The Mechanical Performance of Subscale Candidate Elastomer Docking Seals

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Abstract

The National Aeronautics and Space Administration is developing a Low Impact Docking System (LIDS) for future exploration missions. The mechanism is a new state-of-the-art device for in-space assembly of structures and rendezvous of vehicles. At the interface between two pressurized modules, each with a version of the LIDS attached, a composite elastomer-metal seal assembly prevents the breathable air from escaping into the vacuum of space. Attached to the active LIDS, this seal mates against the passive LIDS during docking operation. The main interface seal assembly must exhibit low leak and outgas values, must be able to withstand various harsh space environments, must remain operational over a range of temperatures from -50°C to 75°C, and perform after numerous docking cycles. This paper presents results from a comprehensive study of the mechanical performance of four candidate subscale seal assembly designs at -50, 23, 50, and 75°C test temperatures. In particular, the force required to fully compress the seal during docking, and that which is required for separation during the undocking operation were measured. The height of subscale main interface seal bulbs, as well as the test temperature, were shown to have a significant effect on the forces the main interface seal of the LIDS may experience during docking and undocking operations. The average force values required to fully compress each of the seal assemblies were shown to increase with test temperature by approximately 50% from -50 to 75°C. Also, the required compression forces were shown to increase as the height of the seal bulb was increased. The seal design with the tallest elastomer seal bulb, which was 31% taller than that with the shortest bulb, required force values approximately 45% higher than those for the shortest bulb, independent of the test temperature. The force required to separate the seal was shown to increase with decreasing temperature after 15 hours of simulated docking. No adhesion force was observed at 75°C, while magnitudes of up to 235 lbf were recorded at the refrigerated temperature. In addition, the adhesion force was observed to increase with bulb height. When compared with the LIDS program requirements, the measured compression force values were found to be below the maximum allowable load allotted to the main interface seal. However, the measured adhesion force values at the refrigerated test temperature were found to exceed the program limits.

Nomenclature

AO	Atomic oxygen
CTE	Coefficient of thermal expansion
$CVCM$	Collected volatile condensable materials
$EDU58$	Engineering Development Unit
ISS	International Space Station
LEO	Low Earth Orbit
$LIDS$	Low Impact Docking System
$NASA$	National Aeronautics and Space Administration
RTD	Resistance temperature detector
TML	Total mass loss

I. Introduction

A new generation docking system is being developed by the National Aeronautics and Space Administration (NASA) to support current and future space operations. The Low Impact Docking System (LIDS)[1] is designed to provide an interface between pressurized structures and vehicles during space operations.

The mating systems currently in use include the Common Berthing Mechanism used to connect elements of the International Space Station (ISS) and the Androgynous Peripheral Assembly System used to dock the Space Shuttle to the ISS.[2] The primary advantage of the LIDS over the existing systems is the reduced risk associated with the docking operation. Current docking/berthing systems rely upon high impact loads to combine the two mating vehicles. This new system uses electromagnets to capture and mechanical actuators to bring the two vehicles together, thereby greatly reducing the loads imparted upon the mating structures. The reduced load of the LIDS minimizes the effect on the activities taking place within the space vehicle or structure (e.g., experiments on the ISS)[3] and enhances the life of the assembly by minimizing structural fatigue.

The current design of the LIDS interface employs two functionally different versions of the system. One of the two LIDS is an active docking system while the other remains passive. The active half of the interface contains a main interface seal, as shown in Figure 1.
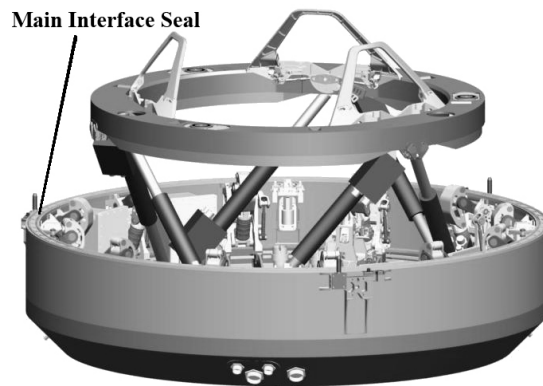
Main Interface Seal

Figure 1. Illustration of an active Low Impact Docking System.

This seal is a critical part of the LIDS since it confines the breathable air inside of the mated vehicles. Any air lost past the seal must be replaced. The passive half of the LIDS-to-LIDS interface provides a smooth flat surface against which the main interface seal docks. The interaction of the gas seal and the flat metal surface is an important design consideration of the LIDS, as it contributes to the overall system leak rate. When docking, the latches of the active LIDS pull the two systems towards each other, compress the main interface seal, and hold the assembly together. The load required to adequately compress the seal is an important factor in properly designing the latch and tab connection. The amount of force that the latches can provide to compress the seal assembly is limited by the weight constraints imposed on all space flight hardware. Should the system not be capable of fully compressing the seal, the air leak rates would be greater than expected. Small variations in elastomer seal geometry can have a pronounced effect upon the required load to compress the seal.[4] This is problematic since the manufacturing tolerances of elastomer seals can be relatively large (±0.005 in.)[5] under the best of circumstances.

The LIDS has a limited amount of force available to separate the interface during undocking. A load of 1.65 lbf per inch of seal has been allocated to overcoming the adhesion forces between the compressed seal and the flat surface on the passive LIDS. If the seal adhesion loads are too great, the two LIDS and their associated vehicles would not separate or the dislodging, breaking, or partial removal of the seal could occur rendering the attachment interface useless.[6]

The researchers at the NASA Glenn Research Center are developing and evaluating several different seal designs to meet the requirements for the LIDS main interface seal. A subset of the requirements state that the elastomer must be low outgassing,[7] the force required to fully compress a subscale seal assembly must be below 9500 lbf, and the adhesion force is limited to 64 lbf, for the seals presented in this study. The candidate seal assemblies were composed of an elastomer material vacuum molded into a metal retainer. An elastomer material was chosen due to its restoring force when compressed that insures seal integrity in the

presence of unfavorable factors such as thermal cycling, vibration, or aging.[8] The results presented in this paper concentrate on assessing the mechanical characteristics of a candidate silicone elastomer for the seal material and aluminum as the metal for the retainer ring.

Silicone elastomer compounds are typically used in seals for space flight applications due to their large range of operating temperature. They can function at cold temperatures better than other elastomer compound classes due to their low embrittlement temperatures. The current exposure temperature of the LIDS is $-75°C$ to $125°C$ and silicone rubber is the only class of elastomer that is commonly molded into seals and remains functional over the expected LIDS operating temperature range of $-50°C$ to $75°C$. A further seal material limitation is that few silicone elastomers meet the low outgas standards that NASA requires of all materials used in space. As the LIDS and its main interface seal operate in a vacuum pressure environment, all materials must conform to NASA-STD-(I)-6016.[7] This standard mandates that outgas byproducts be limited to less than 1.0% total mass loss (TML) and less than 0.1% collected volatile condensable materials (CVCM) when exposed to heat and vacuum pressure, as tested following ASTM E595-07.[9]

In addition, the seal must be able to withstand the exposure to constituents of the harsh space environment. The seal assembly will have to remain functional subsequent to exposures to hard vacuum, atomic oxygen, ultraviolet and particle radiation, micrometeoroids, and orbital debris. Exploration into the effects of these exposures has previously been published.[8, 10–14]

The objectives of the work presented herein were (1) to evaluate the force required to fully compress the seal, and (2) to investigate the adhesion force required to separate the seal. Both of these characteristics were measured on four different seal designs that had the same bulb width and varied in seal bulb height. The seals were tested at the upper and lower limits of the LIDS operating temperature range, as well as at an ambient temperature. The test specimens used in this study were subscale Engineering Development Unit (EDU58) seal assemblies with an outside diameter of approximately 12 in. The leak rate values of all four the these seal designs have been characterized.[14, 15] The mechanical performance of each elastomer seal design is presented in this paper and the obtained results, in combination with previous material characterization tests performed on the same elastomer compounds,[11–15] will be extrapolated to predict full-scale system seal performance.

II.   Experimental Setup

II.A.   Test Specimens

The test specimens were custom designed Gask-O-Seals® manufactured by Parker Hannifin Corporation and referred to as 12inEDU58 seal assemblies. The general design of the seal assembly consisted of an aluminum retainer ring with four silicone elastomers molded into it. A cross-section schematic of the seal is shown in Figure 2, while a photo is presented in Figure 3. The details and dimensions of the elastomer seals within the metal retainer are proprietary designs and are described in general terms only. The elastomer seals were
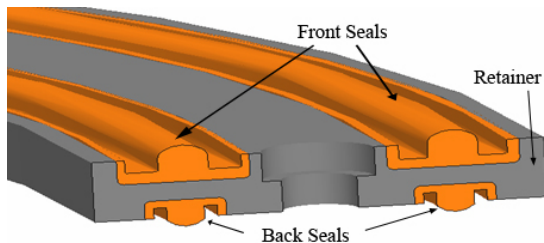

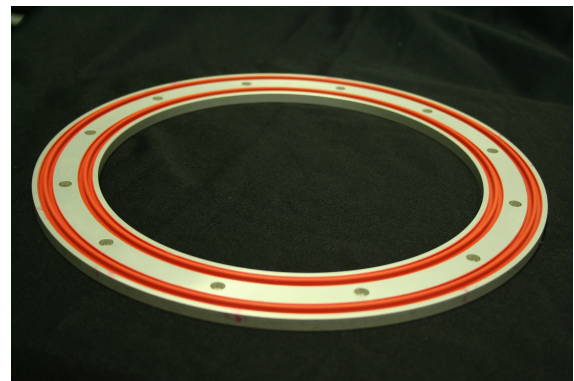Figure 2.   Illustration of the test specimen assembly cross-section with front and back side seals.

Figure 3.   A photograph of the test specimen seal assembly.

made of silicone compound $S0383 - 70$ and vacuum molded into both, the top and bottom surfaces of the aluminum ring. The cross-sections of the seals on the front side were identical, but different from those on the back side. Four front side seal designs of the 12inEDU58 test specimens were explored in this study, and

throughout the paper they shall be referred to as $'-1'$, $'-2'$, $'-3'$, and $'-4'$ designs. The seal designs varied in front side seal bulb height, with $'-1'$ design having the shortest bulb and $'-4'$ having the tallest bulb. All four designs had the same bulb width. The elastomer bulbs of the $'-2'$, $'-3'$, and $'-4'$ designs were 11, 20, and 31% taller than the $'-1'$ design, respectively. The outside diameter and thickness of the retainer were approximately 12 in. and 0.3 in., respectively.

The particular silicone elastomer, Parker Hannifin S0383 − 70, was chosen for manufacturing the seals since the compound has been previously shown to be durable when exposed to simulated LIDS operating environments.[11] Moreover, the material was verified to meet the low outgas requirements with TML and CVCM values below the limits of 1.0% and 0.1%, respectively, as tested per ASTM E595.[9]

II.B. Compression Test System

The compression and adhesion force values were acquired using an Instron model 5584 electromechanically actuated material test system. The test specimens were attached to the load frame using aluminum platens. The platens were coaxially aligned with the centerline of the load frame. An image identifying individual components of the compression test system is presented in Figure 4.
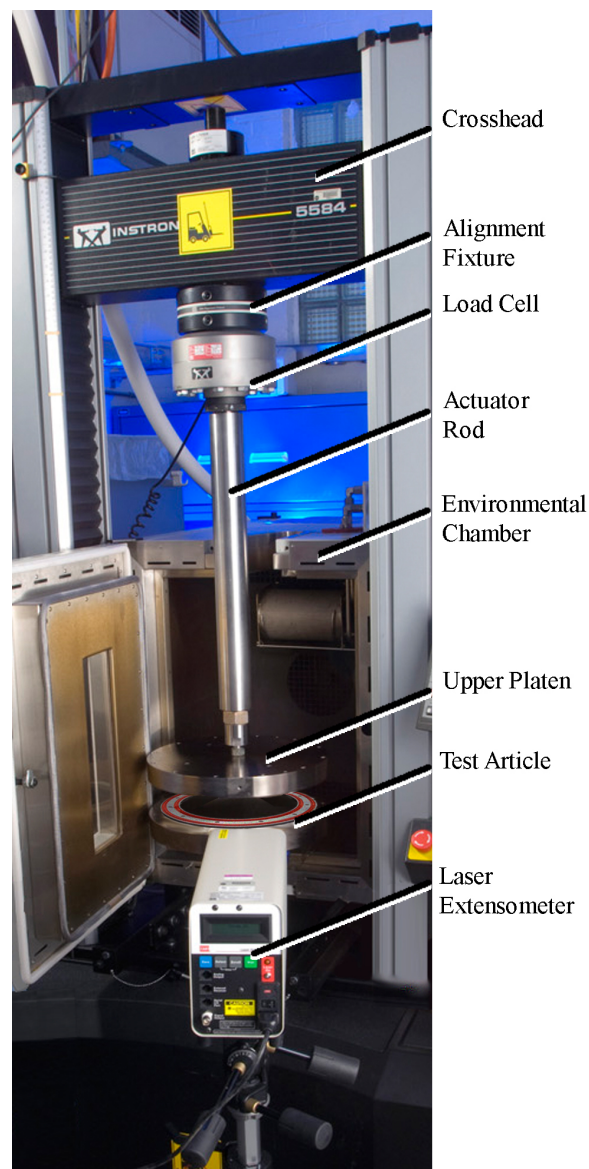

Figure 4. Photograph of the experimental fixture setup.

A given test seal was affixed to the bottom platen and compressed against the upper platen to simulate a docking scenario where a seal would dock against a flat metallic surface. To further simulate the expected docking situation scenarios, the bottom platen was made of aluminum $2219-T851$, while the upper was manufactured from aluminum $6061-T651$. Both platens were coated with between 0.0003 and 0.0005 in. of electroless nickel and the upper platen had a surface finish of better than 16 μin. The platens were designed to allow air to escape from between the seal bulbs and the center of the seal assembly during compression.

Prior to the start of a test, a precision gauge was used to set the distance between the mating surfaces. Subsequently, the distance between the upper and lower assemblies was reduced until their contact surfaces (platen and retainer) were fully compressed against one another. The displacement of the two platens was determined using an MTS laser extensometer, model $LX300$. The speed at which the mating surfaces approached one another, also referred to as the loading speed, was not constant, but was a function of time, as specified by the LIDS design. A close approximation of the docking and undocking closure rate profile of the seal assembly test fixture over a sample distance of 0.5 in. is shown in Figure 5. A given test cycle,
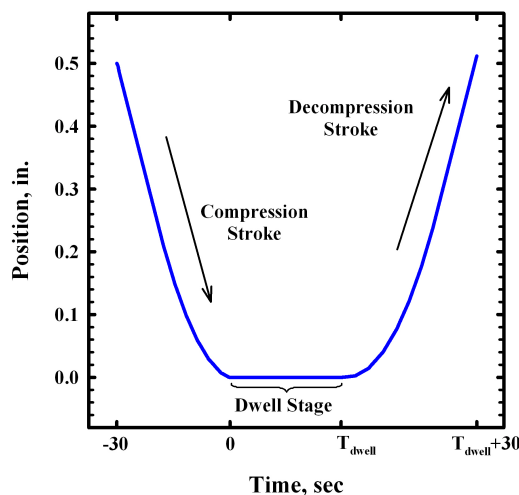

Figure 5. Graphical representation of the upper platen and seal assembly closure rate.

as indicated in Figure 5, consisted of compression, dwell, and decompression stages, where the last is also often referred to as the adhesion stage. In theory, both the compression and adhesion force values could be determined on the same test cycle; however, in the study presented herein, the two tests were separated. For each of the trials during compression load testing, the seal assembly underwent 10 load/unload cycles with 10 second dwell and rest times between cycles. Two trials were carried out at each test temperature with a 30 minute rest time in between. To determine the adhesion forces, only one load/unload cycle at each test temperature was employed with a 15 hour dwell time.

The force required to compress the seal assemblies was measured during the compression stroke using an Instron $2525-171$ load cell with an accuracy of $\pm 1\%$ of the reading. The upper and lower platens were compressed together until approximately 8200 lbf of compression force was recorded. Ten consecutive cycles were utilized to explore the effect of cycling an elastomer seal test specimen on the force required to obtain retainer-to-platen compression. The force required to compress the seal assemblies was determined by searching the acquired data for the force corresponding to the location at which the position reached a constant value, signifying metal-to-metal contact. The accuracy of the method was ± 50 lbf.

The adhesion force between the seal assembly and the mating counter-face was measured during the decompression stroke using an Interface $1020ACK-12-5K-B$ load cell with an accuracy of $\pm 0.24\%$ of the reading. Similar to the compression load test, the seal was compressed until approximately 8200 lbf of force was applied and held for 15 hours of dwell time. The force required to separate the seal assemblies (adhesion force) was determined from the acquired load and position data.

II.C. Temperature Control System

The temperature of the fixture containing the seal assemblies was controlled during the compression and adhesion force testing using an Instron $3119-407$ environmental control system with an accuracy of $\pm 3.5°$C. An image of the temperature control system along with the test fixture elements is shown in Figure 4. Subsequent to installation in the test fixture, the test specimens were conditioned for a minimum of five hours at the test temperature prior to simulated docking in order to allow the platens and seal assemblies to settle at the desired temperature. The temperature of the fixture was monitored using a resistance temperature detector (RTD) attached to the upper platen. The mechanical characteristics of the seals explored in this paper were quantified at four test temperatures: refrigerated $(-50°$C), room $(23°$C), and elevated $(50°$C and $75°$C).

III. Experimental Results and Discussion

III.A. Compression Load

The force measurement of a typical compression load test on a seal made of $S0383-70$ compound where no adhesion is present is shown in Figure 6. The figure illustrates the force response during one cycle composed of three stages, compression, dwell, and decompression, corresponding to those shown in Figure 5. The dwell stage occurs when the seal assembly is held compressed for a predefined period of time, which in the case of the compression load cycles was 10 seconds. It should be noted that usually the force-position plot of a given material is presented as a stress-strain plot, however, due to the seal dimension's intricate and proprietary nature, the displacement was normalized by the given seal bulb height and plotted. For the purpose of quantifying the force values required to compress the four different seal assembly designs, only the loading (compression) part of the cycle will be analyzed in this section.
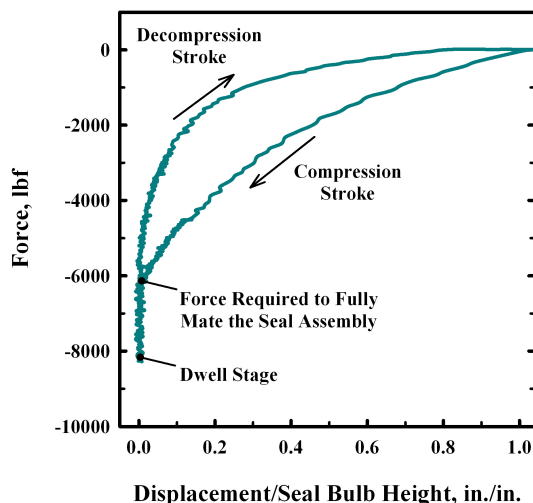

Figure 6. Force-position plot typical of compression force testing of S$0383-70$ elastomer compound.

### III.A.1. Effect of test temperature

Each seal assembly design was represented by a single seal specimen. Each of the four seal assembly specimens was compression load tested at four test temperatures in the following test sequence: $23°$C (trials 1 and 2), $50°$C (trials 1 and 2), $-50°$C (trials 1 and 2), $75°$C (trials 1 and 2), and $23°$C (trials 3 and 4). Two trials at a given test temperature, each consisting of 10 load/unload cycles, were run. For each test trial, the average required compression force of the 10 cycles was calculated. The calculated values, along with the maximum force value recorded over the 10 cycles (usually on the first cycle of given trial) represented by an error bar, are shown in Figure 7 for all four seal designs, all four temperatures, and all trials.
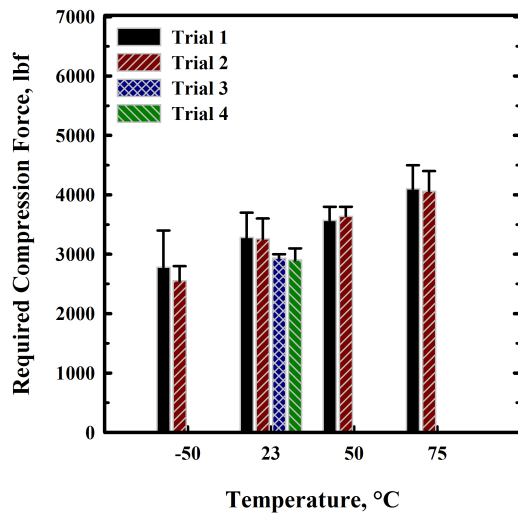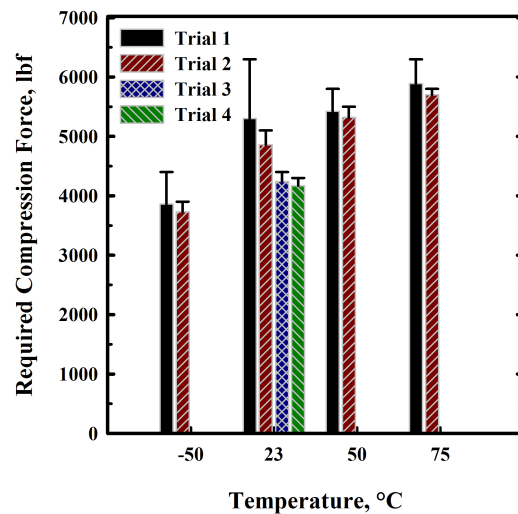
(a) $'-1'$ Seal Design
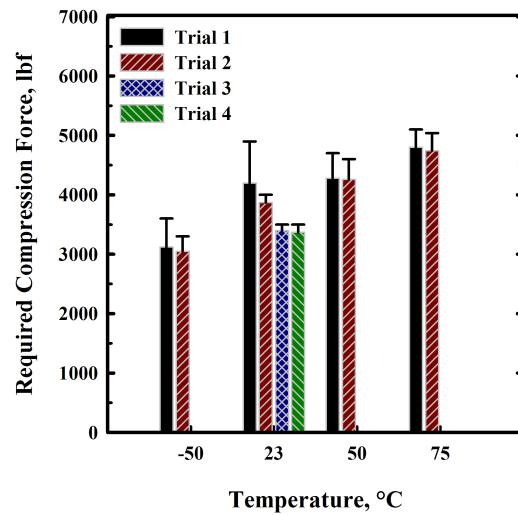
(b) $'-2'$ Seal Design
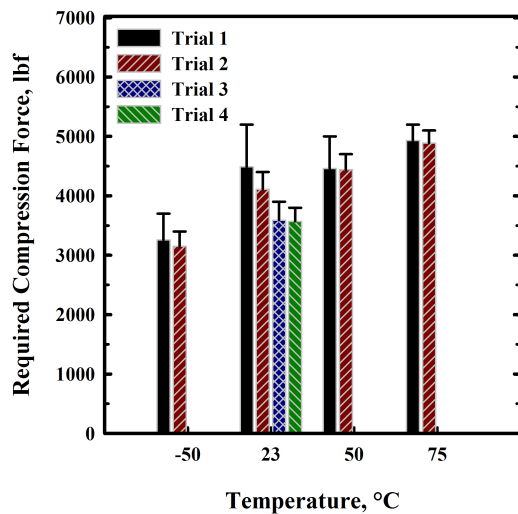
(c) $'-3'$ Seal Design

(d) $'-4'$ Seal Design

Figure 7. Average compression force for four seal assembly designs at four test temperatures; the maximum value recorded is represented by the error bar for each trial.

The single largest influence on the compression load, independent of the seal design, was the test temperature, as shown in Figure 7. Increasing the temperature from $-50°C$ to $75°C$ increased the average required compression force by 48, 54, 51, and 53% for $'-1'$, $'-2'$, $'-3'$, and $'-4'$ seal assembly designs, respectively. Moreover, the increase of the average trial compression force was directly proportional to the test temperature following a quadratic trend. The best-fit curves for each of the seal designs, along with the trial 2 data are shown in Figure 8.
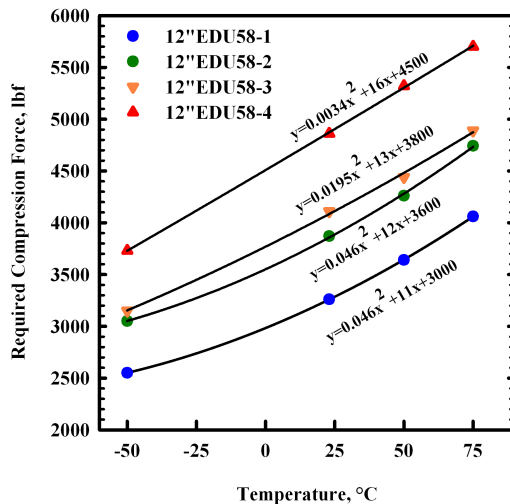

Figure 8. Comparison of average compression force values required for the four seal designs at four test temperatures during trial 2 **along with quadratic best-fit lines.**

To further investigate the effect of test temperature on the force required to fully mate the seals, the force response during the tenth cycle of each seal's first trial was considered, as shown in Figure 9. The tenth cycle was chosen to minimize the effect due to cycling. The figure shows the measured force up to the value required to fully mate each seal assembly (retainer to platen) plotted against the seal's instantaneous height non-dimensionalized by the seal design height. The temperature effect can be observed at two locations on each of the plots. First, since the force during the compression stage is plotted up to the point where the seal is fully mated, the increase in the required compression force with temperature can be observed. In addition, the effect of the temperature can also be noted at the top of each of the charts in Figure 9, where as the temperature decreases, a longer distance must be traveled by the upper platen before it contacts the seal since the elastomer has shrunk due to the lower temperature and the material's coefficient of thermal expansion (CTE of the silicone elastomer is $355 \times 10^{-6}°C^{-1}$).[16]

III.A.2.   Effect of cycling

The design of the composite seal limits the compression of the elastomer by the platen-to-metal retainer contact. Therefore, the maximum displacement of the elastomer was the same for each cycle regardless of cycle, trial, or temperature. However, for a given trial, the maximum stress value occurred when the elastomer was the largest (cycle 1). On subsequent cycles, the elastomer bulb had taken on compression set thereby reducing the corresponding stress level. This occurred again when a new, higher temperature was employed, and any time the seal was allowed to recover (e.g., between trials).

Two trials at a given test temperature, each consisting of ten load/unload cycles, were run on each specimen in order to detect the presence of the Mullins Effect,[17] where the elastomer softens after being compressed by an all-time maximum stress value. Since the same compression force (approximately 8200 lbf) was used for all test cycles, it was expected that after the first cycle, the force required to compress a given seal assembly would decrease. To further illustrate the presence of this phenomenon, the tests at room temperature were repeated (trials 3 and 4) at the end of the test sequence, after each seal specimen has undergone compression load testing at all temperatures.
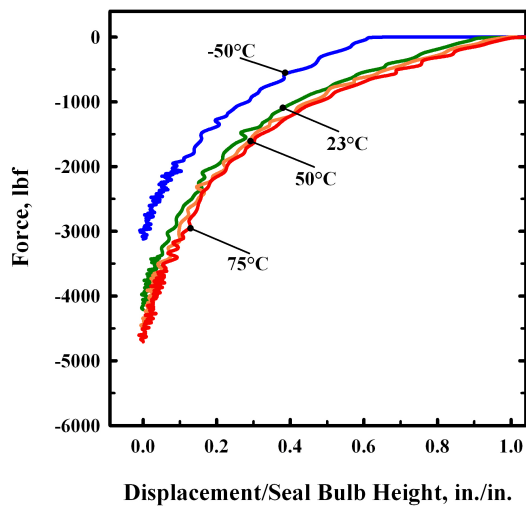
The relaxation of elastomer material subsequent to the first compression (23°C - trial 1) can be observed in Figure 7. This behavior was expected based on Mullins Effect theory,[17] where the seal material softens
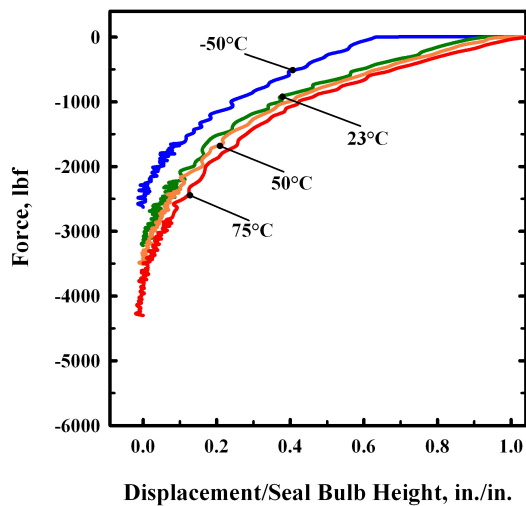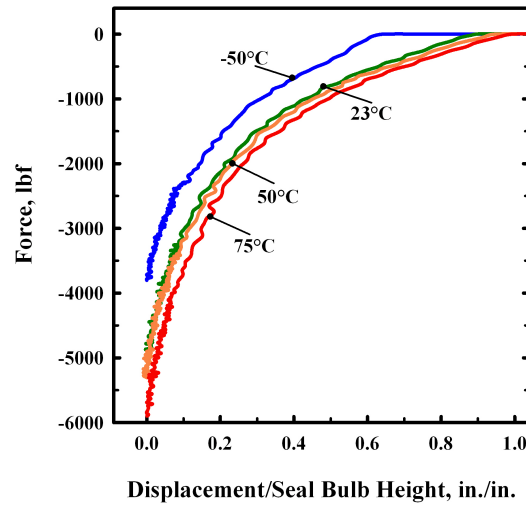
(a) $'-1'$ Seal Design
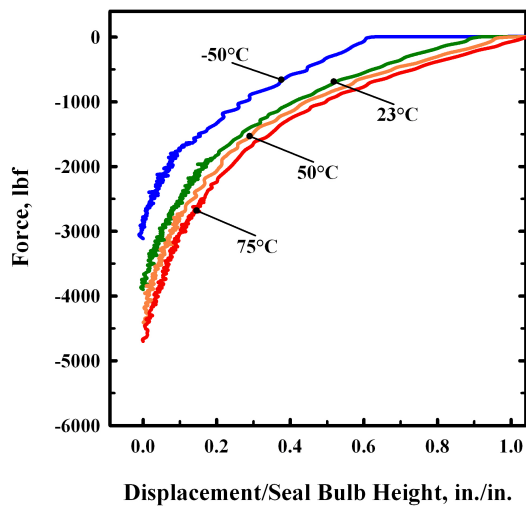
(b) $'-2'$ Seal Design

(c) $'-3'$ Seal Design

(d) $'-4'$ Seal Design

Figure 9. Force response of each seal design during trial 1, cycle 10 compression at four test temperatures.

after the first compression the seal material has experienced. In addition, when the force response of the first 10 cycles of any of the seal designs was plotted, as in the $'-3'$ design shown in Figure 10, the shift in the starting point of the compression can be observed. This behavior is caused by the compression set of the seal upon loading. An insufficient amount of time between cycles was allotted for the elastomer to fully recover prior to the next compression. This figure also illustrates the significant decrease of the force required to fully mate with cycle number. To further illustrate this point, the measured compression force values, rounded to the nearest 100 lbf, of each of the 10 cycles on trial 1 at 23°C for all four seal designs are plotted in Figure 11. For the $'-1'$, $'-2'$, $'-3'$, and $'-4'$ designs, the required force was found to decrease from cycle 1 to cycle 10 by 15, 20, 19, and 22%, respectively. In addition, when comparing the average values over the 10 cycles between trials 1 and 3 at 23°C shown in Figure 7, the force decreased by 11, 19, 20, and 20% for the $'-1'$, $'-2'$, $'-3'$, and $'-4'$ designs, respectively.
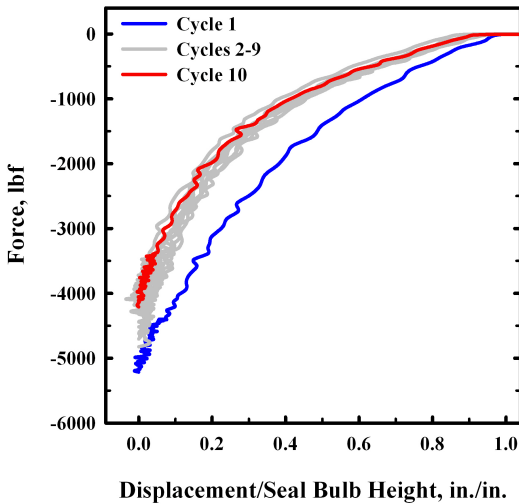

Figure 10. Force response of $'-3'$ seal design during the first 10 loading strokes at room temperature.
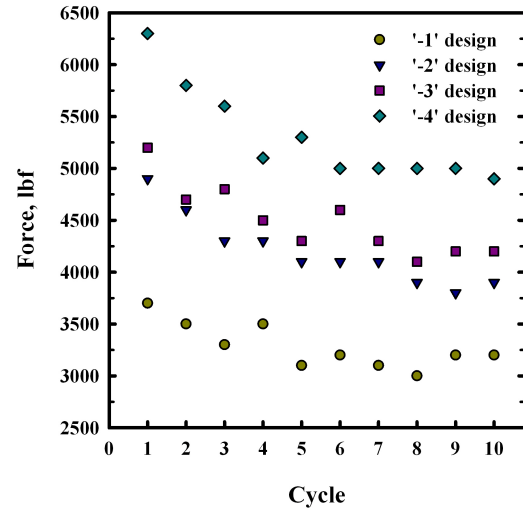

Figure 11. The required compression force values for each seal design during the first 10 compression cycles at room temperature.

III.A.3. Effect of seal design

In order to show the dependence of the required compression force on the seal design, the average force results previously shown in Figure 7 have been compiled and illustrated in Figure 12, where the data presented at 23°C represented the results of trial 3. Clearly, as the seal bulb height increases, the average required compression force also increases. A summary of the increase in the required compression force between the shortest seal height design ($'-1'$) and the three taller designs, considering trial 2 average values, is presented in Table 1 for the four test temperatures. For reference, the average required compression force values for the $'-1'$ seal design during trial 2 runs were 2550, 3260, 3640, and 4060 lbf at −50, 23, 50, and 75°C, respectively.

Table 1. Percent Increase in the Required Compression Force Values Between the $'-1'$ and Other Seal Designs Based on Average Values of Trial 2 at Four Test Temperatures

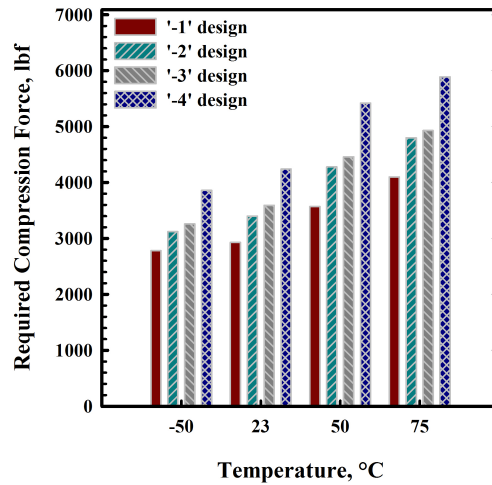| Seal Design	Increase in Required Compression Force, %			
	−50°C	23°C	50°C	75°C
$'-2'$	19.6	18.7	17.0	16.7
$'-3'$	23.5	26.1	22.0	17.2
$'-4'$	46.3	49.1	46.2	40.4

Figure 12. Comparison of average required compression force values between the four seal designs at four test temperatures.

The force-displacement behavior of the seals at $-50°$C is shown in Figure 13, where the x-axis represents displacement (values omitted due to proprietary reasons). This graph demonstrates the effects of seal height on the required compression force. At the top of the graph, a shift in the starting point of the compression load indicates the effect of seal height on displacement of the upper platen required for initial contact with the seal. Once the displacement values were non-dimensionalized by the seal bulb height, the curves collapsed upon each other, as shown in Figure 14; the required compression force remained as the only difference between the results.

The maximum required compression force values observed in this study were 4500, 5100, 5200, and 6300 lbf for the $'-1'$, $'-2'$, $'-3'$, and $'-4'$ designs, respectively. When compared with the LIDS program requirements, each of these values was below the maximum allowable compression force allotted to the main interface seal across the operating temperature range of -50 to $75°$C, adjusted for the diamater of the subscale seals. Additionally, it was observed that the force values were reduced with repeated cycling, eliminating any concern that docking system latch capability would have to accommodate a stiffening elastomer compound.
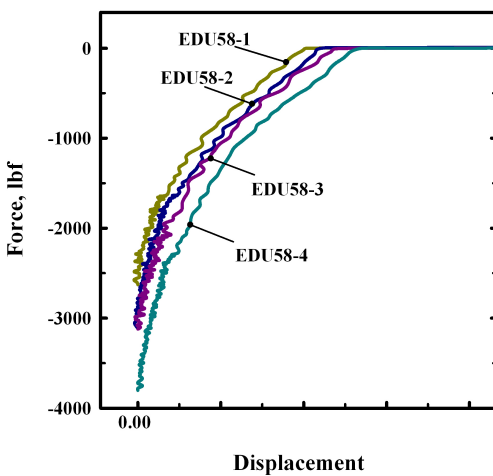

Figure 13. Force-displacement behavior of all four seal designs at $-50°$C test temperature during trial 1, cycle 10 (x-axis values omitted for proprietary reasons).
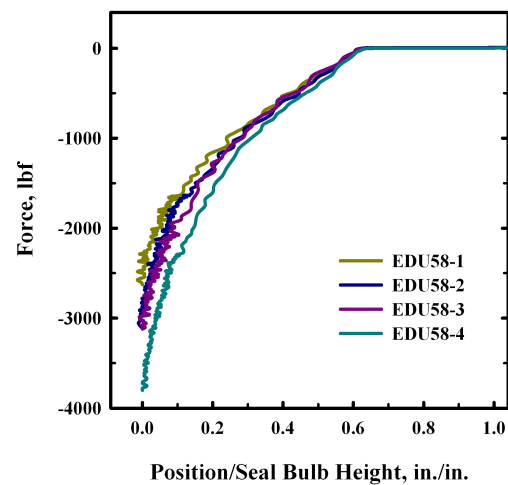

Figure 14. Force-nondimensionalized displacement behavior of all four seal designs at $-50°$C test temperature during trial 1, cycle 10.

III.B. Adhesion Force

A typical force response plot of an adhesion test is shown in Figure 15 for the $'-4'$ seal tested at $-50°$C. Similar to the compression load tests, the cycle was composed of three stages: compression, dwell, and decompression. During the dwell stage, the seal was held fully mated, under a force of approximately 8200 lbf for a period of 15 hours. Only one cycle was run for each seal assembly design at a given test temperature. The presence of adhesion in Figure 15 was observed to be 235 lbf. The same seal assemblies were used for the adhesion force experiments after compression force testing. Therefore, the effect of cycling was neglected since each seal had already undergone numerous cycles.
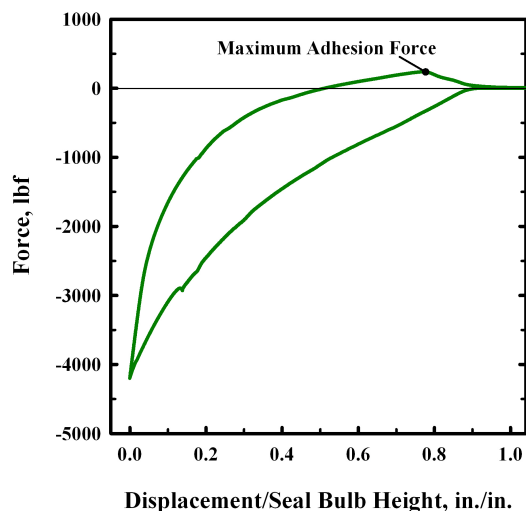

Figure 15. Typical force-displacement plot for adhesion test on S0383 − 70 elastomer compound. Seal design $'-4'$ at $-50°$C.

III.B.1. *Effect of test temperature*

The acquired adhesion force values for all four seal designs and three test temperatures are summarized in Table 2.

Table 2. Adhesion Force Values of All Four Seal Designs and Test Temperatures

	Adhesion Force, lbf		
Seal Design	$-50°$C	$23°$C	$75°$C
$'-1'$	168	15	0
$'-2'$	189	37	0
$'-3'$	227	35	0
$'-4'$	235	45	0

The adhesion between the elastomer seal and the aluminum platen decreased with increasing test temperature, as detailed in Table 2. With the 15 hour dwell time employed, no adhesion was observed at the elevated temperature, a minimal amount was noted at room temperature, and a significant value was recorded at the refrigerated temperature. This phenomena of increased adhesion force with decreased test temperature can be explained by the fact that as the temperature decreases, the surface energy of the material increases. When the surface of the seal is compressed, the polymer tends to adhere to the metal counter-face.

III.B.2. *Effect of seal design*

The adhesion force was found to generally increase with the seal bulb height ($'-1'$ through $'-4'$), as illustrated in Table 2. This behavior was expected given that a taller seal bulb meant a larger contact surface area

when the seal assembly was completely compressed (retainer-to-platen). Considering the adhesion force values recorded at the refrigerated temperature, the force for the $'-4'$ design was found to be 40% larger than that of $'-1'$ design. Similarly, $'-3'$ and $'-2'$ designs exhibited adhesion forces 35% and 13% larger than that of the $'-1'$ seals.

If the maximum allowable adhesion force requirement of the LIDS program (300 lbf) would be distributed equally around the elastomer seal on a per length basis, the subscale seals considered herein would not meet the requirement. For these test samples to meet the expectations of the program, their adhesion force values would have to be below 64 lbf. To mitigate this seal characteristic, there are several options including: lubricating the seal, pretreatment of the seal with atomic oxygen (AO), or changing procedures to narrow the temperature envelope during which undocking would occur. Lubricating the seal may have the undesirable effects of increasing the outgassing of the seal assembly and making maintaining a seal surface free from foreign debris difficult. Pretreatment of the seal with AO would reduce the adhesive force of the elastomer seal. Reasonable levels of AO have been shown to reduce the adhesion tendencies of the seal while not significantly impacting seal leak rate.[14] Table 2 shows that adhesion is problematic only at the refrigerated temperature. Therefore, should undocking temperature envelope be adjusted, the separation would occur at a higher temperature, and lower adhesion could be expected.

IV. Summary and Conclusions

The National Aeronautics and Space Administration is currently developing a new generation Low Impact Docking System designed to provide a safe means of mating current and future space vehicles. Due to the innovative design of the new docking system, the seal assembly, used to prevent the leakage of the breathable air from the pressurized modules into the vacuum of space, must meet certain requirements concerning the maximum force necessary for full compression and separation during undocking (adhesion). The candidate seal assemblies must be made from a low outgassing material, capable of withstanding the detrimental effects of atomic oxygen, ultraviolet radiation, micrometeroid and orbital debris, and a wide operational temperature range ($-50°$C to $+75°$C). Four subscale seal designs have been analyzed herein, all made from a $S0383-70$ silicone elastomer that has previously been shown to meet the outgassing and leak rate requirements. The difference between the four seal designs was the height of the silicone elastomer bulb. The presented results have shown that the force required to completely compress the seal assembly, which creates the most desired configuration to minimize leak rate values, increases as the seal bulb height increases. Similarly, the force required to separate the seal from its mating counter-face, increases with the seal bulb height. In addition, across the operational temperature range, for all four seal designs, the required compression force values were observed to increase with temperature, by approximately 50% from $-50°$C to $75°$C. However, for the same temperature range, the adhesion force was found to increase with decreasing temperature. No distinguishable force was required to separate the seal from its mating counter-face at $75°$C, however, a significant amount of up to 235 lbf was recorded at $-50°$C test temperature after 15 hours of hold time. Comparing the measured values to the system requirements, all four subscale candidate seal designs exhibited compression load values below the 9500 lbf limit, where the highest average compression force of given trial was 6300 lbf. However, at the refrigerated temperature, the seals exhibited adhesion force values higher than levels allowed by the system requirements.

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14. ABSTRACT
The National Aeronautics and Space Administration is developing a Low Impact Docking System (LIDS) for future exploration missions. The mechanism is a new state-of-the-art device for in-space assembly of structures and rendezvous of vehicles. At the interface between two pressurized modules, each with a version of the LIDS attached, a composite elastomer-metal seal assembly prevents the breathable air from escaping into the vacuum of space. Attached to the active LIDS, this seal mates against the passive LIDS during docking operation. The main interface seal assembly must exhibit low leak and outgas values, must be able to withstand various harsh space environments, must remain operational over a range of temperatures from -50 to 75 °C, and perform after numerous docking cycles. This paper presents results from a comprehensive study of the mechanical performance of four candidate subscale seal assembly designs at -50, 23, 50, and 75 °C test temperatures. In particular, the force required to fully compress the seal during docking, and that which is required for separation during the undocking operation were measured. The height of subscale main interface seal bulbs, as well as the test temperature, were shown to have a significant effect on the forces the main interface seal of the LIDS may experience during docking and undocking operations. The average force values required to fully compress each of the seal assemblies were shown to increase with test temperature by approximately 50 percent from -50 to 75 °C. Also, the required compression forces were shown to increase as the height of the seal bulb was increased. The seal design with the tallest elastomer seal bulb, which was 31 percent taller than that with the shortest bulb, required force values approximately 45 percent higher than those for the shortest bulb, independent of the test temperature. The force required to separate the seal was shown to increase with decreasing temperature after 15 hr of simulated docking. No adhesion force was observed at 75 °C, while magnitudes of up to 235 lbf were recorded at the refrigerated temperature. In addition, the adhesion force was observed to increase with bulb height. When compared with the LIDS program requirements, the measured compression force values were found to be below the maximum allowable load allotted to the main interface seal. However, the measured adhesion force values at the refrigerated test temperature were found to exceed the program limits.

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