NASA/TM-20230015308

Dust Tolerance Characterization of Lunar Docking and Hatch Seals

Nathan Jimenez
Glenn Research Center, Cleveland, Ohio

Janice Mather
The University of Akron, Akron, Ohio

Patrick H. Dunlap, Jr.
Glenn Research Center, Cleveland, Ohio

February 2024

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., "quick-release" reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Fax your question to the NASA STI Information Desk at 757-864-6500

- Telephone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Program
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM-20230015308

Dust Tolerance Characterization of Lunar Docking and Hatch Seals

Nathan Jimenez
Glenn Research Center, Cleveland, Ohio

Janice Mather
The University of Akron, Akron, Ohio

Patrick H. Dunlap, Jr.
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

February 2024

Acknowledgments

The authors would like to acknowledge NASA's Human Landing System (HLS) Mission Systems Management Office for supporting this effort, as well as Stephen Gerdts and Heather Oravec for their technical contributions.

Level of Review: This material has been technically reviewed by technical management.

This report is available in electronic form at https://www.sti.nasa.gov/ and https://ntrs.nasa.gov/

Dust Tolerance Characterization of Lunar Docking and Hatch Seals

Nathan Jimenez
National Aeronautics and Space Administration
Glenn Research Center
Cleveland Ohio 44135

Janice Mather
The University of Akron
Akron, Ohio 44325

Patrick H. Dunlap, Jr.
National Aeronautics and Space Administration
Glenn Research Center
Cleveland Ohio 44135

Summary

Low-leakage seals are an enabling technology for future lunar surface systems, and they must be kept clean to ensure that crews have sufficient breathable air for extended lunar surface missions. Previous testing has shown that contamination and debris on seals can cause them to exhibit higher leak rates. However, seal performance in the presence of lunar dust has not been thoroughly characterized, and the size and concentration of dust particles that cause seal leak rates to become unacceptable have not been defined or well understood. To address this knowledge gap, researchers at the NASA Glenn Research Center have been executing a multiphase study to better understand and mitigate seal dust-exposure risks. The focus of this paper is on the first phase of that study, in which tests were conducted to develop a performance database for two representative state-of-the-art seal designs. Leak rates are presented for seals with varying levels of dust contamination, and breakthrough points are identified at which seal leak rates exceeded equivalent leak rate requirements. This phase of the study also investigated the effects of temperature on the seals' ability to hold pressure when contaminated with dust.

Nomenclature

AIAA	American Institute of Aeronautics and Astronautics
APES	Automated Pressure Equalization System
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
CV	coefficient of variation
EVA	extravehicular activity
HLS	Human Landing System
JSC	Johnson Space Center
NDS	NASA Docking System
NDSB2	NDS Block 2
SOA	state of the art
STD	standard
UDDS	Uniform Dust Deposition System

σ	standard deviation
μ	mean

Introduction

NASA's Artemis Program is working toward a goal of innovative and sustainable lunar exploration by the late 2020s (Ref. 1). Low-leakage seals for future lunar surface systems are an enabling technology for a sustained lunar presence. Seals on hatches, docking systems, and critical interfaces on future lunar landers, ascent vehicles, habitation modules, and pressurized rovers must be kept clean to achieve the extremely low leak rates that will be required to ensure crews have sufficient breathable air for extended lunar surface missions. Contamination and debris on these seals can create leak paths for the pressurized atmosphere of a surface asset to escape.

One of the uncertainties involved with achieving a sustained lunar presence lies with the interactions between lunar dust and seals. Lunar dust has unique abrasive, morphological, and electrostatic properties that make it pervasive, damaging, and difficult to mitigate for lunar surface assets (Ref. 2). During the Apollo missions, lunar dust caused mechanical failures of many systems, including seal failures on astronaut suits and sample return containers (Ref. 3).

Until recently, only limited testing had been done to evaluate the effects of lunar dust on seals. In tests on composite seals in which S0383–70 silicone seal bulbs were vacuum molded into metallic retainers, Garafolo and Daniels found that dust-contaminated seals exhibited higher leak rates (Ref. 4). They also demonstrated that seal leak rates decreased after some of the dust was removed from the seals, although leak rates did not return to the same level that was measured for clean seals. Tests by Oravec and Daniels on small O-rings made of S0383–70 silicone revealed similar findings, with high leak rates for dust-contaminated seals and a return to lower leak rates after cleaning (Ref. 5). However, seal performance in the presence of lunar dust has not been thoroughly characterized, and the size and concentration of dust particles that cause seal leak rates to become unacceptable have not been defined or well understood.

Recognizing the risks for dust exposure and contamination of seals on docking mechanisms and extravehicular activity (EVA) hatches, the Human Landing System Program recently funded a multiphase series of tests at the NASA Glenn Research Center to better understand and mitigate seal dust-exposure risks. The original plan for this work was organized into four phases: (1) development of a performance database for current state-of-the-art (SOA) seals, (2) evaluation of the viability of seal cleaning methods, (3) evaluation of the efficacy of alternative seal surface treatments, and (4) evaluation and development of new dust-tolerant seal designs and dust mitigation approaches. This paper focuses on the first phase, development of a performance database for current SOA seals.

Test Objectives and Requirements

While it is intuitive that dust contamination may adversely affect sealing performance, the susceptibility of these seals to dust contamination and the magnitude of the effect of dust on seal leak rates were unknown. To understand and mitigate the risks associated with lunar dust contamination of seals, researchers at Glenn were tasked with characterizing the performance of representative SOA seal designs when exposed to lunar dust simulants. To this end, the test objectives for this test campaign were to

1. Identify dust contamination levels at which seal leak rates become unacceptable.
2. Evaluate the effects of temperature on the ability of seals to hold pressure when contaminated with dust.

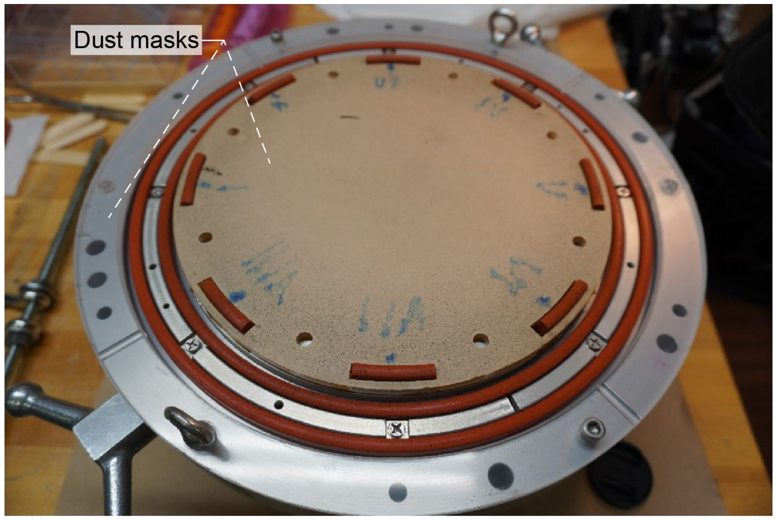

Figure 1.—NASA Docking System (NDS) seal in leak test fixture with dust masks installed.

Methods and Materials

At the start of this study, leak tests were performed on seal test articles to establish baseline leak rates and variability in the seals. The seals were installed in aluminum test fixtures before being contaminated with various amounts of JSC–1A lunar mare simulant. Shown in Figure 1, dust masks were used to keep dust out of critical areas on the fixture, such as pressure ports, vacuum ports, and support seals. The dust contamination level for each test specimen was characterized as a percent area coverage of the surface by optical methods. The seal test article was then mated to another aluminum plate and leak tested in an environmental chamber. A fully assembled test fixture compressed the seals to the same nominal compression loads they would experience during a mission.

A subset of specimens of each seal design was then tested at multiple temperatures. While still fully assembled and compressed, these specimens were brought to warm (max. 74 °C, or 165 °F) and then cold temperatures (min. –50 °C, or –58 °F), with a leak test occurring at each temperature point.

Test Specimens

Because the exact seal designs that would be used on future lunar surface systems were not known, seals of two representative SOA designs were evaluated in this study: the seals for the main docking interface of the NASA Docking System (NDS) and the environmental seals for the Orion docking hatch. To aid in the throughput and feasibility of these tests, subscale versions of these seal designs were used, with the same cross-sectional dimensions as the full-scale flight seal designs but a smaller overall diameter. To assess the effects of lunar dust contamination on seal leak performance, leak rates measured after dust was applied to the seals were compared with scaled-down leak rate requirements values for each seal design.

Both seal designs are made of space-rated silicone materials that enable low leak rates over a wide operating temperature range representative of potential lunar operating conditions while also exhibiting low outgassing properties. However, as-fabricated silicone seals can be tacky and can generate relatively high adhesion forces during hatch opening or undocking if left untreated. High adhesion forces increase the release force needed to separate the seal interface, and they introduce the risk of the sealing material separating from its installation location. For silicone seals, vacuum-rated grease is commonly applied to the seal to reduce these adhesion loads. A thin layer of Braycote® Micronic 601EF (BP Lubricants USA Inc.) vacuum-rated grease was applied to the top surfaces of the seals in this test campaign.

The two seal designs have different geometries and material characteristics, and they may respond to dust differently. Therefore, the effects of dust on the performance of each type of seal were also assessed.

NASA Docking System Seals

The flight version of an NDS seal has a diameter of approximately 50 in. (127 cm). Its multipiece design, shown in Figure 2, consists of an elastomer element with two seal bulbs connected by a web, and a separate metal retainer with periodic protruding pads that pass through openings in the web (Ref. 6). The seal is installed in a groove on the top of the NDS tunnel, and a series of fasteners secures the seal assembly to the base of the seal groove. The elastomer element is made of S0383–70, a 70-durometer silicone material offered by Parker Hannifin Corporation’s Composite Sealing Systems Division. To satisfy fault tolerance and redundancy requirements, the seal has two bulbs. The subscale seal test specimens used in this study had a diameter of 10.875 in. (27.623 cm), corresponding to the centerline diameter of the web. From a dust-tolerance perspective, the NDS seal is installed in a wide groove, leaving most of the elastomer element and seal bulbs exposed to the dust environment. Also, the solid cross sections of the seal bulbs and higher durometer material result in high loads (45 to 60 lbf/in., or 7.88 to 10.51 kN/m) and contact pressures at the sealing interface.

In this study, the leak rates measured for these seals were compared with two different requirement values. When the seals were being developed, the maximum allowable leak rate was 2.5×10^{-3} lbm dry air/day, or 13,125 nanograms per second (ng/s) (Ref. 7). However, for a subsequent implementation of the NDS (NDS Block 2, or NDSB2), the leak rate requirement was reduced to 4.2×10^{-4} lbm dry air/day (2,205 ng/s). The scaled-down requirement values for the subscale seals tested in this study were 5.1×10^{-4} and 8.6×10^{-5} lbm dry air/day (2,688 and 451 ng/s).

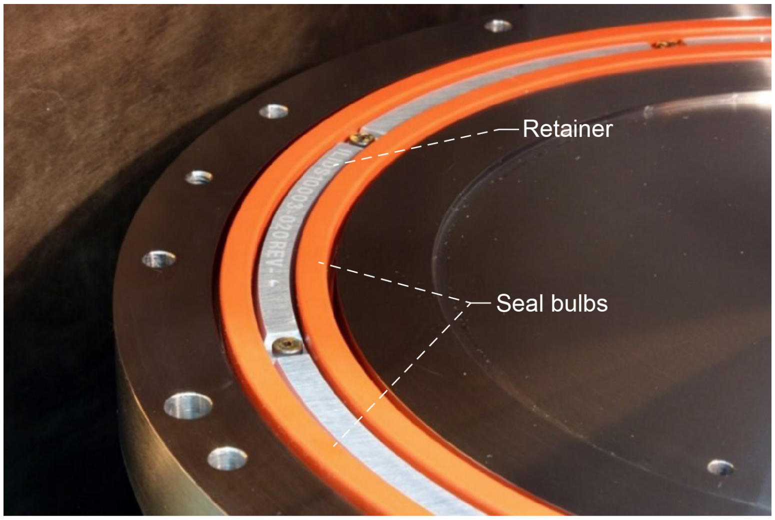

Figure 2.—NDS subscale seal installed in leak test fixture.

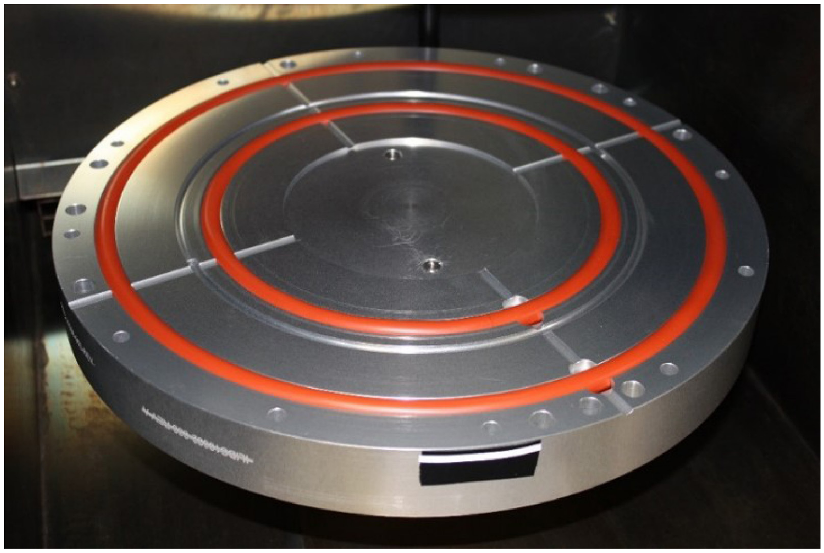

Figure 3.—Orion docking hatch subscale seal installed in leak test fixture.

Orion Docking Hatch Seals

The Orion docking hatch is sealed by a pair of hollow O-rings installed in dovetail grooves with full-scale centerline diameters of approximately 32 and 34 in. (81.3 and 86.4 cm). These seals are made of S7442–40, a relatively soft 45-durometer space-rated silicone material. Figure 3 shows the subscale seals installed in a leak test fixture in grooves that had centerline diameters of 7.8 and 11.8 in. (19.8 and 30.0 cm). In terms of dust tolerance, the seals are largely contained inside the dovetail grooves with only their top surfaces exposed to the dust environment. The hollow cross section and lower durometer material of the design result in lower contact loads (6 to 10 lbf/in., or 1.05 to 1.75 kN/m) at the sealing interface. The maximum allowable leak rate for the full-scale seals is 0.06 lbm dry air/day (3.15×10^5 ng/s), which was scaled down to 0.014 lbm dry air/day (7.33×10^4 ng/s) for the subscale seals tested in this study.

Simulant

The lunar dust simulant used in this study was JSC–1A, a manufactured simulant designed to reflect the physical, chemical, and compositional properties of regolith in the lunar mare region visited by Apollo 14 and 15 (Ref. 8). This simulant was selected for its high glass and lithic content, which provides highly abrasive qualities (Ref. 9). The simulant was sieved, dried, rolled, and stored per NASA–STD–1008 (Ref. 10). It was then sieved to include only particles smaller than 0.0098 in. (250 µm), dried for at least 12 hr at 230 °F (110 °C) per ASTM D2216 (Ref. 11), and stored in the dry environment of the test chamber under a rough vacuum. The simulant was stored in 0.055-lbm (25-g) batches in the antechamber and rolled by hand immediately before testing. The simulant preparation process and storage are described in greater detail in NASA/TM–20210024128 (Ref. 12).

Test Fixtures

The test fixtures used in this study consisted of a lower test plate in which the seal test articles were installed; an upper flat plate; and a thin, flat plate (or intermediate plate) that was installed between the upper and lower plates. The lower test plate for the NDS seals (Figure 2) included a groove in which the seal assembly was installed and a set of ports inboard of the seals to pressurize the inner volume and measure the test temperature and pressure differential across the inner seal bulb. The lower test plate for the Orion docking hatch seals (Figure 3) included two separate dovetail grooves for the seals with similar pressure supply and instrumentation ports. In both arrangements, dust was deposited on the inner seal and the outer seal was used as a support seal to allow a pressure differential with vacuum on the downstream side of the inner seal during leak testing.

During the dust deposition process, only the lower half of the test assembly was installed in the test chamber. Dust masks were used to keep dust out of critical areas on the fixture, such as pressure ports, vacuum ports, and support seals. This allowed dust to be deposited on the seals in the desired locations. After the dust was deposited on the seals, the upper and intermediate plates were installed and the assembly was clamped together with a set of 12 bolts. The lower surface of the intermediate plate then became the sealing surface that the dust-coated seals sealed against during leak testing.

Dust Contamination and Characterization

With the low leak rates required by these sealing applications, a small amount of contamination can result in leak rates that are orders of magnitude greater than the leak rate requirements of the seal. Even a single hair or fiber across the seal can be enough contamination to cause such a leak. In this test campaign, lunar simulant was deposited on the seal test articles using the Uniform Dust Deposition System (UDDS) developed at Glenn (Ref. 12). This system, shown in Figure 4, was developed to provide repeatable, uniform, and automated deposition of simulants on surfaces of interest for dust mitigation testing. Installed inside a glovebox, the UDDS operates at ambient pressure and temperature in a dry environment with a relative humidity inside the chamber of less than 0.5 percent.

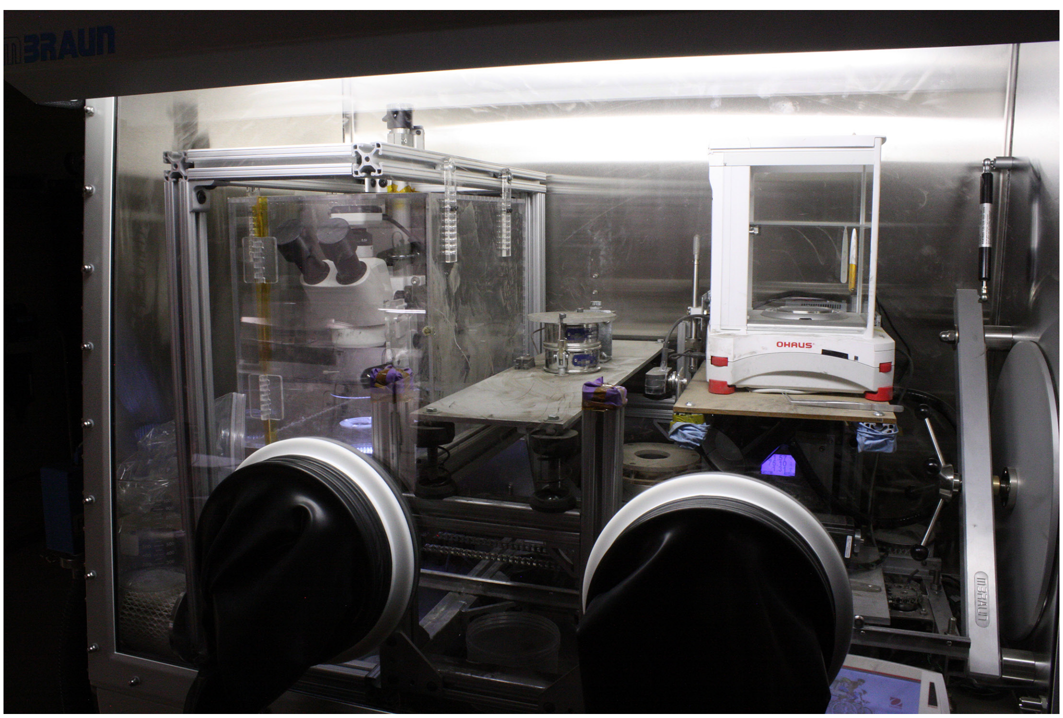

Figure 4.—Glenn Research Center Uniform Dust Deposition System.

At the start of a test, the seal test specimen (installed in its test fixture) was inserted into the test chamber and placed on the rotation stage of the UDDS transfer subsystem. The transfer subsystem then repositioned the test specimen to the center of the glovebox, under the dust deposition plate. The test article was rotated slowly as dust was deposited on the surface from the deposition subsystem. When the dust deposition process was completed, the transfer subsystem moved the test article to the imaging subsystem. After imaging, the test article was removed from the chamber and prepared for leak testing. Additional details about the UDDS can be found in NASA/TM–20210024128 (Ref. 12).

Because the amount of simulant deposited on the seal test specimens was orders of magnitude less than the mass of the test fixtures, dust contamination could not be easily characterized using changes in mass. Instead, the deposited dust was optically characterized using a stereo microscope (Motic® SMZ–171, Motic Instruments Inc.) at a magnification of ×50 and a 10-megapixel microscope camera (Moticam® 10+, Motic Instruments Inc.), as seen in Figure 5(a). The percent of dust covering the analyzed area (2.5 by 2 mm) was the characterization metric. Eight equally spaced locations at the crest of each seal specimen were analyzed to determine the overall percent coverage of dust.

The contamination images were processed using the Fiji package of ImageJ (Ref. 13); Figure 5(b) shows an example output. The images were registered, Z-stacked, segmented, thresholded, and analyzed to obtain a percent area coverage (Ref. 12). These percent area coverage values were compared to obtain a maximum percent area coverage and coefficient of variation (CV) for each specimen. The CV in this study was defined as the ratio of the standard deviation (σ) to the mean (μ) of the percent area coverage.

$$CV = \frac{\sigma}{\mu}$$

The CV gives a measure of the variability of the dust coverage and was helpful in understanding the uniformity of dust coverage along the seal. A lower CV value for a seal sample reflected less variation in percent coverage area measured around a seal with respect to the mean and was indicative of a more uniform deposition.

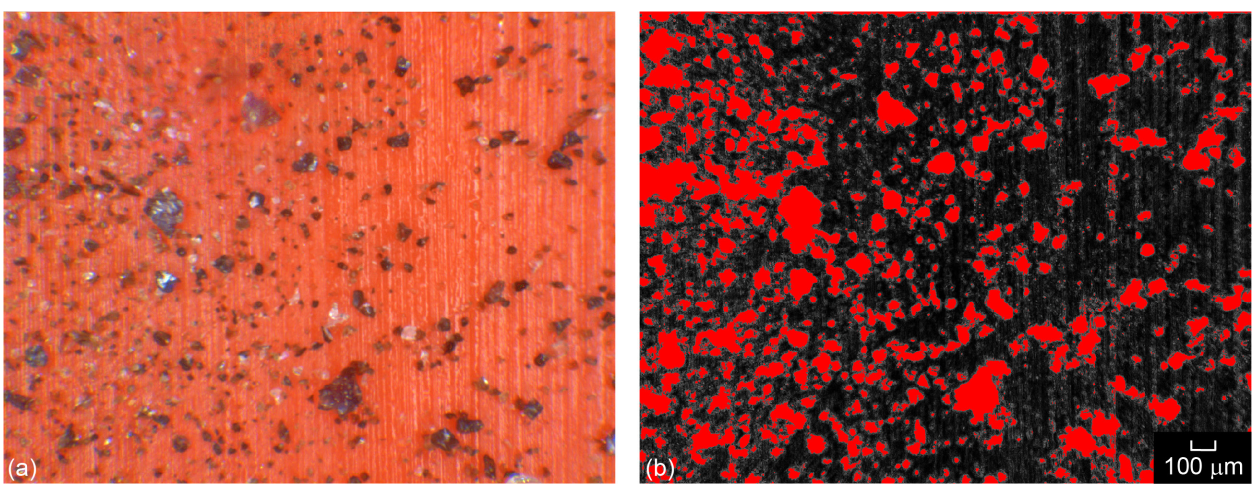

Figure 5.—Imaging output examples. (a) NDS seal with 22 percent dust coverage. (b) Segmented image using Fiji package.

Leak Rate Testing

The leak rate testing of the test articles was performed in an environmental test chamber (Tenney® model BTRC; TPS, LLC) where the test temperature was regulated using the Automated Pressure Equalization System (APES) system developed at Glenn (Ref. 14). The seal article was installed into the environmental chamber shown in Figure 6 and allowed to reach steady-state temperature. The volume between the inner and outer seal was evacuated and the test fixture was pressurized to establish a 14.7-psid differential pressure. The leak rate of the inner seal was characterized using a mass point pressure-decay method.

Leak rates were determined at multiple test temperatures. A test fixture was assembled at room temperature and remained in the assembled state throughout the testing sequence. It was recognized that although the test temperatures were reflective of a space application, the assembly method was not. In a space application, the elastomer seal and the mating surface independently reach a given temperature and then are mated together. A cold elastomer is less compliant than an elastomer at room temperature and may not deform around the dust particles to the same degree. Less deformation could result in a leak path and a higher leak rate than found in this study. However, because all test fixtures were assembled in the same manner and all leak rate testing followed the same procedures, comparison of leak rates at multiple temperatures for various dust coverage amounts was deemed valid.

Figure 6.—Environmental chamber used for leak tests.

Results and Discussion

Leak Test Results

When the test plan for this study was prepared, the goal was to perform leak tests on both types of seals at three different levels of dust contamination corresponding to “light,” “medium,” and “heavy” amounts of dust on the seals. This would then allow plots to be created showing how seal leak rates changed as the amount of dust on the seals was gradually increased. Although the goal was to deposit a uniform, consistent layer of dust all the way around the entire sealing surface on each test specimen, there was some variability in the dust coverage. Therefore, a decision was made to present the test results in terms of the maximum percent area coverage of dust, assuming that the amount of leakage past the seal would be heavily influenced by the areas on the seals that were covered by the most dust. The leak rates were then compared with the leak rate baselines and the requirement equivalent thresholds. A breakthrough percent area coverage was also identified for each seal design, indicating where seal specimens began surpassing the leak rate requirement equivalent threshold for each design.

Results for room-temperature leak tests performed on the NDS subscale seals are summarized in Figure 7. As expected, seal leak rates generally increased as the maximum percent area coverage of dust increased. For maximum percent coverage values up to 14 percent, leak rates were still low, up to about twice the average baseline leak rate for a clean seal. The NDS subscale seal specimens had breakthroughs at a maximum percent area coverage of 16 percent, where the measured leak rate exceeded the NDSB2 equivalent leak rate requirement, and at 22 percent, where the original NDS equivalent leak rate requirement was exceeded. However, seal leak rates varied for maximum percent dust coverage values above 14 percent, with some seals still exhibiting leak rates under the maximum allowable leak rate values at dust coverage values up to 27 percent. Seals with maximum percent dust coverages beyond that level exhibited higher leak rates, with one test specimen being unable to hold pressure. Figure 8 shows representative photographs of dust coverages less than 14 percent (Figure 8(a)) and greater than 22 percent (Figure 8(b)) on NDS seal test specimens.

Results for room-temperature leak tests performed on the Orion docking hatch subscale seals are summarized in Figure 9. As with the NDS seals, leak rates generally increased as the maximum percent area coverage of dust increased. For maximum percent coverage values up to 10 percent, leak rates remained low at up to twice the average baseline leak rate for a clean seal. The docking hatch subscale seal specimens had a breakthrough at a maximum percent area coverage of 14 percent where the leak rate exceeded the Orion docking hatch seal equivalent leak rate requirement. However, as was observed for the NDS seals, leak rates for the docking hatch seals varied for maximum percent dust coverage values above 11 percent, with some seals still passing leak tests at dust coverage values up to 28 percent. In that same range of maximum percent dust coverages, however, several seals were contaminated enough that they were unable to hold pressure. For reference, Figure 10 shows representative photographs of dust coverages less than 10 percent and greater than 14 percent on Orion docking hatch seal test specimens.

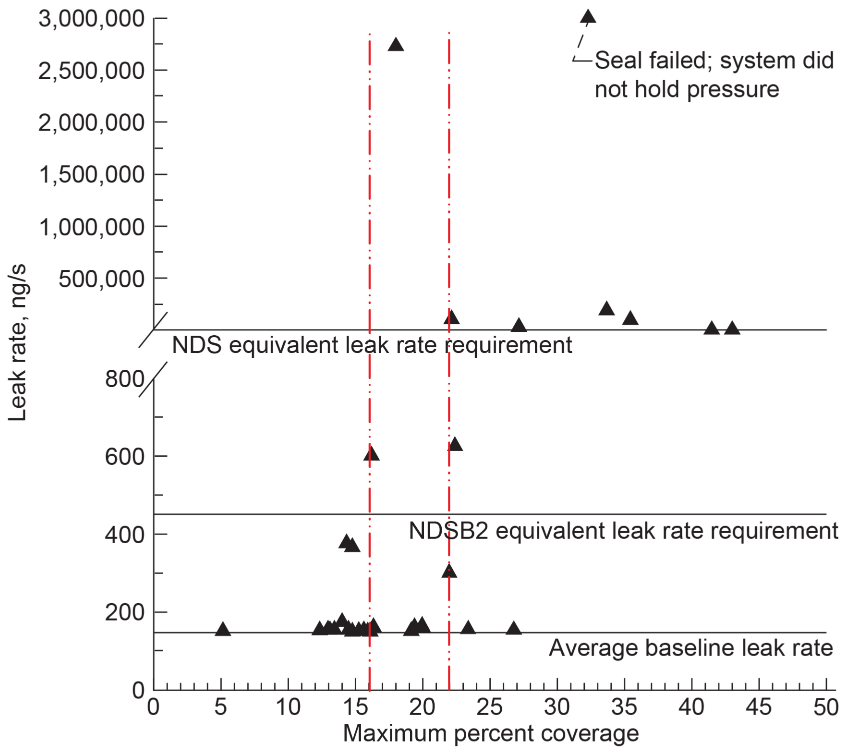

Figure 7.—Leak rates for subscale NDS seals with JSC–1A lunar simulant at 20 °C.

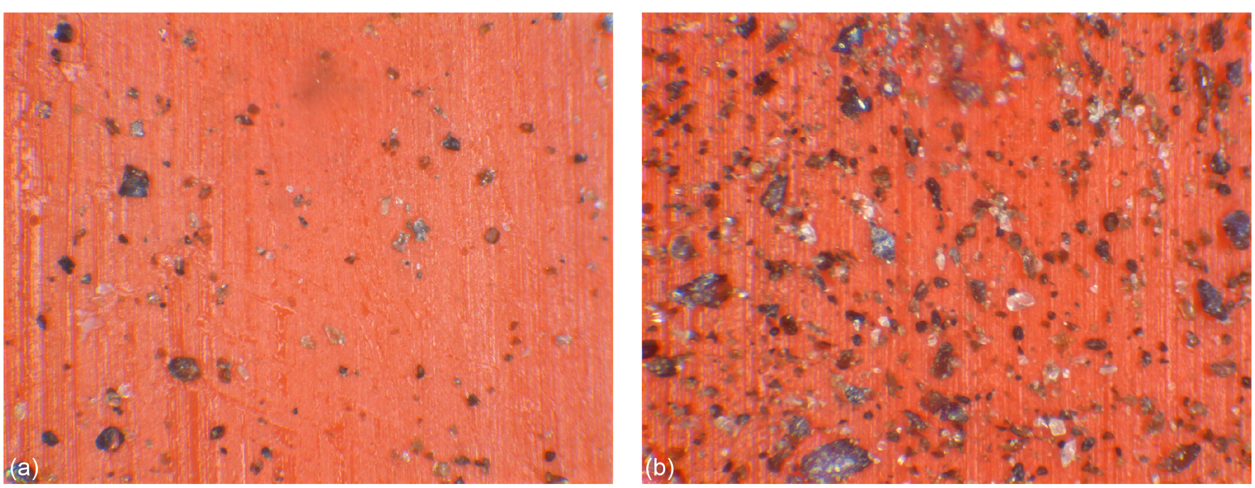

Figure 8.—Dust coverage on NDS seal test specimens. (a) Less than 14 percent. (b) Greater than 22 percent.

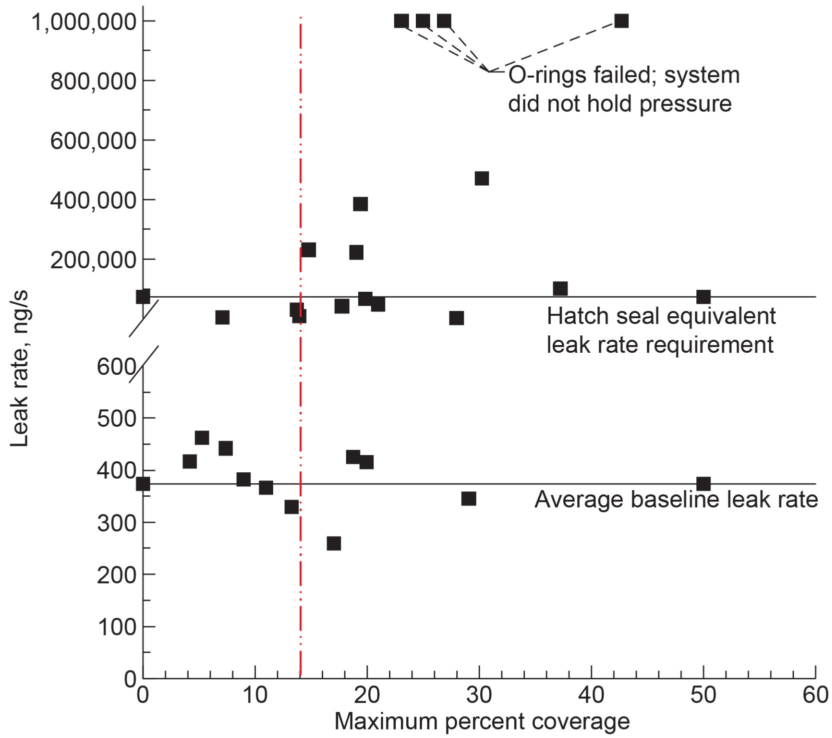

Figure 9.—Leak rates for subscale Orion docking hatch seals with JSC–1A lunar simulant at 20 °C.

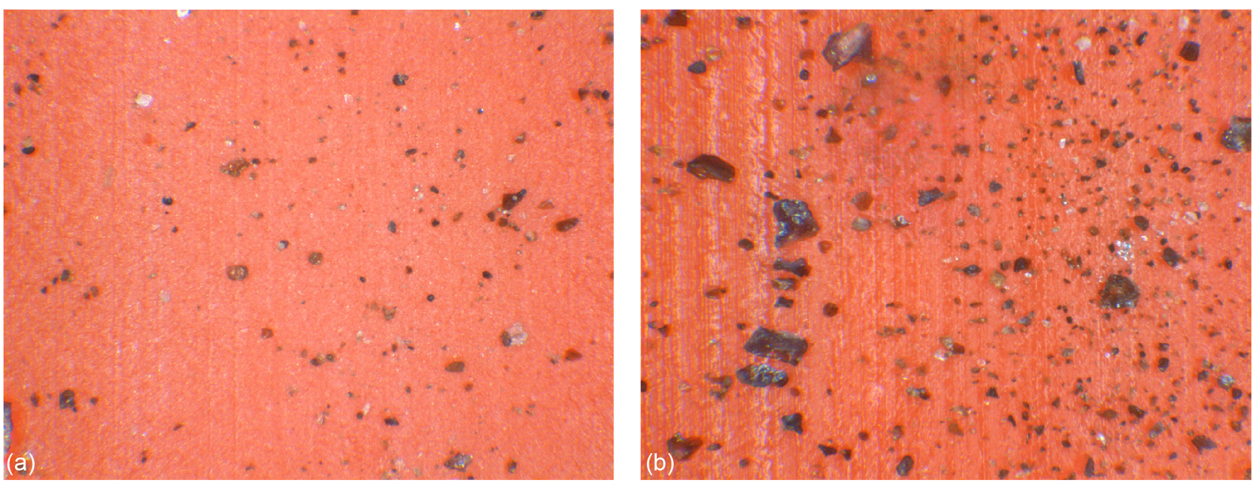

Figure 10.—Dust coverage on Orion docking hatch seal test specimens. (a) Less than 10 percent. (b) Greater than 14 percent.

It is hypothesized that the variable leak rate response was influenced by several factors, including the dust deposition uniformity, coverage pattern, dust particle sizes, and dust particle size distribution.

The CV of the percent dust coverage area of a seal, shown in Figure 11, was an indicator of the deposition uniformity. The NDS seal samples had a median CV value of 0.24 and an interquartile range of 0.16, indicating that 50 percent of the values centered around the median were in this range. The docking hatch seals had a higher median CV value of 0.33 but a tighter spread of data, with an interquartile range of 0.10. With a decrease in uniformity, heavy and light spots of dust coverage on the same seal become more pronounced.

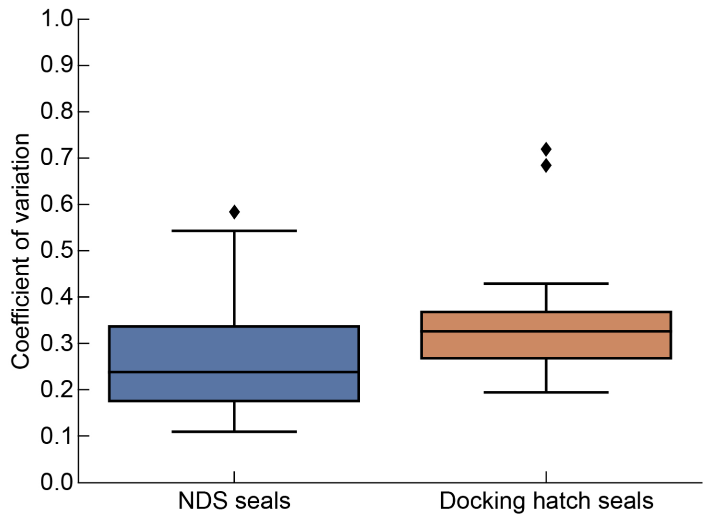

Figure 11.—Coefficient of variation for percent area coverage.

A limitation to this method was the risk that the seal locations imaged with the microscope camera, accounting for about 1 percent of the seal surface, do not convey the true maximum percent area coverage increases as the dust coverage becomes less uniform. In subsequent phases, a macro image analysis method was incorporated into the process to supplement the analysis from the microscope. The macro images analyzed more than 90 percent of the surface area with deposited dust. This method had challenges of its own; the decrease in resolution at decreased magnification resulted in the inability to measure the lower end of the particle size fraction, which may be the most prevalent type of contamination in some locations and presents the most strongly adhering particles (Ref. 15).

In addition to the dust uniformity, other factors also contribute to the leak rate response of a dust-contaminated seal. The dust coverage pattern was of particular interest for seals, given that a radial line of contamination from the inner border to the outer border of the seal interface can cause leak rates significantly above the requirements or even seal failure. This was true even when the overall dust contamination was low.

The particle size and shape, along with the particle size distribution, presented an added layer of complexity. When compressed, individual large grains may deform the seal surface more than agglomerated small particles of the same overall size due to the potentially increased height of the large particle. In addition, the relatively high aspect ratios of these particles presented the risk of the particle's major axis aligning with the depth plane of the microscope, resulting in an artificially low particle size measurement.

Thermal Test Results

Leak tests were performed at multiple temperatures for a subset of the seal specimens. Low to moderate levels of contamination were targeted to evaluate the effects of temperature on leak rates that were expected to be under the leakage thresholds. Contamination levels near the breakthrough points for each seal design were also studied to evaluate whether temperature influenced seal performance with respect to leak rate. The cold and warm temperature extremes tested were representative of potential lunar operating conditions.

Results for the tests performed on the Orion docking hatch subscale seals are shown in Figure 12. In general, the seals exhibited higher leak rates at cold temperatures and lower leak rates at warmer temperatures. Seals with lighter dust contamination levels (max. percent dust coverage of 5 to 9 percent) exhibited low leak rates at and above 36 °F (2 °C). The seal with a maximum percent dust coverage of 15 percent (slightly above the previously defined breakthrough point of 14 percent) had leak rates that exceeded the leakage threshold at room temperature, but it had significantly lower leak rates when it was warmed up to 165 °F (74 °C). All specimens exhibited high leak rates at the coldest temperatures.

The trends observed for the Orion docking hatch seals were less consistent for the NDS seals, as shown in Figure 13. One seal with a maximum percent dust coverage of 16 percent exhibited leak rates higher than the leak rate requirement threshold at the coldest temperatures and lower than the leak rate requirement threshold at warmer temperatures. However, the three other seals tested did not follow that trend.

It was hypothesized that several behaviors may have contributed to these results. The silicone materials the seals are made of typically become stiffer at colder temperatures. Stiff seals may not easily deform around dust particles, thereby creating larger leak paths that could result in higher leak rates. Also, the coefficient of thermal expansion is higher for silicone than it is for the aluminum test fixtures in which the seals were installed. The higher coefficient of thermal expansion will cause the seals to contract with respect to the surrounding structure at lower temperatures, which could result in reduced contact pressure at the sealing interface and higher leak rates. As noted previously, the contact pressure for the Orion docking hatch seals was already lower than the contact pressure for the NDS seals; this could make the docking hatch seals more sensitive to dust contamination at colder temperatures. Additional testing may be required to verify these hypotheses given that thermal tests were performed on a limited number of test specimens.

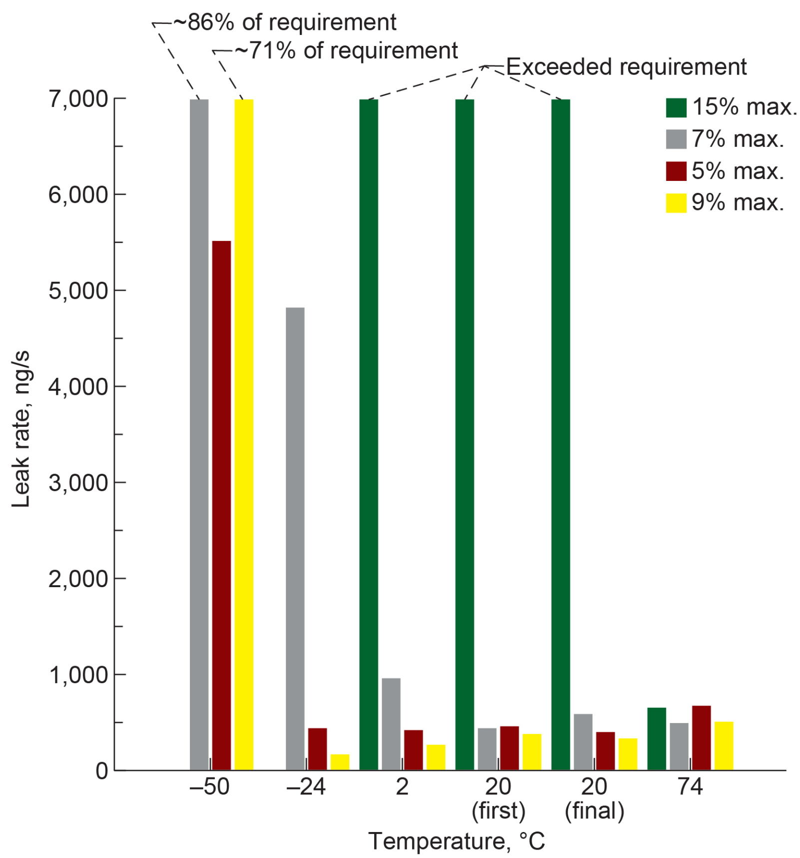

Figure 12.—Leak rates for subscale Orion docking hatch seals with JSC–1A lunar simulant at various temperatures.

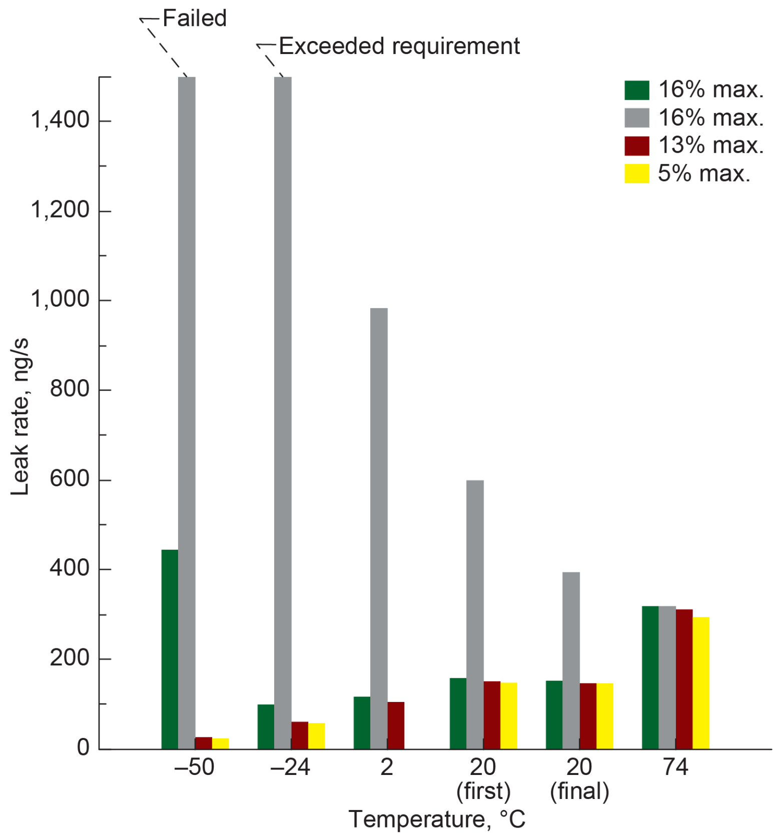

Figure 13.—Leak rates for subscale NDS seals with JSC–1A lunar simulant at various temperatures.

Of note, all tests at the highest temperature tested (74 °C) for each seal of a given design trended to the same leak rate, including tests that failed at room temperature. This was attributed to a combination of two factors. One, as temperature increases, permeation through the seal increases. For seals dominated by permeation, an increase in leak rate is observed. Two, as temperature increases, the elastomer material becomes more compliant, mitigating leakage at the seal mating interface. For seal leak rates dominated by interface leak paths, a decrease in leak rate can be observed. For the NDS dust-contaminated seals, the leak rate trended toward the leak rate of a clean seal tested at 74 °C. Seals with leak rates at 20 °C that were in line with the average baseline leak rate had an increase in measured leak rate at 74 °C, and the seal with a larger-than-baseline leak rate at 20 °C had a decrease in leak rate at 74 °C. The Orion docking hatch seals exhibited the same behaviors. This phenomenon is characteristic of elastomer materials. As temperature increases, the seal material also becomes more compliant, mitigating leakage across the seal interface.

Conclusions

Seals on future lunar surface systems must be kept clean to achieve the extremely low leak rates that will be required to ensure crews have sufficient breathable air for extended lunar surface missions. Previous testing has shown that contamination and debris on seals can cause them to exhibit higher leak rates. However, seal performance in the presence of lunar dust had not previously been thoroughly characterized, and the size and concentration of dust that causes seal leak rates to become unacceptable had not been defined or well understood. To address this knowledge gap, researchers at the NASA Glenn Research Center performed tests to characterize the performance of two representative state-of-the-art seal designs, the NASA Docking System (NDS) and Orion docking hatch seals, at varying levels of dust contamination and at different test temperatures. Based on the tests and evaluations described herein, the following conclusions were made:

- The seals were able to tolerate some level of dust contamination before their leak rates exceeded maximum allowable values.
- Breakthrough thresholds at 20 °C were identified for each seal design where leak rates were demonstrated to exceed equivalent leak rate requirements. These thresholds were found at a maximum percent dust coverage of 14 percent for the Orion docking hatch seals and between 16 and 22 percent for the NDS seals, depending on which leak rate requirement was referenced.
- The NDS seals tolerated slightly more dust contamination than the docking hatch seals before exceeding maximum allowable values. This could be due to the higher loads and contact pressures at the sealing interface for the NDS seals.
- In addition to the amount of dust coverage, seal performance was also influenced by the uniformity of coverage, coverage pattern, dust particle size, and dust particle size distribution.
- Seals contaminated with dust often exhibited higher leak rates at cold temperatures and lower leak rates at warmer temperatures. This may be due to stiffening and contraction of the seals at lower temperatures.
- In cases where the seals held pressure and sealed reasonably well at 20 °C, there was also some evidence of higher leak rates at warmer temperatures. This behavior was indicative of the increase in permeation of the seal at elevated temperatures.

References

1. National Aeronautics and Space Administration: Artemis Plan: NASA’s Lunar Exploration Program Overview. NP–2020–05–2853–HQ, 2020.
2. Taylor, Lawrence A., et al.: The Lunar Dust Problem: From Liability to Asset. AIAA 2005–2510, 2005.
3. Gaier, James R.: The Effects of Lunar Dust on EVA Systems During the Apollo Missions. NASA/TM—2005-213610, 2005. https://ntrs.nasa.gov
4. Garafolo, Nicholas G.; and Daniels, Christopher C.: Contamination Simulation of Elastomer Space Seals With Foreign Object Debris. AIAA 2011–3674, 2011.
5. Oravec, H.A.; and Daniels, C.C.: Leak Rate Performance of Silicone Elastomer O-Rings Contaminated With JSC–1A Lunar Regolith Simulant. ASCE Earth and Space, 2014. https://ntrs.nasa.gov
6. Dunlap, Patrick H., Jr.; and Steinetz, Bruce M.: A Comparison of Candidate Seal Designs for Future Docking Systems. NASA/TM—2012-217722 (AIAA–2012–4075), 2012. https://ntrs.nasa.gov
7. Dunlap, Patrick H., Jr.; Daniels, Christopher C.; and Mayer, John J.: Design and Development of the Main Docking Interface Dynamic Seal for the NASA Docking System. NASA/TP—2015-218747, 2015. Available from the NASA STI Program.
8. McKay, David S., et al.: JSC–1: A New Lunar Soil Simulant. American Society of Civil Engineers, Engineering, Construction, and Operations in Space IV, 1994, pp. 857–866.
9. Schrader, C.M., et al.: Lunar Regolith Simulant User’s Guide. NASA/TM—2010–216446, 2010. https://ntrs.nasa.gov

10. National Aeronautics and Space Administration: Classifications and Requirements for Testing Systems and Hardware to be Exposed to Dust in Planetary Environments. NASA–STD–1008, 2021.
11. ASTM D2216–10: Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM International, West Conshohocken, PA, 2010.
12. Gerdts, Stephen; Jimenez, Nathan; and Dunlap, Patrick H., Jr.: Lunar Simulant Deposition Technique for Dust Tolerance Studies. NASA/TM-20210024128, 2021. https://ntrs.nasa.gov
13. Schindelin, Johannes, et al.: Fiji: An Open-Source Platform for Biological-Image Analysis. Nat. Methods, vol. 9, 2012, pp. 676–682.
14. Garafolo, N.G.; and Daniels, C.C.: Comprehensive Mass Point Leak Rate Technique. Part I: Methodology With Uncertainty and Experimental Error Analysis. The Japanese Society for Non-Destructive Inspection/American Society for Nondestructive Testing Fourth Japan–US Symposium on Emerging NDE Capabilities for a Safer World, The Japanese Society for Non-Destructive Inspection, Tokyo, Japan, 2010, pp. 368–374.
15. Belden, Lacy, et al.: Design of Equipment for Lunar Dust Removal. NASA CR–190014, 1991. https://ntrs.nasa.gov