Developmental Bearing and Bushing Testing for Mars Gearboxes

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Abstract

As a part of NASA Jet Propulsion Laboratory's (JPL) upcoming Mars 2020 mission, Sierra Nevada Corporation (SNC) will be providing a number of new gearbox designs to fulfill various functions in the rover's robotic arms. At the time of the design reviews, SNC was unable to reference published or heritage design data that encompassed the Mars 2020 mission requirements regarding bearing lubricant life and bushing wear. As a result of this lack of information and the accelerated schedule, component-level and gearbox-level developmental testing was performed during the program's procurement phase to substantiate design choices in advance of qualification-level testing of deliverable flight gearboxes. These tests successfully demonstrated that the necessary mission life could be achieved. This paper aims to highlight the benefit of these developmental tests and provide new data in an area previously unpublished for bearing lubricant life [1][2][3] with mean Hertzian contact stresses up to 2.18 GPa (316 ksi). Additionally, the bushing wear test results are included, indicating that the required Mars cold operating temperatures were particularly stressing.

Introduction

SNC was tasked with providing eight different custom planetary gearbox designs to drive mechanisms on the new Mars 2020 rover. Gearbox size and volumetric constraints required high torque-density designs that required pushing the envelope in terms of component stresses in the bearings and bronze alloy bushings supporting the planet gears. The life requirements for several of these gearboxes exceeded requirements for hardware previously delivered by SNC on the Mars Science Laboratory mission, the Lightweight gearbox design study [4], and other published data for Perfluoropolyether (PFPE) bearing lubricant life [1][2][3]. General industrial design standards for bushings were considered uncertain for these applications due to the use of vacuum-rated lubricants and a non-terrestrial operating environment [5].

Summary of Successful Developmental Test Exposures:

- Operating Temperature Range: -70ºC to +70ºC
- Ball Bearing Max Mean Hertzian Stresses:
  - 2.179 GPa (316 ksi) up to 389,501 stress cycles
  - 1.682 GPa (244 ksi) up to 2,621,338 stress cycles
  - 1.517 GPa (220 ksi) up to 29,077,592 stress cycles
- Operating Pressures for Bronze Bushing:
  - 8.487 MPa (1,231 psi) for 1.78 km (5,895 ft) at speeds of 40.1 mm/s (7.89 ft/min)
  - 2.766 MPa (401 psi) for 22.97 km (75,358 ft) at speeds of 17-31 mm/s (3.35-6.10 ft/min)
  - 1.866 MPa (274 psi) for 34.17 km (112,122 ft) at speeds of 17-31 mm/s (3.35-6.10 ft/min)
  - 0.625 MPa (91 psi) for 51.20 km (167,981 ft) at speeds of 17-31 mm/s (3.35-6.10 ft/min)

SNC worked with JPL to define developmental tests for reducing programmatic risk ahead of qualification level testing since there was a lack of widely available data to provide confidence that these operating parameters had a high probability of success. The scope of this developmental testing was strictly focused on demonstrating the capability of these components for the Mars 2020 mission parameters including temperature profile, operating speeds, and frequency of direction changes. As such, these

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results do not guarantee success for alternate mission parameters, nor do they summarize the limits of these components; rather, they provide a handful of data points for which successful operation has been demonstrated.

Planet Support Load Within a Planetary Gearbox

Planetary gearboxes are a power-dense option for translating high-speed, low-torque motor shaft outputs into more useable lower-speed, higher-torque outputs. The planet gears that operate within these gearboxes must be supported by and rotate upon carrier posts. Friction losses at the interface between the planet gears and carrier posts are typically minimized through the use of bushings or rolling element bearings. Rolling element bearings are generally selected in the faster moving, more lightly loaded initial stages of a planetary gearbox. By contrast, bushings may be effectively used in the latter planetary gearbox stages, where their additional drag is counterbalanced by their ability to withstand higher loads with less volume. A well-designed bushing can successfully operate at higher radial loads than a rolling-element bearing of the same proportions. Bushings have also proven to be far more tolerant of slight imperfections or contamination than plain steel bearings. Figure 1 shows the typical construction of a planetary gearbox.

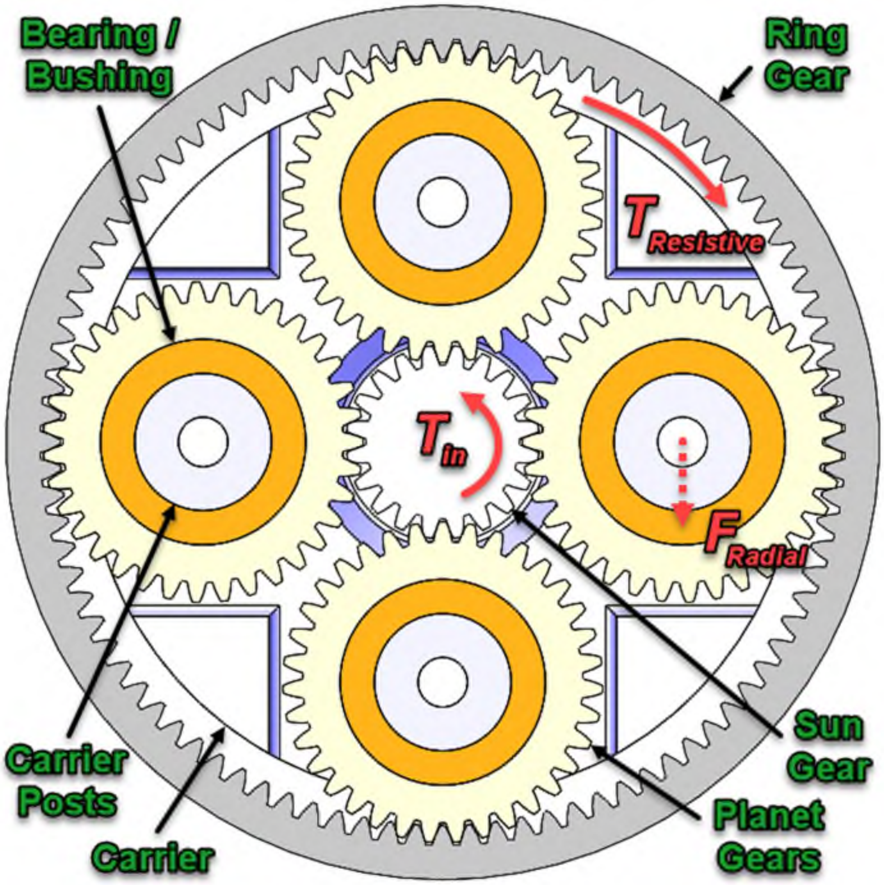


Figure 1. Generic Planetary Gearbox Components and Planet Support Load

Figure 1 also shows the radial load, F_{Radial}, to which the bushing or bearing is subjected as a result of the torque transmission through the gearbox. This radial load is generated as torque and is transferred from the torque input, T_{in}, to the resistive load at the output, $T_{Resistive}$. The severity of this radial load is related in terms of pressure for a bushing and Hertzian contact stress for a rolling element bearing. It is these bushing pressures, bearing stresses, and the associated effects on the lubricant which this developmental testing was designed to evaluate.

The bushing pressures and distances are calculated from the bushing inner diameter and assume that the outer diameter does not rotate relative to the planet gear. Ball bearing Hertzian stresses were calculated with COBRA AHS™ software, using radial play and raceway curvatures provided by the bearing vendor for each serialized bearing.

Component-Level Testing

Because high stresses in ball bearings and bushings presented one of the largest gearbox program risks, component level life tests were expediently developed in order to demonstrate that the final design could meet the 2X life requirement set forth by NASA JPL.

Materials and Lubrication

All materials and lubrication were based on the designed flight configuration at the time of the Detailed Design Reviews. For test expediency, commercially available 440C bearings of the same basic bearing size as the flight configuration were procured to undergo component-level testing. These bearings contained stainless steel crown retainers equivalent to the flight configuration. They were delivered with serialized inspection data for radial play and inner/outer raceway curvature that allowed loads to be tailored to achieve the required max mean Hertzian stresses. The bearings were lubricated with grease plate and a 5-10% free volume fill of 50/50 slurry containing Braycote Micronic 600 EF grease and Brayco 815Z oil. This lubrication fill was selected on the basis of prior published research [6]. Braycote Micronic 600 EF grease was selected over the very similar 601 EF grease because the use of stainless steel components lessened the need for the corrosion inhibiting additives found in 601 EF.

SAE 841 bronze alloy bushings (now procured to material specification CT-1000-K26) were also readily available. This bushing material, in combination with hardened 440C posts, was shown to be most effective in the NASA Phase II SBIR Lightweight Gearbox Technology Program [4]. For lubrication, the bushings were impregnated with Brayco Micronic 815Z oil and the surrounding parts were grease plated with Braycote 600 EF grease.

Component-Level Bushing Testing

The test rig shown in Figure 2 was available from the Lightweight Gearbox program and repurposed to allow for expedient component-level testing on bushings and bearings. This test setup involved a stationary gear blank to hold the outer diameter of the bushing under test with a rotating shaft interfacing with its bore. The radial load was applied with a Radial Load bar, having its fulcrum on the far side of the component under test, and a mass was hung on the near side to generate the radial loads experienced within a planetary gearbox. Finally, the rotating shaft was driven by a motor through a rotary torque sensor via an opening in the thermal chamber wall.

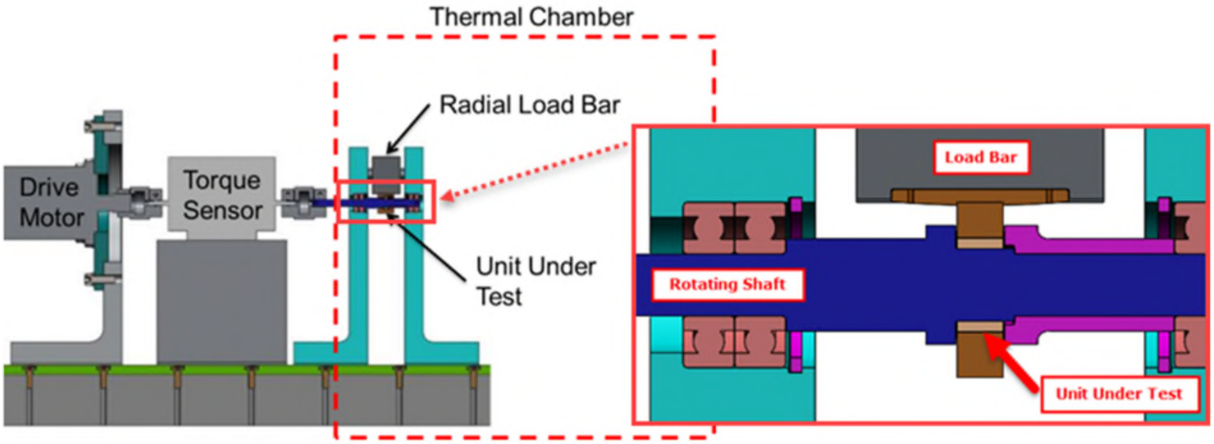


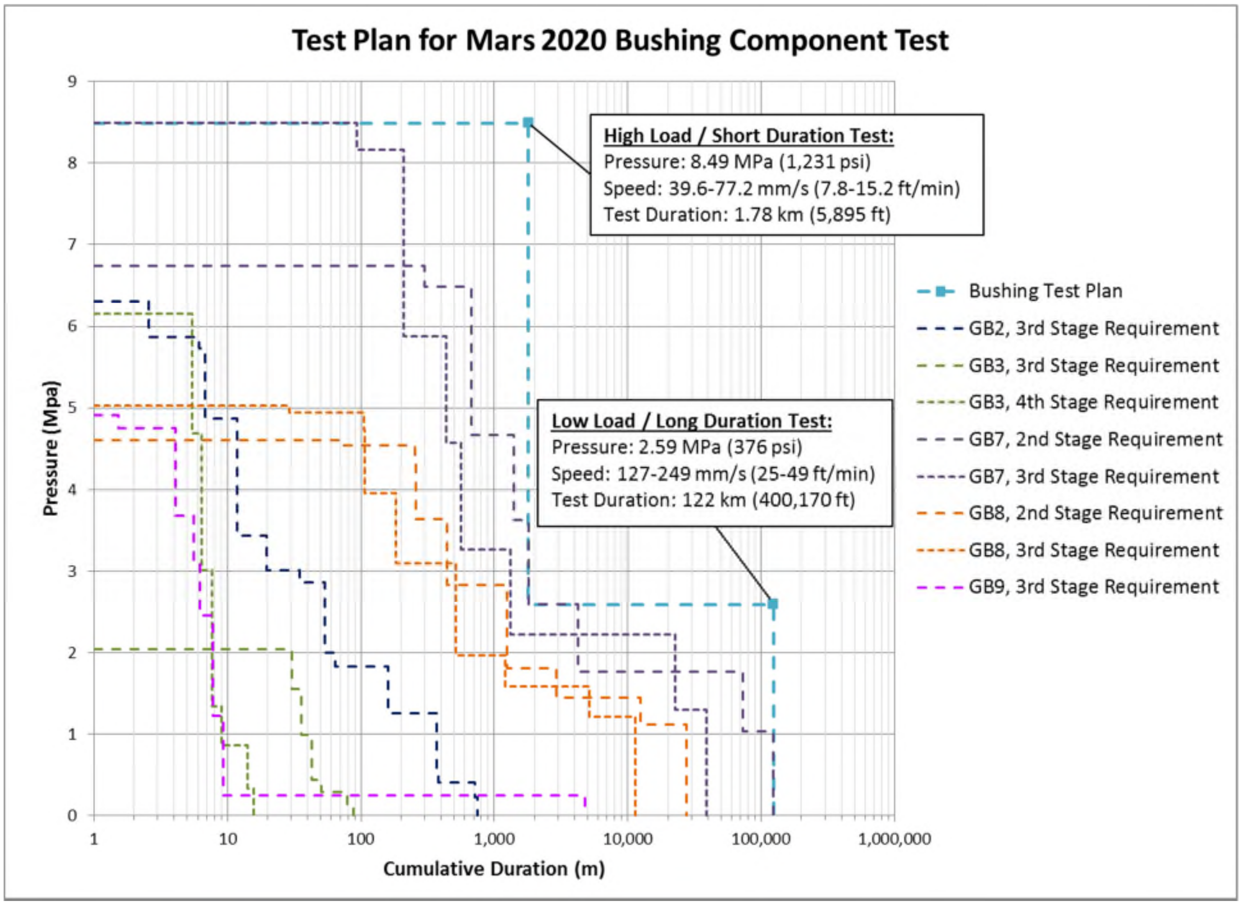
Figure 2. Component Test Fixture

At this point in the program, design reviews were complete and procurement was underway. Table 1 shows the two enveloping design points to which a single bushing would need to successfully operate in order to satisfy the cumulative 2X life requirement. Figure 3 shows the cumulative required operating pressures and durations for each of the five gearbox designs utilizing bushings, along with the enveloping component test points. Some of these design points later changed due to revisions JPL made to the design specifications, further supporting the need for this initial developmental testing.

The test temperature was the final, crucial variable which needed to be defined for this developmental test. The required operational temperature range was -70°C to +70°C. For simplicity and conservatism, the team decided to run the entire test at the worst-case temperature. Elevated temperatures were assumed in design reviews to be worst-case because of PFPE's propensity to chemically break down in high stress environments. Hot environments lower the viscosity of PFPE lubricants, resulting in thinner lubricant film thicknesses for the otherwise same speed and load conditions. When sufficiently thin, the lubricant regime will be near or in boundary contact, which accelerates the breakdown of the lubricant due to the high stresses occurring at the molecular level, shearing apart molecules. Broken down, the lubricant can no longer effectively protect the bushing from more rapid wear.

Table 1. Initial Bushing Operational Requirements

Load Case	Load	Duration	Speed
High Load / Short Duration	8.49 MPa (1,231 psi)	1.78 km (5,895 ft)	39.6-77.2 mm/s (7.8-15.2 ft/min)
Low Load / Long Duration	2.59 MPa (376 psi)	122 km (400,170 ft)	127-249 mm/s (25-49 ft/min)


Test Plan for Mars 2020 Bushing Component Test

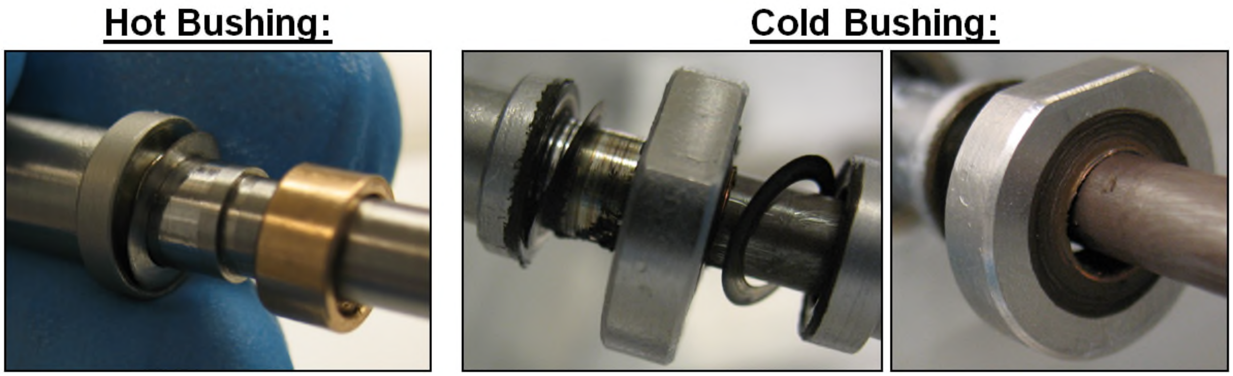
High Load / Short Duration Test:
Pressure: 8.49 MPa (1,231 psi)
Speed: 39.6-77.2 mm/s (7.8-15.2 ft/min)
Test Duration: 1.78 km (5,895 ft)

Low Load / Long Duration Test:
Pressure: 2.59 MPa (376 psi)
Speed: 127-249 mm/s (25-49 ft/min)
Test Duration: 122 km (400,170 ft)

Figure 3. Initial Gearbox Bushing Pressure v. Duration Requirements and Test Plan

To confirm the assumption that the hot operational temperature limit was the more stressing environment, two bushings were tested: Bushing A at the hot extreme (+65°C to +70°C) and Bushing B at the cold extreme (-65°C to -70°C). The two bushings were exposed to the identical loads and life of the High Load/Short Duration load case of Table 1: 8.487 MPa (1,231 psi) load at a speed of 40.1 mm/s (7.89 ft/min) for a total duration of 1.78 km (5,895 ft). Direction was alternated every five minutes as a rough replication of the change in direction to which the gearboxes would be subjected. After this exposure, the bushings were removed from the test fixture and visually evaluated.

Unexpectedly, the wear on Bushing B from the cold test was more severe than on Bushing A from the hot test, as shown in Figure 4. This was likely due to lubricant starvation from sub-optimum oil replenishment at the wear interface due to such cold operating temperatures. The pour point of Braycote 815Z oil is -72°C. Operation between -65°C and -70°C, so close to the -72°C pour point, likely reduced the oil's ability to flow within the pores of the impregnated sintered bushing, hampering its ability to protect the bushing from more rapid wear.



Hot Bushing:

Cold Bushing:

Figure 4. Initial Wear on Bushings: 8.487 MPa @ 40.1 mm/s for 1.78 km

Since the cold environment proved more stressing on the bushings in this flight lubrication scheme, the program updated its life test temperature requirements to bias them colder than originally planned. A new requirement was added to operate at least 25% of the life at an expected mission nominal temperature of -55°C. These cycles were in addition to the existing requirements to operate at least 25% at cold (-70°C) and 25% at hot (+70°C); with the remainder of cycles anywhere between hot and cold temperatures. Also, the life requirements of the dominating gearbox designs (GB7 and GB8) were iterated in JPL's specifications after the initial tests on Bushings A and B. The peak load was reduced from 8.487 MPa (1231 psi) to 8.173 MPa (1185 psi), but the required Low Load duration was increased from 122 km (400,170 ft) to 301 km (987,101 ft), as can be seen in Figure 5.

The remainder of the component-level bushing test was planned to be completed using Bushing A, but biased cold. Having already completed the required operation at hot, this bushing would be exposed to 25% of the updated High Load/Short Duration load case at cold, and then exposed to 100% of the Low Load/Long Duration cycles at a continuous -55°C, as indicated by Test #2 and Test #3 in Figure 5.

The operational profile was also updated for the following tests, incorporating a five-minute pause for every 20 minutes of operation (two cycles of five minutes clockwise, five minutes counter clockwise). This was in acknowledgement that the gearmotors would not be run continuously on Mars, and that the periodic pause may allow for some beneficial oil reflow from the bushing without dramatically increasing the length of the developmental test. Finally, as the Low Load point would correspond to a lower gearbox torque transmission and higher operating speed, the operating speed at 2.45 MPa (356 psi) was increased to 192 mm/s (37.7 ft/min).

Unfortunately, this Low Load testing in the fixture with Bushing A resulted in a premature bushing failure after only 25.58 km (83,914 ft) at 2.45 MPa (356 psi) shown in Figure 5. Furthermore, after the torque cell data was reviewed, it was determined that the bushing began operating in a degraded condition after 19.20 km (62,977 ft). See Figure 6 for the failed condition. While this failure occurred short of the duration required to envelope the life of all design configurations, it was sufficient to satisfy the life requirements of the GB2, GB3, and GB9 designs.

It was believed that the test setup led in part to the premature bushing failure. Clearances in the fixture could allow the radial load bar to apply a slight axial load into the bushing and cause edge loading. Concerns regarding the fixture and the negative test result led to the desire for additional testing that better represented a flight-like configuration within the context of a planetary gearbox. However, as flight-like gearboxes of the GB7 and GB8 configurations would not be available to utilize in testing for several months, the results of this initial test led to a decision to begin a parallel procurement of components that would allow the GB7 2nd Stage and GB8 2nd Stage planet supports to be ball bearings instead of bushings. Without bushings in these locations, the enveloping required life of bushings at low load would be significantly reduced. Additionally, the possibility of ball bearings in these locations would drive the requirements of component-level bearing testing.

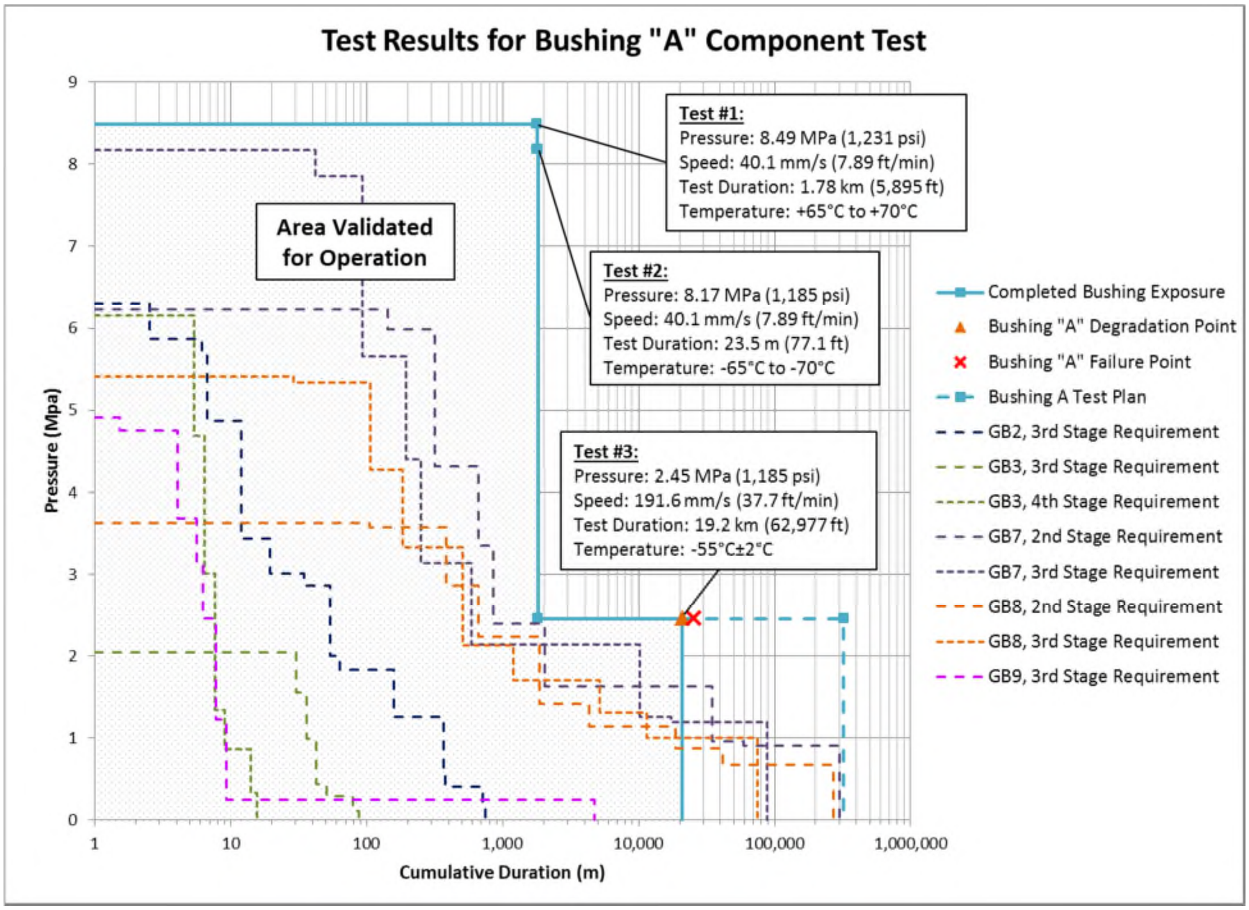


Figure 5. Revised Gearbox Bushing Pressure v. Duration Requirements and Test Results

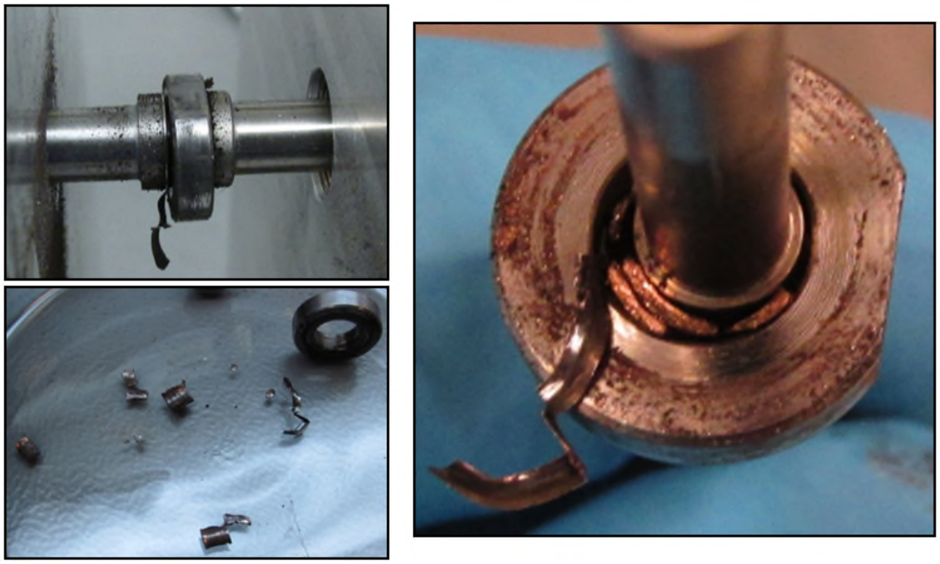


Figure 6. Component-Level Test Bushing Failure: 2.45 MPa @ 191.6 mm/s for 25.58 km at -55°C

Component-Level Bearing Testing

A representative radial ball bearing was tested in the fixture shown in Figure 2, understanding that it would be more tolerant of fixture shortcomings. The bearing was tested at loads, speeds, and durations representative of and encompassing all Mars 2020 gearbox designs, including the newly-planned 2nd Stage applications in the GB7 and GB8 gearboxes.

Ball bearing testing was completed successfully. The max mean Hertzian contact stress, number of stress cycles, and inner race speed of the tested bearing are shown in Figure 7. Although the speed was uniform at each stress level, the lambda factor varied with temperature. The final condition of the bearing grease is shown in Figure 8. The bearing completed approximately 32 million stress cycles at stresses exceeding 1.31 GPa (190 ksi), including 29 million over 1.517 GPa (220 ksi) and nearly 390,000 at 2.179 GPa (316 ksi). Historically available PFPE curves are also shown in Figure 7 for reference:

- The Cumulative Degradation Factor (CDF) curves (“CDF = 2” and “CDF = 8”) indicate greater concern for long life usage of PFPE lubricants without directly cautioning against high stresses at a lower number of stress cycles [3]. The CDF is calculated as the product of max mean stress times the number of stress cycles and is typically expressed in units of 10^{12} psi-cycles (e.g. CDF = 2 is shorthand for 2 x 10^{12} psi-cycles).
- Conversely, curves from other test data (“Upper Limit Line” and “Lower Limit Line”), based on NASA CP-3062 [1], indicate a greater concern for high stresses which accelerate the polymerization and breakdown of PFPE lubricants, but suggest very long life is possible at low stresses.

Stress cycles are the number of times a ball passes across a given spot on the raceway. The conversion from bearing revolutions to stress cycles is a function of bearing geometry as shown in Eq. 1:

$$\#\,Stress\ Cycles = \#\,Revs\ \times N\left[1-\left(\frac{1}{(d+D)/(d-D)+1}\right)\right] \tag{1}$$

Where N is the number of balls, d is the pitch diameter, and D is the diameter of the balls.

It is worth noting that the bearing under test was exposed to all of these stress cycles while running continuously in a thermal chamber cycled to achieve a distribution of 25% hot (+65°C to +70°C), 25% cold (-65°C to -70°C) and the remainder between -65°C and +65°C. Each thermal cycle was approximately 400 minutes with the average test temperature of approximately 0°C. The thermal chamber ramp time made it impractical to include the additional temperature plateau for 25% of cycles at the nominal temperature, -55°C.

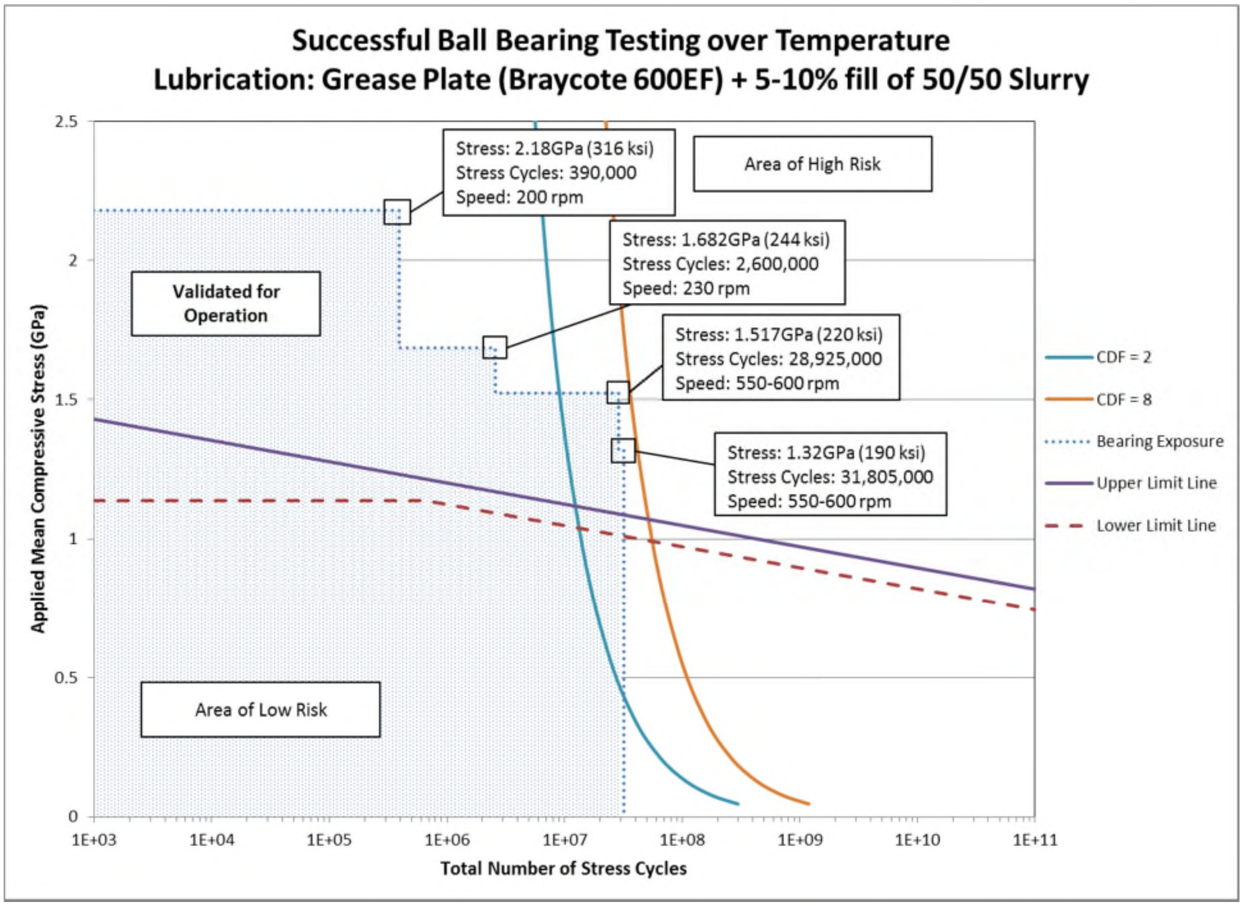


Figure 7. Successful Component-Level Bearing Exposure

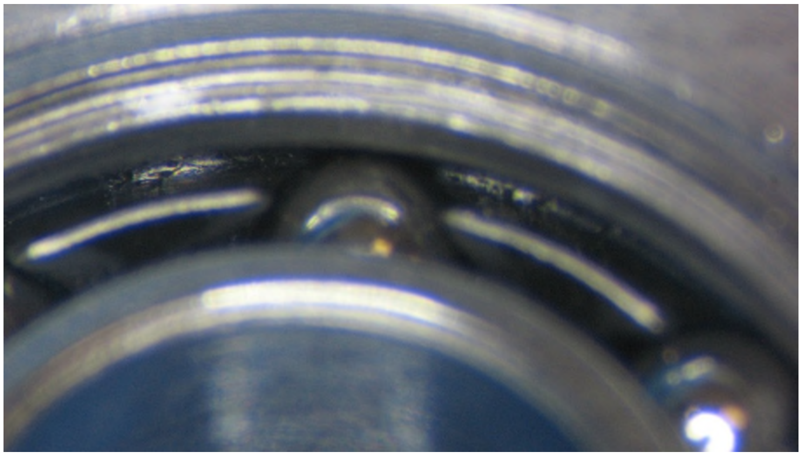


Figure 8. Condition of Grease at Conclusion of Component-Level Bearing Test

Flight-Like Gearbox Testing

Concerns regarding the potential influence of fixture design on the results of the component-level bushing test and the receipt of the flight-like hardware allowed the team to assemble a three-stage planetary gearbox which could be used to execute the life test requirements on flight hardware. In the interim between the component-level bushing tests and this gearbox-level test, JPL changed the life requirements of the dominating gearbox designs (GB7 and GB8), nearly halving them.

In conjunction with using a flight-like gearbox, this test had the added benefit of testing four bushings simultaneously (Reference Figure 1) in addition to the other life-limited gearbox components: gears, ball bearings, and associated lubricant. Concern regarding increased bushing wear seen at cold temperatures was thought to be due to lubricant starvation related to poor mobility of highly viscous oil in the porous bushing. This led to a decision to lubricate two of the four bushings with Brayco 814 oil, a discontinued Castrol product with a pour point and cold temperature viscosity significantly lower than Brayco 815Z oil: 2,121 cSt [7] versus 10,855 cSt [8] at -54ºC. One remaining bottle of Brayco 814 oil was obtained through distribution. Loads were applied to bushings through the gear mesh inside the planetary gearbox in the form of resistive torque by a particle brake. Loads on each planet bushing were calculated based on ANSI/AGMA Standard 6123-B06 [9] Mesh Load factors. This document provides a mesh load factor of 1.25 for four planets with one floating member, meaning the highest loaded planet may carry 31.25% of the total stage torque.

The first gearbox available for testing was the GB2 design, but the flight-like gearbox bushing wear test was designed to encompass the load cases from all of the Mars 2020 applications including GB7 and GB8 as follows:

- Initial run-in at ambient conditions to distribute the lubricant.
- Back to back 1X life tests of the “ground test” cycles (total of 2X) with a temperature distribution of 25% ambient (23°C±5°C), 25% hot (+65°C to +70°C), 25% cold (-65°C to -70°C), and 25% ambient (23°C±5°C).
- Back-to-back 1X life tests of the “mission life” cycles (total of 2X) were conducted at a sustained -55ºC. It is worth noting that the temperature chamber was held at -55ºC during the entire mission life test, even during periods of non-operation. This was considered important for preventing the lubricant from reflowing better at room temperature, potentially providing a false-positive test result.
- All operation, except initial run-in, distributed clockwise and counter clockwise cycles evenly at five-minute intervals. Run-in consisted of 30 minutes operation clockwise followed by 30 minutes operation counter clockwise.

In contrast to the component-level bushing test which failed prematurely, the flight-like gearbox test successfully completed the test protocol. This satisfied the life and loads required for all the Mars 2020 gearbox designs and provided the necessary confidence to proceed with the designed gearbox configurations. The as-tested loads and durations are summarized in Table 2 and illustrated in Figure 9, with the component-level bushing wear test loads and durations shown for reference.

Table 2. As-Tested Flight-Like Gearbox Bushing Exposure

Test Step	Bushing Pressure (MPa)	Total Duration (m)	Bushing Speed (mm/s)
Run-In	0.625	61	17.04
2X Ground Test Cycles	1.258	3,301	
	2.499	157	
	2.954	1,555	
	3.583	16	
	5.155	52	
	5.332	42	
	7.858	100	
2X Mission Life Cycles	0.625	6,788	
	1.375	74	
	2.766	5,533	
	1.886	444	
	0.625	6,728	30.97
	1.375	74	
	2.766	15,670	
	1.886	10,605	

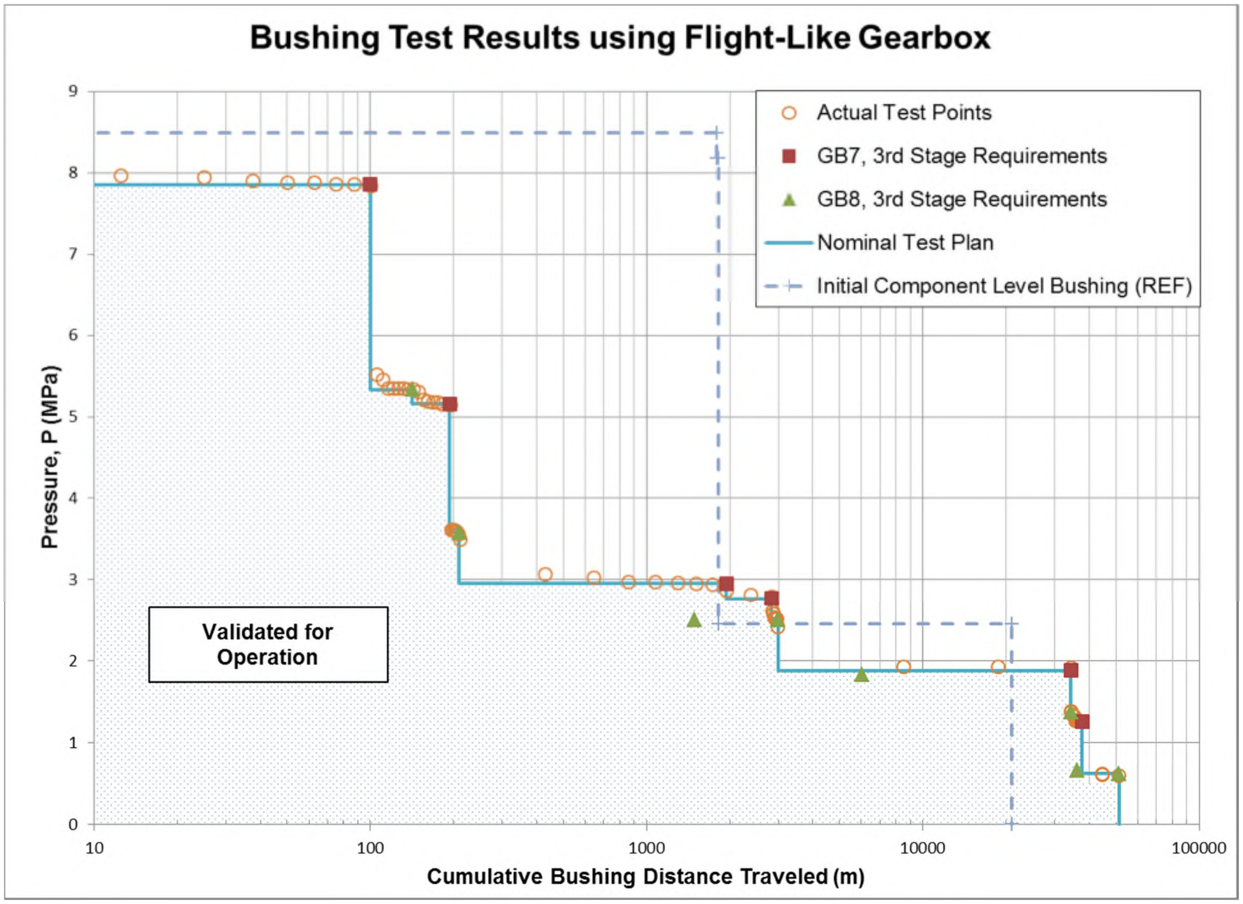


Figure 9. Bushing Wear Exposures

Disassembly and inspection of the bronze alloy bushings and 440C posts at the conclusion of testing are shown in Figure 10. The results of surface roughness measurements along the axial length of the bushing outer diameters are shown in Figure 11. A visual comparison and these roughness measurements indicate the Brayco 814 oil provided superior wear protection to the bushings for this predominately cold operational test. The 814 oiled bushings displayed a surface condition more similar to the virgin bushing pulled from stock for comparison. The improvement seen from the Brayco 814 oil is most likely due to the lower viscosity of 814 at cold temperature versus the 815Z oil allowing improved lubricant flow and replenishment.

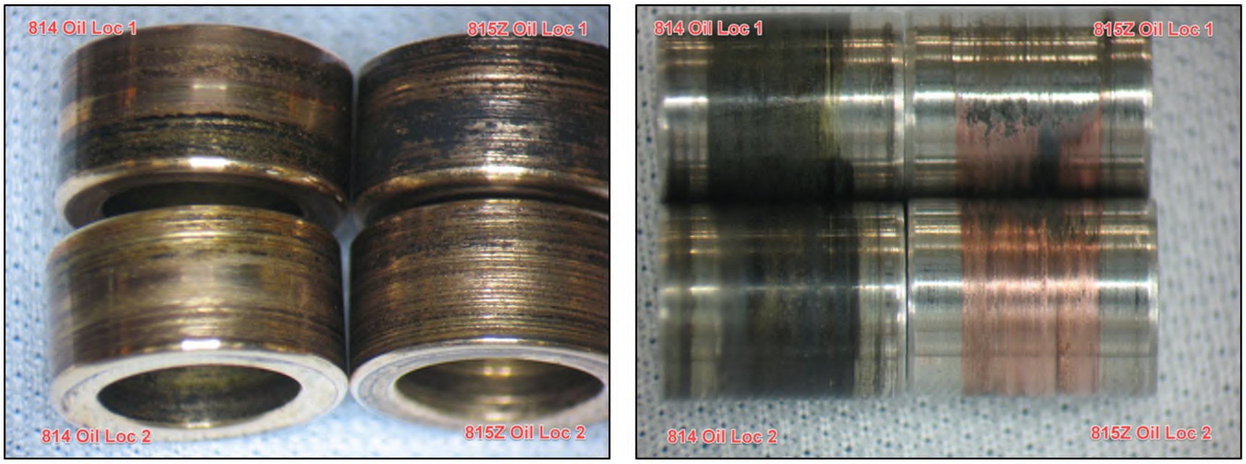


Figure 10. Bushings (Left) and Posts (Right) at the Conclusion of Wear Testing

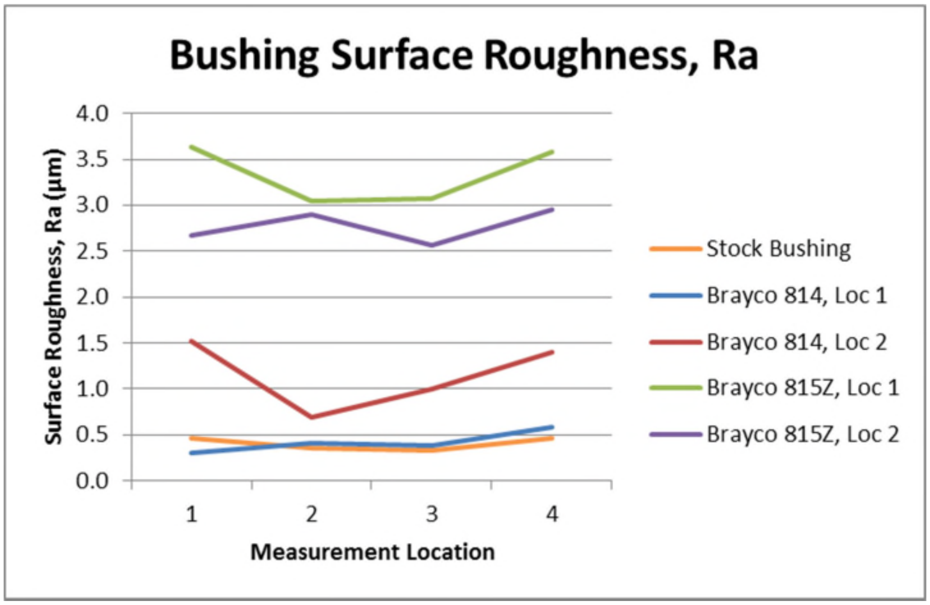


Figure 11. Bushing OD Surface Roughness Measurements

Conclusions

Developmental testing to inform design decisions and provide confidence in qualification life was successfully completed. These developmental tests were not intended to address all possible operational variables, but were specifically targeted to the mission parameters of these Mars 2020 gearbox designs.

Several other observations, conclusions, and areas for future work were recorded as a result of this developmental testing:

- If necessary and financially feasible, a parallel path of procurement different design options while awaiting developmental test results can preserve accelerated program schedules by allowing final design decisions to be informed by those test results.
- PFPE-family lubricants may have successful use for short durations at higher Hertzian contact stresses than previously published. Testing of mission-specific operational characteristics is recommended.
- The extremely cold operating temperatures for Mars mechanisms are particularly challenging for wet lubrication schemes since operation at temperatures near the lubricant pour point may result in poor lubricant mobility, leading to starvation and insufficient protection of wear surfaces, especially for porous bushings.
- While bushings lubricated with either oil completed testing successfully in the flight-like gearbox, bushings lubricated with Brayco 814 oil exhibited less wear than those lubricated with Brayco 815Z oil in SNC's development testing, likely due the lower viscosity of Brayco 814 oil at cold temperatures.
- Every effort should be made to scrutinize test fixtures and test components in the most flight-representative configuration possible to prevent false failures, as was believed to have occurred in the component-level bushing test.

Acknowledgements

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