Extended Life Testing of Duplex Ball Bearings

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Abstract

Sierra Nevada Corporation's Space Systems performed bearing life testing for the Scan Mirror Motor/Encoder Assembly (SMMA), part of the Scan Mirror Assembly on-board the Aerosol Polarimetry Sensor (APS) on the NASA Glory Spacecraft. The baseline bearing life test duration extended beyond the launch date for the Glory Spacecraft; a risk that the program was willing to undertake with the understanding that if any anomalies or failures occurred before the required life was achieved, then the mission objectives or operating profile could be modified on orbit to take those results into account. Even though the Glory Spacecraft failed to reach orbit during its launch in March of 2011, the bearing life testing was continued through a mutual understanding of value between Sierra Nevada Corporation and our customer; with a revised goal of testing to failure rather than completing a required number of life cycles. Life testing thus far has not only exceeded the original mission required life, but has also exceeded the published test data for Cumulative Degradation Factor (CDF) from NASA/CR-2009-215681 [1]. Many lessons were learned along the way regarding long life testing. The bearing life test has been temporarily suspended due to test support equipment issues.

Introduction

Since the Aerosol Polarimetry Sensor is a continuous scanning sensor, the SMMA was required to provide a constant rotational speed to the Scan Mirror Assembly while the APS collected earth atmospheric data for analysis. The APS had a design life of 5 years, encompassing a continuously operating mission life of 3 years at 40.69 RPM resulting in 64.2 million shaft revolutions. As the Scan Mirror Assembly was extremely sensitive to torque variation, there were specified requirements on maximum break-away torque, minimum and maximum drag torque, and torque disturbance that had to be met over the lifetime of the mechanism. The bearings were required to meet those torque requirements at the specified operating speed over an equivalent 2X operating mission life equal to 128.4 million revolutions. Based upon the bearing geometry, preload of the bearings, and the number of operating cycles, the lubricant life of the bearing was uncertain when the CDF was evaluated against the data published in NASA/CR-2009-215681 for Pennzane 2001-based lubrication. Since the bearings are a single point failure in the mechanism and could not be qualified through similarity to existing test data, an in depth bearing life test was required to gain mission confidence. The SMMA Actuator is shown in Figure 1.

Lubricant Lifetime Prediction

As detailed in NASA/CR—2005-213424 [2], the bearing lubricant Cumulative Degradation Factor (CDF) is a method used to determine and compare the relative lubricant lifetime of new applications based upon parameters and test data obtained from heritage programs. The CDF is calculated based on the product of the bearing mean hertzian stress and the number of times a ball passes across a given spot on the raceway and is expressed in units of ball passes•psi (bp•psi). The rotor bearings within the SMMA have a mean hertzian contact stress of 521.7 MPa (75.66 ksi) at nominal bearing geometry and preload. Based upon the bearing geometry, the SMMA rotor bearings experience 22.167 ball passes per shaft revolution. The 1X APS program life requirement of 64.2 million revolutions resulted in a calculated CDF of 107.7 x 10^{12} bp•psi and the 2X APS program life of 128.4 million revolutions resulted in a calculated CDF of 215.4

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x 10^{12} psi-cycles. Both the 1X and 2X life requirements for the APS program exceed the published lubricant test data from NASA/CR-2009-215681, which showed acceptable life test results up to 88 x 10^{12} bp•psi. Since the life of the lubricated SMMA rotor bearings could not be verified by comparative test data, a life test was necessary to validate the design against the specific program requirements.

Figure 1. SMMA Actuator

Lubrication Film Thickness and Lambda Ratio

A valid bearing life test needs to operate within the same lubricant regime as the on-orbit conditions to ensure the wear phenomena are similar. As detailed in NASA Technical Memorandum 88875 [3], the lubrication regime can be estimated from the Lubrication Film Parameter (λ), which is defined as the ratio of the lubrication film thickness divided by the composite roughness of the contacting surfaces. Per STLE SP-34 [4], Lambda ratios less than 1.0 result in Boundary lubrication characterized by a high likelihood of surface asperity contact and resultant wear to the contacting surfaces. This bearing was predicted to have an on-orbit operating temperature primarily in the range of 15°C to 20°C. As shown in Figure 2, the lubrication film parameter at 40.69 RPM is in the boundary lubrication regime with $\lambda < 1$ for this predicted operating temperature range and above.

With the predicted bearing operation on-orbit occurring in Boundary lubrication, it was determined to keep the predicted Lubrication Film Parameter (λ) below 1 for the life test in order to stay within that same lubrication regime and replicate the expected wear conditions. Additionally, there was a goal to complete the 1X portion of the life test within 20 months so that the life test results would be available to the program to support modification of on-orbit operating parameters if required. Accomplishing 64.2 million revolutions within 20 months required a life test speed of at least 73.24 RPM. Figure 3 shows that at 74 RPM, the bearings will stay in Boundary lubrication with $\lambda < 1$ at temperatures of 25°C and above. Lubrication viscous losses increase with bearing speed, generating higher friction torques within the lubricant at 74 RPM, and results in an increase in power and temperature. Since the vacuum chamber was without thermal control, it was predicted that the operating bearing temperature due to frictional self-heating would offset cooling induced by the vacuum chamber cryopump and result in a net steady state bearing temperature of at least 25°C. Any further temperature increase over 25°C would reduce the viscosity of the lubricant and thin the lubricant film, further ensuring that the life test bearings would operate within the Boundary lubrication regime. After evaluating the steady state operating temperature of the bearings in the life test setup, a maximum test temperature limit of 36°C was imposed to limit significant temperature rise while allowing for some environmental temperature fluctuation.

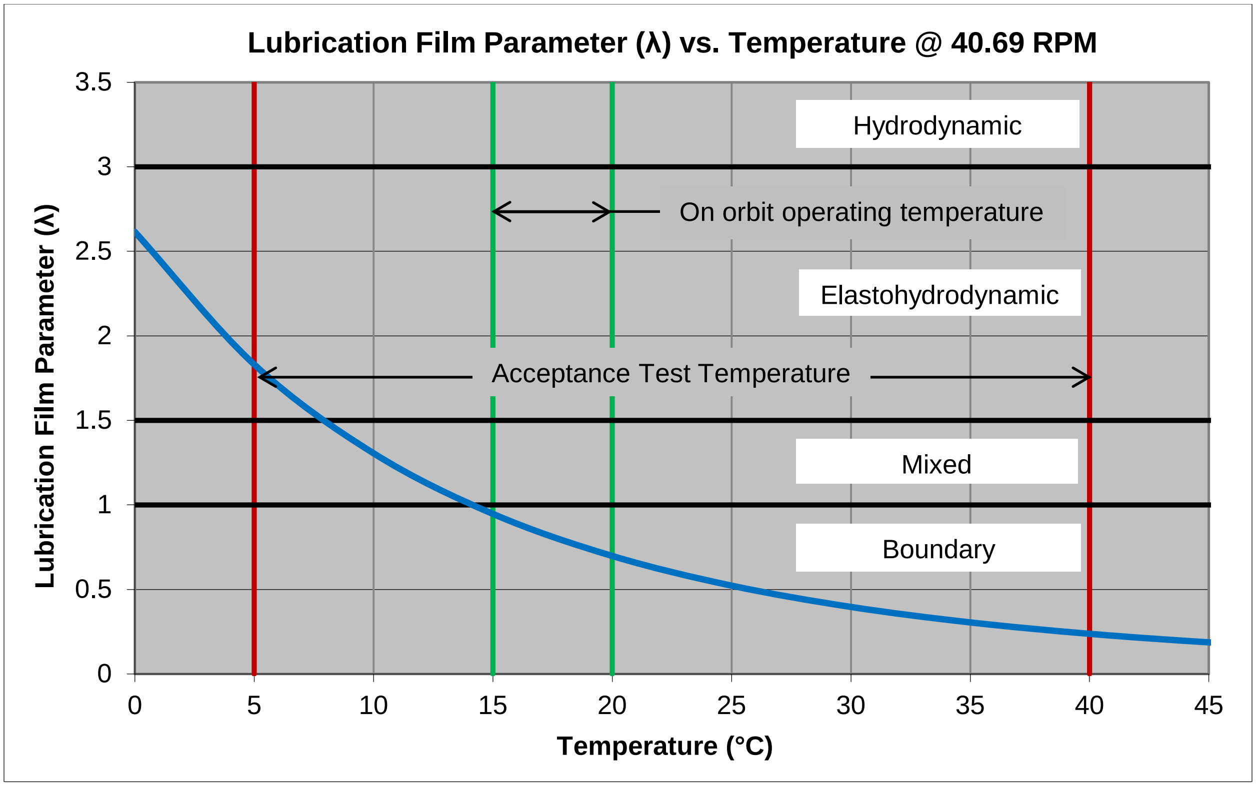

Figure 2. Lubrication Film Parameter (λ) vs. Temperature @ 40.69 RPM

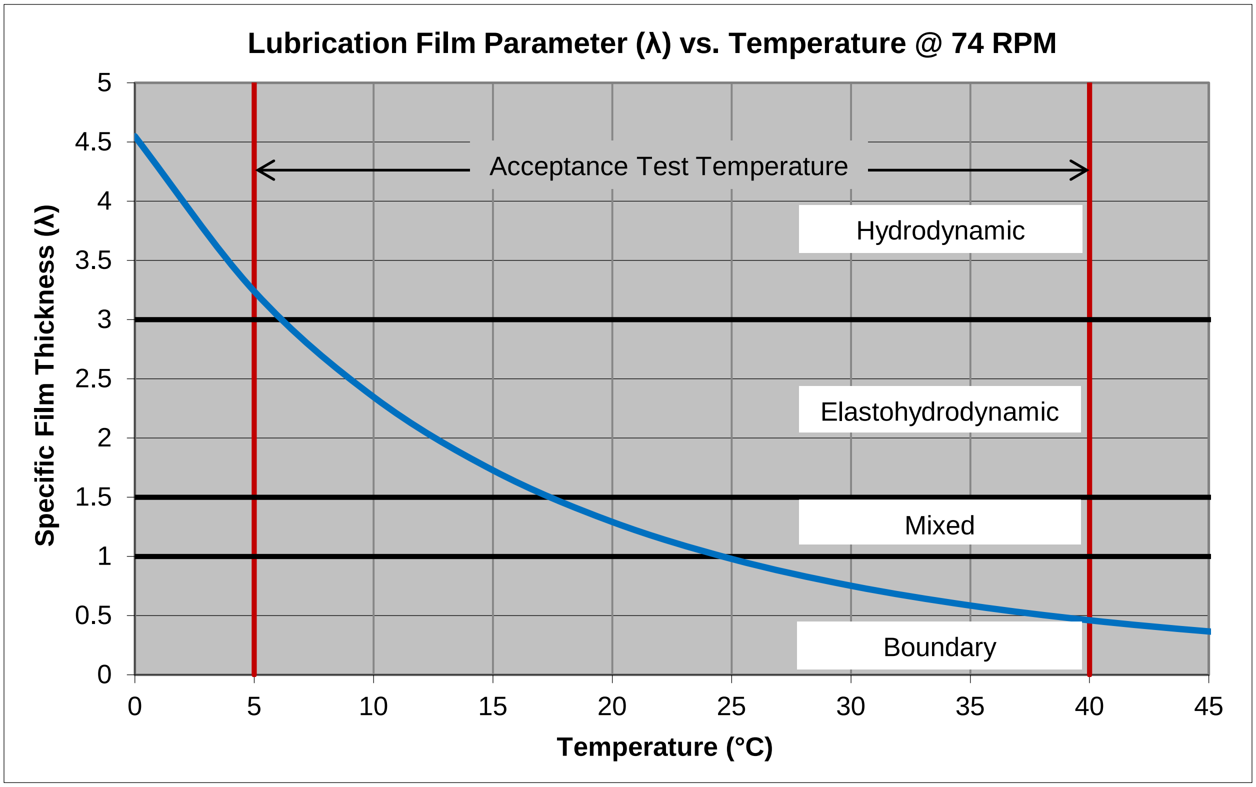

Figure 3. Lubrication Film Parameter (λ) vs. Temperature @ 74 RPM

Design Considerations for Long Life

In order to achieve extremely long life out of a lubricated bearing, special attention has to be paid to the bearing materials, accuracy, design parameters, lubrication, verification, and mounting techniques.

Materials

To maximize reliability and minimize the chance of impurities causing surface weakness or contamination, materials should be of the highest purity grade feasible. For this application, Consumable Electrode Vacuum Melted 440C Stainless was chosen for the balls and raceways. Phenolic was chosen as the ball separator material due to its high level of heritage in vacuum operation.

Accuracy

To minimize inherent torque variation and accuracy error, balls and raceways should be held to the highest accuracy requirements feasible. For this application the raceways were held to ABEC 7 or better and the balls were held to AFBMA Grade 3 or better.

Surface Roughness

To maximize the lubricant film parameter (λ), the surface finish of the balls and raceways should be held to the finest finish feasible. For this application, the balls were held to a maximum Ra of .013 µm (0.5 µin), as controlled by the AFBMA Grade 3 requirements, and the raceways were held to a maximum Ra of .076 µm (3 µin).

Lubrication

Finally, lubrication type and amount should be carefully selected to provide the longest life possible within program requirements such as outgassing restrictions and operating temperature range. The program team solicited inputs from several leading lubrication experts within the space industry and concluded that for this application, Pennzane 2001-3PbNp oil was the best candidate for selection. Oil was chosen over grease since the thickeners and other additives in grease tend to create more inherent torque variation over oil alone. Pennzane 2001 was chosen over Braycote 815Z because it has proven to have longer operating life, as can be seen in the CDF data listed in NASA/CR-2009-215681. Pennzane 2001 was deemed acceptable for this application since the cold operating temperature of only +5°C did not get into the realm of significant viscosity increase. Lead Naphthenate was chosen as the high pressure additive to provide an additional layer of wear protection for boundary lubrication. A wettability test was performed on 100% of the raceways and balls to ensure that the surfaces would yield a uniform coating of lubricant with no signs of beading, gaps, or dewetting. The ball separators were desiccated and vacuum impregnated with the same Pennzane 2001-3PbNp oil.

Component Testing

For bearings with tight requirements on starting torque, running torque, and torque variation; each preloaded bearing pair should be tested for those parameters prior to installation. For this application, the bearing vendor performed those tests on the fully lubricated and internally preloaded bearings and provided that data with each bearing.

Mounting Techniques

To maintain minimal torque variation and consistent loading in the mounted and assembled bearing configuration, the controlling bearing mounting features have to be precisely controlled. For this application, in addition to applying tight tolerances to the housing and shaft mounting shoulders, the bearing inner and outer races were precisely located and bonded in place to minimize misalignment, wobble, and free play while avoiding the inherent variation and residual stresses resulting from interference fits.

Life Test Method

In order to simulate on-orbit conditions as closely as possible while balancing total test duration, cost, and setup simplicity; a life test was performed using the following parts, methods, parameters, and criteria.

Test Articles

Program requirements dictated that the life test bearings be manufactured with the same bearing geometry, ball and raceway material, ball separator material, raceway finishing process, and internal bearing preload as the flight bearings. It was also important to test a large enough sample to be statistically significant. In order to accomplish this most accurately, six duplex bearing sets were taken from the flight procurement manufacturing lot and allocated to the life test. Additionally, all bearings in this lot (flight and life test) were lubricated with the same lubricant lot, quantity, and application method.

Life Test Mounting

The test bearings are mounted in the same back-to-back duplex arrangement as the flight bearings. The bearing clamping arrangement utilizes comparable stiffness clamps with the same number of fasteners and fastener torque to create the same nominal clamp forces as flight. The tolerances of the fixture mounting diameters and shoulders are held the same as the flight part drawings and the same adhesive shimming procedure is utilized to minimize inner to outer race misalignment and wobble.

Life Test Parameters:

- Primary Life Test Goal: 64.2 million shaft revolutions (1X Operating Life) within 20 months
- Secondary Life Test Goal: 128.4 million shaft revolutions (2X Operating Life)
- Revised Life Test Goal: Test to failure as defined by termination criteria listed below
- Load: No external load, internal bearing preload of 133.4 N (30 lb) nominal
- Speed: 74 RPM, selected to balance maintaining equivalent film thickness and lubrication regime while reducing test duration as previously described
- Direction: Unidirectional continuous operation
- Pressure: Vacuum of 6.67E-4 Pa ($5X10^{-6}$ Torr) or better
- Temperature: No active thermal control, vacuum chamber located in an ambient lab environment, natural self-heating of bearing housings allowed up to the maximum predicted on-orbit operating temperature of 36°C

Life Test Data Monitoring

The following key parameters were monitored throughout the life test to ensure required conditions were met:

- Torque: Friction torque periodically monitored and recorded using an data logger with a sample rate of once per millisecond for a duration of one minute, collected every hour
- Temperature: Bearing housing temperatures were recorded once an hour
- Revolution Count: Proximity switch counting once per revolution

Life Test Termination Criteria

Friction torque is the most direct measurement of bearing health available and as such is used as the primary factor in determining when a “test to failure” is completed as follows:

- Friction torque exceeding 125% of the initial setup running torque

Conditions that would warrant pausing the life test in order to determine credibility and impact of the data would be out of family torque conditions such as:

- A sudden increase in bearing friction torque and/or steady state temperature
- An excessively erratic friction torque trace when compared to prior test data or to other bearings under test

Life Test Setup

As can be seen in Figure 4, the life test is performed inside a vacuum chamber. The selected drive motor is not vacuum compatible and is located outside the chamber. The drive motor is a high quality commercial brush DC motor with a planetary gear output; and drives the bearing shaft through a ferrofluidic feedthrough in the chamber wall. The electrical feedthrough brings out the signals to monitor the load cells and the bearing housing thermocouples. The cryopump maintains the required pressure level inside the chamber as monitored by the vacuum gauge.

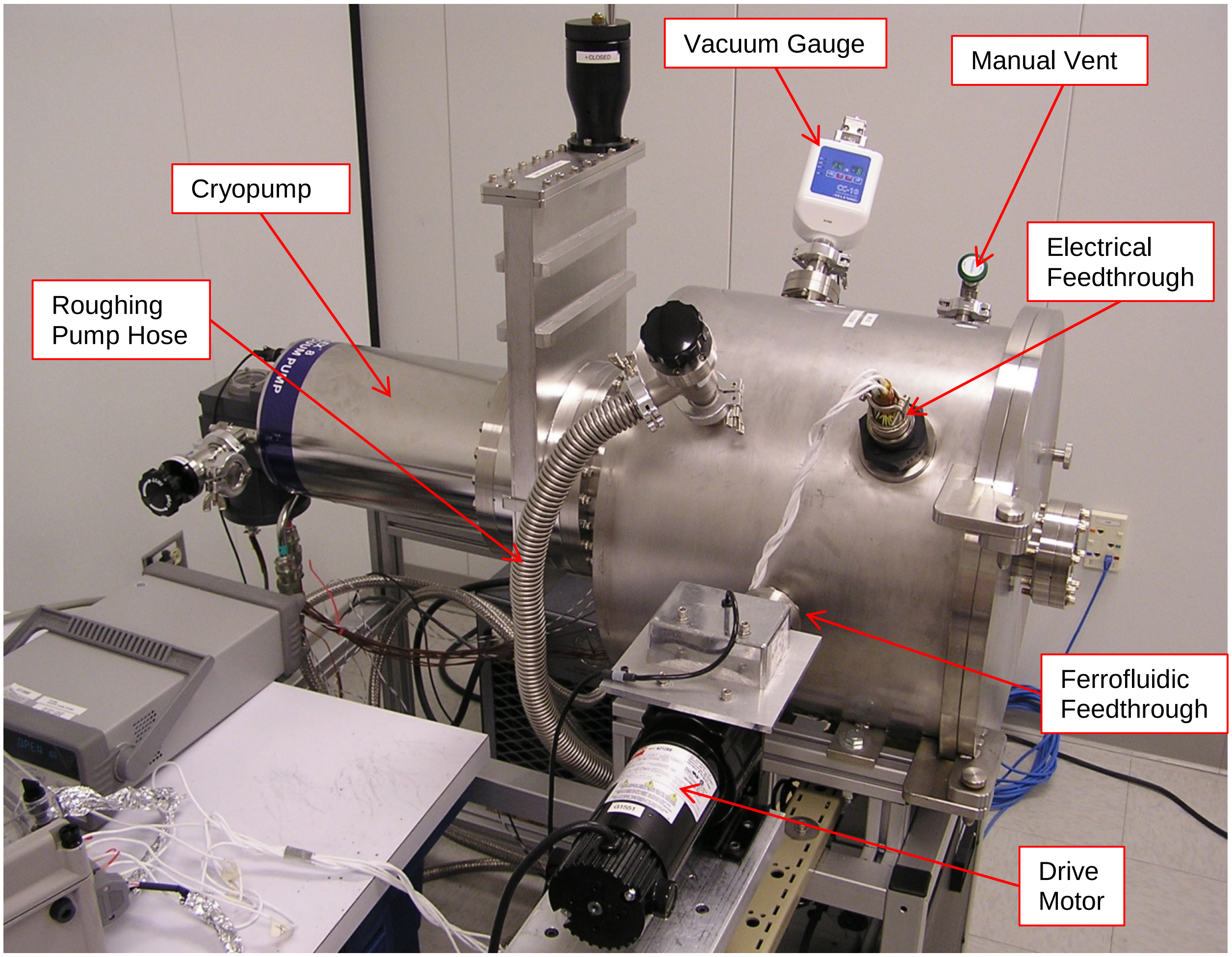

Figure 4. Vacuum Chamber Setup

Inside the vacuum chamber is the bearing life test fixture, as shown in Figure 5. Each bearing is mounted and clamped within its own housing and hub in the same manner and with the same tolerances as the flight application. The six bearing housing assemblies are then loaded onto the drive shaft and clamped in place. The drive shaft is supported by redundant fixture bearings which are spring preloaded. A flexible coupling connects the shaft to the ferrofluidic feedthrough in the chamber wall. The bearing housings each have a resistive arm mounted to the housing outside diameter. The resistive arm contacts the load cells through a ball-in-cup arrangement. Based on the force recorded in the load cell and the moment arm length to the spherical contact, the friction torque within the bearing can be monitored. On the opposite side of the bearing housing a counterbalance is mounted to eliminate torque offset due to the weight of the resistive arm. Thermocouples are mounted to each bearing housing to monitor temperature throughout the test. If one bearing experienced increased torque that did not impact the testing of the remaining bearings, then either all bearings could continue to operate without disturbing the setup or the chamber could be opened up and the load cell for that bearing removed allowing the suspect bearing's housing to spin freely with no resistive load.

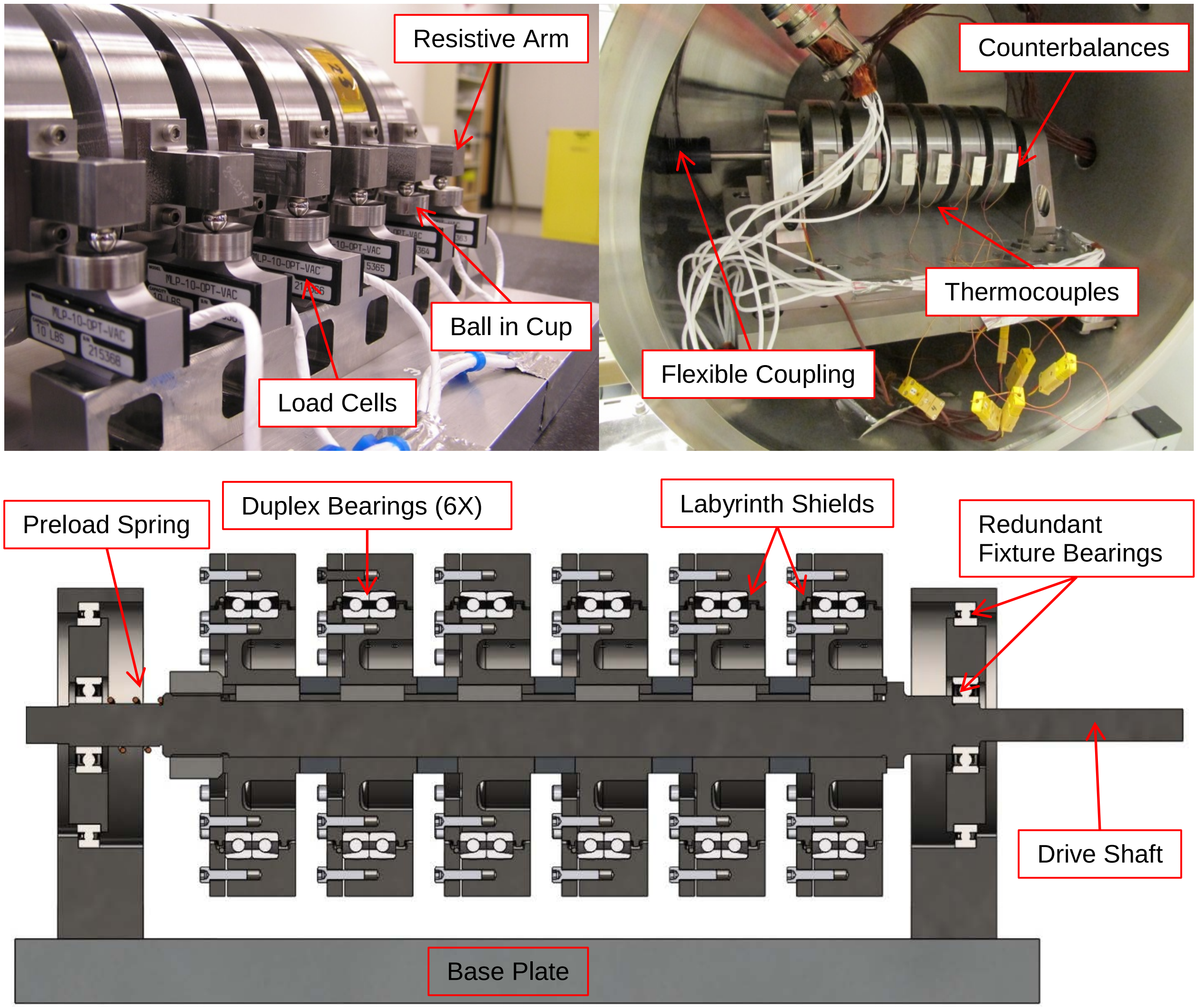

Figure 5. Bearing Life Test Setup

Life Test Results

SMMA Bearing Life testing met and exceeded the 128.4 million revolution requirement for 2X life. The bearings have achieved approximately 202 million shaft revolutions to-date and have not exceeded 125% of the initial setup running torque, nor exhibited credible erratic performance, as defined in the test termination criteria.

Bearing Friction Torque

From the start of the test, it was noted that bearings 3 and 6 had noisier load cell data than the remainder of the bearings. As seen in the Figure 7, both bearings 3 and 6 had significantly higher fluctuation in load cell output. To determine if those two bearings had significant torque variation or if the load cells were producing erratic output, the temperature plots displayed in Figure 8 were reviewed. Bearing temperature will fluctuate with real changes in friction torque as a component of mechanical power. Since the temperature of bearings 3 and 6 did not follow the torque variation, it was determined that those two load cells were providing erratic output. Per discussions with the customer, it was mutually determined to continue the life test on all six bearings and not subject bearings 3 and 6 to test termination requirements. The team concluded that sufficient life test data could be obtained from the remaining four bearings, and with the life test already extending beyond the launch date, it was not worth the additional schedule to stop the test and replace the faulty load cells. Bearings 3 and 6 were still evaluated for gross changes in performance and will still be subjected to a visual inspection at the end of the life test. As can be seen in Figure 6, none of the remaining four bearings experienced any sudden increases in friction torque and all stayed below 125% of the initial torque measurement. Momentary torque spikes were seen any time the test was paused and restarted due to both the inherent higher starting torque in a lubricated bearing plus the fact that the lubricant had cooled off, thereby reducing its viscosity. Since the on-orbit application operates continuously without starting and stopping, starting torque spikes do not impact on-orbit performance and were not considered against the termination criteria.

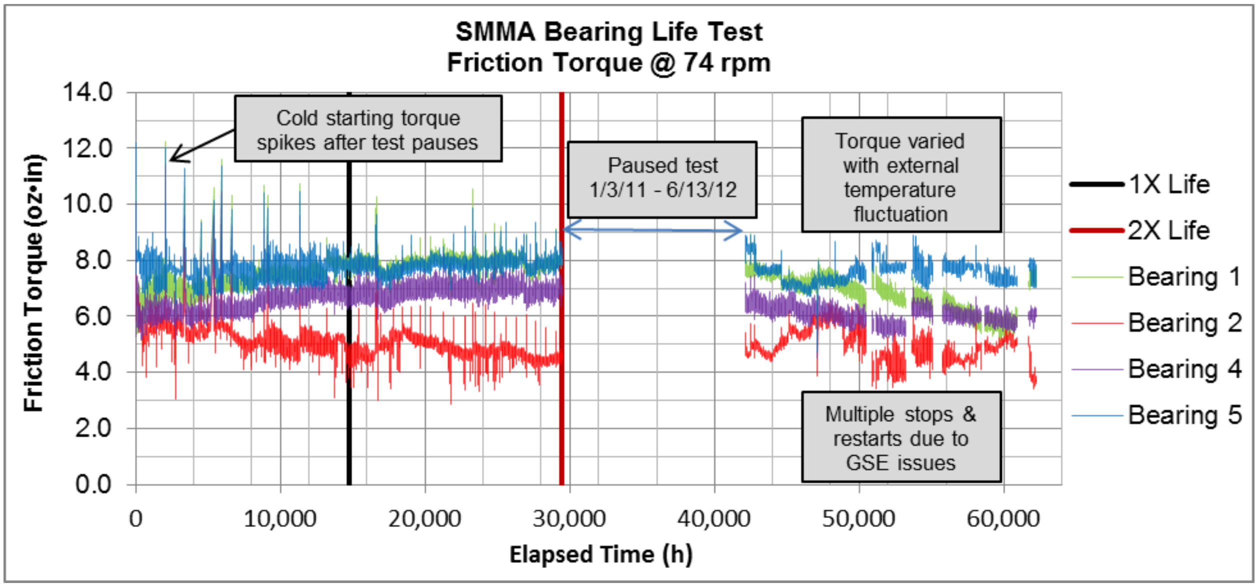

Figure 6. Bearing Friction Torque @ 74 RPM (Bearings 1, 2, 4, & 5)

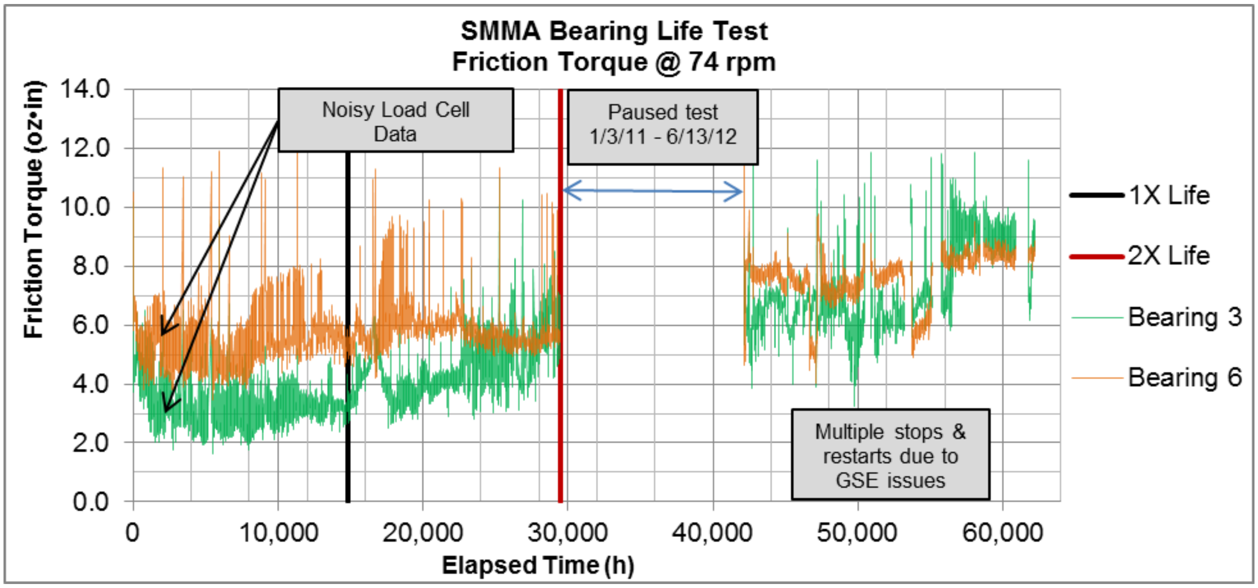

Figure 7. Bearing Friction Torque @ 74 RPM (Bearings 3 & 6)

<u>Bearing Temperature</u>

As can be seen in Figure 8, power generated due to viscous losses did heat each of the bearings to a temperature above the 25°C limit to set to achieve Boundary lubrication during steady state operation, while staying below the 36°C upper limit. There were typical daily and seasonal fluctuations in temperature that corresponded to the ambient temperature in the test room, but no upward trends that would correspond with significant changes in internal bearing losses or lubricant degradation. Any time the test was paused, the cryopump would cool the setup resulting in a cold temperature spike. Following a lengthy test pause for maintenance and to negotiate the extended duration, the test setup was repositioned to a different location in the test lab resulting in a higher ambient temperature and a corresponding increase in the temperature of the bearings. The average temperature of the bearings was 28.6°C during the 2X portion of the life test, slightly elevated from the on-orbit typical operating range of 15°C-20°C. This temperature increase results in a conservative test since lubricant life is potentially cut in half for approximately every 10°C rise in temperature as discussed in NASA/CR-2009-215637 [5].

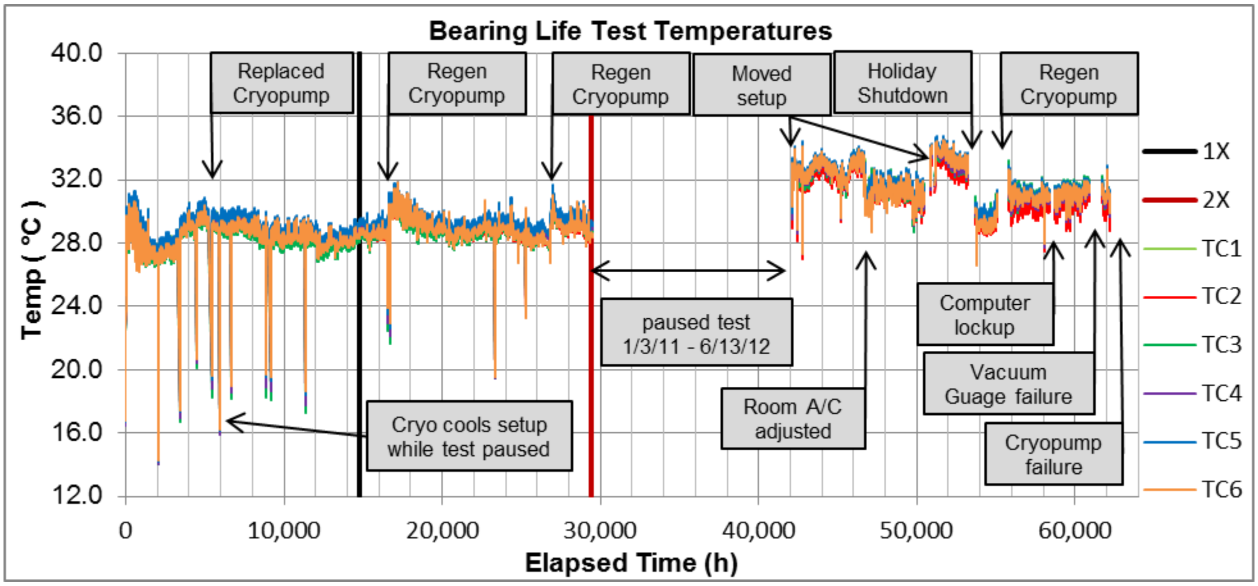

Figure 8. Bearing Temperature

Lubrication Film Parameter

Based upon nominal bearing parameters, nominal bearing preload, on-orbit speed of 40.69 RPM, and a nominal on-orbit operating temperature of 17.5°C, the lubricant film parameter (λ) is calculated to be 0.811. Using those same nominal bearing parameters, nominal bearing preload, life test speed of 74 RPM, and a nominal life test operating temperature of 28.6°C during the 2X portion of the life test, the lubricant film parameter (λ) is calculated to be 0.810. Since the STLE lubricant life factor [4] changes with λ, even within the same lubrication regime, this close correlation in lubrication regime gives a high level of credence to the life test results.

Cumulative Degradation Factor

Taking into account the internal bearing geometry, a mean hertzian contact stress of 521.7 MPa (75.66 ksi) under nominal parameters, and 202 million shaft revolutions; the Cumulative Degradation Factor is calculated to be $338.8*10^{12}$ bp•psi for this test. This data point significantly exceeds $88*10^{12}$ bp•psi, which is the highest tested value of CDF published in NASA/CR-2009-215681 [1] for Pennzane-based oil formulation.

Lessons Learned

Test Quantity

In order to obtain statistical data more representative of the entire production lot and to cover for any test anomalies that arise with ground support equipment (GSE), it is best practice to test as many articles as feasible. As experienced in this life test, two of the six bearings under test had noisy load cell data. Fortunately, the data sample for this test was large enough to clearly identify that those two setups were outliers allowing them to be sufficiently investigated to determine cause. The investigation benefitted greatly from comparing the abnormal test data to the test data from the remaining four test setups, implicating the load cells. Rather than halt the test and wait for replacement load cells, the life test was able to be continued with the data from the remaining four bearings. If the sample size selected for this test was smaller, noisy data would have likely led to a lengthy and costly investigation, jeopardizing the targeted completion date for 1X life testing. Additionally, higher test quantities increase the likelihood that normal manufacturing variations are accounted for in the test data, further validating the test results.

Test Duration

It is highly desirable to test articles to failure whenever possible. Many of the data points listed in the NASA/CR-2009-215681 had the notation "Test Suspension (no failure)" meaning that the bearings/lubricant were functioning normally at the completion of their required life test and could have been operated longer providing better data for future use.

With higher quantities, consider grouping test articles into different life test durations to maximize data usage for future applications. For example, test a portion to 1X mission life, a portion to 2X mission life, and a portion to failure. Multiple test durations are especially important for life test articles that use acceptance criteria that cannot be fully verified during the life test. Such criteria include visual inspection of internal components that require disassembly to perform and measurement of performance parameters which require breaking the life test setup to verify; either of which could jeopardize the validity of additional life testing. In the case of the bearing test described herein, a change in friction torque in the test setup is being used as the pass/fail criteria rather than rely on visual inspection; so testing the bearings to failure results in the most useful data obtainable. Whenever possible, it is preferred to avoid or minimize test pauses so that lubricant temperature and viscosity remain in a steady-state condition and transient data does not have to be rationalized.

Test fixture component selection

Ground Support Equipment (GSE) component selection and required maintenance should be carefully evaluated against the life test duration to minimize test interruptions and erroneous data. In reality, not only is the test article undergoing a life test, but every component in the life test setup is undergoing that same life test. For this test in particular, test equipment was selected based on the initial requirement of 128.4 million shaft revolutions for approximately 40 months. However, once the decision was made to operate the bearings to failure, some of those GSE selections were not sufficient for extended life without additional maintenance, as evidenced by the number of test interruptions seen in Figure 8 after the completion of the 2X portion of the test. Had the life test been planned to operate to failure from the start, then different GSE components may have been selected.

There should be planned maintenance of any test equipment which may fail during the life test and impact the cost and total duration of the test. During this test, there were numerous stoppages resulting from maintenance issues arising with the test equipment.

A DC Brush Motor/Gearhead was selected to drive the bearing test. There is required maintenance to periodically replace the brushes and they were swapped out twice during this life test. Additionally, the entire Motor/Gearbox was swapped out once due to an oil leak between the motor and gearbox causing concerns about insufficient lubrication in the gearbox over the duration of the test. If an indefinite test duration was the original goal, a direct drive motor with closed loop speed control could have been selected to rotate the test shaft due to better control bearing speed over a long duration test, to alleviate concerns about gearhead problems over the duration of the life test, and to minimize rotations on the drive motor bearings.

The cryopump has to be regenerated periodically to clear out collected material in order to be able to maintain the appropriate vacuum level. Regeneration is a fairly quick process, only resulting in a test interruption of approximately 48 hours. Eventually, the cryopump needs to be returned to the manufacturer to be rebuilt resulting in a longer interruption of the test program of approximately 3-4 weeks. Periodic regeneration of the cryopump is inevitable and needs to be factored into the overall test duration. For a longer life test, having a spare cryopump on hand would have reduced the down time due to rebuild.

The vacuum gauge is another maintenance item on vacuum chambers. A cold cathode vacuum gauge was selected over a hot cathode vacuum gauge for this test to obtain longer gauge life at the expense of reduced pressure accuracy. Even so, the cold cathode vacuum gauge had to be replaced after approximately 7 years, well beyond the original planned duration of the life test. Having a spare vacuum gage on hand would have reduced test down time.

Over time, the weight of the metallic hose from the roughing pump connected to the top of the chamber created a pinhole crack in the feedthrough tube allowing external air to leak inside the chamber. This pinhole was able to be filled with epoxy without breaking the test setup. The leak occurred while the test was halted due to another equipment issue, so the slight drop in vacuum level did not impact the validity of the life test. The roughing pump hose was moved to a more robust feedthrough to prevent recurrence.

The chamber was configured without thermal control as a cost savings feature. Lack of thermal control reduced both the initial cost and schedule of chamber equipment as well as reducing the potential for maintenance issues on the thermal control system. However, the downside to that selection was that the temperature of the bearings under test was at the mercy of self-heating and any temperature variations within the test lab ambient environment. The test chamber also had to be moved midway through the test to a new location within the test facility which resulted in a shift in the external thermal environment that was noticeable in the bearing temperature plots. If the natural self-heating of the bearings from operation combined with the external chamber thermal environment had resulted in a bearing temperature outside of the defined operating condition, then there would have been minimal opportunities for correction without significant delay to add thermal control or significant cost to control the chamber using room ambient temperature.

The length of the subject life test exceeded the calibration due dates on a majority of the test equipment. There was a mutual decision made to not stop the test to calibrate equipment, but rather verify equipment calibration at the conclusion of the test. There is still a risk of test equipment falling outside of calibration parameters at the end of test with the impact to be assessed at that time.

Friction Torque Measurement

When measuring small friction torques in bearings, the test setup must be isolated from external vibration as much as feasible and carefully designed to minimize misalignment loads. Several bearing friction torque measurement issues were discovered during the initial life test setup and validation and had to be resolved prior to starting the life test to ensure recording of accurate data.

Vibration coming from the vacuum chamber equipment created enough noise to appear on the torque readings coming out of the chamber. Rather than continuously collect torque data, the friction torque was captured every millisecond for 60 seconds once each hour with the cryopump and the cryopump compressor turned off during that short period to minimize any torque disturbance.

The weight of the load arm created an offset load which in turn created a zero offset in the friction torque measurements. In order to be able to directly measure friction torque in the bearings without a zero offset, a counterbalance weight, as shown in Figure 9, had to be added to the opposite side of the bearing housing. Additionally, the load cell is very sensitive to off-axis loading. The initial concept of a flat surface contacting a spherical post was not sufficient to provide accurate force measurements. The load arm could not be held exactly parallel to the load cell resulting in a slightly misaligned axis of contact. This misalignment combined with the vertical height of the contact point from the load cell caused a small amount of moment loading into the load cell which produced erroneous values. As can also be seen in Figure 9, the contact was modified to incorporate a ball in a spherical cup to better align the load axis with the load cell, as well as raising the load cell to minimize the vertical moment arm distance. These modifications greatly improved the accuracy of the force measurements from the load cell.

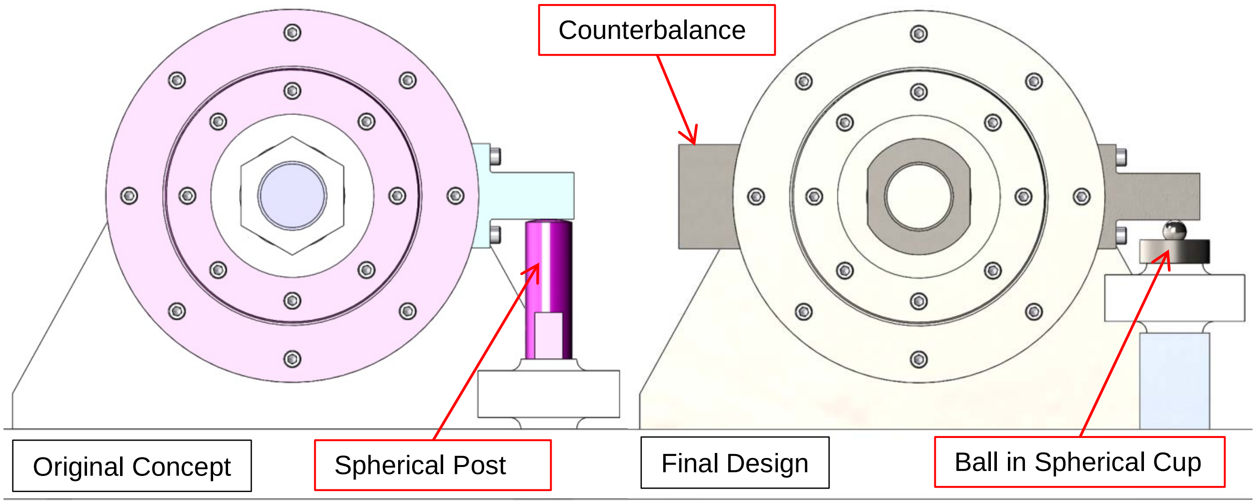

Figure 9. Test Configuration Changes

Life Test Automation

When running automated life testing, special attention needs to be paid to the computer and software portion of the GSE to minimize test interruptions. Since computers accumulate memory usage over time, the test must be paused periodically for the computer to be rebooted. This allows the automated software to reload and clear the memory cache to prevent unplanned and uncontrolled test interruptions due to automated software crashes. Additionally, other programs running on the computer should be eliminated or minimized as much as possible including virus scans and forced software updates. Several computer crashes were attributed to automatic software updates and their impacts on processor and memory usage. One solution was to minimize computer updates to only those deemed highly critical.

Automated testing over an extended life test also stores a tremendous amount of data (over 6 MB per hour for this test) and maintenance of that data must be considered. The data acquisition computer internal hard drive was not sufficient to store the entire life test data and as such would have to be monitored to ensure the capacity was not exceeded resulting in inadvertent test interruption or loss of data. To free up memory storage space on the internal computer hard drive, the test data was transferred to redundant external hard drives approximately once a month for long term storage and backup. Post-processing of significant amounts of test data for trending summaries and reporting was cumbersome and time consuming. Additional forethought should have been given to utilize different tools to create useful charts and reports with less effort.

Since the test was automated, the test setup was manually checked once per working day to verify that the speed was within tolerance, that the daily rev count was as expected, that the vacuum level was within limits, and that the bearing temperatures were within limits and within expectations. While there were not any occurrences of catastrophic anomalies during the testing performed to date, there would have been an additional level of risk reduction if automated safeties would have been incorporated to safely shut down the test in the event of test parameter exceedances such as torque, temperature, vacuum, or speed. These automated safeties were beyond the budgeted scope of the test.

Life Test Conclusions

The lubricated bearings in this life test not only exceeded the required program life, but also demonstrated the capability to greatly exceed the tested CDF values listed in NASA/CR-2009-215681 [1], showing the possibility to operate bearings for extended lifetimes under closely controlled design parameters and similar operating conditions. For this application, a CDF of $338.8*10^{12}$ bp-psi has been achieved with no torque degradation seen to date. In order to achieve this life, bearing parameters including bearing geometry, materials, mounting methods, preloading, lubrication, and component screening should be carefully selected and designed in order to optimize contact stress, assembly alignment, and initial torque disturbance. Life testing has been temporarily halted since October 2014 due to maintenance issues with the Vacuum Chamber, but the test articles are being held under rough vacuum in the test chamber. The life test is planned to resume in 2016 with a continued goal of testing until a significant change in bearing torque is witnessed.

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