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TRIBOLAB: AN EXPERIMENT ON SPACE TRIBOLOGY

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ABSTRACT.

The accurate knowledge of the complex behavior of lubricant systems, both solid and liquid, is a fundamental requirement for the reliable operation in orbit of spacecraft mechanisms. Modern spacecraft, of all types, proliferate with mechanisms whose predictable operation is mandatory.

In flight a spacecraft mechanism must develop its function under a quite hostile environment, which is made up mainly by space radiation, extreme thermal conditions, vacuum, atomic oxygen and mechanical effects like microvibrations. All those conditions are impossible to simulate simultaneously on ground.

Some tribometers flown in the past in order to correlate the flight and ground tests results showed a good correlation of data for simple friction and wear of bulk materials and surface coatings. Nevertheless, new promising materials and processes, never flown before, will be implemented in the experiment to know its behavior against the above mentioned environment and laying stress in μgravity conditions.

TriboLAB is where those factors could be evaluated on a range of solid and liquid lubricants and lubricant systems. Ideally this facility would be serviceable and retrievable for maximum data generation. This facility would additionally be able to qualify and provide information for new or developed lubricant systems.

OBJECTIVES.

In mechanical components of a satellite the mechanism are the most critical. As example in a NASA study of more than 100 anomalies reported in satellites from 1974 to 1994 only four were in mechanical elements and all of them due to lubrication failures.

In practice, the choice of lubricants and its application technique will determine the tribological performance in terms of friction, wear and endurance life. An understanding of fundamental properties of lubricants and their correlation with performance requirements in the specific environment that they will operate is essential for the development of new lubricating materials. Not only to avoid catastrophic failures, but also to reduce power requirements, and to alleviate torque noise which is important in precision pointing mechanisms.

The fundamental overall objective is to investigate tribological phenomena which cannot be simulated by on-ground test facilities. In particular, the effects of microgravity, the continous vacuum to pump away evolving species, the thermal environment, and potential synergistic effects of the Space Station.

Specific objectives are therefore:

- To evaluate the performance and durability of solid lubricants, particularly: surface treatment techniques and cage designs in ball bearings under near zero-g and microgravity perturbations.
- To measure and validate the effectiveness of labyrinth seal designs to restrict fluid loss by evaporation and creep.
- To examine potential synergistic effects of a combined exposure to atomic oxygen, radiation thermal environment, and vacuum over a selection of new coating or surface treatments.

SPACE TRIBOLOGY.

Space tribology is the application of the science and technology of tribology to mechanisms and surfaces that operate in spacecraft. The principal characteristics of vacuum, lack of oxygen and large temperature variations of the space environment result in the use therein of either low vapour pressure fluid lubricants or solid

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lubricants to achieve acceptable friction and low wear. Below are details of two experiments aimed at improving the understanding of the behaviour of space lubricants that greatly benefit from being apply to fly as part of the ISS.

LIQUID LUBRICANTS.

When fluid lubricants are used in spacecraft mechanisms, there is a continual concern on the prevention of fluid loss, by creep and evaporation, to avoid either inadequate lubricant within the bearing system, or contamination by the 'escaped' lubricant. The principal approach is to use a labyrinth seal, or narrow gap, to restrict loss. For a bearing sealed in this way the amount of fluid or fluid additive lost is governed by the following:

- The rate of vaporisation of the oil, which is determined by its molecular weight, vapour pressure and temperature.
- The speed of travel of evaporated molecules (governed by molecular weight and temperature)
- The gaseous pressures within the bearing and outside the labyrinth seal
- The conductance of the labyrinth seal, which is determined from its dimensions and geometry
- Whether flow of gas through the seal is molecular or viscous (determined by dimensions of seal and size of oil molecule).

Several simple models have been developed to describe the flow of molecules through gaps and labyrinths . Most are based on the molecular (as opposed to viscous) flow of relatively small and light gas molecules which, for the purposes of modelling, are treated as spherical particles.

The application of these models to the transport of vapour generated from fluids used in space has met with some apparent success, though valid experimental verification remains lacking. Also, their applicability to low-vapour-pressure fluids and additives having large molecules of complex shape (eg perfluorinated oil molecules are long and chain-like rather than small and spherical) has yet to be demonstrated. The growing use of long chain molecule fluid lubricants in European space mechanisms means that experimental tests on the validation of existing models are urgently needed. A valid test will not occur when constrained by the typical background achieved by terrestrial vacuum chambers.

The use of the TEF facility on ISS allows an unique opportunity to measure and provide validated design for labyrinth seals, in the full and complete environment in which these mechanisms must operate. The ability to return the experiment for measurements on ground after long periods of exposure to vacuum in near zero-g being the fundamental advantages offered by TEF and ISS.

The basic approach will be to compare, for different seal geometries, predicted fluid losses with those measured experimentally. For simplicity the experiment is essentially passive, with only housekeeping measurements of local temperature and pressure. Weight measurements before after flight will determine evaporation losses for a given seal geometry.

The test programme will be based on annular labyrinth designs with annular gap sizes achievable in practice (typically 0.2 mm or less) and having a range of lengths. The foreseen size of an 'effusion cell' will be of the order diameter 60 mm and length 50 mm. To simplify design, the labyrinth seals shall be static Oil reservoirs will be used to physically retain the oil. 'Free' pools of oil are rejected as an oil source, as there is a considerable risk of these flooding the seals and hence being unrepresentative of evaporative flow.

The prototype design of the effusion cell is shown in figure 1, with indicative dimensions. These are typical of the diameter and length of bearing cavities, and allow acceptable tolerances with standard precision manufacturing processes. A minimum of 12 effusion cells are foreseen.

For individual temperature measurement a thermocouple/thermistor is indicated per effusion cell, though clearly a single tray thermocouple/thermistor is probably sufficient. Likewise a tape heater is indicated if increased temperatures are required to ensure adequate fluid loss by evaporation.

As shown in the diagram, it is foreseen that a free volume is required directly above the lubricant reservoir to generate the head of saturated vapour which is then constrained and gradually released by the labyrinth seal. It is vital that the rate of fluid loss is governed by the labyrinth seal and not the rate of evaporation of fluid from the reservoir. In practice this may mean a larger free volume than indicated in the prototype cell.

Care is required to ensure fluid loss does not occur by surface creep, as this potential mask losses by evaporation. Relevant surfaces will be coated with commercial anticreep barrier material to prevent this.

Three basic types of labyrinth seal are currently foreseen:

- Annular gap, which consists of specified radial gap between housing and core, and of defined length.

- Annular gap with multiple 90 deg corners (a stepped annular design) of specified radial gap, and of defined length.
- Annular gap with multiple knife edge contacts, of specified radial gap and of defined length

Based on 12 effusion cells, the proposed approach is to use three oils of well documented vapour pressure characteristics, use the three types of seals defined above and use two values of annular gap. With this approach a complementary matrix of seal parameters is defined.

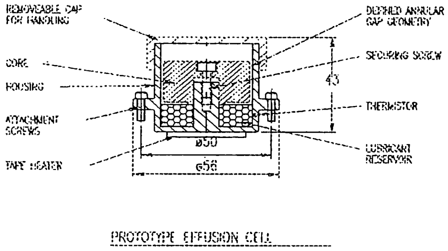

Fig.1 Liquid lubricant test device.

SOLID LUBRICANTS.

Solid or dry lubrication typically used in space mechanisms include mainly soft metals, lamellar solids, polymers and other soft solids such as fluorides and oxides[1]. Major advantages of solid lubricants are the negligible vapour pressures and some are quite insensitive to temperature, being therefore suitable for cryogenic and high-temperature applications. A major disadvantage of conventional solid lubricants relative to liquids or greases is their shorter lifetime. Therefore, there has been an interest in increasing the solid lubricant endurance life relative to system service life.

The two most important requirements to achieve solid film lubrication are a strong coating-substrate adhesion and low resistance to crystalline slip during shear. Another equally important criterion for obtaining effective lubricating action is that the films be applied to contacts of high hardness and high elastic modulus. For a given geometry and load the friction coefficient will be therefore dependent on the film's shear strength and the elastic moduli of the bearing materials. In order to obtain ultra-low friction, the shear strength of the film must be low and the elastic moduli of the bearing material high. It has also been demonstrated that tribological characteristics of coatings (e.g. coefficient of friction) deteriorate as the coating thickness increases. However, in environments such as those of the Low Earth Orbit (LEO), the main concern about very thin coatings exposed to atomic oxygen would be that even a low erosion rate could remove the coating in a relative short time.

In this work it is proposed to evaluate the tribology performance of a new generation of lubricating thin and thick coatings produced by state of the art PVD and Plasma Spraying technologies. Thin films will be mainly multilayers of hard compounds and modified lamellar solids, including also a family of DLC films with tailored gradual compositions. Thick coatings will be mainly produced by plasma spraying and consist of quasicrystalline and functional gradient alloys. All these coating materials will be validated previously by ground testing (e.g. adhesion, endurance and friction tests under vacuum, ATOX, etc.) prior to any further test in the **TriboLAB.**

Lamellar solids such as sputtered MoS2 films have been widely investigated for space or vacuum applications especially since the late 1980s. These films have superior performance than soft lead films and burnished or bonded MoS2 in terms of lower friction coefficients and endurance; however, performance of sputter-deposited MoS2 is dependent on film microstructure. A general trend in coating development in recent years has been the production of dense films with low porosity, to avoid large-scale film debris generation early in wear of space mechanisms. In particular, the advances in magnetron sputtering PVD technology have allowed the development of harder and denser metal-doped MoS2 coatings or multilayer coating systems combining the benefits of underlying ceramic coatings and thin dense solid lubricant films.

Compositionally graded coatings have several advantages over mono or multi-layers conventional coatings. These coatings are prepared by simultaneous deposition of two or more materials in a controlled manner, such that the a compositional profile of the constituents is formed across the thickness of the coating. In this manner, coating designs can be generated in order to meet specific requirements at different depths of the coating[2]. In addition, coating compositions could be tailored to match properties of the substrate in order to alleviate problems caused by material mismatch at the coating substrate interface.

Another new family of materials with promising tribological behavior are the quasicrystalline alloys (QC). These materials exhibit a set of adequate anti-friction properties: low friction coefficient, hardness and high yield strength under compression. QC alloys may be easily produced as coatings on top of metallic and non metallic materials.

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While the tribology of these solid lubricant films can be evaluated under ground laboratory conditions, the combined effect of high vacuum, ATOX and UV exposure under LEO conditions is very difficult to reproduce in ground. The effect of ATOX exposure on some MoS2 films has been previously evaluated[3 4 5], however, the results seem contradictory as to the real effect on friction and shortening of wear life of the coatings. Furthermore it is very difficult if not impossible to replicate all the intervening environmental factors that might behave in synergistic manner. Therefore, there is a need to test the tribology of a new generation of denser, more wear and ATOX resistant solid lubricants simultaneously under LEO conditions. These conditions are extremely difficult to reproduce in a ground-base laboratory.

The TEF facility on ISS represents a unique opportunity to evaluate the tribology performance of a new generation of improved solid lubricant coatings simultaneously with an exposure to LEO conditions, that is ATOX influence, UV and near zero-g.

The ability to monitor the performance of the test and obtain tribological data continuously under these conditions is very useful to gain knowledge of the behaviour of the solid lubricant coatings throughout the exposure under LEO conditions. The opportunity that is given to return the tested coatings for evaluation of the surface degradation after long periods of exposure is a real advantage.

The test approach will be to evaluate the tribology performance of a range of solid lubricant coatings under LEO conditions by a versatile tribotester. These coatings include: multilayer and metal-doped MoS2, a new generation of gradual DLC and composite compositionally graded coatings based on a combination of two or more materials including quasicrystallines. The test will basically consist of a hemispherical rider sliding against the flat and coated face of a disk that rotates at a constant speed. Typical disk size will be about 5 mm thickness by 25 to 35 mm in diameter and the rider will be of 6 mm in diameter with hemispherical end. Normal loads will be in a range from 4.5 to 20 N and the sliding speed from 0.001 to 0.1 m/s.
Surface roughness measurements on the disks by means of optical laser surface profilometry will be performed on the disk materials before and after the flight. This, together with SEM observations, will help to determine the extent of wear damage and the effect of LEO ambient on the exposed and tested surfaces.

Care should be taken to avoid or minimize contamination of the disks with debris or fluid losses from adjacent experiments in the TEF, without impairing or diminishing the influence of LEO environment on tested surfaces.

INSTRUMENT.

Mechanical description.

The TEF program will be run in parallel to the **TriboLAB** project which means that at this moment most of the interfaces have not been defined yet, therefore the mechanical design must be seen like a conceptual design which will be arranged with the TEF interface in the future.

The general design criteria followed to carry out this conceptual design are identified below:

- The baseline test unit is a pin-on-disk for the solid lubricant and the effusion cell for the liquid lubricant. Nevertheless, the implementation of a ball-bearing test unit is under evaluation.
- The number of disks must be maximised to provide to the scientific team as much opportunities as possible to test samples.
- The number of actuators must be minimised to optimise the power and mass budget.
- A failure in one a disk would not imply a global failure in the experiment.

Following these criteria the first approximation to the mechanical design can be seen in figure 2, in which the following points can be highlighted:

- The effusion cells have been allocated in one side of the instrument side.
- To avoide oil contamination a barrier like cold walls could be implemented.
- Two parallel shafts with ten disks each would provide a total of 20 disks available, that could be coated by both sides.
- In case that of the friction whoud rise above a predefined threshold (coef. friction > 3 (TBC)) some security system will be implemented in each disk, in the way of breaking the kinematic link between the disk and the shaft.
- The security system could be a device controlled by a calibrated spring such that when the load achieves a predefined value breaks the joint between the shaft and the disk. That link has to be restablished by hand.
- Two fingers can be applied on each disk, one at the upper face and the other at the lower face.
- Each finger is joined to the basic structure by a flexural pivot (Lucas Free-Flex®) that provide a way to control the normal force over the disk and eliminated the need of a ball bearing.

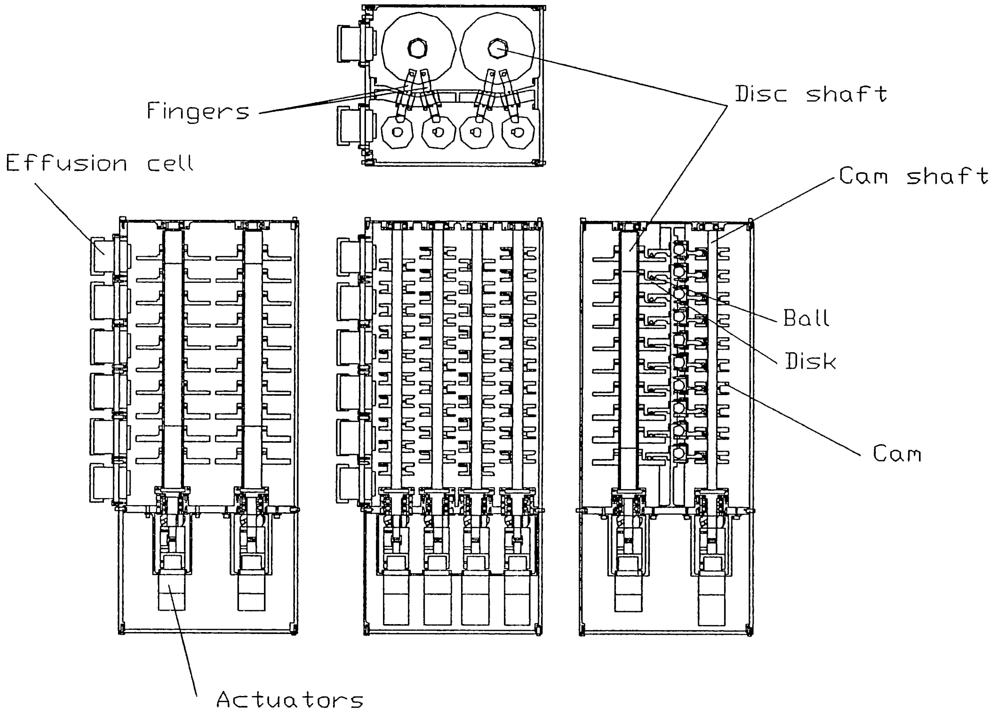

Figure 2 Tribometer Mechanical Design

- The position of each finger is controlled by a cam.
- Four shafts of cams control the position of all fingers, in such way that only one of the total number of fingers is applying force at each moment.
- During the launch, the cams restricts the rotation of the fingers to avoid impact with the disks.
- Each shaft (two disks-shaft and four cams-shaft) will be supported by three ball bearings, lubricated by a well known lubricant.
- The disks-shaft are designed to ease the implementation of the final coating when the instrument is in a well controlled environment, since during the assembly phase there are some doubts about the control of the environment contamination level.

The instrument has two zones: upper and lower. The upper one is the experiment zone were the disks are installed, and the lower is were the actuator and instrument electronic are allocated

The baseline for the actuators are stepper motor plus a reducer; speed controlled in the case of disk-shafts and position controlled for the cam-shafts.

The lower zone is built up by a box which provided housing to the actuators, the electronic and the power subsystem. Some connectors will be installed in that box to link with the sensors and with the TEF power and data lines.

Electronic description.

A block diagram of the instrument control electronic is depicted in figure 3. Basically, the electronic core is a μcontroller of the 8051 family hardened to be used in space which controls the following elements:

- A/D converter. This component receives the sensor signal from a multiplexer which is programmed by the μcontroller. Previously, the sensor signal is conditioned properly in a previous step.
- Motor controller. Each motor will have a dedicated controller (speed or position) which moves the motor through a power driver.

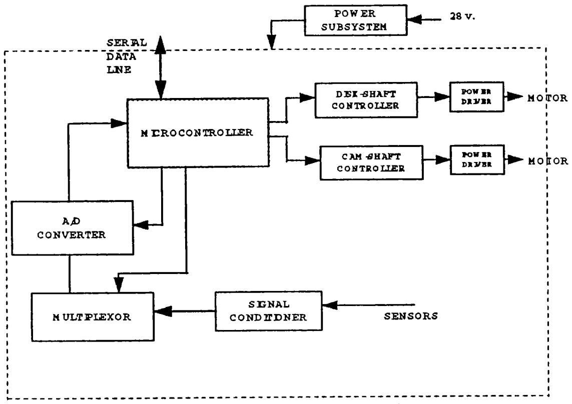

Figure 3 . Instrument electronic

- TEF data line. A serial link with the TEF will be implemented for data interchange.

The design will be as much as simple as possible to optimise resources and to increase the reliability of the concept.

Software design.

The software development will comply with the ESA software standard PSS-05-0. It will be considered a small software project for which guidelines BSSC(96)2 may be applicable.

The experiment software will be structured into two layers:

- Basic Software (BSW).
- Application Software (ASW).

The BSW will provide the interface between the ASW and the hardware drivers (motor drivers, sensor transducers, serial line).

The ASW will perform the experiment commanding and monitorization.

It is assumed that the TC and TM handling is performed by the TEF, i.e. the TEF will decode the TC frames and pass the command to the experiment controller as a ASCII string (TBC), and it will also be responsible to build the TM frames from the instrument controller response.

CONCLUSIONS.

The relevance of lubrication in space mechanisms enforces to look for new materials and new processes that must be tested in conditions as close as possible to its actual working environment, in order to assure its reliability.

A test facility, called **TriboLAB**, has been presented jointly with the background of the liquid and solid lubricant test that will be carried out on it.

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