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The Effect of 17–4 PH Stainless Steel on the Lifetime of a Pennzane® Lubricated Microwave Limb Sounder Antenna Actuator Assembly Ball Screw for the AURA Spacecraft

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Abstract

During ground based life testing of a Microwave Limb Sounder (MLS) Antenna Actuator Assembly (AAA) ball-screw assembly, lubricant darkening and loss were noted when approximately 10 percent of required lifetime was completed. The MLS-AAA ball screw and nut are made from 17–4 PH steel, the nut has 440C stainless steel balls, and the assembly is lubricated with a Pennzane® formulation containing a three weight percent lead naphthenate additive. Life tests were done in dry nitrogen at 50 °C. To investigate the MLS-AAA life test anomaly, Spiral Orbit Tribometer (SOT) accelerated tests were performed. SOT results indicated greatly reduced relative lifetimes of Pennzane® formulations in contact with 17–4 PH steel compared to 440C stainless steel. Also, dry nitrogen tests yielded longer relative lifetimes than comparable ultrahigh vacuum tests. Generally, oxidized Pennzane® formulations yielded shorter lifetimes than non-oxidized lubricant. This study emphasizes surface chemistry effects on the lubricated lifetime of moving mechanical assemblies.

1. Introduction

The recently launched AURA spacecraft contains an instrument suite that includes the Microwave Limb Sounder (MLS), which monitors chemistry changes in the earth's atmosphere. Part of the MLS instrument, the Antenna Actuator Assembly (AAA) mechanism, rotates the MLS antenna during precision scanning of the earth's limb and is essentially a motor-driven Ball Screw Assembly (BSA). Within the BSA, 440C stainless steel balls separate a 17–4 PH stainless steel screw and nut. The BSA is lubricated with a multiply alkylated cyclopentane (Pennzane®) formulated with lead naphthenate but without an antioxidant. In fall 2003, the Jet Propulsion Laboratory started life testing a duplicate component at 50 °C in dry nitrogen. After approximately 10 percent of required lifetime had been accumulated, lubricant darkening and visual lubricant loss on the exposed ball screw were observed (fig. 1). An investigation was initiated to determine the cause. Several areas of concern were examined including, but not limited to, lubricant migration, evaporation, and oxidation.

2. Experimental

2.1 Ball Screw Assembly Design

The BSA consists of a 17–4 PH stainless steel ball screw and nut separated by 440C stainless steel balls. The radially preloaded ball screw has a 0.953 cm (0.375 in.) outside diameter and a 0.254 cm (0.100 in.) lead. The balls nominal diameter is 0.158 cm (0.0625 in.). The ball nut is supported by preloaded bearings that constrain it in the axial direction but allow rotation. When the ball nut is rotated by the motor, the ball screw (prevented from rotating by external linkages) translates freely through the nut. During rotation, the balls in the two ball circuits circulate between the ball screw and nut.

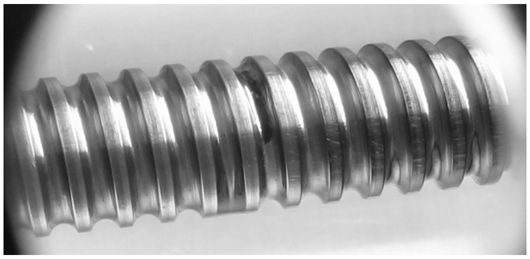

Figure 1.—AAA Ball Screw (at End of Stroke).

For containment and resetting position purposes, hard stops are placed at both ends of the ball screw.

Each end of the nut has a lubricant filled, Nomex felt wiper, which lubricates the ball screw as it extends and retracts (fig. 2). To reduce lubricant loss due to evaporation, a Pennzane® oil without an antioxidant was initially selected because of its ultra low vapor pressure.

The specified minimum hardness for the balls (440C) is 58 Rockwell C (R_c). A ball from each of the two ball circuits had a measured hardness's of 55 and 64 R_c. The specified minimum hardness of the ball screw and nut (17–4 PH) is 38 R_c. Measurements made on an identical unit confirmed that the ball screw and nut have average hardness's of 40 R_c. The 17–4 PH ball screw and nut hardness values are significantly lower than traditional ball screw materials.

2.1.1 Ball screw life test

The BSA was cycled as part of the AAA mechanism life test. The life test began in the fall of 2003 and was still on-going at the time of this publication. The BSA continuously extends and retracts, actuating an antenna simulator in a scanning mode. The test unit is in a non-hermetically sealed, dry nitrogen purged environment (fig. 3).

During the initial life test phase, the AAA mechanism was thermally controlled to 50 °C using an external heater. To shorten its duration, the life test was accelerated by approximately 2.7 times. Even at the accelerated speed of 1.8 revs/sec peak, the BSA still operates in the boundary lubrication regime. Motor current and encoder tracking profiles were collected regularly to monitor performance degradation and visual inspections were done periodically to check for anomalies.

Lubricant darkening was observed after 5 percent of the required life had been accumulated. After approximately 10 percent of required life had been accumulated, lubricant loss became apparent.

Shortly thereafter, the life test was suspended and an investigation initiated. Several areas of concern were investigated including, but not limited to, lubricant migration, evaporation, consumption, and oxidation.

2.1.2 Ball screw life test investigation results

Lubricant samples were collected and subjected to Inductively Coupled Plasma/Optical Emission Spectroscopy (ICP-OES) for elemental analysis and Fourier Transform Infrared (FTIR) spectroscopy for functional group detection (such as the C = O bond formation, a.k.a. oxidation). Metallic wear and lubricant oxidation were identified. Both contributed to the lubricant darkening.

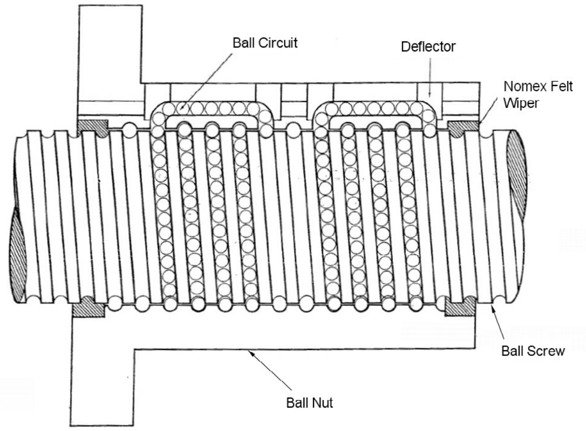

Figure 2.—Ball Screw Assembly Design.

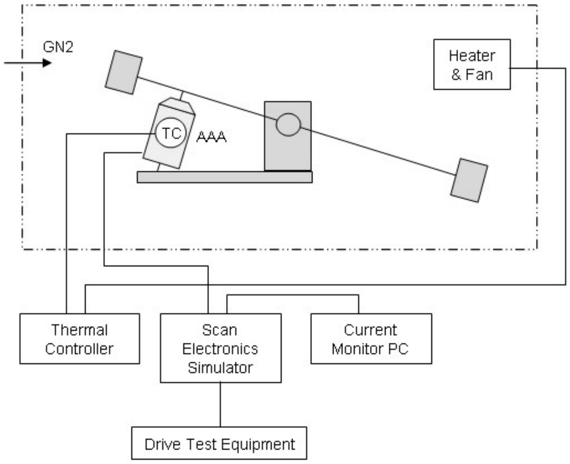

Figure 3.—Life Test Schematic Diagram.

The metallic wear condition was mitigated after the life test configuration was carefully corrected to minimize the bending load on the ball screw, which does not occur in the flight configuration. The BSA's lubricant was replaced with a Pennzane® oil containing an antioxidant additive. The same lubricant replacement process was performed on the flight AAA unit. Because the oil's anti-oxidant would be lost in vacuum and the remaining base oil will return to ultra-low vapor pressure, concerns with the slightly higher vapor pressure of the anti-oxidant formulated oil were alleviated. Additionally, a change in the thermal design lowered the flight temperature to 35 °C and the life test temperature was changed accordingly.

Each previously mentioned area contributed, in varying degrees, to lubricant loss in the life test mechanism. Lubricant loss due to tribological interactions between Pennzane® and

BSA alloys was a surprise to investigators. The following describes the accelerated tribological test method used to elucidate the lubricant and alloy interactions.

2.2 Spiral Orbit Tribometer

The Spiral Orbit Tribometer (SOT) facility (fig. 4) tests lubricants in the boundary lubrication regime. While the SOT is not a direct representation of the ball screw in question, it does provide independent tribological measurements to qualify lubricant/material combination's relative performance. As discussed later in the paper, SOT results correlate well with bearing test relative lifetimes.

The SOT facility is essentially a thrust bearing with flat races and a single, 12.7 mm (0.5 in.) ball. The tribometer simulates motions (rolling, sliding, and pivoting) seen in angular contact bearings. The bottom plate is stationary, the top plate rotates, and the ball is driven in a spiral orbit. The spiral's pitch is directly related to the contact's frictional force. A third plate, termed the guide plate, returns the ball to the original orbit diameter once per revolution. The return force required is measured and is directly related to the friction force, and therefore, the friction coefficient. Test acceleration is achieved by limiting the amount of lubricant on the ball, typically around 50 µg. A full description of the SOT facility can be found in references 1 to 5.

Loads of 22, 62, and 200 N, yielding mean Hertzian stresses of 0.75, 1.0, and 1.5 GPa respectively, were used. Most testing was done at 1.0 GPa. For all the tests, the ball speed was 100 rpm and approximately 50 µg of lubricant was used. Testing was done either in dry nitrogen or in vacuum. For vacuum tests, the vacuum level was at least 10^{-7} Pa and pump down time varied from 6 to 10 hr. The nitrogen environment was obtained by flooding the vacuum chamber with nitrogen through the vacuum pump. In this case, the front window of the tribometer was left open slightly, allowing the test to run at atmospheric pressure.

Prior to testing, all the parts were cleaned. First, they were rubbed with levigated alumina powder and rinsed with filtered, de-ionized water. They were then rinsed in 190 proof ethyl alcohol and blown dry with nitrogen. Next, the parts were ultrasonically cleaned in hexane for 10 min. They were again blown dry with nitrogen and then placed in a UV/Ozone treatment for 15 min. The balls were rotated after 7.5 min to treat the entire surface.

To lubricate the ball, a 1 mg lubricant to 1 ml hexane solution was made. Then, the solution was deposited on the ball with a syringe and the solvent evaporated, leaving behind the desired lubricant quantity. Weight gain, termed lubricant uptake, was measured on a microbalance accurate to ±2 µg. Three weights were averaged to obtain the lubricant uptake.

Lifetime is reported in orbits/µg. The test terminated when the friction coefficient exceeded 0.28. Normalized lifetime is calculated by dividing the total number of orbits to shutdown by the lubricant uptake. In most cases, more than one test at each condition was done and the normalized lifetimes averaged.

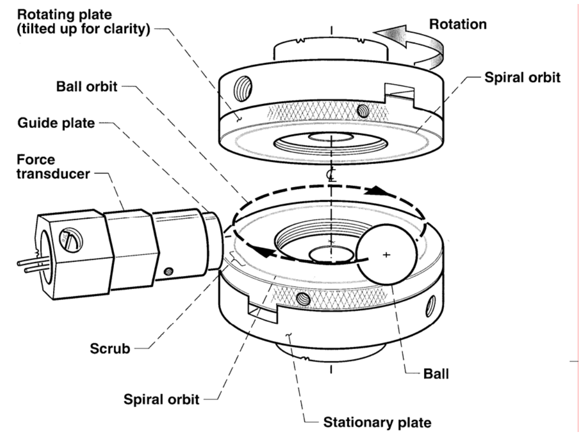

Figure 4.—The Spiral Orbit Tribometer.

Several material combinations were tested. In all cases, the ball was 440C stainless steel. Plates and guide plates were either 440C or 17–4 PH stainless steel. The 440C stainless steel plates were hardened to ~58 R_c and the 17–4 PH plates to 44 R_c (H900 process). Since shorter life was observed using 17–4 PH compared to 440C, a set of 440C parts was annealed and re-heat treated to 44 R_c to test if hardness effects lubricated lifetime.

Several Pennzane® formulations were tested and are listed in table 1. Formulations included different lots, an anti-oxidant additive, a lead naphthenate (PbNp) additive, a phosphate additive, and some oil was deliberately oxidized before testing. In all cases, 99.9 percent pure hexane was used to make the lubricant solution.

TABLE 1.—PENNZANE OILS USED IN AAA BALL SCREW TESTING

Type	Additive	Anti-Ox.	Oxidized	Lot
2001A	3% PbNp	No	No	MN030228
2001A	3% PbNp	No	8d at JPL	MN030228
2001A	3% PbNp	No	66h at JPL	MN030228
2001	3% PbNp	Yes	No	SA030324
2001A	None	No	No	9500924
2001	1% Phosphate	Yes	No	2001 GRC
2001	3% PbNp	Yes	No	MN970319

2.2.1 SOT results

Four major comparisons were made: lifetime between 17–4 PH and 440C stainless steel; lifetime between a vacuum and a nitrogen environment using 17–4 PH plates; lifetime of several different versions of Pennzane®; and lifetime of "as received" oil versus oxidized oil. Because the 17–4 PH parts were significantly softer than the 440C parts, there was some concern over plastic deformation occurring during testing and affecting lifetime. Therefore, a set of 440C parts was softened to the same hardness as the 17–4 PH parts and tested. Additional tests were done with 440C plates that were coated with nickel and chromium. Table 2 and table 3 summarize the SOT test results.

TABLE 2.—LUBRICANT PERFORMANCE USING 17–4 PH PLATES

Lubricant	**Env.**	**Stress (GPa)**	**# of Tests**	**Average Life**	**St. Dev**
MN030228	Vac	1.5	4	467	79
MN030228	Vac	1.0	1	1600	N/A
MN030228 (8d Oxidation)	Vac	1.0	2	593	255
MN030228 (66h Oxidation)	Vac	1.0	4	1074	519
MN030228 (66h Oxidation)	Nit	1.0	4	3628	2362
SA030324	Vac	.75	4	2369	1511
SA030324	Vac	1.0	6	1219	581
SA030324	Nit	1.0	4	3328	3252
9500924	Vac	1.0	2	2346	806
MN970319	Vac	1.0	1	1220	N/A

TABLE 3.—LUBRICANT PERFORMANCE USING OTHER MATERIALS AT 1.5 GPA UNDER VACUUM

Lubricant	**Plate Material**	**# of Tests**	**Average Life**	**St. Dev**
2001 GRC	440C	8	2407	660
MN970319	440C	3	4144	3280
MN030228	440C	1	<10,000	N/A
9500924	Soft 440C	2	2700	40
9500924	440C/Ni Coat	4	1821	804
9500924	440C/Cr Coat	4	4474	2886

Figures 5 and 6 show the lifetimes of two oil lots in dry nitrogen and under vacuum at 1.0 GPa. To minimize surface chemistry effects, one test under each condition was performed on the same sample set. With both oil lots (MN030228 – without anti-oxidant and SA030324 – with anti-oxidant), the lifetime in nitrogen was greater than in vacuum.

Figure 7 shows life results on 17–4 PH steel at 1.0 GPa for different oil lots. Statistically, there is no significant difference between the oils' lubricated lifetimes. It should be noted that some oils had no additives, some had an anti-oxidant, some had lead naphthenate additive, and some had both.

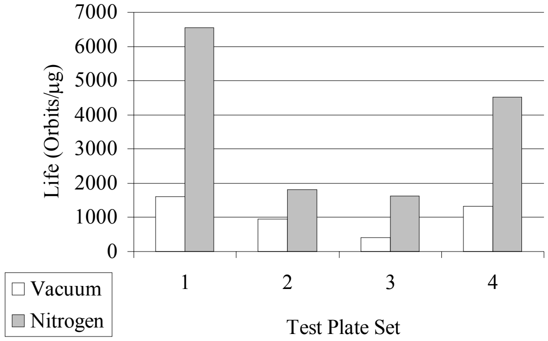

Figure 5.—Lifetime of MN030228, 66 hour oxidized oil on 17–4 PH plates in nitrogen and vacuum.

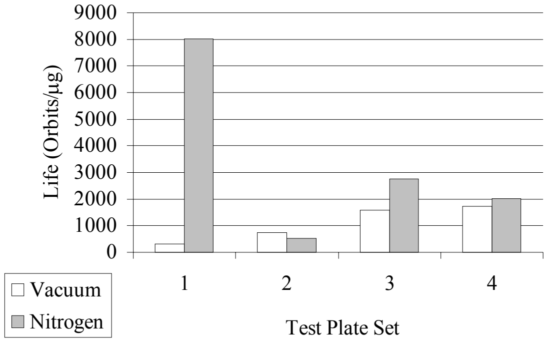

Figure 6.—Lifetime of SA030324 on 17–4 PH plates in nitrogen and vacuum.

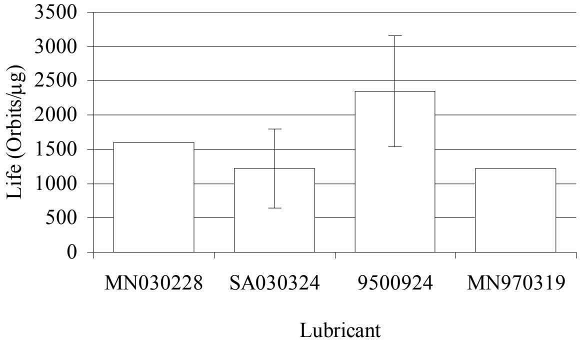

Figure 7.—Lifetime comparison using 17–4 PH parts at 1.0 GPa.

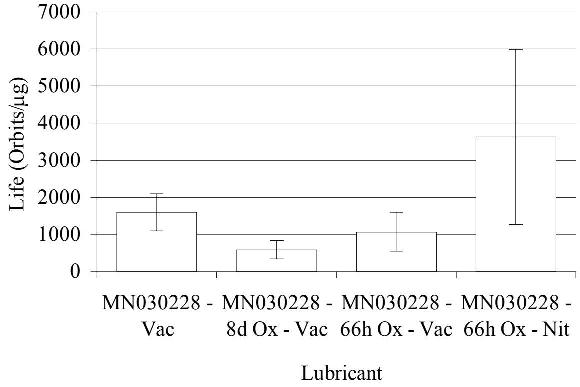

Figure 8.—Comparison of lifetimes using 17–4 PH parts at 1.0 GPa.

Figure 8 shows the relative lifetimes of MN030228 oil, which does not contain an anti-oxidant and had been intentionally oxidized. Under vacuum, life was less for the oxidized oil versus the non-oxidized oil, especially the oil oxidized for eight days. Under nitrogen conditions, the life was approximately the same as the SA030324 oil, which does contain an anti-oxidant.

The lifetime of Pennzane® 2001 was significantly shorter using 17–4 PH plates compared to 440C plates under the same conditions. This can be seen by comparing the 1.5 GPa run from table 2 to the first three runs from table 3. This was observed independently of oil additives or test stress levels. Lifetime was not reduced on the softer (44 R_c) 440C disks compared to the hardened (58 R_c) 440C disks.

3. Discussion

3.1 Material Chemistry Effects

In the boundary lubrication regime, lubricant is continuously consumed within the Hertzian contact zone. Lubricant degrades into a non-lubricating friction polymer or into gaseous fragments. As long as fresh lubricant is entrained into the contact zone, consumption occurs. This is the mechanism that mediates the lubrication process. When all available lubricant is consumed, friction and drag torque increase and the device eventually fail to meet mission requirements. Obviously, this consumption rate is affected by the number of contacts in a device and operating speed. Also, the Hertzian stress level affects the consumption rate; life generally decreases exponentially with increasing Hertzian stress (ref. 6).

In addition to contact, speed, surface finish, and stress, the consumption rate is highly dependant on the lubricant and bearing surface chemistries. Figure 9 shows vacuum SOT testing for four different lubricants on 440C stainless steel. The results indicate a hydrocarbon based lubricant, such as Pennzane®, far out performs perfluoropolyether (PFPE) based lubricants. Additionally, the SOT relative lifetimes correlate well with actual bearing life tests (ref. 7), which are shown in the same figure.

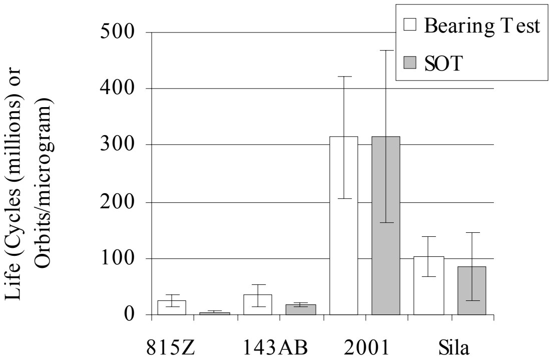

Figure 9.—Lubricant lifetimes of several space lubricants using a SOT and bearing tester (ref. 7).

Another example of surface chemistry’s role in lubricant degradation rates involved life concerns with a ball-screw mechanism in the Chandra X-ray Observatory. The screw was made from 4150 steel, which contains 1 percent chromium; however, to prevent rusting before launch, the screw was chromium plated. The mechanism was lubricated with Fomblin™ Z–25. SOT testing was done with Fomblin™ Z–25 and 4150 steel (1% Cr), chromium plated 4150 steel (100% Cr), and 440C stainless steel (17% Cr) (ref. 8). In all cases, a 440C stainless steel ball was used. Results, shown in figure 10, indicate lubricant lifetime decreases with increasing chromium content.

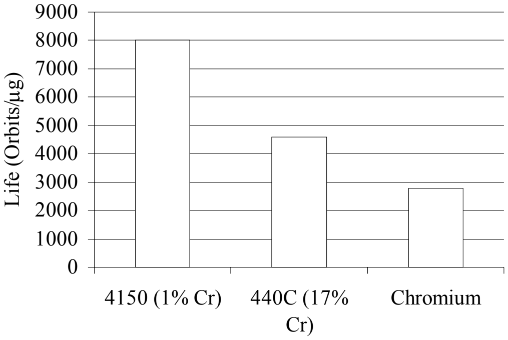

Figure 10.—Lifetimes of Fomblin™ Z–25 in contact with various materials (ref. 8).

3.1.1 The 17–4 PH versus 440C Stainless Steel

The two stainless steels used in the MLS-AAA study, 17–4 PH and 440C, have some important chemical differences. 17–4 PH stainless steel is a precipitation-hardening martensitic stainless steel that combines strength and hardness with excellent corrosion resistance. Besides iron, the major components are chromium (15.5%), nickel (4.5%), and copper (3.25%). 440C stainless steel is high carbon and carbon chromium steel designed to provide corrosion resistance with maximum hardness and is primary steel used for space bearing applications. Iron, chromium (18%), and carbon (1.2%) are 440C’s major components. Typical analyses for 17–4 PH and 440C steels appear in table 4.

TABLE 4.—TYPICAL ELEMENTAL COMPOSITION OF 17–4 PH AND 440C STEELS

Element	17–4 PH (%)	440C (%)
Carbon (Maximum)	0.070	0.95–1.20
Phosphorus (Maximum)	0.0400	0.0400
Silicon (Maximum)	1.0	1.0
Nickel	3.00–5.00	–
Columbium + Tantalum	0.15–0.45	–

Although it is not clear what chemical mechanism is operative in causing the increased consumption of Pennzane® in contact with 17–4 PH surfaces compared to 440C surfaces, both Ni and copper-chromium oxide are versatile catalysts for mediating reactions with hydrocarbons (ref. 9).

3.2 Test Environment

The test environment can play a large role in a mechanism's lubricated life. For example, bearing tests with a hydrocarbon have shown a 5 times life increase in nitrogen gas compared to vacuum tests (ref. 10) and similar tests with a lead naphthenate hydrocarbon formulation yielded a 10 times life increase in nitrogen versus vacuum (ref. 12). Other researchers have reported differences with hydrocarbon based lubricants in vacuum and nitrogen (ref. 13). Spiral Orbit Tribometer tests have shown large differences in relative lifetimes of a perfluoropolyether (Krytox™ 143 AC), where low water vapor concentrations extended lives by an order of magnitude (ref. 13).

In the SOT tests performed, both the 66 hour oxidized oil lot and the SA030324 lot, which contains an anti-oxidant, had a 3 times longer life in nitrogen compared to vacuum. All these results indicate that life testing done under nitrogen is not an accurate representation of the life that can be expected from the same mechanism operating in orbit.

4. Conclusions

1. The unique surface chemistry associated with the 17–4PH stainless steel alloy results in an accelerated rate of lubricant consumption for Pennzane® formulations in boundary/parched lubricated contacts.
2. Life tests run at atmospheric pressure in dry nitrogen do not simulate the on orbit environment and may result in an over estimation of orbital lifetime of moving mechanical assemblies.
3. Partially oxidized hydrocarbon lubricants may lead to lower orbital lifetimes.

5. Lessons Learned

Space mechanism designers utilizing lubricated mechanical moving assemblies made of alloys other than conventional bearing steels, such as 440C or 52100; need to verify that mission lifetimes will not be compromised by adverse lubricant/alloy interactions. Additionally, life test configurations that do not reflect the orbital/operational environment should be thoroughly evaluated for applicability and test accuracy.

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13. ABSTRACT *(Maximum 200 words)*

During ground based life testing of a Microwave Limb Sounder (MLS) Antenna Actuator Assembly (AAA) ball-screw assembly, lubricant darkening and loss were noted when approximately 10 percent of required lifetime was completed. The MLS-AAA ball screw and nut are made from 17–4 PH steel, the nut has 440C stainless steel balls, and the assembly is lubricated with a Pennzane® formulation containing a three weight percent lead naphthenate additive. Life tests were done in dry nitrogen at 50 °C. To investigate the MLS-AAA life test anomaly, Spiral Orbit Tribometer (SOT) accelerated tests were performed. SOT results indicated greatly reduced relative lifetimes of Pennzane® formulations in contact with 17–4 PH steel compared to 440C stainless steel. Also, dry nitrogen tests yielded longer relative lifetimes than comparable ultrahigh vacuum tests. Generally, oxidized Pennzane® formulations yielded shorter lifetimes than non-oxidized lubricant. This study emphasizes surface chemistry effects on the lubricated lifetime of moving mechanical assemblies.

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