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Comparison of Adhesion and Retention Forces for Two Candidate Docking Seal Elastomers

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Abstract

To successfully mate two pressurized vehicles or structures in space, advanced seals are required at the interface to prevent the loss of breathable air to the vacuum of space. A critical part of the development testing of candidate seal designs was a verification of the integrity of the retaining mechanism that holds the silicone seal component to the structure. Failure to retain the elastomer seal during flight could liberate seal material in the event of high adhesive loads during undocking. This work presents an investigation of the force required to separate the elastomer from its metal counter-face surface during simulated undocking as well as a comparison to that force which was necessary to destructively remove the elastomer from its retaining device. Two silicone elastomers, Wacker 007-49524 and Esterline ELA-SA-401, were evaluated. During the course of the investigation, modifications were made to the retaining devices to determine if the modifications improved the force needed to destructively remove the seal. The tests were completed at the expected operating temperatures of -50, +23, and +75°C. Under the conditions investigated, the comparison indicated that the adhesion between the elastomer and the metal counter-face was significantly less than the force needed to forcibly remove the elastomer seal from its retainer, and no failure would be expected.

I. Introduction

Seals are used to maintain gases at desired pressures within a spacecraft. For docking systems, seals between adjoining vehicles are typically a face seal configuration. A face seal configuration allows for easy assembly on-orbit with minimal mechanical mechanisms while reducing the possibility of damage due to scrubbing that may occur with other seal configurations. However, face seal configurations place the seal and its retention mechanism into tension during undocking, risking seal damage and removal.

Elastomer compounds have been found to develop considerable adhesion when compressed against metallic surfaces with various coatings. Quantifying the amount of separation force required to undock the seal from its mating counter-face is a part of ongoing research (Refs. 1 to 6). Elastomer surface treatments have been shown to dramatically reduce, but not completely eliminate, adhesion between elastomer seals and their counter-faces (Refs. 2 and 6). This introduces the possibility that the elastomer seal-to-mating counter-face adhesion may exceed the forces retaining the seal to its host vehicle (Ref. 6). It is critical that the seal not be dislodged or damaged during operation, as this could liberate orbital debris, potentially impairing sealing ability and redundancy. Additionally, damage to a space seal can be a costly disruption to normal operations.

The undocking of a seal from its mating counter-face surface may occur at any temperature within the operational envelope. For docking systems, this temperature may range from as low as -50°C to as high as +75°C (Ref. 7). Over this temperature range, the tensile strength of the elastomer may vary substantially thereby affecting the structural strength of the elastomer part.

During the course of this work, a candidate seal design was evaluated to determine the adhesion that may occur between the seal and its mating counter-face surface. The candidate seal was a two-part design, including both an elastomer and a metal retainer. The silicone elastomer was manufactured separate from the metal retainer, which was designed to mechanically retain the elastomer to the host space vehicle. This design was investigated utilizing two different silicone elastomer compounds. Additionally, the work presented herein quantified the strength of the retaining features of two silicone elastomer candidate seal materials by determining the amount of force required to extract silicone elastomer seals from their retainers. The presented data was acquired from tests on individual subscale seal assemblies at -50, +23, and +75°C.

II. Experimental Setup

A. Test Specimens

The test specimen seal design consisted of two separate components, a two-bulb elastomer seal and a metal retainer. Two silicone elastomer compounds were considered: Esterline Corporation ELA-SA-401 silicone elastomer manufactured by Kirkhill-TA and Wacker 007-49524 silicone elastomer manufactured by Custom Rubber Corp. Select mechanical properties of ELA-SA-401 and 007-49524 were shown in Table 1. Both elastomers were vacuum molded into a shape consisting of two seal bulbs connected by a retaining web feature, see Figure 1. The two bulb design of a primary (inner) seal and redundant (outer) seal provides single fault tolerance to leak rate failure. The outside diameter of the elastomer was approximately 30 cm for all test specimens used.

The elastomer part was tested without any surface pretreatment that may be used to reduce the elastomer's natural adhesive tendencies (Refs. 6 and 9). All test specimens were cleaned of any surface dirt and debris by gently rubbing the surface with a lint-free cloth soaked with isopropyl alcohol. The test specimen was allowed to dry prior to testing.

The metal retainer of the two-part test specimens was manufactured from aluminum 7075-T651. The surface roughness of the aluminum retainer was 0.41 μm or better prior to the application of an anodized surface finish. The metal retainer was designed to fit between the two elastomer seal bulbs when the elastomer and metal components were assembled onto the test fixture, see Figure 2.

TABLE 1.—MECHANICAL PROPERTIES OF TWO SILICONE ELASTOMER MATERIALS (REF. 8).

	ELA-SA-401	007-49524
Durometer	38	40-42
Tensile strength	724 N/cm^2	658 N/cm^2
Elongation	625%	437%
Tear strength	45 N/cm^2	72 N/cm^2

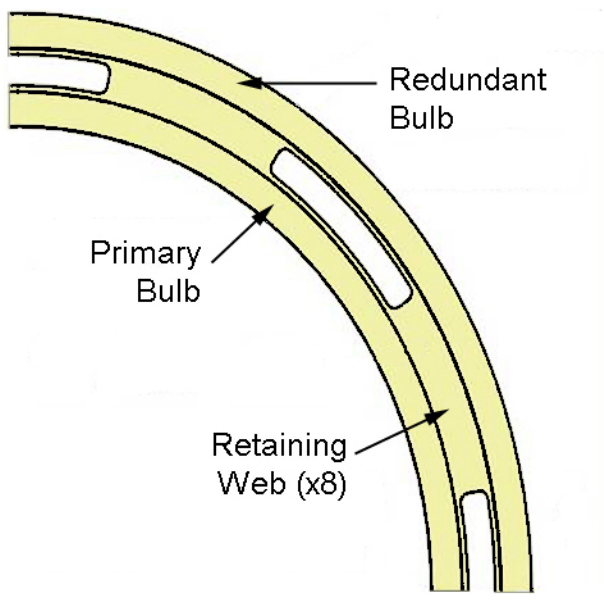

Figure 1.—Illustration of the top view of the elastomer seal of the two-part test specimen.

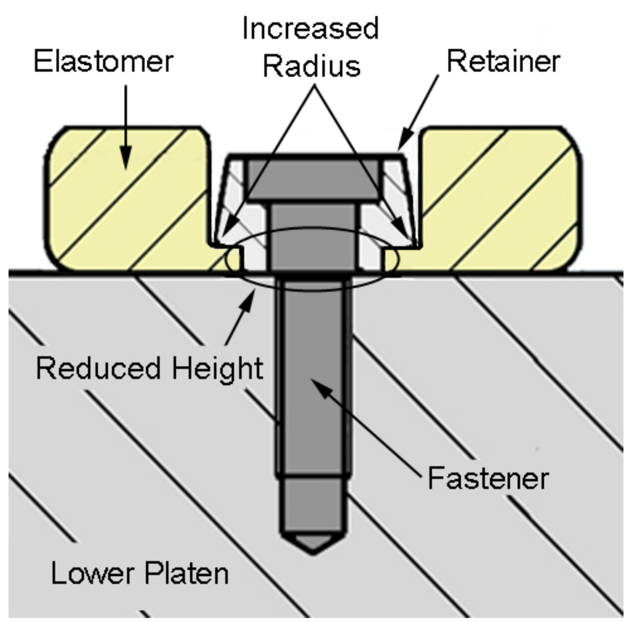

Figure 2.—Illustration of the cross-section of the two-part seal assembly.

Select destructive removal tests were conducted using metal retainers that were modified. These modifications included increasing the radii of the retainers' edges that contact the elastomer and decreasing the height of the retainers' pads, as highlighted in Figure 2.

B. Test Fixture Assembly

1. Retention Failure Tests

The test fixture consisted of one aluminum platen (lower) and one carbon steel platen (upper), in between which the seal assembly was positioned and held, see Figure 3. The elastomer part of the test specimen was attached to the lower platen using the metal retainer and #8-32 size fasteners. As the upper surface of the seal assembly was intended to be the reusable interface, adhesive was utilized to simulate an intentionally excessive level of adhesion to the opposing mating counter-face (the upper platen).

Dow Corning 3145 RTV MIL-A-46146 was used to bond the complete circumference of a single elastomer bulb to the upper platen, utilizing GE Silicone SS4004P primer prior to seal attachment. The test specimen and fixture assembly was cured at 74±3°C for 24 to 48 hours to ensure that the RTV was fully cured.

To quantify the amount of force necessary to extract the elastomer seal from its metal retainer, the test fixture was coaxially aligned and fastened to the actuator rods of an actuation system, as discussed in further detail in Section C.

2. Adhesion Test

The test fixture used to determine the adhesion force between the elastomer component of the seal assembly and its metal counter-face was similar to that which was described in the previous section. The differences were that both the lower and upper platens were made of aluminum, 6061-T651, with a 0.41 μm surface roughness or better prior to surface treatment. A 0.008 to 0.013 mm thick coating of electroless nickel was applied to both platens. No adhesive was applied to the surface of either the elastomer or its counter-face, allowing the natural adhesive tendency to be quantified.

C. Actuation and Temperature Control Systems

The actuation system consisted of an Instron 5584 electromechanical load frame with a temperature control system incorporated, see Figure 4. For each trial, the upper platen was fastened into the load frame using a 5/8"-18 threaded connection. The lower platen was attached to an aluminum platen using four 3/8"-16 screws. The aluminum platen was fastened to the load frame using a single 5/8"-18 threaded connection.

The temperature of elevated (+75°C) and chilled (-50°C) temperature tests was controlled using an Instron 3119-407 environmental control system. The system surrounded the test specimen assembly and its attachments to the load frame. For elevated and chilled temperature tests, the fixture was brought to a steady state temperature within ±5°C of the desired set point prior to testing; cooling of the fixture was carried out with the use of liquid nitrogen. The temperature of the room temperature tests (+23°C) was uncontrolled.

The rate of separation was not uniform, but followed the curve shown in Figure 5.

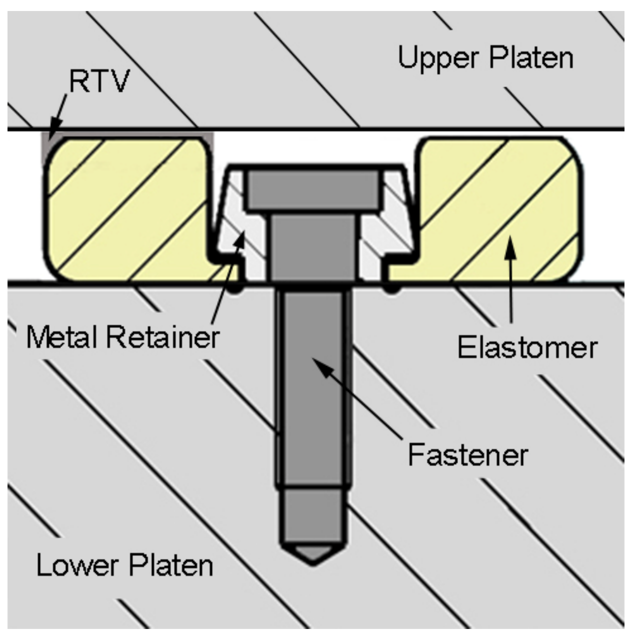

Figure 3.—Illustration of the cross-section of the seal assembly and the location of the adhesive.

D. Instrumentation

The force required by the actuation system to remove the elastomer from its retaining feature or to separate the elastomer from its counter-face was measured by an Interface 1020ACK-12-5K-B load cell. As the load cell was mounted external to the temperature control system, the error of the load cell due to test temperature was negligible. The load cell and its reported measurements had an accuracy of ±0.24% of the reading for both the destructive removal and adhesion tests.

Data was collected at a sampling rate of 40 Hz and written to a PC-based recording device.

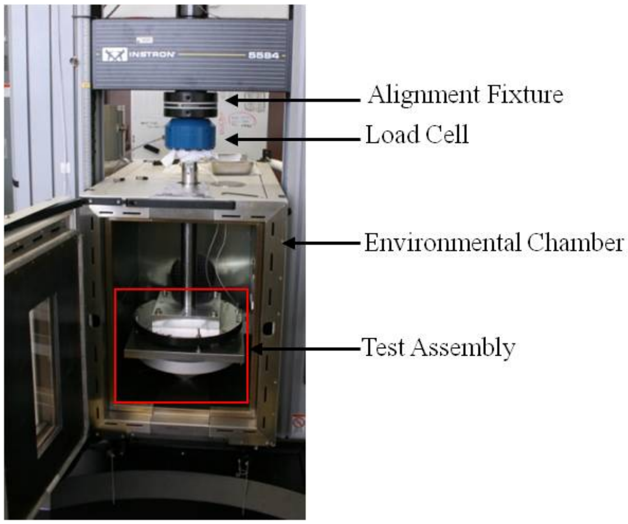

Figure 4.—Photograph of the actuation and temperature control system.

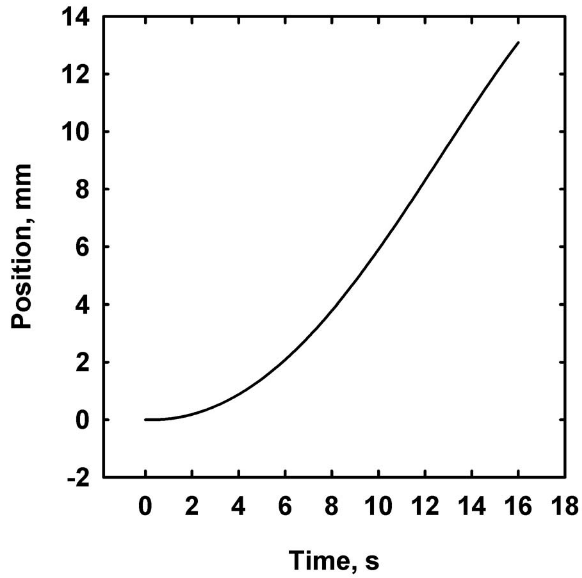

Figure 5.—The separation speed of the actuation system.

III. Results and Discussion

The force required to fail the retention mechanism holding the elastomer in its retainer (referred to as "removal force" or "retention force") was quantified at test temperatures of -50, +23, and +75°C. The obtained retention failure forces were compared to adhesion force values observed in simulated undocking cycles of the same seal design against an electroless nickel plated aluminum platen at the three test temperatures. To facilitate comparisons between tests and designs, the forces were divided by the circumferential length of elastomer seal tested to obtain a normalized force per unit length.

A. Retention Failure Force

A total of two, five test series, were conducted on the two-part seal test specimens. In the first series, the tests were conducted at each of the three test temperatures, -50, +23 and +75°C, for both elastomer compounds. During these tests, it was observed that the retention failure occurred at the contact point between the elastomer and the mechanical metal retainer. In the second series of tests, the retainer was modified as highlighted in Figure 2. In the first modification, the retainer was machined to provide a larger radius at the location where the elastomer and retainer were in contact during extraction. A single test was completed for each material at room temperature. A further modification was investigated; the second modification included the first modification along with a reduction in height of the metal retainer such that the elastomer web was placed in compression upon installation.

In general, the two elastomer compounds behaved in a similar fashion. Upon separation of the upper and lower platens, the elastomer part that was adhered to the upper platen with RTV remained in contact with the upper platen. The metal retainer attached to the lower platen remained fastened to the lower platen. The retaining web, see Figure 1, exhibited extraordinary deformation as shown in the photograph in Figure 6. During this interval, the specimen resisted the maximum amount of force, see Figure 7, as the elastomer reoriented itself under the metal retainer (between 0.0 and 2.0 cm displacement). The elastomer continued to deform until the first of the eight retaining webs failed (approximately 4.0 cm for the -50°C case). The upper and lower platens continued to separate until all eight retaining webs failed, with the force decreasing with each web failure.

The elastomer exhibited the lowest amount of elongation prior to complete failure at +75°C. This was presumed to be caused by a decrease in the strength of the elastomer at elevated temperatures, which caused the retaining web feature to fail at lower levels of displacement. Decreased strength at elevated temperatures also allowed the elastomer to reorient itself under the metal retainer with lower levels of applied force.

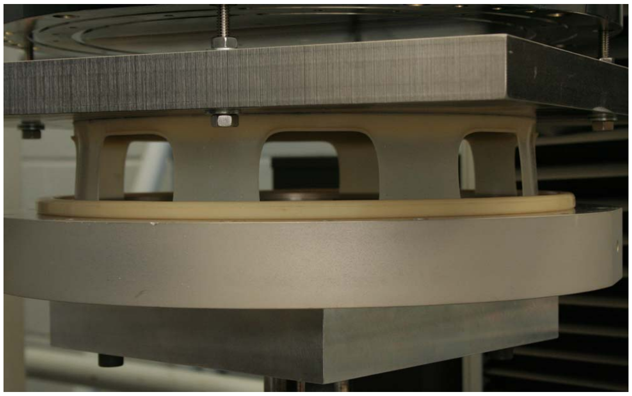

Figure 6.—Photograph of an ELA-SA-401 specimen during a test at +23°C prior to failure.

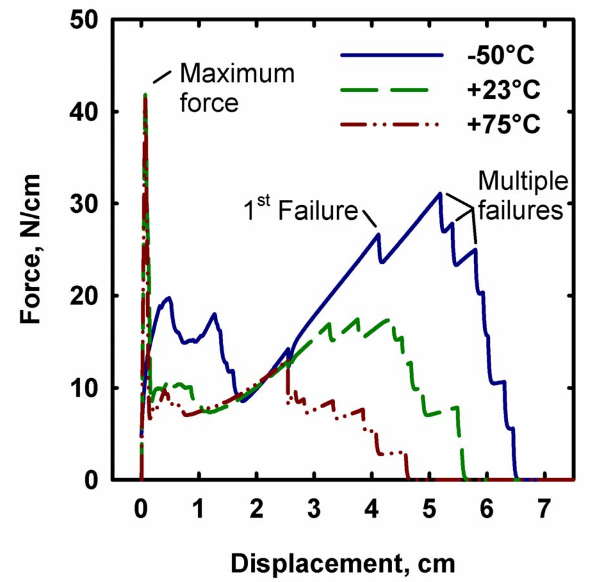

Figure 7.—Force-displacement response of the 007-49524 specimen without retainer modification at -50, +23, and +75°C.

The results of the first series of tests performed to determine the effect of test temperature on the maximum force resisted by the seal assemblies before retention failure are shown in Figure 8. The force resisted by the 007-49524 compound remained relatively stable across the temperatures of interest. The ELA-SA-401 compound showed a marked decrease in the force resisted prior to failure with increasing test temperature.

As the seal was intended to operate across the range of temperatures examined, only the lowest observed force to cause retention failure was of interest for a given compound. For the 007-49524 compound, that value was 31.1 N/cm (at -50°C); for the ELA-SA-401 compound, 38.9 N/cm (at +75°C).

In general, the force required to remove the ELA-SA-401 exceeded that which was needed to remove the 007-49524. For the one experiment conducted on each elastomer at room temperature, the difference was 21%. This was greater than the 10% greater tensile strength, as shown in Table 1.

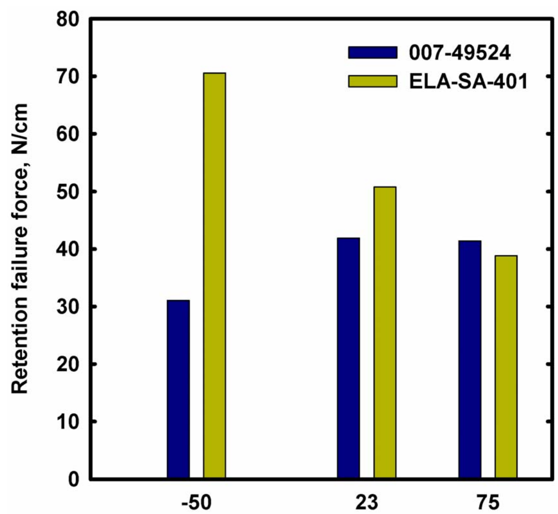

Figure 8.—Maximum force resisted by the seal assemblies of the two materials in the first series of tests at -50, +23, and +75°C.

To determine if minor changes to the retainer design would significantly increase the force necessary to remove the elastomer component from its retainer, two subsequent tests were conducted after retainer modification, as highlighted in Figure 2. As shown in Figure 9, neither increasing the radius of the retainer nor reducing the height of the elastomer improved the retaining performance for the 007-49524 elastomer compound. The removal force was reduced by 24 and 36% with those individual modifications, respectively. The individual modifications produced modest improvements in removal force, 6 and 18% respectively, with the ELA-SA-401 compound, as shown in Figure 10.

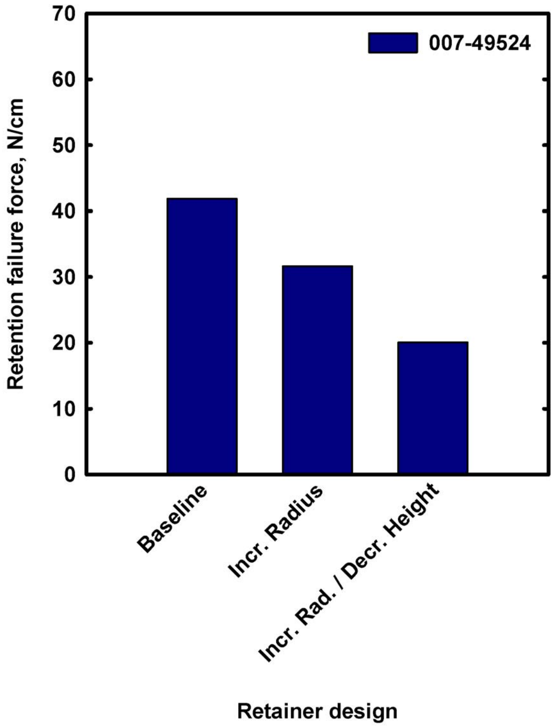

Figure 9.—Retention failure forces of Wacker 007-49524 for three retainer designs tested at +23°C.

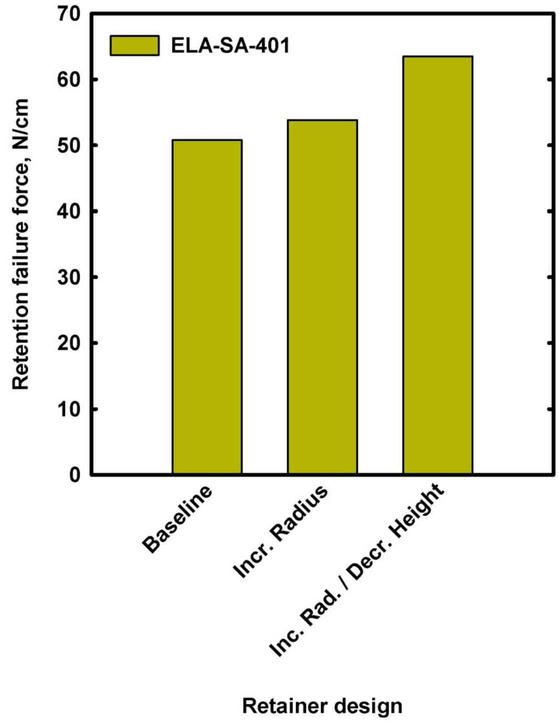

Figure 10.—Retention failure forces of Esterline ELA-SA-401 for three retainer designs tested at +23°C.

B. Adhesion Force

The amount of adhesion between the elastomer seal and its mating counter-face (without adhesive) was measured for each of the two elastomer compounds. Measurements were recorded at each of three temperatures: -50, +23, and +75°C. At room temperature, the specimens were held together for extended periods of dwell time to determine the effect of time.

For both of the elastomer compounds investigated, the highest value of adhesion was recorded when the compression, dwell, and separation occurred at -50°C, see Figures 11 and 12. The highest value of adhesion was 3.5 and 8.0 N/cm for the 007-49524 and ELA-SA-401 compounds, respectively. This observation was in agreement with those of other studies (Refs. 2 and 6) and was attributed to an increase in surface energy at cold temperatures. Conversely, the tests conducted at the highest temperature, +75°C, exhibited the least adhesion.

At room temperature, +23°C, the test specimens were held in compression for up to 72 hours. Intuitively, the level of adhesion was expected to rise with increased dwell times. For the 007-49524 compound, this was the trend observed; however the increase was modest, from 0.59 to 1.4 N/cm, when the dwell time was increased from 2 to 72 hours, see Figure 11.

No significant increase in adhesion level was observed with the dwell times investigated in this study for the ELA-SA-401 compound at +23°C, see Figure 12. The highest level recorded for this dwell time was 3.4 N/cm after 24 hours of compression. The range of adhesion was 0.36 to 8.0 N/cm with the largest value recorded after 2 hours at -50°C.

C. Effect of Separation Speed

As discussed above, the adhesion force showed a strong dependence on temperature and no more than modest dependence on dwell time. In addition to these factors, the displacement of the elastomer seal at the moment of separation was dependent on the amount of adhesion. Since the unloading rate was not uniform, as illustrated in Figure 5, the speed at which the separation occurred was variable over the experimental test conditions. Therefore, an understanding of the effect of separation speed on the adhesion force was a required element of the investigation.

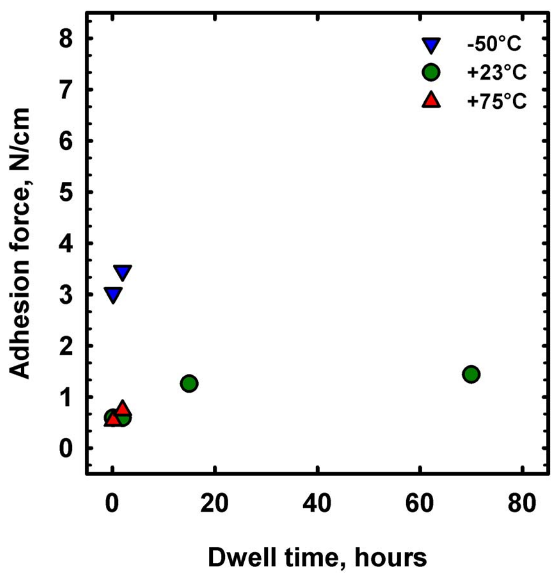

Figure 11.—Maximum adhesion force of 007-49524 observed after various compression dwell periods at -50, +23, and +75°C.

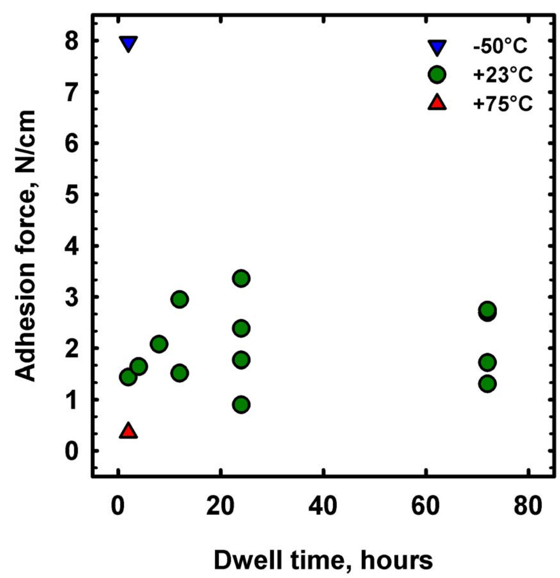

Figure 12.—Maximum adhesion force of ELA-SA-401 observed after various compression dwell periods at -50, +23, and +75°C.

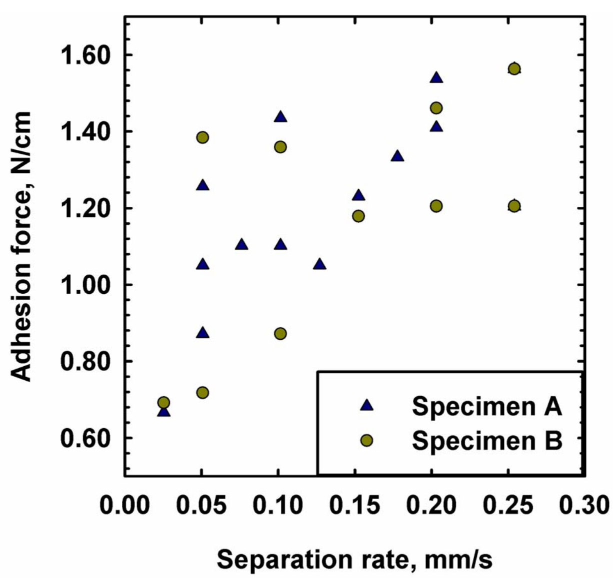

Figure 13.—Adhesion force of ELA-SA-401 at +23°C after 2 hour compression.

A series of experiments was conducted on the ELA-SA-401 elastomer compound at room temperature, +23°C, after being held together for two hours. It was assumed that the separation between the elastomer and counter-face occurred between 0.00 and 0.26 mm of displacement. From Figure 5, the speed over that displacement interval was 0.00 to 0.25 mm/s.

The experiments were conducted on two identical specimens in a random order to minimize any trends that may have occurred with compression/separation cycle count. As shown in Figure 13, the adhesion force tended to increase with the rate of separation. The maximum adhesion was observed at the maximum separation rate tested, 0.25 mm/s. Conversely, the minimum adhesion occurred at the slowest speed.

D. Comparison Between the Retention and Adhesion Forces

A summary table of the retention and adhesion forces described in the previous sections was presented in Table 2. As the adhesion force testing was conducted using the baseline retainer design, only the results from the baseline case were considered in the comparison.

As shown in the table, the retention force exceeded the adhesion force for both elastomers tested at all temperatures by at least a factor of 8.9 and 8.8 for the 007-49524 and ELA-SA-401 compounds, respectively. Therefore, the natural adhesion between the elastomer and its mating counter-face would not be sufficient to cause the undesired removal of the elastomer during separation.

TABLE 2.—SUMMARY OF MINIMUM RETENTION AND MAXIMUM ADHESION FORCES OF BASELINE RETAINER TESTS

	Retention force, N/cm			Maximum adhesion force, N/cm		
	-50°C	**+23°C**	**+75°C**	**-50°C**	**+23°C**	**+75°C**
Wacker 007-49524	31.1	41.4	41.9	3.5	0.59	0.74
Esterline ELA-SA-401	70.5	50.9	38.9	8.0	3.4	0.36

IV. Summary

During the retention failure tests of both elastomer compounds, the elastomer component of the seal assembly failed at the web between the two seal bulbs due to excessive stretching across the metal retainer. Increasing the temperature of the test specimens decreased the force required to fail a design, due to the decreased strength of the elastomer. The amount of force resisted by the seal assemblies prior to destructive removal was 31 to 42 N/cm for the Wacker 007-49524 compound and 39 to 71 N/cm for the Esterline ELA-SA-401 compound.

The natural adhesion between the elastomer component of the seal assembly and its metal mating counter-face was shown to be less than 8 N/cm for both elastomer compounds. The level of adhesion was highest at the coldest temperature tested, -50°C. Increasing the length of time the test specimens were held compressed did not significantly affect the adhesion level observed.

The results of the destructive retention and adhesion tests conducted during the course of this investigation showed that the candidate docking seal designs were resistant to failure due to adhesive loads that may be encountered during operation.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
To successfully mate two pressurized vehicles or structures in space, advanced seals are required at the interface to prevent the loss of breathable air to the vacuum of space. A critical part of the development testing of candidate seal designs was a verification of the integrity of the retaining mechanism that holds the silicone seal component to the structure. Failure to retain the elastomer seal during flight could liberate seal material in the event of high adhesive loads during undocking. This work presents an investigation of the force required to separate the elastomer from its metal counter-face surface during simulated undocking as well as a comparison to that force which was necessary to destructively remove the elastomer from its retaining device. Two silicone elastomers, Wacker 007-49524 and Esterline ELA-SA-401, were evaluated. During the course of the investigation, modifications were made to the retaining devices to determine if the modifications improved the force needed to destructively remove the seal. The tests were completed at the expected operating temperatures of -50, +23, and +75 °C. Under the conditions investigated, the comparison indicated that the adhesion between the elastomer and the metal counter-face was significantly less than the force needed to forcibly remove the elastomer seal from its retainer, and no failure would be expected.

15. SUBJECT TERMS
Elastomer; Silicones; Space seals

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