USE OF CUMULATIVE DEGRADATION FACTOR PREDICTION AND LIFE TEST RESULT OF THE THRUSTER GIMBAL ASSEMBLY ACTUATOR FOR THE DAWN FLIGHT PROJECT

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ABSTRACT

Dawn [1]-[3] is the ninth project in NASA's Discovery Program. The Dawn spacecraft is being developed to enable the scientific investigation of the two heaviest main-belt asteroids, Vesta and Ceres. Dawn is the first mission to orbit two extraterrestrial bodies, and the first to orbit a main-belt asteroid. The mission is enabled by the onboard Ion Propulsion System (IPS) to provide the post-launch delta-V [1]. The three Ion Engines of the IPS are mounted on Thruster Gimbal Assembly (TGA) [2], with only one engine operating at a time for this 10-year mission. The three TGAs weigh 14.6 kg [1].

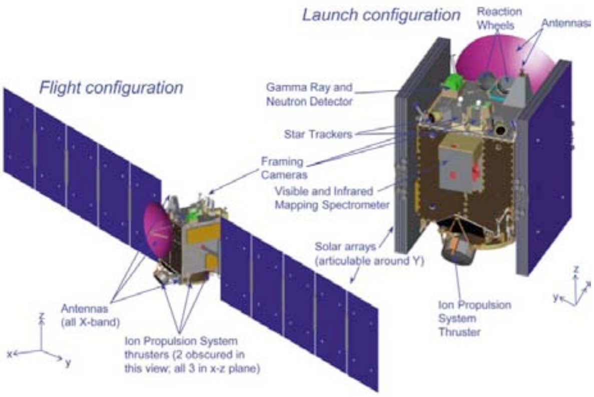

Figure 1 – Dawn Flight System Configuration

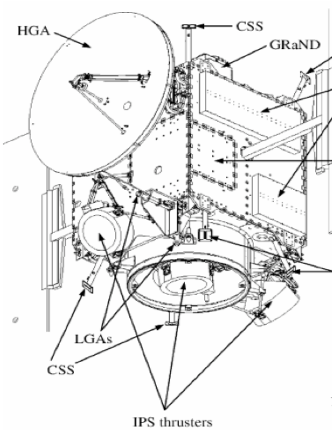

Figure 2 – IPS Thrusters Configuration

Each Ion Engine/TGA is single string with no redundancy. System redundancy is provided by requiring two out of the three Ion Engine/TGA to operate for the full mission duration. The TGA is a hexapod design with two articulating crank-arm actuators, changing the effective length of the legs and providing pointing control for the Ion Engine. A drawing and photo of the TGA hexapod gimbal [2] is shown in Figures 3 and 4.

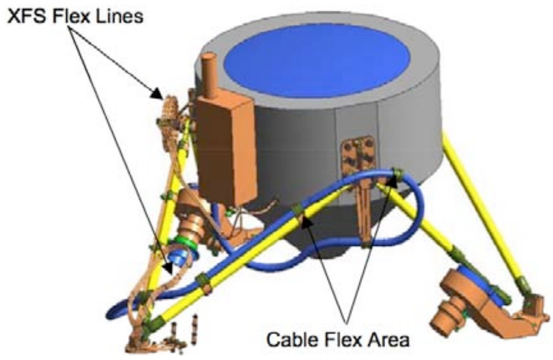

Figure 3 – Dawn Hexapod Gimbal

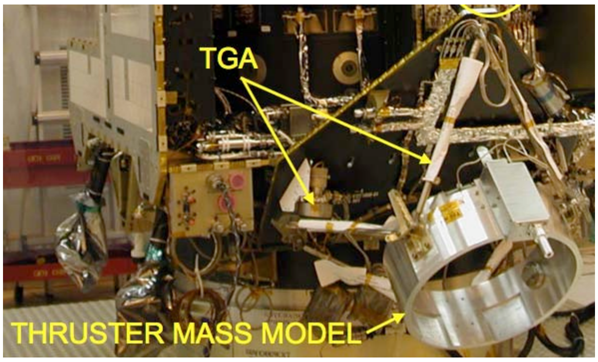

Figure 4 – TGA during assembly (May 2006)

The input to the crank arm actuator is a vendor provided (Starsys Inc., Louisville, CO, USA) gearmotor, with a new two phase 45° stepper motor design driving a two stage (4.333 x 4.333) planetary gearbox. The gearbox has Mars Exploration Rover (MER) heritage and was used in the wheel steering actuators. The gearmotor output then drives a standard

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Harmonic Drive System (HDS) (Type 17 harmonic drive with a 100:1 gear reduction) using 52100 bearing materials in the wave generator bearing. The output angle is 0.024 degree per step. The output stage is designed and built by JPL. The harmonic drive output is then connected to the crank-arm by a duplex 440C Stainless Steel (SS) pair bearing (Figure 5).

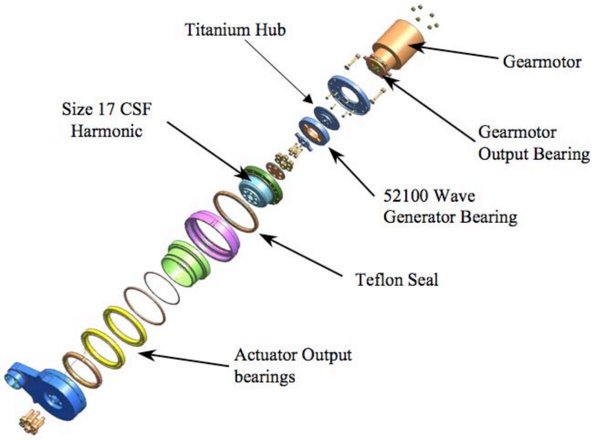

Figure 5 – Dawn TGA Actuator

The TGA crank arm actuator is a new design. The lubricant life prediction as presented at the TGA Critical Design Review (CDR) in May 2004 did not provide sufficient rationale as to why the lubrication will survive the predicted mission life time. Once this deficiency was identified, the Cumulative Degradation Factor [4] (CDF) technique was implemented to determine whether the design could meet the mission lifetime requirement before completing the gearmotor/actuator design and assembly. As a result of this study, numerous changes, including mission duty cycle definition, motor rotor bearing preload value and additional amount of lubricant applied to the rotor bearings were implemented to assure mission success, plus a successful life test. In addition, a revised stepper motor design, using external resistors to stabilize the system resistance, was incorporated in the same time period to work with the existing motor control logic.

1. EXPERIMENTAL

A Spiral Orbit Tribometer (SOT) (Figure 6) was used to study the lifetime of the maraging alloy steel, Vascomax® C-300 gear materials used in the two-stage planetary gearbox. No data existed prior to this study on the new Vascomax C-300 material when used in a mechanical moving assembly (MMA) for space flight. The SOT [5] measures lubricant consumption in the boundary lubrication regime to provide a comparative tribological consumption rate quickly with different material combinations, contact stresses and temperatures.

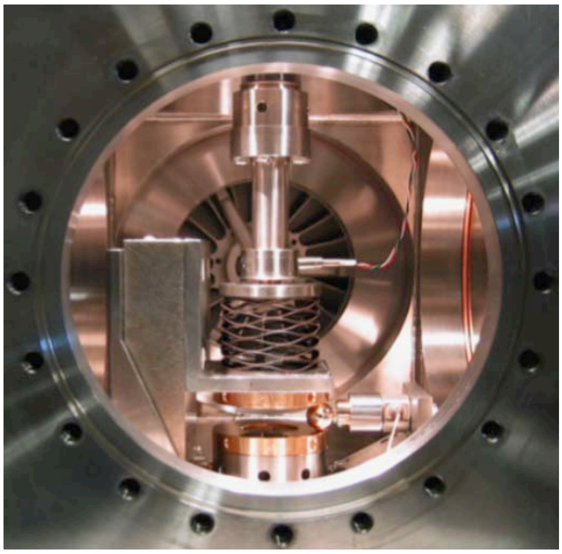

Figure 6 – The Spiral Orbit Tribometer

Custom Vascomax C-300 test and guide plates were fabricated for the SOT, and a 440C SS 1/2 inch (12.7 mm) diameter ball was used as Vascomax C-300 balls were not available. The test plates were run with Braycote® 601EF and 602EF greases, Brayco 815Z and Pennzane® oils with the 440C SS test balls. These SOT tests are then compared with 440C SS test plate/ball used as reference. The purpose of this test is to investigate whether the Vascomax C-300 material has any accelerating effect on the lubricant consumption rate as seen by the 17-4 PH SS with Pennzane in the Microwave Limb Sounder Antenna Actuator Assembly (AAA) [4]. The SOT tests were run in ultrahigh vacuum (< 10^{-6} Pa). A normalized lubricant lifetime was determined by dividing the number of ball orbits at failure (friction coefficient of 0.28) by the amount of lubricant deposited on the ball. This yields a lifetime in orbits/μg of lubricant and is used to compare different combinations and two temperatures.

A dedicated crank arm actuator Life Test Unit (LTU) was initially used in one of the two arms in the Qualification TGA. The LTU was subjected to 6-1/2 thermal cycles between +120°C to -70°C in GN_2 at qualification temperature during actuator level testing, then installed in the TGA for the qualification vibration test to qualification level and duration (2 minutes/axis). Due to a problem with the special welded Resistoflex fitting adaptors during vibration testing, and subsequent retest, the TGA was subjected to a total of 12 minutes of vibration testing, twice the normal duration. After vibration, the LTU was removed from the qualification TGA and replaced with an EM actuator for further TGA comprehensive performance testing (CPT). A post-vibration 1-1/2 thermal cycle test was performed to verify the performance of the LTU. This testing also consisted of Motor Threshold Voltage (MTV) and running torque testing at temperature and ambient. After successfully completing these tests, the LTU was setup in a bell jar vacuum chamber and programmed for a long duration life test, using precise power control to bring the thermally isolated LTU actuator to between +55°C to +89.5°C running temperature in a set profile by heating the winding and the two external resistors.

Periodic measurements using Lab View® software measures the MTV automatically to monitor changes to the internal running friction, giving an indication as to the state of the lubricant inside the LTU. The LTU life test was completed in May 2006, and the LTU disassembled at JPL. The gearmotor was returned to the vendor for further disassembly.

2. RESULTS

2.1 Cumulative Degradation Factor Prediction

The Cumulative Degradation Factor (CDF) analysis initially indicated "**Very Low Probability of Success**" as designed at the CDR. The proposed lubricants for the DAWN TGA are all based on Brayco 815Z, linear perfluoropolyether oil. This oil and its grease variations have been the lubricants of choice for space mechanisms for many years. The gears and gearbox was to be lubricated with Braycote 602EF grease. Braycote 601EF grease and Brayco 815Z oil were to be used in the motor, motor bearings, and output shaft bearings. Both greases contain a PTFE thickener and Braycote 601EF also contains a bentonite clay corrosion inhibitor and sodium nitrite rust inhibitor. The Braycote 602EF only contains MoS_2, a solid lubricant. . The TGA ball bearings are made of 440C stainless steel and the gears are made of Vascomax C-300, maraging steel containing Ni, Co, and Mo.

After examining the relative number of stress cycles of all TGA bearings, it was determined the motor bearings were at greatest risk because they undergo the most cycles. Planet bearings see reduced cycles because of the various gear ratios in the TGA. Therefore, calculations are based only on the motor bearings.

When the 10% mission duty cycle, proposed by JPL, was used in the calculation of the CDF, it clearly indicated that the lubricant in the motor bearing would not survive. With full cooperation from the gearmotor vendor, a different design was implemented to lower the motor rotor bearing preload, to 25% of the initial value at 1.0 ± 0.25 lbf. However, this redesign CDF calculation still yielded the same failure prediction.

For a five-year lifetime, at a 10% duty cycle, the motor bearings will experience approximately 100 million revolutions. This is based on 4,380 hours of operation at 6.25 revolutions/sec. The bearings are small (0.375" OD), 440C SS, Conrad deep groove bearings with eight 1/16" diameter balls. The ball-race conformity is 56% and the free contact angle is 15.6 degrees. The final selected preload was 1.00 ± 0.25 lbf. Assuming a maximum preload of 1.25 lbf, the mean Hertzian stress is 113 ksi. For the eight ball complement, one shaft revolution will yield four ball passes. Therefore, 100 million revolutions yields 400 million ball passes. Multiplying this value with the mean Hertzian stress yields a CDF of approximately 4.5×10^{13} ball passes-psi. For comparison, measured CDF values for several bearing life tests appear in Table 1.

Table 1, Measured Cumulative Degradation Factor

(815 Z Lubricant)

Bearing Life Test	*Cumulative Degradation Factor for Initiation of Lubricant Degradation or Bearing Failure x 10^{12} (ball passes-psi)*
TES LTU Encoder (73 ksi)[a]	2.0[b] (3.8)[c]
Lockheed-Martin[d](109 ksi)[a]	2.2 to 8.7 (Average: 5.5)
Hughes (Flooded)[e] (94 ksi)[a]	2.8
Ball Aerospace[f](65 ksi)[a]	1.4[2] (2.0)[3]
Lockheed-Martin[d](109 ksi)[a]	**26 to 88 (Avg: 67) (Pennzane Oil Formulation)**
CERES Life Test[g] (83 ksi)[a]	**24[h] to 48[h] (Pennzane Oil Formulation)**
MODIS Life Test[i]	**70[h] (Pennzane Oil Formulation)**

[a] Mean Hertzian Stress; [b] Start of Torque Increases; [c] Test Termination; [d] Reference 4; [e] Reference 6; [f] Reference 7; [g] Reference 8; [h] Test Suspension (no failure); [i] Reference 9

Only measured CDF by testing in vacuum were used for comparison as even a small amount of moisture from GN2 or LN2 can greatly reduce the lubricant consumption rate [7].

This prediction was then used as the tool to convince the Dawn project to accept the spacecraft vendor's (Orbital Science Corp., Dulles, VA) mission duty cycle estimate of 1%. With this realistic value of 1% mission duty cycle, and in combination with the lowest practical rotor bearing preload, the prediction using the CDF technique changes to "**High Probability of Success**" for meeting the updated mission requirement with a revised CDF of 4.5×10^{12} bp-psi. This revised CDF is in the midrange of Lockheed Martin's failure range of 2.2 to 8.7×10^{12} bp-psi based on bearing life tests [6].

Although the CDF for bearing tests with Pennzane oil formulations is an order of magnitude greater than for Brayco 815Z, Pennzane was not chosen for the MMA since the unit would be operating at elevated temperature. The vapor pressures of Pennzane formulations are about two orders of magnitude greater than Brayco 815Z at temperatures approaching 90°C. The actual consumption and evaporation rates should be measured with the SOT and in actual bearing life tests at these higher temperatures. The operating temperature for the Dawn TGA, while the Ion Engine is running, is predicted to be between 55 to 89.5°C, and is beyond life test and on-orbit experience for Pennzane formulations. It was felt that the risk of using Pennzane at this temperature is high without a thorough investigation and test program.

2.2 Vascomax C-300 Consumption Rate

The SOT results (Figure 7) indicated Vascomax C-300 did not have an accelerated lubricant consumption rate with Braycote 601EF grease. However, the data did indicate a reduced lifetime on both Vascomax and 440C SS with 602EF when compared to 601EF. The gearmotor vendor was quickly directed to change from the 602EF lubricant (used on MER) to 601EF to maximize life of the gears used on Dawn. Also, all MMA processes for the Dawn TGA at JPL use the 601EF grease with Braycote 600 used for grease plating.

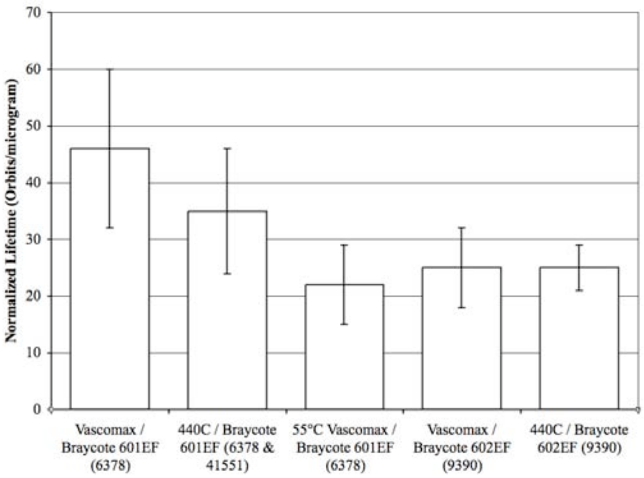

Figure 7 – Vascomax C-300 SOT Test
(< 10^{-68} Pa, 40 RPM, 1.5 GPa mean Hertzian Stress)

2.3 Modifications to the Stepper Motor

The initial gearmotor specification omits the allowable maximum torque and the first generation stepper motor was designed to the maximum capability of the two-stage planetary gearbox. This excessive torque will damage the harmonic drive, producing a calculated torque of more than 1,500 in-lbs. The gearmotor specification was then clarified with clear definition of the winding configuration (shorting of un-powered winding), two missions specified fixed pulse width at 15 and 20 ms, and allowing the addition of external resistors to stabilize motor current (constant voltage driver) over the wide temperature range. The revised motor also incorporated the reduced preload after delivery of the first Engineering Model (EM).

2.4 EM 1 Configuration

The first EM had the original 4 lbf preload and the standard (larger -1) gear with the revised stepper motor. The rationale is that the first path finding EM should be built as quickly as possible with existing hardware. This EM was used in the thermal dyno chamber setup, resulting in the discovery of gear binding at temperatures below –55°C.

2.5 EM2 Configuration

The second EM, EM2, was initially intended to be the LTU. The rotor bearing preload was lowered to 2 lbf easily by using different thickness shim washers. EM2 was assembled with the smaller -2 gears with light hand lapping. The CDF with the 2 lbf was in an acceptable range, but on the high side of the failure range. EM2, with 2.0 lbf and -2 gears, was delivered to JPL and went through the full qualification thermal dyno test profile for 6-1/2 thermal cycles while modifications to the rotor bearing preload was being engineered. This EM2 produced acceptable performance, but with more reduction in output torque at temperatures below –55°C, indicating high internal friction.

2.6 LTU Configuration

Subsequently, the target rotor bearing preload was lowered even further, to 1.0 ± 0.25 lbf for the third unit being built. This unit, the LTU, used a different preload bearing cup design, with each wave spring measured and the cup match machine to bring the preload to the design range. The rotor bearings are grease plated and four additional drops of Brayco 815Z oil added to every other ball for each rotor bearing. The gearbox used the smaller -2 gears with very light lapping to a newly defined "end play" target range for the gearmotor output. After grease plating the gears and the bearings in the planetary gearbox, additional grease strips with Braycote 601EF were applied on the inside of the gearbox housing. After bake out, the LTU was brought down to –108°C cold survival temperature, then 6-1/2 thermal cycles between –70°C to 120°C, with dyno runs at the first and last thermal cycle. Below (Figure 8) is the thermal dyno test result for the LTU in April 2005:

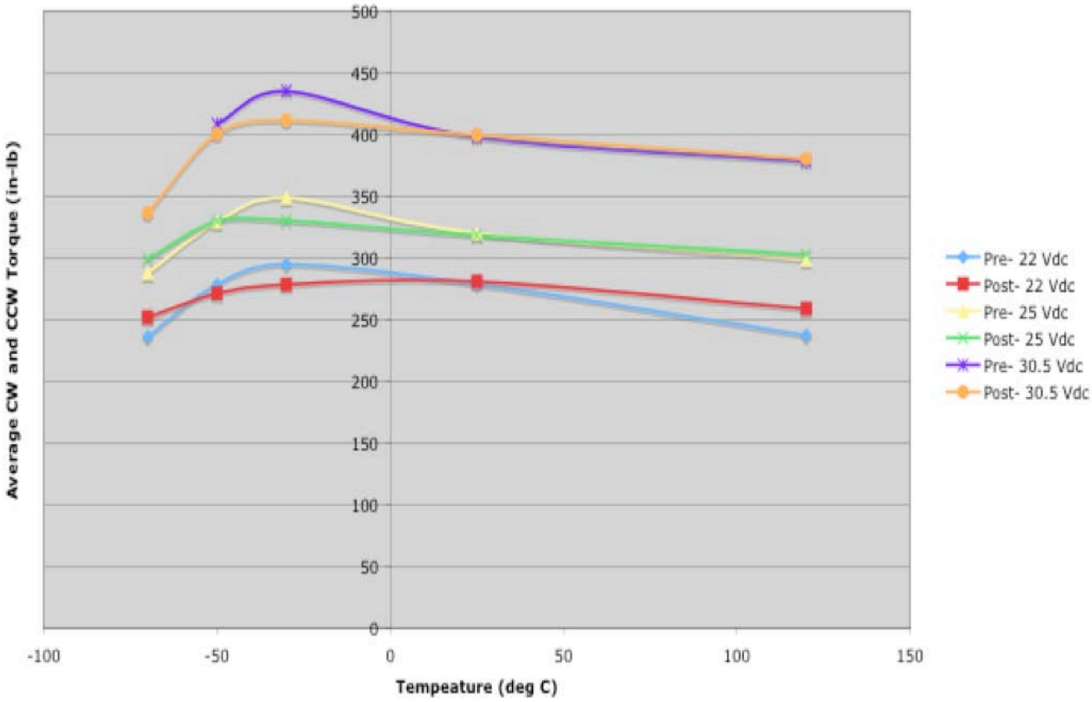

Figure 8 – LTU Pre-Vibe Thermal Dyno Test, 50 pps

The pulse width is commandable from the ground to full pulse width (20 ms) if needed, with an increase of approximately 30 to 40 in-lb of output torque from the 15 ms value.

Post-Vibe thermal dyno test of the LTU in July 2005 produced similar torque output, MTV and no movement due to vibration by measuring the number of steps to actuate the microswitches at the hardstop position.

2.7 HD Wave Generator Bearing Separator Orientation

An EM TGA was built in the summer of 2004, with flight configuration titanium struts, actuator bracket, and all flight like hardware as the vibration test fixture to qualify the three flight ion engines. Instead of a gearmotor, a simple mass model took its place, with manual crank to drive the input to the wave generator of the harmonic drive. The separator was installed on the "closed" side of the flex spline of the harmonic drive. In order to keep the separator from popping off when load was applied, a set of custom shims and a large 400 series SS washer was used to keep the retainer in place. However, during assembly of the actuators with the running gearmotors from the first EM on, the retainer was flipped and installed on the "opened" side of the flex spline on the wave generator bearing. This simple and seemingly innocent change resulted in a situation that, when the wave generator bearing is loaded, the retainer is pushed outward against a titanium gearmotor output adaptor hub. Titanium could, and in this case did, accelerate degradation of the Braycote lubricant. Future gearmotors should fabricate this output adaptor hub with 440C SS materials to prevent this defect so that the retainer, with the Braycote lubricant, will slide on a known material that will not accelerate break down of the lubricant.

2.8 HD Wave Generator Bearing Materials

The off-the-shelf HDS harmonic drive uses 52100 bearings. Much effort was spent on run in and different techniques to prevent the bearing from rusting after precision cleaning. Future gearmotor designs should specify 440C SS bearings to simply processing. The additional lead time using the 440C SS bearing is well worth the wait.

2.9 External Resistive Load

At TGA CDR, the resistive load was estimated at more than 50 in-lb. With a revised crimping procedure for the spherical ball bearings at the end of the struts, redesigned routing for the three 1/8" SS Ion Engine feed lines into a "cloth spring" configuration, and repositioning of the high voltage lines, the measured resistive load at room temperature has been reduced to 6 in-lb maximum. The actuator consistently delivered more than 220 in-lb of output torque, providing more than adequate torque margin with a fixed 15 ms pulse width from 0 to 50 pulses per second (pps).

2.10 Detailed Lubrication Scheme for the Actuator

The two Starsys motor bearings are initially grease plated, then an additional 4 drops of Brayco 815Z oil (15 ± 3 mg total for each bearing) is applied to each bearing, the planetary gears and bearings are grease-plated with Braycote 600 grease, and four Braycote 601EF grease strips applied on the inside of the gearbox housing. On the JPL side, the harmonic drive wave generator bearing, flex spline, circular spline and the duplex bearing pairs are grease plated with Braycote 600, then all lubricated by a 50/50 mix of Brayco 815Z oil and Braycote 601 grease. All bearings are packed at 60 to 75% of free volume with this 50/50 mix. The inside of the flex spline has approximately 400 to 600 mg of this mix to provide a reservoir around the sliding surface for the wave generator bearing outer race. The circular spline and flex spline gears are also filled with this 50/50 mix.

2.11 Test as You Fly, Fly as You Test

The LTU is exactly the same as all flight units. It is "Baked and Shaked" before life test. Also the LTU is tested in vacuum instead of GN2, at the same step rate planned for flight. The temperature profile is based on prediction by integrated thermal analysis with the spacecraft contractor.

2.12 Life Test Setup

The main objective of this test was to temperature cycle a DAWN TGA actuator in vacuum (with target range between 2 to 7 x 10^{-5} Torr pressure during life testing, and vacuum level at least to 10 x 10^{-5} Torr is acceptable during the beginning of the bake-out/pump down stage in order to expedite life test), automatic direction switching at end of travel, consistent with the set temperatures such as three ranges, automated data handling to monitor temperature, weekly inspection of data. Duration is approx. 3 months for a 3X life test run (demonstrate 1% mission duty cycle, 5 years mission life per TGA, 2 TGA functional (out of 3 TGA) for the 10 year DAWN mission life time). Successful demonstration of the 3X life test run or more will meet the DAWN project requirement for life testing of the DAWN actuator.

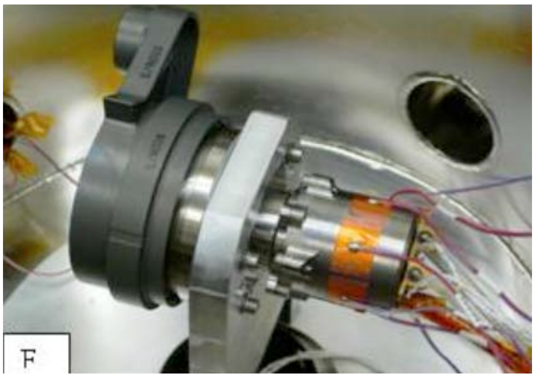

Figure 9 - Dawn LTU prior to Life Test

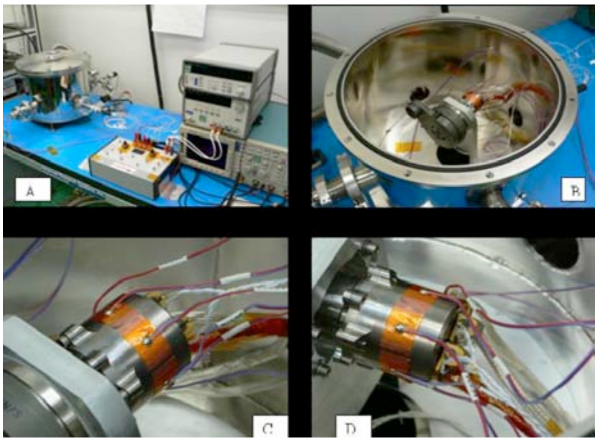

Figure 10 - Dawn LTU in Test Lab

By monitoring the power to run the motor, an increase in power could give a clear indication of the health of the lubricant inside the motor. The point of failure was determined by measuring the Motor Threshold Voltage (MTV) which is the lowest voltage at which the motor will start turning, as evidenced by a drop in current. An initial measurement of the MTV was made at the start of the test of the LTU, and End of Life (EOL) for the LTU (as indicated by an increase of power required to start the motor due to lubricant failure) is defined arbitrarily as 150% of the initial MTV value. Even at the EOL MTV, the value is estimated to be still below the minimum voltage of 22.0 Vdc. The actuator will continue to function at this arbitrary EOL, and well beyond until the increase in friction of the bearings and gears exceeds the power generated by the gearmotor.

2.13 Temperature Profile

The life test was carried out using the temperature profile shown in the figure 11. The profile shown in the figure corresponds to one life cycle. The actuator was first rotated in the clockwise (CW) direction (half cycle) for 245 hours (=168 hrs at 58°C to 72°C + 44 hrs at 78°C to 82°C + 33 hrs at 85.5°C to 89.5°C), then the actuator was rotated for another 245 hours in the counter clockwise (CCW) direction following the same profile to complete one life cycle. This process has been repeated seven times (7X) to meet the re-defined project requirement.

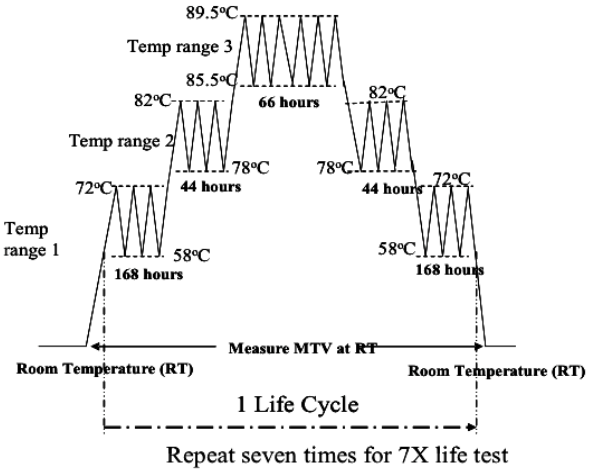

Figure 11– Temp. Profile Based on Mission Prediction

2.14 Life Test Result

As a result of an action assigned to the Dawn Project after the stand-down in March 2006, the NASA independent review team directed that the LTU should aim for a 7X life test, instead of 3X, to prove robustness of this new system. At the elevated temperature, which seems to provide more life (which is opposite from the SOT test data), the first serious sign of lubricant degradation appears at 4.6X life, with the gearmotor overpowering this increased internal resistance, completing the 7X life with abundant torque margin (with MTV at 12 Vdc and a minimum supply voltage of 22 Vdc). Subsequent disassembly of the LTU and the gearmotor indicates the Braycote lubricant initially breaks down at the harmonic drive (HD) wave-generator separator/titanium hub interface, with the lubricant in the rotor bearing in slightly degraded but usable condition.

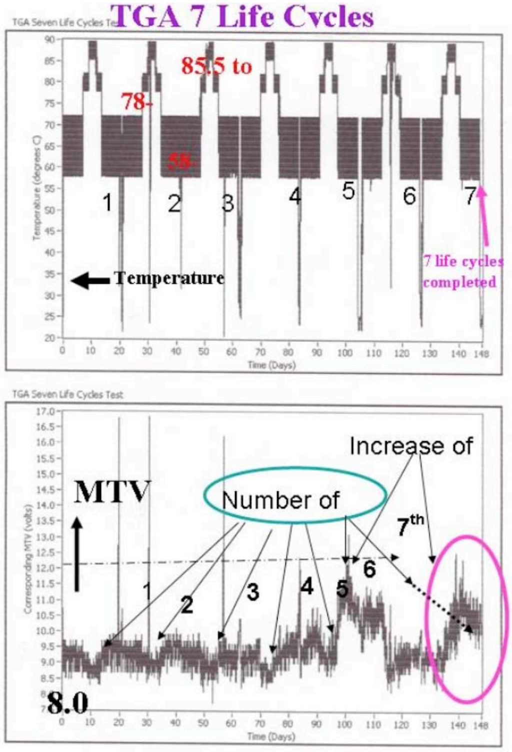

Figure 12 - MTV During Life Test

The three spikes prior to 4.6X life were attributed to test equipment errors. After reset, the MTV returned to the nominal range. At 4.6X life, there is clear indication that the lubricant has broken down, resulting in erratic and a gentle upward trend, accumulating to 5.5X life. The LTU seems to recover but started the upward trend again. Post life test lubricant analysis is shown in Table 2.

Table 2, HD and Output Bearing Post-Life Analysis

Results

The elemental reaction product results are given in the table 1 below as % element in the grease. The Harmonic had considerable amount of Fluoride (Bray degradation product), steel and titanium in the grease.

Table 1. Metals and Fluorides in the Grease

	F^-	Fe	Ni	Cr	Ti
Harmonic	0.75 %	6.5 %	nd<.005%	0.1 %	2.1 %
Duplex A	nd< .001%	nd<.005%	nd<.002%	nd<.002%	nd<.002%
Duplex B	tr 0.002%	tr 0.006%	nd<.002%	nd<.002%	nd<.002%

Discussion

The Harmonic bearing Bray grease is clearly degraded and in a corrosive state. The fluoride degradation product forms metal fluorides that are "Lewis Acids". This can cause corrosion, particularly when exposed to the atmosphere. The grease in the Duplex output bearings is in relatively good condition.

The HD WG bearing separator had rubbed on the titanium adaptor hub, resulting in accelerated degradation of the Brayco lubricant, with end of lubricant life reached before the motor rotor bearing. The HD gears are in excellent condition, with the machine marks on the gears still visible.

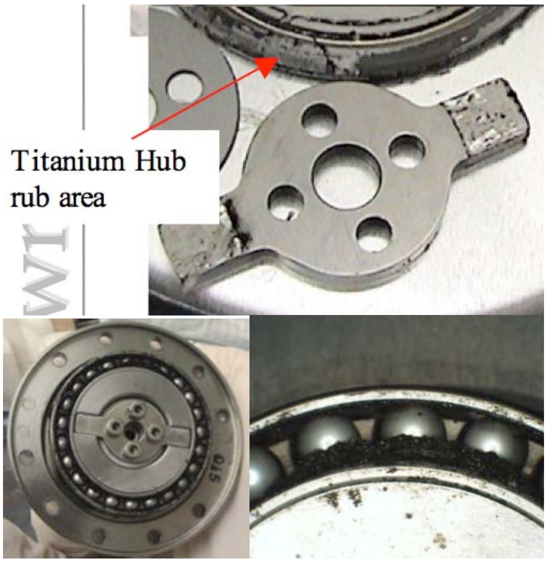

Figure 13 -LTU HD WG Bearing after Life Test

The gearmotor output bearing, in close proximity with the HD, was contaminated by the degraded HD lubricant. The stepper motor rotor bearing, separated by the gearbox, is actually in excellent condition, with a clear film of lubricant around the balls.

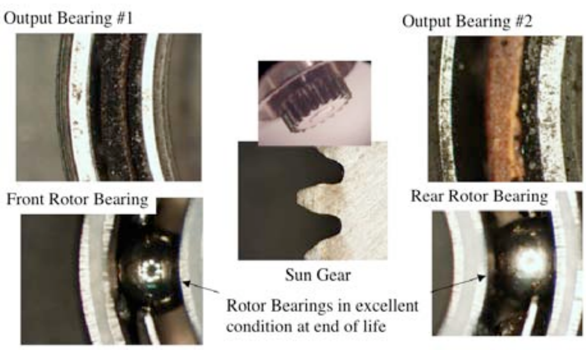

Figure 14-LTU Gearmotor Components after Life Test

The chemical analysis report by JPL's Analytical Laboratory appears in Table 3.

Table 3, Gearmotor Output and Rotor Bearing Post-Life Analysis

Table 1. Metals and Fluorides in the Grease

	F	Fe	Ni	Cr	Ti
Output Bearing #1	0.018 %	2.8 %	nd<.005%	0.57%	0.04%
Output Bearing #2	0.38%	21.0%	Trace	4.3%	2.3%
Front	0.01%	0.14%	nd<.002%	0.03%	nd<.002%
Rear	0.02%	0.30%	nd<.002%	0.059%	nd<.002%

2.15 Post Life Test Analysis

Post-life test gearmotor performance indicates the gearmotor is actually fully "run-in", with gear efficiency approaching 98%. Also, the end play at the gearmotor has increased by 0.16 deg, from an initial 0.7 deg to 0.86 deg.

Table 4, Gearmotor Pre and Post Life Test Data

1. Resistance
   - 1.1. Pre Life
     - 1.1.1. A+/A- - 28.4 Ohms
     - 1.1.2. B+/ B- - 28.4 Ohms
   - 1.2. Post Life
     - 1.2.1. A+/A- - 28.4 Ohms
     - 1.2.2. B+/ B- - 28.4 Ohms
2. Inductance
   - 2.1. Pre Life
     - 2.1.1. A+/A- - 5.9 mH
     - 2.1.2. B+/ B- - 5.9 mH
   - 2.2. Post Life
     - 2.2.1. A+/A- - 6.28 mH
     - 2.2.2. B+/ B- - 6.40 mH
3. Actuator Level Unpowered Detent
   - 3.1. Pre Life
     - 3.1.1. CW – 3.2 in Lb
     - 3.1.2. CCW – 3.0 in Lb
   - 3.2. Post Life
     - 3.2.1. CW – 3.2 in lb
     - 3.2.2. CCW – 3.3 in lb
4. Actuator Level Drop out torque
   - 4.1. Pre life
     - 4.1.1. 22.0 VDC 15 ms CW – 18.0 in oz
     - 4.1.2. 22.0 VDC 15 ms CCW – 20.0 in oz
     - 4.1.3. 30.4 VDC 20 ms CW – 84.0 in oz
     - 4.1.4. 30.4 VDC 20 ms CCW – 82.0 in oz
   - 4.2. Post Life
     - 4.2.1. 22.0 VDC 15 ms CW – 46.7 in oz
     - 4.2.2. 22.0 VDC 15 ms CCW – 41.5 in oz
     - 4.2.3. 30.4 VDC 20 ms CW – 88.9 in oz
     - 4.2.4. 30.4 VDC 20 ms CCW – 85.1 in oz
5. Actuator Level No Load Current Threshold
   - 5.1. Pre life
     - 5.1.1. 15 ms CW – 103 mA
     - 5.1.2. 15 ms CCW – 102 mA
     - 5.1.3. 20 ms CW – 97 mA
     - 5.1.4. 20 ms CCW – 102mA
   - 5.2. Post Life
     - 5.2.1. 15 ms CW – 35 mA
     - 5.2.2. 15 ms CCW – 36 mA
     - 5.2.3. 20 ms CW – 42 mA
     - 5.2.4. 20 ms CCW – 41 mA

3. TEST SUMMARY

At 4.6 times life, the CDF for the LTU is 19.3 x 10^{12} bp-psi. At the end of life test, with MTV at only 12 Vdc, the CDF is 29.4 x 10^{12} bp-psi. This LTU has exceeded the comparable Lockheed Martin life test data. The use of additional oil may have had a significant effect on lifetime. Although lubricant consumption increases with increasing temperature, higher temperatures can improve lubricant supply due to higher resupply rates. This phenomenon has been observed during life tests with Braycote 601EF grease for the Space Shuttle Body Flap Actuator bearings [8]. In these tests, bearing lifetimes at 60°C were greater than at 23°C.

4. CONCLUSIONS

New systems should always be analyzed with the CDF technique to predict lifetime. After that, design and mission planning should be performed within the lifetime predicted. The LTU running at higher temperature actually produced longer life than predicted by life test data at room temperature. Lubricant failure occurred at a CDF of 19.3 x 10^{12} bp-psi. Vascomax C-300 did not accelerate lubricant breakdown, as evidenced by SOT and LTU post-life analysis. The LTU was life tested in high vacuum, providing validity to the test data.

5. LESSONS LEARNED

Implementation of the above techniques increased task cost since these were not in the original plan. However, timely changes to hardware added substantial value to the project with a robust system. Also, a clear understanding of the tribological effects with un-tested materials minimizes schedule risk in case of a life test issue. This allowed completion of a successful life test program of "new" hardware, without jeopardizing the Dawn project for launch.

Space mechanism designers utilizing lubricated mechanical moving assemblies (MMAs) made of alloys other than conventional bearing steels, such as 440C SS or 52100, need to verify that mission lifetimes will not be compromised by adverse lubricant/alloy interactions.

6. ACKNOWLEDGMENTS

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