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In-Situ, On-Demand Lubrication System for Space Mechanisms

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In-Situ, On-Demand Lubrication System for Space Mechanisms

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ABSTRACT

Many of today's spacecraft have long mission lifetimes. Whatever the lubrication method selected, the initial lubricant charge is required to last the entire mission. Fluid lubricant losses are mainly due to evaporation, tribo-degradation, and oil creep out of the tribological regions.

In the past, several techniques were developed to maintain the appropriate amount of oil in the system. They were based on oil reservoirs (cartridges, impregnated porous parts), barrier films, and labyrinth seals. Nevertheless, all these systems have had limited success or have not established a proven record for space missions.

The system reported here provides to the ball-race contact fresh lubricant in-situ and on demand. The lubricant is stored in a porous cartridge attached to the inner or the outer ring of a ball bearing. The oil is released by heating the cartridge to eject oil, taking advantage of the greater thermal expansion of the oil compared to the porous network. The heating may be activated by torque increases that signal the depletion of oil in the contact. The low surface tension of the oil compared to the ball bearing material is utilized and the close proximity of the cartridge to the moving balls allows the lubricant to reach the ball-race contacts. This oil re-supply system can be used to avoid a mechanism failure or reduce torque to an acceptable level, and extend the life of the component.

I- Introduction

1- Overview

Many moving mechanical assemblies (MMA) for space mechanisms rely on liquid lubricants to provide reliable, long-term performance. The proper performance of the MMA is critical in assuring a successful mission. Historically, mission lifetimes were short and MMA duty cycles were minimal. As mission lifetimes were extended, other components, such as batteries and computers, failed before lubricated systems. However, improvements in these ancillary systems over the last decade have left the tribological systems of the MMAs as the limiting factor in determining spacecraft reliability.

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Typically, MMAs are initially lubricated with a small charge (mg) that is supposed to last the entire mission lifetime, often well in excess of five years. In many cases, the premature failure of a lubricated component can result in mission failure **[1–3]**.

Tribological failure of MMAs occurs when the lubricant degrades or evaporates and therefore loses its ability to lubricate rubbing surfaces, bearing balls contacting raceways for example. Since the MMA is still mechanically intact when the lubricant degrades, if lubricant could be re-supplied to the contact, the life of the MMA could be extended. One means of lubricant re-supply has been provided by lubricant reservoirs, but they are bulky, add complexity, and cannot be activated when needed. Rather, they continuously supply lubricant to the contact, often leading to an excess of lubricant supplied to the MMA. Some ball bearings have holes drilled in the raceways next to the contact area **[4]**, but this design is more adapted to large ball bearings.

2- Background of in situ-lubrication and porous reservoirs

To supply fluid lubricant and to assure at least a 5-year mission, porous reservoirs were extensively employed in ball bearings since the 1960's **[5, 6]**. Over the past 40 years, numerous studies were undertaken on impregnated porous materials and their behavior (evaporation, capillary effects on oil release, oil circulation, etc.) **[5–11]**. Porous materials, mainly in the form of retainers, were employed in several space mechanisms **[12–20]**. Oil flow and circulation in porous bearings have been widely studied since the early fifties by Morgan and Cameron **[11]**. Fully described in open literature, this topic has now reached a good understanding level **[21]**. But their effect remained limited as shown by Marchetti et al. **[22, 23]**

One of the ways for oil to be released from a porous reservoir is to raise its temperature. As a consequence, three different phenomena would occur and have an impact on the lubrication of space mechanisms.

The first one is a difference between the thermal expansions of the fluid and the porous matrix. The oil has a greater expansion when heated than the porous solid network **[10, 14, 24, 25]**. Thus, the oil is "ejected" from the reservoir. The differential thermal expansion forces the fluid to be "squeezed out." Jamison **[24]** gave an expression about the quantity of oil ejected, assuming the porosity is isotropic (Dupuit's law). A system was attached to an inertial wheel **[14]** but it was never activated and no evidence of its efficiency given.

The second phenomenon is the Marangoni effect, where a change in the temperature modifies the surface tension of the fluid **[10, 26–32]**. A temperature gradient causes a corresponding surface tension gradient, and so an associated stress. The fluid then moves from the cold zone toward the warm zone. The speed of the fluid is parallel to the thermal gradient. The temperature gradient Prat **[31]** used was 6.4°C.cm^{-1}, as representative of the one existing in ball bearings, while Fote et al. **[10, 26–29, 32]** based their study on gradients between 0.5 and 2°C.cm^{-1}.

The last phenomenon involves the evaporation of the lubricant, the vapor pressure of a material being increased with the temperature. Kato et al. first introduced the idea **[33–36]** on a system to combat the problem of solid coating wear. The system deposited a solid film lubricant into a contact zone during sliding (pin-on-disk) through evaporation. As friction increased, the system could be reactivated and a new coating deposited, thus yielding a virtually limitless lifetime. Termed 'tribo-coating,' this system demonstrated the ability to re-lubricate a contact in-situ. Adachi et al. **[36]** attempted two types of in-situ coating using the solid lubricant indium and a pin-on-disk test device. The first was to deposit a coating on the parts before running the test. This was termed 'vapor deposition.' The second was to deposit the coating while the system was operating. This is called 'tribo-coating.' It was observed that tribo-coating had lower friction and longer life than a vapor deposited coating. Tests conducted on a Spiral Orbit Tribometer have shown that a similar mechanism was able to induce the recovery of the system **[37]**.

3- Objective of the study

In-situ, on-demand lubrication provides a step between having no additional lubricant and large lubricant reservoirs. The in-situ, on-demand lubrication device is a small reservoir that can be remotely activated to provide a minimal charge of lubricant near the contact zone. It is based on the three physical phenomena described above: Marangoni effect, thermal expansion and evaporation. A sensor attached to the MMA monitors its health, as the bearing torque for example, and, when needed, activates the lubricator. The objective of this work was to test the feasibility of using an in-situ, on-demand system with a liquid lubricant under ultra-high vacuum and in a boundary lubricated, rolling contact. The method of lubricant delivery to an unlubricated ball bearing, and the re-lubrication of the mechanism were studied.

II- Experimental

1- Test rig

The GOES rig used for these experiments was first introduced by Jansen et al. **[38]** and is shown in Figure 1. The system is designed to operate at pressures below 5×10^{-6} torr and between temperatures of 23° to 100°C. The device has a computer data acquisition (DAQ) and control system based upon LabVIEW®. The DAQ monitors bearing temperature, torque, load, cross-bearing electrical resistance, and rotational speed. Motion is provided by a computer controlled stepper motor and ferrofluidic feedthrough. The system allows either a constant rotational speed between 0 and 1000 RPM or a precise dither at a desired angle. The rig uses a soft, dead weight loading system. A heating unit can maintain the bearing at a constant temperature between ambient and 100°C or impose a temperature ramp.

Cross-bearing electrical resistance is monitored throughout the test. The inner race is electrically isolated from the rest of the rig. The outer race is grounded. A 1.5-volt supply is provided at the inner race though a 1.5 KΩ resistor. The voltage at the inner race is measured to obtain the voltage drop across the bearing. The cross-bearing resistance can be calculated from the voltage drop. From the resistance data, the lubrication regime can be determined. A low contact resistance indicates operation in the boundary or mixed regime. A high or infinite resistance indicates either operation in the elastohydrodynamic lubrication (EHL) regime or the build up of an electrically insulating friction polymer **[39]**.

The system uses a single angular contact bearing. It is mounted within a fixture, also shown in Figure 1, which holds the inner race fixed and rotates the outer race. A thermocouple is mounted touching the inner race and measures bearing temperature. Torque is monitored using an in-line torque meter.

2- Preparation of the tests

Cleaning

The ball bearings used were MPB 1219, angular contact bearings from MPB, Inc. They were taken apart and the retainer removed. Balls were added to the ball bearing to cope with the absence of cage, reaching a total of 24 balls. This retainerless design has been used in some previous study **[40, 41]**. Parts, made with 440C stainless steel, were then cleaned with hexane and deionized water for 10 min each with ultrasonic assistance. They were then subjected to UV-ozone for 15 min. No lubricant was added to the ball bearing before or after the in-situ, on-demand lubrication system was attached to the ball bearing. Thus, an early failure of the bearing was likely to occur and the efficiency of the re-lubricating system would be evaluated. The bearing with the in-situ, on-demand lubricating system is represented in Figure 2.

Prior to any treatment, the porous rings were measured, then cleaned in a Soxhlet extractor with methanol (HPLC grade) for at least eight hours, and weighed. They were put in a vacuum oven overnight and stored in an inert atmosphere before impregnation. The porous rings were then weighed and their porosity was determined. The rings were made with polyimide, and its main characteristics are presented in Table 1.

Lubricants used for impregnation

The oils considered here were the Krytox 143AB, a perfluoropolyalkylether, and the NYE 2001, a multiply alkylated cyclopentane with additives. Both are commonly used to lubricate space mechanisms, and some of their properties are given in Table 2.

The porous rings were impregnated with the oil by immersing them under vacuum for at least four consecutive days. The lubricants were kept warm (≈ 40°C) to make the impregnation easier. To avoid a spreading excess oil from the porous ring on the ball bearing during the assembly, the impregnation was deliberately chosen to be less than 100%. An impregnation between 70 and 80% was selected, meaning the outer surface of the porous structure was "dry" before being attached to the ball bearing.

3- In-situ, on-demand lubrication system and assembly

The oil reservoir was made with porous polyimide. This material was developed early in the seventies **[42]**, and since used in space mechanisms as retainers in ball bearings or as static reservoirs **[18, 19, 43, 44]**. This material has an important open porosity (Table 1) compared to the usual phenolic resin, and has self-lubricating properties **[45]**.

The thermal expansion of the oil was obtained by attaching a heater on the porous reservoir containing the lubricant. The heater consisted of a metal film deposited on a face of the ring, a fraction of a micrometer thick. The film acted as an electrical resistance heater. The temperature reached is directly proportional to the current passing through the film. The main idea was to use as little current as possible to reach an optimal temperature. The temperature had to be high enough to allow the release of the oil, but also be within reasonable limits, which are the temperature a ball bearing is usually facing in a space mechanisms. A thermocouple was attached close to the lubricator to monitor its temperature.

The in-situ, on-demand lubricator was attached to the inner ring of the ball bearing, very close to the balls and the race. No direct contact occurred between the balls and the lubricator. With the current system, the retainer was removed, but the system could be adapted to any conventional ball bearing. The electrical connections of the lubricator were linked to a power supply. It was always turned on but a relay allowed the current to activate the lubricator when the torque reached an upper threshold, and to terminate it when the torque went below a lower torque limit. The status of the lubricator and its temperature were continuously monitored during the test. A second condition was set up to stop a test. Indeed, as the ball bearing started running without any oil, and because of thermal conductivity of the different elements in contact to each other, the temperature of the ball bearing increased. Tests were run under vacuum, so there was no convection to dissipate the heat generated. This second condition must then be related to the temperature. Indeed, the lubricator became useless when the ball bearing temperature has completely overtaken that of the lubricator since the temperature cannot be controlled anymore. The temperature threshold of the ball bearing was set at 50°C. Here again, the computer data acquisition (DAQ) and control system based upon LabVIEW® was in charge of activating and deactivating the in-situ, on-demand lubricator automatically.

The test was run at a speed of 200 RPM, with an axial load of 20 lb (89 N) in the case of the NYE 2001. With Krytox 143AB, the selected speed was 420 RPM. These conditions must be considered as very severe. Indeed, the ball bearing started operating without any oil and without retainer. This last choice has created conditions of zero entrainment velocity (ZEV) between some balls **[46]**.

III- Results

1- Torque response

An initial test with an unlubricated ball bearing, and no lubricator was run as a reference. It clearly appeared that the bearing was unable to last long in such severe conditions. The torque trace is shown in Figure 3. The time allowed for the in-situ, on-demand lubricator to correct the failure clearly depends on the values of the thresholds to activate and deactivate it. The higher the threshold to activate the lubricator, the less the time left before failure, ranging between a few seconds, and almost one minute.

The test with the Krytox 143 AB showed that the cartridge was able to stabilize the torque and to avoid the failure (Figure 4). The design of the lubricator was not optimum. Indeed, the test had to be stopped because the ball bearing temperature reached the limit. In this case, several points have contributed to have this test stopped: the design of the lubricator was not correct, the speed was too high, and the upper torque limit (5 inch.oz) did not allow enough time to the lubricator to be activated to correct the impending failure.

A second test was performed with the NYE 2001 oil. The design of the lubricator was improved in this test. The speed was reduced to 200 RPM, allowing more time to the lubricator to correct the failure (upper torque limit 2 inch.oz). As shown in Figure 5, the torque remained stable and low enough to allow a modification of the limits to activate and deactivate the lubricator, and showing that some oil had reached the ball bearing. The lifetime compared to the unlubricated ball bearing was improved by a factor 10. While the test was running, an attempt was made to show how efficient the lubricator was. The power supply was voluntarily shut down for almost two hours. The torque progressively increased (Figure 6) and became more and more unstable. Then the power supply was turned on again and the lubricator active again. An immediate drop in the torque was observed. The torque became stable immediately.

2- Oil released

The ball bearings were weighed before and after the test. This gives us an indication on how much oil was transferred from the lubricator. The results are given in Table 3. The ball bearing gained weight, and some traces of oil were found on the rings and balls of the mechanism after the test. The in-situ, on-demand lubricator is based on a polyimide porous structure. Because the humidity could not be controlled during the test and could be a source of errors in the weighings of such structures **[47]**, the weights of the lubricator before and after the tests are not reported in this paper.

IV- Discussion

1- Physical phenomena

As shown in previous studies quoted in the paragraph I-2 of this paper, the capillary effects maintaining the oil within the pores of any porous reservoirs are usually strong enough to avoid any release. One of the main differences between the in-situ, on-demand lubricator system, compared to previous reservoirs developed for space mechanisms, is its proximity to the tribological areas. Moreover, it appeared clear that some energy had to be provided to the system to have the lubricant ejected.

The method chosen was the differential thermal expansion, because of its efficiency and its ease of set up. The conductive metallic layer had a very high resistivity. The knowledge of the current and the voltage applied allowed for the determination of the energy provided, as well as the temperature reached. Since the lubricants and the porous material have totally different thermal expansion coefficients, the quantity of oil removed from the pores could be calculated. Moreover, the polyimide is not a good thermal conductor compared to the oil. The oil was heated more quickly than the porous network was. The lubricator was not activated all the time, so its temperature was not steady and the in-situ, on-demand lubricator was allowed to cool down between cycles.

According to Figure 6, after 1000 s of test, the difference of temperature between the oil and the ball bearing is nearly 10°C. We are assuming that the temperature of the ball bearing is the same as the one of the porous network in which the oil is stored. This assumption is based on the low thermal conductivity of both 440C stainless steel and of porous polyimide, compared to the one of a fluid, and on the fact that the porous reservoir is directly attached to the ball bearing. The oil volume "squeezed out" of the pores is given by the following expressions:

$$V_{oil} = V_{polyimide\ reservoir}.\phi.(1+\alpha_{oil}.\Delta T) \qquad (1)$$

$$V_{pores} = V_{polyimide\ reservoir}.(1+\alpha_{polyimide}.\Delta T)^3 - \frac{m_{polyimide\ reservoir}}{\rho_{polyimide}} \qquad (2)$$

$$\Delta V_T = V_{oil} - V_{pores} \qquad (3)$$

V_{oil} is the volume the oil occupied within the pores of the reservoir. $V_{polyimide\ reservoir}$ is the volume of the porous reservoir, defined by its geometrical dimensions. V_{pores} is the volume occupied by the pores in the porous reservoir. The term $m_{polyimide\ reservoir}$ is the mass of the clean and dry porous reservoir before being impregnated with oil. ΔT is the expression of temperature difference between the oil and the porous reservoir when the lubricator is activated. Only one face out of the four faces of the porous reservoir is heated, so we could consider that only one fourth of the oil given by the equation 3 above is really ejected from the pores. Considering a difference temperature of roughly 10°C (Figure 7), and using the values from Tables 1 and 2, the volume of oil released is nearly 5.8 mg in the case of the oil NYE 2001. This value is extremely high compared to the mass gain of the ball bearing given in Table 3. Nevertheless, this oil is not any more stored in the pores and is now available and very close of the rolling elements.

The first aspect to consider is the temperature increase. The ball bearing started without any lubricant, so its temperature naturally increased. This temperature increase was transmitted to the lubricator attached to the ball bearing, causing a release of oil, implying that the in-situ, on-demand lubricator is self-sufficient in some way. Unfortunately, leaving the system operating this way could cause severe damage to balls and races.

The lubricator is directly attached to the ball bearing. It is clear that the activation of the lubricator would cause an increase of the temperature of the ball bearing and the oil in it. When the test has started, there was no oil in the ball bearing. Thus, the torque stabilization, observed in Figures 4 to 6, is mainly due to the release of oil within the mechanism. Not much oil was released, explaining why the lubricator is continuously activated and deactivated (Figure 6, lubricator status). An explanation of the torque reduction when the lubricator is activated could be also a reduction of the oil viscosity due to the temperature increase. Nevertheless, according to the Figure 7, the temperature of the ball bearing was in a 5°C range during the test, if we did not take into account the beginning of the test. Such a variation of temperature will not cause a large change in the viscosity.

Once the oil was released from the pores, there are several means to allow it to reach the tribological areas. First is by evaporation and condensation. In spite of their low vapor pressure, space oils evaporate a little, and their vapor pressure is greater at higher temperature. At the temperature the lubricator reached, the released oil temperature is higher than the one of the races and the balls according to the temperature monitored in the ball bearing (Figure 7). So, a condensation of vapor was more likely to occur. Furthermore, since the porous cartridge is very close to the balls, condensation on other non-tribological surfaces could be avoided.

The second point is the capillary effect. Once the oil is ejected, it will spread and reach a place such as a corner where it will be trapped. In the configuration presented in this study, the only place where the oil could go is the place the porous cartridge is attached on the inner ring. The oil then forms a reservoir of lubricant and spreads slowly on the races. This aspect could be a criticism, stating that when the heater is off, the porous cartridge could absorb the lubricant previously ejected, i.e. a porous system acting as a “well of oil,” i.e., “a sponge” as quoted in the literature. This remark is valid only for the oil in the immediate vicinity, or touching the cartridge. But it is less likely to occur to the oil on the balls and on the races, which is moving. Nevertheless, if mechanisms had to face this problem, with the consequences of a starvation regime and of an increase of torque, the lubricator would be then activated and would correct the failure to come.

The wettability of the 440C stainless steel surface also helped spreading of the oil. Both oils have a very low surface tension (Table 2), and the surface energy of the 440C stainless steel is generally very high (2400 $mN.m^{-1}$ for pure iron) **[48]**. These values imply that once the oil is in contact with a polished 440C stainless steel surface, spontaneous spreading could be expected.

The last phenomenon involved to "drive" the oil toward the balls and races is the Marangoni effect **[25, 26, 30, 31, 49, 50]**, consisting of lubricant migration caused by a temperature gradient. Indeed, since the rig was operating without any lubricant on the balls and the races, an increase of temperature in the bearing happens. But, once the lubricator is activated, the tribological areas are cooler compared to it. The oil is located in the warmer area of a temperature gradient. This causes a gradient in the surface tension of the lubricant, which tends to cause a migration of oil to the cooler area. Generally, this effect is very slow. But compared to mechanisms where the races are generally the "warm" part of the gradient, the in-situ on-demand lubricator causes an inversion of the thermal gradient. And what was formerly a burden, and a cause of oil loss and starvation of the contact, the thermal gradient is now driving the lubricant toward the tribological area.

In each of the last three situations described before, the lubricant is poured slowly and in small quantity into the contacts, avoiding torque peaks.

2- Extension of the lifetime. Power consumed

All the phenomena described before occurred simultaneously and contributed to providing the ball bearing with oil in the tribological area when the mechanism was approaching failure. They helped to maintain the torque at an acceptable level. Figure 6 shows that the lubricator was able to create a torque reduction when activated. It has also demonstrated that in the case of a lubricated ball bearing progressively reaching failure, the mechanism could be returned to normal status. Compared to an unlubricated ball bearing, there is obviously a gain in lifetime.

The test with the oil NYE 2001 was stopped manually after 5 hours, while the torque was stable. It corresponded to an increase in lifetime of a factor 45 compared to the unlubricated ball bearing. The test conducted with Krytox 143AB has led to an increase in lifetime of nearly a factor 5.

Another factor is the power consumed by the in-situ, on-demand lubricator. This parameter is critical in a spacecraft where the available power is always limited. The system operated at a potential around 35 V and a current around 30 mA. This represents a total power consumption of roughly 1.0 W. In the case of the test with the oil NYE 2001, the lubricator was activated during a total duration of nearly 2200 s, corresponding to 0.61 W.h.

V- Conclusion

An in-situ, on-demand lubrication system was developed. The system was able to correct a mechanism before failure occurred under conditions where the failure was more likely to be fatal to the mechanism. The system, designed mainly for space applications, is neither volume nor power intensive. The system can be easily extended to conventional ball bearings used in applications where lubrication failure is a main concern.

The main objective is either to have a lubricant reservoir in a retainerless ball bearing, or a back-up system in a more conventional mechanism. Indeed, there is usually an initial charge of lubricant in any mechanical assembly. A potential failure is generally very progressive and can be detected. The in-situ, on-demand lubricator could be used in a critical system to maintain the mechanism operational, and so extend its lifetime.

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Table 1: Properties of the porous polyimide **[50]**

average pore radius (μm)	0.5
porosity ϕ (%)	≈ 25
permeability (m^2)	2.1.10–15 *** [51]**
density $\rho_{polyimide}$ ($g.cm^{-3}$)	≈ 1.5
thermal expansion coefficient $\alpha_{polyimide}$ ($°C^{-1}$)	$4.2.10^{-5}$
reservoir volume $V_{polyimide\ reservoir}$ (cm^3)	≈ 0.375
mass of the clean and dry reservoir $m_{polyimide\ reservoir}$ (g)	≈ 0.428

* value obtained using the Kozeny-Carman expression of the permeability

Table 2: Properties of the lubricants

	NYE 2001 [52]	**Kryox 143AB [52]**
viscosity (Pa.s)	0.270 (20°C) 0.090 (38°C)	0.230 (20°C) 0.085 (38°C)
vapor pressure (Pa)	$1.4.10^{-4}$ (100°C)	$5.0.10^{-4}$ (38°C)
surface tension ($mN.m^{-1}$)	≈ 31.0	≈ 21.0
thermal expansion coefficient α_{oil} ($°C^{-1}$)	≈ $2.6.10^{-2}$	≈ $9.5.10^{-3}$

Table 3: Mass evolutions of the ball bearing

	before the test	**after the test**		
oil tested	mass of the dry and clean ball bearing (g)	mass of ball bearing (g)	mass of oil gain (μg)	cause of the end of the test
Krytox 143AB	14.07342	14.07610	**+268**	ball bearing temperature exceed 50°C
Nye 2001	14.07250	14.07331	**+81**	manual shutdown

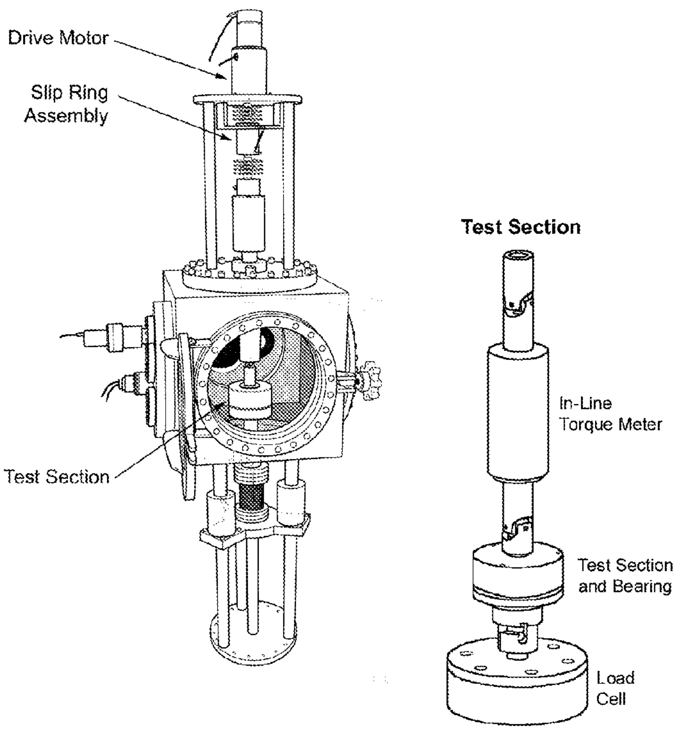

Figure 1: GOES rig

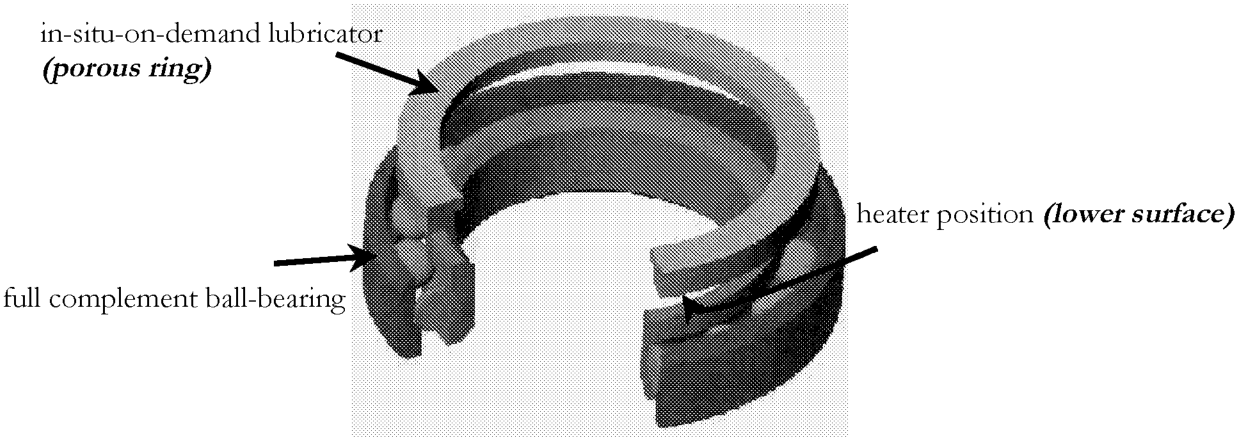

Figure 2: Lubricator attached to the inner ring of a full-complement ball bearing

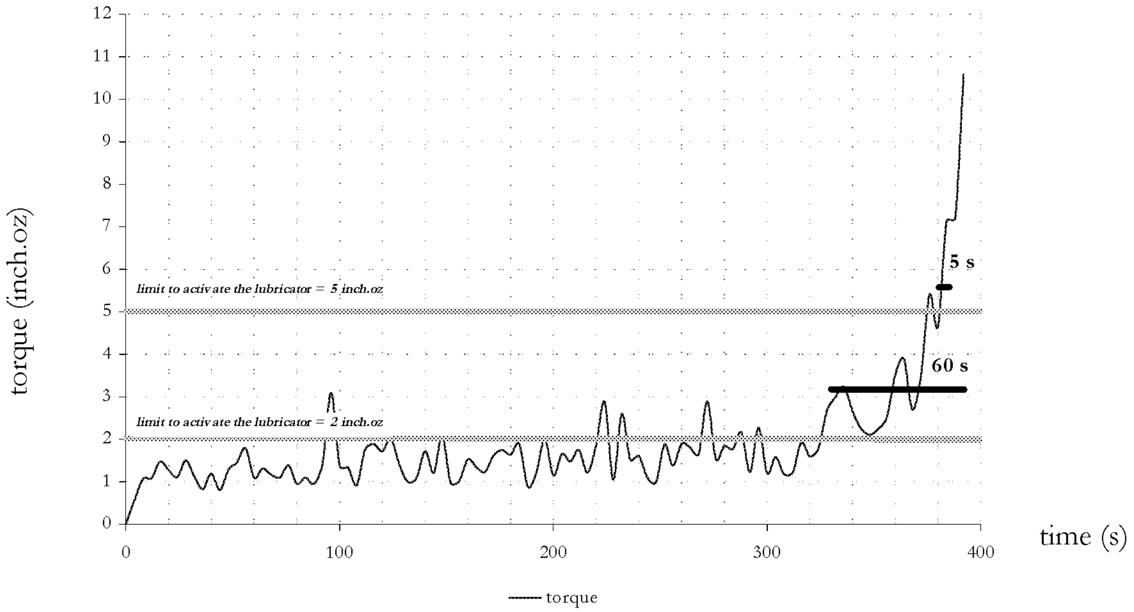

Figure 3: Torque trace of a non lubricated ball bearing and time left for the in-situ, on-demand lubricator to correct the failure (load: 20 lb, speed: 200 RPM)

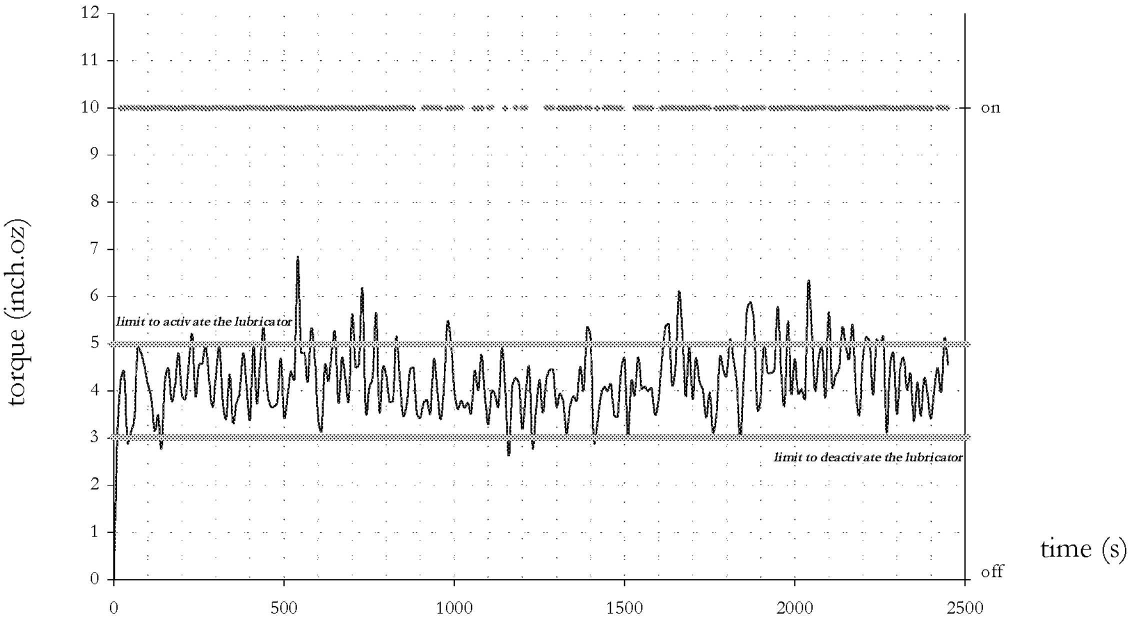

Figure 4: Torque trace of ball bearings with in-situ, on-demand lubricator with Krytox 143AB (load: 20 lb, speed: 420 RPM)

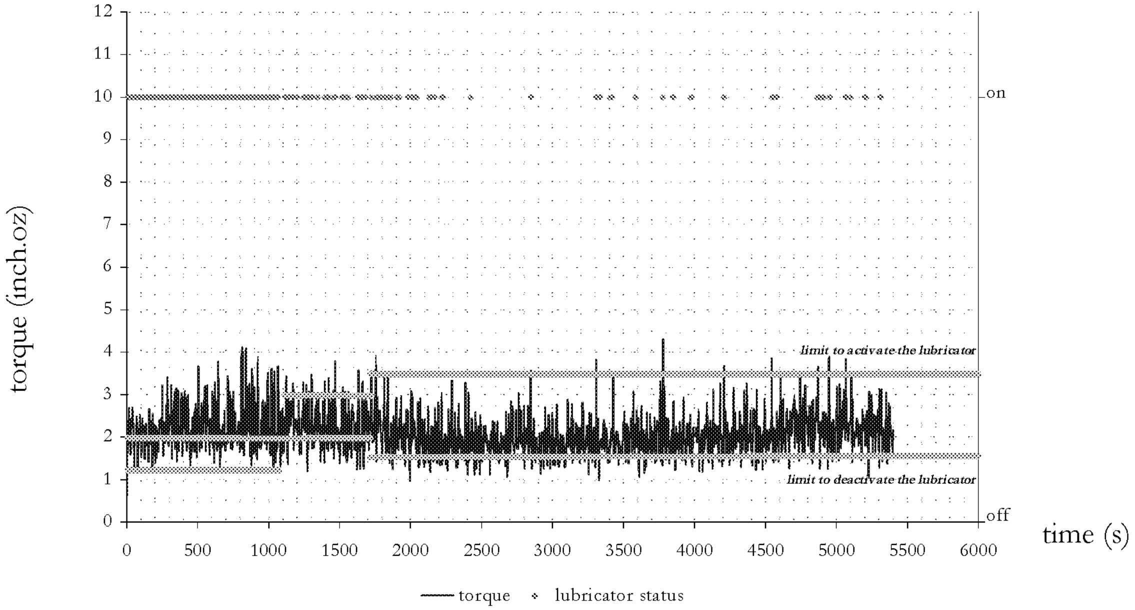

Figure 5: Torque trace of ball bearings (load: 20 lb, speed: 200 RPM) with in-situ, on-demand lubricator with NYE 2001

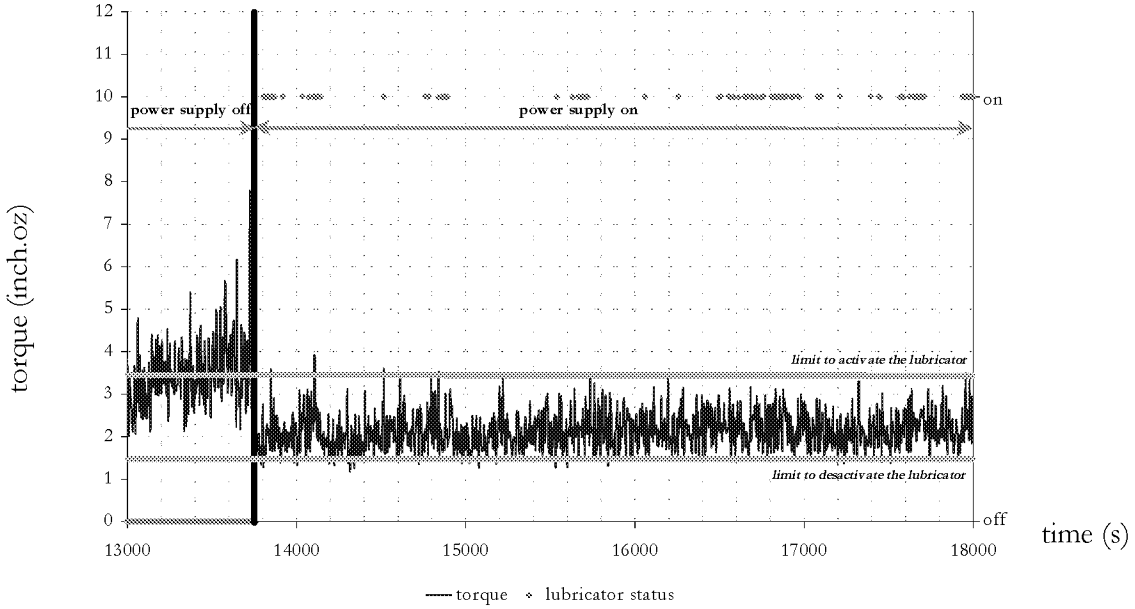

Figure 6: Torque trace of ball bearings (load: 20 lb, speed: 200 RPM) with reactivation of the in-situ, on-demand lubricator with NYE 2001

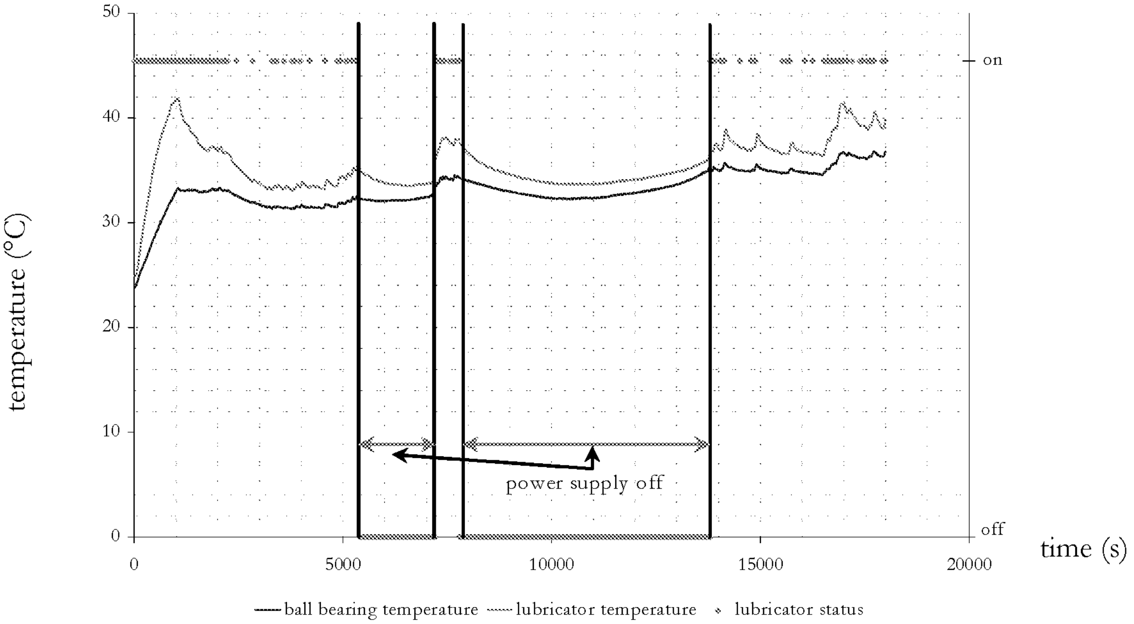

Figure 7: Temperature of the lubricator and of the ball bearing during the test with the oil NYE 2001

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13. ABSTRACT ***(Maximum 200 words)***

Many of today's spacecraft have long mission lifetimes. Whatever the lubrication method selected, the initial lubricant charge is required to last the entire mission. Fluid lubricant losses are mainly due to evaporation, tribo-degradation, and oil creep out of the tribological regions. In the past, several techniques were developed to maintain the appropriate amount of oil in the system. They were based on oil reservoirs (cartridges, impregnated porous parts), barrier films, and labyrinth seals. Nevertheless, all these systems have had limited success or have not established a proven record for space missions. The system reported here provides to the ball-race contact fresh lubricant in-situ and on demand. The lubricant is stored in a porous cartridge attached to the inner or the outer ring of a ball bearing. The oil is released by heating the cartridge to eject oil, taking advantage of the greater thermal expansion of the oil compared to the porous network. The heating may be activated by torque increases that signal the depletion of oil in the contact. The low surface tension of the oil compared to the ball bearing material is utilized and the close proximity of the cartridge to the moving balls allows the lubricant to reach the ball-race contacts. This oil resupply system can be used to avoid a mechanism failure or reduce torque to an acceptable level and extend the life of the component.

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