# Lubricant Degradation in High-Load, High-Cycle Actuator Test Using Heritage Harmonic Drives for the Multi-Angle Imager for Aerosols Instrument

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## Abstract

The Multi-Angle Imager for Aerosols (MAIA) instrument features a pushbroom spectropolarmetric camera on a two-axis gimbal, which is actuated throughout the mission duration for multi-angle imaging, target revisiting, and inflight calibration. Each gimbal axis is driven by an existing design Mini Dual Drive Actuator (MDDA), which features a duplex brushless DC motor and redundant size 10 pancake Harmonic Drive (HD) gearset within its drive outputs. As the size 10 pancake assembly is no longer available from Harmonic Drive, LLC, units were acquired from long-term flight storage. Due to the load and speed profiles, as well as the continuous operation required of the actuators, an endurance test was conducted to verify acceptability of the mechanism for the application, based on fatigue life. Approaching the two-life milestone, the test failed due to breakdown of the Braycote 601EF lubricant, with a final apparent overall gearbox efficiency of 7%.

Disassembly and SEM inspection revealed two distinct flavors of degraded and polymerized lubricant, tooth and race wear, material adhesion onto rolling wave generator bearing surfaces, and non-trivial amounts of corrosion. Due to the dither behavior and relatively high loads, it seemed breakdown due to high contact stress was the likely culprit. This led to the decision to change the drive output subassembly lubricant from Braycote 601EF grease and Bray Oil 815Z, to Rheolube 2000 grease and Nye Synthetic Oil 2001. Since the motors were already built using Braycote, and the lot of Harmonic Drives (HD) and duplex bearings had already been processed with Braycote, testing to verify compatibility and re-wettability of the two lubricants began. Meanwhile, a complete disassembly and inspection was performed, down to the individual bearing-ball level.

The inspection revealed corrosion within the Wave Generator bearings, even on inner diameters of inner races that were bonded onto the Wave Generator hubs, despite having been stored in hydrocarbon oil. Specialized inspection also brought the black oxide coating application of the HD circular splines into the spotlight, just as chemical analysis revealed an unexpected presence of copper in the degraded lubricant. Black oxide, old adhesive, and corrosion were removed from the HD assemblies, they were processed with Pennzane-based lubricant, and the endurance test began again. This paper provides recommendations regarding use of mechanisms from long term storage, even if stored in seemingly ideal conditions, and documents a discovery process unique to work with heritage hardware. Also addressed is a performance comparison between Braycote 601EF and Rheolube 2000, as well as the Pin on Disc Test results regarding their compatibility along with evidence that, contrary to prevailing belief, it is possible to functionally rewet with Pennzane hardware that was once processed with Braycote.

## Introduction

<u>MAIA Instrument</u>

The Multi-Angle Imager for Aerosols (MAIA) mission objectives are to assess the impact of mixtures of airborne particulate matter of different sizes and compositions on human health, and to collect multi-angle spectropolarmetric imagery over targets of interest with respect to air quality and climate research. The MAIA instrument is class 3, and features a pushbroom spectropolarmetric camera on a two-axis gimbal, which is actuated throughout the mission for multi-angle imaging, target revisiting, and inflight calibration.

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There are several heritage aspects of MAIA which are reminiscent of the Multi-angle Imaging SpectroRadiometer (MISR) mission, which has been using a multi- angle imaging approach to image aerosols in the atmosphere, imaging targets from nine angles, using nine cameras, since the year 2000. The reduction of the number of cameras required from nine for MISR to one for MAIA, is largely thanks to the Bi-Axis Gimbal Assembly (BGA), which articulates the MAIA camera to achieve multi-angle pointing.

A key heritage item in the MAIA instrument design is the Mini Dual Drive Actuator (MDDA), which is a single-fault tolerant electromechanical device, used by MISR as its Cover Actuator, and as the North and South Calibration Plate Actuators. It also flew on Cloudsat and Galaxy Evolution Explorer (GALEX). The MDDA is valued largely due to its redundancy, providing the high-reliability desired to produce necessary mission-critical motions. The single-string Mini Uni-Drive Actuator was used on Mars Pathfinder for the High Gain Antenna Gimbal Actuators. Its design was inspired by the Standard Dual Drive Actuator, originally designed at JPL by Doug Packard. [1] The MAIA MDDAs will marry the applications of the Mars Pathfinder gimbal operation and the multi-angle imaging of MISR, with one MDDA driving each of the two axes of the MAIA BGA.

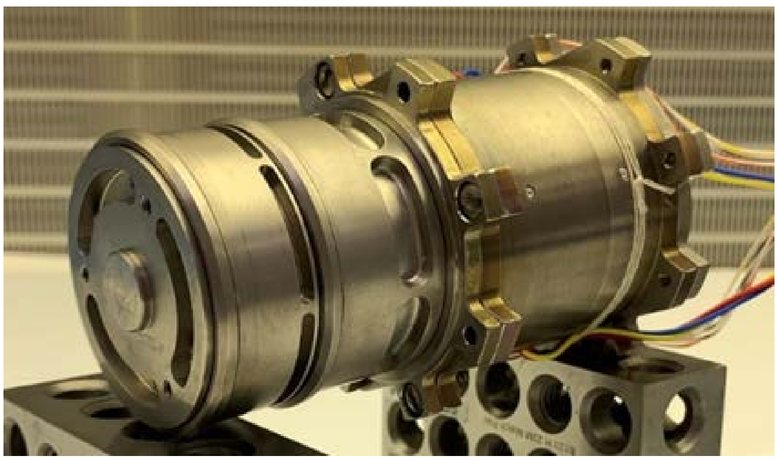

*Figure1. Mini Dual Drive Actuator*

However, the MAIA project seemed to be in luck, as there existed a set of spare Harmonic Drive units in flight storage, which had been originally purchased by the Cloudsat project. The Cloudsat actuator build had occurred just following MISR in the 1990s, and used the MDDA as its Reflector Mechanism. As fate would have it, the lot of flight spare size 10 pancake HDs had been preserved in their original heat-sealed packaging, locked away in flight stores since their receipt in 1995, as delivered by their namesake manufacturer who, at that time, was operating under a different ownership than the Harmonic Drive LLC of today. Flight spare duplex output bearings were also identified, as well as spare Duplex Motors, which would end up getting sent back to Ducommun Technologies, their original manufacturer, to be rewound and have bonds, wires, and Hall sensors replaced, for the new MAIA application.

<u>MAIA Actuation and the Endurance Test</u>

In flight, the two MAIA MDDAs will drive two slightly different load and speed profiles, with sweeps as well as stop and stare motions, dependent on the axis for which they are designated and the mode of operation of the instrument. The nominal expected output loads are around half of the maximum load rating of the size 10 HD, which is documented at 5.1 Nm (45 in-lb), and the application was one of continuous use throughout the mission life. Even with heritage and redundancy, no other MDDA application was similar enough to avoid some testing. This called for the execution of a new test, with the intention of verifying the fatigue life of the mechanism and its endurance with the MAIA operational profiles.

For simplicity, a hybridized profile was created, to capture both the higher loads and the requirement for repeated gear tooth engagement of the off-track axis profile, and the higher speed and larger rotational output distance required of the on-track axis. The profile was conservative, and yielded a series of test events to be repeated in cycles, each with a 2.3 Nm (20 in-lb) continuous applied output load being driven at a speed of eight degrees per second, with dither frequencies requiring direction changes every 1.5, 6.5, or 16 seconds. The test would run for three times longer than one mechanical life, with a total runtime of almost 700 hours, equating to approximately 13.5 million equivalent Wave Generator input revolutions.

Additionally, since the updated MAIA Duplex motors were specified to have a minimum stall torque of 184 mNm (26 in-oz), and the HD gear ratio is 244:1, a risk to be addressed was that the actuator could easily exceed the 5.1 Nm (45 in-lb) momentary peak (ratchet) torque rating of the size 10 HDs. Although test records could not be located, the memory remained of the earlier completion of static, sustained no-ratchet verification testing up to a 11.3 Nm (100 in-lb) output load, completed for the MISR program. Thus, passing this test before, after, and throughout the three times life program would also be a success criteria for the Endurance Test campaign at large.

The element of the MDDA most susceptible to wear due to fatigue is the HD output gearing. One of the two redundant drive output subassemblies served as the test article, shown in Figure 2. The HD was to be grease plated using Braycote 601EF and the duplex bearings with Braycote 600EF, both using Brayco 815Z oil, reflecting the heritage grease plating and packing method. The unit was mounted into a simple dynamometer fixture, driven by a brushed test motor, loaded with a brake, along with an input torque transducer and output transducer measuring torque and speed. The simplicity of the setup was intended to allow for continuous operation, to be monitored by a chart recorder, and checked on periodically by engineering.

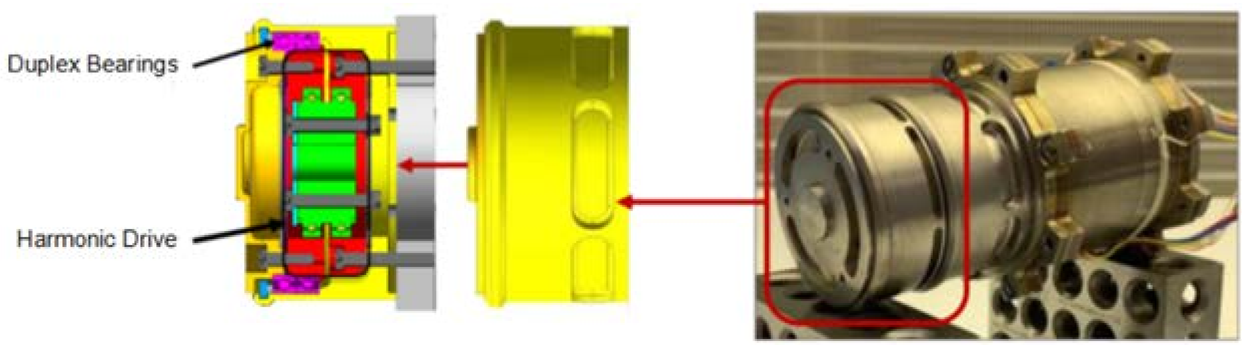


*Figure 2. Endurance Test Article, the MDDA Drive Output Subassembly*

The HDs, and a spare lot of the necessary 440C duplex output bearings, were pulled from flight storage and taken to the cleanroom for cleaning and inspection. The Wave Generator subassemblies had been delivered with their AISI 52100 bearings and 304 CRES spacers bonded onto the Wave Generators hubs, and, per the original source control drawing, a black oxide coating had been applied to the ductile iron circular splines and the AISI 1144 Stressproof Steel® Wave Generators per MIL-DTL-13924. Everything was heavily coated with a layer of a lightweight water-displacing hydrocarbon oil. Similar to the HDs, the Timken duplex bearings were still sealed in their original packaging, also covered in hydrocarbon oil.

The HDs were partly disassembled, leaving the bonded Wave Generator subassemblies intact, and ultrasonically cleaned using acetone, followed by Vertrel XF, and a final oven bake. They were inspected under 15x magnification by engineering and quality and, after receiving passing inspection results, the units were immediately grease plated using Braycote 601EF (10% by mass) and Vertrel (90% by mass), re-inspected, and sealed in moisture barrier bags under dry nitrogen gas purge. The same process was followed for inspecting and processing the duplex bearings, using Braycote 600EF, and all of the packages were stored in the cleanroom to await further assembly steps. When the Drive Output subassembly was completed, a layer of Braycote 601EF was applied to each of the Wave Generator bearings as required to obtain 100% ball coverage, which was manually run-in while also adding 12 drops of Brayco 815Z Oil to each bearing (each of which also contains a phenolic retainer). Braycote 601EF was manually added onto all circular and Flexspline teeth, with excess removed after assembly.

## Endurance Failure

The First Life

The test began with completion of start-up torque measurements of the Drive Output subassembly, and an average value of 11.1 mNm (1.57 in-oz) was observed, landing nicely within the acceptance criteria of <14.1 mNm (2.0 in-oz), per the original size 10 HD source control drawing. The required sustained static output load of 11.3 Nm (100 in-lb) was maintained for 60 seconds with no ratcheting behavior observed, in both directions. The subsequent running portion of the test kicked off, and for the first 27 hours, the input torque required to drive the output torque load of 2.3 Nm (20 in-lb), alternating directions every 6.5 seconds at a rate of 8.0 deg/s, was an average of 38.1 mNm (5.4 in-oz). The input torque dropped to 35.7 mNm (5.05 in-oz) (-6.5%), shown in the left panel of Figure 3, corresponding with an increase in speed of 0.58 deg/s (+6.7%) across a 52 minute period. The speed returned to its approximate initial condition (there was no speed controller in the configuration) starting around ~170 hours, and the input torque increased, to around 41.7 mNm (5.9 in-oz). Then, in the final 16.5 second dither time test event, at around 210 hours, the output speed dropped to about 87% of its starting value, and the input torque increased to a maximum of 45.2 mNm (6.4 in-oz), about 18% higher than the starting value.

However, after about 30 hours, the speed and input torque seemed to level back out, ending with an average input torque of ~38.1 mNm (5.4 in-oz) and an output rate of about 8.0 deg/s. The first life was complete, reaching over 250 hours of as-run test time. Despite the variation along the way, the consistent starting and ending input torque and speed measurements seemed like indicators of a successful first life. The startup torque was re-measured, and an average value of 4.8 mNm (0.68 in-oz), still defined as passing, was observed. The sustained 11.3 Nm (100 in-lb) no-ratchet test was successful again, and life two was ahead.

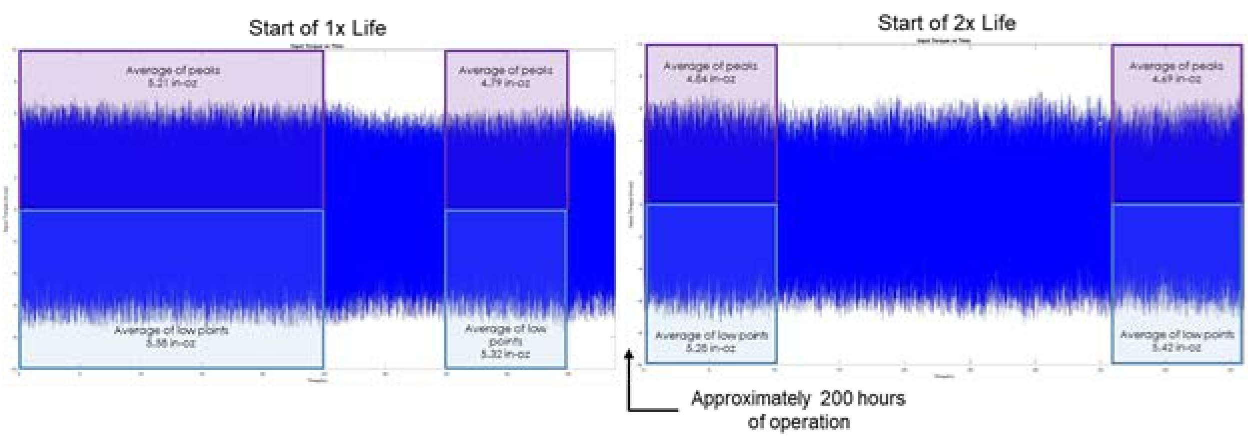


*Figure 3. Comparison of input torque observed over the initial 45 hours of the first and second lives.*

The Death March

At the onset of life two, the average input torque was back down to 35.7 mNm (5.06 in-oz), which corresponded nicely to the run-in value seen after the first life settled. As shown in Figure 3 and, although the speed was around 12% higher than it was at the close of the previous test, the lower measured torque reduced concern associated with the higher speed, and the test proceeded. Both measured values climbed slowly to 38.1 mNm (5.4 in-oz) and 9.0 deg/s over the course of the following 75 hours. Then, another change appeared with about a 0.5 deg/s speed drop over a half hour period, accompanied by an input torque increase to 41 mNm (5.8 in-oz).

This marked the beginning of the roller coaster ride to come. Speed increased, then decreased, then increased again over the following 15 hours, reaching a local high of 9.77 deg/s. After another 10 hours, the speed had dropped back down to 8.4 deg/s. The input torque followed the pattern of increasing with the speed decreases, and vice versa, over this 56.4 hour run with a 16 second direction change timing. At the profile end, input torque was an average of 43.4 mNm (6.15 in-oz). After this, the death march began.

At the start of each event type to follow, as well as in between, the motor voltage was readjusted to obtain the desired speed, and the input torque would swell in response and subside again as the speed would drop back down, like a snake swallowing prey (or a system without speed control). The effect of one such adjustment can be seen in the middle of the 1.5 second dither time test event in the shaded center panel of Figure 4. After 34 hours, the system stopped cycling, and the measured input torque seemed to change exclusively in the uphill direction, until it reached an average of almost 72 mNm (10.2 in-oz), or double the observed value at the start of life two. See Figure 4 and Figure 5.

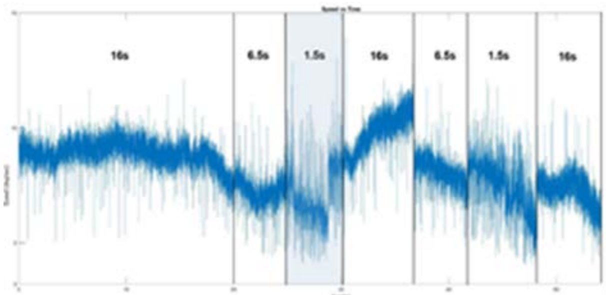


*Figure 4. Output Speed Variation Observed During the Second Life*

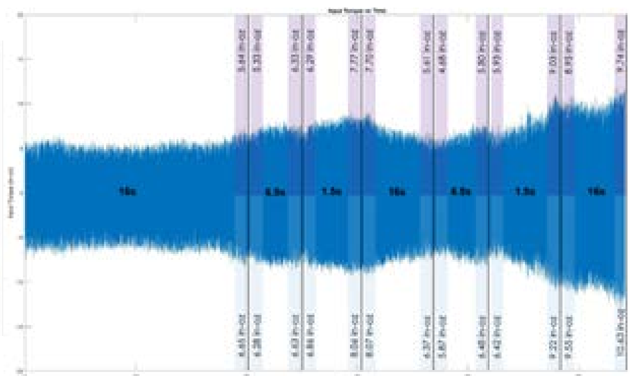

*Figure 5. Input Torque Variation Observed During the Second Life*

In the final stretch of life two, a marathon run with a 6.5-second dither time delay was embarked upon. The speed had dropped from the initially set value, but seemed to settle out at just over 7.0 deg/s, which lasted almost 15 hours. Then, things declined. Over a three hour period, the speed dropped from 7.0 to 4.5 deg/s, which was the lowest yet observed speed, shown in Figure 6, and the input torque increased to the highest yet seen value of 91.1 mNm (12.9 in-oz), shown in Figure 7. The passing of 5 more hours brought hope, then another 5 hours brought despair. When it seemed like the system had settled itself at 4.5 deg/s and a drag torque of just over 84.7 mNm (12 in-oz), the motor voltage was driven back up to obtain the desired output speed.

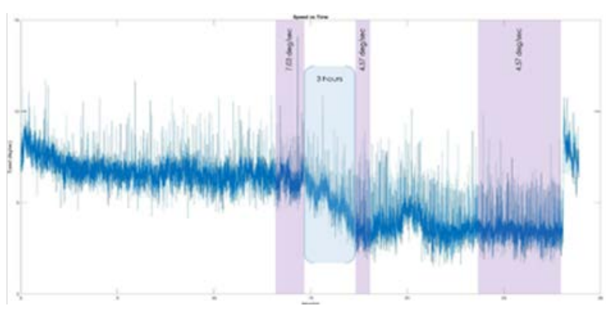

*Figure 6. Output Speed Degradation in the Final 6.5 Second Dither Time Test Event*

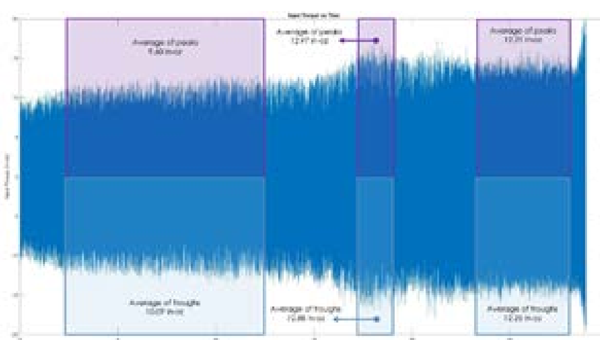

*Figure 7. Input Torque Increase in the Final 6.5 Second Dther Time Test Event*

This time, when the speed was increased to the desired value, the system faught harder than before. Input torque climbed quickly, exceeding previous test maximums, as seen in the far right of Figures 6 & 7. In addition to the behavior was a simultaneous temperature spike of 10°C on the test article housing in under a half hour, with no change to the ambient environment. When the data for both lives was concatenated, as shown in Figure 8, it was clear that this final 6.5 second dither time test event showed unacceptable performance. The test was halted for further assessment.

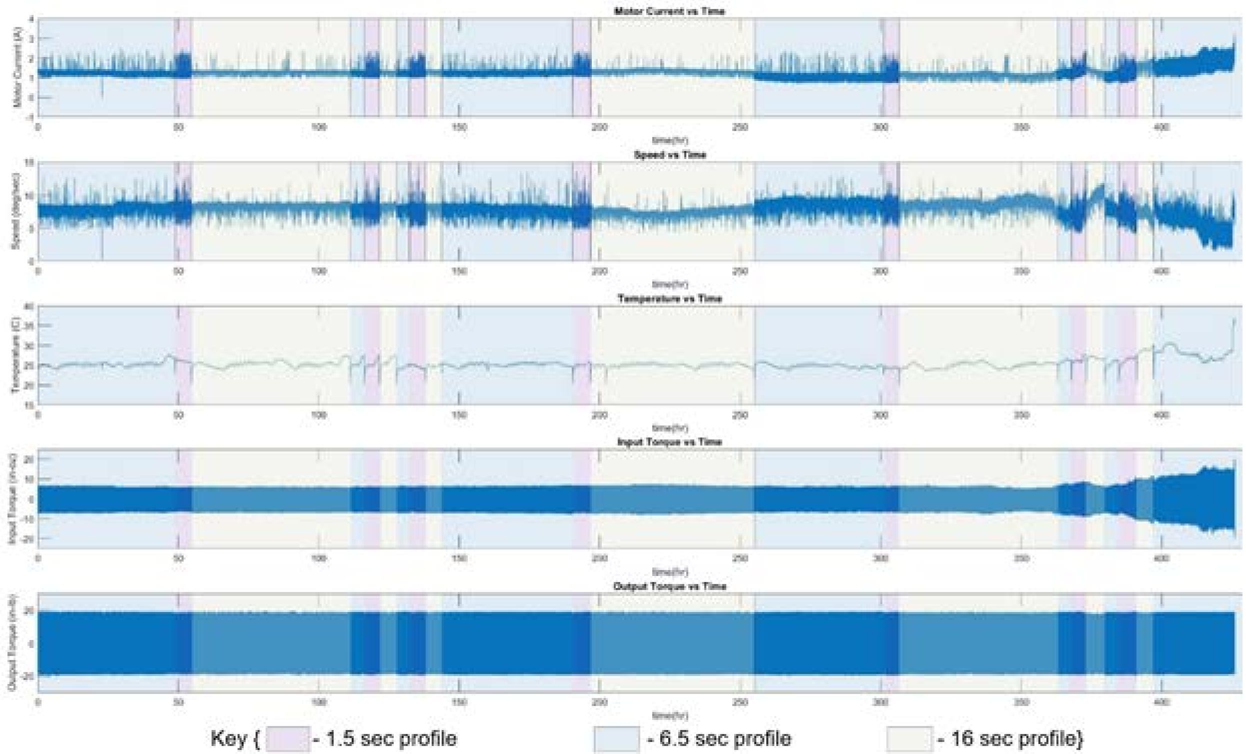


*Figure 8. From Top to Bottom, Measured Motor Current, Speed, Housing Temperature, Input Torque and Output Torque from the Endurance Test, Throught the Final 6.5 Second Dither Time Test Event*

<u>The Final Surrender</u>

For the endurance test that had been completed, data had been logged at 1 Hz. It was decided to perform a final test run with a higher sample frequency, holding the output speed to the 8.0 deg/s target value, and running with a 16-second dither time delay under the full 2.3 Nm (20 in-lb) load. This one last batch of data was desired before the unit was to be disassembled, never to be run in the same configuration again. This final run followed the pattern of the input torque and speed rising and falling in terrifying opposition, growing increasingly worse as time processed. The test reached a climax when the input torque values climbed to a whopping 141 mNm (20 in-oz), where it sat for about 26 hours, with the speed continuing to descend throughout.

Then, the system turned a strange corner. The input torque dropped, about 40 minutes before which the titanium housing temperature climbed 5 degrees Celsius in about 20 minutes. The output speed experienced a major noise reduction at the onset of this temperature increase, and proceeded to exceed 10 deg/s, the highest value observed yet. A few blips followed, before the input torque necked down to 77.7 mNm (11 in-oz). See Figure 9. After seven hours, the rollercoaster ride ended, as the motor began to stall. See Figure 10 for the full test dataset. The time had definitely come for disassembly. Beforehand, the start-up torque and no-ratchet torque tests were conducted. The no-ratchet torque was successful again, and the start-up torque test pushed the acceptable limits, with a peak measured value of 24.7 mNm (3.5 in-oz).

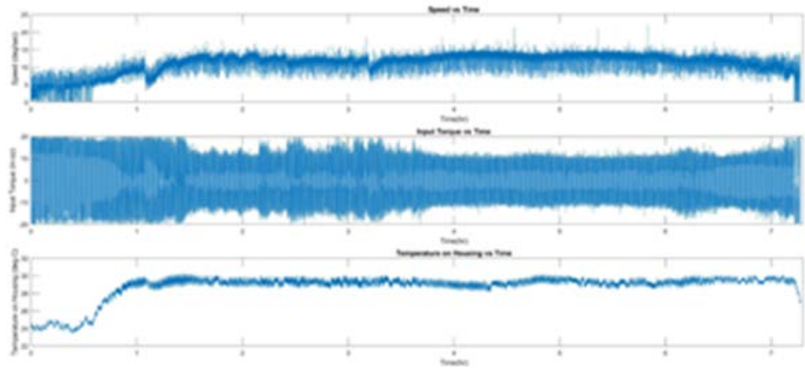

*Figure 9. From Top to Bottom, Speed, Input Torque, and Temperature up to Termination of the Final 16 Second Dither Time Test Event*

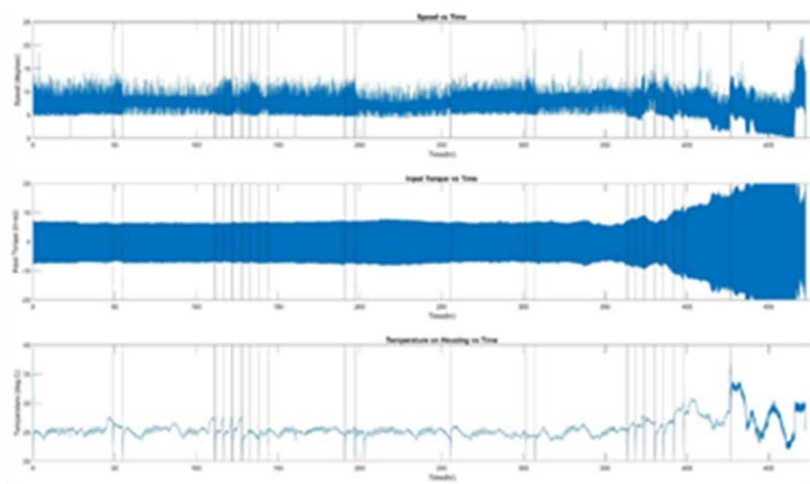

*Figure 10. From top to bottom, speed, input torque, and housing temperature for entire test, including finally executed 16s dither time added test event. Vertical lines indicate test event separation points. Sawteeth in temperature data induced by local thermostat.*

Removal of a single piece part revealed severely degraded lubricant in the Drive Output subassembly. The grease within the Wave Generator bearings looked like copper colored glitter, and felt like the glitter was mixed with dried glue. The material surrounding the tooth interface of the Flexspline and the Circular Splines was black in color and crumbly, with a texture similar to clay mixed with brown sugar. Refer to Figure 11, panels 1 and 2 show the blackened sample within the gear mesh, and panels 3 and 4 show the glittery Wave Generator bearing samples. Each sample was sent to the analytical chemistry lab for analysis, and the HD assembly was ultrasonically cleaned using Vertrel XF, then sent for Scanning Electron Microscope (SEM) imaging and Energy Dispersive X-Ray (EDX) analysis.


*Figure 11. Panel 1: Drive Output Subassembly After Removal of Dynamic Spline, Showing Output Tetth of Flexspline, and Static Spline. Panel 2: Dark, Crumbly Material Gathered in the Static Spline Feature During Disassembly. Panel 3: Wave Generator Subassembly with Flexspline Installed. Panel 4: Opened Drive Output Subassembly Before Distrubance of HD Components*

The HD showed wear on all teeth, biased with the worst damage on the dynamic spline tooth interface, and on most Wave Generator bearing surfaces. Damage on the teeth and bearing races was aligned with the line of action of the bearings. SEM revealed wear to the Flexspline teeth, shown in Panel 4 of Figure 12, which corresponded with Dynamic Circular Spline tooth wear, shown in Panel 1 of Figure 12. The Flexspline had been slipping on the wave generator bearing outer races, with polymerized grease product in between, and as a result, damage was seen on the inner diameter of the Flexspline (shown in Panel 2 of Figure 12) and the outer diameters of the bearing outer races (shown in Panel 5 of Figure 12). Flexspline material was removed at that interface, combined with the bearing grease product, and redeposited onto the Wave Generator bearing balls (see Panel 3 of Figure 12) and ball tracks.

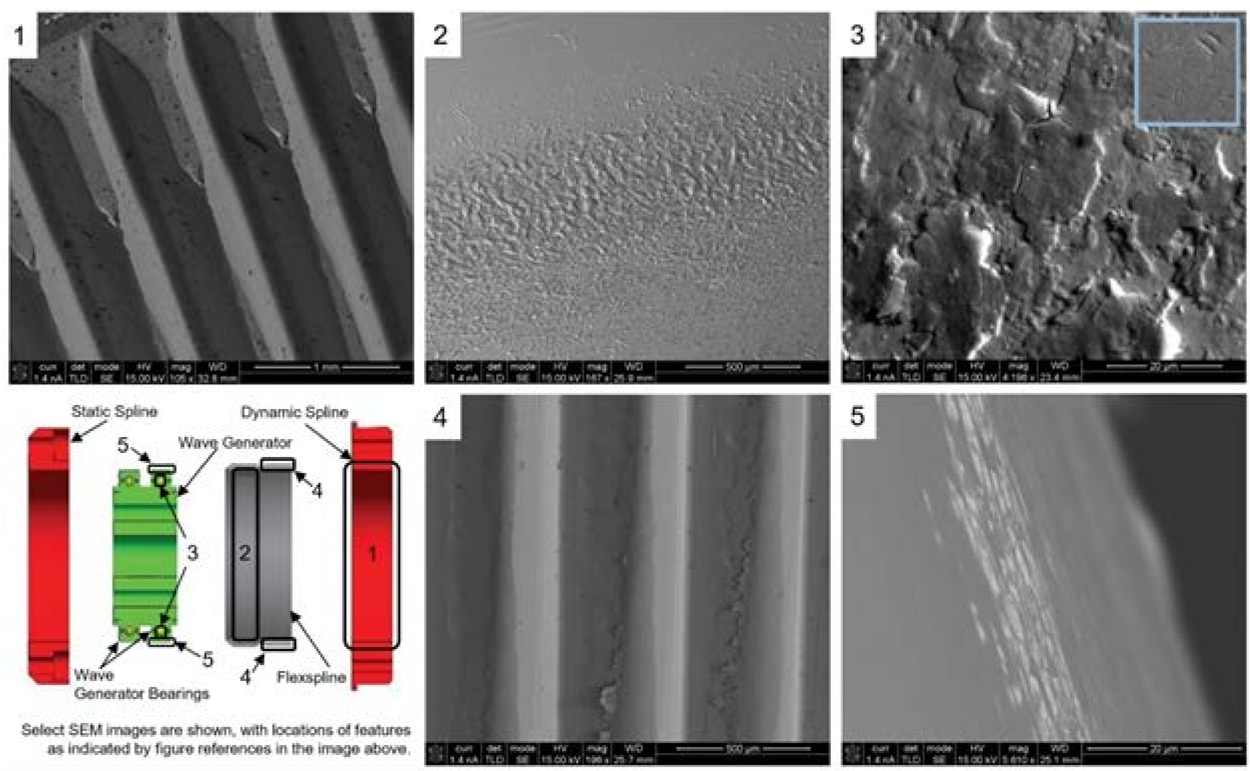


*Figure 12. Panel 1: Dynamic Spline tooth wear. Panel 2: Damaged Flexspline, input side inner diameter-damage pattern reflects ball track load path. Panel 3: Flexspline material adhesion onto bearing ball (increased chromium & nickel seen as dark patches via EDX). Inset shows representative “normal” ball surface at similar scale. Panel 4: Flexspline output side tooth wear. Panel 5: Damaged bearing outer race- pattern reflects ball track load path.*

Raman spectroscopy of the samples revealed the coppery hue to be due to iron oxide, and EDX SEM results showed increased concentrations of oxygen on the bearing races and ball surfaces. Both results indicated the presence of corrosion. X-Ray Fluorescence (XRF) detected the presence of iron, chromium, nickel, and copper in both grease samples. Iron, the Circular Spline material, and chromium and nickel, constituent materials of the Flexspline, corresponded with the worn teeth observed on both via the SEM inspection. The presence of copper was an unexpected discovery.

*Table 1. Anion Content for Harmonic Drive Braycote Samples, Expressed as Microgram Anion in the Water Extract used in Sonication, per gram of Braycote (ppm).*

| Sample | Amount (mg) | Fluoride (ppm) | Chloride (ppm) |
|---|---|---|---|
| Control – New Braycote 601EF | 27.51 | < 0.88 | 4.60 |
| Braycote 601EF – Bearing Sample | 26.54 | 45.5 | < 2.3 |
| Braycote 601EF – Tooth Sample | 25.76 | 110 | 3.38 |

Anion levels measured using Ion Chromatography in the blackened tooth grease sample and the glittery bearing grease sample are shown in Table 1. Extremely high fluoride levels in both samples, especially in the tooth sample, indicated Braycote degradation had occurred. The higher Fluoride level in the tooth sample seemed due to the higher stress experienced by the grease at that interface, due to the sliding interaction between the HD spline teeth.

The Braycote had clearly polymerized and the grease performance and appearance, with the wear patterns along the ball paths of the splines and bearings, were reminiscent of failures described by Conley and Bohner in their report on early perfluoropolyalkylether (PFPE) lubricant testing. [2] It seemed the continuous operation of the HD at a load which was 45% of its maximum rated value, along with the dither-like motion profile, were too much for the Braycote to handle. The severe degradation of the Braycote, especially in the high-shear HD sliding gear mesh, and the presence of the notorious Lewis acids in the samples (higher at the tooth interface) seemed consistent with the summary of PFPE breakdown under high stress by Herman and Davis. [3] The conclusion was drawn that breakdown of Braycote occurred due to the high loads and cycles, and polymerization of the grease caused lubricant starvation of the assembly, increasing the rate of wear to the splines and bearing components. The rollercoaster effect apparent in the input torque and output speed test data appeared to demonstrate the effect of the generation of the friction polymer and its reaction with oxides to produce metallic fluorides to act as in situ solid lubricants (yielding a momentary improvement in performance), followed by the effect of these fluorides as catalysts to accelerate the PFPE breakdown (resulting in subsequent drops in performance). [3]

## Path to Resolution

Due to the status of the MAIA program, it was too late for load reductions, and the MDDA design similarly could not be changed. The decision was made to change lubricants for the Drive Output Subassembly from PFPE Braycote (Braycote 601EF and Brayco 815Z) to hydrocarbon-based Pennzane products (Rheolube 2000 and Nye Synthetic Oil 2001) to leverage its increased lifetime capability. While known to demonstrate an increased lifetime and a decreased wear rate, use of Pennzane lubricants is also known to reduce cold temperature performance, due to its increase in viscosity with reducing temperature. [4] The in-flight thermal environment for the MDDA would be benign, operating nominally somewhere between 0°C to 30°C, so obtaining adequate performance in flight was not at risk, but demonstrating torque margin at the more extreme cold temperatures required in ground testing was.

Additionally, no experience could be referenced using Pennzane with ductile nodular cast iron for flight, so material compatibility needed to be established. Furthermore, the Duplex Motors used for the MDDAs had already been built and delivered with Braycote 600EF, and, since no appropriate seals existed in the MDDA design, a cross-contamination question was raised regarding the potential impact of migration of one lubricant into the region of the actuator where the other was located. Finally, there was extreme uncertainty whether the part lubricated with Bray could be reliably relubricated with Pennzane due to differences in wetting characteristics.

Three tests were executed to provide confidence in: (a) the compatibility of the Pennzane with the HD component materials, (b) the ability to maintain MDDA performance in the event of cross-contamination due to lubricant migration, and (c) the ability of the MDDA to achieve 100% torque margin against a 5.1 Nm (45 in-lb) requirement at the MAIA coldest operational test temperature of -20°C. For (a), an accelerated test would be completed, running the Drive Output Subassembly with the updated Pennzane lubricants, after which inspection and chemical grease analysis would be completed. Regarding item (b), a Pin-On-Disc test was to be completed using a mixture of Rheolube 2000 and Braycote 600EF. Finally to address (c), cold temperature testing would be completed to evaluate the trade between maximizing the Pennzane grease and oil fill amounts and minimizing the cold temperature input drag.

Rewetting & Initial Accelerated Test

The entire lot of HD units and Duplex bearings had been cleaned, inspected, and processed with Braycote lubricants together, and thus, it had to be removed from all of them, including their phenolic retainers. The units were all sent to the Laboratory for Applied Tribology at JPL, to be cleaned and re-processed. To remove the Braycote, the parts were placed into a vapor degreaser, where they sat for several days, followed by ultrasonic agitation, both using Vertrel XF. The Wave Generator subassemblies still remained intact, with bearings and spacers bonded onto the Wave Generators. Their disassembly was discussed, but concerns that were presented regarding potential damage to the irreplaceable flexible bearings during the disassembly and reassembly process prevailed. Some patches of corrosion were visible on the Wave Generator bearing races, which were removed using Scotchbrite. The HD and the duplex bearings were then grease plated using a 10% Rheolube 2000 and 90% Heptane by mass solution. An additional grease fill of Rheolube 2000 with a mass of 0.1151 g was added to the Wave Generator bearings, resulting in 0.0027 g of Rheolube mass applied per each of the 42 bearing balls shared across the pair of bearings.

In this configuration, the HD was reassembled into the Drive Output Subassembly along with a similarly prepared Duplex bearing pair, and the accelerated test was conducted using the Endurance Test fixture. The test article drove a 3.4 Nm (30 in-lb) load in the clockwise direction for 72 hours consecutively at a rate of 16 deg/s. No significant change resulted in input torque nor in speed across this test. The near-constant input torque measured across the test gave confidence in the ability to re-wet the assembly with Pennzane and to subsequently perform well under an aggressive set of initial conditions. After completion of the 72 hours, the test article was disassembled, revealing the Pennzane inside to have a normal consistency, but to be grey in color. The grease sample was sent to the analytical chemistry lab to look for any signs of a potential impending lubricant breakdown.

The gray color of the lubricant was verified to be primarily iron and chromium, with a small amount of titanium (the housing material), by XRF imaging. Fourier Transform Infrared spectroscopy (FTIR) was performed to determine that no significant changes had occurred in the bulk grease chemistry, and there was no evidence of oxidation in the sample. The Direct Analysis in Real Time - Mass Spectrometry (DART-MS) method showed no significant change in the molecular weight of the sample when compared to a comparable new, un-tested sample as well. Overall, the accelerated test yielded a passing result, verifying that the HD and the duplex bearing pair had been successfully rewetted, and the Pennzane lubricants could be trusted to be materially compatible with the HD.

Pennzane Cold Testing

The components were cleaned using Heptane to remove the Pennzane, and re-coated with a fresh Rheolube 2000/Vertrel XF 10/90 mass ratio grease plate layer. This time a Nye Synthetic Oil 2001/ Rheolube 2000 slurry with a 50/50 mass ratio was also applied to the Wave Generator bearings and a 70/30 oil/grease ratio applied to the duplex bearings. The duplex bearings received 0.077 g of slurry to each of the two bearings. A total of 0.11 g of the 50/50 mass ratio slurry was added to each Wave Generator bearing.

The HD and duplex bearings were then reinstalled into the Drive Output Subassembly, which was installed into the Endurance Test fixture. The system was run with no applied load at speeds of 8.0 and 4.5 deg/s and temperatures of -20°C, -8°C, and 30°C. Startup torque tests were also conducted over temperature. The results of this testing are shown in the panels indicated as “Cold Test 1”, of Figure 13.

Another test was run with updated ratios, to understand the effect of reducing the oil percentage while increasing overall mass of applied slurry. The Nye Synthetic Oil 2001/Rheolube 2000 ratio this time was 39/61 by mass for the Wave Generator Bearings, and 36/64 for the duplex bearings. The resultant drag and startup torque values obtained over temperature are shown in the panels indicated as “Cold Test 2”, of Figure 13. See Table 2 for lubricant parameters related to both Cold Tests.

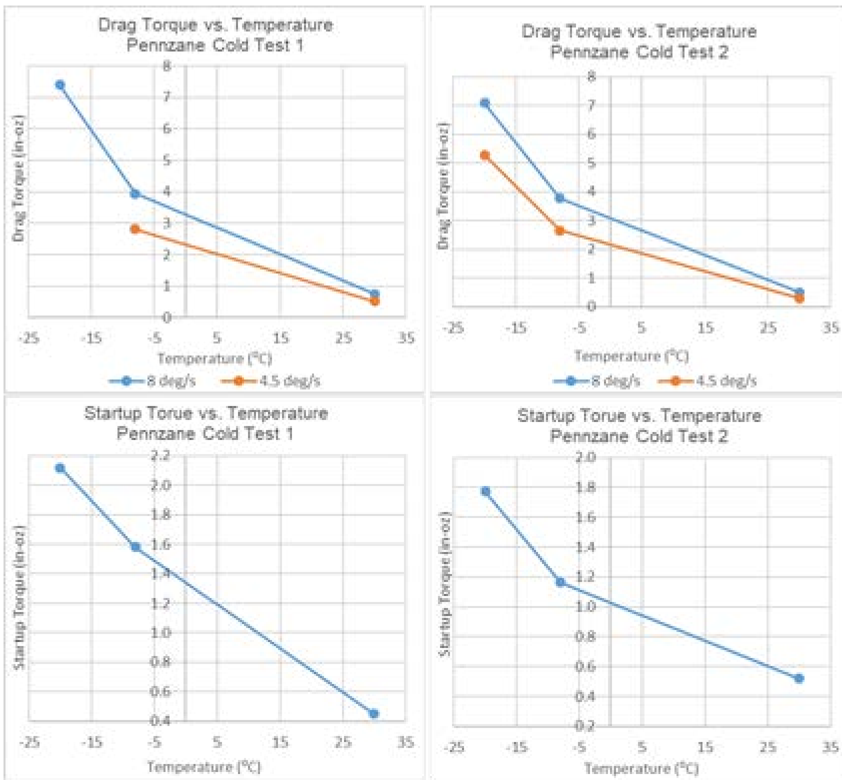

*Figure 13. Test Data from the Cold Tests Conducted to Define Grease & Oil Fill Quantities.*

The second tested lubricant configuration was chosen due to the improved performance, combined with the additional slurry mass of the assembly. The desire for a higher slurry mass was to minimize any future risk of lubricant starvation. The drag torque values were acceptable, thanks to the high-torque output of the re-wound Duplex motors, and the relatively high current available from the instrument power bus.

*Table 2. Lubricant Application Parameters for Cold Tests 1 & 2.*

| Cold Test | Item | Nye Synthetic Oil 2001/Rheolube 2000 Ratio (% mass) | Slurry Mass per Bearing (g) |
|---|---|---|---|
| 1 | Wave Generator Bearings | 50/50 | 0.11 |
| 1 | Duplex Output Bearings | 70/30 | 0.077 |
| 2 | Wave Generator Bearings | 39/61 | 0.137 |
| 2 | Duplex Output Bearings | 36/64 | 0.115 |

Pin-On-Disc Testing

To address the concern of cross-contamination damage due to potential inter-mixing of Pennzane and Braycote, Pin-On-Disc testing was conducted with a 50/50 by mass mixture of Braycote 600EF and Rheolube 2000. The test was conducted at a 0.77 m/s rate in one rotational direction, with a pin pressure of 500 MPa. The result is shown in Figure 14. An increase in the coefficient of friction (CoF) was seen at the test onset, which settled relatively quickly after about 200 m, staying constant until around 3.5 km. After this, the measurement noise and the CoF both increased and fluctuated slightly until the test was completed after 7.5 km of pin travel through the lubricant mixture. The test demonstrated that there would be no significant detriment to performance with a potential long-term mixing of the Rheolube and the Braycote.

A Final Lubrication with an Unexpected Twist

The results of the Pennzane accelerated test, cold testing, and Pin-On Disc testing all gave the green light to reattempt the Endurance Test with the new lubricant configuration. A final spare, un-used and un-designated HD remained, and was selected to be the first to receive the new treatment. The unit was cleaned first with the vapor degreaser and Vertrel XF to remove the Braycote 601EF, then reprocessed using a 10/90 by mass Rheolube 2000/Heptane grease plate, followed by a 40/60 by mass Nye Synthetic Oil 2001/Rheolube 2000 slurry fill process. When the HD was installed into the Drive Output Subassembly, a small piece of debris was found in the Wave Generator bearing lubricant, accompanied by a crunchy feeling upon bearing rotation. The unit was re-cleaned, re-inspected, and received an additional abrasive touch-up to remove some newly found corrosion. New lubricant was applied, and a similar result occurred with a mysterious grease discoloration discovered upon higher-level assembly of the HD, accompanied by more bearing crunch.

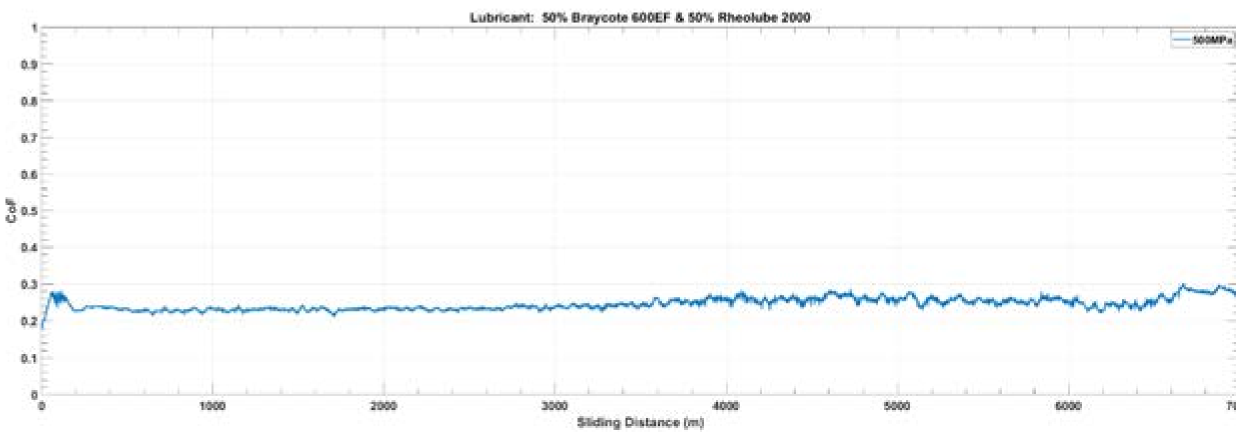


*Figure 14. Pin-On-Disc Results for 50/50 by Mass Braycote 600EF/Rheolube 2000 Lubricant on 440C (58-62 HRC) Substrate in a Uni-Directional Test Configuration with a Pin Pressure of 500 MPa and Rate of 0.77 m/s.*

Thus the time had come to completely disassemble the Wave Generator subassemblies, down to the individual ball level, for inspection. Each bearing was pressed off of the Wave Generator, preserving serialization between the two sets of bearing components. This revealed a significant amount of corrosion, on the bearing balls and races, and along ball paths. The source of the crunchiness was confirmed. The corroded surfaces were abraded as much as possible, the components were cleaned with boiling deionized water followed by Heptane, reassembled into bearings, which were re-bonded onto the Wave Generators. The Wave Generator assemblies were then re-grease plated and filled, as before.

The coppery appearance of the bearing sample had been due to high levels of iron oxide, according to the Raman spectroscopy results. It was highly likely that similar high levels of corrosion hiding in the corners of the Wave Generator bearings in the previously failed Endurance Test helped accelerate the PFPE degradation, readily able to help produce the high Lewis acid fluoride contents seen in Table 1.

All the while, a simultaneous deeper inspection of the Circular Splines revealed that their black oxide coatings did not demonstrate the expected physical properties. Namely, it seemed unnaturally thick for a hot black oxide conversion coating, and instead could be scraped off with a dental pick, turning to powder in the process and revealing a bare surface. It appeared to be a room-temperature, or cold, black oxide application, which is a deposited layer of copper selenium as opposed to a conversion coating, which is not included in the MIL-C-13924 specification as an acceptable black oxide application process.

This understanding of the black oxide type provided the clue to the rogue copper discovered in the previous XRF grease analysis results. The cold temperature black oxide coating had been slowly scraped into the grease by the sliding tooth action during the Endurance Test, and, in addition to generating debris in the tooth mesh grease, it was certainly not performing as a corrosion inhibitor for the Circular Splines, as it was intended.

This meant the Circular Splines had to be abraded as well, to remove all of the undesirable black oxide coating. After this was completed, the units were re-cleaned with Heptane, re-grease plated, and slurry filled as before. This time, when the completely renovated HD was reassembled into the Drive Output subassembly, rotation was smooth, and lubricant was clean. See Figure 15 for Circular Spline images before, during, and after cleaning and re-assembly.

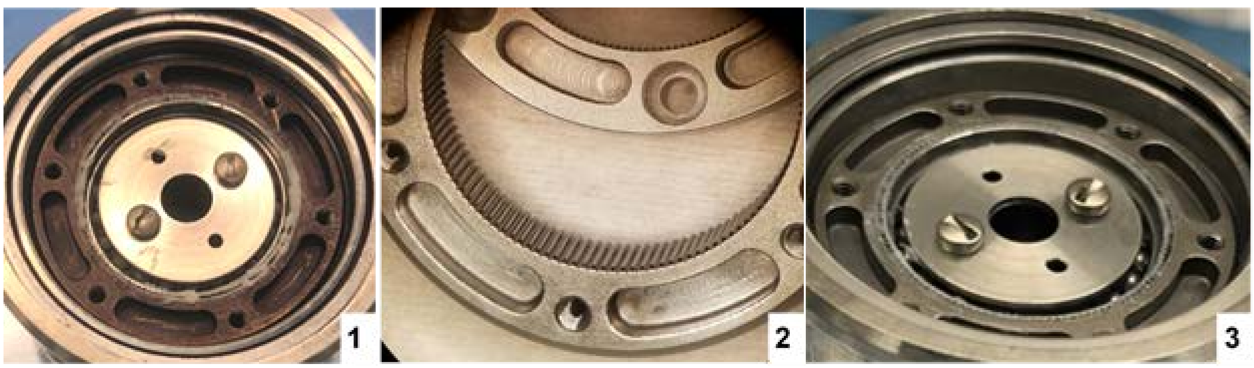


*Figure 15. Panel 1: Harmonic Drive with Room Temperature Black Oxide on Circular Splines, Dynamic Spline Shown, Installed into Drive Output Subassembly, with Braycote 601EF at Tooth Interface. Panel 2: Clean Circular Splines with Black Oxide Removed. Panel 3: Clean Harmonic Drive Circular Spline, Dynamic Spline shown, Installed into Drive Output Subassembly, with Rheolube 2000 at Tooth Interface.*

<u>The Final Endurance Test</u>

The new Pennzane lubricant configuration needed to be vetted by running it through a successful Endurance Test. A refined test profile was created, reducing the loads and varying them based on the three dither timings. The target speed was reduced to be the flight maximum value of 7.75 deg/s, instead of 8.0 deg/s. Cycle counts were scrutinized, and the definition of an actuator mechanical life was reduced from 4.5 to 3.7 million input revolutions. The test would be run for a total of two time one life instead of three times, reflecting a hesitation against over-conservatism, since the JPL standard policy calls for a 2x mechanical life test for wear-life limited elements. This brought the required total HD input revolutions for a successful test declaration down from 13.5 to 7.4 million. The fixture was also modified to include a pulley and weights at the output, such that the brake would be used to apply different bi-directional output drag loads, and the pulley system would simulate the uni-directional load of the flight anti-backlash mechanism, present in the BGA design to facilitate pointing accuracy. A simple control system was also implemented, with a speed controller and position-based sensor feedback to make the testing automatic and consistent.

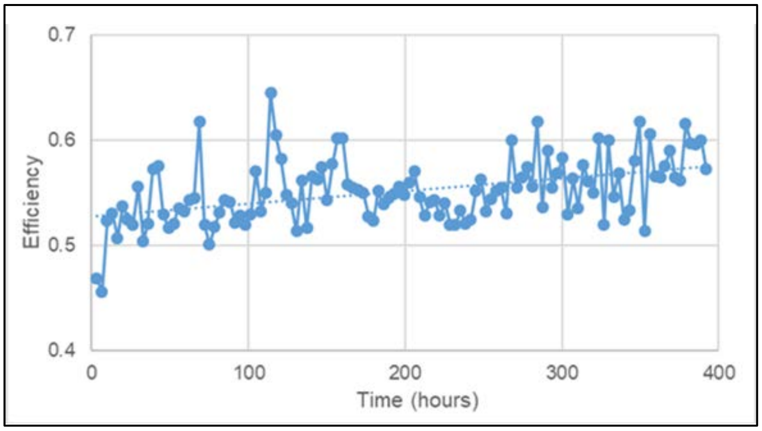


*Figure 16. Harmonic Drive Lifting Efficiency vs. Time during the Final Endurance Test*

Initial startup torque values were low with an average measured value of 6.0 mNm (0.86 in-oz), compared to the 11.1 mNm (1.57 in-oz) for the Braycote 601EF initial measurement. Variations seen in input torque and output speed across this test series were due to operator error in tuning of the bi-directional applied load and speed setting. Despite some setting errors, the telltale sign of the success of the Pennzane Endurance Test was the slight but steady increase in the HD lifting efficiency over the total 400 hour period. Corresponding with the increase in efficiency over the two times one mechanical life, the final measured startup torque after test completion had actually reduced from 6.0 mNm (0.86 in-oz) to 5.1 mNm (0.72 in-oz). The test was finally over.

## Conclusions

The long standing controversial relationship between Pennzane and Braycote was challenged by the MAIA MDDA application. The Pennzane ability to functionally rewet hardware that had previously been processed with PFPE lubricant was demonstrated by the completion of the accelerated 72 hour test. The test showed no change in the efficiency over its duration, despite the aggressive load and speed profile. This indicated that the Pennzane effectively lubricated the rolling and sliding surfaces of the HD and Duplex bearings, and maintained this effectivity for 72 consecutive hours in one direction. Post-test chemical analysis showed no indications of any impact to the lubricant itself due to the operational profile. Thermal testing also showed the re-wettability to persist over temperature. The Pin-On-Disc test results gave confidence regarding the chemical compatibility of the lubricants over a long life, and their ability to lubricate effectively despite their intermixing. These test results gave the MAIA project the confidence to proceed with the unconventional solution of changing to Pennzane-based lubricants in the middle of the program, resulting in an MDDA assembly that has a Braycote lubricated motor, and rewetted Pennzane output gearing, all in one package.

The relatively uncommon process of pulling flight hardware from storage to revamp for a new flight application provided challenges to the team. The long-term storage conditions, bagged and sealed in hydrocarbon oil, proved to be inadequate for the 52100 HD Wave Generator bearings over the two decades the units were shelved. To reliably use this inherited hardware, a full disassembly, down to the individual bearing-ball level, and detailed chemical and abrasive cleaning was required in order to locate and eliminate all of the hidden locations of the corrosion that had developed over time. For certain components to be used from long-term storage, a similar total disassembly and detailed inspection is recommended, even if the assemblies appear to be acceptable by external visual inspection. Specifically, those that use materials that are sensitive to corrosion, such as 52100 steel, and are inherently difficult to inspect due to hidden geometry, such as bearing assemblies. Trust, instead, that corrosion is sneaky and will wait hiding in a crevice or shadow, to ruin hardware performance when least expected.

Finally, the black oxide surprise turned out to be another unexpected result of using hardware from long term storage. The HD units used for the MAIA project were originally received in the 1990s, at a time when their manufacturer was not yet certified in compliance with ISO 9001. At the time, material certifications were not required as a part of purchase orders (which is a requirement now). A perfect storm of conditions set the stage for the application of the cold temperature black oxide to be missed, despite the long duration they were possessed. If the units had been part of a lot that was intended to be used in short order, the discovery would have been made during testing of the other projects. The use of hardware drives being purchased as a solitary lot, intended to be immediately shelved, and the minimal involvement from the quality organization at the time of purchase, meant the discrepancy snuck in, undetected, to be discovered instead during the development of the next generation of MDDAs decades later. As a result of this discovery, a recommendation is made for heightened inspection to be completed of hardware that was either received before quality process changes, or before any significant changes in the ownership of or certifications obtained by the supplier.

## References


1. Packard, Douglas T.; "Dual Drive Actuators"; Proceedings, 16th Aerospace Mechanisms Symposium; May 13-14, 1982; NASA CP-2221.

2. Conley, Peter L. and Bohner, John J.; "Experience with Synthetic Fluorinated Fluid Lubricants"; Proceedings, 24th Aerospace Mechanisms Symposium; April 1 1990; NASA-CP-3062.

3. Herman, Jason and Davis, Kiel; "Evaluation of Perflouropolyether Lubricant Lifetime in the High Stress and High Stress-Cycle Regime for Mars Applications"; Proceedings, 39th Aerospace Mechanisms Symposium; May 1, 2008; NASA/CP-2008-215252.

4. Venier, Clifford; Casserly, Edward W.; Jones, William R., Jr.; Marchetti, Mario; Jansen, Mark J.; Predmore, Roamer E.; "Tribological Properties of a Pennzane-Based Liquid Lubricant (Disubstituted Alkylated Cyclopentane) for Low Temperature Space Applications"; Proceedings, 36th Aerospace Mechanisms Symposium; April 1, 2002; NASA/CP-2002-211506.


## Acknowledgments


This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, Pasadena, California. © 2020. California Institute of Technology. Government sponsorship acknowledged.

The author would like to thank JPL chief engineer, and original delivering engineer of the MDDA, Michael R. Johnson, from the Jet Propulsion Laboratory (JPL), for patiently providing his never ending technical guidance and mentorship. Also, thanks to Allison Ayad, for her tireless support during the failure investigation and her valuable data reduction, also through JPL. Thank you to Duval Johnson, of the Laboratory for Applied Tribology at JPL, who spearheaded the disassembly, cleaning, and detailed inspection of the Wave Generator subassemblies, and skillfully completed the Braycote removal and rewetting of the Harmonic Drives and duplex bearings with Pennzane. Thank you to the expertise of Mark Balzer, also of the Laboratory for Applied Tribology at JPL, who identified the cold temperature black oxide coating. Many thanks also to the Analytical Chemistry Laboratory at JPL, namely Nick Heinz, Mark Anderson, and Bill Warner, who performed all chemical grease analysis described in this paper.

Lastly, but not least, the author would like to make a special acknowledgement of Harmonic Drive, LLC. Harmonic Drive, under their current ownership, has successfully provided flight hardware to JPL for decades. In recent years, the author of this paper, specifically, has received more than thirty pancake style HD units (in size 14) which have been inspected and approved by JPL QA, and have been integrated into high reliability flight actuators for multiple projects, including successful life test completion. No anomalies related to any of the HD units have resulted during these program developments.