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Performance Evaluation of an Actuator Dust Seal for Lunar Operation

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Summary

Exploration of extraterrestrial surfaces (e.g., Moon, Mars, asteroid) will require durable space mechanisms that will survive potentially dusty surface conditions in addition to the hard vacuum and extreme temperatures of space. Baseline tests with lunar simulant were recently completed at the NASA Glenn Research Center (GRC) on a new Low-Temperature Mechanism (LTM) dust seal for space actuator application. Following are top-level findings of the tests completed to date in vacuum using NU-LHT-2M lunar-highlands simulant. A complete set of findings are found in the conclusions section.

- Tests were run at approximately 10^{-7} torr with unidirectional rotational speed of 39 RPM.
- Initial break-in runs were performed at atmospheric conditions with no simulant. During the break-in runs, the maximum torque observed was 16.7 lbf-in. while the maximum seal outer diameter temperature was 103 °F.
- Only 0.4 mg of NU-LHT-2M simulant passed through the seal/shaft interface in the first 511,000 cycles while under vacuum despite a chip on the secondary sealing surface.
- Approximately 650,000 of a planned 1,000,000 cycles were completed in vacuum with NU-LHT-2M simulant.
- Upon test disassembly NU-LHT-2M was found on the secondary sealing surface.

Nomenclature

ACD	NASA's Advanced Capabilities Division
AMS	Aerospace Materials Specification
ESMD	NASA's Exploration Systems Mission Directorate
ETDP	NASA's Exploration Technology Development Program
IPP	NASA Innovative Partnership Program
JSC-1A	Lunar Mare Regolith Simulant
LTM	Low Temperature Mechanism
NI	National Instruments
NU-LHT-2M	NASA/USGS-Lunar Highlands Type 2 Medium Grade
SMM	NASA's Structures Materials and Mechanisms Project

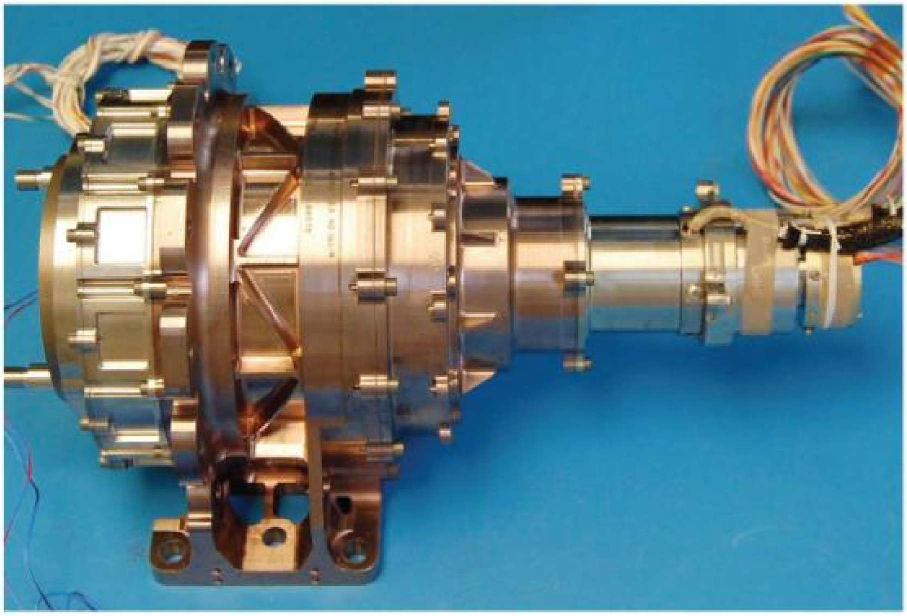

Figure 1.—Mars Science Laboratory (MSL) Robotic Arm Shoulder/Elbow Actuator.

Background

Funded through the NASA Innovative Partnership Program the performance tests on Aeroflex's dust seal were performed in cooperation with Aeroflex, NASA Langley Research Center (LaRC), NASA Jet Propulsion Laboratory (JPL), and GRC. GRC researchers from the Tribology and Mechanical Components Branch and the Space Environmental Durability Branch working under NASA's Dust Mitigation Program conducted tests on a novel low-temperature mechanism seal. The Low-Temperature Mechanisms project is under NASA's Exploration Systems Mission Directorate, Advanced Capabilities Division, Exploration Technology Development Program (ETDP), Structures Materials and Mechanisms Project. The Dust Mitigation Program falls under ETDP.

Dust seal technology originally developed for the Mars Exploration Rover (MER) program (Wheel Steering Actuator) by Aeroflex was developed for use on mechanisms for the lunar surface. The seals would be used to prevent lunar dust from entering mechanism compartments such as an actuator compartment, Figure 1 (Ref. 1). Key customer requirements for the actuator motor include:

- 5 years operational life in the lunar environment.
- 300 million motor revolutions or 10,000 km of traverse
- 70 thermal cycles at lunar conditions

Test Objectives and Requirements

Aeroflex was tasked to deliver a redesigned lunar dust seal to GRC, LaRC, and JPL for performance evaluation. LaRC was responsible for performing tests at vacuum and lunar-like surface temperature while GRC was responsible for performing tests at vacuum with lunar simulant at ambient temperature. Performance parameters included seal drag and seal temperature rise. Seal drag torque measurements were required to provide adequate torque margin for the motor. Seal metal temperature measurements were required to quantify the heat generation to the actuator due to seal-shaft friction. Following initial break-in tests under atmosphere and vacuum, the seal was planned to be tested for 1,000,000 cycles under vacuum with lunar stimulant added to the shaft/seal interface.

Given the above customer requirements the test objectives were as follows:

1. Assess seal durability in a simulated lunar environment.
2. Assess seal drag torque generated in a simulated lunar environment.
3. Assess seal temperature rise due to drag torque generated during simulated testing.

Two sets of test seals and shafts were run-in at Aeroflex prior to delivery to GRC. Seal drag torque was measured at low RPM both clockwise (CW) and counterclockwise (CCW) and was found to increase with decreasing temperature. Also, a constant test speed of 39 rpm was selected based on the actuator design. The actuator contained a three-stage gearbox at 4:1 gear reduction per stage with an overall 64:1 speed reduction from the input shaft speed of 2,500 rpm. Since future missions to the Moon might include its polar regions, the simulant NU-LHT-2M was chosen as its particle composition differs from JSC-1A, a mare type simulant, as shown in Table 1 (Ref. 2).

Experimental Set-Up

Seals

Two seals were delivered to GRC for evaluation. The seal comprised both a primary and secondary sealing interface. Surface finish measurements were made of the Aeroflex test shaft using a Taylor-Hobson PGI 1200 Form Talysurf at four circumferential locations resulting in an average surface finish of 13 µin., Figure 2. Figure 3 shows pre-test data at one axial location on the shaft surface.

TABLE 1.—PARTICLE TYPE MODAL DATA, AND PLAGIOCLASE MOLAR% ANORTHITE, FOR THE LUNAR REFERENCE MATERIAL (REF. 2)

	64001/ 64002	NU-LHT-1M	NU-LHT-2M	OB-1	JSC-1	JSC-1A	JSC-1AF	FJS-1	MLS-1
Lithic Fragments	31.11	0.00	0.00	0.00	90.92	90.92	91.93	80.18	52.28
Glass	8.88	22.37	7.17	52.63	0.00	0.00	0.00	0.53	36.57
Agglutinates	32.51	29.02	23.49	0.00	0.00	0.00	0.00	0.00	0.00
Plagioclase	23.32	38.78	54.89	43.95	1.54	1.54	3.39	14.11	2.60
(Plag. An%)	95	80	80	75	68	70	70	50?	47
Olivine	0.00	2.88	9.51	0.04	5.63	5.63	4.13	1.13	0.01
Clinopyroxene	0.64	2.04	3.98	0.07	1.33	1.33	0.42	1.20	2.21
Orthopyroxene	3.24	4.37	0.20	0.00	0.01	0.01	0.01	0.04	0.03
Spinel minerals	0.03	0.05	0.01	0.19	0.00	0.04	0.02	0.05	0.03
Fe-sulfide	0.01	0.00	0.04	0.00	---------	0.00	0.00	0.00	0.00
Ca-phospates	0.12	0.00	0.43	0.00	0.00	0.00	0.00	0.00	0.00
Ilmenite	0.13	0.33	0.19	0.00	0.00	0.08	0.00	0.15	1.07
Native Iron	0.01	0.00	0.00	0.00	--------	0.00	0.00	0.00	0.00
Other (sim. only)	--------	0.16	0.07	3.12	--------	0.46	0.09	2.62	5.21
Total	100	100	100	100	100	100	100	100	100

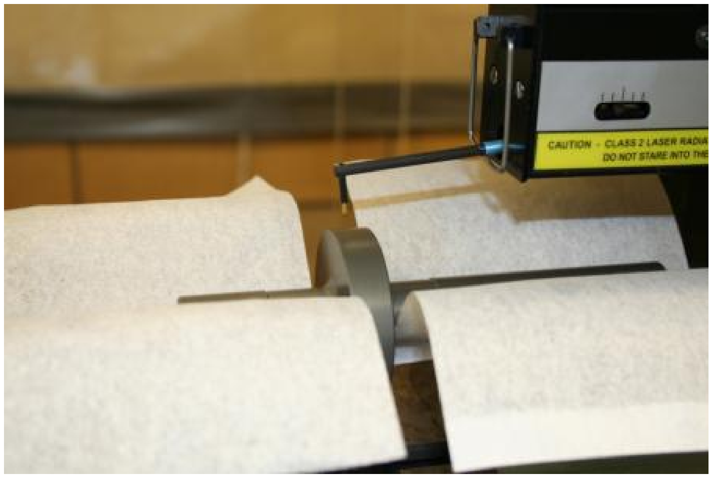

Figure 2.—Profilometry of Aeroflex Test Shaft.

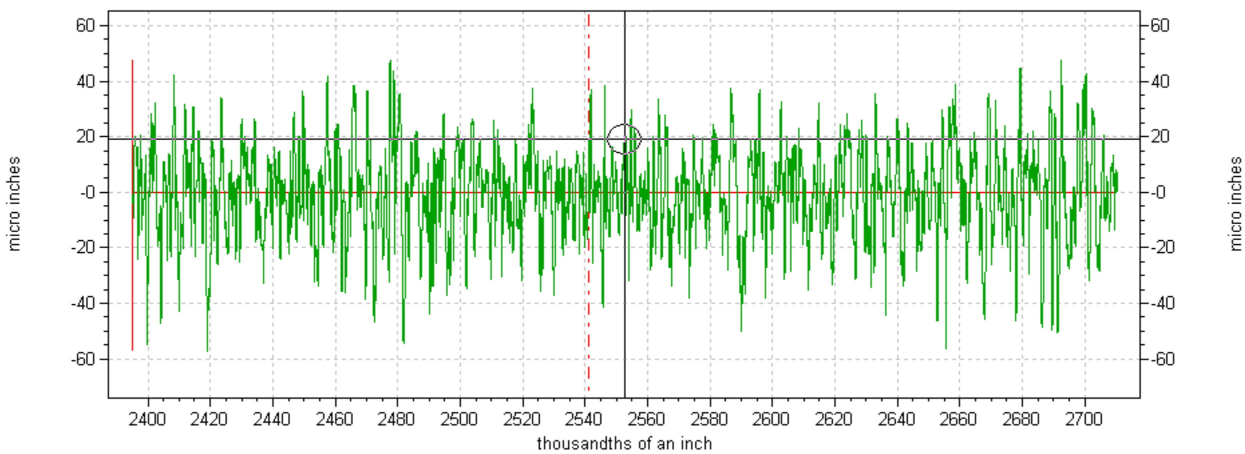

Figure 3.—Sample Surface Profile of Aeroflex Test Shaft.

Vacuum Bell Jar, Instrumentation, DAQ

Tests were performed on a dust seal test stand enclosed within in a vacuum bell jar capable to 10^{-7} torr, Figure 4. Due to space constraints, the seal and shaft were tested with the seal and shaft centerlines oriented vertically within the vacuum bell-jar. The test set-up represented a more conservative approach relative to a horizontal test shaft arrangement (e.g., lunar rover on the surface of the Moon) in that it allowed the simulant to flow freely through the shaft/seal interface. The seal was clamped between machined aluminum blocks with the seal assembly sitting on a machined Teflon disk which, in turn, sat on a platform. The test shaft had a slight interference fit with the secondary sealing interface on the order of 0.001 to 0.002 in.

The upper aluminum block had armatures positioned 180° apart which contacted Omegadyne compression load cells (Model LC302-25, 25 lb range, ± 0.5 percent FSO accuracy) rigidly mounted on the machined platform. Friction generated between the shaft and seal generated a torque which was sensed as a compression load on the load cells. Torque was calculated from each load cell using two inches as the moment arm (i.e., nominal distance from the shaft centerline to the load cell centerline). The total torque due to friction between the seal and shaft was the sum of the torques calculated from each load cell. Friction between the bottom aluminum block and the Teflon spacer was assumed negligible. The load cells' calibration was validated by applying 0 to 10 lbf-in. of torque using a Precision Instruments torque wrench (Model DS1F384CZHM, Range 24 lbf-in., 0.05 lbf-in. accuracy) to the hex nut rigidly attached to the cup clamped on top of the test shaft. Comparison of the applied torque to the output of the load cells showed a one-to-one correspondence with an R^2 value of 0.99. Finally, thermocouples were placed on the outer diameter of the seal and within the free-space of the bell-jar, Figure 5. Cycles were measured through existing motor outputs.

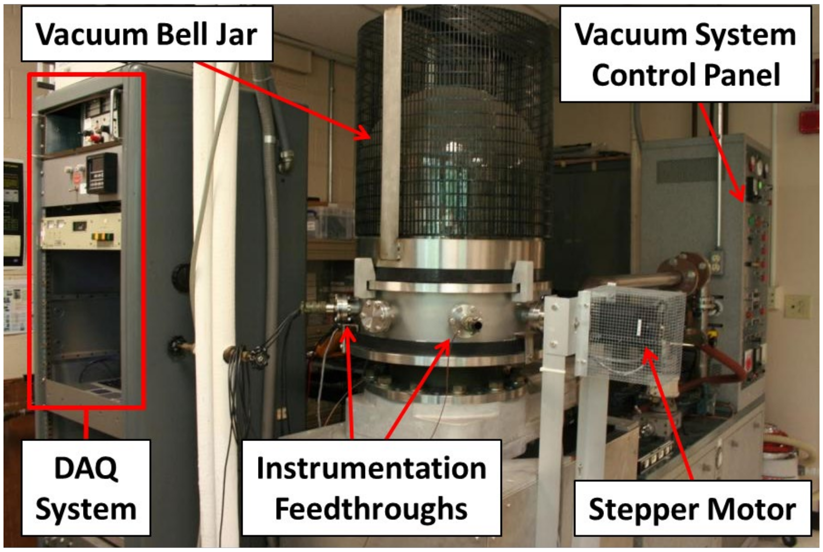

Figure 4.—GRC Vacuum Bell Jar Test Set-Up.

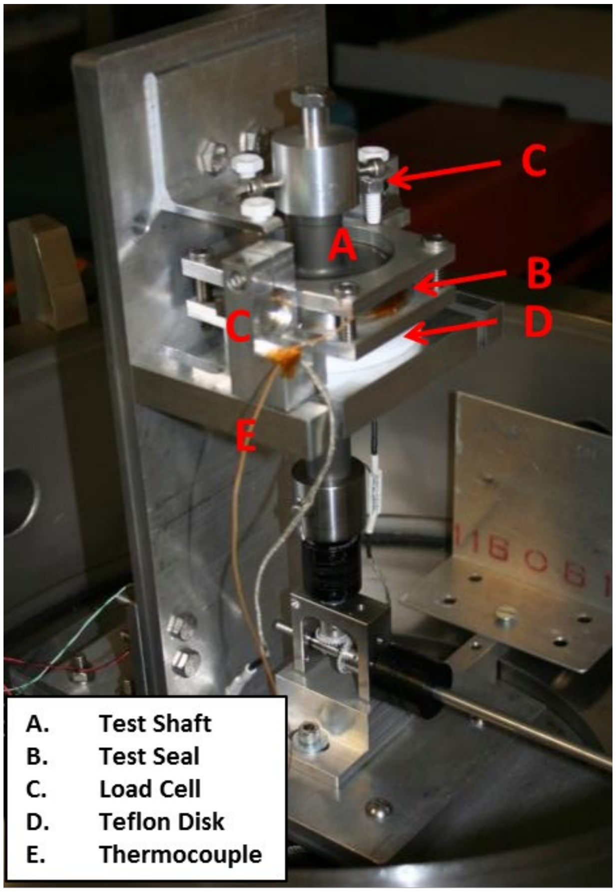

Figure 5.—Dust Seal Test Stand.

Data were acquired at 4 Hz continuously or manually through a LabView program via a National Instruments cDAQ-9172 chassis with NI analog input four-channel modules 9211 (24-bit, ±80 mV, 14 S/s), 9264 (16-bit , ±10 V, 25 kS/s/ch), and cRIO-9215 (16-bit , ±10 V, 100 kS/s/ch). The program monitored and recorded seal torque, seal temperature, and cycles. The motor direction, speed, and number of cycles were controlled through LabView.

General Test Procedure

The torque-arms were positioned to slightly contact the load cells. For tests with simulant, pre-weighed NU-LHT-2M was poured carefully onto the top of the shaft/seal interface as shown in Figure 6. Then, the bell-jar was closed and a vacuum was applied. The test set-up was allowed to stabilize overnight. Prior to starting the motor, the vacuum level was measured, typically 10^{-7} torr. The seal temperature was also measured and the load cells were nulled in LabView. The rotational speed was pre-set to 39 RPM and the number of cycles was set, typically 20,000. Time, cycle count, seal temperature, and seal torque were recorded at a rate of 4 Hz. The test was monitored at regular intervals throughout the day. Daily tests were complete approximately 8.5 hr from start.

Because of the limited number of prototype seals available for testing, testing occurred in three phases to methodically step through break-in testing through both vacuum and simulant testing, Table 2.

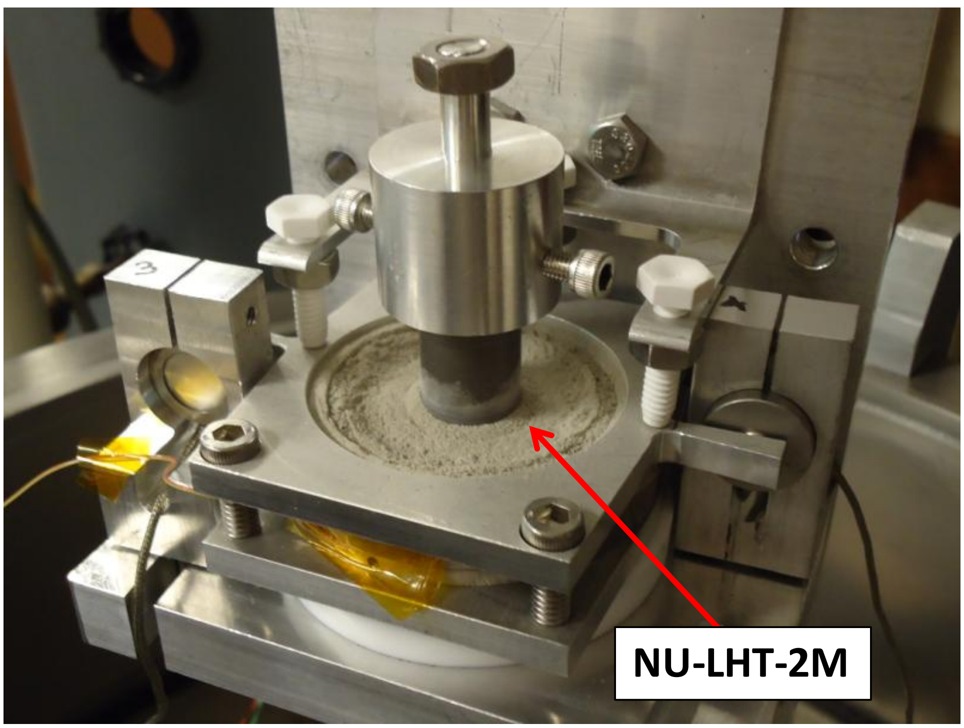

Figure 6.—Dust Seal Test Stand Loaded with NU-LHT-2M.

TABLE 2.—PLANNED DUST SEAL TEST PHASES

Test phase	Temperature	Nominal pressure	NU-LHT 2M simulant	Comments
1	Ambient	Ambient	No	Break-in
2	Ambient	Vacuum	No	Test vacuum effects
3	Ambient	Vacuum	Yes	Test simulant and vacuum effects

Results and Discussion

Test Phase 1: Break-In Tests at Ambient Conditions, No Simulant

The first series of tests were performed for intentionally short durations at ambient conditions to slowly break in the seal and shaft into a matched set. The run-in period was continued until torque and temperature measurements approached steady-state values. Four main tests runs of 2,500, 2,000, 12,000, and 1,048 cycles provided break-in seal temperature and seal drag torque data. Approximately 18,000 cycles were completed during break-in runs, Table 3. Torque data from break-in tests show a repeatable quick initial rise to peak values followed by a relatively slower asymptotic to steady-state values. Data scatter increasingly varied from 1 to 4 lbf-in., Figure 7. The data scatter is likely due to inadvertent misalignment at the right-angle gearbox to test shaft connection followed by premature wear of the gearbox housing bearings. The gearbox housing was replaced and realigned with the test shaft prior to Phase 2 testing. Additionally, Braycote 601 was applied to the gearbox prior to the start of each subsequent test. Temperature data during break-in tests show a relatively linear rise to steady-values with data scatter less than 1 °F, Figure 8.

Data for the initial 2,500 cycle break-in test was lost due to data acquisition issues. Reconstruction of the data by the test engineer is shown in Figure 9. Characteristically, seal torque values appear to peak early (16.79 lbf-in. at 266 cycles) in the test run followed by a gradual decrease in levels towards the end of the test. Similarly, seal temperature values follow a gradual rise to peak levels (103.2 °F at 1,333 cycles). During the 2,500 cycle break-in run strong mechanical oscillatory noise levels were observed from the test set-up. At approximately 1,333 cycles a noticeable drop in noise levels was observed. From 2,223 cycles to the end of the test sound levels were negligible. It is likely that the inadvertent misalignment mentioned earlier at the gearbox to test shaft connection led to unwanted axial and periodic once-per-rev seal wear in addition to the expected circumferential wear.

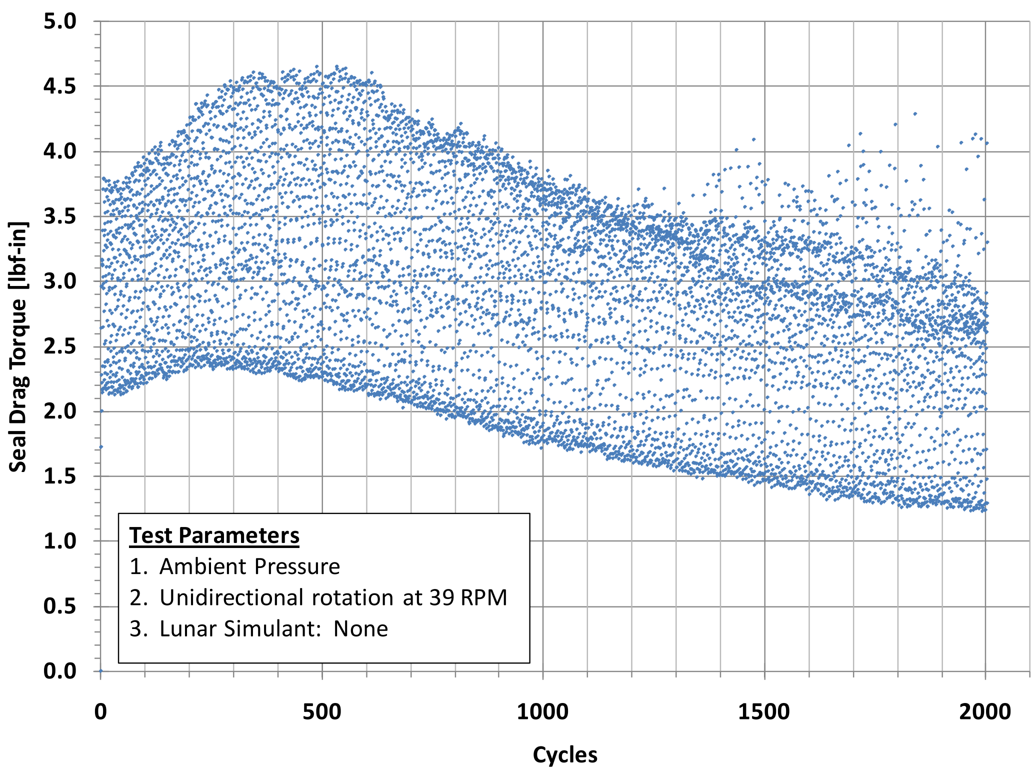

Figure 7.—Aeroflex Dust Seal Performance Test at GRC. Test 5, Table 3.

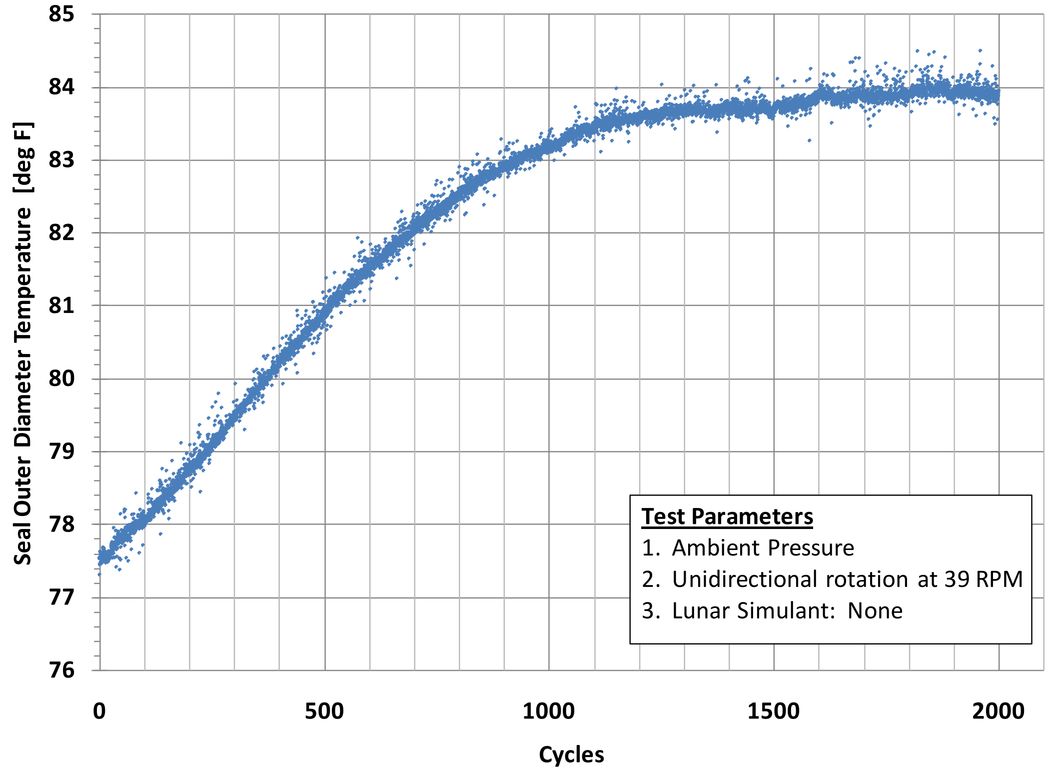

Figure 8.—Aeroflex Dust Seal Performance Test at GRC. Test 5, Table 3.

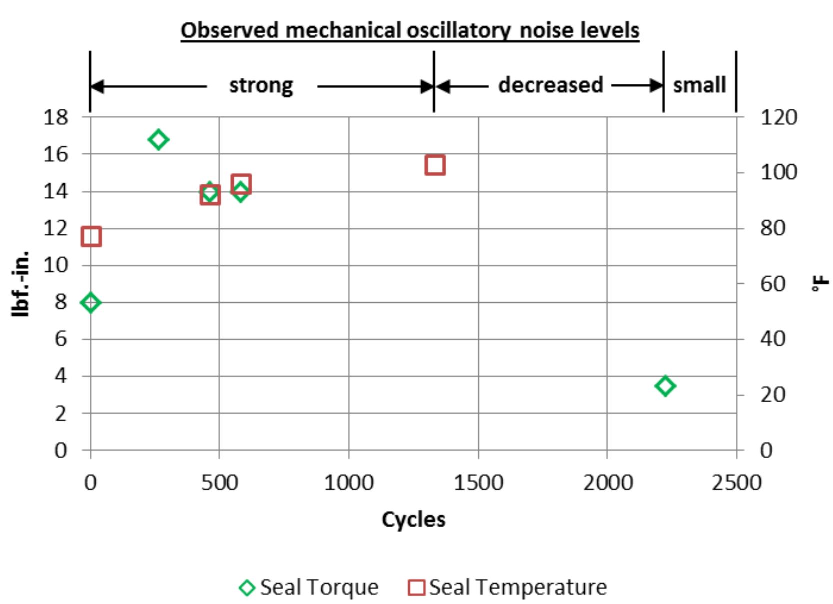

Figure 9.—Reconstructed data for the initial 2,500 cycle test for the Aeroflex Dust Seal at ambient conditions with no simulant.

TABLE 3.—DUST SEAL TEST LOG

Test no.	Description	Cycles completed	Total cycles	Cycles (vacuum, simulant)
1	atm, no simulant, sys check	96		N/A
2	atm, no simulant, sys check	170	266	N/A
3	atm, no simulant, break-in	2,500	2,766	N/A
4	atm, no simulant, sys check	450	3,216	N/A
5	atm, no simulant, break-in	2,000	5,216	N/A
6	atm, no simulant, break-in	12,000	17,216	N/A
7	atm, no simulant, break-in	1,048	18,264	N/A
8	atm, no simulant, sys check	133	18,397	N/A
9	atm, no simulant, sys check	40	18,437	N/A
10	5×10^{-7} torr, no simulant	2,000	20,437	N/A
11	4×10^{-7} torr, NU-LHT-2M	14,040	34,477	14,040
12	3×10^{-7} torr, NU-LHT-2M	14,040	48,517	28,080
13	$?\times10^{-7}$ torr, NU-LHT-2M	10,000	58,517	38,080
14	$?\times10^{-7}$ torr, NU-LHT-2M	21,060	79,577	59,140
15	$?\times10^{-7}$ torr, NU-LHT-2M	21,060	100,637	80,200
16	3×10^{-7} torr, NU-LHT-2M	21,060	121,697	101,260
17	2×10^{-7} torr, NU-LHT-2M	18,720	140,417	119,980
18	2×10^{-7} torr, NU-LHT-2M	21,060	161,477	141,040
19	3×10^{-7} torr, NU-LHT-2M	20,000	181,477	161,040
20	4×10^{-7} torr, NU-LHT-2M	20,000	201,477	181,040
21	3×10^{-7} torr, NU-LHT-2M	17,500	218,977	198,540
22	2×10^{-7} torr, NU-LHT-2M	20,000	238,977	218,540
23	2×10^{-7} torr, NU-LHT-2M	15,000	253,977	233,540
24	2×10^{-7} torr, NU-LHT-2M	20,000	273,977	253,540
25	3×10^{-7} torr, NU-LHT-2M	20,000	293,977	273,540
26	3×10^{-7} torr, NU-LHT-2M	20,000	313,977	293,540
27	2×10^{-7} torr, NU-LHT-2M	20,000	333,977	313,540
28	2×10^{-7} torr, NU-LHT-2M	20,000	353,977	333,540
29	2×10^{-7} torr, NU-LHT-2M	20,000	373,977	353,540
30	2×10^{-7} torr, NU-LHT-2M	20,000	393,977	373,540
31	3×10^{-7} torr, NU-LHT-2M	20,000	413,977	393,540
32	2×10^{-7} torr, NU-LHT-2M	20,000	433,977	413,540
33	3×10^{-7} torr, NU-LHT-2M	18,000	451,977	431,540
34	2×10^{-7} torr, NU-LHT-2M	20,000	471,977	451,540
35	3×10^{-7} torr, NU-LHT-2M	20,000	491,977	471,540
36	3×10^{-7} torr, NU-LHT-2M	20,000	511,977	491,540
37	2×10^{-7} torr, NU-LHT-2M	20,000	531,977	511,540
38	3×10^{-7} torr, NU-LHT-2M	20,000	551,977	531,540
39	3×10^{-7} torr, NU-LHT-2M	20,000	571,977	551,540
40	4×10^{-7} torr, NU-LHT-2M	20,000	591,977	571,540
41	3×10^{-7} torr, NU-LHT-2M	20,000	611,977	591,540
42	3×10^{-7} torr, NU-LHT-2M	20,000	631,977	611,540
43	2×10^{-7} torr, NU-LHT-2M	20,000	651,977	631,540
44	3×10^{-7} torr, NU-LHT-2M	20,000	671,977	651,540

CTE Effects

The seal temperature rise measured at its outer diameter is consistent with the measured initial 0.001 to 0.002 in. interference fit between the seal and shaft. The frictional heat generated at the seal-shaft interface increased the temperature of both components causing simultaneous thermal growth. In addition, because the secondary sealing surfaces have a thermal expansion coefficient (CTE) approximately six times higher than the test shaft, the steady-state assembly temperature would need to increase by 10 to 40 °F to allow a 'non-interfering' line-to-line contact at the seal shaft interface, Figure 10. This temperature range depends on potential manufacturing tolerance variations for both seal and shaft. Also, the thermal mismatch suggests a 'warm-up' period for the seal-shaft pair in which higher initial torque and temperature levels would be observed. Finally, since two secondary sealing surfaces are in contact with the shaft, the frictional heat generated will be greater due to twice the surface area in contact with the shaft. Note that the temperature and heat generated at the interface is higher than observed since seal temperature is currently measured at the outer diameter of the seal rather than at its inner diameter.

Consider also at the end of every test, based on the seal/shaft diametral tolerances and corresponding CTEs, the secondary sealing surfaces will tend to cool first due to their higher CTE than the shaft. It is speculated that the secondary sealing surfaces may briefly contact the shaft until thermal equilibrium is re-established. The amount of seal-shaft interference would depend on component wear levels and initial assembly interference fits. During Phase I testing the maximum temperature rise, ~26 °F, corresponded with the peak torque of 16.7 lbf.-in. Because of the misalignment found during post-test inspection, the heat generated would be a combination of initial interference fit and misalignment. Subsequent tests during Phase I testing showed less than a 10 °F temperature rise. Corresponding seal drag torque levels were also well below the 16.7 lbf-in. peak, with levels no higher than approximately 6 lbf-in.

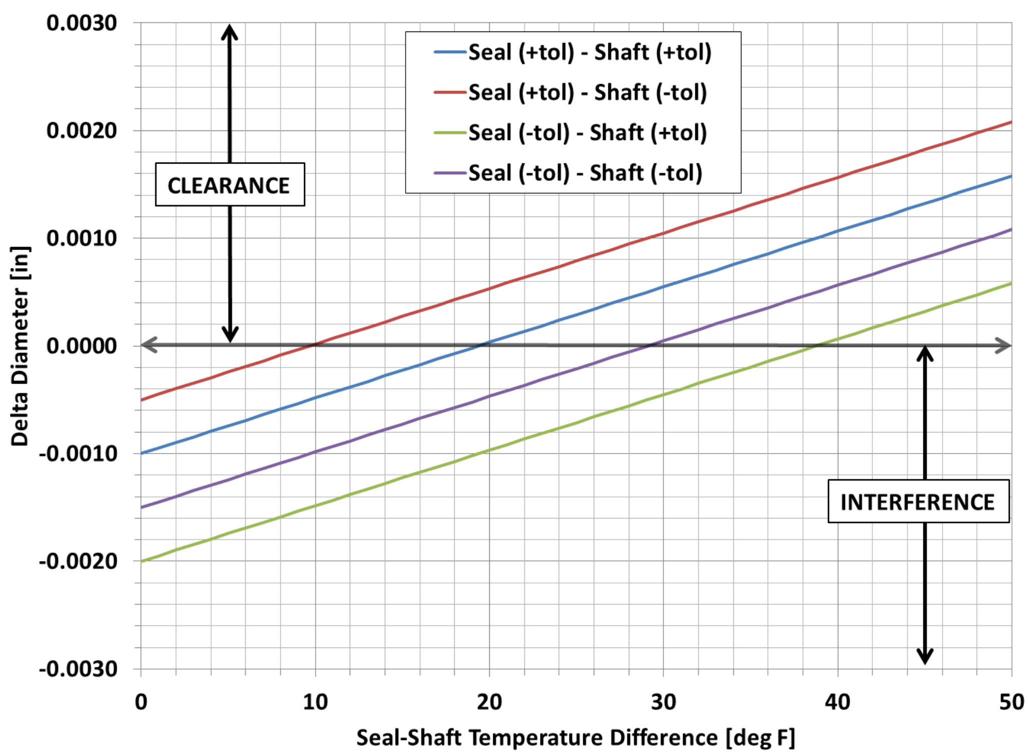

Figure 10.—Calculated final diameter differences between seal and shaft interfaces after temperature rise.

Seal Break-In Performance

In the process of breaking-in the seal-shaft pair into a matched set, some understanding was gained on seal performance from observed temperature and drag torque measurements. The seal temperature at the beginning of each test was found to decrease over the total 18,000 cycles during Phase I testing, Figure 11. The data generally follows a proportional 1/x function starting from a peak of 0.97 °F rise per 50 cycles to about 0.20 °F rise per 50 cycles. After 3,000 cycles the seal temperature rise (0.34 °F per 50 cycles) has dropped over 60 percent from starting values. Because the seal temperature rise may add to unwanted heat load in the overall actuator design (i.e., on-board electronics), a break-in period may be necessary for the seal-shaft combination prior to its intended use. A proportional 1/x relationship is also observed when plotting the seal drag torque rise per 50 cycles versus total number of cycles Figure 12. Note that the

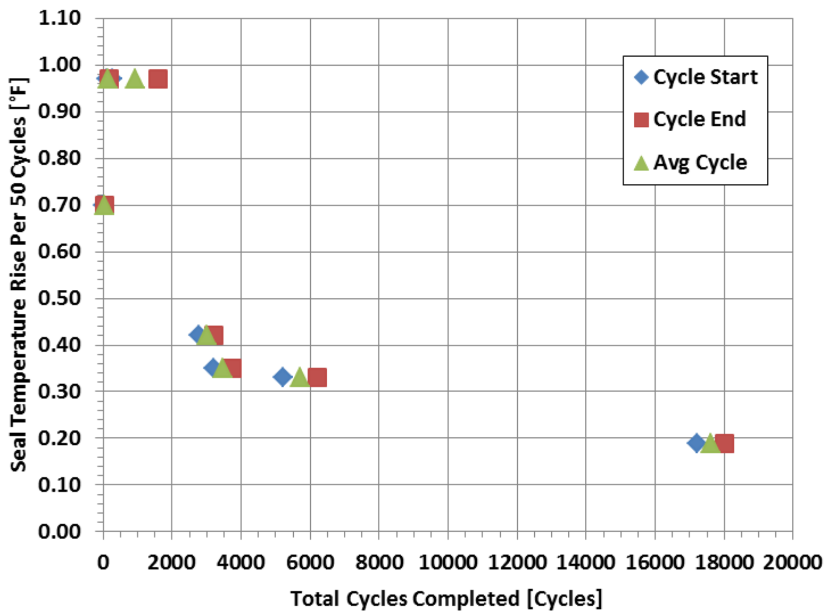

Figure 11.—Seal Temperature Rise Per 50 Cycles at 39 RPM, Ambient, No Simulant.

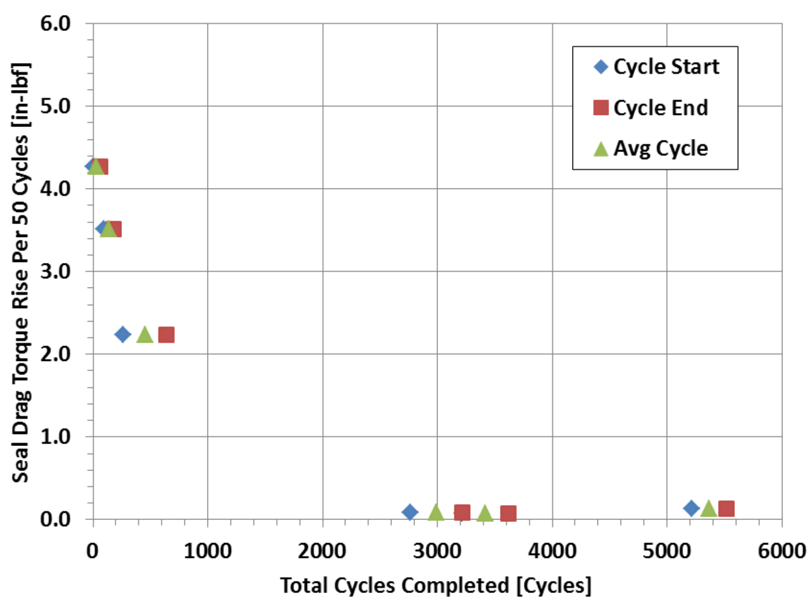

Figure 12.—Seal Drag Torque Rise Per 50 Cycles at 39 RPM, Ambient, No Simulant.

maximum seal drag torque of 16.7 lbf-in. occurred at 643 total cycles corresponding to a slope of 2.23 lbf-in. per 50 cycles. The previous two data sets prior to this maximum observed seal drag torque had observed slopes of 4.27 and 3.52 lbf-in. per 50 cycles. In hindsight, if the previous break-in tests at these slopes had been allowed to run more than a couple hundred cycles each, a higher seal drag torque than the 16.7 lbf-in. might have been observed. After 3,000 cycles the rise in seal drag torque is less than 0.2 lbf-in. per 50 cycles. This represents a drop of over 90 percent in value from the start of this test period. Based on this data, some consideration for a break-in period may be necessary for the seal-shaft pair to mitigate unwanted loading of the actuator.

Test Phase 2: Test in Vacuum without Simulant

During the re-alignment of the seal and shaft but prior to testing in vacuum, a small piece of secondary sealing interface was found to have broken off. It was unclear whether previous testing or disassembly and reassembly of the test set-up caused the piece to fracture in the first place. Despite the fractured piece and the misalignment issues mentioned earlier the seal performed well through at least 500,000 cycles in vacuum.

Since testing priority centered on obtaining seal performance data in vacuum with simulant and because of the various testing issues encountered and overcome during the seal break-in period, the decision was made to perform one test in vacuum without simulant and then to move on to the vacuum/simulant tests. This decision also took into account the limited number of prototype seals available to test and also a concern that the seal life might have inadvertently been used up due to the misalignment issues in the previous test set-up. Thus, the effect of vacuum on seal drag torque or temperature rise without simulant would not be suitably addressed. A 2,000 cycle run was performed in vacuum, approximately 5×10^{-7} torr, and 39 RPM but without simulant. Figure 13 and Figure 14 show the seal drag torque and temperature results of the 2,000 cycle run in vacuum. Seal drag torque levels were between 0.6 to 0.8 lbf.-in. with 0.1 lbf.-in. of data scatter. Corresponding seal temperatures rose approximately 1.3° from 82.6 to 83.9 °F with a data scatter of 0.25 °F. Steady state values were not attained for either seal drag torque or temperature because of the relatively short test run.

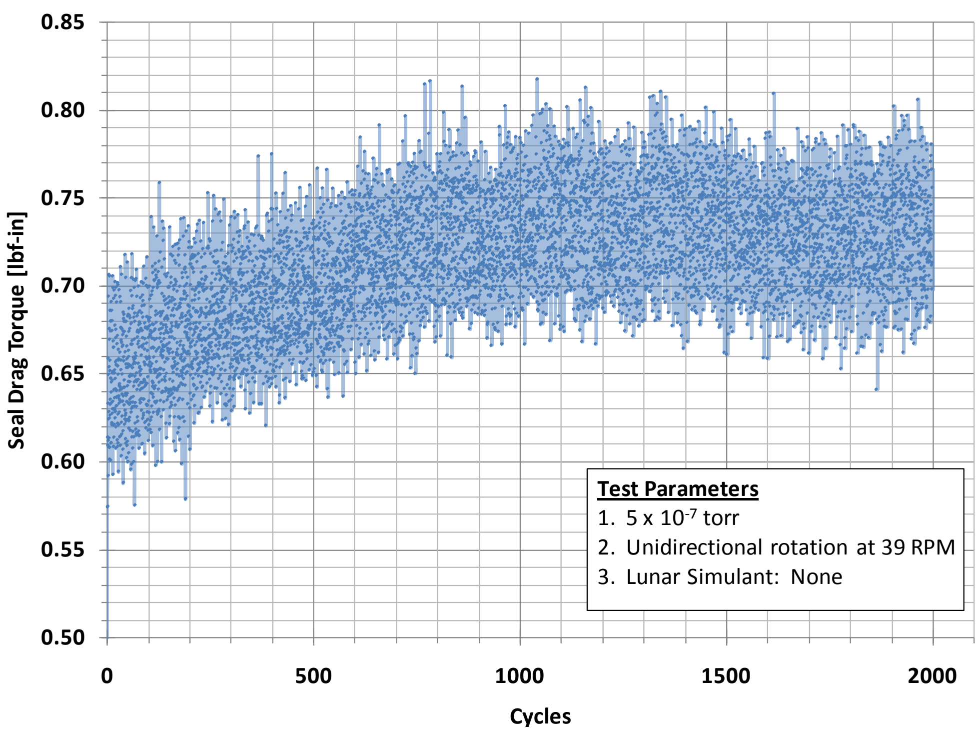

Figure 13.—Aeroflex Dust Seal Performance Test at GRC. Test 10, Table 3.

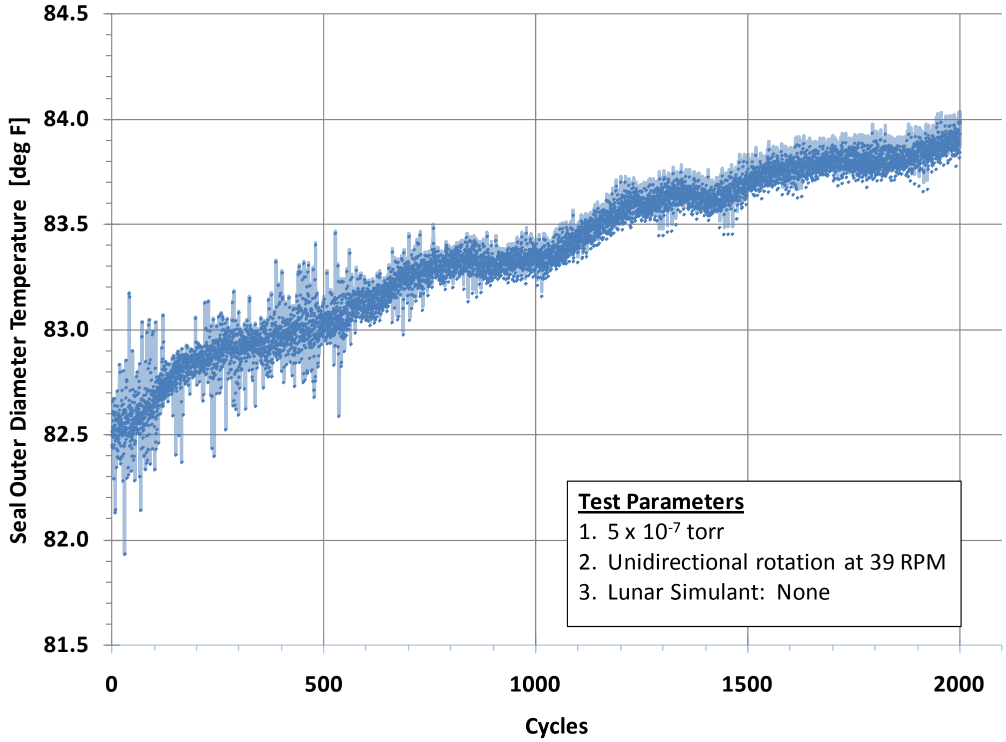

Figure 14.—Aeroflex Dust Seal Performance Test at GRC. Test 10, Table 3.

Test Phase 3: Tests in Vacuum with Simulant

Daily runs of 10,000 to 20,000 cycles per day were run in vacuum with the lunar simulant, NU-LHT-2M, Table 3, Tests 11 through 44. The shaft speed was constant at 39 RPM. The initial plan was to check for dust penetration through the seal-shaft interface at preset intervals. Upon further consideration, it was likely that disturbing the test set-up would confound subsequent test results and prevent comparison to previous test data. More specifically, in the current designed test set-up, precise re-alignment of the shaft and seal could not be guaranteed. Thus, seal torque and temperature would have to be monitored closely to determine if the simulant had penetrated the seal-shaft interface. A good indication of simulant penetration through the interface would be if seal drag torque levels fell below zero. Accounting for the accuracy of the load-cells a calculated value of 0.14 lbf-in. was determined as a seal drag torque lower limit for potential simulant penetration through the interface. Further, a decrease in the seal temperature rise during daily tests would be indicative of reduced friction or interference between the seal and shaft. While a zero temperature rise would certainly suggest little to no friction between the shaft and seal, this test parameter would not clearly indicate simulant penetration through the interface. Some friction may result from rubbing of the simulant between the shaft and seal.

Seal drag torque curves in vacuum with simulant differed from those run at atmospheric conditions without simulant mainly by the lack of a steady rise in torque levels at the start of the test. In fact, nearly all tests run in vacuum with simulant started with an almost immediate maximum in torque levels. Figure 15 and Figure 16 show typical torque and temperature curves. As observed previously, both data sets show a gradual trend to asymptotic values. This immediate maximum was observed to increase to a maximum level on the first eight consecutive tests. Figure 17 shows peak torque levels ranging from approximately 1.2 lbf-in. at the start of the vacuum tests with simulant to 7.6 lbf.-in. around 120,000 cycles.

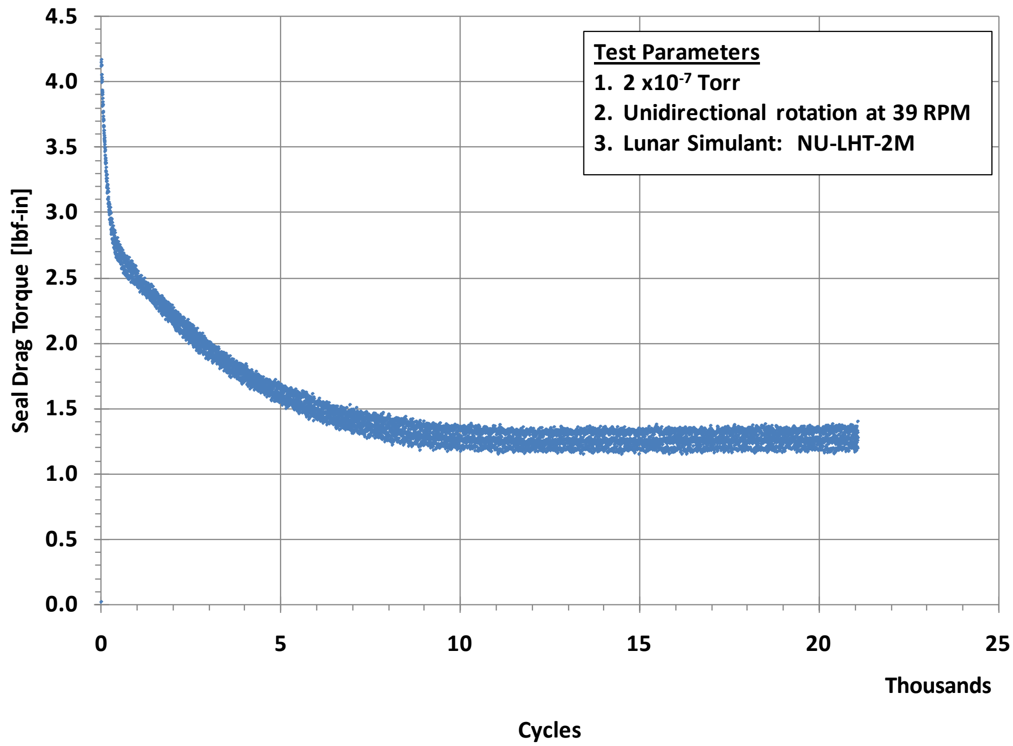

Figure 15.—Characteristic Seal Drag Torque versus Cycle Curve. Test 14, Table 3 .

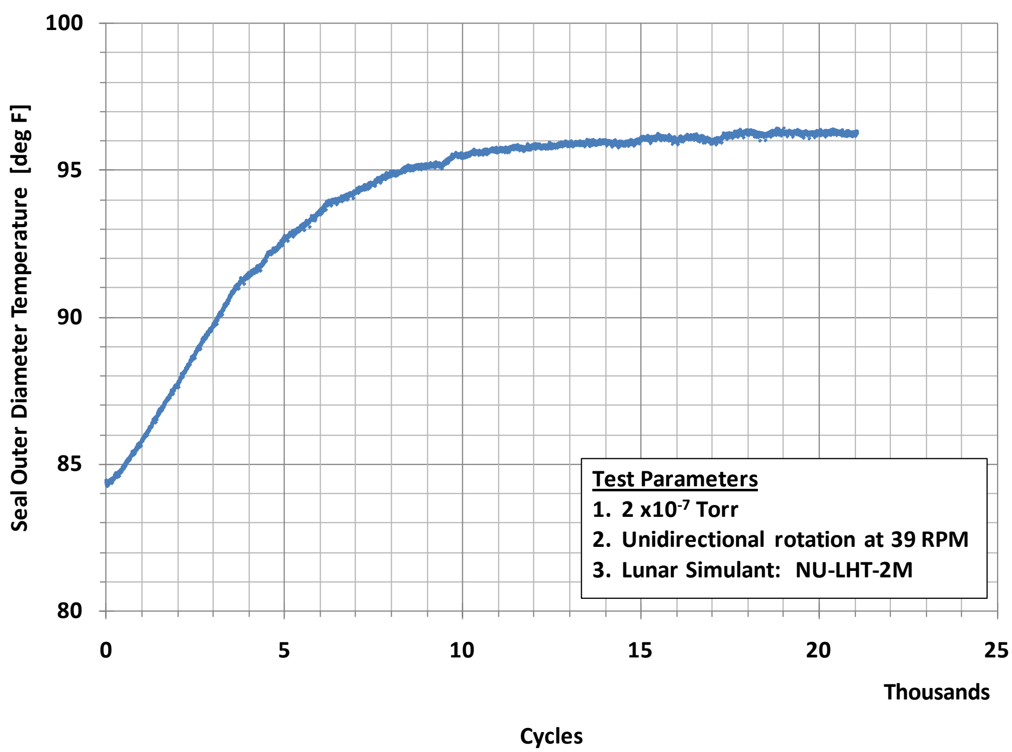

Figure 16.—Characteristic Seal Outer Diameter Temperature versus Cycle Curve. Test 14, Table 3 .

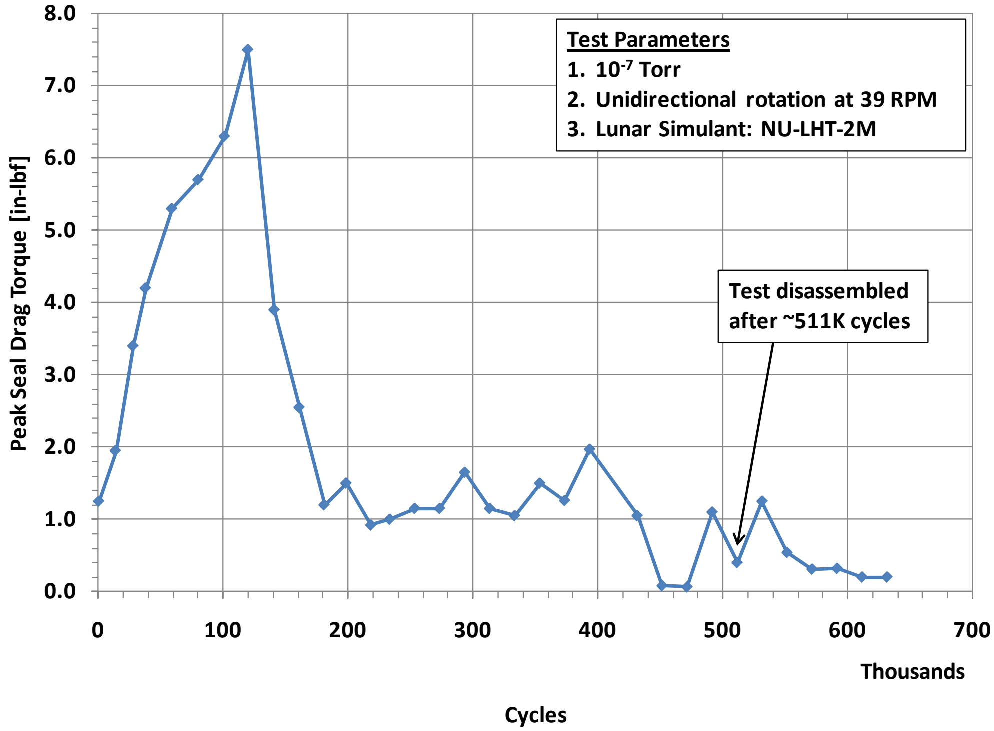

Figure 17.—Aeroflex peak seal drag torque at test start (39 RPM, Vacuum, NU-LHT-2M).

The drop in peak torque levels is indicative of further wear-in of the seal-shaft during this test phase. The initial increase in torque at each test start may also be due to test operations. It is possible that since testing was stopped each day, simulant may have entered the seal-shaft interface via gravity, minute vibrations in the vacuum system, the existing chip in the secondary sealing surface, and possibly small gaps between the seal and shaft due to wear. Without disassembly of the test set-up for reasons already mentioned previously, these hypotheses are noted and unconfirmed. Following these initial test observations, the peak torque level was observed to decrease during successive tests (4.0 and 2.5 lbf-in.) through 160,000 cycles, thereafter remaining in the 1.0 to 2.0 lbf-in. range for the remainder of the tests. The drop in peak torque level is indicative of a much longer break-in phenomena of the seal and shaft pair through 160,000 cycles. Also, it was observed for each test run that the cyclical time period to decrease from peak torque levels to 25 percent of that value decreased with each run through the first 140,000 cycles, Figure 18. This value remained well below 1,000 cycles for the remainder of the testing in vacuum with simulant, indicating a decrease in the long-term seal-shaft wear phenomena discussed previously. Finally, the data provided by Figure 18 provide additional insight into the seal-shaft pair operational start-up torque characteristics.

Figure 19 shows the starting and ending seal outer diameter temperatures over the 600,000+ cyclic test period. Note that the actual seal-shaft interface temperature would be higher than observed at the seal outer diameter. The seal temperature rise for each test during the first 100,000 cycles (8 to 14 °F) were greater than the remainder of the test period (<5 °F) in vacuum with simulant. This generally coincides with the peak torque levels seen in Figure 17. Figure 20 shows a plot of seal temperature rise per 50 cycles over the total number of cycles in vacuum with simulant. This rise in seal temperature has generally been observed at the start of each test until approximately 1,000 to 2,000 cycles had been completed. Again, larger temperature rises were observed during the first 120,000 cycles (0.06 to 0.11 °F per 50 cycles) than during the remainder of tests (0.02 to 0.06 °F per 50 cycles). The highest values are 9 times less than the maximum observed during previous break-in runs (0.96 °F per 50 cycles). These data sets also suggest further wear-in of the seal and shaft during the initial 100,000 to 120,000 cycle time period during tests in vacuum with simulant. They also provide potential operational insight into the seal-shaft temperature rise at start-up.

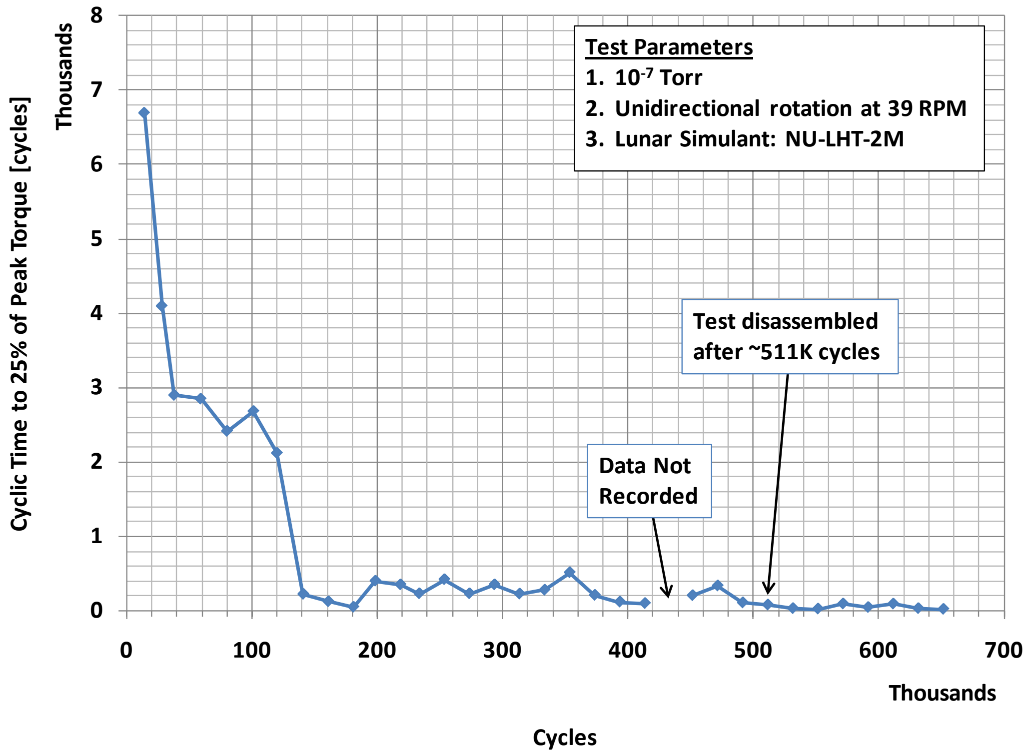

Figure 18.—Cyclic time to 25 percent of peak seal drag torque at 39 RPM, Vacuum, NU-LHT-2M.

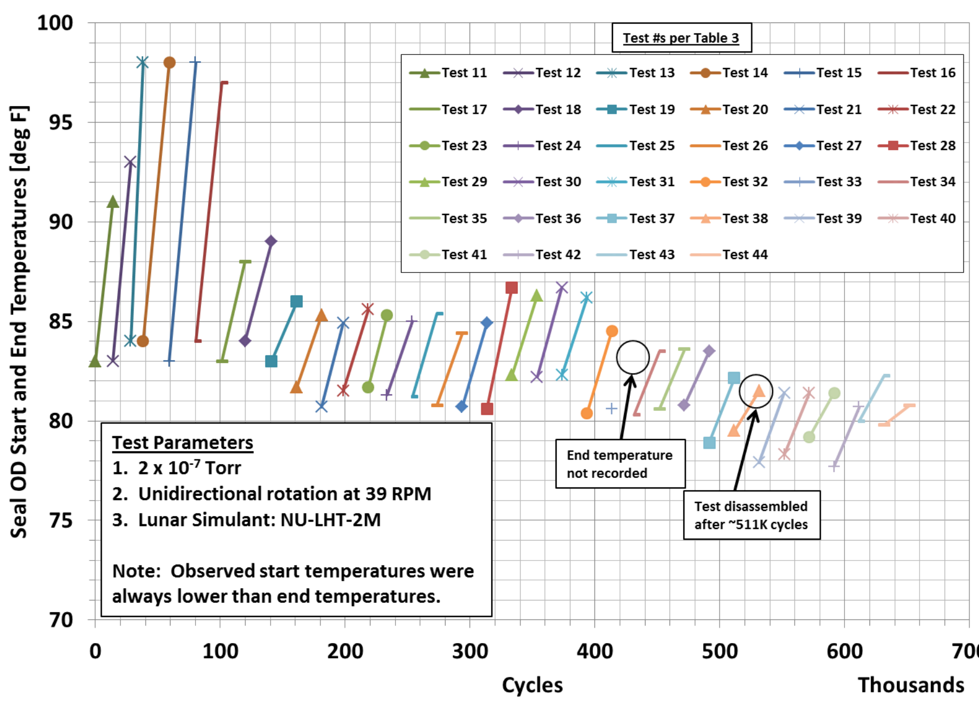

Figure 19.—Seal outer diameter temperature during tests in vacuum with simulant.

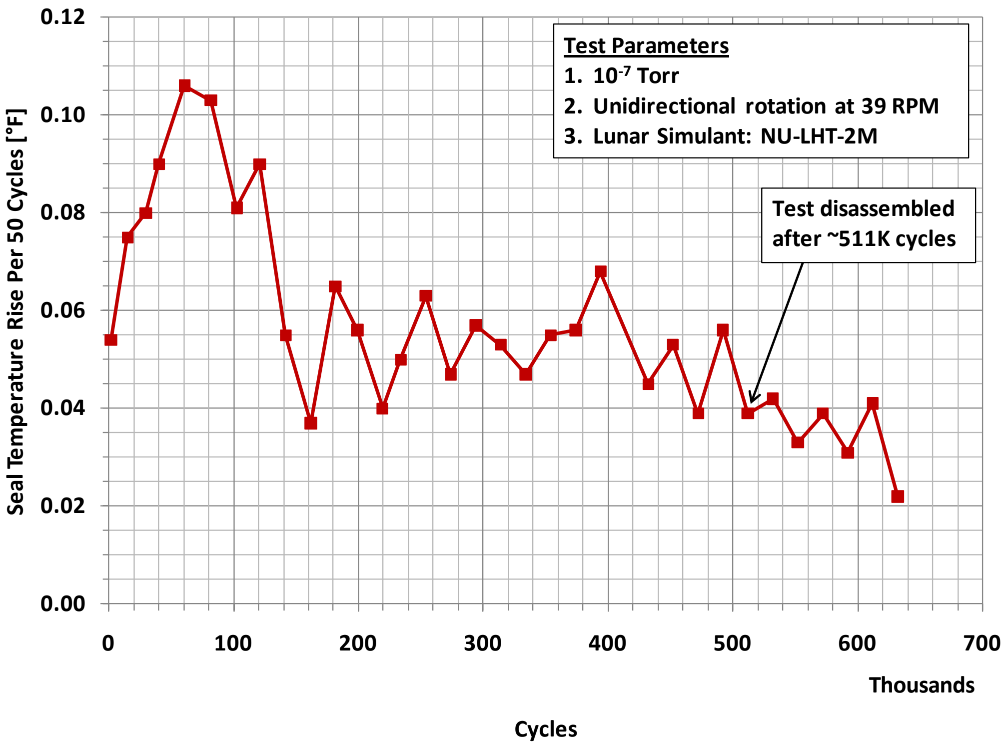

Figure 20.—Seal temperature rise per 50 cycles at start of tests in vacuum with simulant.

Based on the 0.14 lbf.-in. load cell accuracy limits, Figure 21 shows the first time seal drag torque levels were low enough that a statistically zero torque value was plausible. Some simulant penetration through the seal-shaft interface is possible because of the minimal interference between the seal and shaft. The low torque values were observed towards the end of the test at approximately 141,000 total cycles in vacuum with simulant, Test 18, Table 3. Over the next 300,000 cycles with each day of testing completed, more of the torque versus cycle curve would approach this statistical limit. At approximately 471,000 total cycles in vacuum (Test 35, Table 3), seal drag torque values approached essentially 0 lbf.-in., Figure 22. The torque spike that occurred 16,500 cycles for this test may have due to simulant penetration through the seal-shaft interface. Data acquired during the next two days of tests confirm seal drag torque values dropping to zero levels towards the end of the 20,000 cycle run. Thus at 511,000 completed cycles (Test 37, Table 3), the decision was made to check the Teflon disk for simulant. The disk located below the seal-shaft assembly as shown in Figure 5 was designed to capture simulant that penetrated the seal-shaft interface. The remaining simulant located on top of the seals/shaft assembly was carefully vacuumed prior to disassembly of the test fixture. Although seal drag torque measurements were indicative of potential simulant penetration through the interface, upon disassembly of the seal and shaft, approximately 0.4 ± 0.2 mg of simulant were found, Figure 23, which was far less than expected. Table 4 shows the results of the analysis performed which involved carefully weighing four pieces of tape, ‘capturing’ the simulant in the Teflon disk with the tape, and then weighing the tape and simulant together. The seal and shaft were ‘clamped’ together at disassembly to minimize any misalignment in the test set-up. Thus, no further wear observations or measurements were possible on either the seal or shaft.

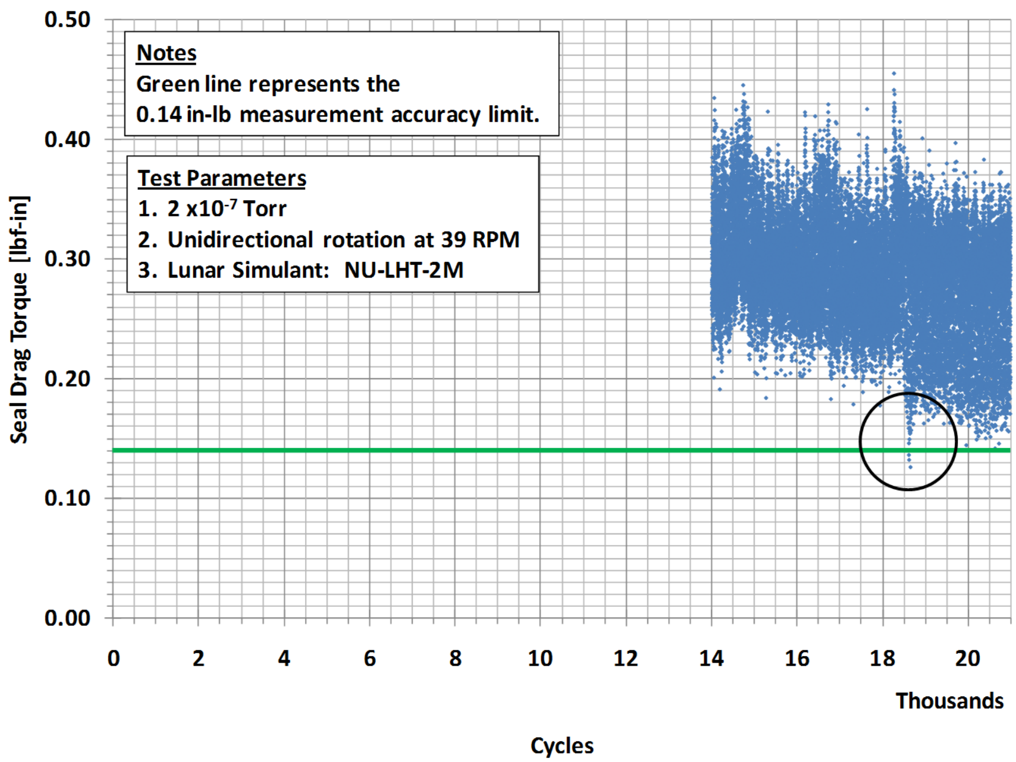

Figure 21.—Seal drag torque approaches statistically zero levels. Approximately 141,000 cycles in vacuum with simulant completed. Test 18, Table 3.

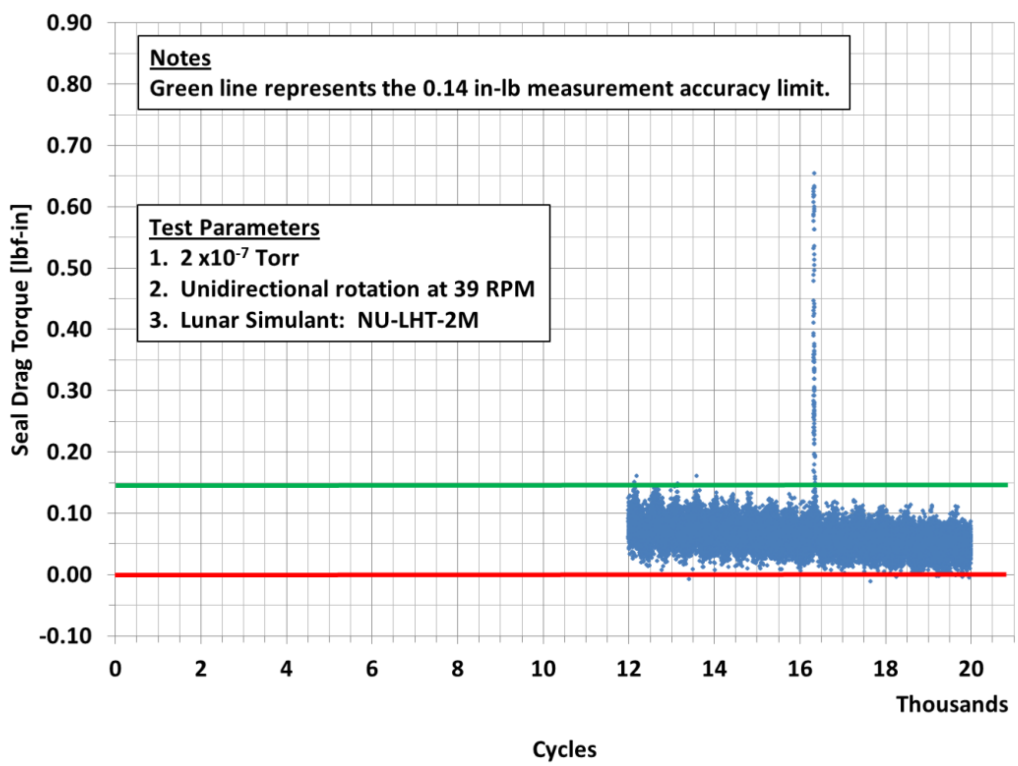

Figure 22.—Seal drag torque approaching zero level values. Approximately 471,000 cycles completed. Test 35, Table 3.

Figure 23.—NU-LHT-2M simulant found (~0.4 mg) at base of Teflon cup after 511,000 cycles in vacuum.

TABLE 4.—AMOUNT OF NU-LHT-2M SIMULANT FOUND IN TEFLON CUP AFTER 511,000 CYCLES IN VACUUM
[Measured in October after 500,000 cycles, in grams.]

Sample	Tare	Tare+Dust	Dust	Error
Tape 1	0.0333	0.0334	0.0001 ±	0.00005
Tape 2	0.0303	0.0304	0.0001 ±	0.00005
Tape 3	0.0369	0.0370	0.0001 ±	0.00005
Tape 4	0.0412	0.0413	0.0001 ±	0.00005
		Total	0.0004 ±	0.0002

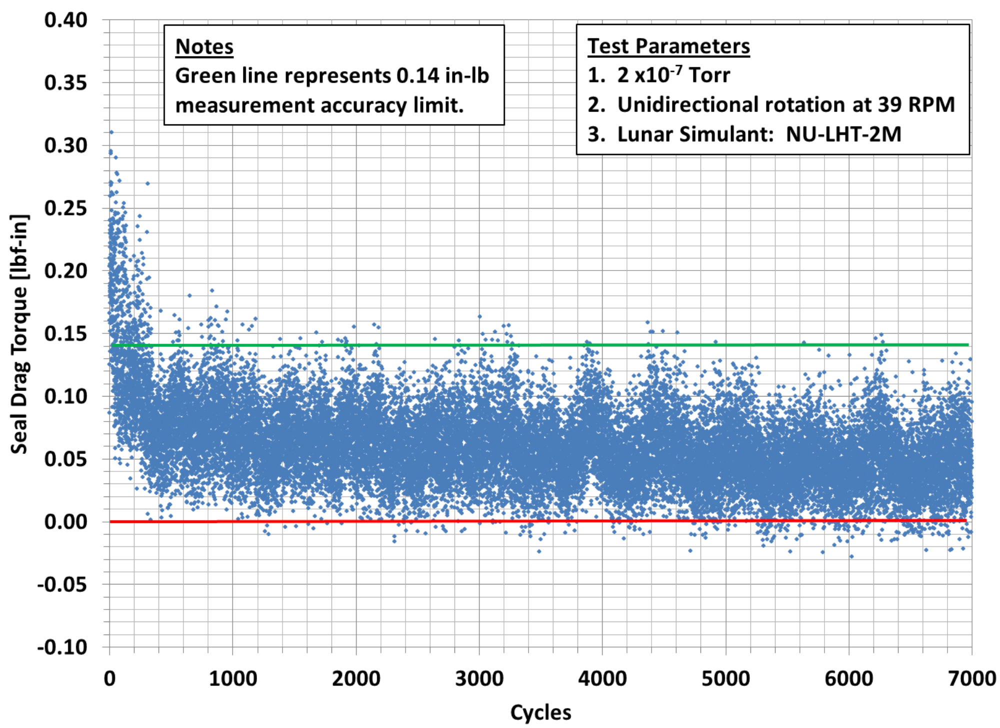

Figure 24.—Seal drag torque beginning to drop below zero levels. Approximately 570,000 cycles (Vacuum and Simulant) completed at start of this test. Test 41, Table 3.

Since a goal of the test program was to attain 1,000,000 cycles under vacuum with simulant, the seal and shaft were carefully reassembled and 11.9 grams of simulant were poured into the opening at the seal-shaft interface located at the top of the assembly. Another 140,000 cycles (seven tests at 20,000 cycles each) were completed after this check on simulant penetration through the interface. As seen in Figure 17, aside from one test at approximately 530,000 cycles, where the starting torque was over 1.0 lbf-in., the remaining seven tests showed starting torque levels under 0.6 lbf-in. Ending torque levels were nearly zero. The cyclical time to 25 percent of the starting torque level for each individual test was attained by 100 cycles for the final seven tests, Figure 18. Seal temperature rise, Figure 19 was limited to 2 to 3 °F for each of these seven tests. Plots of the daily torque-cycle curves showed torque levels approaching 0 lbf-in. at approximately 800 to 1,000 cycles rather than the 18,000 to 20,000 cycles prior to the simulant check. Testing between 570,000 and 590,000 total cycles (Test 41, Table 3) in vacuum with simulant showed a drop to zero torque within 2,000 cycles of the start of test, Figure 24. Finally, Figure 25 (Test 44, Table 3) shows where torque levels drop to zero values within 200 cycles. These observations are indicative of little to no wear between the shaft and seal. Upon disassembly at the conclusion of over 650,000 cycles, approximately 1.8407 ± 0.0007 grams of simulant were found in the Teflon cup at the bottom of the fixture, Figure 26 and Table 5. The decision was made to stop the performance test on the Aeroflex seal and begin disassembly of the test set-up.

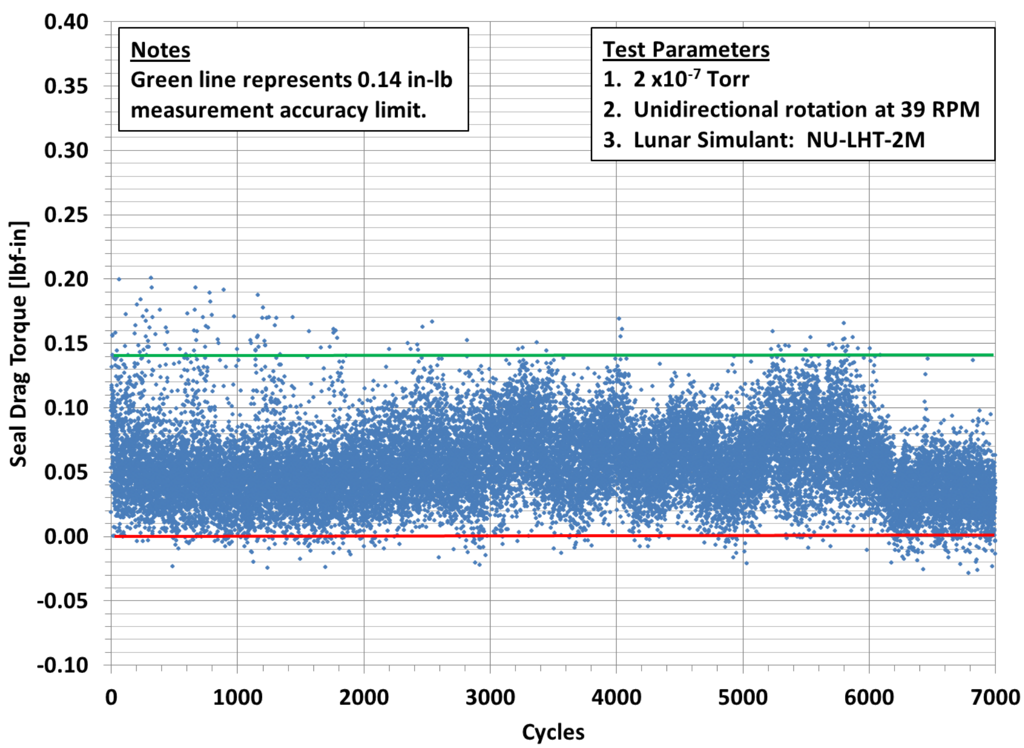

Figure 25.—Seal drag torque dropping below zero levels at test start. Approximately 630,000 cycles (Vacuum & Simulant) completed at start of this test. Test 44, Table 3.

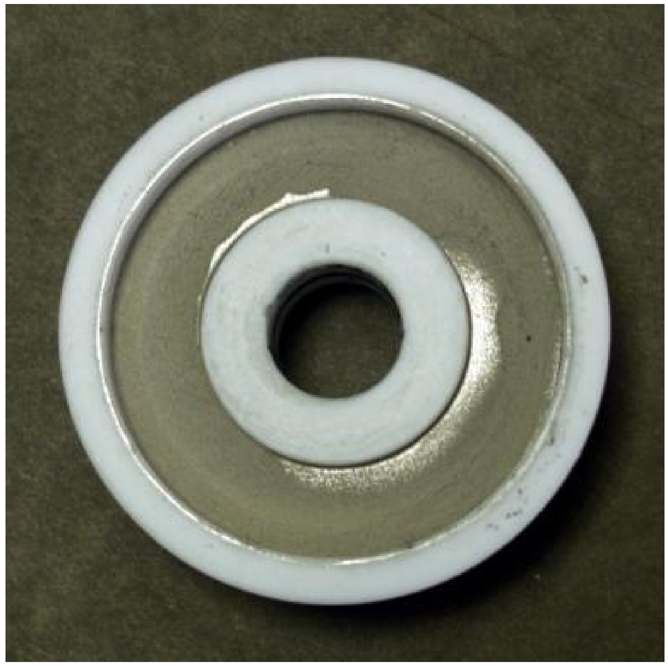

Figure 26.—NU-LHT-2M simulant found (~1.8 g) at base of Teflon cup after ~650,000 cycles testing in vacuum.

TABLE 5.—AMOUNT OF NU-LHT-2M SIMULANT FOUND IN TEFLON CUPAFTER BETWEEN 511,000 AND 650,000 CYCLES IN VACUUM
[Measured on November 3, 2010, after 600,000 cycles, in grams.]

Sample	Tare	Tare+Dust	Dust	Error
Paper	0.4126	2.2293	1.8167 ±	0.0005
Tape 1	0.0329	0.0379	0.0050 ±	0.00005
Tape 2	0.0261	0.0328	0.0067 ±	0.00005
Tape 3	0.0316	0.0439	0.0123 ±	0.0001
		Total	1.8407 ±	0.0007

Disassembly of Aeroflex Seal Test Set-Up

The test shaft and Aeroflex seal were clamped rigidly and removed from the vacuum chamber test stand, Figure 27. Removal of the test shaft showed additional NU-LHT-2M at the seal inner diameter at the secondary sealing surfaces. The primary sealing surface located upstream of the secondary sealing surfaces was not readily visible. The shaft surface that interfaces with the seal's secondary sealing surfaces was observed to have wear marks consistent with the assembled axial location of the seal secondary sealing surfaces, Figure 28. This feature would need to be quantified with a profilometer and compared to baseline surface roughness readings. Disassembly of the seal clamp fixture showed a light coating of simulant on various surfaces. Upon closer inspection of the seal inner diameter, simulant was observed at the primary sealing surface and packed between the secondary sealing surfaces. In hindsight, it is unknown when the simulant started to gather in between the secondary sealing surfaces. It is highly likely that the chip in the secondary sealing surface contributed to the large amount of simulant found between these surfaces. It is probable that the seal may have continued to function effectively through the goal of 1,000,000 cycles if the chip in the secondary sealing surface had not occurred at the start of the tests in vacuum with simulant. The remaining amount of simulant observed on various seal and fixture surfaces during the second disassembly has not yet been quantified aside from the 1.8407 ± 0.0007 grams found in the Teflon cup.

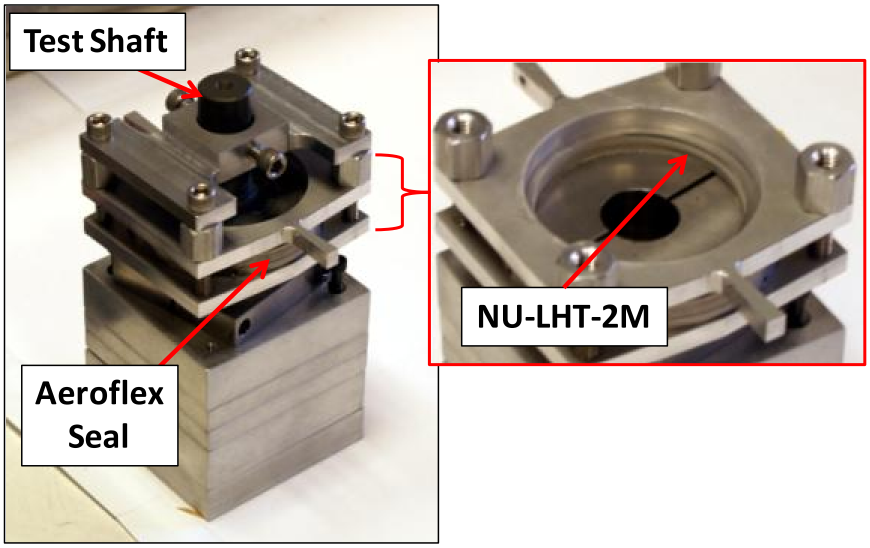

Figure 27.—Disassembled test fixture showing presence of NU-LHT-2M at seal inner diameter.

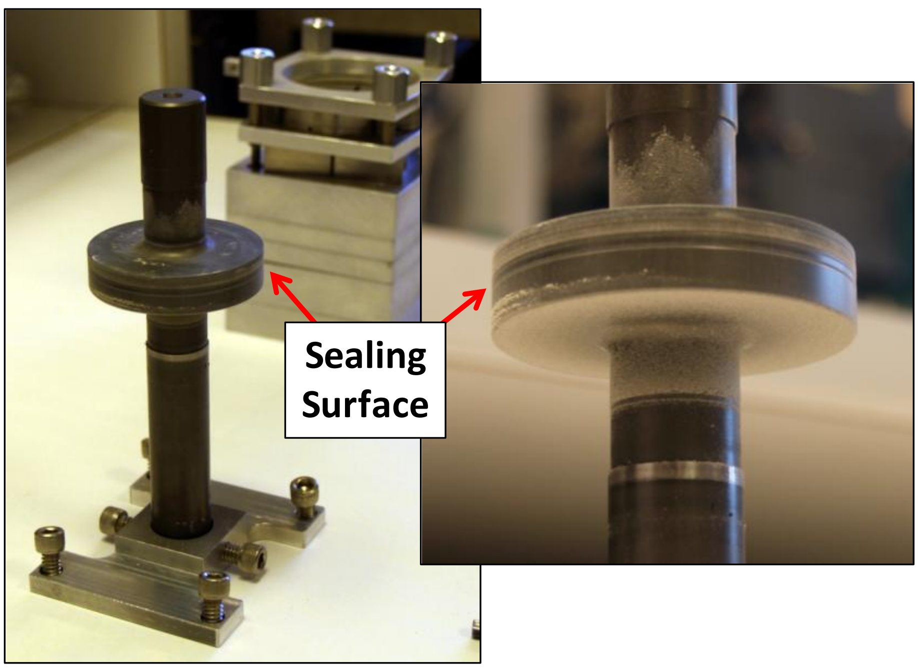

Figure 28.—Aeroflex test shaft showing wear indications on sealing surface.

Conclusions

Overall

- The Aeroflex seal was conservatively tested by orienting the seal/shaft interface such that NU-LHT-2M was gravity-fed through the interface.
- Testing was done at 39 RPM per actuator design output speed and unidirectional.
- Testing was limited to a single run per day and thus tests were stopped at the end of each run.
- The Aeroflex seal completed approximately 670,000 cycles with 650,000 cycles in vacuum ($\sim 10^{-7}$ torr) with NU-LHT-2M simulant.

Break-In

- Approximately 20,000 cycles were used to slowly break-in the seal and test shaft into a matched set under atmospheric conditions without simulant.
- Seal torque levels peaked at 16.8 lbf-in. during break-in runs in atmospheric conditions without simulant (i.e., the first 20,000 cycles). This is lower than the 30 lbf-in. dry seal friction test results first reported by Aeroflex during their break-in testing.
- During break-in runs at atmospheric conditions without simulant, the seal drag torque rise diminished from 4.2 lbf-in. per 50 cycles at the start of break-in runs to less than 0.20 lbf-in. per 50 cycles at approximately 3,000 cycles.
- The maximum seal temperature rise was approximately 26 °F, as measured at the seal outer diameter, and occurred during the same break-in test.
- Seal temperature rise diminished from 0.96 °F per 50 cycles at the start of break-in runs to 0.34 °F per 50 cycles at approximately 3,000 cycles.
- Given break-in torque and temperature data, some period of break-in is suggested to mitigate unwanted loading of the actuator.

Vacuum and NU-LHT-2M

- The seal temperature rise measured at the outer diameter of the seal is consistent with the initial interference fit between the seal and shaft, around 1 to 2 mils.
- Because the secondary sealing surfaces have a CTE 6 times higher than that of the shaft, an estimated 10 to 40 °F temperature rise is estimated at the sealing surface. Interface contact is expected until thermal equilibrium is re-established and should be accounted for relative manufacturing tolerances, break-in period, and intended operations.
- During runs in vacuum with NU-LHT-2M, peak drag torque rose to approximately 7.6 lbf-in. at 120,000 cycles and then fell to less than 2.0 lbf-in. after 180,000 cycles, an indication of long-term wear due to operations.
- The cyclical time to 25 percent of the peak torque level for each test remained below 600 cycles after 140,000 cycles in vacuum with NU-LHT-2M. This provides some insight into the seal-shaft start-up torque operational characteristics.
- The seal temperature rise during tests in vacuum with NU-LHT-2M peaked at 14 °F during the first 100,000 cycles and then fell below 5 °F for the remainder of the tests. This provides some insight into the seal-shaft temperature rise operational characteristics.
- During tests in vacuum with NU-LHT-2M the seal temperature rise remained below 0.11 °F per 50 cycles compared to a peak of 0.96 °F per 50 cycles during break-in runs.
- Approximately 141,000 cycles were completed when seal drag torque measurements could statistically be at zero levels, based on load cell design accuracies.
- Approximately 471,000 cycles were completed when seal drag torque measurements approached zero levels.
- At approximately 570,000 cycles, seal drag torque measurements were consistently approaching zero levels.

Post-Test

- Only 0.4 mg of NU-LHT-2M had passed through the seal and shaft interface into the Teflon cup after approximately 511,000 cycles testing in vacuum despite a small chip in the secondary sealing surface.
- Reassembly and test of the seal for an additional 140,000 cycles found 1.8 grams of NU-LHT-2M passing through the seal/shaft interface.

- During final disassembly, additional NU-LHT-2M was found packed in between the secondary sealing surfaces of the Aeroflex seal. This amount and other simulant found in and around test surface fixtures have not yet been quantified.
- It is unknown when the simulant started to gather in between the secondary sealing surfaces. It is likely that the chip in one of the secondary sealing surfaces strongly contributed to the large amount of simulant found between these interfaces. It is probable that the seal may have continued to function effectively through the goal of 1,000,000 cycles if the chip in the secondary sealing surface had not occurred at the start of the tests in vacuum with simulant.
- The test shaft had an initial surface finish of 13 µin. Wear marks were observed on the test shaft sealing interface and are consistent with the assembled location of the seal's secondary sealing surfaces. A wear profile on the test shaft has not yet been performed.

Lessons Learned

- A thorough alignment process is necessary for the rotating machinery to ensure minimal vibration and inadvertent wear to the test article.
- Disruption of the test for maintenance or non-automated operation is acknowledged as an uncontrolled variable but is a necessary part of the test sequence. For greater test fidelity, future tests would eliminate or greatly reduce these variables.
- During non-run periods, the NU-LHT-2M lunar simulant can potentially filter through the shaft/seal interface due to mechanical vibrations in the vacuum system. At test start-up a slight increase in torque has been observed and may be due to the dust filtering through the interface. Some type of damping in the vacuum system may be necessary to minimize the mechanical vibrations.
- Periodic lubrication of the right-angle gear-box with Braycote 601 was necessary to reduce the wear rate of the bevel gear teeth. A methodology is needed to automatically lubricate the gears without stopping the test. Alternatively, a set-up without the right-angle gear box would preclude the need for gear lubrication.
- Disassembly and reassembly of the seal and shaft after the break-in period may have caused an inadvertent mismatch of the interface causing additional wear during tests in vacuum. A methodology is necessary to quantify the level of wear to both sealing interfaces without undue additional wear (e.g., match-marking test hardware prior to disassembly).
- A new test set-up is being considered for quantifying the amount of simulant passing through the seal/shaft interface without having to disassemble the test set-up.

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