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Evaluation of an In-Situ, Liquid Lubrication System for Space Mechanisms Using a Vacuum Spiral Orbit Tribometer

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ABSTRACT

Many moving mechanical assemblies (MMAs) for space applications rely on a small, initial charge of lubricant for the entire mission lifetime, often in excess of five years. In many cases, the premature failure of a lubricated component can result in mission failure. If lubricant could be re-supplied to the contact in-situ, the life of the MMA could be extended. A vacuum spiral orbit tribometer (SOT) was modified to accept a device to supply re-lubrication during testing. It was successfully demonstrated that a liquid lubricant (Pennzane®/Nye 2001A) could be evaporated into a contact during operation, lowering the friction coefficient and therefore extending the life of the system.

INTRODUCTION

Many moving mechanical assemblies (MMAs) 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 [1].

Typically, MMAs are initially lubricated with a small charge (mg) that is supposed to last the entire mission lifetime, often in excess of five years. In many cases, the premature failure of a lubricated component can result in mission failure [2].

Tribological failure of MMAs occurs when the lubricant degrades or evaporates and therefore loses its ability to lubricate tribological contacts, 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. Zaretsky [3] reviews some of the relubrication systems developed in the past. For high-speed bearings, centrifugal oilers [4], positive commandable lubricators [5] and wick feed systems [6] have been studied. Oozing flow lubricators [7] have also been successful for high-speed systems.

Lubricant reservoirs provide another means of lubricant re-supply, 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 supplied lubricant. Porous retainers that have been impregnated with lubricant are also considered as a source [8].

On demand, in-situ lubrication provides a step between having no additional lubricant and large lubricant reservoirs. The in-situ lubrication device (ISLD) is a small reservoir that can be remotely activated to evaporate a minimal charge of lubricant into the contact zone. A sensor can be attached to the MMA to monitor its health, bearing torque or motor current, for example, and, when needed, activate the heater on the ISLD.

The concept of introducing lubricant into an operating contact was first introduced by Kato et al. [9–12]. A system was developed in order 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. [10] 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.

The objective of this work was to test the feasibility of using an in-situ evaporation system with a liquid lubricant under ultra-high vacuum and in a boundary lubricated, rolling contact. Deposition on an unlubricated ball and re-lubrication of a ball with an initial lubricant charge was studied.

EXPERIMENTAL

TRIBOMETER

A vacuum spiral orbit tribometer (SOT) was used for these experiments and is pictured in Figure 1. The tribometer simulates a thrust bearing. A single 12.7 mm diameter ball is sandwiched between two flat plates that simulate raceways. The lower plate is fixed while the top plate is rotated. During rotation, the ball moves in a spiral orbit that is directly related to the friction coefficient. A third plate, called the guide plate, is used to return the ball to its original orbit diameter once per revolution. The force the ball exerts on the guide plate is measured and the friction coefficient can be calculated. The tribometer is further described in Reference 13 and its previous usages appear in References 14 to 16.

The contact resistance between the ball and two plates is also measured. This is a good indicator if a film or friction polymer is present. During boundary lubrication or a non-lubricated contact, the resistance is near zero. As a film or friction polymer layer develops the resistance increases. As this layer is worn away, the resistance returns to zero.

The tests were performed under ultra-high vacuum ($<10^{-6}$ Pa). The ball, plates, and guide plate were made from AISI 440C stainless steel, a common material for bearings used in space applications. The plates were polished to an average surface roughness (R_a) of 0.05 µm. The ball was grade 25.

LUBRICANT

The liquid lubricant used is an unformulated synthetic hydrocarbon (multiply alkylated cyclopentane). It is marketed as Pennzane® (Nye 2001A). It is fully described in Reference [17].

SAMPLE PREPARATION

The ball, disks, and guide plate were sequentially cleaned for five minutes each in ultrasonic baths of hexane, methanol, and distilled water. They were then UV-Ozone cleaned [18] for 15 minutes to remove residual organic residue.

LUBRICANT APPLICATION

Accelerated testing is achieved by limiting the amount of available lubricant. During the test, the lubricant is continuously consumed and eventually the lack of lubricant leads to an increase in the friction coefficient. Failure is defined as when the friction coefficient exceeds some predetermined value, normally 0.28, and the test is shutdown. In a standard test, the ball is lubricated with approximately 50 µg before the test begins. Only the ball is lubricated.

For the in-situ lubrication tests, the SOT was modified (Figure 2) with a heater and collimator. The heater cup contained a drop of liquid Pennzane® (Nye 2001A). When the friction began to rise above a steady state value, the heater was turned on and lubricant evaporated. The heater cup consumed 15 to 30 watts of power during these evaporations. The collimator allowed evaporant to reach only the wear track on the rotating upper plate and prevented its undesirable deposition elsewhere in the chamber. Once the proper evaporation temperature (~250°C) of the heater cup was reached, the temperature was maintained until the friction coefficient dropped below the desired level.

TESTING

For the first test, the ball was unlubricated at the onset of the test. The test was started at a low mean Hertzian stress (0.9 GPa) and the in-situ lubrication device (ISLD) was turned on. The ISLD was left on until the friction dropped to the value (0.08) that is seen with a normally lubricated ball. The mean Hertzian contact stress was then increased to 1.5 GPa. The test was allowed to run until the friction coefficient exceeded 0.15.

For the second test, the ball was also unlubricated at the beginning of the test. The same initial lubricant deposition as in test 1 was performed. Once the proper friction coefficient (0.08) was obtained, the mean Hertzian stress was again increased to 1.5 GPa. The test was allowed to run until the friction coefficient exceeded 0.15. At this time, the ISLD was re-activated and a second deposition took place and the friction returned to 0.08. The test limit was again set at 0.15, but was manually shutdown since the coefficient of friction did not exceed 0.15 during the test.

For the third trial, the ball was initially lubricated with 40 μg as in a standard test. The test was started with a mean Hertzian stress level of 1.5 GPa. When the friction exceeded 0.15, the ISLD was turned on and re-deposited a lubricant charge. This was repeated six times and then the test was manually shutdown.

RESULTS

The friction trace and resistance profile for the tests can been seen in Figures 3 to 8. Test 1 demonstrated that a liquid lubricant could successfully be deposited using an evaporation technique. During this test, an initial friction coefficient of ~0.08 was obtained. This correlated well with previous SOT experiments [2] where the ball was pre-lubricated. The slowly increasing friction during the test also mimicked that of a normal test. Normalized lifetimes (orbits/μg) previously obtained by the SOT could not be compared since the amount of lubricant on the ball was unknown.

Test 2 successfully demonstrated that re-lubrication of a contact that was beginning to fail was possible.

Test 3 was the closest representation of a real bearing application. During this test, the ball was initially lubricated and run at full contact stress. As the friction coefficient increased, the ISLD was activated as needed to re-lubricate the contact several times. Using this technique, a lifetime far in excess of any previous test was obtained.

DISCUSSION

Since it was not known how much Pennzane would be evaporated, the length of time the heater was on varied from deposition to deposition. The time ranged from 15 sec to 1 minute. Also, the temperature control was done manually. The target temperature for evaporation was 225°C, but there was some variance (±10°C). These two factors account for the variability in lifetime between the various in-situ deposited lubricant cycles.

As a precursor to failure, the electrical resistance increased. This is especially noticeable in Test 3. It is believed that the resistance is an indication that a friction polymer is forming as the lubricant degrades. Examination of the disks after test conclusion revealed that there was a substantial amount of residue on the disks.

Lubricated mechanisms enable successful operation of all spacecraft. These operations include: scanning, spectral selection, sensor alignment, star and sun tracking, and attitude control. Almost all of these mechanisms are "lubricated for life" upon launch and are not accessible once in space. The only exceptions are low earth orbiting applications such as the International Space Station and the Hubble Space Telescope. These latter applications are visited by the space shuttle and components can usually be replaced via an extra vehicular activity (EVA).

However, in most cases, a component bearing failure will result in a degradation of function, which may represent a single point failure. This, in turn, can lead to mission failure. Vast improvements in spacecraft design have now exposed the lubricated components to be the weak link in attaining mission objectives.

Normally, lubricated bearings in space do not wear out in the classic sense, but rather consume all available lubricant resulting in high torques that eventually exceed the driving mechanism's capability. Liquid lubricated systems can survive for many years on an astonishingly small amount of lubricant. For example, Kingsbury [19] has shown that the spin axis bearings in a large Control Moment Gyroscope (CMG) could be effectively lubricated with about 10 micrograms of lubricant per hour.

A smaller bearing cartridge (101 size, full complement) was operated for 440 days in vacuum at 12,000 RPM. [20]. Only about 1/3 of the original reservoir amount of lubricant was consumed (about 2.3 grams). This represents about 100 micrograms per hour. However, calculations [21] have shown that only 0.2 micrograms per hour are needed for steady state operation.

Of course, these calculations are for a continuous flow into the bearing. For a conventional small instrument bearing in a space mechanism (such as the GOES filter wheel) [22], an initial charge of 20 mg is added at buildup. Additional lubricant is impregnated into the porous retainer. However, it is unlikely that any of the lubricant in the retainer is available for use. In fact, porous retainers have been shown to act as sponges rather than suppliers of lubricant [23].

Assuming that this bearing would only require 0.2 micrograms per hour for nominal operation and that all of this charge was available for use, 20 mg would theoretically allow for over 10 years of operation. Of course, there are other loss mechanisms in a bearing, including evaporation and creep. Evaporation losses can be estimated but creep losses cannot.

Therefore, small additions of lubricant "on demand" could effectively prolong bearing life indefinitely. This has been demonstrated in the current work.

Of course, lubricant evaporations will require an expenditure of energy that is usually in short supply in space mechanisms. Thus, every effort will have to be made to minimize the energy required by the heater during evaporation. Although no effort was made with the present apparatus to minimize energy consumption, miniaturization of the heater and its integration into a bearing housing should allow for operation at much lower energy consumption rates.

SUMMARY OF RESULTS

- An in-situ lubrication device for liquid lubricants was successfully demonstrated.
- The ability of a liquid lubricant to re-lubricate a contact that was approaching failure (higher friction) was also demonstrated.
- A friction coefficient comparable to a "normally" lubricated ball can be obtained with an in-situ system.

CONCLUSION

In-situ liquid lubrication in vacuum is feasible and should be incorporated in full-scale bearings for long-lived space mechanisms.

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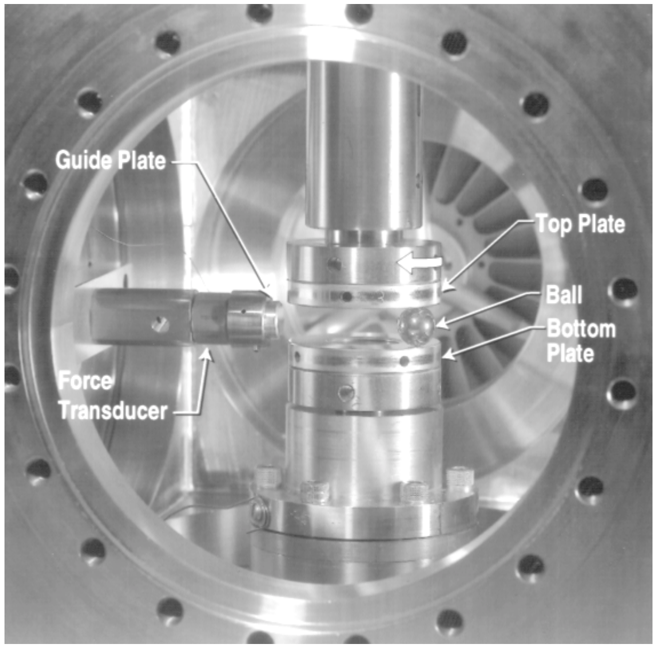

Figure 1 – The Spiral Orbit Tribometer (SOT).

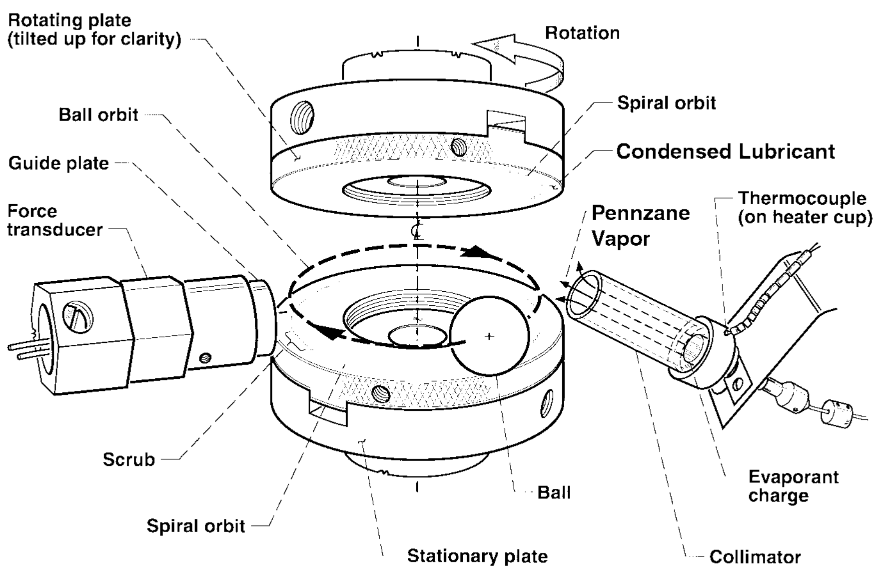

Figure 2 – SOT modified with in-situ lubrication device. Top plate rotated upwards for better view.

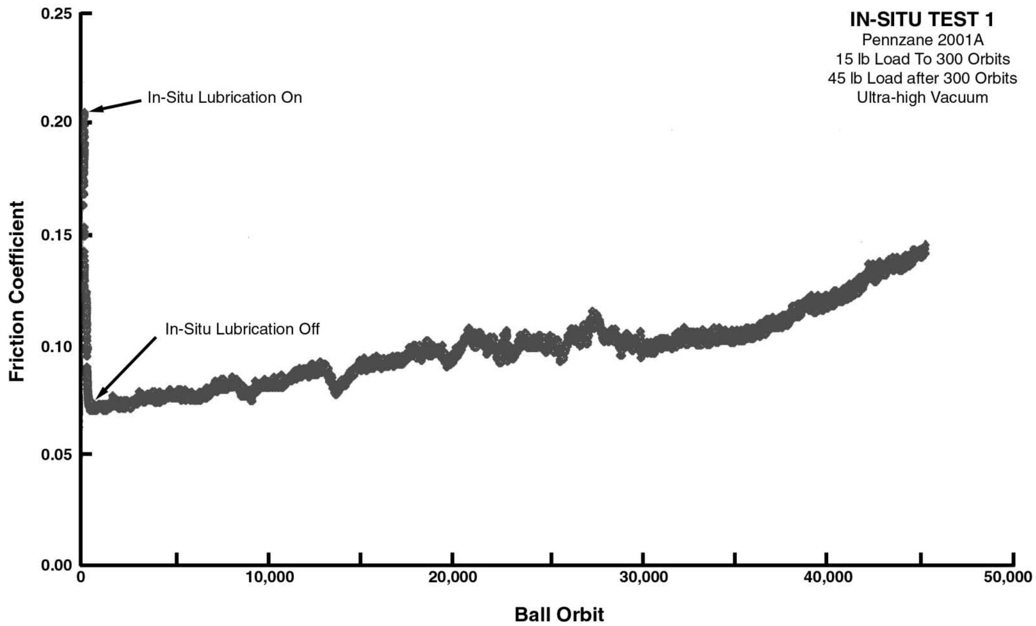

Figure 3 – Friction Coefficient as a function of ball orbit for in-situ test 1.

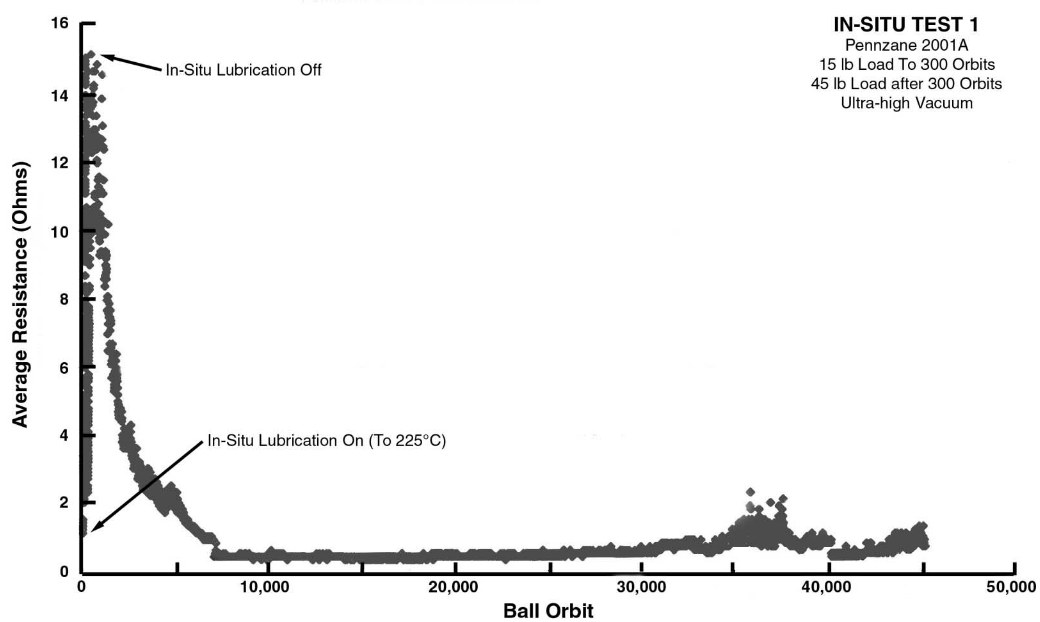

Figure 4 – Average resistance as a function of ball orbit for in-situ test 1.

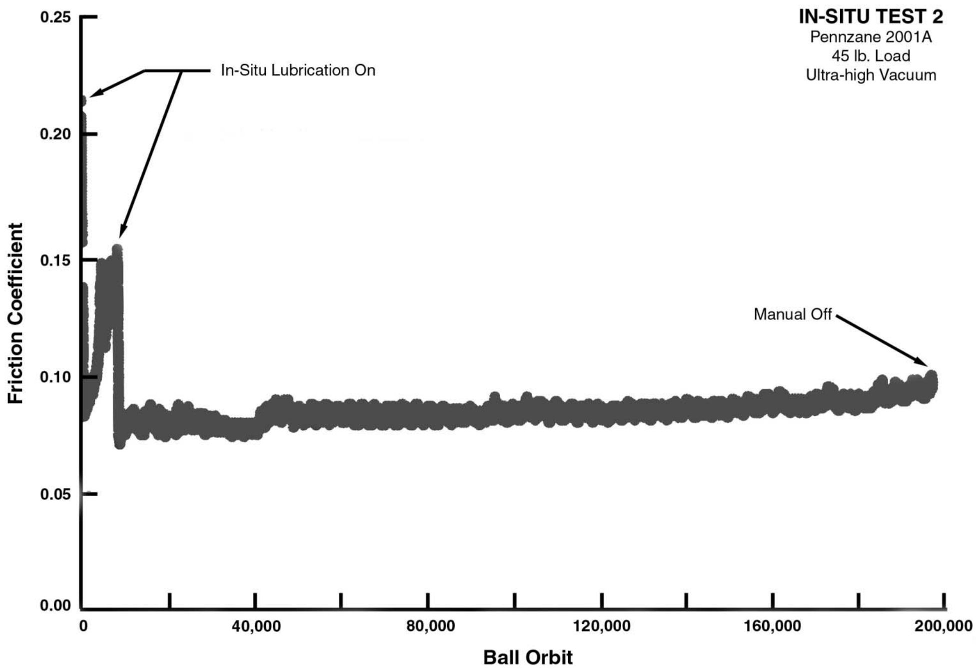

Figure 5 – Friction coefficient as a function of ball orbit for in-situ test 2.

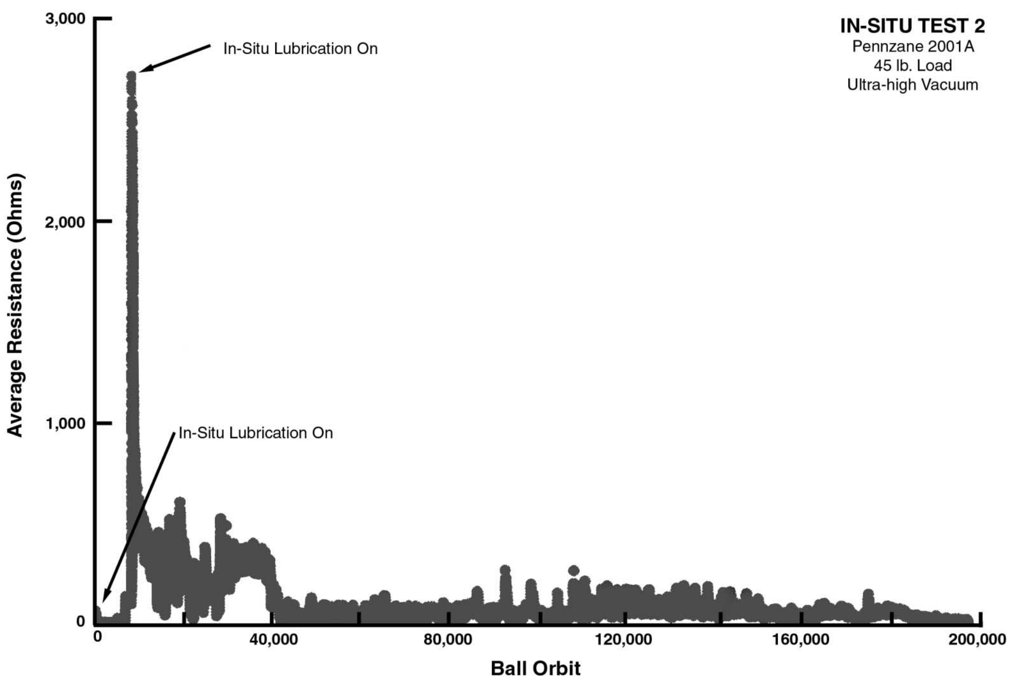

Figure 6 – Average resistance as a function of ball orbit for in-situ test 2.

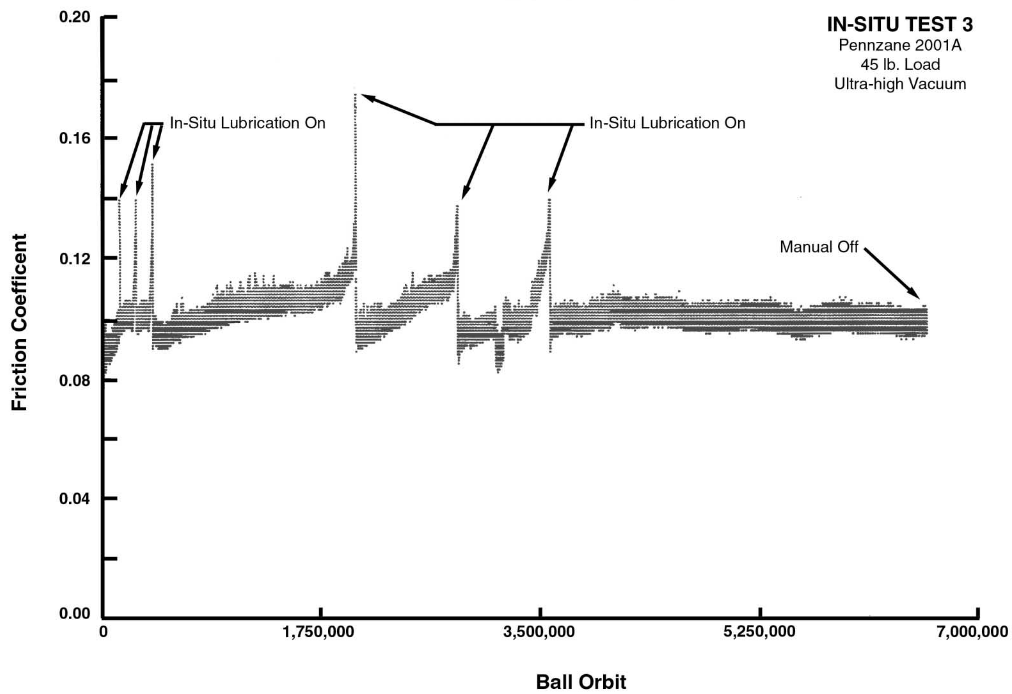

Figure 7 – Friction coefficient as a function of ball orbit for in-situ test 3.

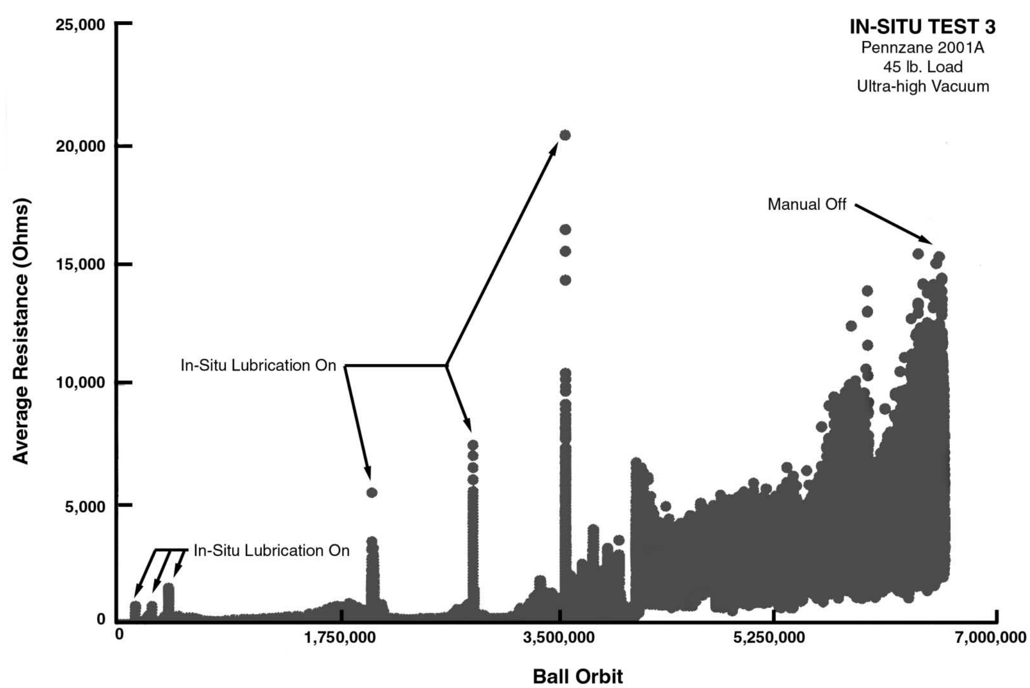

Figure 8 – Average resistance as a function of ball orbit for in-situ test 3.

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

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