered as a standard process routinely carried out.

The pros and cons for lead lubrication may be listed as:

Pro:
- excellent adhesion
- low, consistent and temperature-independent torque
- very long life under vacuum
- applicable to bearings, gears and ball screws
- usable at cryogenic temperatures

Con:
- flake wear debris from the lead bronze cage can cause torque noise problems. ESTL is investigating alternative materials for cages.

- operation in air must be limited to fairly low speed and short duration e.g. 10^5 revs.at 100 rpm for a 20mm ID bearing.

4.4 Bearing Torque Characteristics of Solid Lubricant Films in Vacuo.

With the aim of comparing levels of torque and of torque noise from ball bearings under identical conditions, data from ESTL have been assembled to show what is to be expected of the three most common lubricants discussed above.

Table 2 shows the details of the method of lubricant application, the associated cage material, the type, size and preloading of the ball bearings used in this comparison. In all the tests an arbitrary level of torque ten times the initial DC level was chosen to represent torque "failure".

4.4.1 Torque Results

The histories of torque tests over 2 million revolutions (or until torque failure, as defined above) are collected in Table 3. As a comparison the result for an unlubricated, but degreased, bearing is included. Very rapid failure is encountered.

The MoS_2-sputtered bearings tended to start with a moderately high torque (20×10^{-4} Nm) but it soon fell to a $6 - 10^{-4}$ Nm (at 40N preload) where it remained until usually a sudden steep rise and torque failure. Films sputtered at ESTL and at LSRH Switzerland exhibited broadly similar behaviour but bearing lives varied from $0.7 - 3 \times 10^6$ revs for films sputtered at ESTL and from $2 - 3.66 \times 10^6$ revs for films sputtered at LSRH. The torque traces were some of the smoothest that we have observed and we would now recommend sputtered MoS_2 where low torque noise is important and the life requirement is not above 10^5 revolutions, or equivalent rolled distance.

The ion-plated, lead-filmed bearings exhibit reasonably steady DC (average) torque but there is considerable fluctuation in the peak-to peak torque. This latter is defined here as the maximum total swing of torque either side of zero during slow rotation of the bearings in two opposite directions. This bi-directional check of the torque was carried out at regular intervals in these tests. For the lead film there is no effect of a previous run at 100N preload on the torque. None of the lead bearings failed by the above criterion. The PTFE-composite caged bearings were considerably more erratic in their average torque than the lead filmed bearings and the torque was prone to rise quite suddenly over a few thousand revolutions and as quickly to subside. Nevertheless, the peak-to-peak amplitudes of torque were less than those of the ion-plated lead, as Table 3 shows. There was a discernable effect of previous running at low load (i.e. below critical stress) upon the torque in the 250N run (above critical). The bearings run immediately at 250N showed high DC torque initially but this gradually reduced with time. Such initial high torque was absent if the bearings had been run at sub-critical stress beforehand but there were still periods of high torque during the run. For these bearings 100N preload caused the critical Hertzian stress.

It is appropriate to complete this section with the second precept of space tribology:

> Precept 2: In designing a space mechanism avoid making its operation dependent upon close control of the coefficient of friction.

5. LIQUID LUBRICANTS

The use of liquid lubricants in space is not new and it is fair to say that all early American satellites relied upon it. Ball Bros. were the leaders in the field in the USA and the move to dry lubrication has been slow. In Europe we went strongly for dry lubricated systems, largely driven by the success of the lead system, but also because their advantages were clear.

In consequence liquid systems in Europe have received less attention but have not been ignored. A de-spin system which has been running under test in vacuum at ESTL for more than 7 years is liquid lubricated. The Solar Array Drive for Space Telescope, the Instrument Pointing System and the bearings of the Antenna Pointing Mechanism on L-SAT, all have liquid lubricated bearings.

5.1 Hydrocarbon Oils

In Europe BP Ltd (U.K) developed, at the request of RAE, two space oils with very low vapour pressure.

BP 110 is a very fine cut natural hydrocarbon with a claimed vapour pressure of 10^{-10} torr or lower at room temperature.

BP 135 is a synthetic tri-ester with a higher viscosity index than BP 110.

BP. Ltd. further developed two greases upon these oils but of quite different formulation from normal greases. (Ref.13).

The thickener is based on an oleophilic graphite-lead composite capable of forming stable semi-solid structures on dispersion in a suitable base fluid. The proportion of thickener is 17%, which is unusually high, but it also provides a marked improvement in the extreme pressure and boundary lubricating properties.

The use of graphite in a space environment is very unusual since it is well known that graphite in a wholly dry atmosphere acts as an abrasive. In the case of the BP greases the special method of preparing the graphite to render it oleophilic makes it operate in a vacuum environment very satisfactorily.

Both of these oils have been subjected to extensive testing over the past seven years and the BP 110 and its grease BP 2110, have been shown to give longer bearing lives in vacuum than competitive lubricants. In most tests BP 135 has not equalled the life achieved by BP 110 but has given good results for many applications, and is useful where its higher viscosity index may be an advantage.

At ESTL a de-spin mechanism has been running at 60 rp.m. under thermal vacuum conditions for seven years without any change in performance. Lubrication is achieved by a small quantity (about 5% fill) of BP 2110 grease in each bearing combined with Nylasint oil stores charged with BP 110 oil. The thermal conditions in the chamber are maintained at 20°C whilst the shaft of the mechanism is driven between -5°C and + 45°C. The performance of this mechanism has been excellent with no change in any operating parameter except a small rise in motor current attributable to magnet deterioration.

5.2 Synthetic Oils

In general, synthetic fluids usable as space lubricants fall into two broad categories:-

- silicones
- fluorinated polyethers.

In the early years of space many silicones were tried as space lubricants with widely different results. Their advantages are a high viscosity-index, good thermal stability and fair to good lubricating properties, but their volatility in space environment may not be significantly better than some hydrocarbon oils, and their surface creep characteristics are notoriously bad.

Silicones in space have now been displaced by perfluoralkylethers such as the Krytox and Fomblin fluids. However, the lubricating properties of these fluids are not general and only some of them have found application in space. In some applications such as sliprings they can lead to excessive wear rates and the formation of polymers. However used in the right application they can give excellent performance and their extremely low (10^{-11} - 10^{-13} torr) vapour pressures at room temperature makes them most attractive for mechanisms with critical cleanliness requirements.

5.2.1 Fomblin Z25

Probably the most significant addition to space lubricants is a polyfluoralkylether manufacturered by Montedison in Milan called Fomblin Z25. The Fomblin Y series of fluids has been well known in the vacuum industry for many years but the introduction of Fomblin Z, which has a different chemical structure, was something of a breakthrough for space lubrication. The fluid has the very high viscosity index of 345 and a vapour pressure that is certainly below 5×10^{-12} torr at room temperature. It is the only oil known to the authors which passes the Agency's material out-gassing test, giving TML/RML % 0.01/0.01 and cvcM% 0.00.

The Bray Oil Co. in the USA have for several years distilled the Italian raw stock to make Bray 815Z, which has been flown on a number of USA satellites mostly in the form of a PTFE thickened grease, Bray 3L38RP, and will fly in Space Telescope in the solar array development mechanism.

During the last two years the fluid has been subjected to numerous tests at ESTL.

Bearings of two different conformities are being run at speeds of 20, 100, 200 and 1400 rpm. Full elasto-hydrodynamic lubrication is achieved at about 250 rpm. In the case of low conformity bearings at 1400 rpm the torque reduces suddenly and torque noise increases after a short time indicating the onset of starvation conditions. A black deposit has been observed in these bearings which has been identified as a polymer. In initial tests the high conformity bearings at 1400 rpm were accidentally contaminated with a hydrocarbon oil which resulted in a good performance but a milky deposit. Repeat tests with rigorously pre-cleaned cages are showing similar deterioration in average torque and torque noise. This work will be fully reported when complete.

The load carrying capacity of the fluid tested on the Falex machine is very good, giving a failure load in excess of 15,500N (3500 lb).

In pin and disc tests to evaluate its boundary lubricating properties it has performed equally with KG 80 and BP 110 for wear rate and coefficient of friction. (Ref.10).

The conclusion to date is that its use is acceptable in low speed applications where boundary lubrication is required and in Europe it is currently being applied to the bearings of IPS, Space Telescope Solar Array Drive and the L-SAT Antenna Pointing Mechanism.

For the present the oil should not be used in sliprings where it may increase the wear rate and can lead to complete failure by the formation of debris.

The grease 3L38RP has been used in small gear boxes but data on permissable tooth loading, shear breakdown or polymer formation is very limited.

Future use of the oil under conditions of EHD lubrication is dependent upon the results of the ongoing test programme at ESTL, the objective of which is to determine the limits of its range of application. Its use in optical instruments is not excluded but has yet to be demonstrated by valid test.

Before any application of this oil to a space mechanism is contemplated it is strongly advised to seek the guidance of ESTL who has carried out most of the relevant work.

6. THE CODIFICATION OF SPACE LUBRICANT SYSTEMS & PROCESSES

The behaviour of any tribological systems is governed by a large number of factors, many of which are difficult to control. Material properties, both macro and micro, surface condition, presence of micro quantities of contaminants, system geometry, speed, load, duty cycle are only some of the variables. In consequence any lubrication process to be acceptable for space must be subject to the following precepts:-

Precept 3: - Any lubrication process used for space application must be fully codified and documented to ensure consistent repeatability of performance.

Precept 4: - The lubricant used must be approved and validated for space to a recognised specification and must be source traceable.

Precept 5: - The test programme to determine the performance of the lubrication system must reproduce all the operational conditions of duty cycle, environment and life that it will experience in the application.

The use of a commercial system for a space application is acceptable only if it fulfils these three precepts. The Agency has issued a guide to the preparation of process procedures. (Ref.14).

7. CONCLUSION

In attempting to cover the whole field of space lubrication in a short paper the authors have set themselves an impossible task. Much relevant and important detail has had to be omitted. But the purpose of the paper is to provide a useful brief overall view which will, it is hoped, give the non-specialist a picture of a highly complex subject, and some guidance in the choice and application of a lubricant in spacecraft mechanisms.

TABLE 1.

APPLICATION	DUTY	LIFE	ENVIRONMENT	LUB. REQUIREMENTS
Momentum Wheels	Continuous Rotation at 3000-4500 rpm.	7-10 yrs	Closed low pressure He	Liquid: Maintenance of a controlled flow of lubricant into EHL zone to achieve low and consistent torque. Low wear rate.
Solar Array Drive	Continuous rotation at 1-16 revs. per day	7-10 yrs	Space exposed Thermal -40°C to +65°C	Solid or liquid: Boundary lubrication with consistent torque. No contamination, moderate load, corrosion protection.
Antenna Pointing Mechanism	Slow intermittent operation over small angle and occasional fast tracking	7-10 yrs	Space exposed Thermal -40°C to +65°C	Solid or liquid: Boundary lubrication with consistent torque. No contamination. Moderate to high load capacity, corrosion protection
Instrument Pointing Systems	Slow intermittent operation over small angle, very high precision	1-4 weeks 5 yrs storage	Space exposed Thermal -20°C to +60°C	Liquid: Boundary lubrication with low and consistent torque. No contamination. High load capacity, corrosion protection
De-Spin Mechanism	Continuous operation at 15-60 rp.m.	7-10 yrs	Space exposed Thermal -40°C to +65°C	Solid or liquid, controlled quantity of oil or grease. Low and consistent torque over temperature range. Low wear rate, corrosion protection.

TABLE 1 (cont.)

APPLICATION	DUTY	LIFE	ENVIRONMENT	LUB. REQUIREMENTS
Solar Array (Hold down points and latches)	Deploy and retract	50 operations	Space exposed Thermal -60°C to -80°C Launch vibration loads	Dry. High load capability, good fretting resistance
Focussing Mechanism	Intermittant operation cycles 10000 to 100000	7-10 yrs	Space exposed Thermal 0°C to 20°C	Dry. Low and consistent friction. Absolute freedom from contamination. Low wear rate. Corrosion protected.
Filter wheels, shutters, beam splitters etc.	Intermittant operation 10.000 - 20.000 cycles	7-10 yrs	Space exposed Thermal 0°C to 20°C	Dry or liquid.Low and Absolute freedom from contamination.Corrosion protection.
Slip rings and brushes	1) Low speed continuous	7-10 yrs	Space exposed	Dry.Low and consistent friction. Absolute freedom from contamination. Low and consistent electrical noise.
	2) High speed intermittent	7-10 yrs	Thermal -40°C to +65°C	Dry or liquid,low wear rate, low electrical noise
Gears	1) Intermittent operation 1000 Cycles	7-10 yrs in space	Space exposed Thermal -40°C to +65°C	Dry or liquid. Low and consistent-friction. No contamination
	2) Continuous operation	7-10 yrs	" "	Dry or liquid. Low wear and low friction.No contamination

TABLE 1. (cont.)

APPLICATION	DUTY	LIFE	ENVIRONMENT	LUB. REQUIREMENTS
Rotating Scanner	Continuous operation operation at 15-60 rpm.	7-10 yrs	Space exposed Thermal -0°C - 20°C	Solid or liquid, controlled quantity of oil or grease. Low and consistent torque. Absolute freedom from contamination.
Booms	1) Deploy only	50 operations	Space expoosed -40°C to +65°C	Dry: Consistent friction over temperature range
	2) Deploy and retract.	100 operations after long space stay	Space exposed Launch vibration loads	Dry: Consistent friction over temperature range and life. No contamination.
Solar Array (Hinges)	1) Deploy only	20 operations	Space exposed Thermal -60°C to +80C	Dry.Consistent friction over temp.range.
	2) Deploy and retract.	50 operations after long space stay	Space exposed Thermal -60°C to +80C	Dry or liquid. Consistent friction over temp.range for long life required. No contamination.
Antenna Deployment	Deploy only	20-50 operations	Space exposed Thermal -60°C to +80°C	Dry.Consistent friction over temperature range.

TABLE 2

LUBRICANTS AND BEARING DATA

LUBRICANTS

Solid Lubricant	Cage Material	Method of Application
PTFE film	PTFE/glass fibre/MoS_2 composite (commercially available).	Film formed by transfer from the cage during bearing rotation.
MoS_2	1% C/1% Cr steel (EN31), machined and ground	RF sputtered film approx. 0.5 micron thickness All bearing components sputter coated.
Pb	11% Pb tin bronze cast alloy (Commercially available)	Raceways ion-plated with lead to thickness between 0.2-0. 5 μm Balls not coated

BEARING DATA

Type of bearing	angular contact
Size	20mm ID, 42mm OD
Contact angle	15°
No. of balls	10
Ball diameter	7.14mm
Ball conformity	1.14
Precision	ABEC 7 or 9
Axial preloads used	40N, 100N and 250N

Table 3. Torque Results From Bearing Tests (All Bearings Completed 2 x 10^6 Revs at 100-600 RPM Unless Stated).

Lubricant	Axial Preload	Range of Average torque (Nmx10^{-4})	Range of Peak-to-peak torque (Nmx 10^{-4})	Remarks
NONE (DEGREASED)	40N	12 - 43	105 - 144	Torque failure after 1,340 revs
SPUTTERED MoS_2	40N	6 - 10 (20 initally)	50 - 100 (up to 220 initially)	Low DC torque noise,but torque failures between 0.7 and 3.6 x 10^6revs.
ION-PLATED LEAD	40N	16 - 26	80 - 150	NO TORQUE FAILURES DC torque steadier than for PTFE but peak-to-peak torque (noise) greater
	100N	40 - 50	150 - 450	
	250N (After 100N)	100 -180	400 -1100	
	250N (No run-in)	80 -160	500 -1300	
PTFE-COMPOSITE CAGE				NO TORQUE FAILURES
	40N	6 - 50	34 - 160	-Stress below limit
	100N (After 40N)	10 - 60	75 - 250	-Stress at limit (1x10^6 revs only)
	250N (After 40/ 100N)	50 -500	250 -1050	-Stress above limit.Periods of high DC torque.
	250N (No run-in)	40 -500	150 - 700	-Stress above limit. Initially high DC torque.

* Bearing lives with MoS_2 -sputtered film varied from 0.7 to 3 x 10^6 revs for films sputtered at ESTL to 3.6 x 10^6 revs for films from LSRH, Switzerland.

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