Mars 2020 Motor Bearing Failure, Investigation and Response

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Abstract

The prime movers in each joint of the external robotic arm of NASA Jet Propulsion Laboratory's (JPL) Mars 2020 rover are planetary gearmotors containing a brushless DC motor and brake assembly, designated as M45S. Qualification life testing was performed at multiple levels of assembly in an effort to retire risk to the program. A significant failure occurred within the motor in the process of executing a life test at the gearmotor level of assembly. The combination of bearing retainer, lubrication scheme, test temperatures, and long life led to a stall failure of the M45S front bearing at 78 million revolutions, not satisfying the life test requirement of 105.2 million motor revolutions, which is double the expected life. Ultimately, increasing the minimum life test temperature from -70°C to -55°C allowed for successful qualification of the robotic arm joints with the baseline bearing configuration. Details of the requirements, design, life test, test failure investigation, response, and lessons learned will be presented.

Application and Requirements

Reliable performance of the two-meter-long robotic arm carried by the Mars 2020 rover, shown in Figure 1, is central to the success of this mission. Each joint of this robotic arm is driven by a M45S motor and brake assembly. The M45S was incorporated into three different planetary gearmotor designs covering multiple applications: shoulder and elbow (ShEl), wrist and turret (WAT), and feed. The ShEl and WAT gearmotors were then further integrated into harmonic drive mechanisms in the robotic arm. Each application has unique load and life requirements based on the estimated robotic arm usage and travel. Of these, the ShEl application provides the enveloping requirement for mission life at 52.6 million motor revolutions, resulting in a margined life test requirement of 105.2 million motor revolutions.

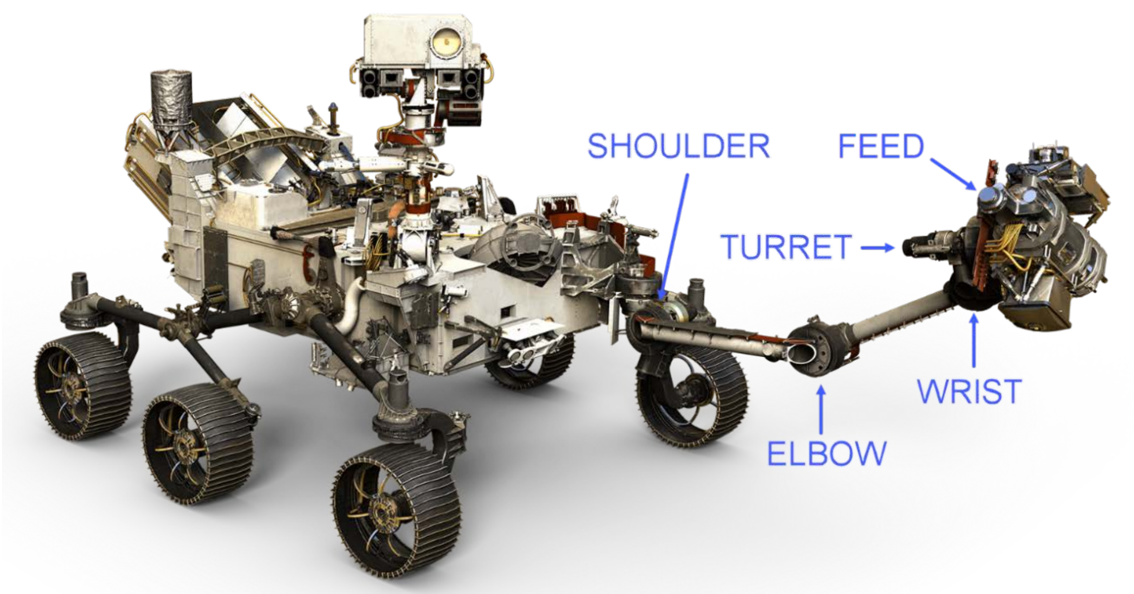

Figure 1 – Robotic Arm of the Mars 2020 Rover (Courtesy of NASA/JPL-Caltech)

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Proceedings of the 45th Aerospace Mechanisms Symposium, NASA Johnson Space Center, 2020

The M45S has two primary functions: (1) provide the required torque and speed when powered and commanded to move, and (2) hold position when unpowered. Motor holding torque capability, necessary for maintaining the robotic arm's position when the motor is unpowered, was a crucial requirement in the design and development of the M45S motor and brake assembly, but is not covered in this paper. Rather, the operational motor requirements and the failure to demonstrate margined life capability against those requirements will be discussed.

In operation, the M45S motor was required to produce a minimum torque of 0.13 N•m at a minimum speed of 3,000 rpm across an operational temperature range of -70°C to +70°C. Given the bias of the Martian environment to colder temperatures and the associated increase in drag torque of the downstream gearing, a second performance requirement was given for temperatures at or below -30°C: minimum torque of 0.20 N•m at a minimum speed of 2,400 rpm. These two performance points were the basis of the motor design and sizing.

Additional design goals and test requirements regarding operation at colder temperatures increased the difficulty of the program. Specifically, there was a program goal to minimize torque variation over the wide operational temperature range. A limited torque uncertainty across operating conditions would allow JPL to calculate output torque produced by the motor solely as a function of the current input. In real terms, this translated to design direction to avoid adding excessive lubricant to the motor bearings, understanding that additional lubricant would increase the motor drag and therefore the torque uncertainty at colder temperatures.

Additionally, one of the most challenging test requirements, necessary to represent the bias of operation at colder temperatures, was to satisfy the following distribution of temperatures in the execution of the margined life test (105.2M motor shaft revolutions):

- Minimum 25% of the revolutions at the hot extreme (+70°C).
- Minimum 25% of the revolutions at the cold extreme (-70°C).
- Minimum 25% of the revolutions at the nominal operating temperature (-55°C).

Design and Evaluation

The M45S motor and brake assembly was comprised of a brushless DC motor with Hall commutation and a friction brake assembly. The rotor at the core of the M45S was supported by two radial ball bearings, spring preloaded in a face-to-face orientation. Each double-shielded, SR3 size bearing contained a crown steel retainer and was lubricated with a grease plate of Braycote 600EF followed by the addition of a 1:1 by volume slurry mixture of Braycote 600EF grease and Brayco 815Z oil to fill 5% to 10% of the bearing's void volume. The quantity of lubricant was minimized in order to keep torque losses low, and to reduce drag torque variation over temperature extremes. It should be noted that the combination of a grease plate prior to the addition of 5% to 10% fill of 1:1 grease/oil slurry resulted in a total lubricant condition of 8% to 13% volume fill and a grease/oil ratio closer to 2:1.

This lubrication approach was selected based on its heritage success [1] [2] [3]. Additionally, the crown steel retainer had heritage, being successfully used in Mars Science Laboratory gearboxes and in developmental testing for Mars 2020 gearbox designs. However, the combination of this retainer configuration, the lubricant fill, and the high number of revolutions required to be performed at the margined operating temperature, -70°C, pushed this bearing configuration beyond the acceptable limits of operation. This will be explained in detail.

A simplified cross-section of the M45S motor is shown in Figure 2.

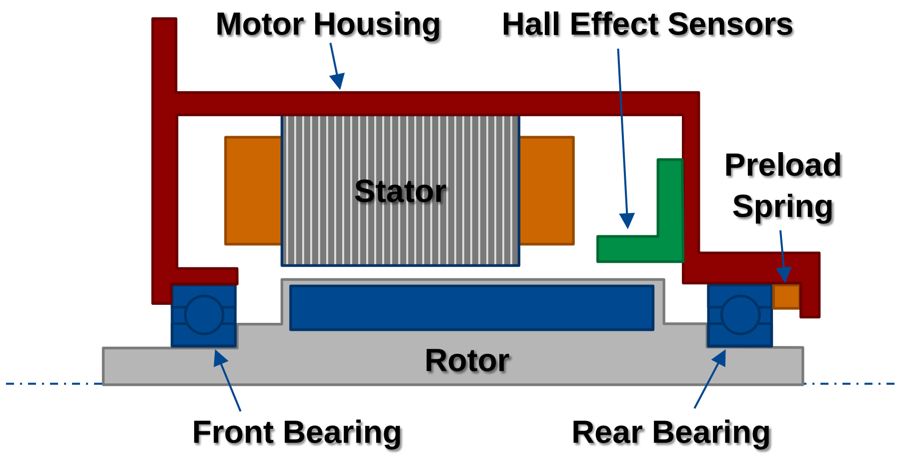

Figure 2 – Simplified M45S Motor Cross-Section (Brake omitted for clarity)

The rotor magnets overhang the rear of the stator to allow efficient Hall sensor commutation. This overhang increased the load on the front motor bearing due to the magnetic forces attempting to self-center the rotor within the stator. As a result, Hertzian contact stresses were expected to be higher [0.99 GPa (144 ksi)] in the front bearing and lower [0.80 GPa (116 ksi)] in the rear bearing. These are reasonable values for a long life application.

The bearing lubrication film parameter (λ), a ratio of the lubrication film thickness to the composite roughness of the contacting surfaces between the ball and raceway, was calculated using COBRA-AHS analysis software across temperatures ranging from -70°C to +70°C and speeds ranging from 1,500 rpm to 7,100 rpm. The analysis indicated a mixed boundary condition λ of 1.7 at slower speeds and higher temperatures, and a hydrodynamic (HD) condition (λ >3) for higher speeds and colder temperatures [4] [5]. The lubricant's viscosity is a function of temperature and increases at colder temperatures. This increase in viscosity inherently increases the lubrication film thickness, which in general, results in longer bearing life as the lubricant is able to insulate the bearing elements from direct contact [6]. However, a simple extrapolation of lubricant viscosity going cold may be insufficient for understanding impact on bearing life. As will be shown in Figure 10, the lubricant ceases to function effectively when approaching its pour point, resulting in starvation effects that dramatically reduce bearing life.

In addition to Hertzian contact stress and the lubrication film parameter, lubricant stress cycles are used in evaluating bearing life. These are defined as the number of times a ball passes across a given spot on the raceway, a function of the bearing's pitch diameter, ball diameter, and quantity of balls. See Eq. 1 in reference [2] for calculation details and an example in reference [5]. The lubricant stress cycles for the bearings in the M45S motor were 469 million for the margined life requirement of 105.2 million motor revolutions.

Published and other available data summarizing acceptable limits of Hertzian contact stress and lubricant stress cycles indicated that the M45S design was exceeding limits of proven lubricant life, but not in an area of known failure [3] [7]. The data indicates that at least 30-60 million lubricant stress cycles could be expected for contact stresses around 1.0 GPa (145 ksi), with failure to be expected beyond 600 million lubricant stress cycles. Being between the limits of proven success and known failure, bearing lubricant life was identified as a significant program risk throughout the design phase.

In response, the bearing balls were coated with titanium carbide (TiC), shown to quadruple the life of the perfluoropolyether (PFPE) lubricant at Hertzian contact stresses of 1.0 GPa or less [8]. Concurrent with the M45S design effort, developmental bearing life testing was being performed on similar bearings being used on a separate Mars 2020 contract to supply gearboxes. This testing was intended to demonstrate bearing life capability in the low cycle count, high load regime [2]. Unfortunately, it was not possible to adapt that test setup to encompass the speeds or cycle count required for the M45S motor design. Consequently, demonstration of M45S bearing life was deferred until its design verification (DV) life testing.

Performance and Life Test Results

M45S Performance

The goal to minimize torque variation over temperature was a significant program concern and drove the decision not to implement a higher bearing lubricant fill. Performance testing was completed and proved that the chosen motor design, including bearing lubrication, performed consistently across the entire operational temperature range. The net motor torque constant, including viscous losses from lubrication, across a temperature range of -70°C to +70°C resulted in a torque uncertainty of ±0.005 N•m at the 0.200 N•m output torque level at constant speed. This value was within the original program goal of ±0.009 N•m. With respect to torque uncertainty concerns, the chosen design and lubrication scheme proved highly effective.

Life Testing and Results

Identified early in the program as an area of risk, the lubricant life was ultimately tested during the M45S DV life test, which exposed the unit to twice the expected life, or 105.2 million motor revolutions. This life test, completed in early 2019, had been delayed due to other M45S design and integration challenges. These delays postponed the retirement of the bearing life risk. As a result, within six weeks of finishing the M45S DV life test, two of the M45S gearmotor life tests (ShEl DV and WAT DV) were completed or stopped due to anomalous conditions.

This timing afforded the opportunity for near-concurrent visual inspection of motor bearings experiencing the same operational temperature environment, but different total motor revolutions with various speed and load combinations. The revolution count and condition of the M45S motor bearings from these three initial life tests were compared for similarities and differences, shown in Table 1.

Table 1 – Results of Life Tests Ending in Early 2019

Life Test	Motor Revs / % of 2X Life	Temperature Distribution	Post-Life Performance	Visual Bearing Condition
M45S Motor-only	105M / 100%	25% min. @ -70°C 25% min. @ -55°C 25% min. @ +70°C	Acceptable	Poor
WAT Gearmotor	66M / 100%		Acceptable	Marginal
ShEl Gearmotor	78M / 74%		**N/A – Stalled**	Very Poor / Damaged

Figure 3 provides a visual comparison of the condition of the front bearing from the M45S motor of each of these three units, with the following observations:

- Motor-Only: Slightly rough rotation; dry, powdery, dark wear debris; retainer ball pockets worn
- WAT: Rough rotation; clumped, dark wear debris
- ShEl: Very rough rotation; retainer periodically caught under balls; nearly empty of any lubricant or wear debris; damage to retainer visible

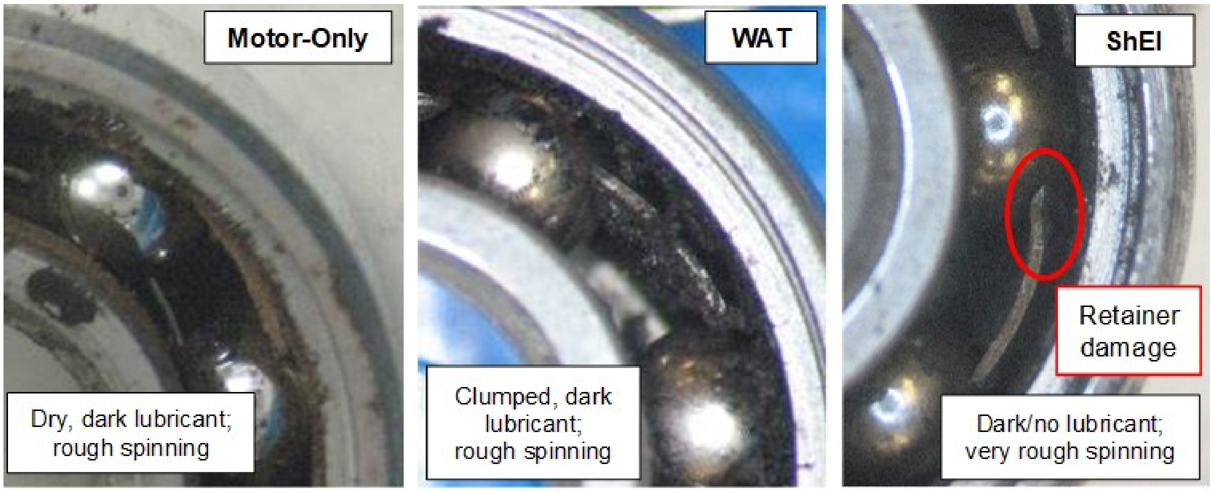

Figure 3 – Post-Life Test Condition of Front M45S Motor Bearings

<u>Details of the ShEl Life Test and Termination</u>

The program required that life tests perform twice the expected number of Integration and Test (I&T) and Mission revolutions over at least 10 thermal cycles, each consisting of temperature plateaus at +70°C, -70°C, -55°C, and +20°C. Additionally, the gearmotor output revolutions were required to be approximately equally distributed across the thermal cycles with a minimum of 25% of the revolutions to be performed at each of the +70°C, -70°C, -55°C plateaus. The balance of revolutions could be performed at any temperature between +70°C and -70°C, but were mostly completed around +20°C.

By early 2019, nearly all of the gearmotor DV life tests had been completed without issue. However, the ShEl life test unit unexpectedly stopped operating during the -55°C plateau (just after the -70°C plateau) of thermal cycle 6 of 10 in early 2019. Figure 4 provides an overview of the data acquired during this plateau, including the three stall events that occurred prior to halting operation for evaluation. The stall events are indicated by the three sharp rises in the motor current and temperature followed by recovery.

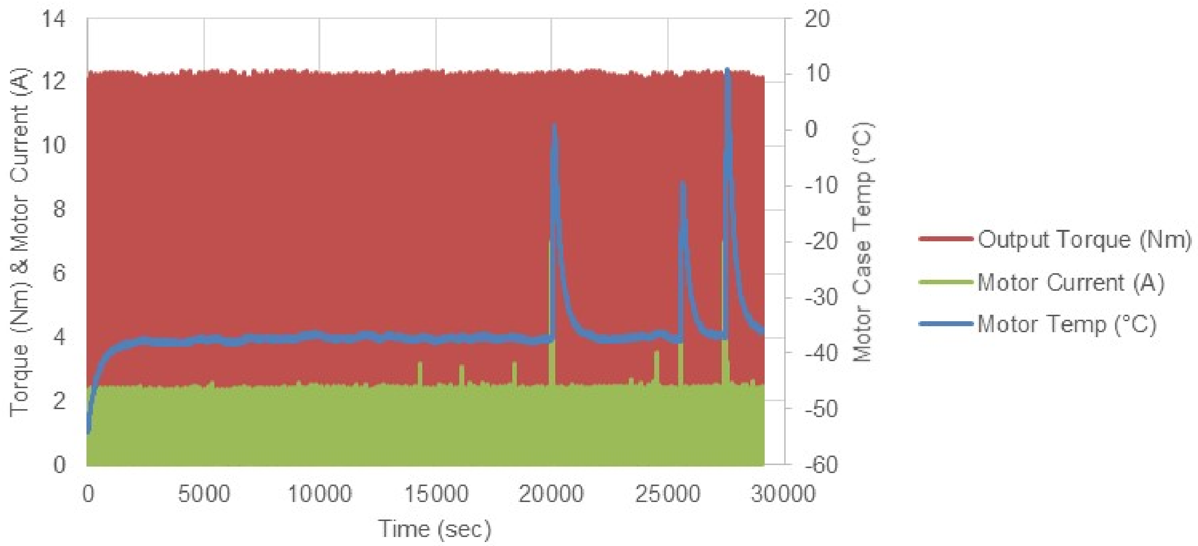

Figure 4 – Output Torque and Motor Current Data Acquired During Thermal Cycle #6, -55°C Plateau

Figure 5 provides detailed data of the first stall event as it occurred, with the following explanation:

- Per the automated profile, the unit began execution of 80 seconds of operation in the CW direction.
- After approximately 15 seconds of operation against the prescribed torque of approximately 6.6 N•m, the measured output speed of the unit unexpectedly dropped to 0 rpm and the motor current jumped to the 7 A current limit.
- The unit remained in this state for approximately 60 seconds, until the automated profile removed power from the motor. The motor remained off for 15 to 20 seconds, as planned.
- The automated profile initiated operation in the CCW direction.
- Operation then proceeded nominally for the next 80 to 90 minutes until a second stall event was encountered with the same signature as the first (reference Figure 4). Note, some initial torque noise is visible on the graph and is associated with the cogging effects of the hastily stopped hysteresis brake dynamometer.

All three stall events were readily identified by the sharp increase in motor housing temperature associated with Joule heating from the motor current being at its 7 A limit.

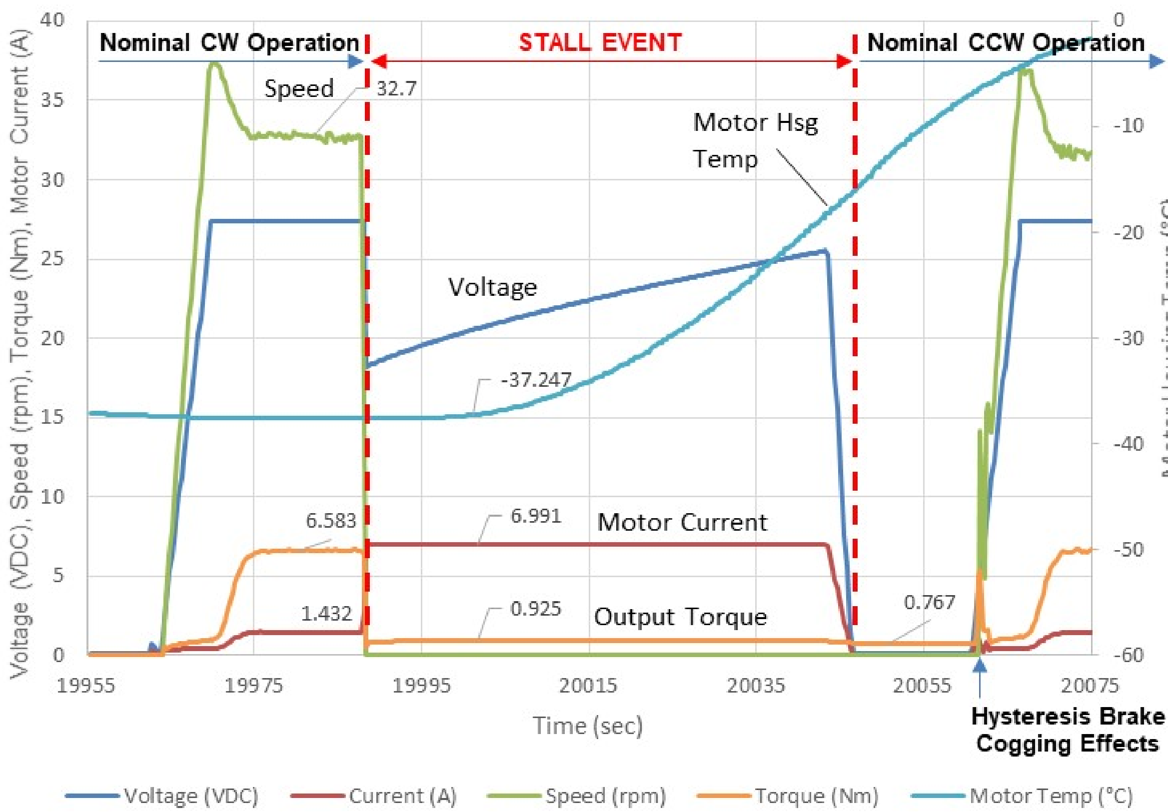

Figure 5 – Detailed Data Acquired during First Stall Event of ShEl DV in Life Cycle 6 of 10

Test Failure Investigation

The team first needed to determine whether the stall was due to an anomaly within the unit under test (UUT) or the mechanical or electrical ground support equipment (MGSE / EGSE). The life test setup was more complicated than most due to the requirements to apply resistive torque and axial load simultaneously, while supporting the UUT in the thermal chamber and recording data as noted. The complexity of the test setup presented multiple opportunities for the root cause to be found in the MGSE / EGSE. A block diagram of the complicated ShEl life test setup is shown in Figure 6, with data acquired from components identified in the orange boxes.

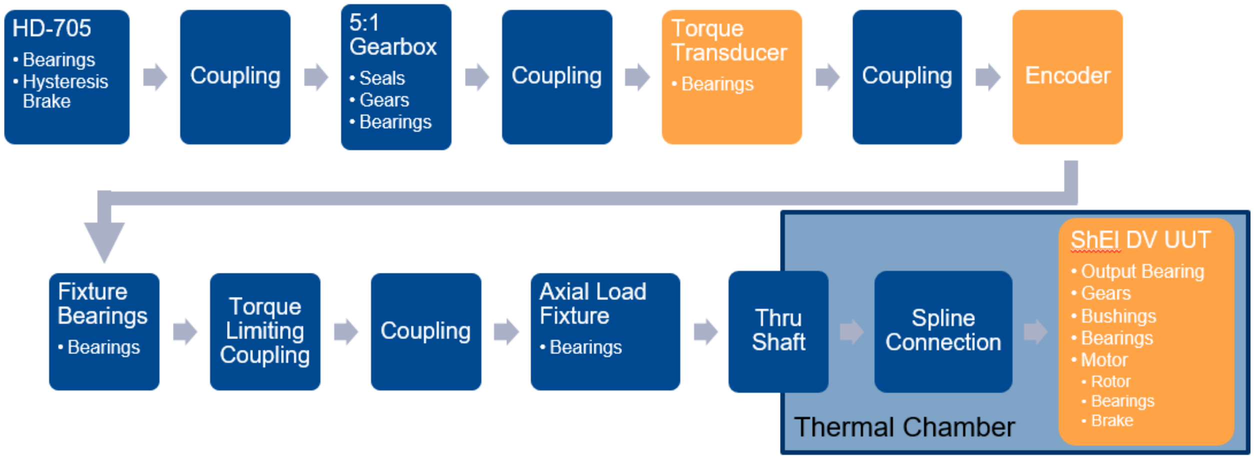

Figure 6 – Block Diagram of Complex ShEl DV Life Test Setup

The following describes the sequence of the investigation to determine the source of the ShEl DV unit life test anomaly:

1. To determine if the EGSE was responsible, the team attempted to recreate the stall event while recording the current of each motor phase and the voltage of each Hall sensor with an oscilloscope. Result: stall was recreated and oscilloscope data indicated EGSE was performing nominally.
2. The performance of the motor's brake was characterized to ensure it was not inadvertently engaging and stopping the motor. Result: motor brake performance was verified to be nominal.
3. Thermal chamber was taken to ambient temperature and a recreation of the stall event was again attempted in a manner that would allow a determination of the source of the anomaly: MGSE or UUT. Result: stall was recreated and there was no wind-up or tension in the MGSE test setup to indicate that it was causing any issues.
4. UUT was disconnected from all MGSE and a Startup Sensitivity health check was attempted to verify the motor was able to initiate rotation at a current value in family with prior health checks. The UUT failed to rotate with up to 2.8 A applied, when far less current was generally needed to initiate rotation. This provided convincing evidence that the source of the stall was within the UUT itself.
5. JPL performed a computed tomography (CT) scan on the motor and discovered that the source of the stall condition was within the front motor bearing; the crown steel bearing retainer jammed under a ball, as shown in Figure 7.

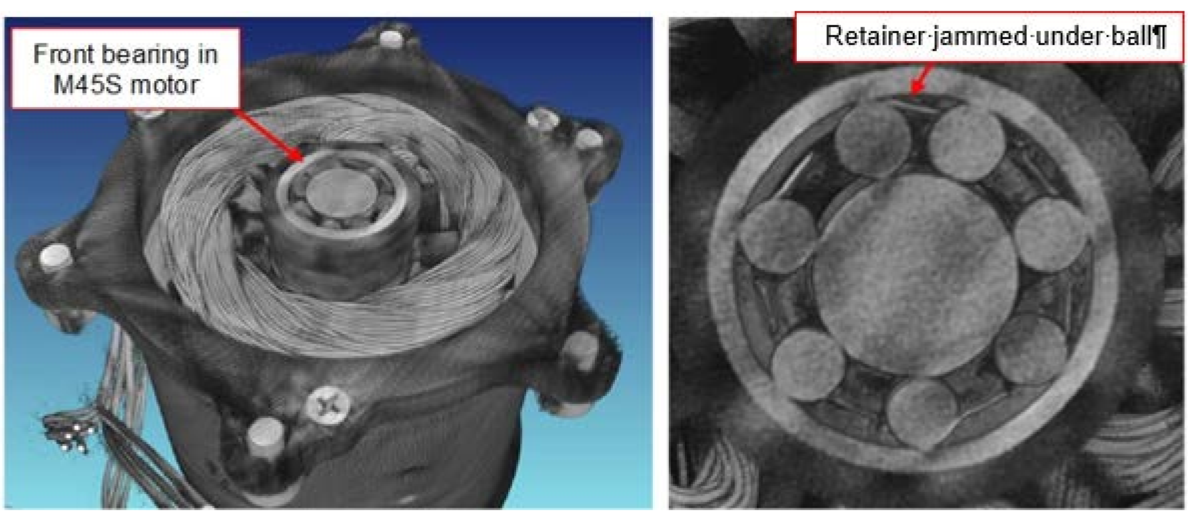

Figure 7 – CT Scan of Front M45S Bearing within ShEl Life Test Unit (Courtesy of NASA/JPL-Caltech)

The UUT was returned and disassembled at SNC. The interior condition of the motor, particularly the front bearing, was evaluated by both SNC and JPL personnel. The following observations were made regarding the condition of the ShEl gearbox and motor:

- No significant anomalies were found within the ShEl gearbox.
- No significant anomalies were found within the M45S brake assembly.
- In disassembly of the motor, the rear bearing rotated smoothly and residual, dark, and slightly wet lubricant remained.
- A significant amount of wear debris was present on both sides of the front motor bearing: motor rotor and motor pinion. See Figure 8.
- The front bearing rotated roughly and caught occasionally. Two fingers of the ball retainer were visibly damaged. The bearing was very dry and empty of both lubricant and wear material (appeared to have been ejected into motor rotor and motor pinion areas). The inner (piloting) diameter of the crown steel retainer included a rolled burr. Further inspection found that this inner diameter was measurably enlarged, allowing radial movement of the retainer to the point where the outer diameter of the retainer could contact the inner diameters of the outer race. Additionally, there were indications that the retainer spine contacted the interior surface of the bearing shield, indicating that the retainer ball pockets had worn to allow excessive axial movement of the retainer. See Figure 9 for the appearance of this damaged front bearing.

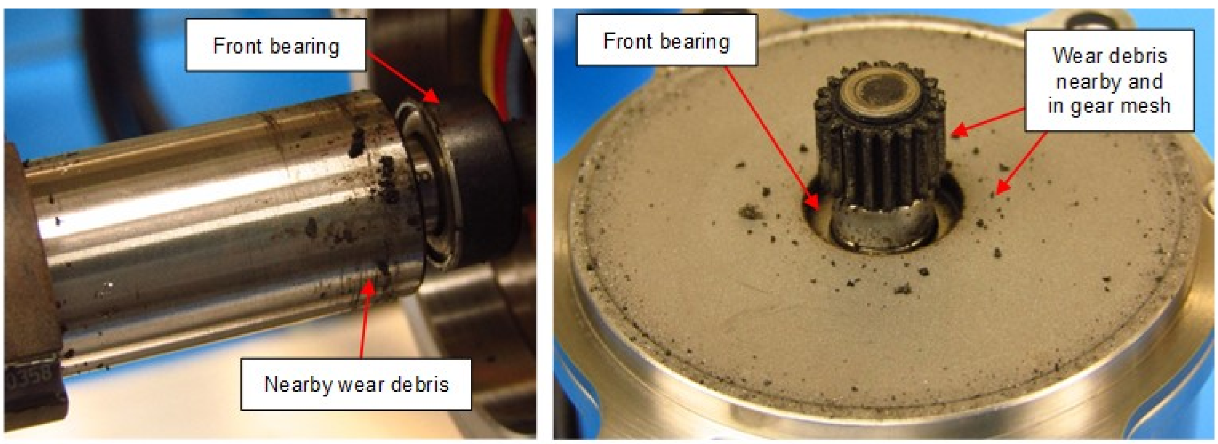

Figure 8 – Wear Debris Surrounding the M45S Front Motor Bearing from ShEl DV Unit

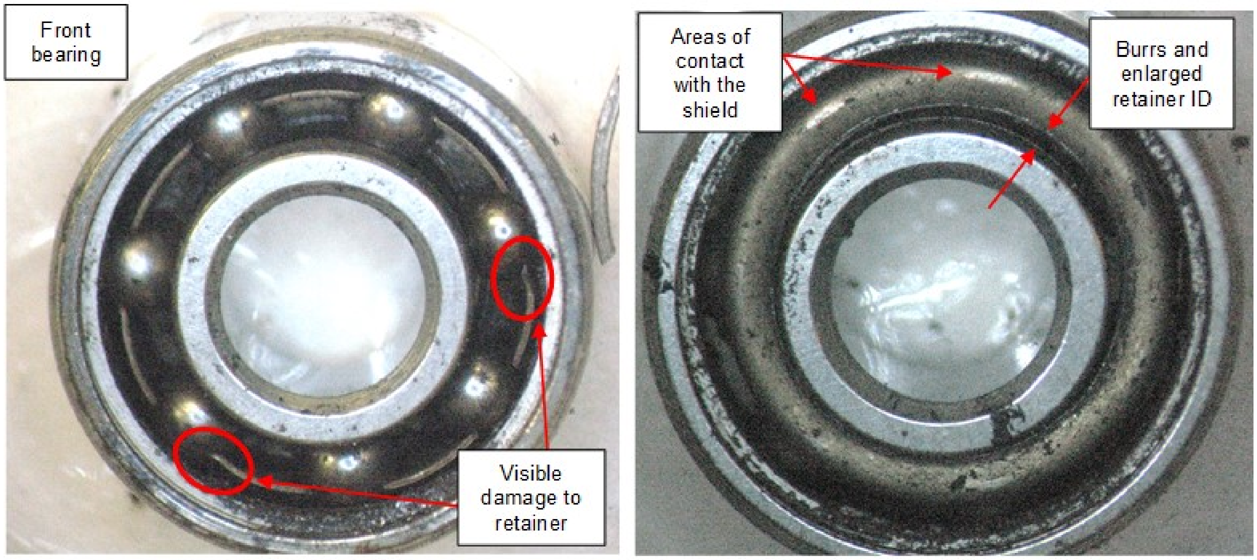

Figure 9 – Interior Inspection and Retainer Observations on M45S Front Motor Bearing from ShEl DV Unit

The results of this and other unit teardowns led to the development of the following failure sequence theory:

1. Operation at the -70°C temperature plateau, very close to the lubricant pour point of -72°C, rendered the lubrication scheme ineffective, resulting in lubricant starvation conditions.
2. Starvation conditions, never a desired condition for long life bearing operation, had the most significant effects on the crown steel retainer, wearing first at the inner diameter (ID) of bearing retainer spine, where guided.
3. Retainer wear debris mixed with grease, accelerating wear as the grease became an abrasive mixture with the wear particles.
4. Retainer ID continued to grow with wear, allowing it to move radially out of position.
    a. Ball pockets began to wear against balls, generating debris and burrs.
    b. Outer diameter faces of the retainer began to wear on the outer ring and inside of shields.
5. Wear debris led to increased drag in the bearings, causing increased noise in the motor current signature.
6. Eventually lubricant was depleted and dry debris was ejected from the bearing.
7. Two types of failure were observed:
    a. The bearing retainer was jammed between the ball and outer ring, stalling the motor. This mode was the initial life test failure observed in the original ShEl DV M45S motor.
    b. The build-up/plating of wear particles and depleted grease on raceways removed radial play from the bearing and caused a significant increase in drag/motor current, but not an outright motor stall. This failure occurred in the M45S SN013 motor that had replaced the original ShEl DV motor to complete the margined gearbox life test.

Response to M45S Bearing Failure

This life test failure occurred on one of the last gearmotor DV life tests and after the delivery and integration of the flight gearmotors into the Mars 2020 rover's flight robotic arm. The state of the program and the severity of the issue resulted in parallel recovery paths being pursued:

1. "Use as is" – Determine an operating temperature range that would allow the baseline, delivered bearing configuration to achieve the margined life test requirement. The goal was ensure the lubricant was able to flow and protect the crown steel retainer from lubricant starvation wear.
2. "Refurbish" – Determine a superior bearing configuration that would achieve the margined life test requirement without failure. Adjust operating temperature range as necessary to maintain acceptable torque uncertainty.

"Use as is" was the option with least impact to the assembly and integration work already accomplished by the Mars 2020 rover team. However, the refurbishment option was simultaneously pursued as a backup plan in the event there was no reasonable operating temperature range that allowed the delivered hardware configuration to achieve the margined life test requirement.

SNC and JPL had a number of M45S motors available as test beds for testing various bearing configurations across various temperature ranges. In addition, SNC possessed a number of motor controllers, test consoles, and thermal chambers to support simultaneous testing. Among many options, the collective program team considered the following variables valuable to compare:

- Minimum mission life test temperature
- Speed
- Lubricant mix ratio and percentage of fill
- Retainer material

Within three weeks of determining the front motor bearing to be the cause of the ShEl DV life test stall, the JPL-SNC team had begun a modified life test on two available M45S motors of the baseline bearing configuration. Both the flight spare motor (SN019) and a non-flight thermal correlation motor (SN032) began life testing, alternating between two less severe temperature plateaus: -35°C and +25°C. To increase the fidelity of these life tests and match the test flow, the motors were exposed to the random vibration environment prior to the beginning of life testing. Although they had the same baseline bearing configuration, SN032 performed its life test at the high end of the operational speed (7000 rpm), and was completed within three weeks, whereas SN019 performed its life test at the low end of the operational speed (1500 rpm), and took two months to complete. In reality, the actual motor speed in mission operation on the rover could be at any speed in between. These two speeds were selected to bound mission operation, since speed could have a potentially significant impact in the bearing lubrication film parameter and overall bearing life.

In parallel to these efforts, the program team chose to procure an alternate crown phenolic retainer in the “refurbish” path in lieu of the baseline crown steel retainer. This decision was made due the determination that the root cause of failure was the compounding deterioration of the crown steel retainer in the absence of effective lubrication at cold temperatures. The premise was that the porous phenolic retainer had more published heritage success and itself was a potential lubricant reservoir, inherently resistant to lubricant starvation. To this end, JPL was able to successfully modify four bearing sets to include crown phenolic retainers in place of the crown steel version, each set having a different lubrication scheme, as follows:

- 58.1 mg (30% void volume fill) of Braycote 600EF grease only
- 38.7 mg (20% void volume fill) of Braycote 600EF grease only
- 30 mg (15.5% void volume fill) of 2:1 slurry of Braycote 600EF grease : Brayco 815Z oil
- 22 mg (11.5% void volume fill) of 2:1 slurry of Braycote 600EF grease : Brayco 815Z oil

The purpose of the various lubrication schemes was to compare cold temperature performance. This performance testing was used to determine the drag of each bearing configuration with respect to temperature in order to assess the torque uncertainty associated with these alternate configurations. The JPL Motion Control Subsystem (MCS) team evaluated the results of this testing with respect to torque uncertainty goals. The cold performance test results for these lubricant configurations are shown in Figure 10, with the following observations:

- SN012 motor with 58.1 mg grease reached the 0.6 A current limit and could not operate at or below -50°C. Even at warmer temperatures, the no-load current was above 0.5 A and this lubricant configuration was deemed unusable by the JPL MCS team.
- The other three configurations had acceptable performance but only the SN016 motor with 38.7 mg grease and SN012 with 22 mg slurry proceeded to life testing.
- The data showed a low torque characteristic at temperatures at or below -60°C. This characteristic is believed to be from a starvation condition where the lubricant is so close to its pour point that its high viscosity does not allow for it to effectively flow within and relubricate the bearing components. While this produces low drag torque, it is not acceptable for a long life application.
- Peak torque was found to occur around -50°C indicating that the lubricant viscosity was still high due to the low temperatures but was able to flow within the bearing.

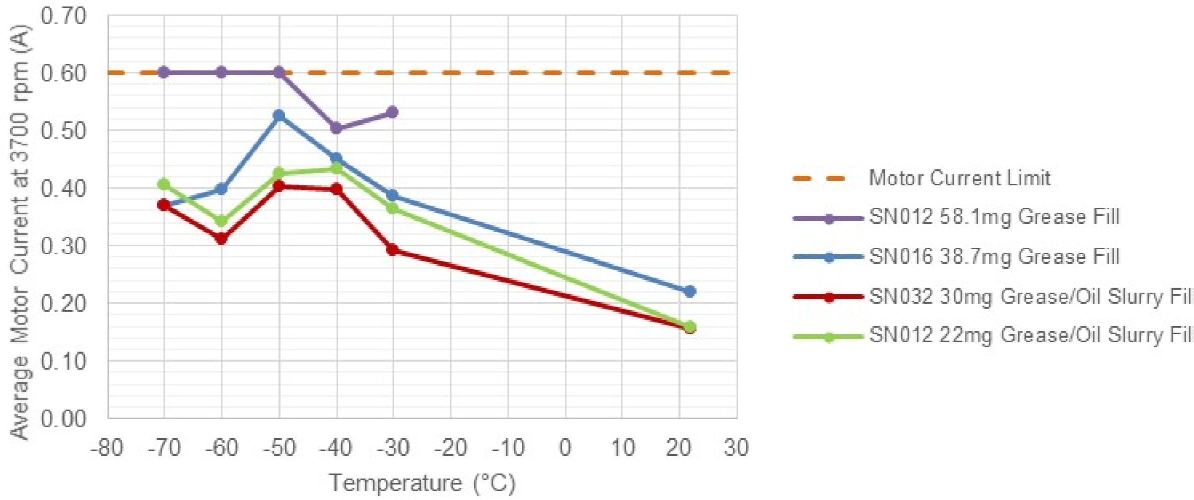

Figure 10 – M45S Cold Performance with Phenolic Bearing Retainer and Various Lubricant Schemes

The timeline of recovery for the M45S motor, including assembly, test, and teardown inspection events is shown in Figure 11 with the following details:

- Testing, including random vibration, began with the baseline bearing configuration in SN019 and SN032, modifying the operating temperature range to -35°C to +25°C to be less severe than the original -70°C to +70°C.
- Refurbishment of SN012 and SN016 was completed after receiving bearings with phenolic retainers and the noted grease fill from JPL.
  - Cold temperature drag testing revealed that the bearings in SN012 with 58.1 mg grease fill had excessively high drag. That unit, therefore, was not selected to continue to life testing.
  - SN016 did proceed to life testing over the -35°C to +25°C temperature range in the event that the SN032 with the baseline bearing configuration failed.
- SN032 life testing successfully completed with favorable results over the -35°C to +25°C temperature range, indicating that the baseline bearing configuration was capable of meeting the margined life requirements with a minimum operating temperature of -35°C.
  - As a result, life testing of SN016 was halted and the unit was made ready for a different set of bearings. By this point, SN016 had accumulated 75 million revolutions (71% of margined life).
- With successful results of the baseline bearing configuration at -35°C, the program set out to determine if either the baseline or a refurbished bearing configuration could successfully meet the margined life requirements with a lower minimum operating temperature of -55°C, still warmer than the original requirement of -70°C. A lower minimum operating temperature would reduce the needed motor heater power, conserving the rover's limited power supply for mission operations. This testing was performed with three units:
  - The slow speed, long-duration SN019 life test, already in progress, was modified to make up ground at the -55°C plateau.
  - SN016, refurbished to include the baseline bearing configuration, was run at full speed.
  - SN012, refurbished with bearings JPL modified to include phenolic retainers and the 22-mg slurry fill, was run at full speed as well.
- SN012 and SN016 were exposed to both the random vibration environment and the Planetary Protection (PP) Bake-out, which required at least 122 hours at +114°C and a pressure of less than 1×10^{-5} torr. The bake-out was included to ensure that the bearing lubricant would be conditioned in a manner consistent with the flight motors.
- All three motors finished testing within a week of each other. A Technical Interchange Meeting (TIM) was held to review all motor performance data and visual bearing conditions.

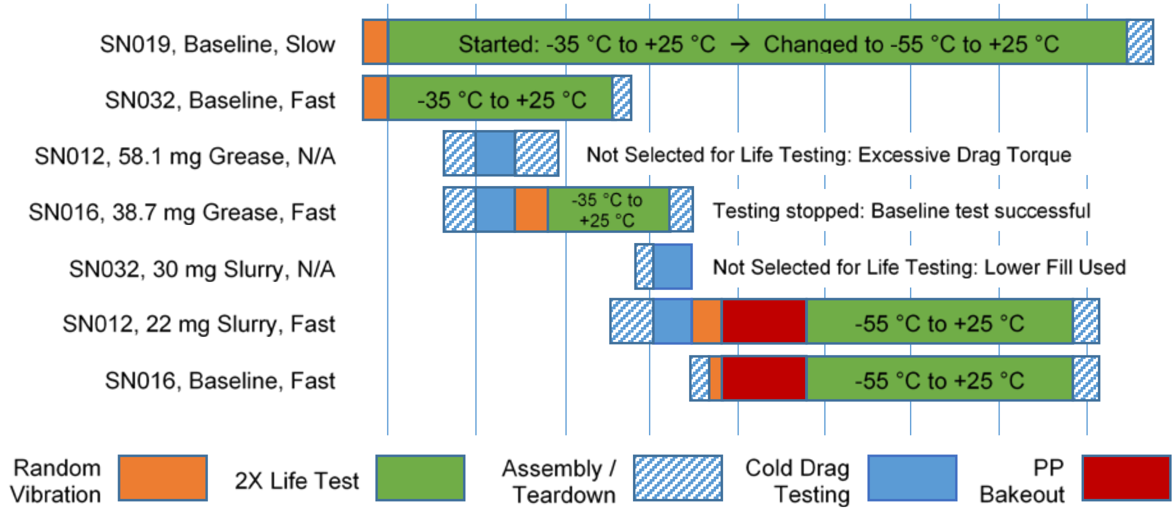

Figure 11 – Timeline of M45S Motor Recovery Assembly, Test, and Teardown Events

In the TIM, the decision was made to proceed with the baseline bearing configuration for the qualification and flight mechanisms, provided the minimum mission life test temperature was increased from -70°C to -55°C. Furthermore, since the M45S was capable of meeting performance requirements at colder temperatures and the concern was regarding reduced mechanism life, it was recommended that the power allocation for robotic arm motor heating be in proportion to the expected life of each joint. This allocation would conserve limited rover power resources while maximizing overall robotic arm life. Practically, this means that a joint that is expected to experience minimal revolutions could be operated colder than a joint that is expected to experience the most revolutions. Additionally, it was recommended that heater power continue to be used as available to maximize life, not just to achieve a minimum -55°C operating temperature.

Motor performance was acceptable for all five of the M45S recovery test configurations. A summary of the variables tested and the outcome of those tests are shown in the matrix of configurations and environments in Table 2:

Table 2 – M45S Motor Bearing Recovery Test and Results Matrix

Motor SN	Retainer / Lubricant	I&T Temperature / Motor Revolutions			Mission Temperature / Motor Revolutions			Total Revs	Speed (rpm)	Visual Cond.
SN032	Crown Steel [1]					-33°C	+25°C	106M	7000	OK
						53.0M	52.8M			
SN016	Crown Phenolic [2]					-33°C	+25°C	76M	7000	Good
						42.4M	33.1M			
SN012	Crown Phenolic [3]	-70°C	+25°C	+70°C	-55°C	-35°C	+25°C	106M	7000	Good
		1.86M	3.88M	1.79M	39.3M	29.5M	29.9M			
SN016	Crown Steel [1]	-70°C	+25°C	+70°C	-55°C	-35°C	+25°C	106M	7000	OK
		1.86M	3.87M	1.79M	39.2M	29.4M	29.8M			
SN019	Crown Steel [1]	-70°C	+25°C	+70°C	-55°C	-35°C	+25°C	105M	1500	OK
		1.85M	3.85M	1.81M	39.2M	29.4M	29.3M			

[1] Baseline Lubrication: Grease Plate of Braycote 600EF Grease with 5% to 10% fill with 1:1 slurry by volume of Braycote 600EF grease and Brayco 815Z oil

[2] No grease plate. Filled with 38.7 mg Braycote 600EF Grease, or ~20% fill

[3] No grease plate. Filled with 22 mg of 2:1 slurry of Braycote 600EF grease: Brayco 815Z oil, or ~11.5% fill

Figure 12 is a comparison of the post-life test condition of the front motor bearing from various units:

- Left: Original M45S DV motor-only life test with mission temperatures of -70°C to +70°C. Bearing spun roughly and the lubricant/wear debris was dry and dark.
- Center: M45S SN016 full-speed baseline bearing life test with modified mission temperatures of -55°C to +25°C. Bearing spun smoothly and lubricant was still present and slightly discolored around the retainer ball pocket areas.
- Right: M45S SN012 full-speed life test with modified mission temperatures of -55°C to +25°C and a phenolic retainer with 22 mg grease/oil slurry fill. Bearing spun smoothly and lubricant was plentiful and minimally discolored.

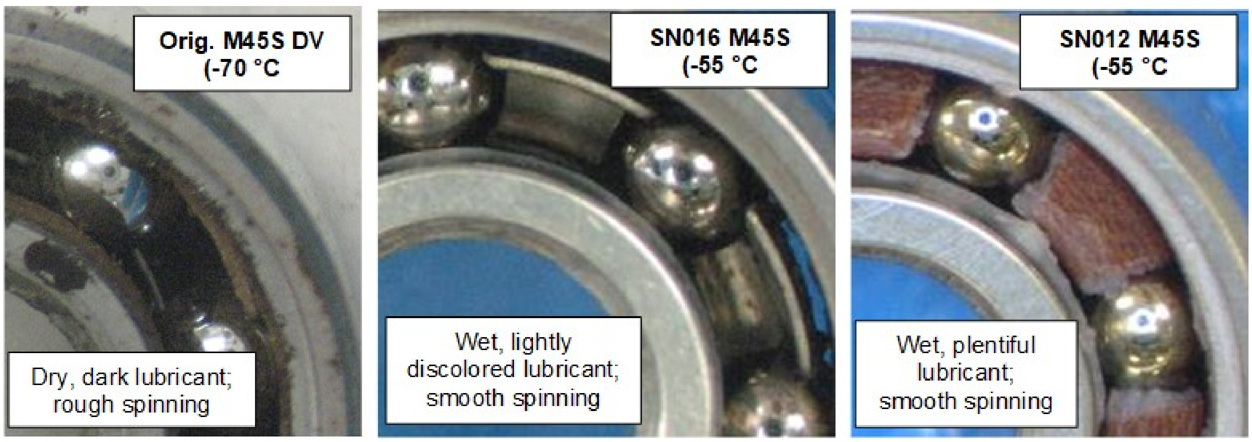

Figure 12 – Post-Life Condition of Front M45S Bearings

Conclusions and Lessons Learned

<u>Conclusions</u>

While the end-of-life condition of the bearings with phenolic retainers was superior to those with baseline crown steel retainers, the level of risk and schedule impact associated with replacing bearings installed in flight motors was deemed too significant. Multiple life tests confirmed that increasing the minimum mission life test temperature from -70°C to -55°C resulted in the baseline bearing configuration meeting the margined life requirements. The team planned to implement this change in minimum operating temperature by allocating the motor heating power budget proportionally based on the life requirement of each M45S motor application. By October 2019, the robotic arm joint assemblies, using SNC gearmotors containing the M45S motor with the baseline bearing configuration, were qualified for flight after successfully completing their margined life tests utilizing an increased minimum mission life test temperature of -55°C, providing additional confidence in the chosen solution.

<u>Lessons Learned</u>

- Programs should evaluate the appropriateness of applying a 15°C thermal uncertainty margin in combination with the 2X margin on required revolutions during life testing, especially when the temperature margin results in a significant viscosity change in the lubricant.
- Given the -72°C pour point of Brayco 815Z oil, operation at -70°C resulted in a starvation condition. Future work should evaluate newer lubricant formulations with lower pour points if long duration operation at -70°C is unavoidable.
- Bearing drag testing over temperature may be useful as a means of determining the low-end temperature limit for effective wet lubrication. Bearing drag normally increases with decreasing temperature, but drag torque was shown to decrease below this low-end temperature limit as the lubricant cannot flow and the bearing operates in a lubricant starvation condition.

- Bearing lubricant life depends on many factors in addition to industry accepted Hertzian contact stress and lubricant stress cycles. A developmental life test of the flight configuration of bearings is recommended as early as possible to ensure success while accounting for as many other variables as possible: bearing retainer design and material, lubricant fill, test temperature and duty cycle, film thickness at design speed(s), etc.
- Engineering should identify and resolve conflicting design requirements early in the program: low drag torque and long life requirements are potentially in conflict with a wet lubrication scheme.
- In this design and environment, phenolic retainers would have provided longer life than crown steel retainers.

Acknowledgements

The authors wish to express appreciation to the Motion Control Subsystem (MCS) team at JPL for their collaboration in this investigation and resolution. Specific contributors of importance were Mark Balzer, Andrew Kennett, and Alex Ferreira. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, under the Prime Contract NNN12AA01C between Caltech and NASA under subcontract number Subcontract 1541135. Government sponsorship acknowledged.

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