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# Effects of Low Earth Orbit on Docking Seal Materials

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This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

This report contains preliminary findings, subject to revision as analysis proceeds.

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## Abstract

Spacecraft docking seals are typically made of silicone elastomers. When such seals are exposed to low Earth orbit (LEO) conditions, they can suffer damage from ultraviolet (UV) radiation and atomic oxygen (AO, or monoatomic oxygen, the predominant oxygen species in LEO). An experiment flew on the International Space Station (ISS) to measure the effects of LEO on seal materials S0383-70 and ELA-SA-401 and various mating counterface materials which included anodized aluminum. Samples flown in different orientations received different amounts of UV and AO. The hypotheses were that most of the damage would be from UV, and 10 days or more of exposure in LEO would badly damage the seals. Eighteen seals were exposed for 543 days in ram (windward), zenith (away from Earth), or wake (leeward) orientations, and 15 control samples (not flown) provided undamaged baseline leakage. To determine post-flight leak rates, each of the 33 seals were placed in an O-ring groove of a leak test fixture and pressure tested over time. Resistance temperature detectors (RTDs), pressure transducers, and LabVIEW (National Instruments) programs were used to measure and analyze the temperature and pressure and calculate leakage. Average leakage of control samples was $2.6\times10^{-7}$ lbs/day. LEO exposure did not considerably damage ELA-SA-401. The S0383-70 flight samples leaked at least 10 times more than ELA-SA-401 in all cases except one, demonstrating that ELA-SA-401 may be a more suitable sealing material in LEO. AO caused greater damage than UV; samples in ram orientation (receiving an AO fluence of $4.3\times10^{21}$ atoms/cm$^2$) and in wake ($2.9\times10^{20}$ atoms/cm$^2$) leaked more than those in zenith orientation ($1.58\times10^{20}$ atoms/cm$^2$), whereas variations in UV exposure did not seem to affect the samples. Exposure to LEO did less damage to the seals than hypothesized, and the data did not support the conjecture that UV causes more damage than AO.

## Introduction

### Motivation

After two spacecraft dock, the safety of the crew and the success of the mission are threatened by the potential for air to leak from the interior of the spacecraft, where the pressure is approximately one atmosphere, to the exterior, a vacuum environment. A seal must be formed between the two docking spacecraft to prevent air from leaking out. NASA is developing advanced space-rated elastomeric seals for a new spacecraft docking system which will enable spacecraft to dock with the International Space Station (ISS) and other spacecraft (Refs. 1 and 2). The docking system seal presses and mates against either a metal flange (such as on ISS) or against an identical seal on another spacecraft. Candidate seal materials were space-exposed to determine their durability to LEO.

## Threats of the Space Environment

Prior to docking the seals will be exposed to the low Earth orbit (LEO) space environment. There are risks associated with this environment such as exposure to vacuum, atomic oxygen (AO), ultraviolet (UV) radiation, charged particle radiation, temperature extremes, and impacts with meteoroid and orbital debris (Refs. 3 to 6). Exposure to LEO can cause physical damage to a seal such as embrittlement and erosion, thereby compromising its ability to function and threatening crew safety and mission objectives (Ref. 7). The extent of exposure to each threat is dependent on the orientation of the sample during flight. Orientations include: windward (also referred to as ram, is forward-facing), leeward (also known as wake, is rear-facing), zenith (facing away from Earth), and nadir (Earth-facing). In general, surfaces in the windward orientation receive higher levels of AO whereas zenith oriented surfaces typically receive relatively high UV exposure (Ref. 8). Specimen in-flight testing conditions are determined by measurements and modeling the exposures for the particular flight scenario and orientations for the specimen being considered.

## Prior Work

In this work two silicone seal materials were studied (S0383-70 and ELA-SA-401); previous studies by de Groh et al. tested a similar material, S0899-50 (Refs. 9 and 10). It was found that S0899-50 had the highest adhesive tendencies of the three, which could not be sufficiently lowered by AO pre-treatment (Ref. 9), and to be badly damaged by UV (Ref. 10). The S0899-50 compound was judged to be unsuitable for docking seal use. Three types of metal counter-faces (bare and anodized aluminum, and nickel coated aluminum) were flown with the S0383-70 and ELA-SA-401 elastomers. We have not found prior published work presenting space exposure and testing of metal counterface materials.

Atomic oxygen exposure has previously been used as a pre-treatment method to reduce seal adhesion and was found to have positive effects on the functionality of S0383-70 and ELA-SA-401 as compared to untreated samples. As shown by de Groh (Ref. 9), Garafolo (Ref. 7), Daniels (Ref. 11), and de Groh (Ref. 12), the pre-treated seals adhered less, were less damaged by UV radiation and space AO, and the leak rate did not increase significantly. Penney (Ref. 13) found that, in untreated samples, leak rate increased significantly with temperature.

Other types of pre-treatment options being explored to control excessive adhesion include specialized greases applied to the surface of the seals, and vacuum ultraviolet (VUV) radiation exposure. In a study by Berkebile (Ref. 14), greases were used to mitigate dust contamination. K. de Groh (Ref. 15) used grease to prevent AO erosion, but found that the coating could be compromised by dust and scratches. Work by H. de Groh (Refs. 12 and 16) focused on grease outgassing and using grease to lower adhesion and prevent UV and AO damage through the employment of UV blocking additives to the grease. These works (Refs. 12 and 16) found that outgassing, adhesion, and UV and AO damage were sufficiently mitigated. It was found by de Groh (Ref. 17) that small doses of VUV lowered the adhesive tendencies of S0383-70 in both seal-to-seal and seal-to-metal configurations and that leakage was not adversely affected.

Prior work by Linton et al. (Ref. 18) found negligible change in the permeability of silicone S383 and Viton V747 after ground-based exposure to UV and AO. This is likely because they measured bulk permeability through the thickness of sheet stock. Radiation and AO cause the degradation of a seal primarily through damage to the seal’s surface, due to chemical changes, and mechanisms such as mud-tile cracking. Such surface cracking of silicone elastomers due to AO exposure is discussed by Banks (Ref. 19); and Chang-Su Huh et al. showed evidence of scissoring of side chain Si-$CH_3$ and cross-linking on the surface of silicone rubber due to UV exposure (Ref. 6). Dever and Banks found that shorter (140 to 185 nm) wavelength UV damaged DC93-500 silicone rubber less than longer wavelengths (185 to 200 nm) due to the deeper penetration of the longer wavelengths (Ref. 20).

## Candidate Elastomers

Two candidate silicone elastomer compounds are presented in this study: S0383-70 (Parker Hannifin Corp.) and ELA-SA-401 (Esterline Corp.). These were chosen because of their relative ability to remain flexible at low temperatures, low hardness (durometer rating), vendor recommendation, and the successful history of S0383-70 in NASA flight programs (Ref. 21). The compounds can be differentiated by their color and durometer ratings: S0383-70 is rust colored and has a Shore A durometer of 70; ELA-SA-401 is blond with a durometer rating of about 50.

## Involvement With MISSE

Ground-based LEO environment testing facilities do not accurately simulate all aspects of space exposure (Ref. 11), so to fully understand the reaction of the seals to LEO, #2-106 size O-rings and counterface materials were flown as part of the Seals Experiment on the Materials International Space Station Experiment-7 (MISSE-7). MISSE is a series of experiments that received in-flight exposure to the LEO environment while mounted on the ISS (Ref. 15). MISSE-7 was launched on Shuttle mission STS-129 and placed on the exterior of the ISS at an altitude of approximately 190 km on November 23, 2009. MISSE-7 was retrieved May 20, 2011 and returned on STS-134 after receiving 543 days of LEO exposure. Figure 1 shows MISSE-7 on ISS.

## Adhesion Mitigation

Silicone elastomers have natural adhesive tendencies that help prevent seal leakage, but frequently make separating coupled parts problematic, potentially resulting in damage to the seal or an inability to un-dock. Application of specialized grease or exposure to vacuum ultraviolet (VUV) radiation are two potential solutions (Refs. 12 and 17). Another promising ground facility pre-treatment used to lower adhesion is AO exposure, in which highly reactive unpaired oxygen atoms combine with silicon on the surface of the elastomer to create a glassy, non-adhesive $SiO_x$–rich layer (Ref. 9). Ground-based AO pre-treatment has affects that differ from exposure to AO in space; the former is beneficial in certain cases whereas the latter contributes to erosion and degradation. All flight seals included on the MISSE-7 Seals Experiment were AO exposed pre-flight to a fluence of $1\times10^{20}$ atoms/cm$^2$ $\pm$ $0.1\times10^{20}$ atoms/cm$^2$ with the expectation that such a pre-treatment could be used on the full-scale docking system seals to control adhesion.

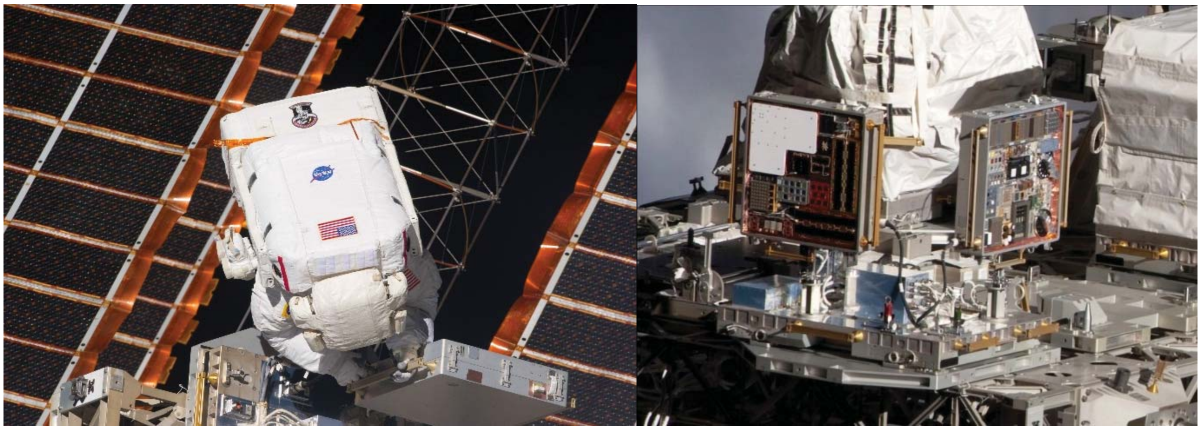


Figure 1.—Left: Astronaut placing MISSE-7 on ISS; Right: MISSE-7 mounted and open on ISS exposing various experiments to ram, wake, nadir or zenith exposure.

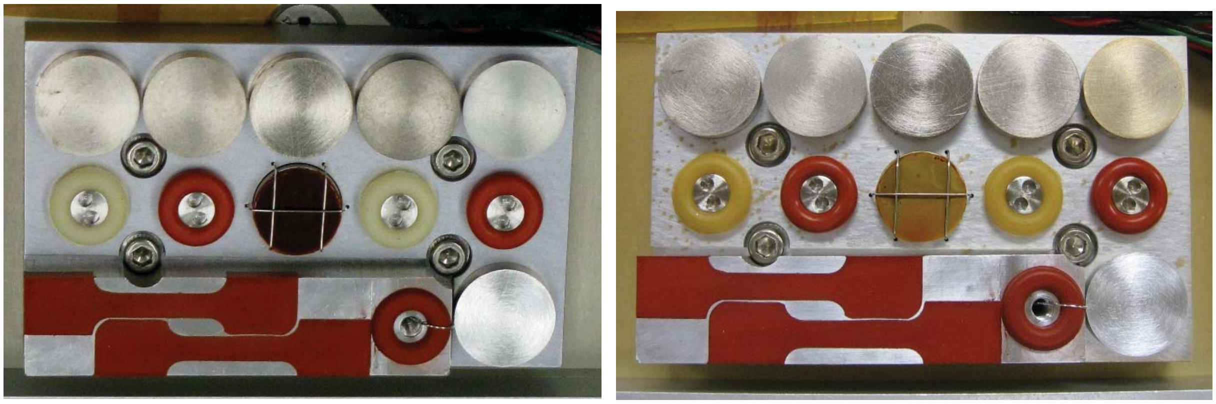
## Objectives

The objective of the experiment was to characterize the effects of LEO exposure on the sealing performance of S0383-70, ELA-SA-401, and anodized aluminum. This includes analysis of the effect of different MISSE-7 flight orientations (and therefore various AO and UV exposures) on both elastomer and metal surfaces, and the effect of AO pre-treatment on seal durability and performance.

# Experimental Procedures

## Flight Hardware and Test Articles

This experiment included samples mounted on three aluminum trays; each tray was mounted on ISS in a different flight orientation. The windward (Fig. 2) and leeward trays were identical, each containing two S0383-70 seals, three ELA-SA-401 seals, six aluminum flanges with various surface treatments, two RTV566 tensile samples, one RTV566 O-ring, and one Kapton (DuPont) AO fluence witness sample. One of the 3 ELA-SA-401 samples was placed underneath the Kapton, and thus was exposed to vacuum only. The zenith tray contained two S0383-70 seals and two ELA-SA-401 seals and is shown in Figure 3. All O-ring seals were size #2-106 with an outer diameter of approximately 0.38 in. The 4 flanges shown in


Pre-flight

Post-flight

Figure 2.—Pre and post-flight images of the 4 cm wide, windward MISSE-7 Seals Experiment assemblies.

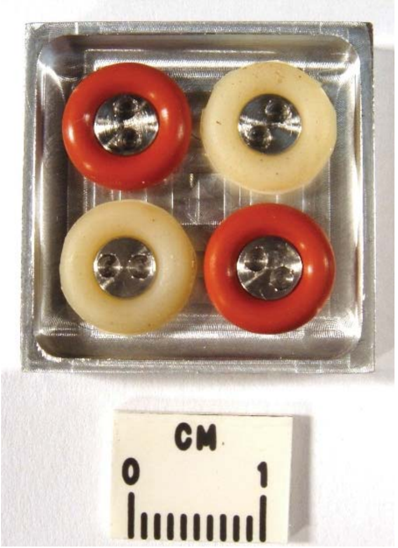


Figure 3.—Pre-flight zenith facing samples.

Figure 2 on the top-left were all made from 6061 T651 aluminum and electroless nickel plated. The flange at the top-right was 6061 T651 aluminum and MIL-A-8625 Type II anodized. The flange shown at the bottom right side in Figure 2 was bare, uncoated 6061 T5 aluminum. Data included in this report is limited to tests of the S0383-70 and ELA-SA-401 O-rings mated against the anodized leeward flight sample, or pristine stainless steel.

The mold for the RTV566 tensile samples was attached to the flight assembly. The tensile specimens were cast directly into the mold. Half of the RTV566 O-ring was cast, allowed to cure, and then removed from the mold; the mold was then refilled, and the cured half placed on the uncured half in the mold, there-by creating the complete O-ring.

## In-Flight Exposures

After modeling radiation received during flight, and analysis of various Kapton HN witness samples (Ref. 8), it was approximated that:

- Windward orientation received an AO fluence of $4.3\times10^{21}$ atoms/cm$^2$ and 2,400 ESH (Equivalent Sun Hours) of UV;
- Leeward received an AO fluence of $2.9\times10^{20}$ atoms/cm$^2$ and 2,000 ESH of UV; and
- Zenith received an AO fluence of $1.58\times10^{20}$ atoms/cm$^2$ and 4,300 ESH of UV.

The Sun has an irradiance in the UV wavelength range (<400 nm) of approximately 110.9W/m$^2$ (Ref. 3); thus an equivalent Sun hour (ESH) is equal to about 0.4 MJ/m$^2$; thus the exposures listed for windward, leeward and zenith were 960, 800, and 1720 MJ/m$^2$, respectively.

## Imaging and Physical Characteristics

Pre and post-flight macro images were taken along with post-flight optical microscope (OM) images in order to document visual changes of all samples. Sample mass and dimension measurements were taken pre and post-flight. A Mettler balance was used to determine mass within ±0.2 mg; additional mass measurement uncertainty is expected due to estimated moisture content variations of up to 0.03 percent (0.04 mg) in the elastomers (Refs. 22 and 23). The total uncertainty associated with mass measurements is 0.17 percent thus changes in mass less than 0.17 percent are considered insignificant. Calipers (Inerapid by Brown & Sharpe) were used to measure specimen outer diameter and thickness. Total uncertainty was 1 and 2 percent for the outer diameter and thickness, respectively.

## Post-Flight Leak Rate Measurements

Post-flight leak testing was done using the MISSE Flow Fixture (MFF) wherein seals were placed in the metal O-ring groove of the MFF and compressed against a metal plate (Fig. 4). The groove was 0.078 in. deep and the O-ring thickness was approximately 0.103 in., thus 25 percent compression was imposed. The metal mating surface (counter-face) was either pristine stainless steel or the anodized aluminum alloy flight sample (6061 in the T651 heat treated condition). Temperature and pressure were monitored while one atmosphere pressure differential was imposed between the air contained within the seal and the external atmosphere to simulate the pressure differential between the interior of the spacecraft and the vacuum of the space environment. The MFF system was hermetic and leak tested using a helium leak detection system. The temperature of the compressed gas was measured using an RTD (resistance temperature detector) with an uncertainty of ±0.2 K. The average pressure was measured using two calibrated pressure transducers; the pressure transducers had a range of 0 to 20 psig and a percent of full scale output accuracy of ±0.05 percent. The MFF system included a large reservoir of air contained in

Figure 4.—Plates of the MFF, a #2-106 O-ring, and anodized aluminum alloy counter-face at the center of the top plate.

a water bath. The bath helped to maintain a constant temperature, and the reservoir provided a large supply of air for the test, so that a moderate leak across the seal would not cause a large pressure drop in the system. Temperature and pressure data were collected and analyzed with LabVIEW programs (Ref. 24). The air mass in the system was determined using the ideal gas law:

$$m = PV/RT$$

where P is pressure, V is volume, R is the ideal gas constant, and T is temperature. The leakage was determined by the slope of the mass verses time curve at a pressure of 1 atmosphere (14.7 psi). The MFF systems and LabVIEW programs were similar to those used by Daniels (Ref. 11). Leak rate uncertainty was determined using error analysis techniques similar to those presented by Daniels (Ref. 11) and Garafolo (Ref. 25). As shown by Daniels (Ref. 11) the highly accurate measurement techniques result in negligibly small bias and precision errors and minute error bars for an individual leak rate measurement. However, there was significant variability between repeat leakage tests. For these reasons, further discussion of the uncertainty of individual tests was omitted. For most test conditions, 2 or 3 tests were done; the average standard deviation of the resulting data was used to define the uncertainty (error bar). The stainless steel counter-face and O-ring groove were cleaned between each test. The anodized Al flight counterface was never cleaned.

## Results and Discussion

### Mass and Size Changes

Mass and dimension measurements are presented in Table 1. Mass changes of less than 0.17 percent are within measurement uncertainty as are diameter changes of < 1 percent and thickness changes < 2 percent. Mass loss for S0383-70 was negligible for O-rings flown in the windward and leeward orientations but not for specimens in the zenith orientation. This can be explained by considering the AO and UV doses in the different orientations and the compounds expected responses: In general silicone elastomers are not expected to lose significant mass during AO exposure because incoming oxygen reacts with Si forming a stable $SiO_x$ phase; however, UV exposure can break chemical bonds in the compound resulting in radicals that are subsequently drawn off by the vacuum of space. This is reflected in the mass loss response of S0383-70 where UV exposure and mass loss were lowest for the leeward oriented specimens, and highest for zenith oriented. Mass loss for ELA-SA-401 was similarly highest for the zenith oriented samples; mass loss for ELA-SA-401 was consistently higher compared to S0383-70. Mass loss for all cases was less than the NASA requirement of < 1 percent. Mass loss was negligible for the ELA-SA-401 O-rings exposed to vacuum only (zero AO and UV) and for the metal specimens.

TABLE 1.—MASS AND DIMENSIONAL CHANGES OF ELASTOMER O-RINGS AND METAL DISK SPECIMEN DUE TO EXPOSURE TO LEO

[Specimens in the “Vacuum” orientation were covered by Kapton thus received no AO or UV.]

| LEO flight mode | Specimen type | Pre-flight mass, g | Post-flight mass, g | Average mass change, percent | Pre-flight outer dia., in. | Pre-flight thickness, in. | Post-flight outer dia., in. | Post-flight thickness, in. | Average outer dia. change, percent | Average thickness change, percent |
|---|---|---|---|---|---|---|---|---|---|---|
| Windward | S0383-70 | 0.1445 | 0.1442 | –0.1383 | 0.37 | 0.1 | 0.3755 | 0.1 | 0.743 | –0.150 |
| Windward | S0383-70 | 0.1449 | 0.1448 | | 0.372 | 0.1 | 0.372 | 0.0997 | | |
| Windward | ELA-SA-401 | 0.135 | 0.1346 | –0.2219 | 0.376 | 0.106 | 0.373 | 0.102 | –1.243 | –2.363 |
| Windward | ELA-SA-401 | 0.1355 | 0.1353 | | 0.385 | 0.105 | 0.3785 | 0.104 | | |
| Windward | Bare Al | 1.67 | 1.6698 | –0.0089 | 0.4935 | 0.1205 | 0.494 | 0.124 | –0.050 | 0.466 |
| Windward | Anodized Al | 1.6596 | 1.6595 | | 0.4955 | 0.119 | 0.496 | 0.119 | | |
| Windward | Ni coated Al | 1.7 | 1.6998 | | 0.497 | 0.1235 | 0.4965 | 0.125 | | |
| Windward | Ni coated Al | 1.6694 | 1.6693 | | 0.4942 | 0.1203 | 0.4935 | 0.12 | | |
| Windward | Ni coated Al | 1.6869 | 1.6868 | | 0.4948 | 0.1218 | 0.494 | 0.1215 | | |
| Windward | Ni coated Al | 1.6788 | 1.6786 | | 0.495 | 0.121 | 0.4945 | 0.12 | | |
| Vacuum | ELA-SA-401 | 0.1355 | 0.1356 | 0.0738 | 0.381 | 0.107 | 0.379 | 0.105 | –0.525 | –1.869 |
| Leeward | S0383-70 | 0.1443 | 0.1442 | –0.1019 | 0.376 | 0.1 | 0.3705 | 0.1 | –1.266 | 0.495 |
| Leeward | S0383-70 | 0.1486 | 0.1484 | | 0.374 | 0.101 | 0.37 | 0.102 | | |
| Leeward | ELA-SA-401 | 0.1373 | 0.1368 | –0.3295 | 0.386 | 0.106 | 0.3795 | 0.1055 | –2.089 | –0.472 |
| Leeward | ELA-SA-401 | 0.1357 | 0.1353 | | 0.381 | 0.106 | 0.3715 | 0.1055 | | |
| Leeward | Bare Al | 1.663 | 1.6628 | –0.0158 | 0.4955 | 0.1195 | 0.496 | 0.1205 | 0.134 | 1.715 |
| Leeward | Anodized Al | 1.6923 | 1.6919 | | 0.4965 | 0.1225 | 0.497 | 0.1275 | | |
| Leeward | Ni coated Al | 1.6991 | 1.6988 | | 0.4965 | 0.1225 | 0.497 | 0.1225 | | |
| Leeward | Ni coated Al | 1.6651 | 1.6649 | | 0.496 | 0.119 | 0.4965 | 0.121 | | |
| Leeward | Ni coated Al | 1.6883 | 1.6881 | | 0.4955 | 0.121 | 0.496 | 0.123 | | |
| Leeward | Ni coated Al | 1.7023 | 1.702 | | 0.4975 | 0.1225 | 0.499 | 0.125 | | |
| Vacuum | ELA-SA-401 | 0.135 | 0.1349 | –0.0741 | 0.383 | 0.105 | 0.38 | 0.104 | –0.783 | –0.952 |
| Zenith | S0383-70 | 0.1482 | 0.1477 | –0.3756 | 0.373 | 0.102 | 0.373 | 0.102 | –0.134 | –0.495 |
| Zenith | S0383-70 | 0.145 | 0.1444 | | 0.374 | 0.101 | 0.373 | 0.1 | | |
| Zenith | ELA-SA-401 | 0.1381 | 0.1374 | –0.5129 | 0.386 | 0.107 | 0.3765 | 0.104 | –2.068 | –1.402 |
| Zenith | ELA-SA-401 | 0.1349 | 0.1342 | | 0.388 | 0.105 | 0.3815 | 0.105 | | |
| Control | S0383-70 | 0.1459 | 0.1459 | 0.0000 | 0.375 | 0.105 | 0.369 | 0.101 | –0.733 | –1.905 |
| Control | S0383-70 | 0.1464 | 0.1464 | | 0.371 | 0.101 | 0.3715 | 0.101 | | |
| Control | ELA-SA-401 | 0.1374 | 0.1375 | –0.0382 | 0.38 | 0.107 | 0.385 | 0.107 | –0.786 | 0.000 |
| Control | ELA-SA-401 | 0.134 | 0.1338 | | 0.381 | 0.105 | 0.37 | 0.105 | | |
| Control | Bare Al | 1.6936 | 1.6936 | 0.0059 | x | x | x | x | | |
| Control | Anodized Al | 1.6898 | 1.69 | | x | x | x | x | | |
| Control | ELA-SA-401 | 0.1347 | 0.1346 | –0.0742 | 0.376 | 0.106 | 0.3705 | 0.105 | –1.463 | –0.943 |

The outer diameter and thickness of S0383-70 O-rings did not change substantially for any of the orientations. By comparison ELA-SA-401 shrank more, though shrinkage was still very small with a maximum of –2.36 percent for the thickness of the windward ELA-SA-401 O-rings. Control ELA-SA-401 and S0383-70 O-rings shrank an average of approximately 0.8 and 1.3, respectively, indicating that some shrinkage is expected as part of the natural aging process for the compounds.

## Damage Determined by Leak Rate

Figure 5 presents seal leakage results. Reference seals were pristine; Control seals received the $1\times10^{20}$ atoms/cm$^2$ AO pre-treatment; Vacuum received the AO pre-treatment and were flown in space but were covered by Kapton thus received no additional AO or UV; all other elastomer samples were space-exposed and their orientation is indicated. “SS” refers to the seal being mated with the pristine stainless steel counterface; “Al” indicates that the seal was mated to the leeward space-exposed anodized aluminum specimen. The results presented in Figure 5 were from either a single test or the average of two or three repeat tests with the same seal and counter-face; repeats were done for 11 of the conditions shown in Figure 5. The average percent standard deviation for these tests was 71 percent; this value was used to characterize leak rate uncertainty and defined the error bars shown in Figure 5. Figure 5 shows that the leakage for Reference and Control samples is about the same, thus AO pre-treatment does not cause an increase in seal leakage. The leakage of the Vacuum ELA-SA-401 seals was about the same as the windward, leeward, and zenith samples, showing these doses of AO and UV to have little effect on seal leakage for this elastomer compound. Leakage for space exposed S0383-70 seals was much higher than the Control and Vacuum seals of the same type, indicating damage severe enough to compromise functionality. The effects of space exposure on anodized aluminum (Al) appear very small since on average it performed as well as pristine SS in Reference and Control tests, and in all space exposed ELA-SA-401 tests. Leakage of space exposed S0383-70 paired with anodized aluminum was however consistently higher than with SS, indicating the effects of damage on S0383-70 are exacerbated by the exposed Al counter-face.

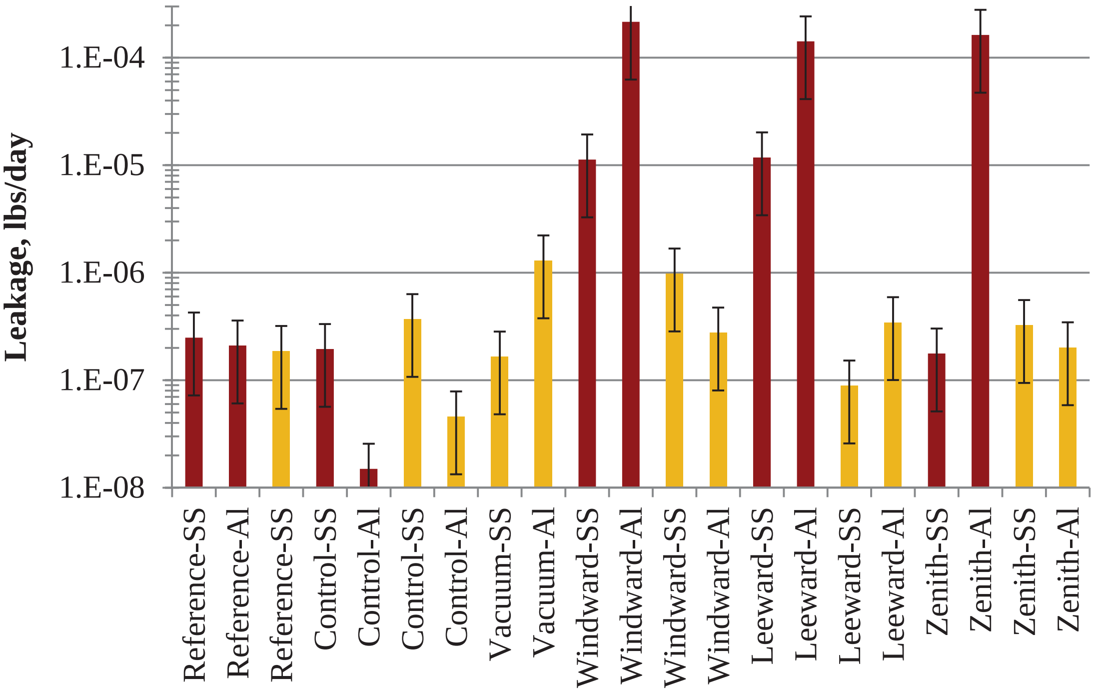


Figure 5.—Air leak rates for seals tested against the anodized aluminum flight sample (Al) and pristine stainless steel (SS). Dark-red bars are S0383-70; gold bars are ELA-SA-401.

Atomic oxygen caused more damage than UV; windward and leeward samples (which received high AO) leaked more than those in zenith orientation (low AO), whereas variations in UV exposure did not seem to affect the samples. A greater sample size is necessary to confirm the consistency of these conclusions. Sources of error may include the differences in shape and size as compared to a full-scale seal for the docking system, as well as between the way these samples were tested compared to actual use of the docking system seal (which is not seated in an O-ring gland). Error may also have been caused by the small number of samples analyzed. Prior work has shown significant damage of silicone rubber resulting from small doses (1 MJ/$m^2$) of UV (254 nm) (Ref. 16). The major differences between (Ref. 16) and the MISSE-7 results presented here were (Ref. 16) employed a larger seal with a rectangular cross section, pressed between two flat plates (no gland) and 15 percent compression rather than 25 percent.

The findings of this study are in disagreement with a similar study reported by Daniels et al. (Ref. 11). Daniels et al. flew S0383-70 and ELA-SA-401 #2-106 O-rings on MISSE-6, exposing them to 18 months of windward and leeward orientated LEO and found the performance of ELA-SA-401 to be worse compared to S0383-70. The reasons for this inconsistency are unknown. One contributing factor may have been in the process by which O-rings were chosen for use. The quality of the ELA-SA-401 O-rings was not consistent, so in this work the O-rings were examined and only the best were included in the study.

## Conclusions

Leakage rates of Reference elastomer samples were very similar to the leakage rates of the Control samples indicating that AO pre-treatment did not cause a significant increase in seal leakage. Thus, AO pre-treatment appears to be an effective method of reducing adhesion without compromising the integrity of the seal. A comparison of the leakage rates of the ELA-SA-401 seals that were in a Vacuum and the ELA-SA-401 specimens that were exposed to LEO conditions suggests that the varying doses of AO and UV as the result of a windward, leeward, and zenith orientations on the ISS had little effect on leak rate. However, the leakage rates of LEO exposed O-rings made of the S0383-70 elastomer compound were markedly higher than the S0383-70 Control specimens. This indicates that the S0383-70 compound was damaged as a result of LEO exposure and that the damage was severe enough to compromise the functionality of the seal. The anodized aluminum exposed to LEO did not show signs of significant damage or compromised functionality, as it performed nearly as well as pristine stainless steel when mated to ELA-SA-401 test specimens. Despite this apparent lack of damage, the leak rates of the S0383-70 O-rings were dramatically higher when paired with the aluminum rather than stainless steel mating surface. This indicates that the effects of damage due to LEO exposure to the S0383-70 elastomer compound were worsened by being paired with the exposed anodized aluminum counterface. The results of this experiment indicate that ELA-SA-401 is more durable to LEO exposure, however additional testing is needed due to the presence of contradicting data in the literature.

## References

1. Dunlap, P., Steinetz, B., and Daniels, C., “Overview of LIDS Docking Seals Development,” 2008 NASA Seal/Secondary Air System Research Symp., NASA/CP—2009-215677, Nov. 18, 2008, pp. 223-231.
2. Lewis, J.L., Carroll, M.B., Morales, R.H., and Le, T.D., National Aeronautics and Space Administration (U.S. Government), Washington, D.C., “Androgynous, Reconfigurable Closed Loop Feedback Controlled Low Impact Docking System With Load Sensing Electromagnetic Capture Ring,” U.S. Patent No. 6,354,540, March 12, 2002.
3. NASA, “Constellation Program Design Specification for Natural Environments,” CxP 70023 Revision A, 2008.
4. Yang, J.C., de Groh, K.K., editors, “Materials Issues in the Space Environment,” MRS Bulletin, Vol. 35, Jan. 2010, pp. 12-19.

5. de Groh III, H.C., Steinetz, B.M., “Effects of Hypervelocity Impacts on Silicone Elastomer Seals and Mating Aluminum Surfaces,” AIAA-2009-5249; also printed as NASA/TM—2009-215836.
6. Chang-Su Huh, Bok-Hee Youn, Sang-Youb Lee, “Degradation in Silicone Rubber Used for Outdoor Insulator by UV Radiation,” Proc. of the 6th Int. Conf. on Properties and Applications of Dielectric Materials, June 2000, Xi’an China, pp. 367-370.
7. Garafolo, N.G., Bastrzyk, M.B., Daniels, C.C., “The Effects of Atomic Oxygen on the Sealing and Mechanical Performance of an Elastomer Seal,” Proceedings of the 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Expositions (January 2010), AIAA-2010-1440.
8. Yi, G.T., de Groh, K.K., Banks, B.A., Haloua, A., Imka, E.C. and Mitchell, G.G., “Overview of the MISSE 7 Polymers and Zenith Polymers Experiments After 1.5 Years of Space Exposure,” Proceedings of the “12th International Symposium on Materials in the Space Environment (ISMSE 12),” Noordwijk, The Netherlands (ESA SP-705, March 2013); NASA/TM—2013-217848.
9. de Groh III, H.C., Miller, S.K.R., Smith, I.M., Daniels, C.C., Steinetz, B.C., “Adhesion of Silicone Elastomer Seals for NASA’s Crew Exploration Vehicle,” Proceedings of the 44th AIAA, ASME, SAE, ASEE Joint Propulsion Conference and Exhibit (July 2008), 2008-215433.
10. de Groh III, H.C., Daniels, C.C., Dever, J.A., Miller, S.K., Puleo, B.J., Waters, D.L., Finkbeiner, J.R., Dunlap, P.H. Jr., Steinetz, B.M. “Space Environment Effects on Silicone Seal Materials,” National Aeronautics and Space Administration Technical Memorandum, Washington D.C. NASA/TM—2010-216332-REV1.
11. Daniels, C.C., Wasowski, J.L., Panickar, M.B., Smith, I.M., “Leak Rate Performance of Three Silicone Elastomer Compounds after Ground-Simulated and On-Orbit Environment Exposures,” Proceedings of the 3rd AIAA Atmospheric Space Environments Conference (June 2011), AIAA-2011-3823.
12. de Groh III, H.C., Puleo, B.J., Steinetz, B.M. “Effects of Atomic Oxygen and Grease on Outgassing and Adhesion of Silicone Elastomers for Space Applications,” National Aeronautics and Space Administration Technical Memorandum, Washington D.C. NASA/TM—2012-217263.
13. Penney, N., Wasowski, J.L., Daniels, C.C., “Temperature and Atomic Oxygen Effects on Helium Leak Rates of a Candidate Main Interface Seal,” Proceedings of the 46th AIAA, ASME, SAE, and ASEE Joint Propulsion Conference and Exhibit (July 2010), AIAA-2010-6986.
14. Berkebile, S., Gaier, J.R. “Adhesion in a Vacuum Environment and its Implications for Dust Mitigation Techniques on Airless Bodies,” AIAA-2012-3465, NASA/TM—2012-217723.
15. de Groh, K.K., Banks, B.A., Dever, J.A., Jaworske, K.J., Miller, S.K., Sechkar, E.A., and Panko, S.R., “NASA Glenn Research Center’s Materials International Space Station Experiments (MISSE 1-7),” NASA/TM—2008-215482.
16. de Groh, H.C., Puleo, B.J., Waters, D.L., Miller, S.K., “Anti-Adhesion Elastomer Seal Coatings for Ultraviolet and Atomic Oxygen Protection,” NASA/TM—2014-218334.
17. de Groh III, H.C., Puleo, B.J., Waters, D.L., “Use of VUV Radiation to Control Elastomer Seal Adhesion,” Proceedings of the 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference (July 2013) AIAA-2013-3915.
18. Linton, R.C., Finckenor, M.M., Kamenetzky, R.R., Gray, P., “Effects of Atomic Oxygen and Ultraviolet Radiation on Candidate Elastomeric Materials, Test Series No. 1, 1993, NASA TM-108408.
19. Banks, B.A., de Groh, K.K., Rutledge, S.K., Haytas, C.A., “Consequences of Atomic Oxygen Interaction with Silicone and Silicone Contamination of Surfaces in Low Earth Orbit,” NASA/TM-1999-209179.
20. Dever, J.A., Banks, B.A., “Effects of Vacuum Ultraviolet Radiation on DC93-500 Silicone,” Jol. Spacecraft and Rockets, Vol. 43, No. 2, 2006, pp. 386-392.
21. Finkbeiner, J.R., Dunlap Jr., P.H., Steinetz, B.M., Daniels, C.C., “Apollo Seals: A Basis for the Crew Exploration Vehicle Seals,” AIAA-2006-5259, NASA/TM—2006-214372.

22. Gong, B., Tu, Y., et al., “Moisture Absorption Characteristics of Silicone Rubber and its Effect on Dielectric Properties,” 2013 Annual Report Conf. on Electrical Insulation and Dielectric Phenomena, IEEE, DOI: 10.1109/CEIDP.2013.6748283, pp. 430-433.
23. Gubbels, F., “Silicones in the Electronics Industries,” in Inorganic Polymers, DeJaeger, R. and Gleria, M. editors, Nova Sci. Pub., 2007, last retrieved 10/8/2014 http://www.dowcorning.com/content/publishedlit/chapter11.pdf
24. Dunlap Jr., P.H., Daniels, C.C., Wasowski, J.L., Garafolo, N.G., Penney, N., and Steinetz, B.M., “Pressure Decay Testing Methodology for Quantifying Leak Rates of Full-Scale Docking System Seals,” NASA/TM—2010-216244, April 2010, 45th Joint Prop. Conf. and Exhibit, AIAA-2009-5319, Aug. 2009.
25. Garafolo, N.G. and Daniels, C.C., “Comprehensive Mass Point Leak Rate Technique. Part I: Methodology with Uncertainty and experimental Error Analysis,” JSNDI/ASNT 4th Japan-US Symp. on Emerging NDE Capabilities for a Safer World, 2010.